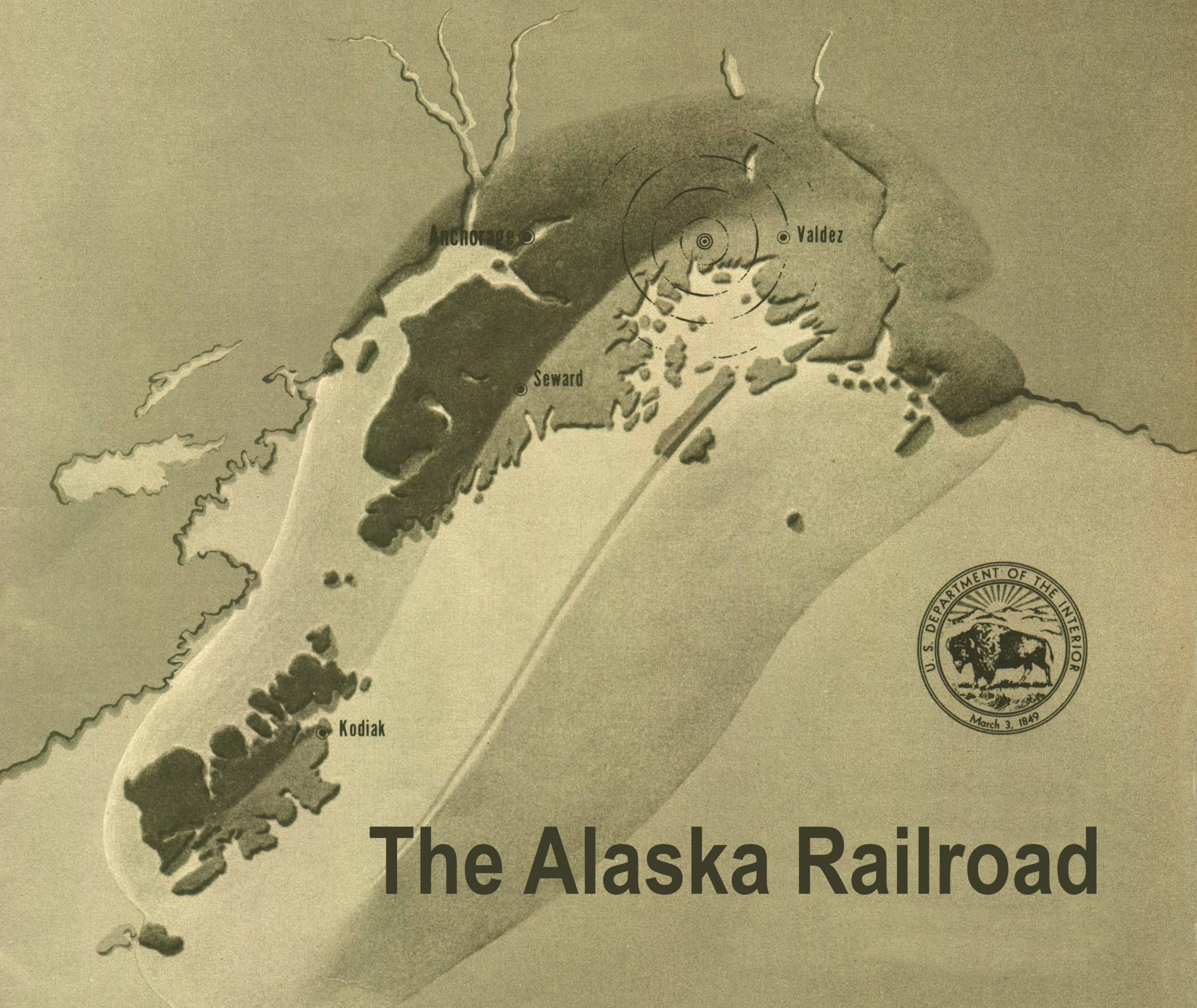
The Alaska Earthquake
March 27, 1964

Effects on Transportation and Utilities



The Alaska Railroad

GEOLOGICAL SURVEY PROFESSIONAL PAPER 545-D

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THE ALASKA EARTHQUAKE, MARCH 27, 1964:
EFFECTS ON TRANSPORTATION, COMMUNICATIONS, AND UTILITIES

Effects of the Earthquake Of March 27, 1964, on The Alaska Railroad

By DAVID S. McCULLOCH and MANUEL G. BONILLA

A description and analysis of the geologic controls of earthquake damage to The Alaska Railroad, with emphasis on damage caused by the mobilization of unconsolidated sediments

GEOLOGICAL SURVEY PROFESSIONAL PAPER 545-D

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THE ALASKA EARTHQUAKE SERIES

The U.S. Geological Survey is publishing the results of investigations of the earthquake in a series of six professional papers. Professional Paper 545 describes the effects of the earthquake on transportation, communications, and utilities. Chapters in this volume already published are on the Eklutna Hydroelectric Project in Anchorage; the effects of the earthquake on air and water transport, communications, and utilities systems in south-central Alaska; and the effects of the earthquake on the Alaska Highway system. This report is the final chapter of Professional Paper 545.

Other professional papers, already published, describe the field investigations and reconstruction, and the effects of the earthquake on communities, on regions, and on the hydrologic regimen. A selected bibliography and an index for the entire series will be published in the concluding volume, Professional Paper 546.

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[Plates are in pocket]

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EFFECTS OF THE EARTHQUAKE OF MARCH 27, 1964, ON THE ALASKA RAILROAD

By David S. McCulloch and Manuel G. Bonilla

ABSTRACT

In the 1964 Alaska earthquake, the federally owned Alaska Railroad sustained damage of more than $35 million: 54 percent of the cost for port facilities; 25 percent, roadbed and track; 9 percent, buildings and utilities; 7 percent, bridges and culverts; and 5 percent, landslide removal. Principal causes of damage were: (1) landslides, landslide-generated waves, and seismic sea waves that destroyed costly port facilities built on deltas; (2) regional tectonic subsidence that necessitated raising and armoring 22 miles of roadbed made susceptible to marine erosion; and (3), of greatest importance in terms of potential damage in seismically active areas, a general loss of strength experienced by wet water-laid unconsolidated granular sediments (silt to coarse gravel) that allowed embankments to settle and enabled sediments to undergo flowlike displacement toward topographic depressions, even in flat-lying areas. The term "landspreading" is proposed for the lateral displacement and distension of mobilized sediments; landspreading appears to have resulted largely from liquefaction. Because mobilization is time dependent and its effects cumulative, the long duration of strong ground motion (timed as 3 to 4 minutes) along the southern 150 miles of the rail line made landspreading an important cause of damage.

Sediments moved toward natural and manmade topographic depressions (stream valleys, gullies, drainage ditches, borrow pits, and lakes). Stream widths decreased, often about 20 inches but at some places by as much as 6.5 feet, and sediments moved upward beneath stream channels. Landspreading toward streams and even small drainage ditches crushed concrete and metal culverts. Bridge superstructures were compressed and failed by lateral buckling, or more commonly were driven into, through, or over bulkheads. Piles and piers were torn free of superstructures by moving sediments, crowded toward stream channels, and lifted in the center. The lifted piles arched the superstructures. Vertical pile displacement was independent of the depth of the pile penetration in the sediment and thus was due to vertical movement of the sediments, rather than to differential compaction. The fact that bridge piles were carried laterally without notable tilting suggests that mobilization exceeded pile depths, which averaged about 20 feet. Field observations, largely duplicated by vibrated sandbox models of stream channels, suggest that movement was distributed throughout the sediments, rather than restricted to finite failure surfaces.

Landspreading generated stress that produced cracks in the ground surface adjacent to depressions. The distribution of this stress controlled the crack patterns: tension cracks parallel to straight or concave streambanks, shear cracks intersecting at 45° to 70° on convex banks where there was some component of radial spreading, and orthogonal cracks on the insides of tight meander bends or islands where spreading was omnidirectional.

Ground cracks of these kinds commonly extended 500 feet, and occasionally about 1,000 feet, back from streams, which indicates that landspreading occurred over large areas. In areas of landspreading, highway and railroad embankments, pavements, and rails were pulled apart endways and were displaced laterally if they lay at an angle to the direction of sediment displacement. Sediment movement commonly skewed bridges that crossed streams obliquely. The maximum horizontal skew was 10 feet.

Embankment settlement, nearly universal in areas of landspreading, also occurred in areas where there was no evidence for widespread loss of strength in the unconsolidated sediments. In the latter areas embankments themselves clearly caused the loss of bearing strength in the underlying sediment. In both areas, settlement was accompanied by the formation of ground cracks approximately parallel to the embankment in the adjacent sediments. Sediment-laden ground water was discharged from the cracks, and extreme local settlements (as much as 6 ft) were associated with large discharges.

Landspreading was accompanied by transient horizontal displacement of the ground that pounded bridge ends with slight or considerable force. The deck of a 105-foot bridge was repeatedly arched up off its piles by transient compression. Bridges may also have developed high horizontal accelerations. One bridge deck, driven through its bulkhead, appears to have had an acceleration of at least 1.1 to 1.7 g; however, most evidence for high accelerations is ambiguous.

Limited standard penetration data show that landspreading damage was

not restricted to soft sediments. Some bridges were severely damaged by displacement of piles driven in sediments classified as compact and dense.

Total thickness of unconsolidated sediments strongly controlled the degree of damage. In areas underlain by wet water-laid sediments the degree of damage to uniformly designed and built wooden railroad bridges shows a closer correlation with total sediment thickness at the bridge site than with the grain size of the material in which the piles were driven.

Local geology and physiography largely controlled the kind, distribution, and severity of damage to the railroad. This relationship is so clear that maps of surficial geology and physiography of damaged areas of the rail belt show that only a few geologic–physiographic units serve to identify these areas:

1. Bedrock and glacial till on bedrock. No foundation displacements, but ground vibration increased toward the area of maximum strain-energy release.
2. Glacial outwash terraces. Landspreading and damage ranged from none where the water table was low and the terrace undissected to severe where the water table was near the surface and the terrace dissected by streams.
3. Inactive flood plains. Landspreading, ground cracking, flooding by ejected ground water, and damage were generally slight but increased to severe toward lower, wetter active flood plains or river channels.
4. Active flood plains. Landspreading, ground cracking, and flooding were nearly universal and were greater than on adjacent inactive flood plains.
5. Fan deltas. Radial downhill spreading and ground cracking were considerable near the lower edges of the fan deltas and were accompanied by ground-water discharge. Landslides were common from edges of deltas.

Damage, landspreading, ground cracking, vibration, and flooding by ground water generally increased with (1) increasing thickness of unconsolidated sediments, (2) decreasing depth to the water table, (3) proximity to topographic depressions, and (4) proximity to the area of maximum strain–energy release.

INTRODUCTION

Within 2 hours after the first tremor of the Alaska earthquake of March 27, 1964, the federally owned Alaska Railroad had sustained more than $35 million worth of damage. The destructive agents took many forms. Seismic sea waves, landslides, and waves generated by slides from the edges of deltas largely destroyed or severely damaged complex and costly port facilities at Seward and Whittier — ports through which passed most of Alaska's waterborne freight. The damage was compounded by seismic shaking, ground cracking, and burning fuel carried inland by the waves (Grantz and others, 1964; Kachadoorian, 1965; Lemke, 1967). More than 100 miles of roadbed settled or was displaced and broken by ground cracks in areas underlain by unconsolidated sediments. In the same areas, 125 bridges and more than 110 culverts were damaged or destroyed. Landslides overran or carried away several miles of roadbed and destroyed or severely damaged buildings and utilities. Other railroad structures were destroyed or damaged by seismic shaking. Tectonic subsidence lowered the land as much as 5.5 feet along the railline and made about 35 miles along the shore susceptible to flooding at high tide and to accelerated marine erosion.

The type and severity of the damage to the rail belt were largely controlled by the geology, the physiography, and the proximity to the area of strain release. Damage was concentrated in areas underlain by wet water-laid noncohesive young sediments in which grain size ranged from silt to gravel. Similar structures on older drier sediments, or on till or bedrock, were nearly undamaged. The seismic shaking mobilized the sediments, which then spread laterally toward topographic depressions carrying along the overlying embankments. At stream crossings the bridge superstructures were compressed, and their supports crowded together as the sediments moved toward the stream channels (McCulloch and Bonilla, 1967). In addition to being damaged by these permanent displacements of the foundation materials, bridges were subjected to transient horizontal displacements, some of which had considerable force.

Spreading of unconsolidated granular sediments commonly occurred on fans and deltas, but was more widespread and highly damaging to structures on the extensive flat or nearly flat areas. The term "landspreading" is proposed for this type of ground movement, first to describe the distension that occurs within the sediments, and second to bring attention to the fact that it occurs on flat or nearly flat ground as opposed to landsliding which has the connotation of downslope movement. The phenomena described as landspreading can probably be largely attributed to liquefaction. However, because landspreading may have been due in part to other causes, it is preferable to avoid a term that specifies a single mechanism.

This report has two parts. The first describes damage to structures as an indication of the behavior of foundation materials during the earthquake. These observations are then used to explain the formation, location, and pattern of some of the ground cracking that occurred over very large areas. Other topical subjects are included in this first part. In an effort to be of use to designers building structures in similar areas, the damage is described in some detail and some estimates are made of the forces that were exerted on the structures.

The second part of this report is a mile-by-mile description of the surficial geology and the damage to the railroad and some of the adjacent areas. This part documents the close relation of the geology to the distribution, severity, and type of damage; it serves as a record which should prove useful in the future development of these and similar areas; and it provides an opportunity to record details of damage to particular structures not included in the preceding topical discussions.

As a preface to the discussion of railroad damage, the following descriptions, by I. P. Cook (written commun. 1969), chief engineer, and from the Railbelt Reporter (1964, p. 4–5), of the events following the earthquake are given so that the reader may appreciate the tremendous job that faced the small staff of The Alaska Railroad, and their immediate and energetic response.

I. P. Cook wrote that, on Friday, immediately following the earthquake:

First to arrive at the dispatching headquarters of the Railroad's Terminal Building was John Manley, the General Manager. True to Railroad tradition, other Railroaders appeared on the scene and each began to check out his particular responsibility.

Communication with line points of the Railroad was virtually wiped out, and the only assessment that could be made before darkness set in by headquarters staff people was that in the immediate area of the Anchorage Terminal.

With the first rays of dawn on Saturday, various officials met with the General Manager and a plan was outlined for assessing damages and corrective action. Helicopters and fixed-wing airplanes were brought into service from commercial companies to gain access for inspection and determination of damage. On this first morning after the earthquake, General Manager John Manley, together with Cliff Fuglestad, Engineer of Track, made a helicopter flight as far as the Hunter Flats and also over to Tunnel Door 2 on the Whittier Branch. Simultaneously, Engineer of Structures, Bruce Cannon, together with Roadmaster Paul Watts, started north over the Railroad as far as Willow, determining damage. A fixed-wing airplane was dispatched to Seward with Assistant Chief Engineer Charles Griffith. He was met at Seward by Chief Engineer Irvin Cook, who had made his way in from the Kenai Lake area.

Assistant General Manager, Dick Bruce, and General Roadmaster, Jack Church, traveling by car and on foot were able to survey the damage between Anchorage and Suntrana, source of the coal used to generate much of the heat and power consumed in Anchorage.

As these various flights and reports arrived back in Anchorage and a summation was made of the damage, initial loss could readily be placed at $20 million dollars. Some 200 miles of railroad were totally immobilized. The flights revealed that in excess of 110 bridges were rendered unserviceable. Miles of track were warped out of line and rails twisted. Landslides accounted for over 2½ miles of lost grade. Numerous avalanches which had been triggered by the shock covered the tracks as much as 20 to 30 feet and had carried away communication lines. The port of Seward facilities were virtually wiped out by a combination of seismic action, tidal waves, and fire. Our secondary Port of Whittier fared somewhat better, but was far from operable. The vital car barge slip was gone.

Several major shops and industrial structures were either 100 percent destroyed or required extensive repair at our Anchorage headquarters and other line points; 225 pieces of rolling stock were either lost, or badly damaged.

Emergency communication lines were quickly restored to allow Railroad personnel at various points along the Railroad to gain communication and to receive instructions as to restoration procedures.

On Saturday, the Railbelt Reporter said that:

Communications employees were back on the job and they managed to get the microwave system south going as far as Mile 92 by running all repeater stations on emergency power. Men started north to clean up the open wire circuits.

In the office, employees were trying to bring order out of the jumble. File cabinets had toppled over, light fixtures had fallen, spraying desks, chairs and floors with glass; cabinets had opened, spilling contents.

March 29, 1964 — By Sunday night, our Communications people had the microwave system in operation to Portage, despite the fact that both the 150-foot tower and the wooden tower at Portage had been severely damaged.

From March 30, 1964 on — After a harrowing weekend, punctuated by over 40 aftershocks, Alaska Railroaders in full force rolled up their sleeves and started putting their railroad back together again.

Communications had a 'whoop and holler' circuit into Seward by March 30 and by March 31, they had five channels of communication into that stricken city.

Train and enginemen offered their services wherever they were needed, and helped with the gigantic clean-up job.

Anchorage Freight Depot employees, their regular jobs temporarily eliminated by the quake, were recruited for other jobs. All through that first week they worked, righting file cabinets, pounding drawers back into shape, cleaning up broken glass and furniture, filling Preco heaters, carrying water for rest rooms, moving furniture. There was no heat in the General Office Building and no water. Employees brought jugs of water for drinking and making coffee. Of necessity, slacks, warm sweaters, jackets, and fur-lined boots became the accepted attire of women employees.

* * * * *

During the next few days, Harriet LaZelle and her girls in the Employment Bureau, hired between 200 and 300 temporary employees to assist in the big job ahead. Long lines of men extended into the passenger depot, as they waited to be fingerprinted by the special agents before being transported to damaged areas.

Mechanical employees busied themselves tearing down the Wheel Shop, two walls of which had collapsed during the quake. They set up offices for the chief mechanical officer and his staff in the Diesel Building as fast as furniture and equipment could be retrieved from the condemned Wheel Shop.

* * * * *

Secretary to the Chief Engineer, Fran Moore, had this to say about Engineering:

"On Monday morning, following the quake, the department moved ahead en masse and despite much adversity (lack of communication, transportation, etc.), things began happening. Contractors moved in along the line, and with their huge machines began at once the clearing and dozing operations needed in the rebuilding of Uncle Sam's farthest north railroad.

"Within days, on April 6, the first freight train moved north from Anchorage to Fairbanks; the Palmer branch was opened, and work along the southern portion of the line was progressing rapidly.

"Fills were made, bridges repaired, and rail was laid. Divers were sent to Whittier to probe under the water for possible salvage. 'Whirly-birds' airlifted personnel up and down the line, surveying the wreckage, and brought them back to report what they had seen and what was needed for repairs. Work-weary, red-eyed roadmasters and supervisors reported in, received their new instructions, and went back to the job and their equally tired men. Sleep was all but forgotten, but The Alaska Railroad is being rebuilt."

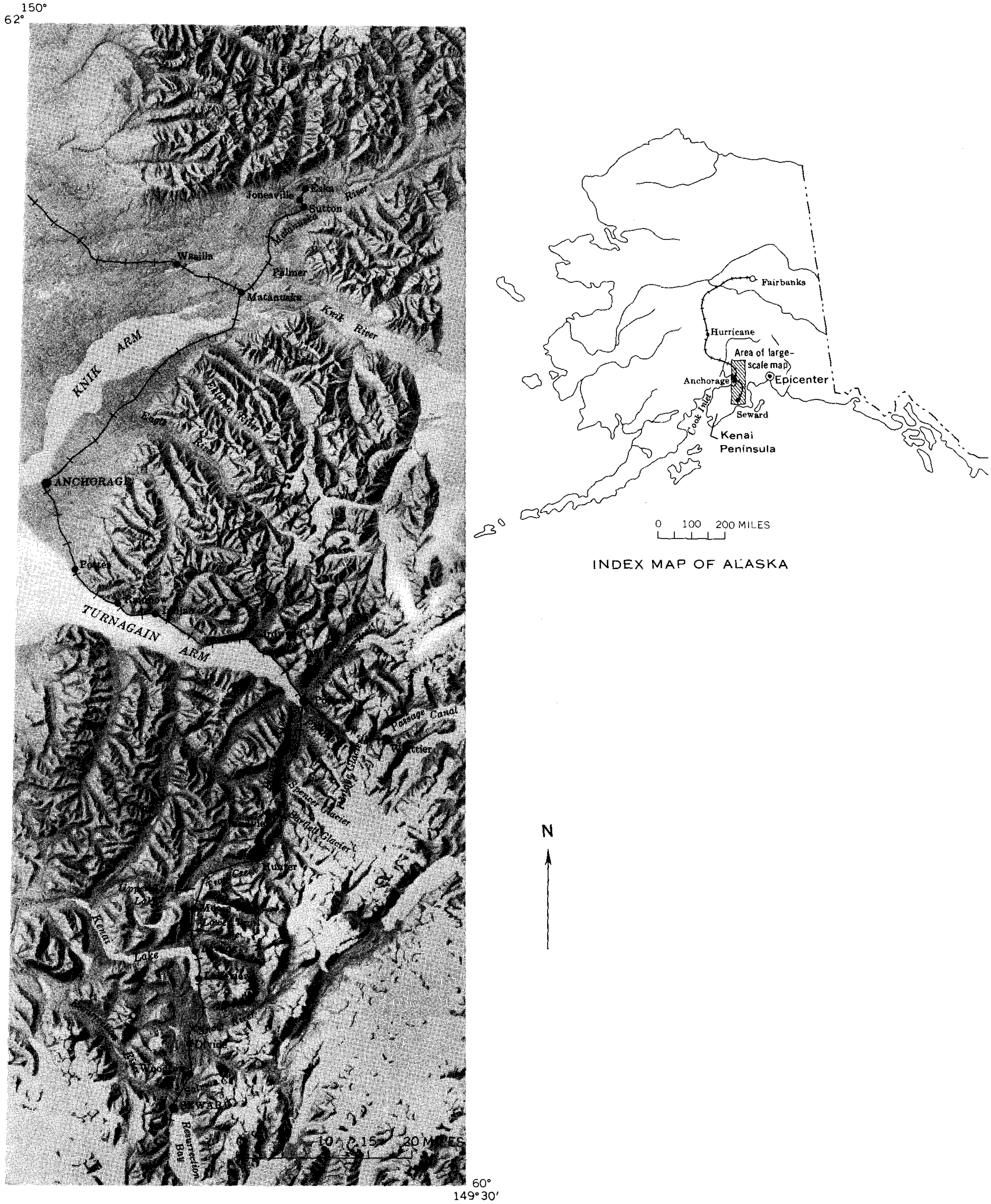
The story was the same, from devastated Whittier and Seward to the south, to Fairbanks in the north, Alaska Railroaders rallied to do their bit in this great catastrophe.

ACKNOWLEDGMENTS

The authors are grateful to many employees of the railroad who took some of their valuable time during the busy days of reconstruction to be of assistance, especially the following: J. E. Manley, general manager; I. P. Cook, chief engineer; C. L. Griffiths, assistant chief engineer; B. E. Cannon, engineer of structures; Clifford Fugelstad, engineer of track; Jack Church, trackmaster; James Morrison and Arnie Hesness, engineers; Carl Nelson, electrical supervisor; and Francis Weeks, accountant. In addition, subsurface and other information along the highway was obtained from Bruce Campbell and Frank Buskie of the Alaska Department of Highways. C. A. Hill, D. K. Conger, and C. H. Harned of the consulting engineering firm of Clair A. Hill and Associates of Redding, Calif., provided reports on changes in railroad grade, information on the Potter Hill landslide and borings in the Portage area. Aerial photographs of the railroad were made available by the U.S. Army in Anchorage. Professor A. M. Johnson of the geology department of Stanford University derived the equations used in the analysis of compressive forces that were exerted on a bridge; A. Kennedy of the U.S. Forest Service, Anchorage, supplied several of the photographs; Webb Hayes, of the engineering firm of Earl and Wright, of San Francisco, which acted as a consultant to the railroad during reconstruction, reviewed the description of damage to railroad buildings in Anchorage; and Frank McClure, of McClure and Messinger, consulting structural engineers, Oakland, Calif., reviewed the sections titled "Summary and Conclusions" and "Construction in Areas of Potential Landspreading."

LOCATION AND PHYSIOGRAPHIC SETTING

The southern terminus of The Alaska Railroad is the deepwater all-weather port of Seward, built on a fan delta in Resurrection Bay fiord on the Gulf of Alaska (fig. 1). North from Seward (mile 0) the rail line runs about 64 miles across the steep and rugged glaciated terrain of Kenai Peninsula to Portage, where it is joined by a 12-mile spur line to a second deepwater all-weather port at Whittier, on Prince William Sound. From Portage to Anchorage the rail line is built along the north shore of



1.—Location of The Alaska Railroad.

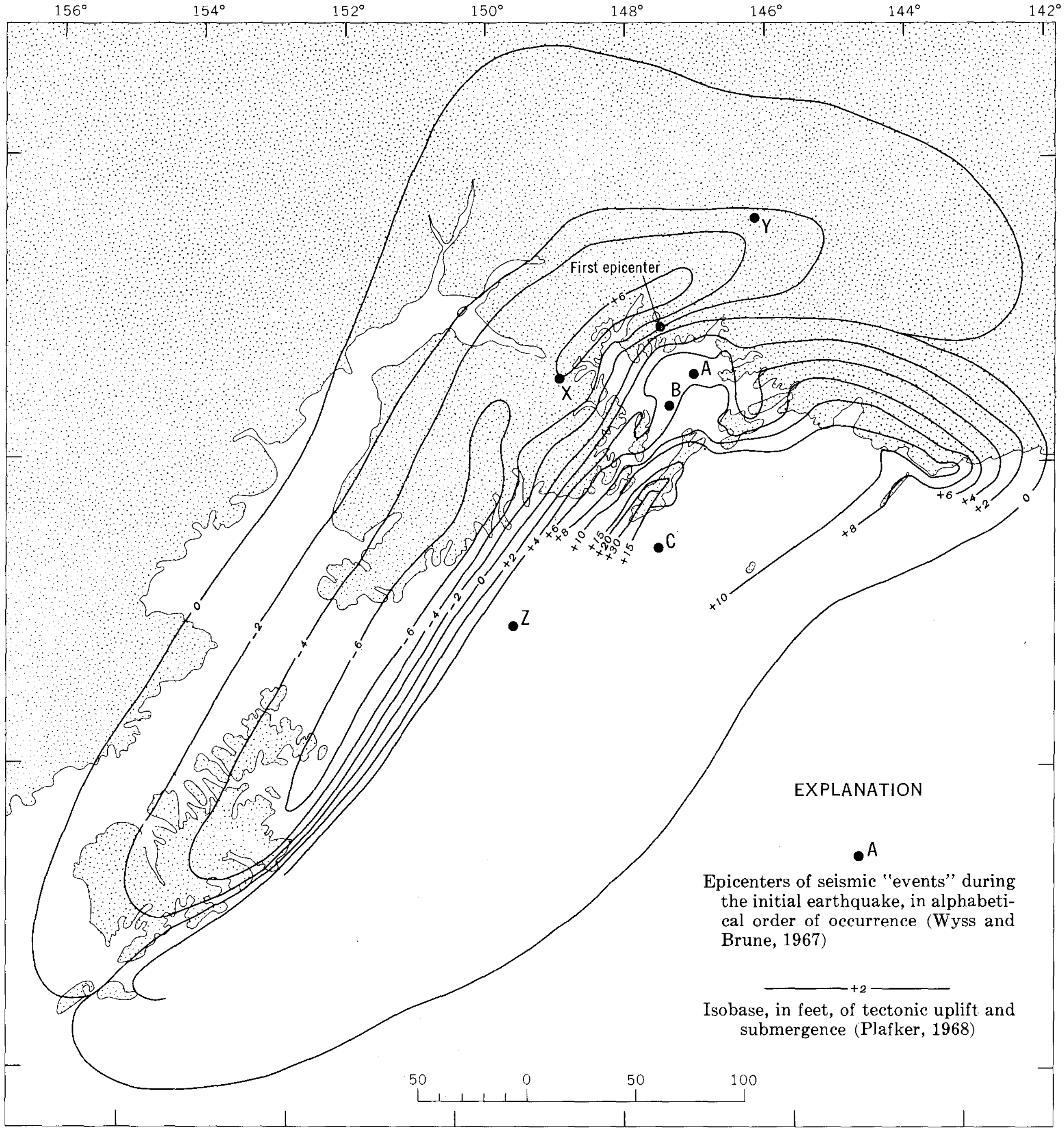
Turnagain Arm at the foot of steep mountains; at Potter it swings inland over gently rolling plains of glacial deposits to the main rail yards in Anchorage, mile 114, on the shore of Cook Inlet. Leaving Anchorage, the line continues across the glacial plain along the southeast side of Knik Arm to the wide flood plain of the Knik and Matanuska Rivers that empty into the head of the arm at about mile 146. At Matanuska, on the northern edge of the flood plain, the line is joined by a 22-mile spur that follows the northwest side of the Matanuska River to Palmer, Sutton, Jonesville, and Eska. The main line turns west at Matanuska, then swings north in a long curve along the valley of the Susitna River which it follows through the mountainous terrain near Mount McKinley National Park. Crossing the drainage divide of the Alaska Range at Summit (mile 312.5) the rail line continues north in the Nenana River valley to the town of Nenana at mile 411.7. From here it swings to the northeast and reaches Fairbanks at mile 470.3.

The mountainous topography between Seward, Whittier, and Potter, and in the Mount McKinley Park area has restricted possible railroad location. Across the Kenai Peninsula the rail line is built on the floors of steep-walled elongate glaciated valleys, and, except where crowded to the side of the valley by lakes or rivers, it is built far enough from the walls to avoid snow avalanches and landslides. Because of these restrictions, the rail line had to be built on marshes, active flood plains, and in the Nenana River valley on known landslides (Wahrhaftig and Black, 1958). Thus much of the damage to the rail line that resulted from displacements or loss of bearing strength of the soft sediments could not have been avoided.

THE EARTHQUAKE

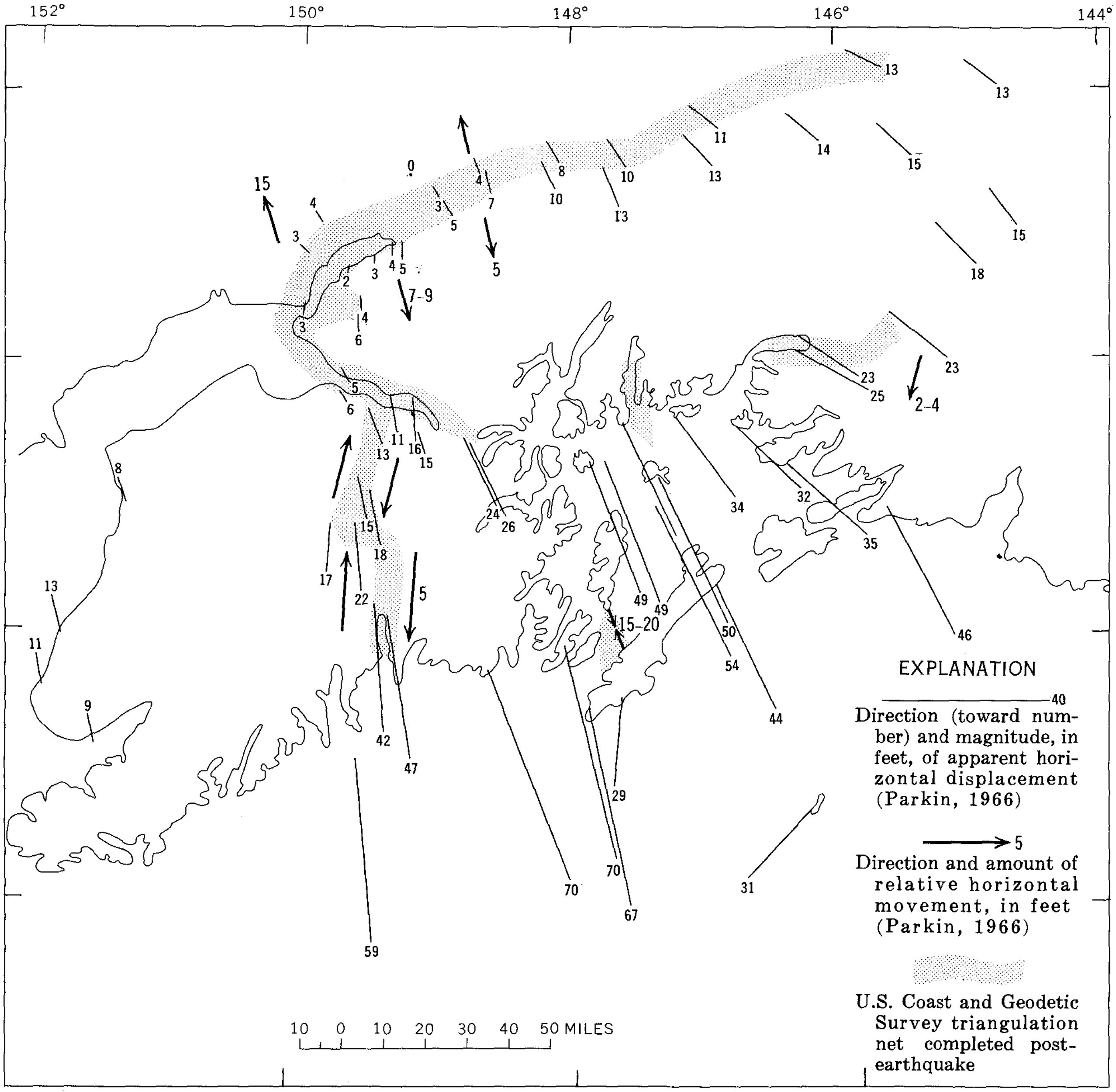
The great Alaska earthquake occurred at 5:36 p.m., Alaska standard time, on March 27, 1964. The epicenter has been located approximately 80 miles east-southeast of Anchorage, on the shore of Unakwik Inlet (fig. 2). The hypocentral depth is not known, but is thought to have been between 12.5 and 31 miles (20 to 50 km). The epicenter lies between elongate southwest-trending belts in which the surface of the earth was uplifted and subsided. The amount and distribution of the land-level changes have been mapped by Plafker (1965, 1968), and he proposed the following low-angle thrust model to explain the regional uplift and subsidence: Prior to the earthquake, strains were generated within the continental crust as it was underridden by the oceanic crust and mantle. At some critical strain, rupture occurred along a major zone of weakness, or megathrust, that may coincide with the base of the continental crust along the continental margin. Wilson and Tørum (1967) have suggested that the rupture was triggered by the coincidence of large-amplitude earth tides which increased the stress with low-water tides (Berg, 1966) which reduced the resistance to thrusting by unloading the surface above the thrust. At the time of rupture, that part of the strain which had been stored elastically in the continental rocks above the rupture was released, and the rocks were driven to the southeast over the rupture surface. From the surface deformation pattern and seismic data, Plafker infers that the rupture surface may have intersected the Aleutian Trench, and then dipped gently to the northwest for a distance of about 300 km, to a depth of about 40 km. Thus, with the release of elastic strain a zone of surface uplift was produced when continental rocks were driven up the dip of the rupture surface; while to the northwest, the land surface was lowered by elastic horizontal extension and vertical attenuation of the crust behind the thrust block. A thrust is also favored by Stauder and Bollinger (1966) who have demonstrated that there was a uniformity of motion in one preshock, the main shock and the aftershock sequence. They believe the combined *P*-wave first motion and *S*-wave polarization in the aftershocks favor movement on a low-angle thrust plane, not on a steeply dipping plane as suggested by Press and Jackson (1965).

Large horizontal displacements were measured by the U.S. Coast and Geodetic Survey during their 1964–1965 retriangulation of the preearthquake triangulation net (Parkin, 1966). Accepting Parkin's assumption that a station about 35 miles northeast of Anchorage was not displaced hori-



2.—Location of the epicenters of recognizable seismic events that occurred during the earthquake (Wyss and Brune, 1967) and areas of tectonic uplift and subsidence in south-central Alaska (Plafker, 1968).

zontally, the resurvey indicates a general and increasing horizontal displacement to the southeast in the subsided and landward part of the uplifted areas (fig. 3). The horizontal displacements have been interpreted as indicating a widening of about 5 feet across Matanuska Valley and a right-lateral displacement of about 5 feet along the net between Sunrise and Seward (Wood, 1966, p. 121). There is as yet no independent evidence for lateral displacement along this latter part of the net; however, from Moose Pass to Seward the net follows a conspicuous topographic trough which probably owes its origin to faulting. The possibility of displacement along the line from Moose



3.—Horizontal displacement that accompanied the earthquake.

Pass to Seward may be important in assessing the damage to the railroad, which lies in this trough.

Because much of the damage to the railroad resulted from changes in foundation materials that are time-dependent and cumulative, the duration of seismic vibration was of extreme importance in determining the kinds and degree of damage. Wyss and Brune (1967) have shown in an analysis of *P*-phases on worldwide seismograms that there were three distinct and an additional three probable events during the main shock (fig. 2). These events occurred at increasing distances from the epicenter at 9, 19, 28, 29, 44, and 72 seconds after the initial origin time. The Richter magnitude of the first *P*-pulse was 6.6; successive phases had larger amplitudes. The largest *P*-wave amplitudes had a magnitude of 7.8, and occurred about 60 seconds after the first arrival of the *P*-wave train. The distribution of the epicenters and the time of origin of the events indicate that the railroad was subjected to a long period of severe shaking from seismic waves that were generated over a wide area.

Estimates of the duration of strong ground motion along the rail line range from 3 to 4 minutes, and estimates of the total duration of perceptible ground motion vary even more. In Anchorage, shaking timed by watch indicates that on unconsolidated sediments strong motion lasted 3 to 4 minutes and perceptible shaking had a total duration of about 7 minutes (Shannon and Wilson, Inc., 1964a). At Portage, which is underlain by several hundred feet of water-saturated fine-grained sediments, perceptible ground motion may have lasted as much as 15 minutes (Kachadoorian, 1965). To the south, at the west end of Kenai Lake in an area also underlain by at least 200 feet of unconsolidated sediment, John Ingraham reported that after a period of about 8 minutes, the large trees were still swaying as if in a high wind. John Kehdon made the same observation in the same area (Railbelt Reporter, 1964). In Seward, at the southern end of the rail line, also on unconsolidated sediments, strong motion lasted 3 to 4 minutes (Lemke, 1967).

The earthquake was followed by a series of strong aftershocks with magnitudes reported to be as high as 6.7 (Wood, 1966, p. 68). Despite the size of these aftershocks, there is no evidence that any caused additional damage to the railroad.

EARTHQUAKE EFFECTS

BRIDGE DAMAGE CAUSED BY DISPLACEMENT OF FOUNDATION MATERIALS

Damaged railroad bridges have been described in many studies of earthquakes (Hobbs, 1908; Hollis, 1958; Japan Soc. Civil Engineers, 1960; Duke, 1960). It is difficult, however, to compare these descriptions and to understand the damage-causing mechanisms because (1) the bridges were damaged by different seismic events, (2) the bridges vary greatly, from those built of bamboo to those built of heavy masonry, and (3) the kinds measurements taken by the various observers are not consistent. In contrast, for the Alaska earthquake it was possible to make comparable measurements of damage to many bridges of the same design and construction.

Most of the bridges within the area affected by the earthquake are the type shown in Figure 4. They are open wood trestles, supported on wood piling, with wood bulkheads. Piles are driven to a calculated bearing capacity of 15 tons. In larger and more complex bridges on steel piles, the piles are driven to a calculated bearing capacity of 35 to 50 tons. Some few bridges have concrete or multiple piers and steel decks.

Bridge damage resulted from (1) permanent horizontal and vertical displacements of foundation materials, (2) transient horizontal displacement of the ground, and (3) high accelerations generated within bridge structures by the amplification of ground motion. Because damage usually resulted from some combination of these elements, it is necessary to discuss some details of the damage to evaluate each of these elements. In a few cases, observations provide approximations of the forces that were exerted, which may be useful in the design of similar structures in other seismically active areas. But of equal importance is the conclusion that the observations provide evidence that the gross behavior of a wide range of noncohesive materials can be generally predicted without detailed site information.

HORIZONTAL DISPLACEMENT

In nearly every damaged bridge, bents were shifted both horizontally and vertically, as shown diagrammatically in figure 5. Shifting occurred without vertical rotation; thus bents remained nearly vertical. Most horizontal displacement took place in the line of the bridge. In addition, where the bridge deck buckled laterally there were up- or downstream movements of the bents, but these piles appear to have been dragged by the deflecting superstructure (see p. D116).

Most displaced bents were torn free of the superstructure. Some pile caps remained attached to the piles and were pulled from the bolts that secured them to the stringers (fig. 5). Other pile caps remained secured to the stringers, but the piles pulled free of the drift pins that attach them to the pile cap and the sway braces were often split and detached from the caps. In other bridges, the pile caps were partially pulled from the stringers and the piles and were rotated between the shifting piles and the deck. Displacements of the bents probably very nearly reflect the movement of the foundation materials, because the connections between the piling and the superstructure appear to have offered little resistance to the horizontal displacement of the piles. If the connections at the tops of the bents had held, their bases would have rotated streamward, as were the bases of some of the piers

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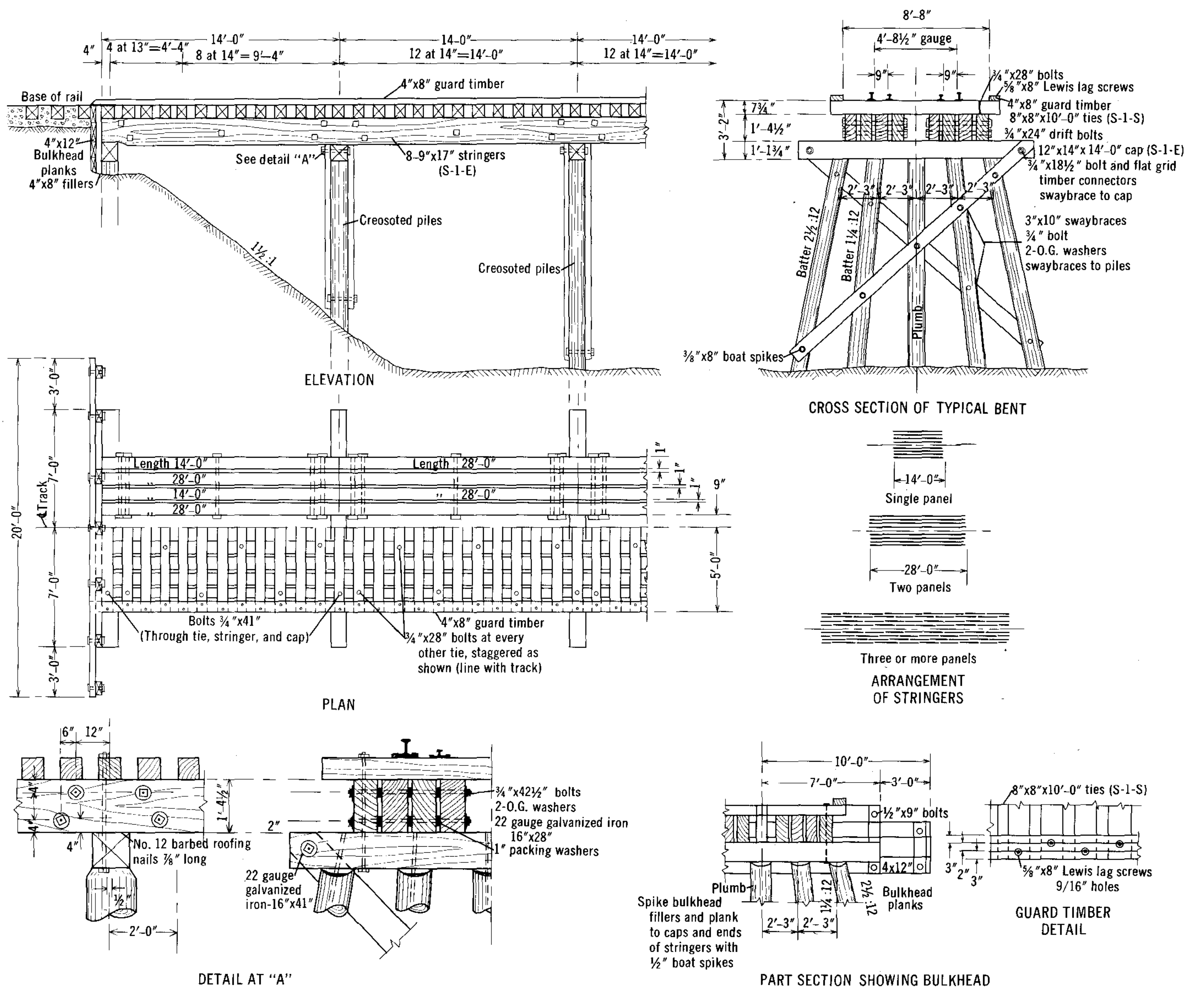
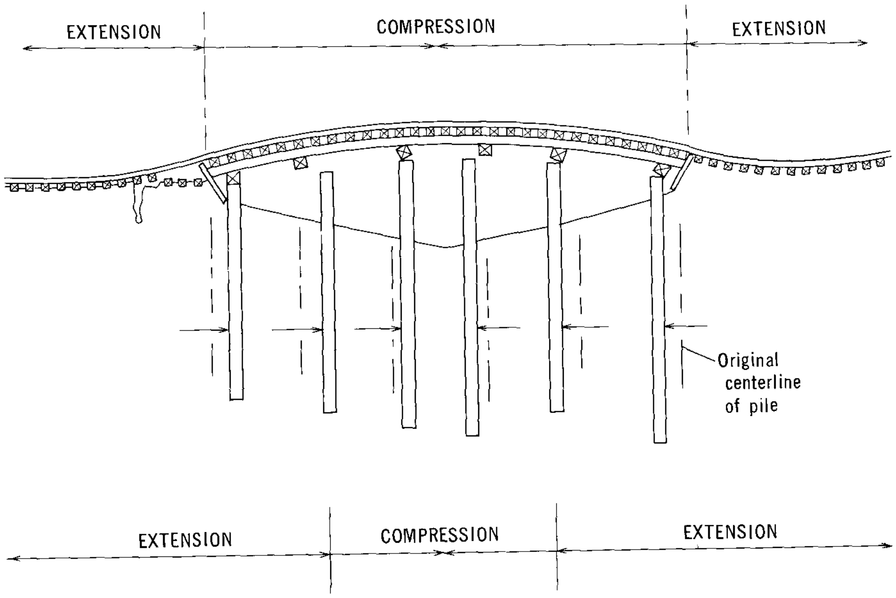


4.—Construction plans for a standard open-deck wood-pile trestle. Drawings by The Alaska Railroad.



5.—Typical displacement of bridge piles. Most piles were crowded toward the center of the stream. The distance between piles increased at the bridge ends and decreased toward the bridge center. Piles in the center usually stood higher than at the ends.

under the highway bridges whose tops were held apart by steel decks (fig. 6).

Relative horizontal displacements between bents, as determined by measuring offsets between the pre- and postearthquake position of the bents on the stringers, are plotted as bar graphs on figures 7 and 8. Distances between bents increased, remained unchanged, or decreased. The displacements are shown on the graphs in terms of the interpreted behavior of the foundation material as extension, no change, or compression.

In figure 9 the movements between bents are summarized for the short (12- to 45-ft), intermediate (60- to 98-ft), and long (105- to 150-ft) bridges shown in figures 7 and 8. In order to compare bent movement in bridges of various lengths, the amount of movement between adjacent bents is given as the percentage of the bridge length.

Most bents were shifted toward the streams. The fact that distances between bents generally were increased near the bridge ends and were decreased toward the centers of the streams indicates that there were zones of extension at the margins and compression at the centers. This is most clearly shown in the short bridges. In intermediate and long bridges the bent movements were more complex. There was usually extension at the margins but there were often several zones of compression and extension on the valley floor. Some, but not all, zones of compression were located at distinct channels.

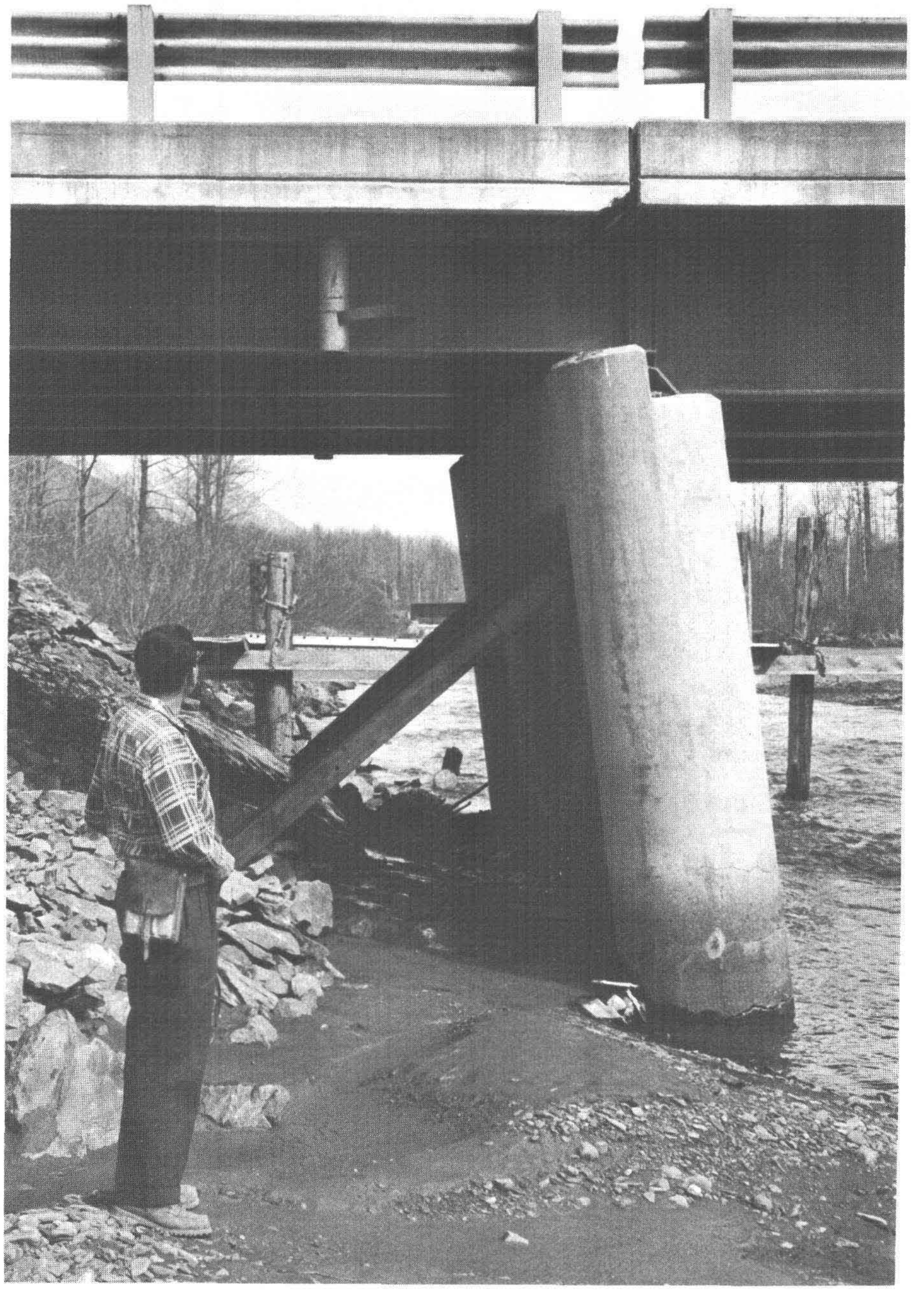
In all but six bridges, the net compression shown by interbent measurements exceeded the net extension (fig. 10). Net compression was generally 20 inches or less, regardless of bridge length, but in two bridges compression was as large as 64 and 81.5 inches.

In addition to having their supporting bents torn free, most stringers were put into compression by converging streambanks. Distances between streambanks were decreased by as much as 6.5 feet (table 1). As a result, the stringers acted as struts, and either jammed into the fillers on the bulkheads (fig. 11) or, where compression was greater, drove through the bulkhead planks (fig. 44). In some bridges most of the compression was released at one end, and the stringers were thrust up over the top of the bulkhead onto one of the approach fills.

Compressive forces not released by failures at the bulkheads produced lateral deflections in the decks of several bridges (those at mile 37.0, 37.3, 63.0). Stringers were either thrown into long horizontal bends, or were broken at sharp kinks, with as much as 8 feet of lateral deflection at the apex of the bends (figs. 12, 18). At mile 34.5 the distance between bulkheads of a 105-foot wood bridge was decreased by 2.0 feet. The resulting compression jackknifed the deck up off its pilings (fig. 13). The apex of the bend in the deck occurred where four of the eight stringers were butt-jointed; the remaining four stringers were broken. This is the only bridge in which it is clear that compression contributed to arching. In other arched bridges the decks lay in contact with most of the piling, and arching resulted primarily from vertical displacement of piling (see p. D114), on which the deck lay passively.

VERTICAL DISPLACEMENT

Displaced foundation materials often had a vertical component of movement; at many bridges the tops of piles were higher at midstream than near the banks. Less commonly, there was no vertical displacement, and pile tops were level. There were no bridges in which piling was lower in stream centers. As a result, many bridges were arched upward and others



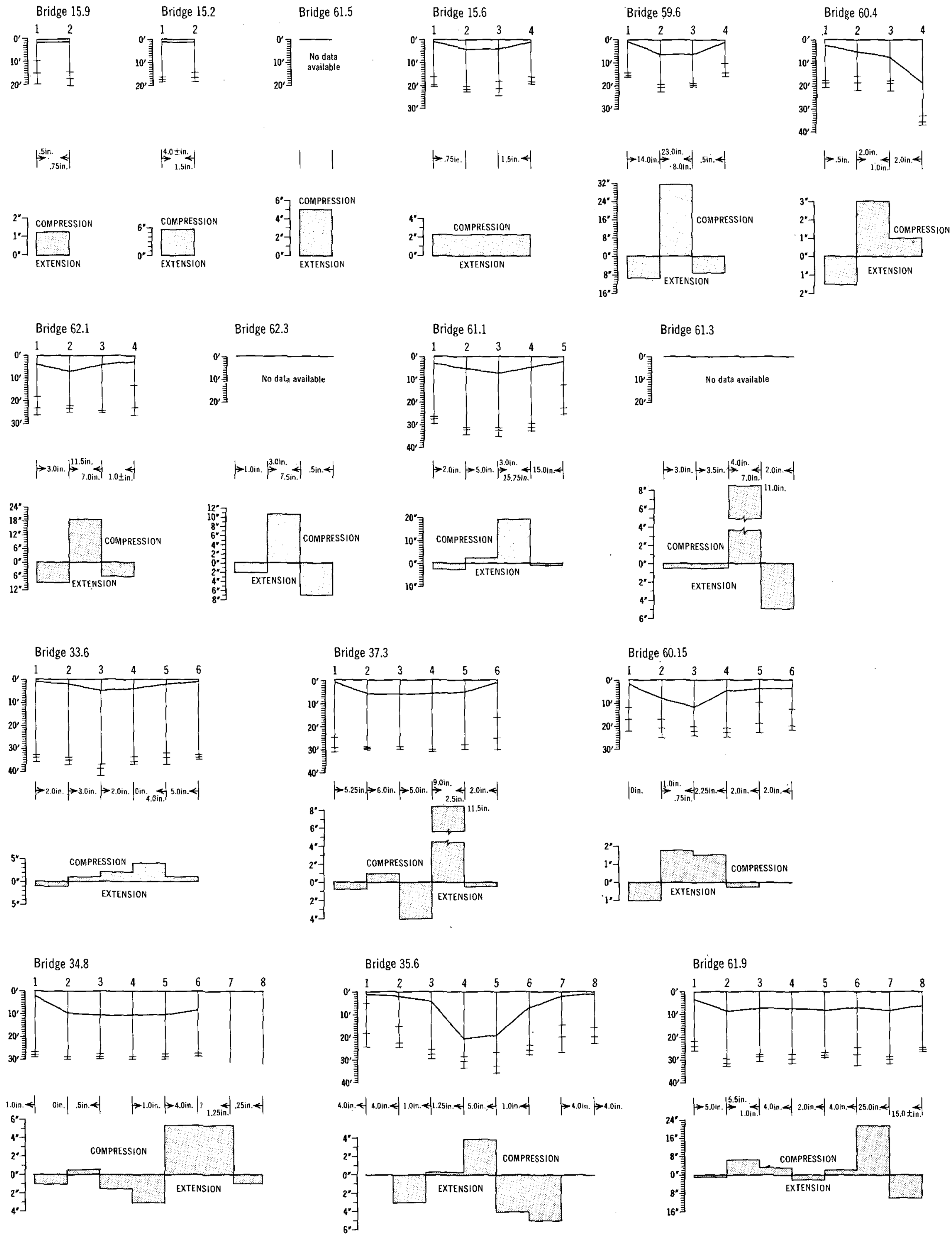
6.—The pier of a highway bridge at Resurrection River that was rotated as its base was carried toward the channel while its top was restrained by the deep central steel deck beam. A crack that formed in the pier is visible just above the water.

remained relatively flat. In only one bridge (63.5) was there a downward arch in a superstructure. However, even in this bridge the piling was higher in the stream center. The downward arch was formed when the stringers were thrust upward over the top of the bulkhead and onto the approach fill which left the superstructure unsupported to the place where the sagging stringers again found bearing on the piling (fig. 14).

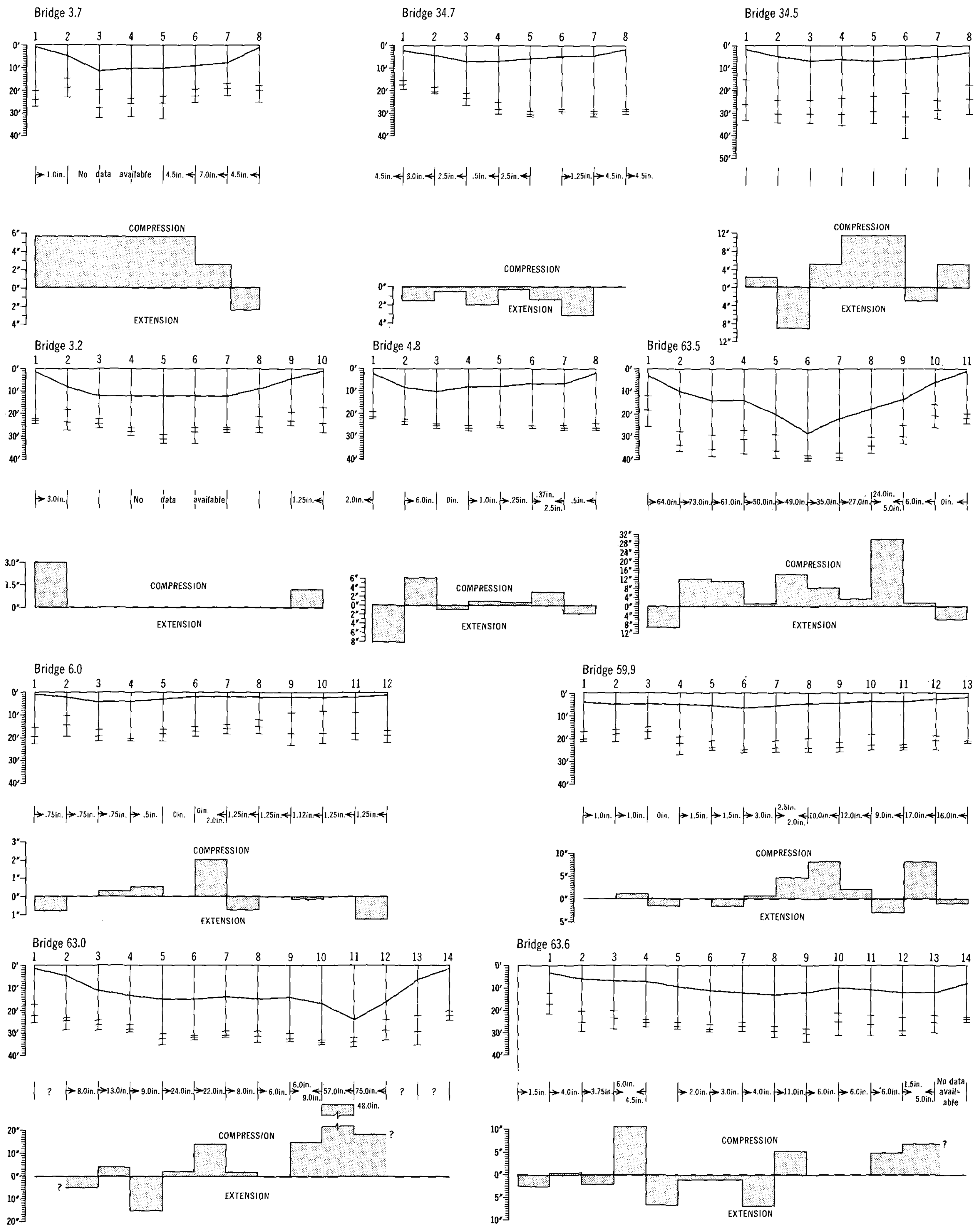
Vertically displaced piles were common in arched bridges in which the stringers were put into compression by streamward movement of the banks. It is improbable that the arching of the deck pulled the piling upward because the skin friction of the outward battered piles would have greatly exceeded the strength of the connections between the stringers and the piles. This is not to say that compressional arching could not have contributed to uplifting of the piles to the point at which these connections failed, for in one bridge (34.5), as previously described, compression alone produced arching in stringers torn free of their supporting piling. However, both in this bridge and in most others, upward pile movement occurred despite the fact that these connections had been severed by horizontal displacements of the bents. Furthermore, piles were also higher under the centers of bridges in which the stringers were not compressed—where arching decreased the distance between the ends of the stringers sufficiently to avoid compression between converging bulkheads. Thus, vertical pile displacements, whether slightly assisted by the arching or opposed by the weight and stiffness of the stringers, indicate an increasing vertical component of movement of the foundation materials toward the stream centers.

The independence of vertical pile displacement from deformation of the bridge superstructure is shown clearly by an observation of Lawson and others (1908, p. 218) after the great 1906 California earthquake:

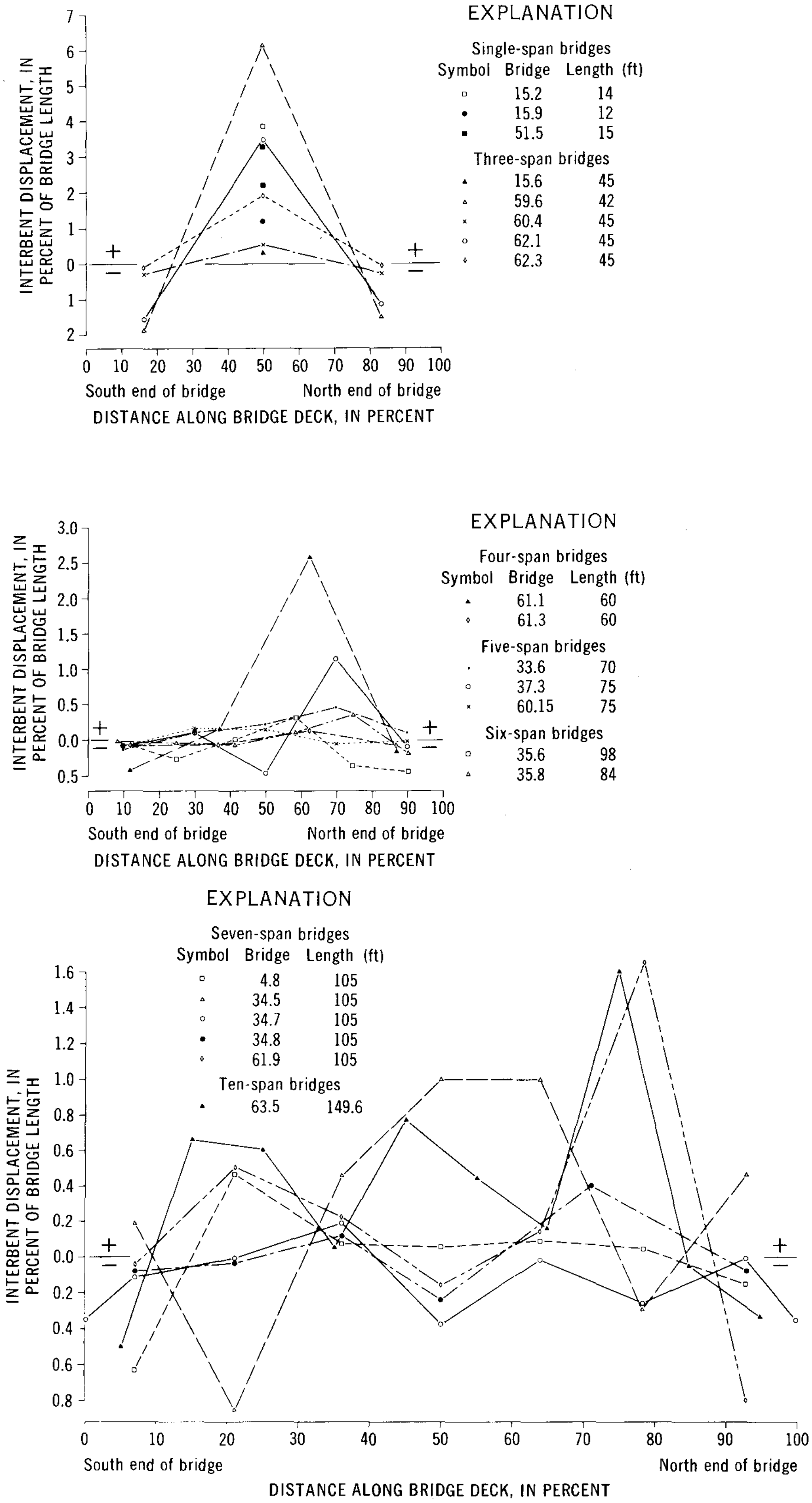
* * * At the bridge over Coyote Creek, on the Alviso-Milpitas road, the concrete abutments were thrust inward toward each other about 3 feet. A pile driven in the middle of the stream, which had been cut off below the water-level, was lifted about 2 feet and now rises above the water.



7.—Pile penetration length and relative horizontal displacement of bents of one- to seven-span open wood trestle bridges. The horizontal displacements are shown in terms of interpreted behavior of the foundation material: Extension, distance between bents increased; no change; and compression, distance between bents decreased. The shallowest, average, and greatest depths of penetration in each bent are indicated by horizontal lines.



8.—Pile penetration length and relative horizontal displacement of bents of seven- to 14-span open wood trestle bridges. The horizontal displacements are shown in terms of interpreted behavior of the foundation material: Extension, distance between bents increased; no change; and compression, distance between bents decreased. The shallowest, average, and greatest depths of penetration in each bent are indicated by horizontal lines.



9.—Relative horizonal displacements between bents of open wood trestle bridges plotted as the percentage of the bridge length. Horizontal compression of foundation materials indicated by +, horizontal extension by —.

TABLE 1.—*Damage to*

Bridge	Length (feet)	Type	Vertical distortion	Horizontal distortion	Compressed (C) or extended (E)	Measured streambank convergence (C) or divergence (D) (measured stringer length minus measured distance between bulkheads at level of top of bents)	Net compression or extension of streambed sediments determined by relative horizontal movement of bents	
							Compression	Extension
Mile 3.0	187	Two 80-ft through steel girder spans with one 13.5-ft open wood trestle on each end.	None	Central pier 8 in. west and outer piers 2± in. west of approaches.	C			
3.2	135	Open wood trestle; nine 15± ft spans.	3-in. arch	Middle of bridge 10 in. west of approaches.	C		9.5 in.	
3.3	136	One 80-ft through steel girder span with two 14± ft open wood trestles on each end.	None	Middle span 30 in. west of south bulkhead and 6 in. west of north bulkhead.	C			
3.7	105	Open wood trestle; seven 15± ft spans.	6-in. arch with 4th and 5th bent high.	North approach 1 ft west of south approach.	C		5.5 in.	0
4.3	42	Open wood trestle; three 14± ft spans.	Arched 1 in.		C			
4.8	105	Open wood trestle; seven 15± ft spans.	Arched about 8 in.	5-in. horizontal displacement between approaches.	E		0	3.5 in.
6.0	165	Open wood trestle; eleven 15± ft spans.	½-in. arch at 5th bent.	5th through 12th bent moved 2 in. to west of bents 1 through 4.	C		1.88 in.	0
6.6	135	Ballast deck, wood; nine 15± ft spans.	None	None	Neither		0	0
14.5								
15.2	14	Open wood trestle; one 14± ft span.	None	South end bridge 18 in. east of north end.	C		6.5 in.	0
15.6	45	Open wood trestle; three 15± ft spans.	2-in. arch	South approach offset 20 in. east relative to north approach.	C		1.75 in.	0
15.9	12	Open wood trestle; one 12± ft span.	None	None	C		1.75 in.	0
16.1								
16.6	60	Open wood trestle; four 15± ft spans.	None	None	Neither			
20.0	252	Open wood trestle; eighteen 14± ft spans.	8-in. arch at 6th bent	None	E			
21.4	30	Open wood trestle; two 15± ft spans.	Slight		E			
23.5	105	Open wood trestle; seven 15± ft spans.	None	None	Neither			
25.5	120	Open wood trestle; eight 15± ft spans.	None	None	Neither			
29.5	285	Open wood trestle; nineteen 15± ft spans.	None	None	C			
33.0								
33.6	70	Open wood trestle; five 14± ft spans.	6-in. arch with maximum at 4th bent.	North approach offset to west relative to south approach.	C		7 in.	0
34.5	105.3	Open wood trestle; seven 15± ft spans.	Jacknifed at 4th bent breaking stringers. At peak deck approximately 4¼-ft high.	North approach offset 1.2 ft west relative to south approach.	C	2.0 ft C	2.2 ft	0
34.7	105.0	Open wood trestle; seven 15± ft spans.	2-ft arch over whole bridge with maximum at 5th bent.		E	1.1 ft D	0	18 in.
34.8	105	Open wood trestle; seven 15± ft spans.	2-ft arch over whole bridge with maximum at 4th bent.	North approach offset 2 ft east relative to south approach.	E			¾ in.
35.6	98	Open wood trestle; seven 14± ft spans.	1.5-ft arch over whole bridge with maximum at 4th and 5th bents.	North approach offset 2 ft west relative to south approach.	E		0	8 in.
35.8	84	Open wood trestle; six 14± ft spans.	10-in. arech over whole bridge with maximum at 4th bent.		C		1.55 in.	0
36.7	28	Open wood trestle; two 14± ft spans.						
37.0	435	Open wood trestle; twenty-nine 15± ft spans.	Slight lowering of end bents and ends of bridge.	North approach offset 2 ft east relative to south. Sharp kink with 6-ft displacement between bents 24 and 28.	C			
37.3	75	Open wood trestle; five 15± ft spans.	6-in. arch primarily by lowering of embankment on north side of bridge.	North approach offset 2 ft west relative to south. Sharp kink with 4-ft displacement between bents 1 and 4.	C		7.25 in.	
41.6	70	Open wood trestle; five 14± ft spans.	3-in. arch due to lowering of fill on north approach.	North approach offset 0.5 ft west relative to south approach.	C			
46.8	75	Ballasted deck truss on concrete piers on bedrock.						
47.2	60	One 60-ft deck girder on bedrock.						
47.55	21	One 21-ft beam span ballasted deck on piles built of concrete capped rails.						
51.8	161	One 133-ft deck truss with one 14-ft beam span on each approach.						
52.0	85	One 85-ft deck truss						
52.45	29	One 29-ft beam span						

railroad bridges

Compression (C) or extension (E) measured at level of stringers and (or) steel spans (inches)	Evidence of repetitive compressive blows at bridge ends		Bridge higher than approach fills at bulkheads		Bulkheads								Remarks
					Rammed		Rotated		Raised above (+) or lowered below (−) bridge (inches)		Horizontal skew (inches)		
	South	North	South end	North end	South	North	South	North	South	North	South	North	
16.5 C	0	2	5.5 in	0	Yes	Yes	Yes	Yes	0	−0.75			
9.5 C	0	0	8 in	5 in	Yes	Yes	Yes	Yes	0	−3	E7		
21 C	0	4	8 in	8±in	Yes	Yes	Yes	Yes	−.5			W5.5	
5.5 C	0	0	6 in	4±in	Yes	Yes	Yes	Yes	−2.5	−1⅛			
	0	0	Slightly	Slightly	Yes	Yes	Yes	Yes		−½		W1$\frac{1}{16}$	
1.5 E	0	2	¾–4½ in	1½ in	No	Yes	No	Yes	−2⅝	−¾	No	E½	
2 C	0	0	0	0	Yes	Yes	Yes	Yes			No	No	
0	0	0	4	0	No	No	No	No	0	0	No	No	
6.5 C	0	0	0	8 in	Yes	Yes	Yes	Yes					
1.75 C	1	0	Slightly	Slightly	Yes	Yes	Yes	Yes					
1.75 C	0	2	Slightly	2 in	Yes		Yes	Yes	0	−1⅞			
	0	0	0	0	Yes	No	No	Yes	−1	−1½			
12 E	0	0	0	0	No	No	No	No	0	0	0	0	
7½ E	0	5			Yes	Yes	Yes	Yes					
	0	1	0	½ in	No	Yes	No	No	0	0	0	0	
	2+	2+	½ in	0	Yes	Yes							
	0	0	0	0	Yes	Yes	Yes	Yes	0	0	0	0	
7 C	0	0		½ in	Yes	Yes	Yes	Yes					
	4	4	0	0	Yes	Yes	Yes	Yes					
	2	0	0	0	Yes	Yes	Yes	Yes					
¾ E	0	0	0	0	No	Yes	No	Yes	−3½	−½	W1½	0	
8 E	2	1			Yes	Yes	Yes	Yes	0	−3	0	E1	
					Yes	Yes			−2	0			
21½ C				10 in	Yes	Yes		Yes		−3		W2½	
		Several			Yes	Yes	Yes			−3			
			0	1.5 ft	Yes	Yes							
													No damage to bridge. Bridge on bedrock. Report by B. E. Cannon; not see by authors.
													Do.
													Slight spalling on abutments; anchor bolts and expansion joints not damaged. Report by B. E. Cannon; not seen by authors.
													No damage to bridge. Built on bedrock. Report by B. E. Cannon; not seen by authors.
													Do.
													Do.

TABLE 1.—*Damage to*

Bridge	Length (feet)	Type	Vertical distortion	Horizontal distortion	Compressed (C) or extended (E)	Measured streambank convergence (C) or divergence (D) (measured stringer length minus measured distance between bulkheads at level of top of bents)	Net compression or extension of streambe sediments determined by relative horizontal movement of bents	
							Compression	Extension
54.1	256	One 200-ft through girder with one 28-ft wood span in each approach.						
58.7	180	Open wood trestle; twelve 15± ft spans.	Slight lowering of bridge ends with lowering of approach fills.	North approach offset approximately 2.5 ft relative to south approach.	C			
59.6	44.95	Open wood trestle; three 14± ft spans.	3-in. arch over whole bridge.	North approach offset approximately 8 in. east relative to south approach.	C	1.45 ft C	14.5 in.	
59.9	180	Open wood trestle; twelve 15± ft spans.	None	North approach offset approximately 3 ft east relative to south approach.	C		17 in	
60.15	75	Open wood trestle; five 15± ft spans.	10-in. arch over whole bridge with maximum at 3d bent.	None	C		1 in	
60.4	45	Open wood trestle; three 15± ft spans.	4-in. arch over whole bridge with maximum at 2d bent.	North approach offset approximately 2 to 4 in. east relative to south approach.	C		2.5 in	
61.1	60	Open wood trestle; four 15± ft spans.	5-in. arch by lowering of north bulkhead bent.	North approach offset approximately 8 in to west relative to south approach.	C		16.75 in.	
61.3	60	Open wood trestle; four 15±ft spans.	6-in. arch over whole bridge.	North approach offset 4 to 5 in. east relative to north end.	C		5 in	
61.5	13.8	Open wood trestle; one span.	1-in. arch over whole bridge.	North approach offset approximately 18 in. east relative to south approach.	C	4 in. C	4 to 6 in.	
61.9	103.8	Open wood trestle; seven 15±ft spans.	1-ft arch over whole bridge with maximum at 4th and 5th bents.	North approach offset 2 ft west relative to south approach.	C	1.8 ft C	20 in	
62.1	43	Open wood trestle; three 15±ft spans.	10 in. arch over whole bridge.	North approach offset unmeasured distance to east relative to south approach.	C	.6 ft C	4 in	
62.3	45	Open wood trestle; three 15±ft spans.	6 in	North approach is old bridge covered with embankment. Now 1±ft. east relative to south approach	C		8 in	
63.0	194.8	Open wood trestle with planked walkways outside rails; thirteen 15±ft spans.	1.6 ft	Sharp bend of 8 ft maximum displacement in 45 ft. North approach. approximately 14 in. west of south approach	C	4.4 ft C	83 in	
63.5	149.6	Open wood trestle; ten 15±ft spans.	North half of bridge arched up 1 ft at bent 7; south half of bridge arched down 1 ft at bent 3.	North approach offset 10 ft west relative to south approach.	C		64 in	
63.6	208.95	Open wood trestle; fifteen 15±ft spans.	2.5-ft arch over whole bridge.	North approach offset 7 ft west relative to south approach.	C			
75.2	75	Open wood trestle; five 14±ft spans.			C		4 in	
83.0	75	Open wood trestle; five 14± ft spans.	4-in. arch over whole bridge with maximum at 4th bent.	Center of bridge displaced 2¾ in. west.	C			
83.5	75	Open wood trestle; five 14-± ft. spans.	6-in. arch over whole bridge with maximum between 3d and 4th bents.	None	C			
93.46	60	One 60-ft steel deck truss on concrete abutments.	None		C			
112.8	192	One 80-ft steel deck girder with four 14-± ft open wood trestle spans on each approach pile pier at end of steel span.	None	None	C			
114.3	193	One 123-ft through steel truss with one 35-ft steel beam span on each approach.	None		C			
127.5	308	Five steel deck girders. From south to north they are 74 ft, 40 ft, 80 ft, 40 ft, 74 ft. Concrete piers and abutments.	4 to 5-in. arch		Neither			
136.4	86	One 60-ft steel through girder with one 13-ft open wood trestle on each approach.			Probably neither.			
140.8	80	One 80-ft steel through girder on concrete piers.			C			

railroad bridges—Continued

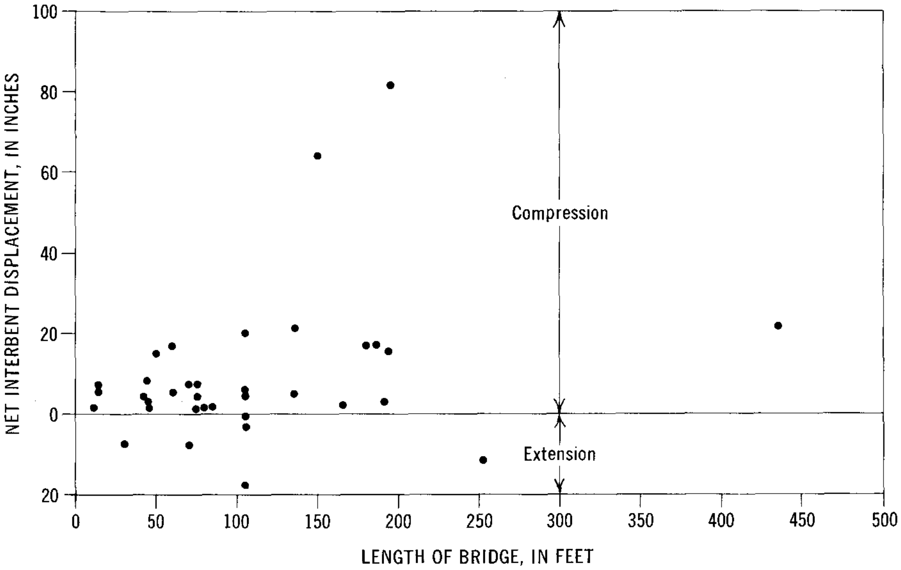
Compression (C) or extension (E) measured at level of stringers and (or) steel spans (inches)	Evidence of repetitive compressive blows at bridge ends		Bridge higher than approach fills at bulkheads		Bulkheads								Remarks
					Rammed		Rotated		Raised above (+) or lowered below (−) bridge (inches)		Horizontal skew (inches)		
	South	North	South end	North end	South	North	South	North	South	North	South	North	
													No damage to bridge. Report by B. E. Cannon; not seen by authors.
					Yes	Yes							
14.5 C	0	0	1.5 ft	5 in	Yes	Yes	Yes	Yes	0	0	0	0	
17 C	0	0	21 in	31 in	Yes	Yes	Yes	Yes					
	0	0	0	3 in	No	Yes	No	Yes					Buried bulkhead three ties north of bridge. Embankment dropped 2.5 ft on north side of this buried bulkhead.
	0	0	0	0	Yes	Yes		Yes					
	0	0	1 ft	1.5 ft	Yes	Yes	Yes	Yes					
C	0	0	4-8 in	6 in	Yes	Yes	Yes	Yes					
	0	0	6-10 in	1.5 ft	Yes	Yes	Yes	Yes			W1.5	E	
	0	0		2.5 ft	Yes	Yes	Yes	Yes					
	0	0		4 in	Yes	Yes	Yes	Yes		−3¾	E3		
					Yes	Yes	Yes	Yes					
	0	0	8 in	2 ft	Yes	Yes	Yes	Yes			E3		
	0	2	0	1.7 ft	Yes	Yes	Yes	Yes					
	0	5	0	1.5 ft	Yes	Yes	Yes	Yes					
			Yes	Yes	Yes				−4	−6½			
			0	0		Yes		Yes	0	0			
1-4½ C													Concrete abutment on north end has rotated toward stream at its base.
2½ C			10 in	Slightly	Yes	No	Yes						Pile pier at south end of span moved estimated 2 to 4 in. streamward.
15½ C													
													No evidence of movement.
				Slightly?									No evidence of movement of steel on concrete piers. No data on wooden spans.
1¾ C			1-2 in	1-2 in									Concrete abutments crowded together. Steel jammed tight. B. E. Cannon.

TABLE 1.—*Damage to*

Bridge	Length (feet)	Type	Vertical distortion	Horizontal distortion	Compressed (C) or extended (E)	Measured streambank convergence (C) or divergence (D) (measured stringer length minus measured distance between bulkheads at level of top of bents)	Net compression or extension of streambed sediments determined by relative horizontal movement of bents	
							Compression	Extension
142.9	112	Open wood trestle; eight 14±ft spans.	8½-in. arch over whole bridge with maximum at 5th bent.					
146.4	856	Ten 80-ft steel through girders and four 14±ft open wood trestle spans on north approach.						
147.1		Three 123-ft steel through trusses with one 25-ft 7-in. steel beam span on each approach.						
147.4		One 123-ft steel through truss with one 25-ft 7-in. steel beam span on each approach.						
148.3								
152.1		Open wood trestle; five 14± ft spans.						
152.3		Open wood trestle, two 14 ± ft spans.						
154.86		Ballast deck, wood; seven 13-ft 6-in. spans.						
264.1								
266.7								
284.2								
								WHITTIER
F 1.2	126	Open wood trestle; nine 14 ± ft spans.						
F 2.1	211	Open wood trestle; fifteen 14 ± ft spans.						
F 5.7	196	Open wood trestle; fourteen 14 ± ft spans.		None visible on aerial photographs.	Probably C.			
F 9.4	56	Open wood trestle; four 14 ± ft spans.	Slight arch over whole bridge seen on oblique aerial photographs.	East end of bridge moved 1 to 2 ft north of west end as seen on aerial photographs.	Probably C.			
F 10.7	98	Open wood trestle; seven 14 ± ft spans.	Arch over whole bridge with maximum at northwest end seen on oblique aerial photographs.	Aerial photographs show northwest end of bridge moved southwest relative to southeast end of bridge.	Probably C.			
								SUTTON
A 0.3	112	Open wood trestle; eight 14 ± ft spans.			Probably C.		0 to 7 in.	
A 12.0	56	Open wood trestle; four 14 ± ft spans.						
A 12.6	302	Two 14 ± ft open wood trestles; one 60-ft steel through girder; six 14-ft open wood trestles; one 60-ft steel through girder; five 14 ± ft open wood trestles.						
A 17.0	70	Open wood trestle; five 14 ± ft spans.			Probably C.			
A 18.0	98	Open wood trestle; seven 14 ± ft spans.						

railroad bridges—Continued

Compression (C) or extension (E) measured at level of stringers and (or) steel spans (inches)	Evidence of repetitive compressive blows at bridge ends		Bridge higher than approach fills at bulkheads		Bulkheads								Remarks
					Rammed		Rotated		Raised above (+) or lowered below (−) bridge (inches)		Horizontal skew (inches)		
	South	North	South end	North end	South	North	South	North	South	North	South	North	
					Yes	No							
													"Erratic pier movement, but not serious. Trestle damaged." B. E. Cannon.
													Broken concrete pier (No. 3) Base of pier shifted south 12 in. Expansion normal in trusses. Tail spans jammed; anchor bolts spalled out of concrete. B. E. Cannon.
													North pier and abutment shifted west about 12 in. Pier 3 moved south about 12 in. off one roller of two roller bearings. Tail spans jammed. B. E. Cannon.
													Seventy-foot span sheared anchor bolts and jammed. Lurch crack humped bridge but did not break piles. Pile bents 48 to 59 demolished. B. E. Cannon.
													Piling moved out from caps about 2 or 3 in. B. E. Cannon.
													No damage; on good ground. B. E. Cannon.
													Rocked on rocker joints. Movement about 3 in. Had to reset expansion joints. B. E. Cannon.
													Steel spans jammed together.
													Two deck truss spans jammed against central arch span. B. E. Cannon.
BRANCH													
													Tidal wave damage: broke some piles. B. E. Cannon.
													Undamaged. B. E. Cannon.
													Out of shape. Three bents at south and two at north end crowded toward center. B. E. Cannon.
													Had to add fillers over some pile caps. B. E. Cannon. (That is, bridge was arched.)
													Two bents at southeast end of bridge moved northeast; two bents at northwest end of bridge moved southwest. Three bents have been removed but bridge is still 4 ft out of line. B. E. Cannon.
BRANCH													
													Bents crowded toward center and end bents shoved in. B. E. Cannon.
													No damage. B. E. Cannon.
													Do.
													Bents crowded toward center. B. E. Cannon.
													Thirty-inch offset in approaches. Piles moved more than 24 in. in bent 2 and tipped. Heavy movement in bents 1, 6, 7, and 8. B. E. Cannon.



10.—Net horizontal compression or extension of bents, compared with the lengths of bridges.

It should be emphasized that the vertical displacements given above are in relative terms only, and that without some reference one could also say that there was downward displacement of the end bents. The true sense of movement is difficult to establish because of the lack of postearthquake control, and the fact that damaged bridges were in areas in which there is reason to believe that there was general, but unmeasured, consolidation and settlement.

There is, however, some evidence from the Portage area that there was actual upward movement of the piles in the stream centers. In table 2 the preearthquake elevations of bridges are compared with the postearthquake elevations as determined by a level survey made by Bonilla and William Webb of The Alaska Railroad. The effects of regional subsidence are eliminated by referring both pre- and postearthquake elevations to nearby bedrock (U.S. Coast and Geod. Survey bench mark Q12). The survey was run in a closed loop from mile 64.21 to bridge 63.0 and in an open-ended line from mile 63.0 south to bridge 61.9. Closure error on the loop of 0.42 foot appears from reoccupied stations to have been cumulative, and is thus redistributed proportionally over the loop.

TABLE 2.—*Adjusted relative postearthquake elevations, in feet, of bridges in the Portage area*

Bridge (mile post)	Preearthquake elevation	Postearthquake elevation [1]	Closure correction [2]	Elevation change	Elevation change corrected for 1.33 ft consolidation [3]
61.9	33.48	32.8	------------	−0.68	+0.65
62.1	32.99	31.53	------------	−1.46	−.13
62.3	32.67	31.6	------------	−1.07	+.26
63.0	32.14	31.3	+0.21	−.63	+.70
63.5	31.86	31.7	+.14	−.02	+1.31
63.6	31.69	32.5	+.115	+.93	+2.26

[1] Preearthquake elevations corrected for regional subsidence.
[2] Distributed proportionally to horizontal distance on survey loop.
[3] Consolidation measured at Union Oil well, Portage.

The differences in the pre- and postearthquake altitudes indicate that the tops of the arched bridges varied from 1.46 feet below to 0.93 foot above their preearthquake positions. However, these differences ignore consolidation. Consolidation of 1.33 feet was measured where the ground surface settled around the 600-foot-deep casing of the Union Oil Co. well (fig. 111). Undoubtedly consolidation varied over the area, and may have been less or greater than 1.33 feet. If 1.33 feet is taken as representative, at all but one bridge (62.1) there was upward movement of foundation materials relative to the land surface—movement that ranged from 0.26 to 2.26 feet.

It might be argued that differential consolidation of the foundation materials played some role in the vertical movements of the piling. If differential consolidation were important, shallow piling within surface materials, which presumably would have undergone the most consolidation, would be moved farther downward than more deeply driven piling, which penetrated more compact layers. However, the available pile-penetration data for arched bridges (fig. 15) suggest that penetration depth and vertical displacement are relatively independent. Arching always occurred in the stream centers—regardless of the length of pile penetration.

Vertical displacements of sediments in stream and channel centers have been noted in many earthquakes, and it appears that the phenomenon is general. For example, H. H. Hayden (in Oldham, 1899, p. 285) showed a photograph of a bamboo bridge over a canal, about which he says:

The canal being, as already stated, a line of weakness, it is not surprising to find that the banks on each side are cut up by fissures, while its bed has risen, in some cases through several feet, the central portion now being above the water: this is well shown by the bamboo bridges which have shot up in the center. The same effect is seen in numerous places between Rangpur and Kuch Bihar, where bridges of small span cross canals, small water channels or swamps. If the bridge has a central pier, then this pier has been thrust up and the bridge broken.

Similarly, Steinbrugge and Moran (1956, p. 25) state that in irrigated areas with a high water table that were affected by the Fallon-Stillwater earthquake of 1954 there were

* * * spectacular cracks due to ground movement of canal banks and adjoining land, lurching toward canals or streams were noted. * * * These cracks tended to parallel the canals or streams. A corollary to this type of ground movement was the rising of the bottoms of canals, which often rose above the former water surface.

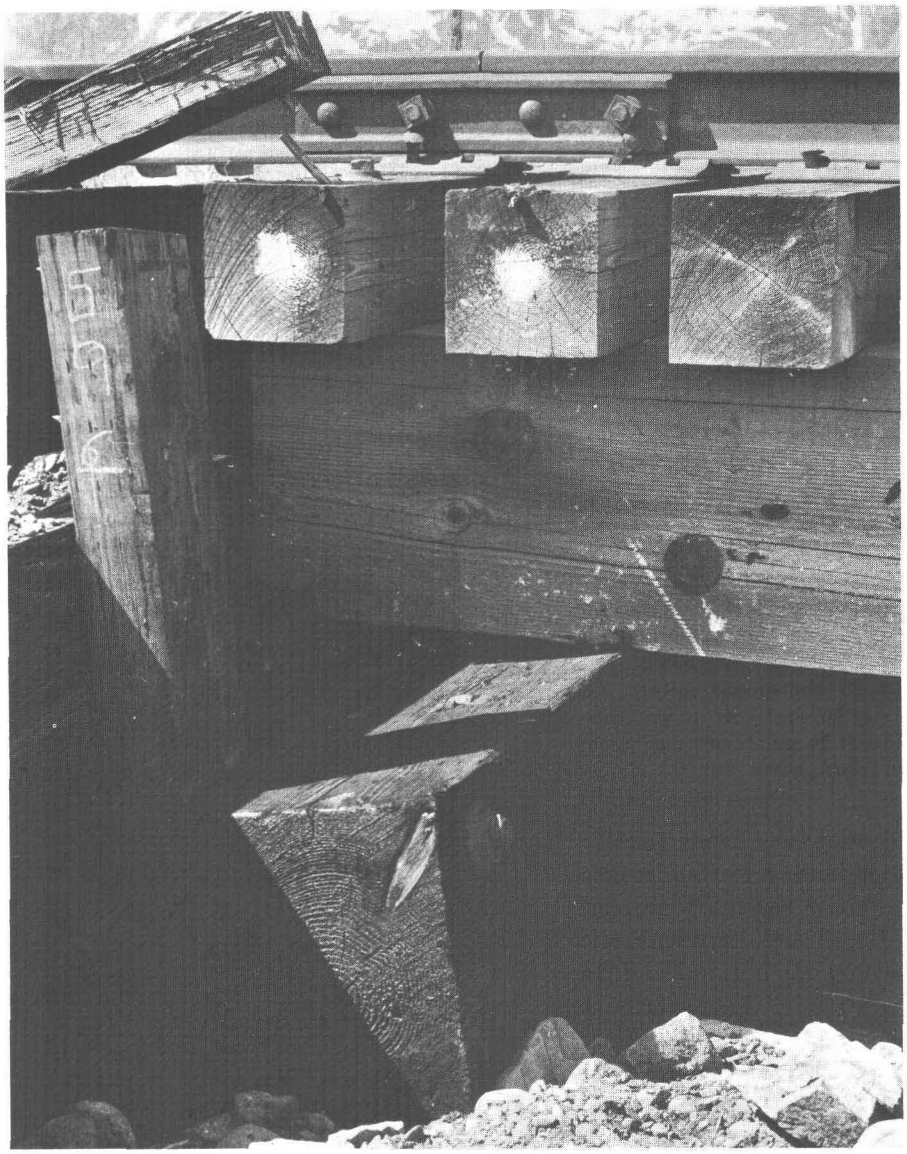
They show a photograph of the central part of a canal bottom protruding from the water and they cite an unpublished U.S. Bureau of Reclamation study that states (p. 31):

In the Lone Tree and Stillwater areas, canal banks settled from 1 to 3 feet, at the same time the bottoms of canals were raised from 1 to 2 feet, and in an extreme case the bottom of a drain ditch was forced up approximately 5 to 6 feet, by the heaving action of the earthquake.

The great 1906 San Francisco earthquake produced a similar observation by Adams and others (1907, p. 341) who state that

* * * on marsh land near the Bay Shore, one mile west of Alvarado * * *. During the quake the channel of the creek [probably Alameda Creek] disappeared, its bottom being raised to the general level of the adjoining land.

This earthquake produced a somewhat similar observation by Jordan (1906, p. 298) in marshy ground at the south end of Tomales Bay:

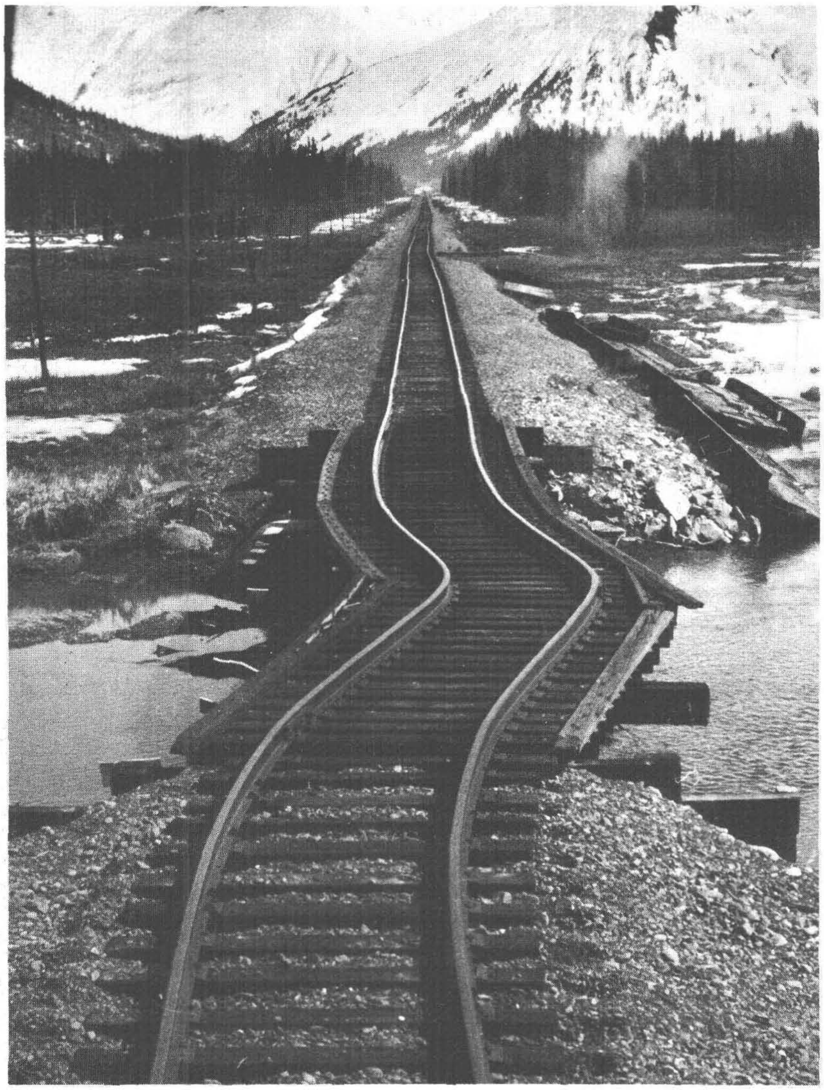


11.—Stringers jammed into the bulkhead planking as the result of a decrease in distance of 14½ inches between streambanks at bridge 59.6.

The two banks of the stream [Paper Mill Creek] were forced toward each other so that the length of the bridge was shortened by about six feet and the bridge was correspondingly humped at its north end, an arch about six feet high being forced up.

FOUNDATION MATERIAL FAILURES INDICATED BY BRIDGE DAMAGE

The patterns of damage to bridges, and, in particular, the horizontal and vertical displacements of piles, piers, and abutments make it possible to infer the movement of the foundation materials at bridges and their mechanism of failure. Because connections between piles and superstructures were so easily broken, it can be assumed that piles were carried nearly passively and that their displacements generally reflect those of the foundation materials. A cross section of a typical compressed bridge (fig. 16) shows that piles were shifted streamward and upward, and that the founda-



12.—Laterally buckled and broken stringers of bridge 37.3, resulting from 7¼ inches of streambank closure.

tion materials were extended at the the stream edges and compressed in the middle of the valleys. Because the piles were shifted with little or no tilting, movement of the foundation materials was probably as deep or deeper than the pile tips. Pile penetration in open wood trestles ranged from about 10 to 30 feet, but in longer bridges it was as much as 125 feet. Bending of the piles cannot be ruled out, and undoubtedly some occurred in the very long piles; however, there is no independent evidence to show that any piles were bent. If bending did occur it was well below the surface, and there probably were no large differences in the amount of horizontal displacement of the foundation materials within the depths of the average wood pile.

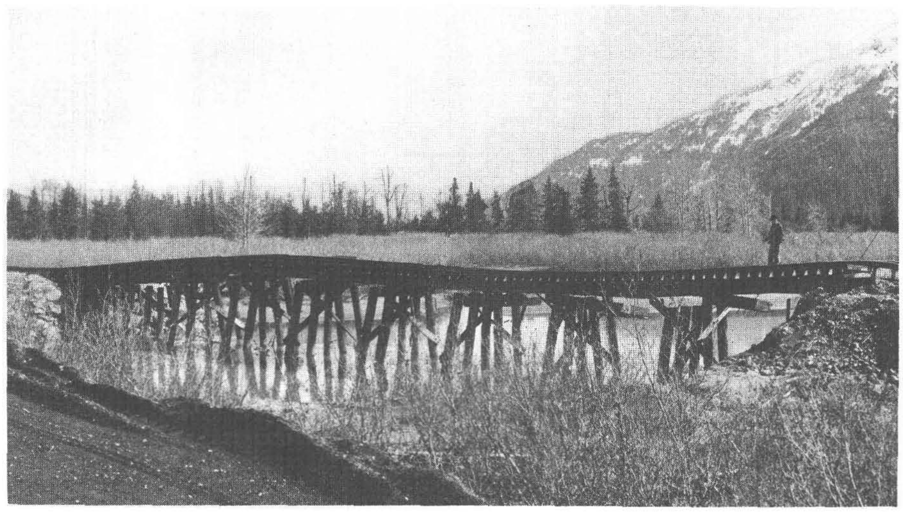
The absence of tilting in the piling, or any other evidence of rotational failures, and the attenuation and compression of the moving foundation materials accompanied by an upward displacement on the floors of the streams, indicate that the foundation materials underwent a kind of flowage in which there was rearrangement of the materials at the intergranular level. Sand ejected from cracks on stream floors (figs. 13, 17) indicates that excess water pressures developed within the sediments. These observations suggest that the foundation materials may have undergone liquefaction. Liquefaction is known to occur during earthquakes (Seed, 1967) and results when ground motion compacts saturated granular sediments. If the water in the sediments cannot escape, or escapes only slowly, the grains of the sediment become reordered in such a way as to increase the load on the interstitial water. As the pressure of the confined water increases, the sediment starts to liquefy and lose strength; when the water pressure is equal to the load of the overlying materials, the sediment will have become completely liquefied and will have no strength.

Field observations show that as the foundation materials became liquefied, they were subjected to increasing hydrostatic forces fixed in large part by the amount of relief and shape of the stream valley. The sediments responded with flowlike displacement that produced a general lowering of the streambanks accompanied the upward movement of the sediments under the stream floors. If sediments moved upward only under the floors of valleys in which there was net horizontal compression, the upward movement might be attributed to compression of the sediments under the centers of the stream floors resulting from the extension of the adjacent sedi-

13.—Bridge 34.5 jackknifed upward by compression at the bulkheads. Note the mounds of fine-grained sediments ejected with ground water through cracks in the stream floor.

ments; however, bridges in which all interbent distances were increased, yet which were arched (for example, 34.7, 34.8, 35.6), make it clear that even though all the sediments are undergoing extension, they still react to hydrostatic forces, and move upward in an effort to fill the depression.

The fact that all bridges were either flat or arched upward suggests that the foundation materials maintained some strength and did not become completely liquefied. If liquefaction had been complete, piling would have been driven downward by the weight of the decks. The static load per pile of an open wood trestle with piles 30 feet long would be approximately 2,820 pounds. The buoyancy of the piles would reduce the effective downward force on each pile; however, the buoyancy of a 10-inch-diameter pile embedded 20 feet in sediment having a density of 2 would be only 1,360 pounds. This leaves a downward force of 1,460 pounds per pile. It also seems unlikely that the sediments became completely liquefied in a zone at some depth below the surface, while the surface materials retained enough strength to support the piles, because the piles shifted without tilting and the surface sediments underwent attenuation and compression. It seems, rather, that movement must have been distributed throughout the sediments for most of the depth of the piles. Borings indicate the sediments are generally layered, inhomogenous, and lenticular, and the varying resistance to penetration indicates that they are of differing density. If such an inhomogenous soil system is subjected to seismic vibrations, one would expect that some parts of the soil column would become liquefied more easily than others, because of the differences in density and the ease or difficulty with which water might move into or out of a given soil layer. It is also probable that, in addition to the varying capacities of the materials to liquefy, the water in the soil was subjected to repeated transient reversals in hydrostatic pressure resulting from compression and dilation of the sediments during seismic vibrations. It has been demonstrated that such changes in pressure occur during



14.—Streambank closure of 64 inches drove the deck of bridge 63.5 through the south bulkhead up onto the top of the embankment. The tops of the piles beneath the deck describe an upward arch, and the deck sagged at the right until it encountered the piles. Photograph by The Alaska Railroad.

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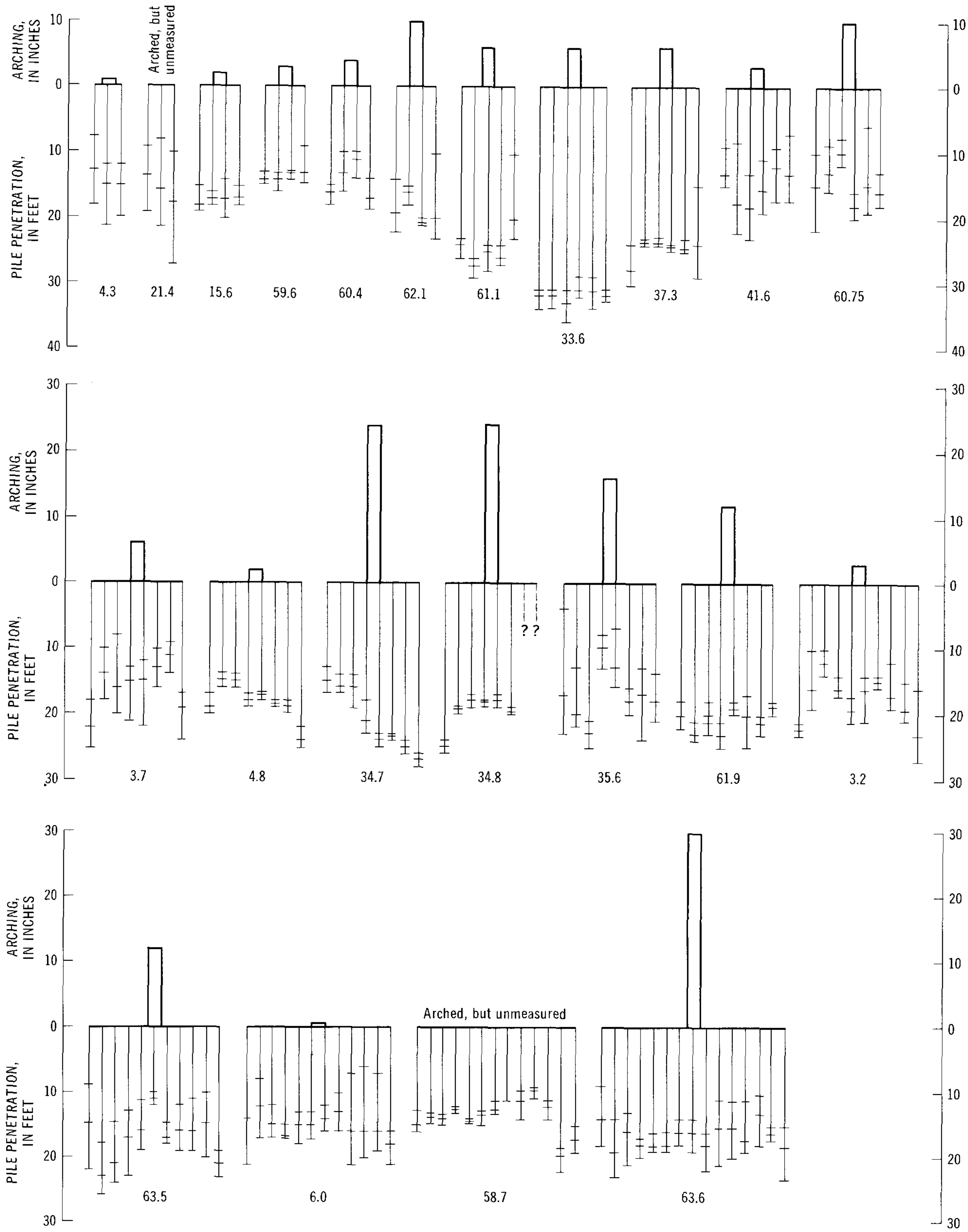
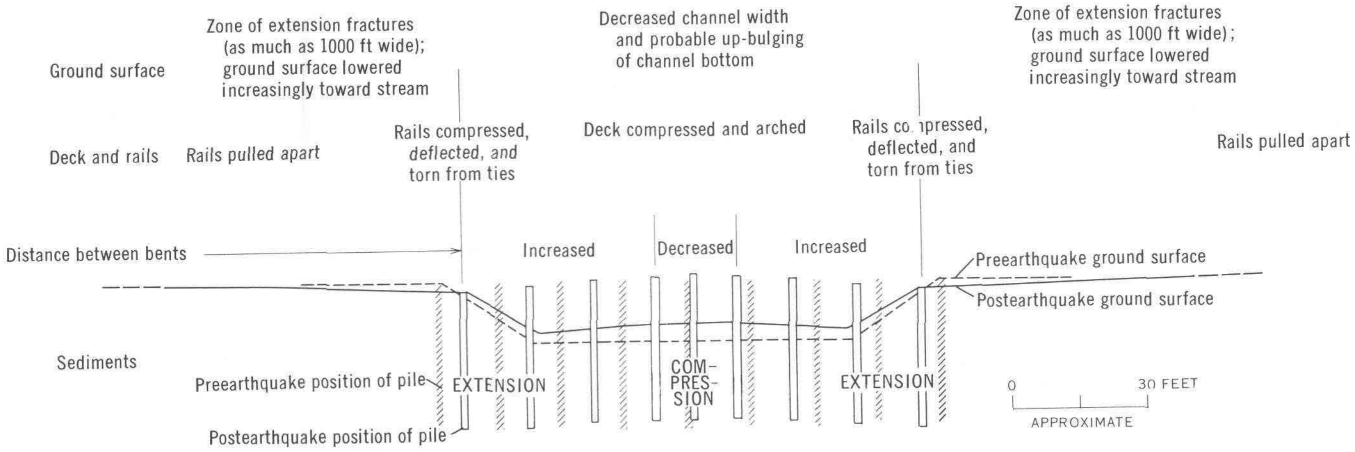


15.—Arching of decks and pile penetration in open wood trestles. The shallowest, average, and greatest depth of penetration in each bent are indicated by horizontal lines. Arching always occurred in the stream centers, regardless of the distribution of the pile penetration.



16.—Generalized diagram of a typical compressed open wood trestle. Piles were displaced toward the stream and upward in the stream center. The fact that interbent distances increased at the ends of the bridge and decreased under the middle shows that the sediments were extended at the edges and compressed at the center of the stream channel. Extension, continuing back from the streambanks, formed fractures in the ground and embankments and pulled rails apart.

earthquakes if the water is confined (Leggette and Taylor, 1935) as it must be if liquefaction is to occur. It has also been pointed out by Eaton and Takasaki (1959) that all four major types of earthquake waves produce changes in pressure; *P* and Rayleigh waves, being dilatational and compressional, cause pressure changes directly, while *S* and Love waves, being shear waves, may produce pressure changes by originating additional *P* and Rayleigh waves. Fluctuations in hydrostatic pressure resulting from seismic waves cannot be calculated without considerable knowledge of the geometry of each confining body (Cooper and others, 1965). However, it is possible that the hydrostatic pressures generated by seismic waves make a small but critical contribution to pore-water pressures which allow some layers to liquefy, while with succeeding dilation the reduction in pore-water pressure allows the layer to develop some strength. Because the Alaska earthquake was accompanied by a long period of *P*-wave generation (see p. D8), changes in pore-water pressure due to the passage of seismic waves may have been an important factor in the degree of mobility reached by the sediments.

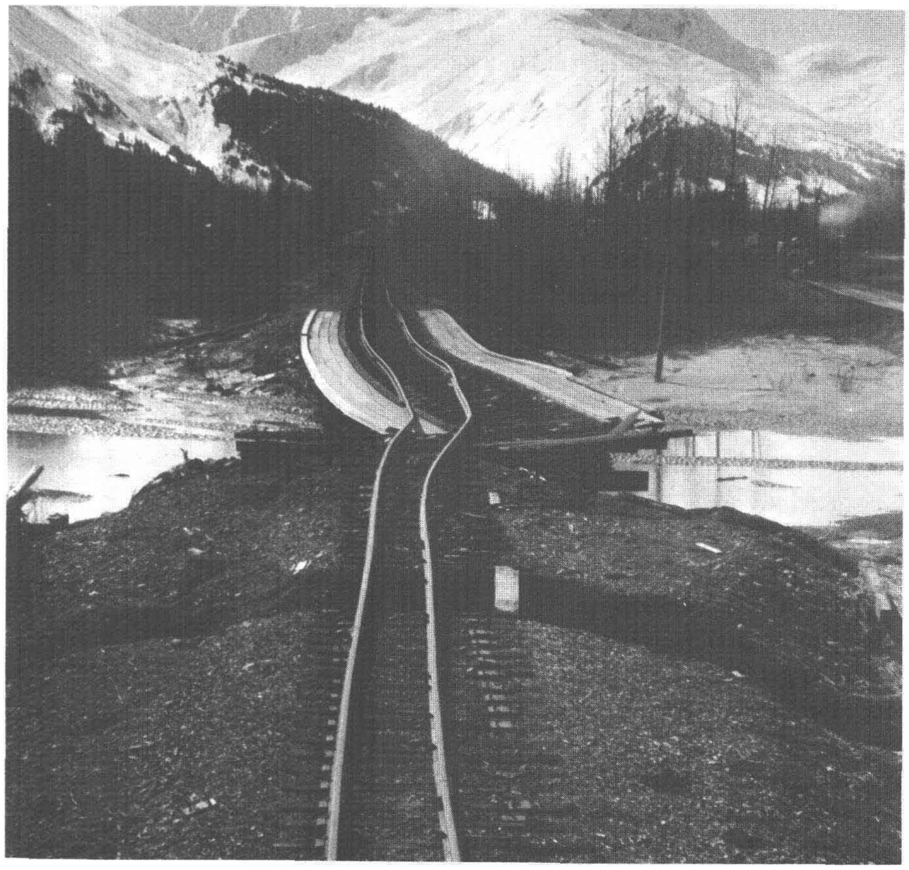
In addition to undergoing fluctuations in pore-water pressure, the vertical component of ground motion of the sediments would alternately increase and decrease the weight of the overburden on any given layer. Because of their generally inelastic behavior, soft wet sediments respond more to low- than to high-frequency vibrations (Gutenberg, 1957). If such sediments are relatively deep, and lie within a bowl, there is some evidence that the sediments may resonate (Newmark, 1965).

17.—Mounds of sand ejected with ground water from cracks in the floor of the stream at bridge 34.7 on Hunter Flats.

Mobile seismic arrays of the U.S. Geological Survey have recorded resonancelike oscillations on tide lands adjacent to San Francisco Bay (R. Borcherdt, oral commun., 1968). If resonance occurs, it would increase the magnitude and velocity of the surface displacements by generating nearly periodic loops of ground motion, with successive positive and negative peaks which in turn would maximize the change in the overburden load on any given layer. Because the degree of liquefaction (partial or complete) depends upon how closely the pore-water pressure approaches the overburden load, periodic changes in the overburden load might produce changes in the degree of liquefaction. Thus the soil mass might be characterized as containing many discrete areas in which varying degrees of liquefaction occur during a succession of pulses. The soil mass would thus be able to flow intermittently while maintaining enough strength to support the bridges.

In addition, the discharge of ground water to the surface that occurred throughout the shaking must have lowered pore-water pressure, and is likely to have resulted in partial rather than complete liquefaction of the sediments.

Movement of the sediments toward the stream valleys extended for some distance back from the streambanks. Embankments were broken by tension fractures and the rails pulled apart (fig. 18) as the underlying sediments moved toward the stream valleys. Tension fractures in embankments as much as 600 feet from a stream valley (fig. 19) suggest that the sediments became mobilized long distances away from the streams.



18.—View to the south of bridge 63.0. Compression, which deflected the deck 8 feet to the east in a sharp kink, broke the stringers. A wide tension fracture in the foreground broke the embankment; it shifted to the right at the fracture and skewed the bridge.

MODEL STUDY OF FOUNDATION FAILURES

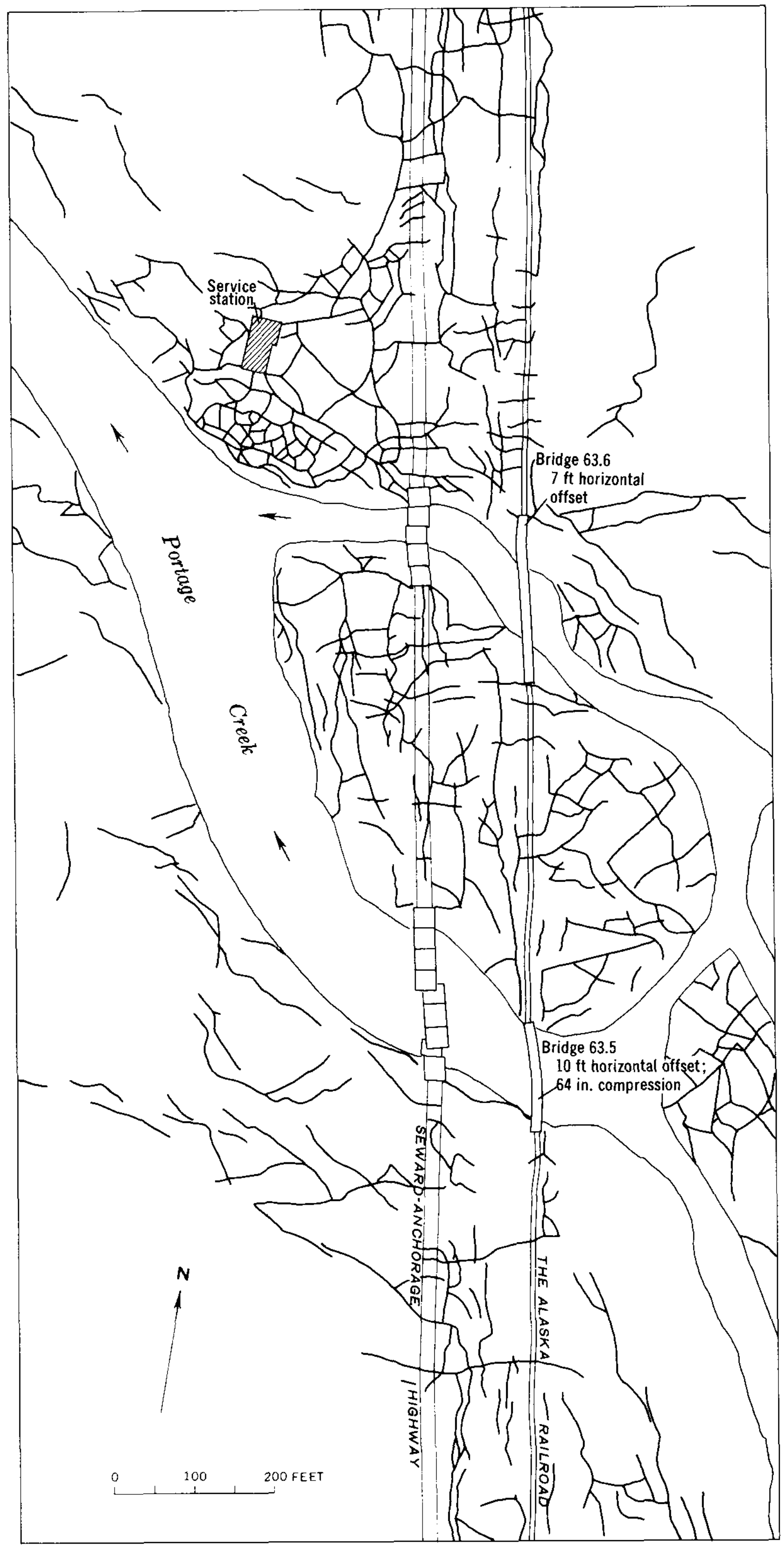
An approximation of both the horizontal and vertical movements at some depth within the sediments can be made by comparing pre- and postearthquake positions of piles, if one makes the following assumptions: that the piles were not bent below the ground surface, that the movement of a pile is representative of the displacement of the sediments along its entire length, and that the vertical displacements are upward. Figure 20 shows the inferred sediment movement for a three- and a seven-span bridge. At each bridge the inferred direction of particle movement as represented by flow lines is directed toward, and steepens in, the center of the valley. However, the number of assumptions makes this interpretation suspect.

To get some feel for the distribution of particle movement with depth, several sandbox experiments were performed. The box containing the model (fig. 21) was 24 inches square by 8 inches deep, and had a removable side. Rounded quartz-sand of the grain-size distribution shown on figure 22 was spread in horizontal layers alternating with either one or four layers of 100-mesh carborundum. The carborundum was sifted in a thin layer onto the sand surface. The position of each dark layer and the top of the sand were transferred to a record on the top of the box with a sliding wire gage mounted on a rider.

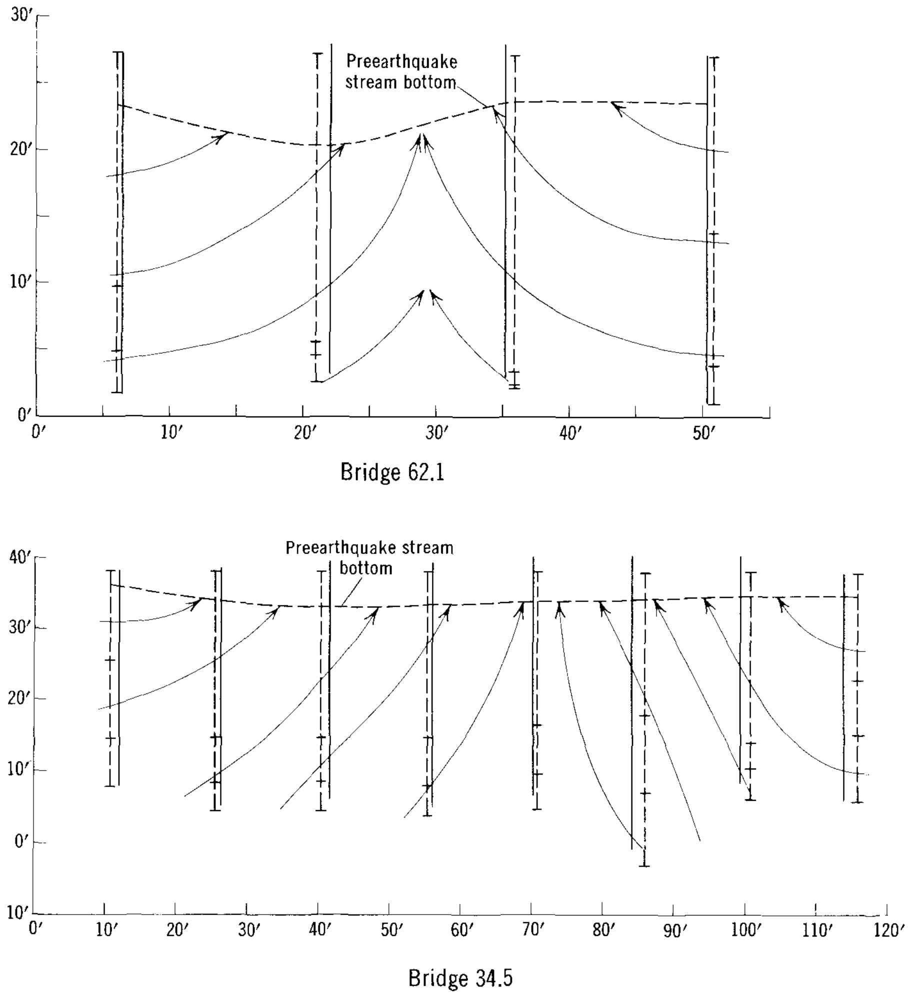
The sand was then saturated by slowly admitting water through a perforated plastic tube at the base of the side walls. When the sand was thoroughly wet, each side of the box was raised an inch or so off the table and then quickly lowered to strike the table top to consolidate the sand. During consolidation, water rose above the surface of the sand. The water was then very slowly withdrawn with a pipette from the plastic filler tube until it was just below the level to which a channel was then cut by making successive passes with a trough-shaped metal scoop. The position of the surface was remeasured, and the shape of the channel recorded. Water was added slowly until there was about one-sixteenth of an inch standing on the channel bottom; the model was again repeatedly raised and quickly lowered to the table top until the channel edges were seen to have converged. The box was then drained, and the sand cut away to expose a face in the middle of the box where the surface measurements had been taken.

In a one- and a four-layer model (figs. 21, 23, 24), the surface outside the channel was generally lowered. The amount of lowering increased toward the channel edges. The channel edges also moved together, and the slope of their sides decreased. The channel bottoms were raised above their original positions.

Beneath the channels, the dark layers were arched upward. If one assumes that the lowering of the surface well back from the channel was due only to consolidation and that consolidation decreased proportionately with depth, then the central arched portions of the



19.—Ground cracks at Portage Creek, as mapped from aerial photographs. Note the open network of fractures south of the service station, on the island, and on the point of land southeast of the island; note also that the tension fractures are generally perpendicular to the highway and railroad embankments.



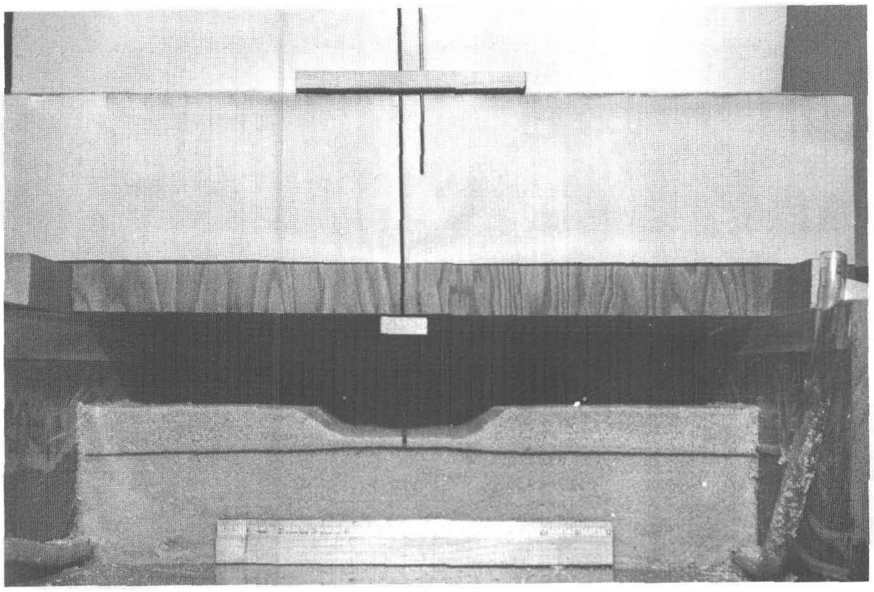
20.—Sediment movement suggested by displacement of bents in two arched bridges, based on the assumptions given in the text. The preearthquake bent positions are indicated by dashed lines, on which the shallowest, average, and deepest pile penetration lengths are indicated by horizontal lines.

black layers also were raised above their original positions.

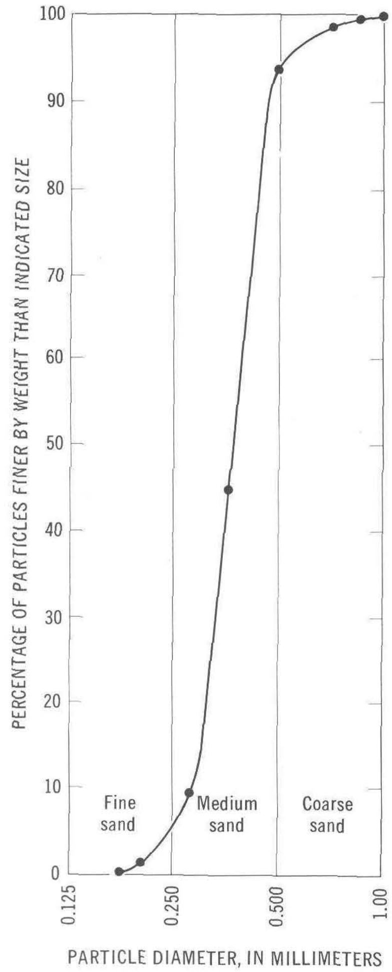
The rising of the channel bottoms to above the preshake position clearly indicates that some material moved upward, and therefore also laterally. However, having only horizontal layers in the model, lateral movement could only be measured by relative thinning or thickening between dark layers — because consolidation occurred during the final shaking, changes in thickness of these beds might also be attributed in part to differential compaction.

To measure lateral movement more directly, a four-layer model was built into which a vertical grid of carborundum was injected through a cannula (fig. 25). The pre- and postshake grids are compared in figure 26*A*. The preshake positions of the horizontal layers have been lowered, as described for previous models, to allow for consolidation.

The distribution of particle movement throughout the model is shown by vectors that originate at the preshake positions of the grid intersections, and pass through the postshake positions (fig. 26*B*); the length of each vector is doubled in the figure to make small movements visible. The vectors make it possible to draw particle flow lines — lines drawn in the direction of particle movement — as indicated by the displacement of the grid intersections. The flow lines show that, to the sides of the channel, material rose obliquely toward the channel to about the height of the channel bottom, where it converged with material moving somewhat downward and more directly toward the channel. Under the channel, flow lines become progressively steeper and become vertical in an area of convergence to the left of the channel center. Eight additional vectors were drawn between



21.—Sandbox with one side removed. The box measures 24 inches square and 8 inches high. Water was injected through a perforated plastic pipe at the base of the side walls. Measurements were transferred with a sliding wire gage from the model to a record above. The point of the wire gage is at the top of an arched carborundum layer under the center of the channel.

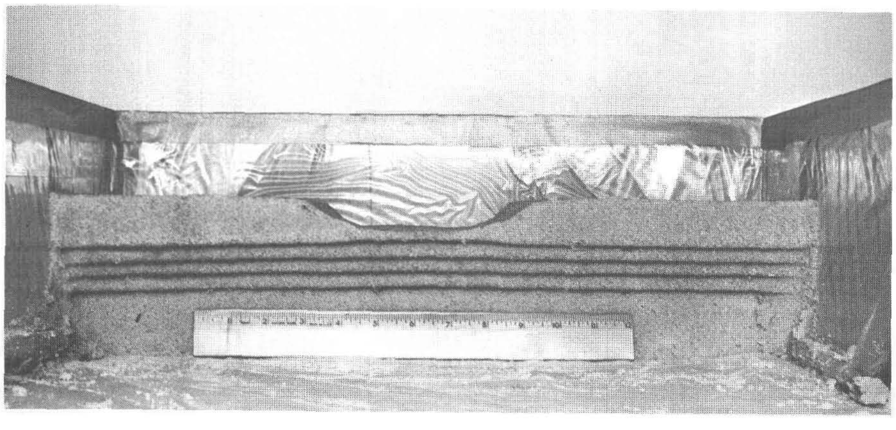


22.—Grain size distribution of well-rounded quartz sand used in the sandbox model.

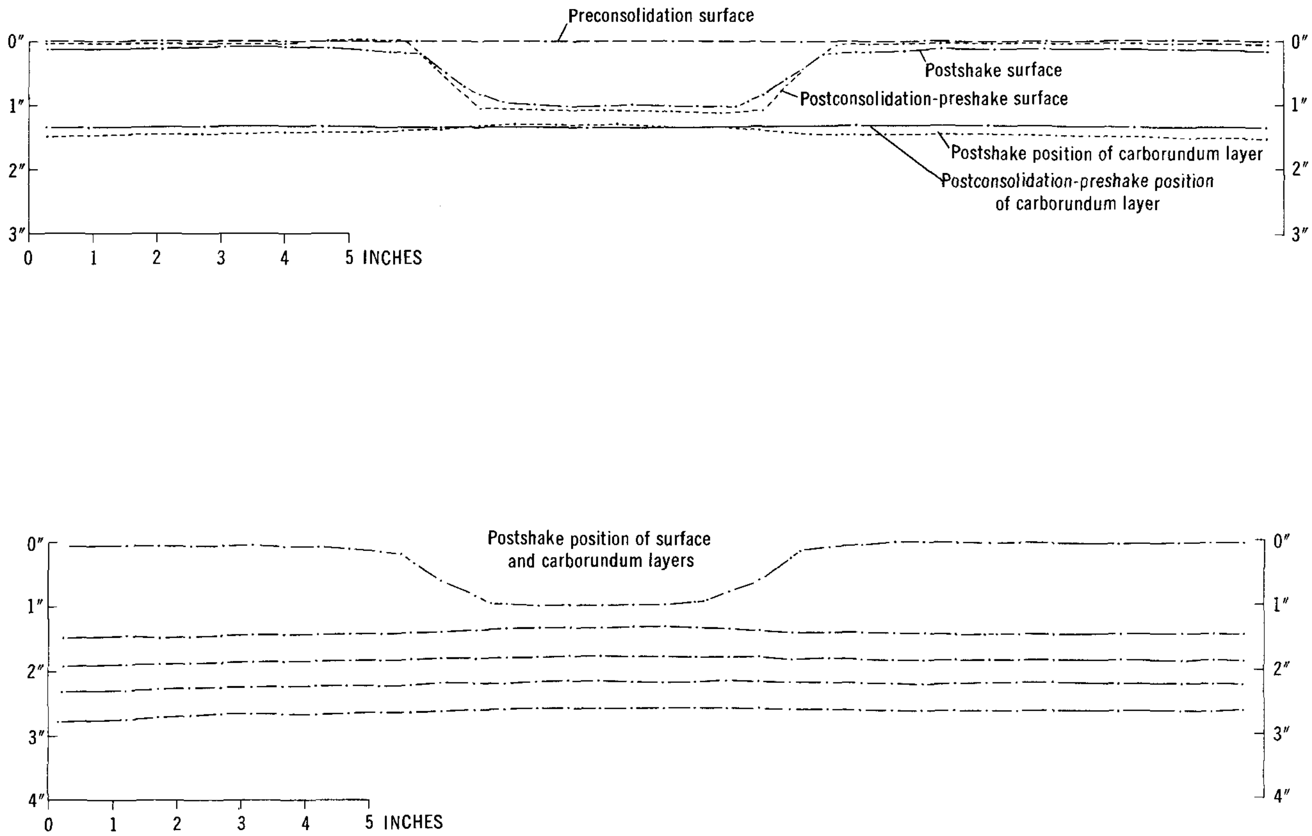
the upper dark layer and the surface by connecting the midpoints of four of the pre- and postshake vertical lines on either side of the channel. The asymmetry of the flow lines and the development of diverging flow lines at the lower outside edges of the model are probably the result of unequal application of the distorting force, sidewall effects, and some consolidation around the plastic filler pipe at the base of the sidewalls.

The particle displacement can also be treated quantitatively, and in figure 26*B* contours are drawn in which each contour interval is one-ninth of the length of the largest vector, and the value at any vector is taken to be located at the postshake position of the grid intersection. The large displacements at the channel sideslopes suggest that they are local failures not related directly to particle movement in other parts of the model. Distortion of the vertical lines at the sideslopes (fig. 25) indicates that these local failures occurred by movement distributed throughout the sideslope material, rather than on a single failure surface. Counterparts of these local failures in the model did not occur in the field.

These models show the following movements of material that are similar to those observed on the surface at stream crossings, or are inferred from pile displace-



23.—A four-layer model showing upward arching of the carborundum layers beneath the channel. Note that the amplitude decreases in successively lower layers.



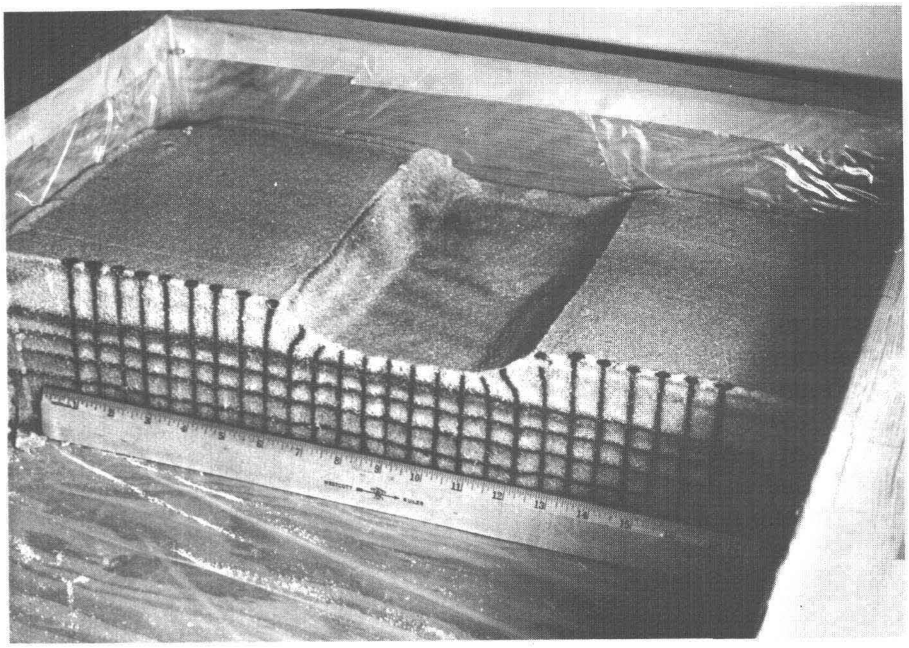
24.—*Upper:* A single-layer model showing the location of the carborundum layer and model surface before consolidation, the location of the surface and the channel cut after consolidation, and the final postshake position of the surface, channel, and carborundum layer. Note that the surface of the model was progressively lowered toward the channel. The edges of the channel were displaced toward the channel; the bottom of the channel rose to above its postconsolidation position, and the carborundum layer was arched above its original position. *Lower:* A four-layer model showing lowering of the surface toward the channel and arching of the carborundum layers beneath the channel.

ments to have taken place beneath the surface.

1. Areas of lateral extension on the surface adjacent to the channel (the areas of extension fracturing in embankments and ground surface).
2. Progressive lowering of the surface toward the edges of the channels.
3. Closure of the channel edges.
4. A pattern of flow lines similar to those inferred from displaced piling (fig. 20).
5. Rising of the channel bottoms (as shown by bridge arching).
6. Horizontal extension of material to some depth to the side and under the edges of the channels and compression under the central part of the channel.

Zones of horizontal compression and extension in the model are shown in figure 26*C*. If a properly scaled imaginary bridge (pile penetration of 20 ft and maximum unsupported pile length of 10 ft) were built across the model channel, it would be a five-bent bridge, with bents located as shown in figure 26*C*. Horizontal displacements of the sediments would have produced compression between central bents and extension, or no compression, between the outside bents. Assuming that the vertical displacement of each bent was the mean of the vertical displacements of the material at the bent, the deck would have developed an upward arch of about 4 inches, with the crest of the arch at the central bent. Thus the horizontal and vertical displacements of the imaginary bents would have been quite similar to those observed in real bridges.

Although these models appear to produce effects similar to those observed at stream crossings, in the absence of a dimensional analysis, we hesitate to draw direct conclusions about the real case from the model. It should be pointed out, however, that in real cases the displacements of sediments are similar through a wide range of physical parameters and probable energy inputs. Thus the pa-



25.—Postshake view of a four-layer model with a vertical carborundum grid shown in figure 26.

rameters to be used in a dimensional analysis vary greatly. For example, the size of the materials varies by several orders of magnitude, from silt to coarse cobble gravel; stream valley widths vary by at least one order of magnitude, from less than 15 feet to more than 400 feet; and the bridges, which lie in diverse orientations and different physiographic situations, 45 to 90 miles from the epicenter, undoubtedly were subjected to seismic energy that differed in frequency distribution, amplitude, direction, and duration.

The foregoing model of displacement distributed throughout the soil differs from previously proposed explanations for similar surface observations in other great earthquakes. Decreases in stream channel widths have usually been attributed to block gliding of a soil mass on a horizontal incompetent layer that is exposed in the side or at the bottom of a stream channel (for example, Oldham, 1882, p. 52-54; 1899, p. 87; Fuller, 1912, p. 48). It has been suggested that if the force of the horizontal component of ground motion exceeds the tensile strength of the soil mass, a block of soil will be detached and move on the incompetent layer toward the free or unconfined face at the stream channel. Large block-glide slides did occur in Alaska (Hansen, 1965); however, no evidence for block gliding was found at the edges of stream channels (see p. D56–D57). This mechanism is restrictive, for it necessitates the presence of an incompetent layer at the proper depth in all places where stream channel widths are decreased. The large areas over which stream narrowing occurred makes the presence of such a layer unlikely.

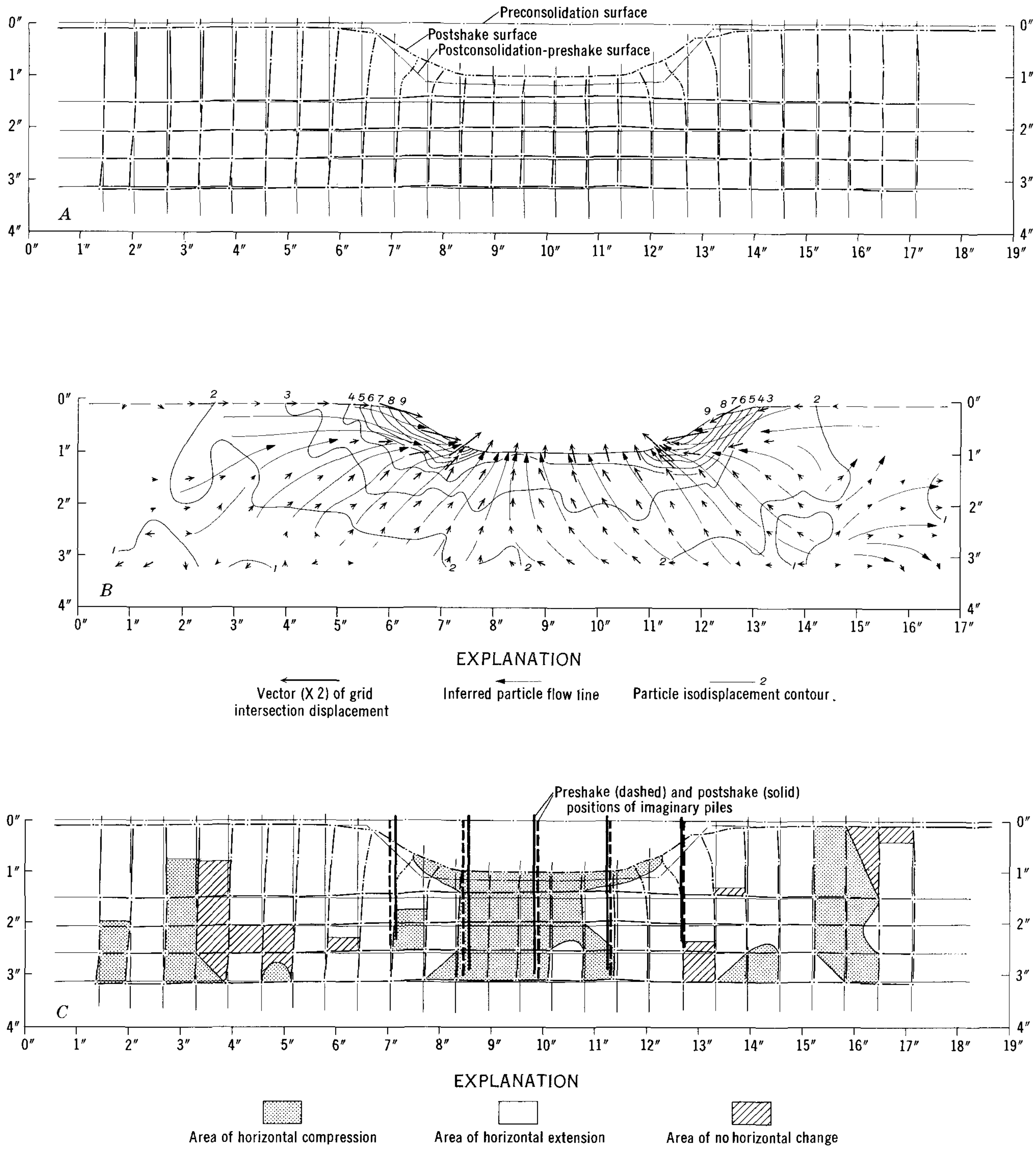
The upward movement of the bottoms of stream channels has also been widely observed in great earthquakes. A good example is given by R. D. Oldham (1899, p. 105–106; also see p. D22–D23, this paper):

> This filling up of river channels took place over a large area, but probably nowhere so conspicuously as in the tract of lowland which lies between the foot of the Garo Hills and the Brahmaputra. This tract is intersected by numerous channels, which carry a limited drainage in dry weather, but, when the Brahmaputra is in flood, help to carry off the surplus waters that would otherwise submerge the country they drain. Before the earthquake these channels were from 15 to 20 feet deep, and in the dry weather the country was intersected by steep-sided depressions of this depth, at the bottom of which flowed a shallow stream. During the earthquake the bottoms of all these channels were forced up till level with the banks on either side, and during the ensuing dry weather the drainage of this tract, instead of flowing in deeply sunken channels flowed nearly level with the general surface of the land in shallow sandy channels.

Oldham (p. 105) suggested that at some depth beneath the alluvium into which the stream channels are cut, there is a bed of loose sand in which (hydrostatic?) pressure is built up during the earthquake. The stream channels, being the thinnest part of the alluvium over this layer, are forced upward in response to the pressure within the sand bed.

This mechanism has the distinct disadvantage of no substantiation for the existence of a sand bed. Further, it requires the special circumstances of such a sand layer over very large areas — not only in India but also in Alaska.

In addition to the objections given above, these explanations for narrowing and uplifting of stream channels do not account for the simultaneous occurrence of both narrowing and uplift. The model of movement distributed throughout the sediment, as inferred from the pile displacements and the sandbox model, appears to have the advantage of predicting that both should occur. This model also seems more realistic because



26.—*A*, Deformation of a four-layer model with a vertical grid (fig. 25). Light lines indicate the pre- and postconsolidation positions of the surface and the vertical grid, and the positions of the horizontal layers in which the preshake consolidation has been distributed proportionately with depth. Dark lines indicate postshake positions of the surface and vertical and horizontal grid. *B*, Particle flow lines indicated by vectors drawn from the pre- to the postshake positions of the grid intersections shown in *A*. The length of each vector has been doubled to make small displacements visible. Contours of equal particle displacement are drawn as ninths of the length of the longest vector. *C*, Areas of horizontal compression in the model shown in *B*, and the preshake and postshake positions of bents of an imaginary bridge. Light and dark grid lines same as in *A*.

it does not require a special geologic situation.

FOUNDATION DISPLACEMENT DAMAGE TO LARGE BRIDGES

Many large bridges of complex structure were damaged by movements of the foundation materials. Being generally more deeply driven than in small bridges, the displaced piles of the large bridges may present evidence of still deeper movements in the foundation materials. In the following sections of this report, three bridges just north of Seward are first discussed as a unit to show the generally similar pattern of damage to somewhat dissimilar bridges in the same physiographic and geologic environment. This discussion is followed by brief descriptions of damage to five large bridges, the northernmost of which is at mile 146.4 on Knik River. Damage to other large bridges is recorded in table 1 and in the mile-by-mile description of the railroad.

RESURRECTION RIVER–MINERAL CREEK BRIDGES

Three railroad and three adjacent highway bridges that cross the flood plain shared by Resurrection River and Mineral Creek just north of Seward were severely damaged. All three railroad bridges had to be replaced with entirely new structures. The low-relief flood-plain surface was severely fractured. Fracturing (figs. 27, 28) was accompanied by the ejection of a considerable amount of water.

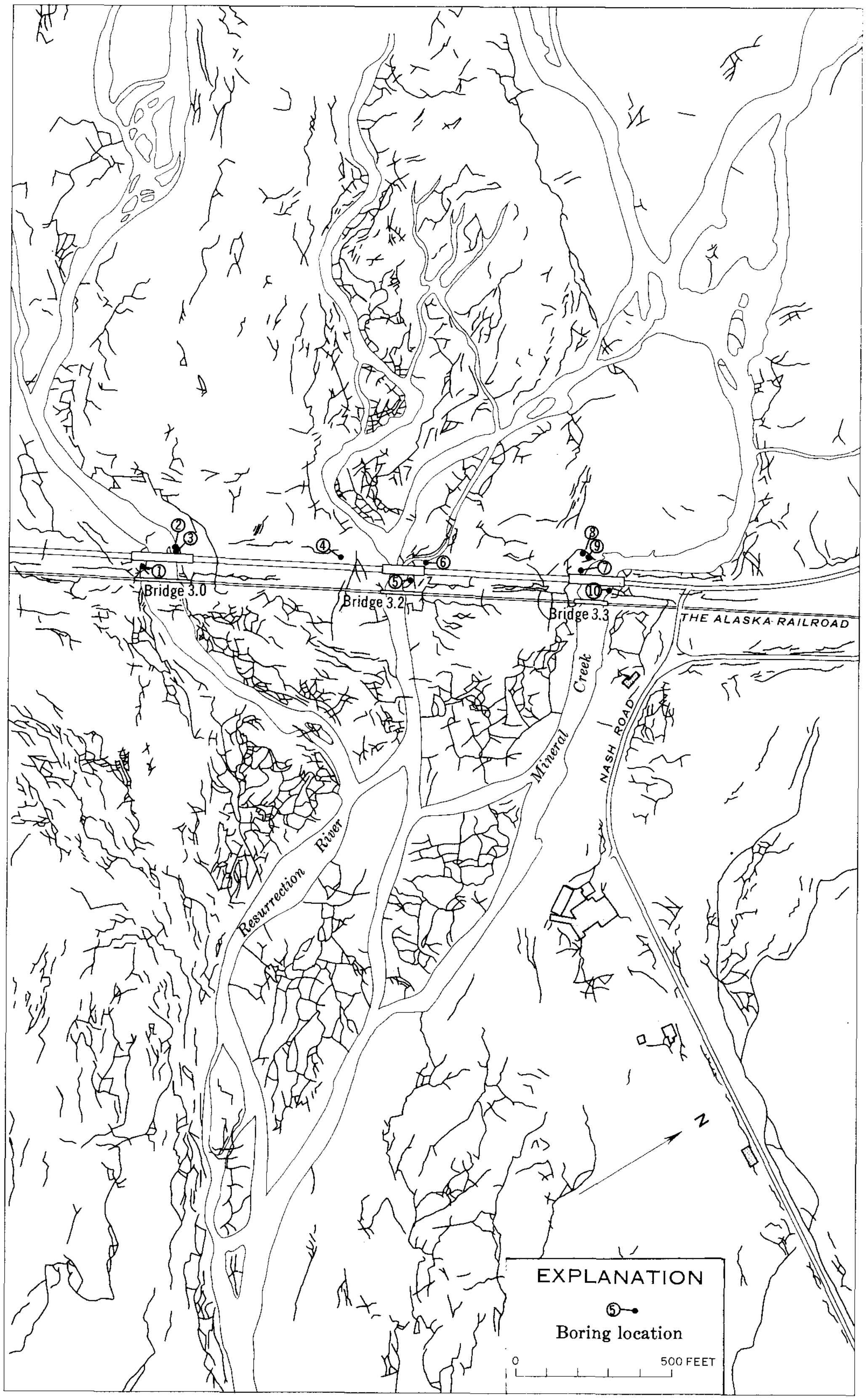
All the railroad bridges were damaged by compression at the deck level, and their supporting piles were shifted streamward. In addition, the railroad embankment shifted to the southeast, parallel to the contours, and carried the ends of the bridges along with it. The damage to each of the three bridges is described below.

Bridge 3.0 crosses the southern branch of Resurrection River and is 187 feet long (fig. 29). Its two 13.5-foot open wood-trestle end spans bear on a seven-pile bent at the bulkheads and a cribbing on pile-supported piers that carry two 80-foot through steel girders. The central pier rests on four rows of nine piles, and the outer piers have three rows of nine piles. Compression at the deck level totaled 13½ inches. The steel deck beams were driven 4 and 5½ inches into the ends of the wood stringers, and the wood stringers were driven 1.5 and 2.5 inches into the bulkheads. Compression was accompanied by endways pounding (shown by pebble dents between the last tie and fillers on the north bulkhead).

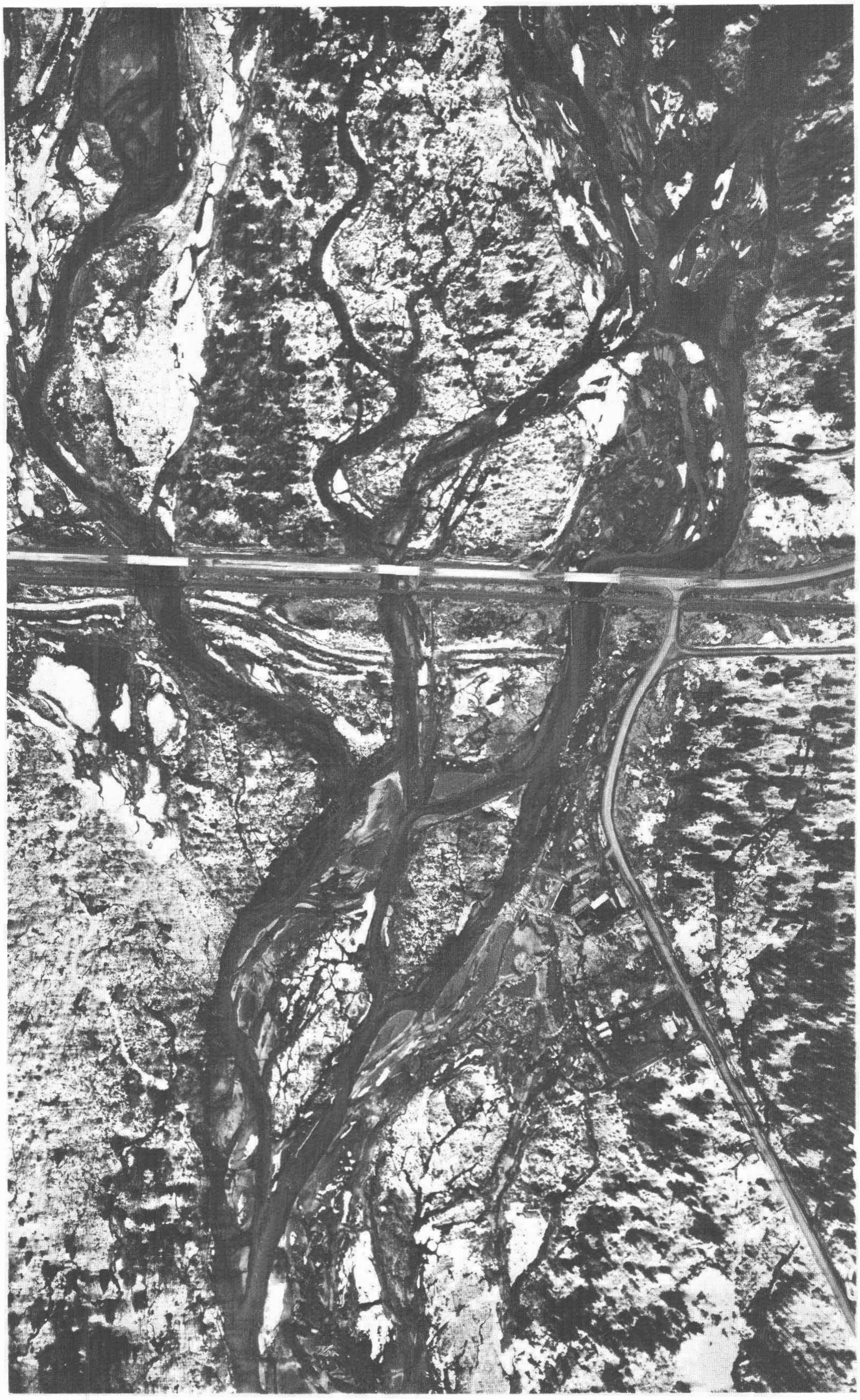
Piles at the bulkheads and piers were shifted streamward. All moved with no detected vertical rotation. The horizontal displacements ranged from 1½ to 11 inches; there was extension of the valley bottom sediments at the stream edges and compression in the center (fig. 29). The centers of the piers, originally under the bridge shoes, were displaced as shown by vertical chalk lines drawn up from the centerline of the central row of piles (fig. 29). As the piers shifted, rockers on the bridge shoes were driven to their extreme positions, and with continued movement of the piers, the cribbing was rotated, which placed more weight on the outside row of piles in each pier. The redistribution of the weight may have caused the vertical movements that occurred in piles under the piers. The tops of the piles in each row stood successively higher toward the streams. Despite the greater heights streamward, the cribbing was cantilevered off most of the streamward row of piles. In the south pier, only three of the nine piles in the row were bearing; the rest ranged from three quarters of an inch to 6 inches below the cribbing. In the north pier all the streamward piles stood an inch or so below the cribbing. The transfer of the load to the outside piling and the decrease in skin friction which must have occurred during the movement of the sediments probably caused the outer row of piles to be driven downward into the sediments. Because these piers are closely spaced and depend primarily on skin friction for most of their bearing capacity, it also seems likely that downward movement of the overloaded piles may have produced a negative skin friction which pulled the unloaded streamward row of piles downward.

In addition to moving streamward, the outer piers shifted 8 inches downstream of the central pier, and the bulkheads and approach fills were carried 4 to 5 inches more; the central pier was thus left 12 to 13 inches upstream of the approaches. As shown in figure 29, the downstream edges of the steel girders were jammed together, and the metal shoes were rocked inward, their bases lifting ¾ and 1¾ inches off the cribbing. On the upstream side of the same pier the girders were pulled 3-3/16 inches apart. The compression of the steel spans at the downstream edge of this central pier may have exerted some downward force, for the top of the pier was tilted about 2 inches in the downstream direction.

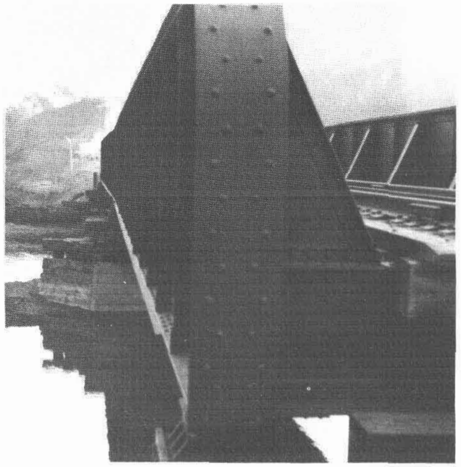
For comparison, the adjacent highway bridge is shown in figure 30. Deck level compression drove the steel into the abutment, breaking the back wall. The abutment and pier were shifted streamward. The top of the pier was prevented



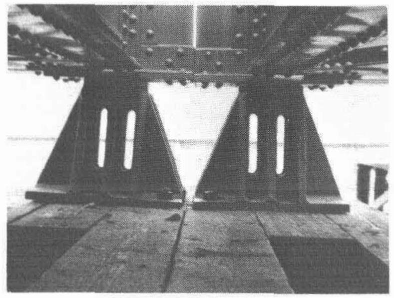
27.—Ground cracking on the flood plains of Resurrection River and Mineral Creek. Numbers indicate borings, the logs of which are given on figures 29, 31, and 32. Cracks were mapped from aerial photographs taken by Air Photo Tech, Anchorage.



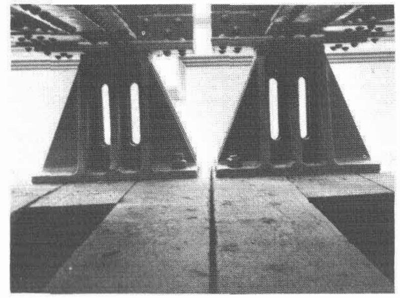
28.—Aerial photograph of area mapped on figure 27 of Resurrection River and Mineral Creek flood plains. Photograph by Air Photo Tech, Anchorage.



View south showing ends of bridge displaced downstream relative to its center

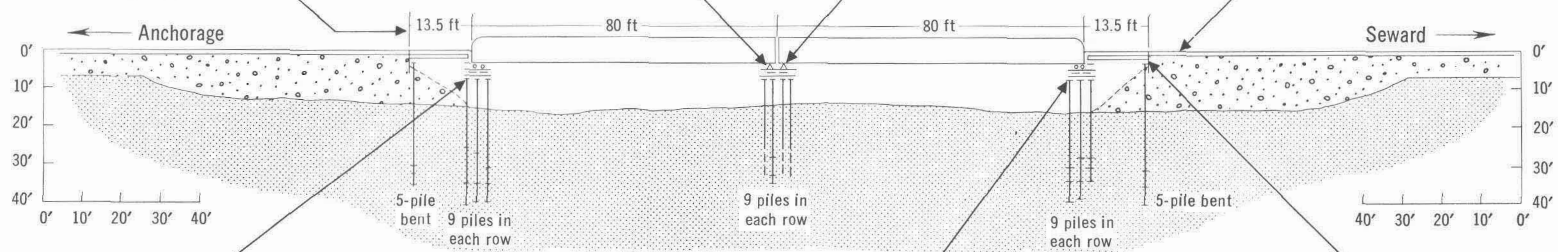


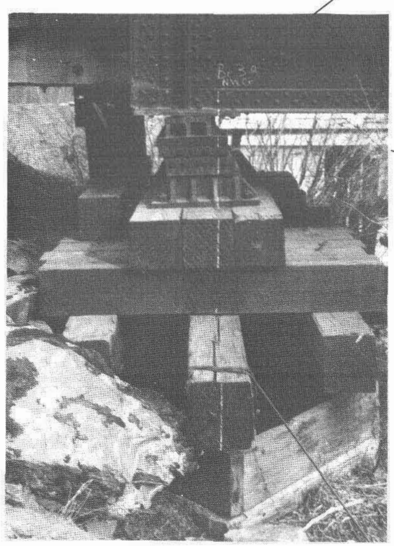
Fixed bridge shoes on the downstream side of the central pier were pried upward at their outward edges as the spans above were driven together

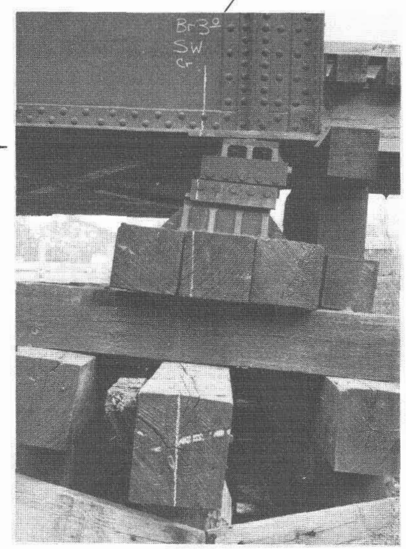


Fixed bridge shoes on upstream side of the central pier were not displaced

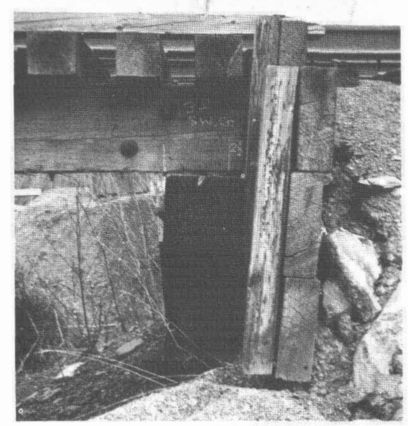
Central rail on bridge driven back into approach fill



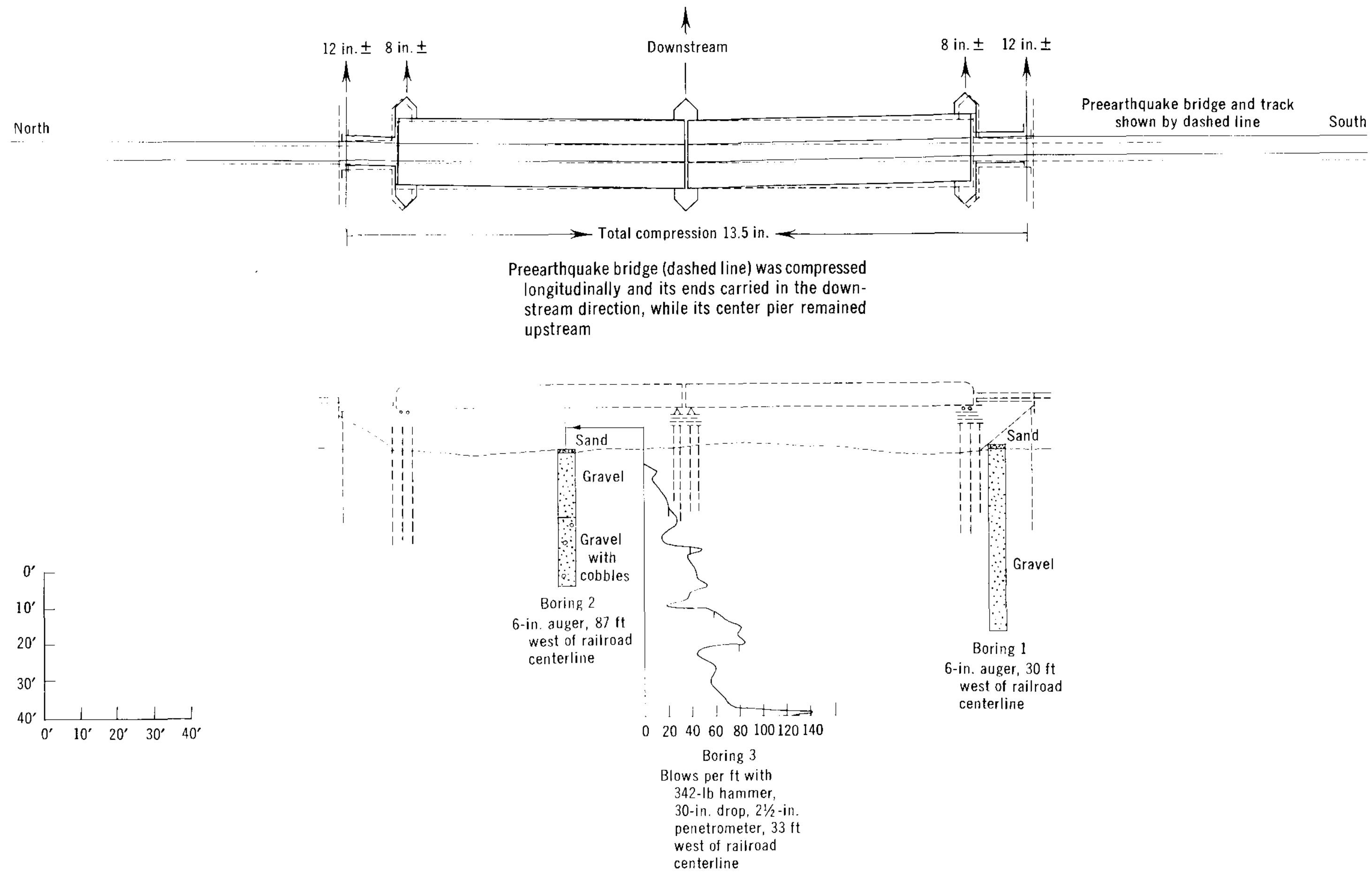




Piles shifted streamward, rotating the cribbing. Vertical chalk lines drawn upward from the pile cap at the pier center show the amount of horizontal displacement at the bridge shoes. Note that the nested rollers are driven into their extreme positions. Wooden stringers were driven 4 inches and 5½ inches into the central steel spans (shown by crowded ties in upper left of left photograph)



Deck stringers driven 2½ inches into the bulkhead. Rails pulled free at ties on the embankment. Bulkhead rotated back into the fill and guard timber driven over top at the bulkhead



29.—Bridge 3.0; construction, damage, and subsurface information. Subsurface data projected to rail line at proper altitude.

30.—Looking southeast toward highway bridge (No. 596) at Resurrection River. Streamward movement of the foundation materials compressed the deck, breaking the abutment backwall, and carried the abutments and bases of the piers toward the channel. Being restrained at the top, the pier was broken at the ground line. Similar damage occurred at the other end of the bridge.

from moving laterally by the deep central steel span, but its base was carried streamward, rotating the pier and cracking it at the waterline. Damage to this bridge was typical of the adjacent highway bridges—in all of which the abutments were rammed by the steel, and the piers were broken and shifted streamward at their bases.

Bridge 3.2, a nine-span 135-foot open wood trestle (fig. 31), crosses the northern branch of Resurrection River. Pile data for this bridge are shown in figure 8. Deck-level compression drove the stringers 1¼ inches into the north bulkhead, crushed the fillers, and drove the top of the bulkhead back into the fill. At the south bulkhead the stringers were driven 8 inches past the piles into the bulkhead, and here, too, the top of the bulkhead was shoved back into the fill.

There was no appreciable settlement of the south approach fill, but the north fill settled about 5 inches relative to the bulkhead, and the bulkhead was pulled down about 3 inches below the deck by the fill. Settlement of about this same amount continued to the next bridge (fig. 31).

As shown in figure 31, the downstream shifting of the bents increased away from the center of the stream, the ends of the bridge and the approach fills being carried about 10 inches downstream from the center of the bridge. There was also some crowding of the piles toward the stream, but the displacements were not measured.

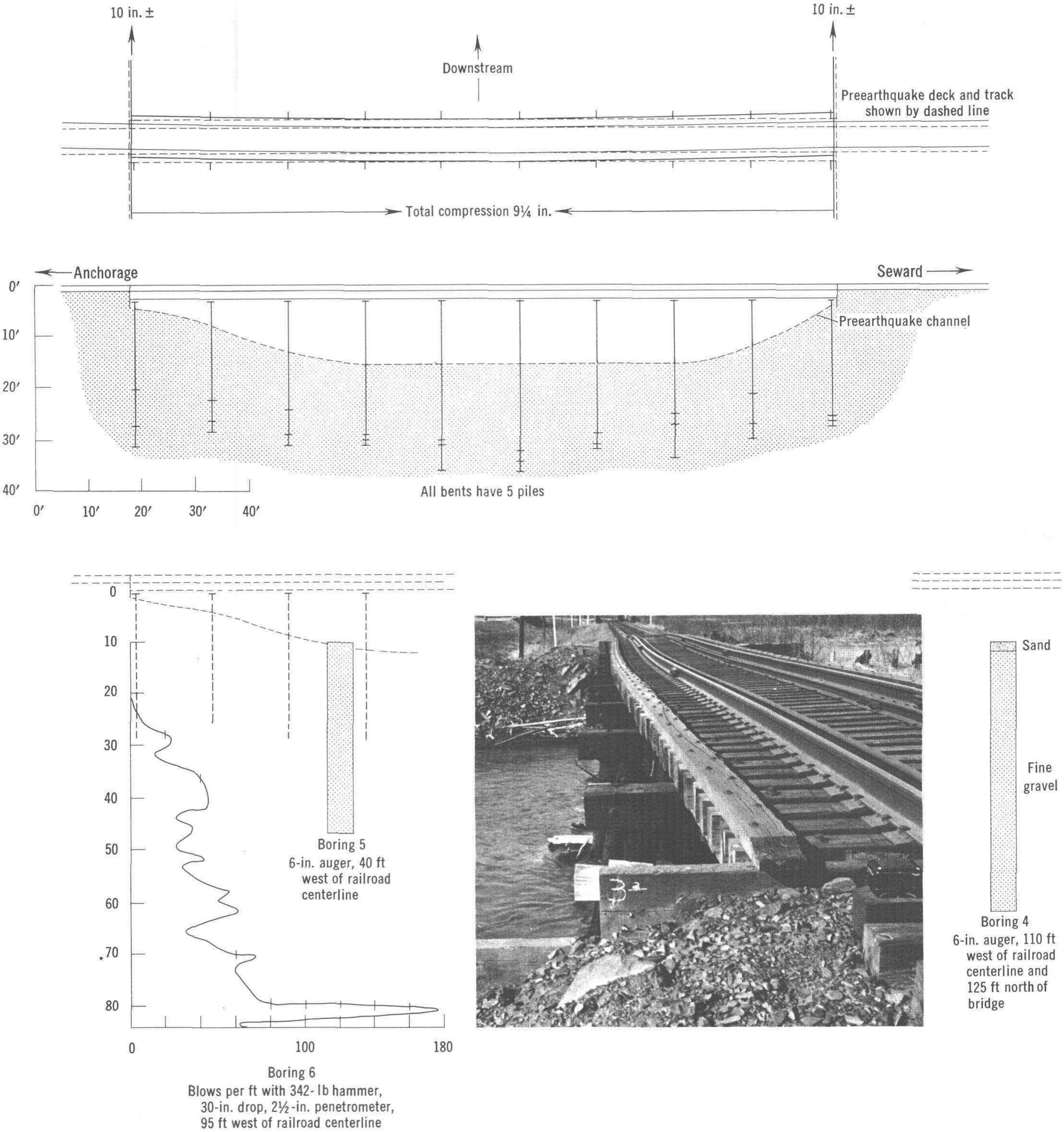
Mineral Creek bridge, at mile 3.3, has a total length of 136 feet and is built with an 80-foot central steel through girder and two 14-foot pile-supported open wood trestles at each end (fig. 32). The damage to this bridge was very much like the damage to the similar bridge at mile 3.0. Compression, totaling about 19 inches developed at the deck level, driving stringers into bulkheads and into the central steel spans. At the north bulkhead the stringers were shoved at least an inch past the piles, forcing the top of the bulkhead bents into the fill. Multiple pebble dents between the last tie and the filler show that compression was accompanied by at least four compressive blows.

At the south bulkhead the stringers drove about a foot past the piles. The pile cap was torn nearly free of the piles, and the stringers shoved the bulkhead planks back into the fill, tearing the planks free of one of the fillers. The stringers were driven at least 2 inches into the north end of the steel girder and 4 inches into the south end, crushing the intervening ties.

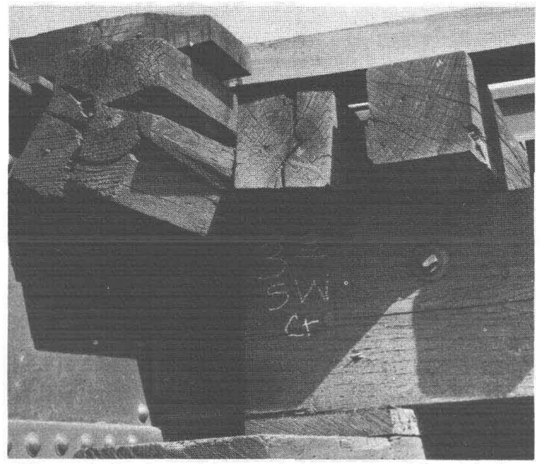
Piles in the bents and piers shifted streamward, horizontal displacements ranging from 1 to 20 inches. The valley bottom sediments were extended at the valley margins and compressed in the center (fig. 32). There was no detected vertical rotation of the piles, with the exception of the piles between the southern wood trestle, whose tops were tilted 4° toward the stream.

As the pier piles shifted streamward, the nested rollers in the south bridge bearings were driven to their extreme positions, and the northern fixed bearings were rotated, their streamward edges lifting up off the cribbing about ¾ of an inch. Rotation of the cribbing streamward at its base increased the weight on the outer row of piles. As at bridge 3.0, the outer row of piles were all bearing on the cribbing, most of the central piles were bearing, and the cribbing was cantilevered an inch or more above the inner rows of piles.

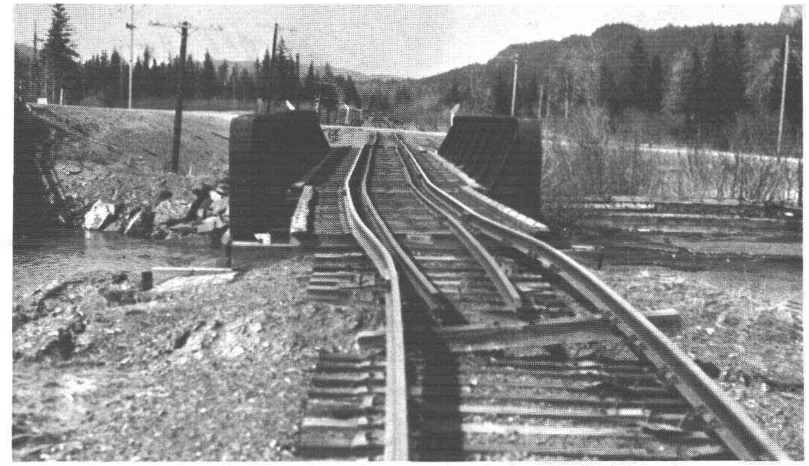
Settlement of the grade of about half a foot both north and south of the bridge left the bridge standing high, and tore the track from the ties on the approach fills. The set-



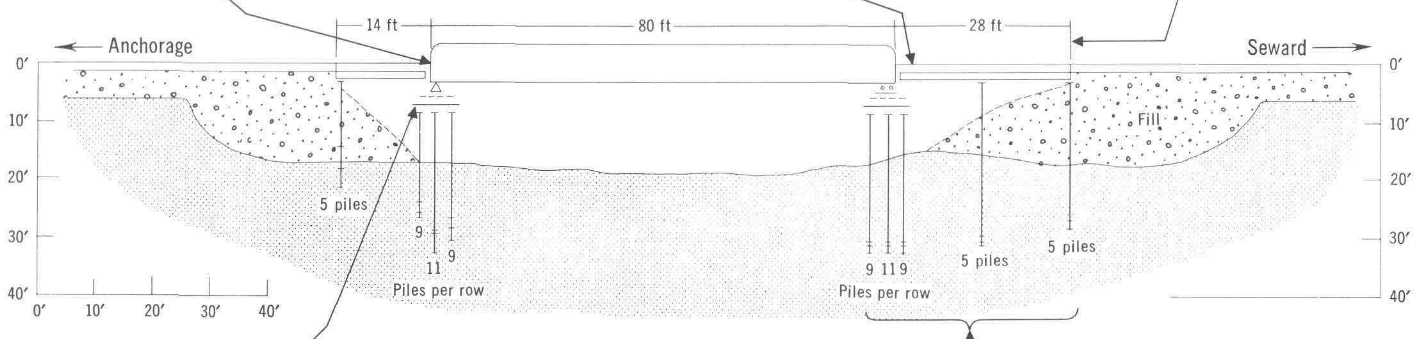
31.—Bridge 3.2; construction, damage, and subsurface information. Subsurface data projected to rail line at proper altitude.

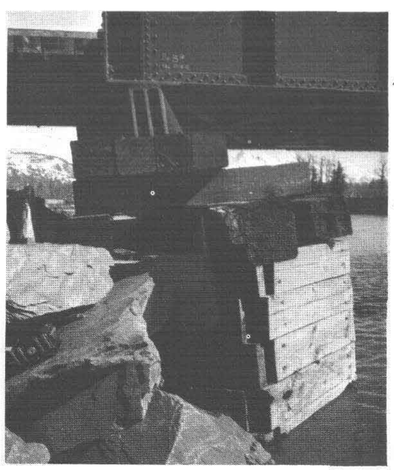


Ties crushed and crowded as wood stringers were driven into the *steel central span*; stringers driven 2 inches into the steel at left and 4 inches below

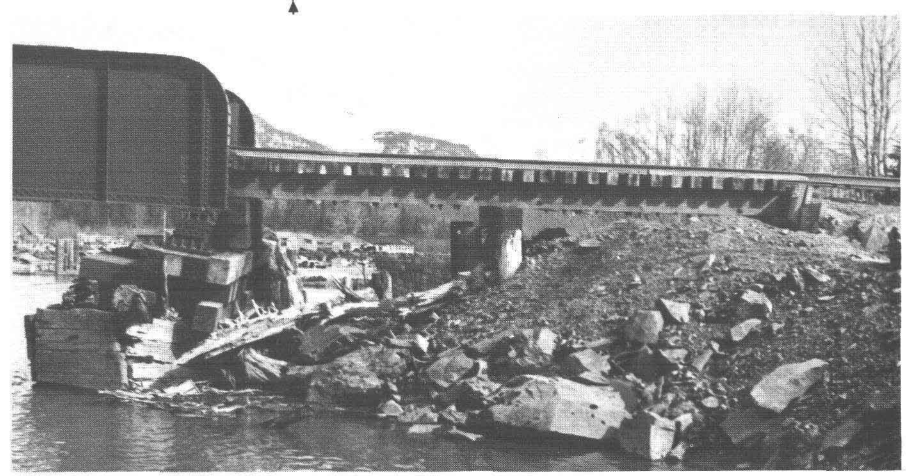


View north over bridge, showing end spans and embankments offset downstream (right) from highway fill located at left

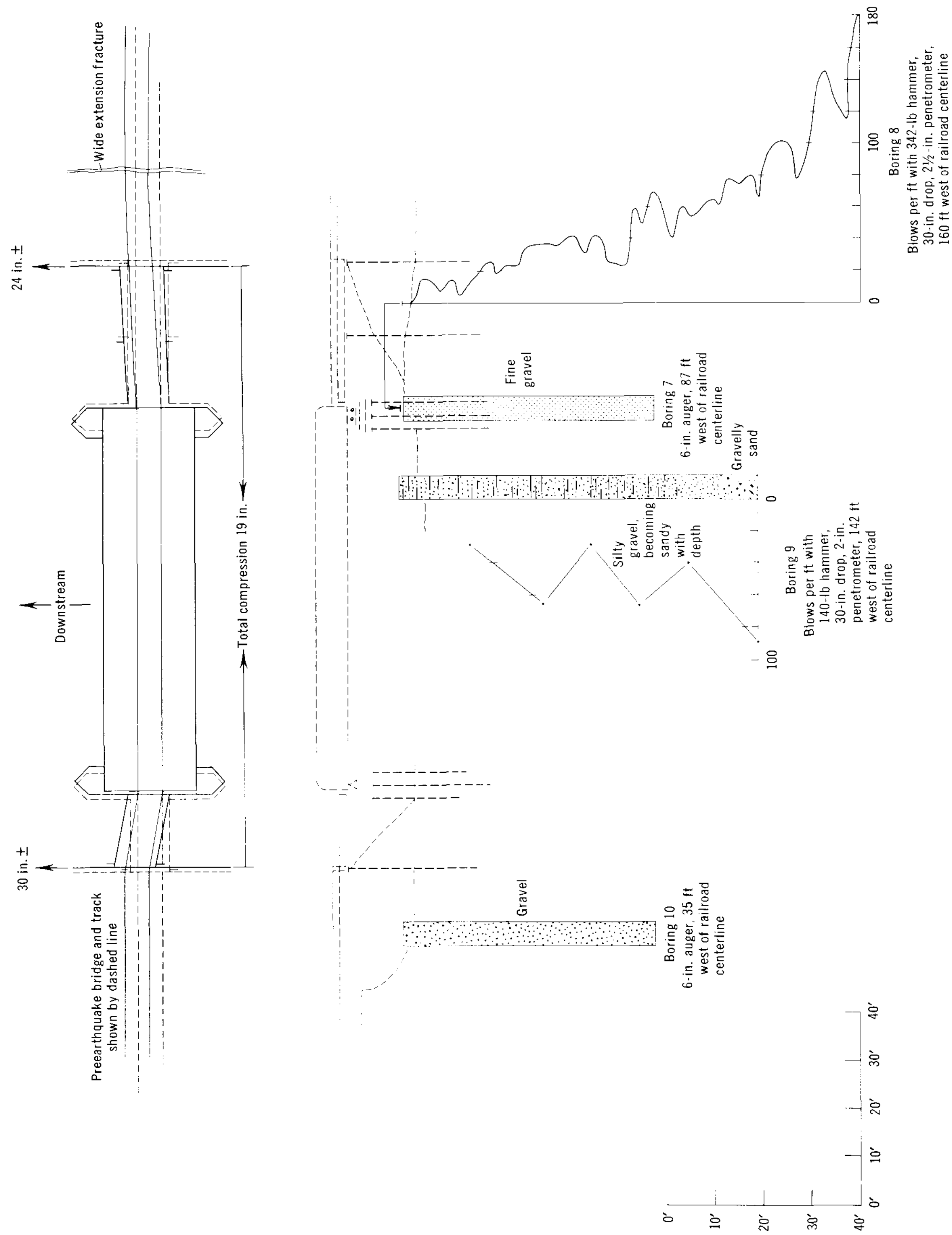




Piles shifted streamward in the piers, rotating the cribbing and driving the nested rollers in the bridge shoe (at right) to its extreme position



Streambanks moved closer together, driving wood stringers into the central span and about 1 foot past the bulkhead piles. The bulkhead was rotated and driven into the fill, and the guard timber was shoved over the top of the bulkhead. The rails were pulled free of the ties on the approach fill. The piles between the wood spans were shifted 22 inches to the left of the pile cap. Light-colored pile in foreground from older bridge



32.—Bridge 3.3; construction, damage, and subsurface information. Subsurface data projected to rail line at proper altitude.

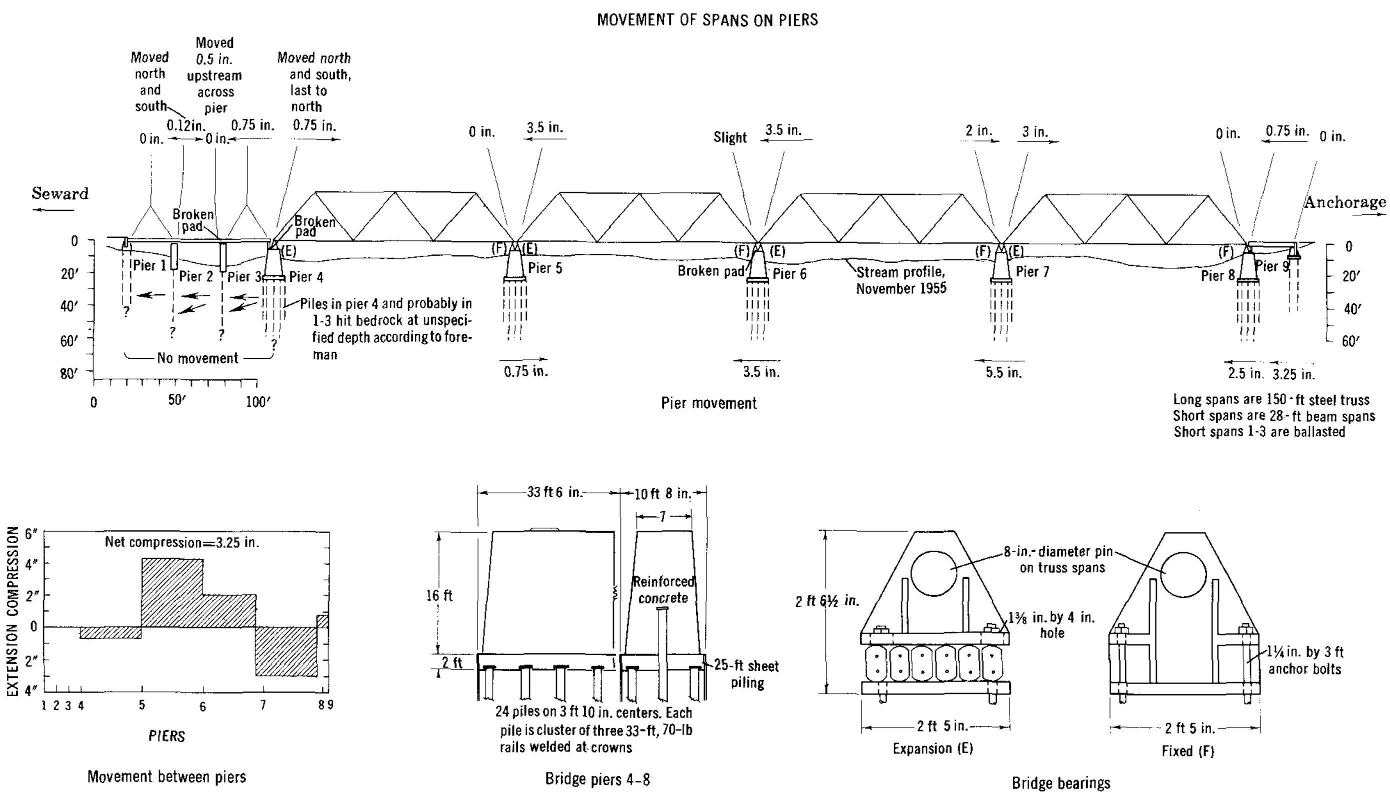
tling of the fill and possibly the lowering of the sediments under the fill pulled some of the bulkhead piles downward and left them about an inch below the caps. The bulkheads were also pulled down. The lower plank and eastern filler of the northern bulkhead were pulled 2 inches downward and 2 inches eastward with the shifting fill, while the upper planks and bulkhead cap were held by the stringers to which they were bolted.

As at the adjacent bridges, the grade was shifted to the southeast, parallel to the stream which skewed the approach spans and left the central span about 30 inches upstream. The bulkhead bents were carried with the grade; the bents under the wood trestle spans between the bulkheads and piers were carried a somewhat lesser distance.

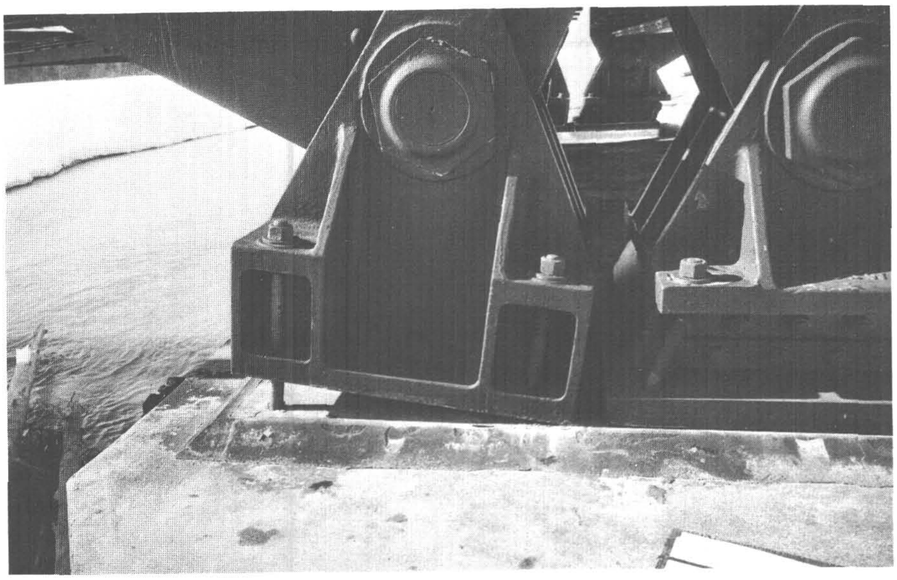
The foundation materials involved in the displacements that damaged the three bridges just described are known from borings made in 1964 along the highway just west of the rail line. The locations of the borings are shown in figure 27 and the subsurface data are projected at their proper altitudes in relation to the rail line in figures 29, 31, and 32. All the sediments are noncohesive; field identifications range from sandy and silty gravel to fine gravel to gravel. With the exception of hole 2, at bridge 3.0, in which cobbles were found below 20 feet, the gravel averaged less than three-fourths of an inch in diameter, with a maximum of about 3 inches. All the sediments were saturated, the ground-water table lying at, or within 2 feet of, the surface. Penetration resistance generally increased downward, although there were some inversions. Within the depth of the sediments penetrated by the piling, the materials were compact to dense. Penetration resistance on a standard penetrometer (140-lb hammer, 30-in. drop, 2-in. sample spoon) was 30 to 40 blows per foot, and a second penetrometer (342-lb hammer, 30-in. drop, 2½-in. penetrometer) encountered resistance of 20 to 25 blows per foot. In summary, the materials were noncohesive, saturated, and compact to dense.

SNOW RIVER BRIDGE

Construction and displacements of the sub- and superstructure of the Snow River bridge (14.5) are shown in figure 33. The concrete piers and abutments rest on steel piling composed of three 70-lb-per-yd railroad rails welded at the crowns. In piers 4–7 and the northern abutment, these piles gain their bearing by friction, while at the south end of the bridge the abutment and piles of the first three piers probably bear on bedrock. These latter piers and abutments did not move. The remain-



33.—Construction and damage to Snow River bridge (14.5).



34.—Fixed end bearing lifted from pier at north end of sixth span of bridge 14.5. Anchor bolt pulled free of concrete. In adjacent expansion bearing, nested rollers were driven to the extreme position.

der move generally toward the river. Maximum displacement was 5.5 inches. Piers shifted without tipping, and, if the piling was not bent, sediments to depths in excess of 45 to 55 feet must have been involved in the displacement. There was neither upward movement nor settling of the piers, and no noticeable upstream or downstream displacement. Rollers on expansion bearings of piers 5 and 6 were driven to their extreme positions. Fixed bearings were shifted, and on the north end of the sixth span, where compression was maximum, the edge of the bearing was rocked upward off the pier (fig. 34). Anchor bolts were bent and stretched but none were sheared. No boring data are available for this bridge.

TWENTYMILE RIVER BRIDGE

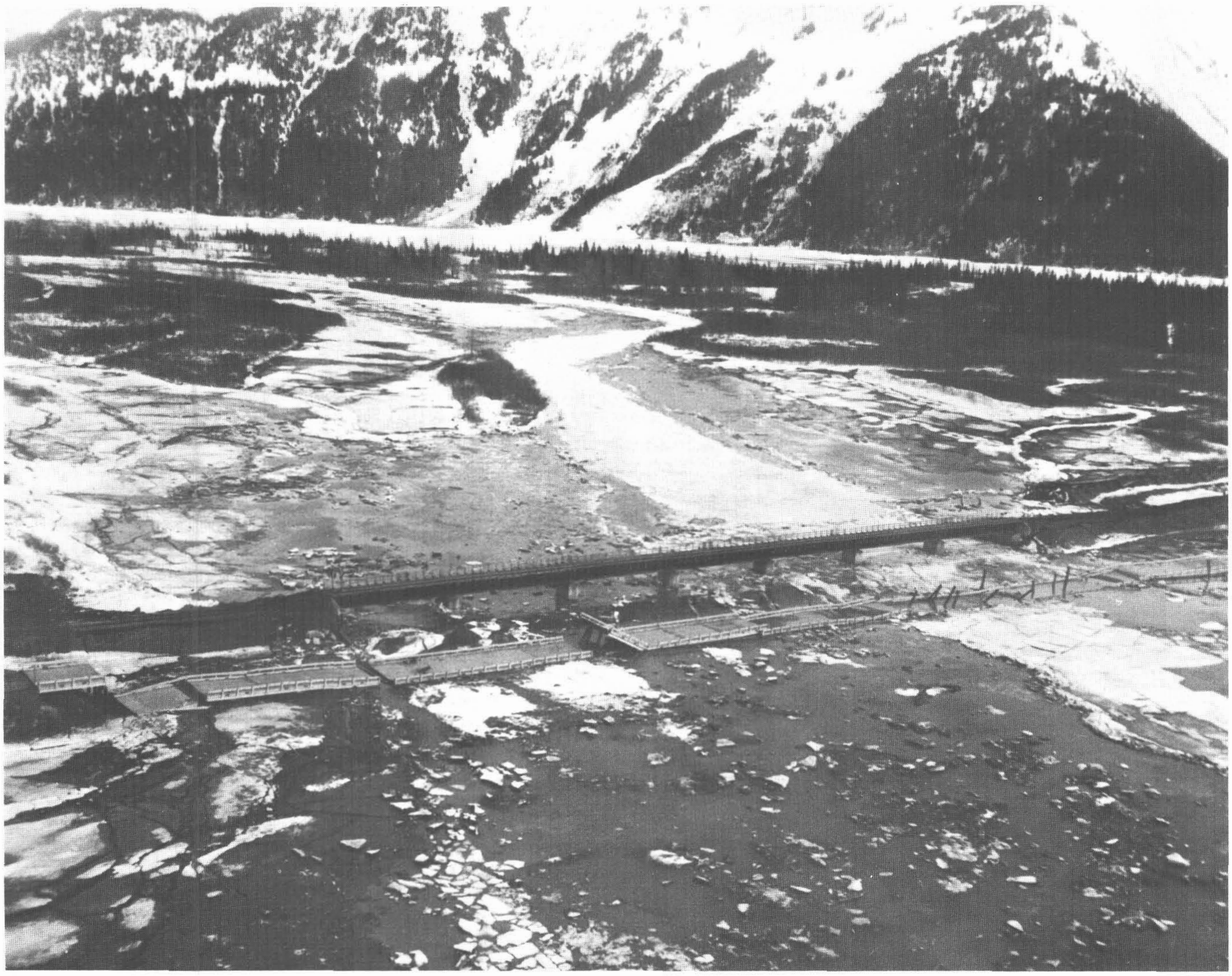
The long heavy Twentymile River bridge (64.7) is built of seven 70-foot 1-inch steel deck trusses supported on concrete piers and abutments (figs. 35, 36). Repairs were made before the authors had the opportunity to record differential movements of all spans on all piers; thus real displacements cannot be determined. Displacements shown on the figure are only the larger movements of two piers relative to the bearings of the overlying spans. Movement of the piers must have been more general, because compression at the deck level jammed all the trusses together, and drove the end trusses into the abutments and broke away the backwalls (fig. 37). Anchor bolts were sheared on three piers and the abutments. The positions of the rebuilt abutment backwalls and the base of the preearthquake abutments indicate that total compression was about 5 feet 2 inches. The piers and abutments were carried on 11 to 14 piles composed of three 65- to 70-lb-per-yd railroad rails welded at the crowns. Penetration ranged from about 32 to 49 feet, and, as noted on p. D132, the sediments into which the piles were driven consisted of 2 to 20 feet of sandy fine gravel underlain by sand, often containing small amounts of fine gravel (holes 8–13, fig. 112).

No rotation of the piers was observed, but there was some downward displacement. Postearthquake releveling by The Alaska Railroad shows that the northern abutment was displaced downward 0.88 foot relative to U.S. Coast and Geodetic Survey bench mark Q12 located on bedrock 1.8 miles to the north. Because there were no differential vertical displacements in the substructure, similar downward displacements probably occurred in all substructure elements, and may have resulted from compaction of sediments, rather than downward movement of the piers through the sediment.

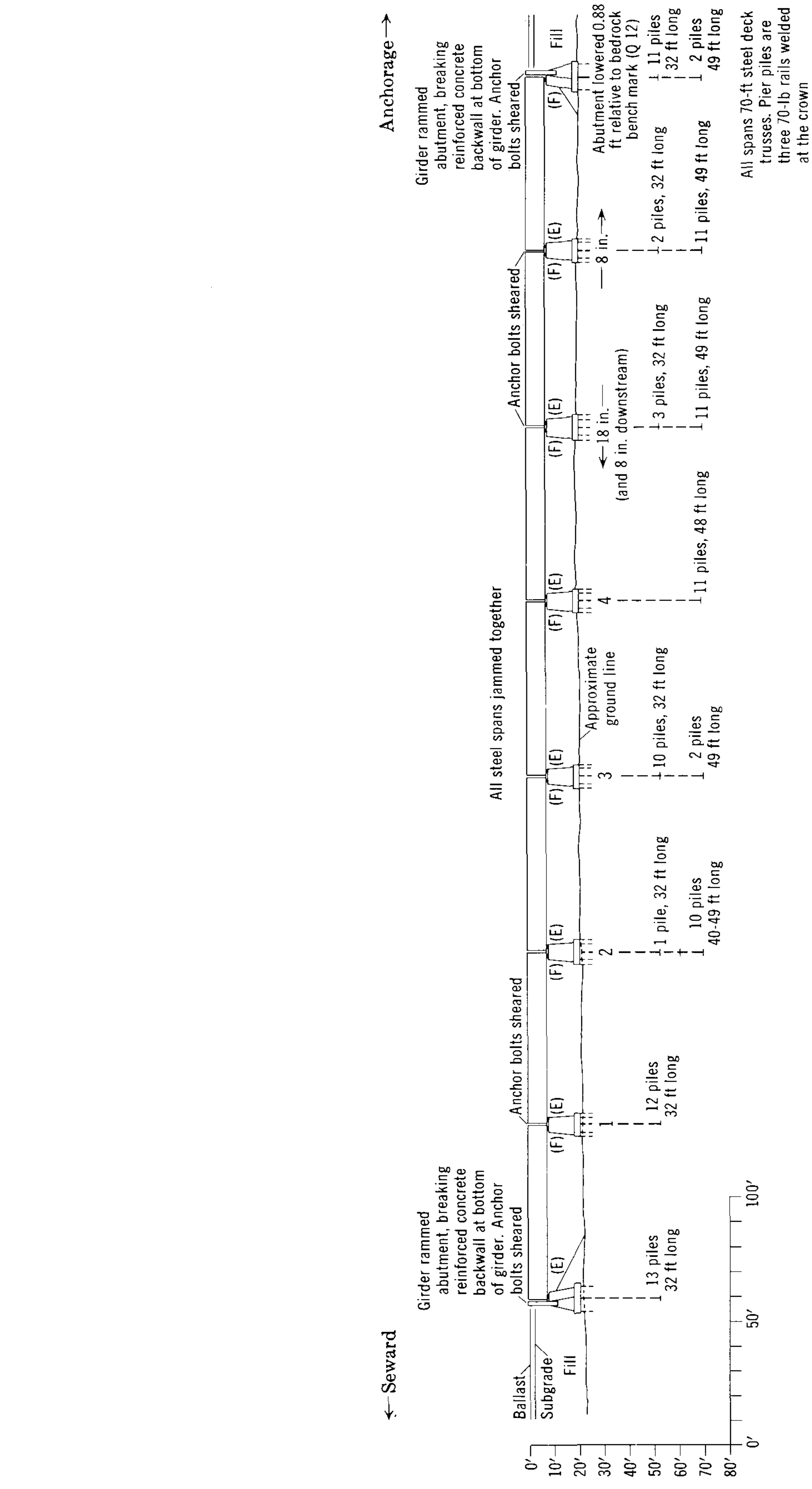
SHIP CREEK BRIDGE

Ship Creek bridge (114.3) has two 35-foot steel-beam span approaches and a central 123-foot through truss carried on pile-supported concrete abutments and piers (fig. 38). Abutments and piers shifted streamward, the deck was put in compression, and each end span jammed against the central span and into the abutment backwalls. Total compression at the deck was about 13 inches. Movement of the piers was so great that the expansion bearings were reset 9½ inches from their former positions and the fixed bearings were displaced 5½ inches. Although reported to be undamaged (Fisher and Merkle, 1965, p. 255–256), the bridge was closed to traffic until new bearing surfaces were constructed on the pier tops.

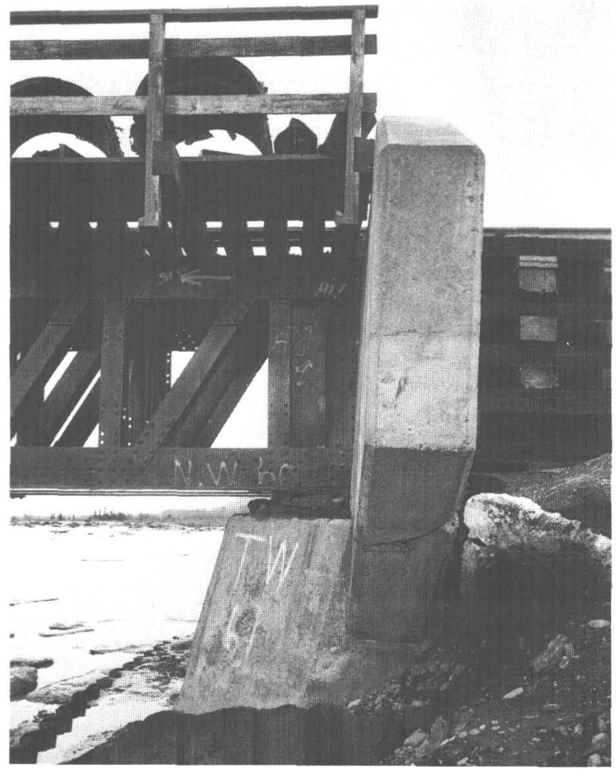
Piers are carried on 45 wood piles 30 to 35 feet in length. Piles in the abutments are three 70-lb-per-yd railroad rails welded at the crowns; their lengths range from 66 to 128 feet, and the outside rows are battered outward at about 13°.



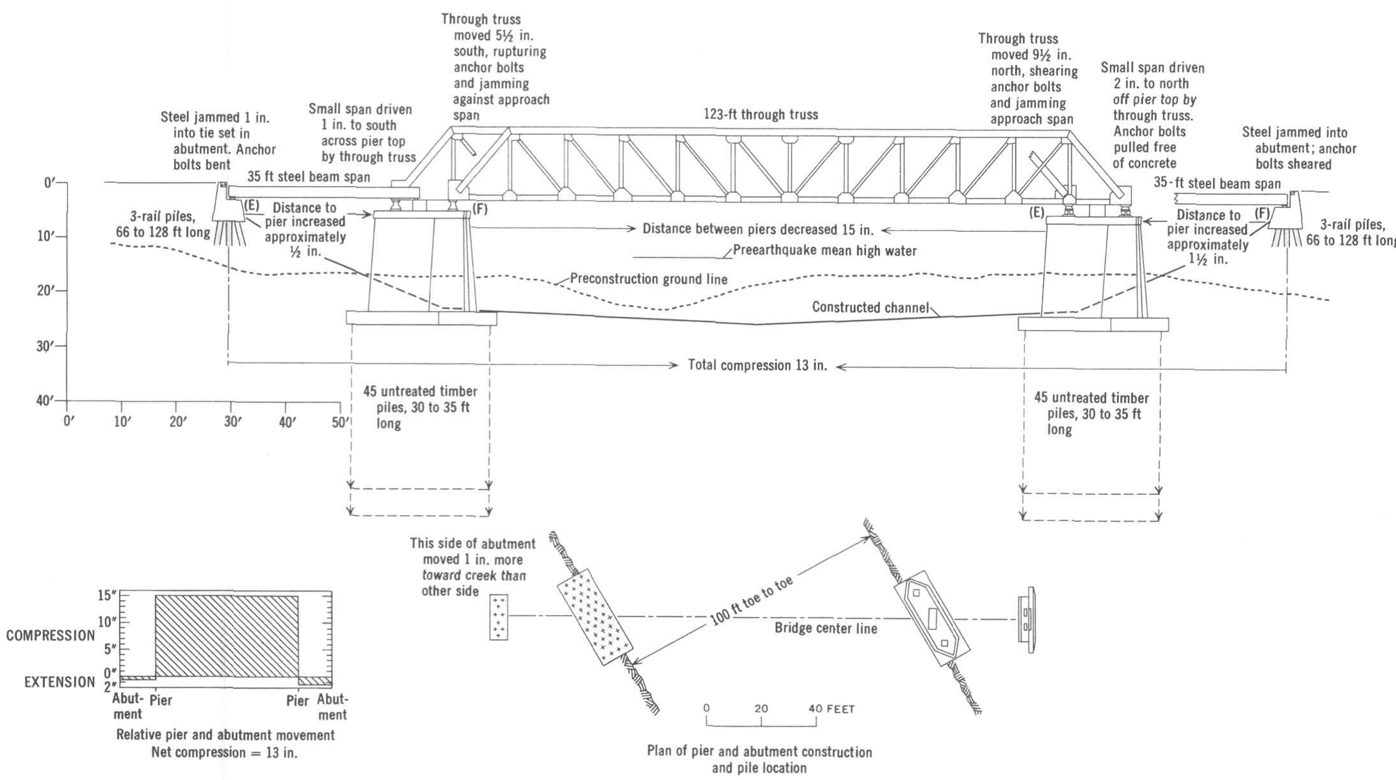
35.—Railroad bridge (64.7) and highway bridge at Twentymile River, Portage. All concrete deck sections of the highway bridge except one were knocked from their piles, and some piles were driven through the concrete. The railroad bridge was compressed and some of its piers shifted (see fig. 36). Note the severe cracking in the embankments, flood-plain, and tidal sediments (see pl. 3). Photograph by Arthur Kennedy, U.S. Forest Service, Anchorage.



36.—Construction of and damage to Twentymile River bridge (64.7).



37.—Damage to Twentymile River bridge. Left: Concrete abutment broken away after earthquake to relieve pressure on spans. Note tilted bearing shoe and missing sheared-off anchor bolt. Right: North abutment backwall broken by thrust of steel deck.



38.—Construction of and damage to Ship Creek bridge (114.3).

The surface sediments at the bridge site are estuarine, probably predominantly in the silt-clay size range (fig. 126). No subsurface data are available at this location; however, it is likely that the deeper piling in the abutments may enter the gravels that form low terraces a short distance upstream.

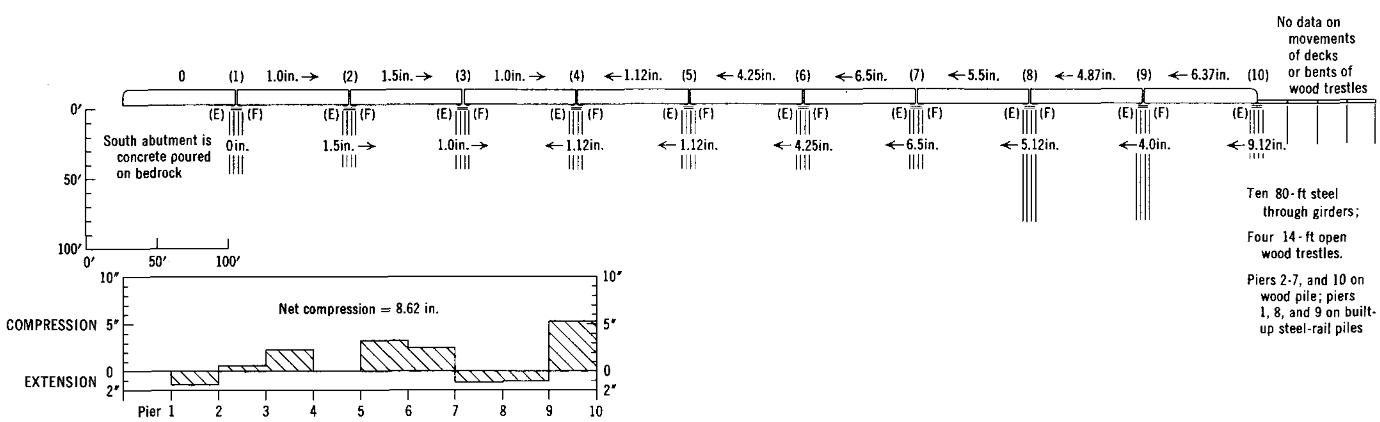
KNIK RIVER BRIDGE

The Knik River bridge (146.4) crosses the southernmost channel of Knik River (pl. 1). Its ten 80-foot through steel girders are supported on piers of two types — most are wood cribbing on wood piles, but those near the channels, where scour is greatest (piers 1, 8, 9), were replaced prior to the earthquake by concrete piers on welded-rail piling (fig. 39). The southern span rests on a concrete abutment built on bedrock. The northern steel span is joined to four 15-foot open wood trestles. Displacements of the piers and decks show a maximum of 9.12 inches for a pier and 6.37 inches for a deck. No measurements were made of the displacements of the wood trestles on their pile bents.

The next four large bridges to the north (147.1, 147.4, 147.5, 148.3; pl. 1) were damaged by similar displacements of piling and decks. This damage is described on page D156 and is summarized in table 1. The properties of the underlying sediments are described in the section on the relationship of damage to grain size, thickness, and density of foundation materials (p. D66–D67).

SUMMARY

1. Damage to the long complex bridges followed the same pattern as that of the small wood trestles. Decks were compressed with considerable force (concrete abutments broken, anchor bolts sheared, bridge bearings torn free of piers, and stringers crushed), as the piers and abutments were generally crowded toward the rivers. With the exception of Knik River, where sediment displacement was complex, sediments were extended at river margins and compressed in the middles, in the pattern typical of smaller creeks.
2. Vertical arching so common in wood trestles was absent or very small in long bridges. The absence or near absence of arching in long bridges may be due in part to downward movement of the heavily loaded piles through the mobilized sediments (as suggested by differential vertical pile displacement at Resurrection River and Mineral Creek bridges, and by releveling to piers and abutments on Twentymile River bridge). It may also reflect the fact that sediments everywhere achieved nearly the same general degree of mobility, so that in a given duration of shaking only a certain amount of movement could occur toward topographic depressions. This suggested relation of shaking duration and degree of mobility would explain why, for a wide range of channel widths, compression usually amounted to about 20 inches or less (fig. 10). The bridges that had larger total compressions were in the Portage area, where eyewitnesses described considerably longer ground motion.
3. Long piles did not prevent damaging streamward displacement of piers and abutments.
4. Where piles were on, or close to, bedrock (Snow River and Knik River bridges), there was no permanent lateral displacement of the substructure but there was some minor displacement of the overlying deck.



39.—Construction of and damage to Knik River bridge (146.4).

TRANSIENT HORIZONTAL DISPLACEMENT OF GROUND, AND RELATED BRIDGE DAMAGE

Endways pounding damaged both railroad and highway bridges. The steel girders of highway bridges were slammed repeatedly into their concrete abutments, and wooden stringers of railroad bridges rammed and damaged the wood bulkheads.

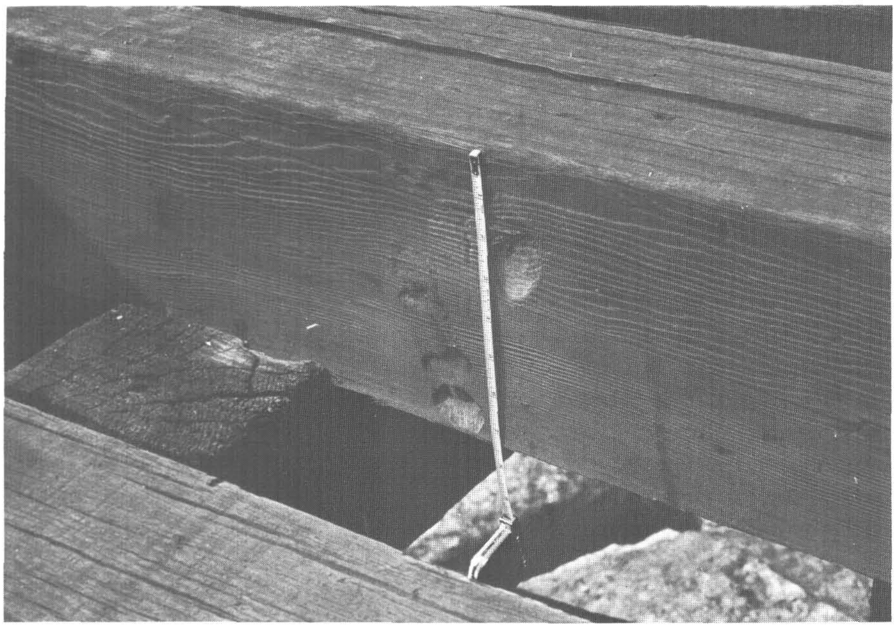
The force of the repetitive horizontal blows is difficult to estimate, because their effects are combined with those produced by compression resulting from streamward shifting of bulkheads and abutments. However, Charles P. Smith (1965, p. 25), chief bridge engineer for the Alaska Department of Highways, concluded from a study of damaged highway bridges that "most of these structures were subjected to large horizontal acceleration which resulted in almost every case in failure of the superstructure to substructure connections." From the strength of sheared anchor bolts and the deadweight of the superstructures, he concluded (p. 23) "a horizontal force approaching 2 *g* was necessary to shear such bolts. Actual forces may have been greater."

Among our observations on railroad and adjacent highway bridges, there were none which showed that the shearing of anchor bolts could clearly be attributed solely to large horizontal accelerations. Anchor bolts were sheared where there was streamward shifting of the abutments, and, because these compressive forces were great enough to break concrete abutments and piers and tear pilings from decks, there is little doubt that they were sufficiently great to shear anchor bolts as well.

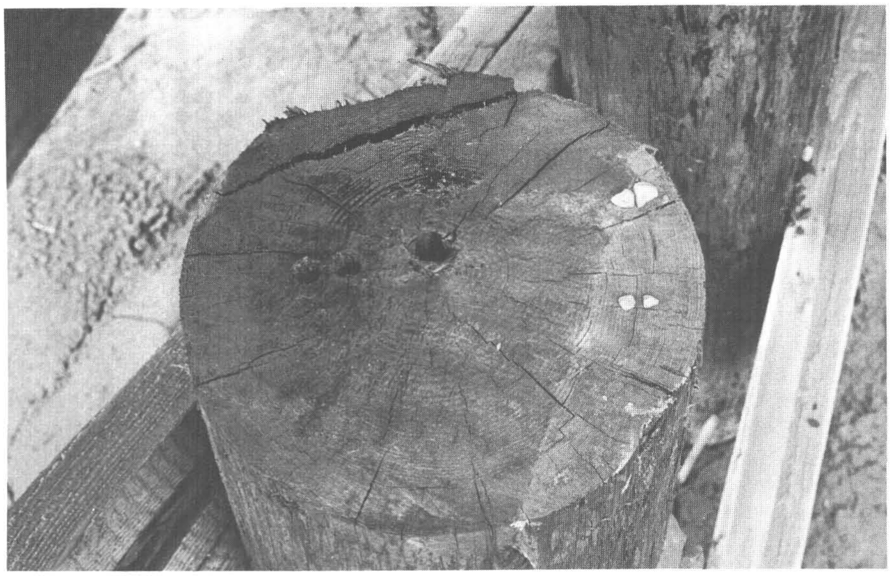
The series of dents made by pebbles that were caught between bulkhead fillers and end ties of bridge decks provide one source of evidence for transient horizontal displacement. During compression the pebbles were driven into the wood, and during relaxation the pebbles fell, only to be caught again by the succeeding compression. Repetitive pebble dents were common (table 1) despite the special circumstance of requiring that pebbles be in the proper place during the earthquake. Thus, transient horizontal displacement must have been the rule, rather than the exception.

Not only were pebble dents common, but they occurred in all types of displacement—in bridges highly compressed by streamward movement of sediments, and in bridges pulled apart endways on fans and deltas by radial downhill spreading of the sediments. At the bridges that pulled apart, the dents provide evidence that considerable force was associated with the transient horizontal displacement. For example, the following three bridges were ultimately pulled apart, yet all were damaged by transient horizontal displacement: (1) At bridge 34.8 the stringers hit the north bulkhead with sufficient force to crush and split the fillers; (2) the stringers of adjacent bridge 34.7 drove the top of the south bulkhead back into the fill; (3) and at bridge 21.4 pebble dents record at least four blows, and the stringers rammed the bulkhead planks, tore them from the fillers, and forced them back into the fill.

The pounding rate can be approximated at one bridge by interpreting a series of pebble dents. The pebble dents shown in figure 40 range from about 1 to 1½ inches apart. Assuming that the pebble was in free fall between dents, the time that elapsed between dents can be calculated by $t=\sqrt{\frac{2s}{g}}$, where t is the time of fall in seconds, s the distance in centimeters, and g the force of gravity. Times required for the free fall of 1 to 1½ inches are 0.07 to 0.09 second.



40.—Multiple dents on the end tie of a bridge deck made by a pebble that was caught as it fell between the filler (foreground) and tie during endways compression.



41.—Two impact holes made by a drift pin in the pile cap as the deck of the bridge was alternately raised and lowered onto the piles (see also figs. 13, 95). Stream channel is to the right.

Using 0.07 to 0.09 seconds for the free-fall times making the assumption that the pounding was harmonic, a pounding rate can be estimated. If one assumes a wide range for the part of the compression-relaxation cycle during which the pebble was in free fall, the real rate should lie between the extremes. Assuming that the free-fall time was from 1/5 to 1/2 the cycle, the pounding rate should lie between 2.22 to 7.14 cycles per second. Clearly the assumptions make these figures questionable; furthermore they represent data from only one bridge. However, their magnitude suggests that this transient horizontal displacement is produced by considerably higher frequency ground displacements than those of observed surface waves, where periods are in the range of several seconds. (See, for example, Coulter and Magliaccio, 1966, p. C10.)

Although pebble dents provide a means of estimating the pounding rate, they do not distinguish horizontal motion of the ground from horizontal motion of the bridge. Further, they do not give an indication of the forces involved. However, both the sense of horizontal ground motion and a minimum estimate of the forces involved in the transient horizontal displacement can be determined from the damage to a 105-foot-long open wood trestle at mile 34.5 on Hunter Flats (see p. D114). The deck of this bridge was alternately arched upward off the piles by compression, and dropped down onto the piles during relaxation. Impact holes in the pile tops, made by the drift pins that normally connect the pile caps to the piles, record from two to four compressive episodes, and there may have been more (fig. 41).

Although it is clear that transient horizontal displacement resulted in compression of the bridge deck, it is difficult to assess the forces involved. For example, had the deck been flat and firmly secured to the piles, the force needed to arch the structure would have been extremely large. On the other hand, if the connections between the deck and piles had already been severed, or if the deck had been initially arched by vertical pile movements, the requisite force would have been less. Some connections to piles may have been severed, because there is evidence of streamward movement of piling during the transient compression. This movement is indicated by the shift in position of the impact holes from the drift pins; they lie toward the streambank side (left) of the original position of the pin (fig. 41). The bridge was also probably slightly arched by the vertical pile displacements that accompanied streamward shifting (fig. 42).

Assuming that connections to the piles were severed and that there was some initial arching due to vertical pile displacement, the minimum force required to arch the deck a small but finite amount up from the supporting piles can be calculated as follows (Professor Arvid Johnson, Geology Dept., Stanford Univ., written commun., 1968):

$$1=P\left[\frac{1}{P-1}-\frac{3/8wL^4}{EI\pi^2h}\right],$$

where

w=weight per linear inch of deck per stringer (6 lb),
L=length of deck (1,260 in.),
E=Young's modulus for the stringer (1.4×10^6),
I=[moment of inertia=stringer width (9 in.)$\times$stringer depth (17 in.)$\times\frac{\pi}{L}$]$\div$12,
h=height of initial arch in bridge deck,

and

$$P=\frac{p}{Fs},$$

where

$$p=EI\left(\frac{\pi^2}{L}\right),$$

Fs=horizontal compressive force exerted on each stringer. Thus, the total compressive force needed to lift the deck from the piles is $Fs \times 8$ (number of stringers).

The force necessary to arch the deck off the piles is calculated for initial arches of 1 to 40 inches (fig. 43). The initial arch in the deck, resulting from vertical pile displacement, is unknown, but it was probably less than the 24 inches described by the pile tops after the earthquake (fig. 42). (The force that would have been exerted by the embankment on the bulkhead to develop the compression on the deck is also shown in figure 43).

It should be emphasized that these are minimum forces, because the arching is treated as static, rather than dynamic; the additional resistance to arching that must have resulted from both the inertia of the deck and the increased resistance to rapid bending of the stringers is ignored. If the compression was as rapid as was suggested by the pounding rate indicated by the pebble dents, the actual forces would have been considerably greater.

As noted earlier, the evidence for high horizontal accelerations in bridges is made ambiguous by the effects of compression that resulted from streamward displacement of foundation materials. However, the ambiguity does not mean that the possibility of high accelerations can be safely ignored. Accordingly, an estimate of horizontal accelerations is warranted.

At mile 61.9, the stringers of a 105-foot open wood trestle were driven through the planking of one bulkhead. The fact that the ends of the stringers were not broomed or battered (fig. 44) suggests that penetration occurred either as the result of slow continuous compression, which seems unlikely in light of the widespread evidence for horizontal pounding, or as the result of rapid horizontal acceleration.

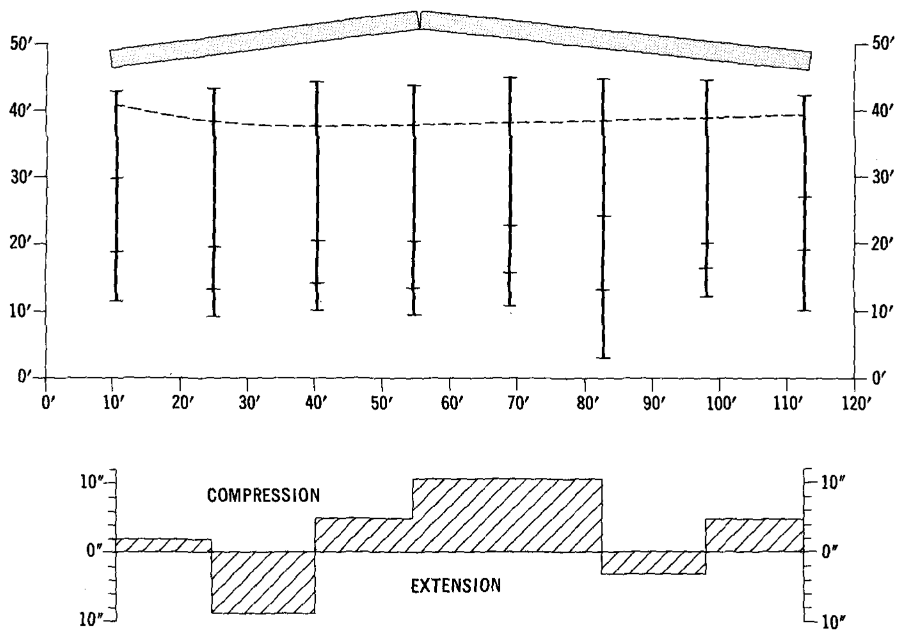
An estimate can be made of the force needed to penetrate the planks. Static resistance to penetration of washers as much as 2½ inches in diameter on bolts pulled across the grain of Douglas-fir reaches a maximum of 1,000 pounds per perimeter inch of washer (Scholten, 1966). If the force is dynamic rather than static, the wood offers considerably more resistance; William Bohannon (U.S. Forest Products Laboratory, Madison, Wisc., oral commun., 1968) suggests that the dynamic resistance would be increased to between 2,000 to 3,000 pounds per perimeter inch.

If one considers the stringers in bridge 61.9 to be a single penetrating body, and disregards breakage parallel to the length of the bulkhead planks along the top and bottom of the packet of stringers, penetration can very conservatively be said to have occurred only along the two 17-inch vertical edges of the penetrating body. Thus, penetration occurred for a length of 34 inches. If penetration resistance varied from 2,000 to 3,000 pounds per inch, the force exerted on the bulkhead must have exceeded some value between 68,000 and 102,000 pounds.

It must now be asked if the embankment fill would have been able to withstand such force without failing. By assuming that the embankment was not frozen and that it would fail as a wedge, as shown in figure 45, the force needed to produce failure can be calculated by Coulomb theory (Taylor, 1948, p. 499):

$$P=\tfrac{1}{2}\gamma H^2 Kp,$$

where P is force per horizontal foot of bulkhead, γ the unit weight (assumed to be 100 lbs per ft^3), H the height along the bulkhead, and Kp the passive pressure coefficient. Assuming the angle of internal friction for the granular



42.—Postearthquake positions on bents and deck of bridge 34.5. Relative interbent movements shown in graph.

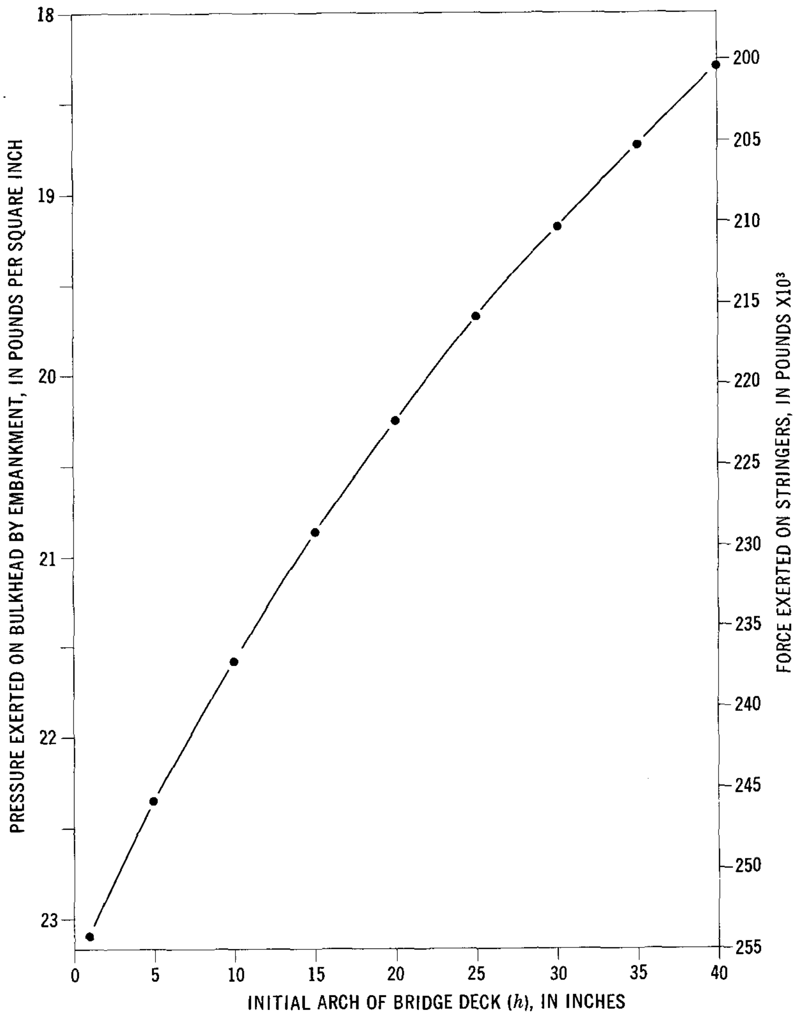
noncohesive fill to be 30° and the force directed normal to the bulkhead, $Kp=3$ (Taylor, 1948, p. 500). By this equation, $P=630$ pounds. Treating the fill as if its vertical transverse cross section were rectangular and its width equal to the longest bulkhead plank (20 ft) rather than tapering upward (to a width of 14 ft), a somewhat liberal estimate of the force required to produce failure would be $20P$ or 12,000 pounds. Thus, the force needed to produce passive failure is only about one-third that needed to produce static penetration of the bulkhead by the stringers and between one-fifth and one-fourth that needed to produce dynamic penetration. If the embankment fill did not have sufficient seasonal frost to significantly change its shear strength, resistance to penetration would have been developed by the inertia of the fill rather than by its resistance to failure along a plane, and thus penetration may have been due to the rapid application of force.

If penetration resulted solely from horizontal acceleration of the bridge deck, the acceleration, as calculated by the dead weight of the entire superstructure (16,932 lbs) and the penetration resistance of the bulkhead planks would range from 1.12 to 1.68 g. Even the lowest of these values must exceed ground-surface accelerations that occurred in this area; thus, the high accelerations may have been produced by amplification (whipping) within the bridge structure. As shown by Parmelee and others (1964) in a theoretical study for the design of a pile-supported bridge for Elkhorn Slough, Calif., high accelerations, which greatly exceed ground-surface accelerations, can be developed within this type of structure. In the bridge which they studied, they concluded that, given ground-surface acceleration of 0.28 g, an acceleration of 1.2 g would be developed at the bridge deck.

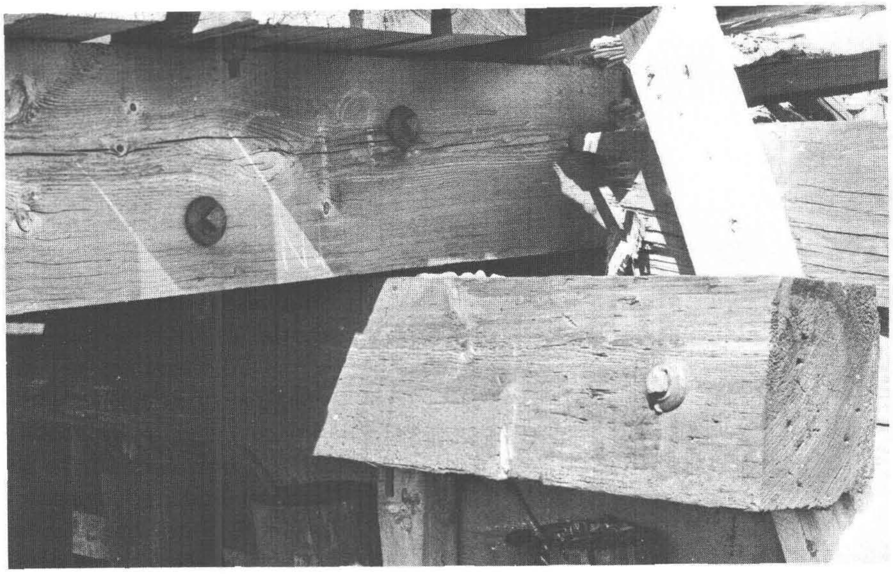
GROUND CRACKING

Ground cracks formed during the earthquake over an extremely large area—an area approximately the size of the state of California. The ground cracking occurred in a coastal belt that extended from the southwest end of Kodiak Island to the northeast. The area includes the Kenai Peninsula, extends about 150 miles north of Valdez along the northern edge of the Copper River Basin, and then swings to the southeast to the vicinity of Yakutat. Much of this ground cracking has been described in the U.S. Geological Survey Professional Paper series on the Alaska earthquake, as well as in other papers such as those by Reimnitz and Marshall (1965) and McCulloch and Bonilla (1967).

Most ground cracks, exclusive of those associated with landsliding, occurred in granular water-laid deposits on fans, deltas, flood

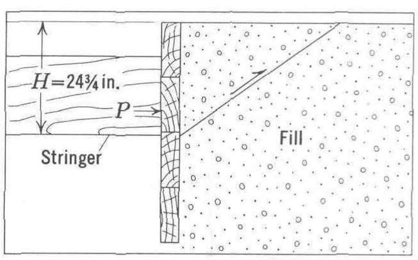


43.—Compressive force on the stringers of a 105-foot open wood trestle necessary to lift the superstructure just free of the piles, given some initial arch in the deck. The force exerted on the bulkhead by the embankment is also given.



44.—Unbattered stringers of bridge 61.9 driven through the south bulkhead planks.

plains, and tidal flats. The few exceptions were (1) cracks in glacial till that have been attributed to movement along a possible deeply buried fault on the northwest side of Kenai Peninsula (Foster and Karlstrom, 1967) and (2) a few cracks in till, observed by the authors at Portage Lake, which may have propagated upward from the underlying glacial outwash. Cracks were also observed in sandy till on steep slopes adjacent to lakes in the Copper River Basin (Oscar Ferrians, oral commun., 1968). The position of the water table had an important influence on the presence or absence of ground cracking and on the horizontal displacement of foundation materials. For example, the most severe ground cracking occurred in low-lying active flood-plain terraces that were nearly at the water table. Inactive flood-plain terraces in these same areas, the tops of which stand somewhat higher above the water table, were considerably less fractured. The exact depth to the water table is not known in most places, but in the areas of severe cracking it probably was less than 10 feet below the surface. Similarly, on most alluvial fans and deltas, cracking was limited to a fringe at the distal edge, where the water table approaches the surface; water was commonly ejected from cracks at the lower edge of this fringe of cracking.



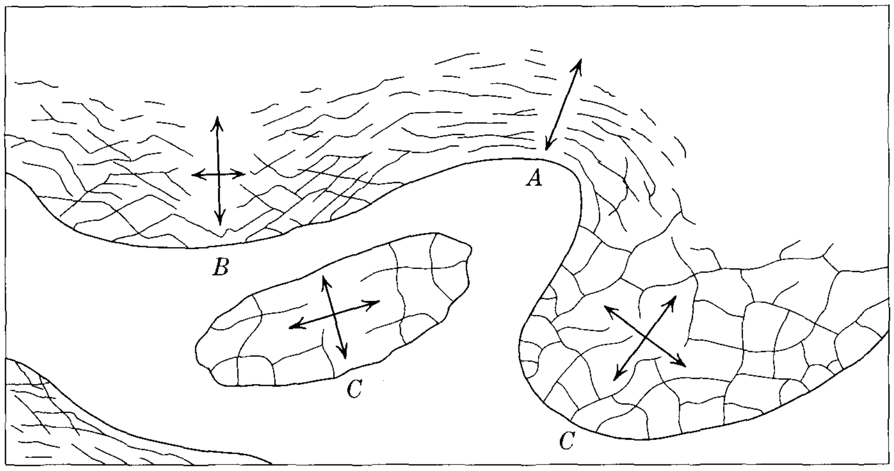
45.—Location of a possible Coulomb failure surface in an embankment due to force exerted on the embankment by bridge stringers.

The following types of ground cracks were most important in their effects on the railroad structures: (1) cracks resulting from landspreading—permanent lateral displacement and spreading of unconsolidated sediments, and (2) cracks formed by embankments.

CRACKS CAUSED BY PERMANENT LATERAL DISPLACEMENT OF FOUNDATION MATERIALS

One of the most common kinds of ground cracking was that which occurred along the margins of streams, gullies, and other topographic depressions (pls. 1–3; figs. 19, 27, 100, 136). The location and pattern of much of this cracking appear to be related to stress formed in the ground surface in response to the relatively deep permanent lateral displacement and spreading of the underlying sediments toward topographic depressions (McCulloch and Bonilla, 1967). It is clear from the horizontal offsetting and tension fracturing in embankments and from the pull-aparts in the rails, which commonly occurred as much as 500, or a maximum of about 1,000, feet back from the edges of streams, that wide areas underwent lateral displacement toward depressions. It is also evident from the horizontal displacements of embankments at stream crossings that sediments moved more or less directly toward the adjacent depressions.

The probable relationship between the surface stress distribution and cracking adjacent to stream valleys is shown in figure 46, in which the inferred stress directions are shown by arrows. In areas affected by this kind of ground cracking that were bounded by straight or concave streambanks (*A*, fig. 46), the movement of the underlying sediment was somewhat convergent or unidirectional. Cracks that formed were generally parallel to the stream and normal to the stress, suggesting that they are tensional failures. Adjacent to convex streambanks (*B*, fig. 46), where the cracking resulting from streamward movement did not extend far back from the stream edge, the spreading of the underlying sediments formed two perpendicular principal directions of stress, the major stress perpendicular and the minor stress parallel to the streambank. The resulting cracks formed at an intermediate position between the strain axes, and intersected at about 45° to 70°, suggesting that they were shear fractures. Cracks of this type were the most common kind on the distal edges of fans and deltas where the distortions of embankments and powerlines and the extension of bridges indicate that radial downhill spreading of the sediments occurred at some depth beneath the surface (see Sections 5, 6, 9, 10). In areas where the sediments spread in many directions, such as on the insides of meander bends and on small islands (*C*, fig. 46), the dominant crack pattern was an open network of curved or linear fractures that commonly intersected at right angles. The pattern of these cracks is similar in several respects to orthogonal thermal contraction cracks in frozen ground (Lachenbruch, 1962) that result from progressive tension failures. Where the stress in the surface layer is isotropic, orthogonal contraction cracks are curvilinear, intersecting at about 90°, and the crack-bounded blocks are randomly distributed. Where there is some preferred stress, the crack pattern can become highly rectilinear. In the formation of thermal contraction cracks, the preferred stress may result from a local heat source, such as a stream, whereas the rectilinear orthogonal fractures produced during the earthquake appear to have been due to the concentration of stress in the axes of abandoned channels that form small, elongate, generally parallel depressions in the surface.

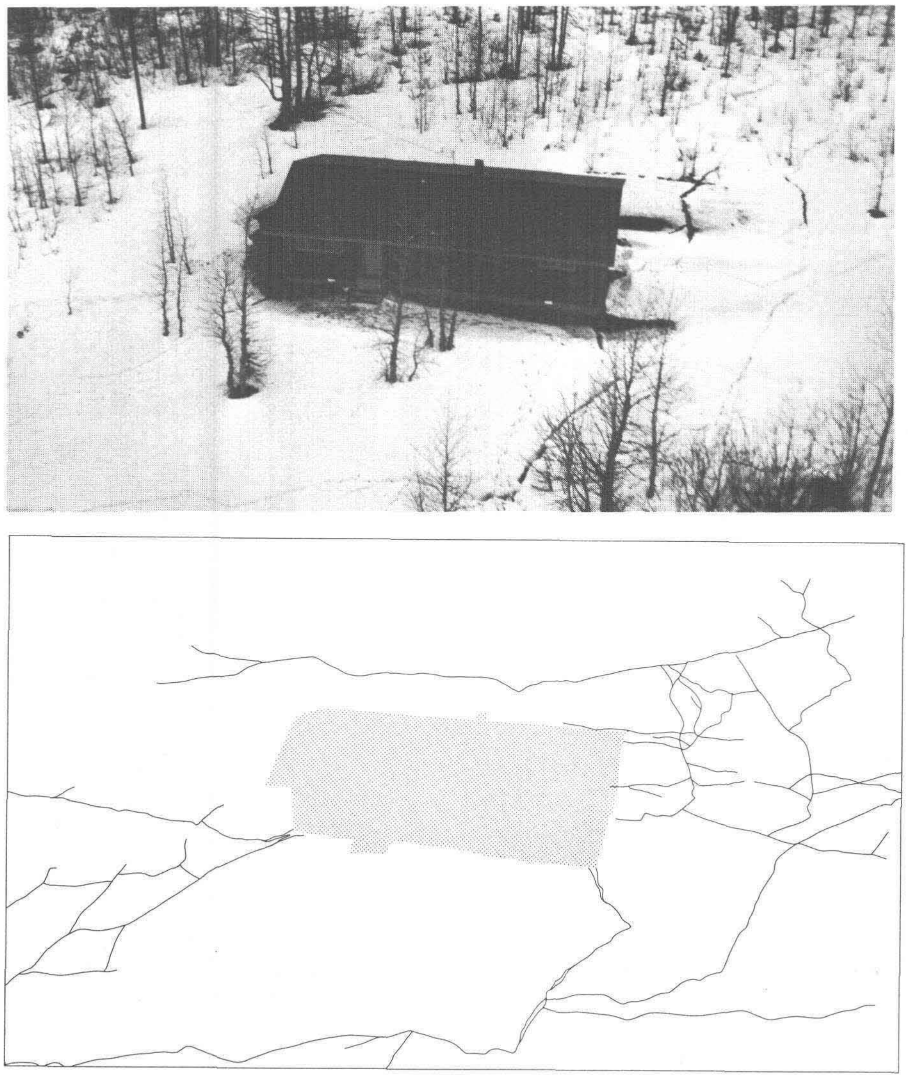


46.—Relationship between probable stress and ground cracking produced by landspreading toward a topographic depression. Arrows indicate directions of principal stress. Tension cracks form at right angles to the stress on straight and concave banks (*A*) ; shear fractures form on convex banks where the largest principal stress is perpendicular to the bank (*B*) ; cracks are orthogonal where stress is omnidirectional, as on islands or highly convex areas (*C*).

It was commonly observed that the distances between adjacent fracture-bounded surface blocks increased toward the streams and depressions. This observation is consistent with the model of surface failure, in which lateral displacement of the underlying sediments is initiated at the depression, and then progresses outward to the adjacent area.

On the cracked parts of fans, deltas, and flood plains, ground cracks commonly formed at the external corners of buildings. One such building, the U.S. Forest Service crew house on the flood plain in Portage valley, is shown in figure 47. The ground cracks went through the foundation, and the building had to be moved to a new foundation (Arthur Kennedy, U.S. Forest Service, Anchorage, written commun., 1967). Similar cracking on fans, deltas, and flood plains is shown in figure 48, in which the general direction of the lateral displacement of the sediments beneath the surface was to the right. Three of the houses shown in this figure are from a map by R. W. Lemke and R. D. Miller (in Lemke, 1967, fig. 15) of the cracking on Jap Creek fan just north of Seward (see p. D98). On this map, 14 houses are shown to have been intersected by 46 cracks, 36 of which extend diagonally from the corners of the buildings. Lemke noted that such cracks were common but gave no explanation of their occurrence.

If, as suggested above, the surface materials were put in tension by lateral displacement of the underlying sediments, any sharp external angle in a hole through the frozen plate of surface sediments would concentrate the strain, and should be the site of a fracture. Once a fracture has been formed, the amount of force necessary to propagate the crack is reduced, because the sides of the fracture act as lever arms and increase the stress at the point of rupture; Inglis (1913) has shown that the stress at the apex of a crack in a plate is proportional to the square root of the length of the crack and inversely proportional to the radius of curvature of the angle at the apex of the crack. Because these cracks are initiated at weak



47.—Photograph and sketch of ground cracks localized at the corners of the U.S. Forest Service crew house on Portage Creek flood plain. Cracks broke the foundation and the building was moved to a new foundation. Photograph by Arthur Kennedy, U.S. Forest Service, Anchorage.

points in the surface and because the force needed to produce continued fracturing decreases as the fracture develops, such fractures should form early in the development of surface stress and the cracks should be relatively long.

Similar cracks, located at the corners of houses, were common behind the scarps of the big block-glide slides in the Anchorage area (see, for example, Shannon and Wilson, Inc., 1964a, pl. 8.2). This stress in the surface appears to have extended back from the slide scarps.

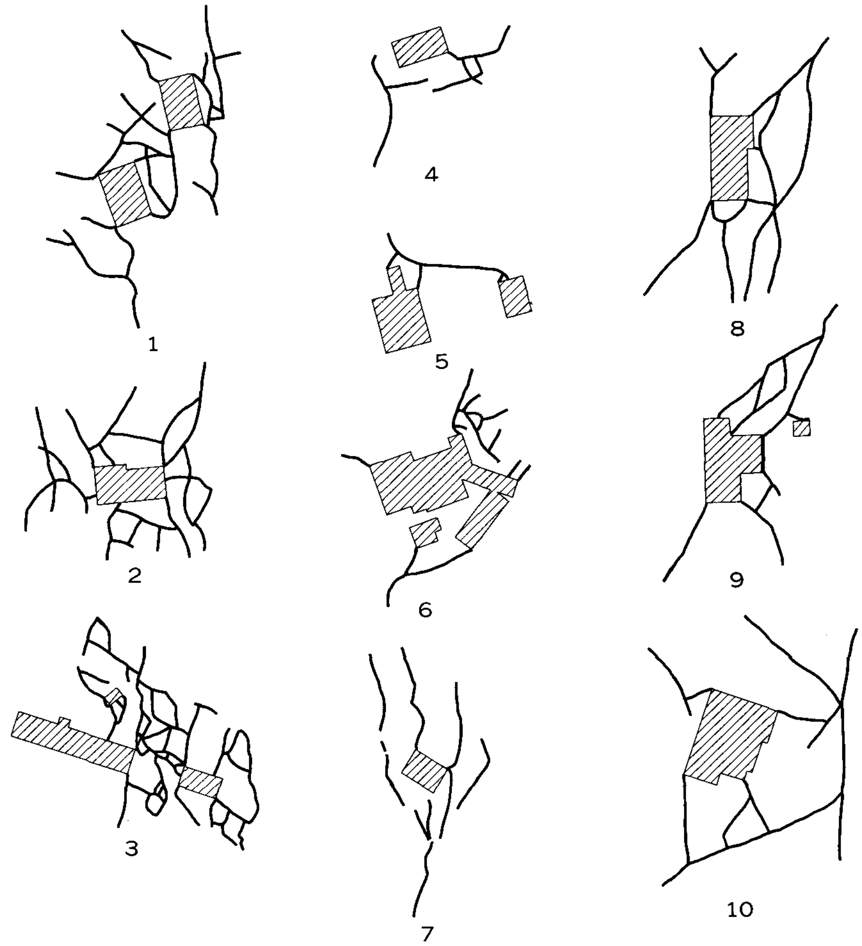
LANDSLIDING AND LURCHING

Ground cracks that form beside streams and rivers during earthquakes have commonly been ascribed to landsliding and lurching. The sliding is often described as being of the block-glide type, in which surface blocks move on some weak nearly horizontal stratum, such as a clay or liquefied sand layer, Oldham, 1899; Fuller, 1912) at or above the level of the river bottom. The lack of tilting in the displaced bridge piles suggests that landsliding of the rotational type did not occur along the streams. Lurch cracks, as defined by Steinbrugge and Bush (1960), are "* * * surface cracks due to horizontal vibration forces (as opposed to gravity forces associated with landslides)." Although these mechanisms clearly produce ground cracks, there is little evidence that they were important in the stream-margin cracking in the areas studied along the railroad.

The evidence against the importance of landsliding and lurching is as follows: If shallow block-gliding or lurching were important, the horizontal displacement of the surface material should exceed that of the underlying material. However, the net horizontal displacement of sediments beneath the surface as measured by displacements of bridge piles closely approximated that of the surface sediments as measured at the deck level (table 1). In three of the bridges, in which interbent measurements indicated net extension of the underlying sediments and in which measurements were also made at the deck level, there was exact agreement in two and a discrepancy of only 2 inches in the third (table 1). Thus, even where the bridges exerted no compressive force on the adjacent surface materials, there was no evidence of lurching or landsliding.

Lurching and shallow landsliding are also argued against by the fact that in most areas the ground was frozen, and it is unlikely that either the horizontal vibrations or shallow slides, in which the strength of the surface material would have been important, could have developed sufficient force to break frozen ground (the strength of the frozen ground is discussed on p. D58). In addition, lurching and shallow block-gliding would not produce the commonly observed upward movement of adjacent midstream sediments. Finally, the fact that cracking was omnipresent and omnidirectional would necessitate either omnidirectional vibrational forces of sufficient strength to produce such fractures or the presence everywhere of materials at the proper depths to provide glide surfaces along which sliding occurred. Neither of these possibilities seems likely.

In summary: All the evidence—(1) the patterns of many ground cracks, (2) their location beside topographic depressions and on fans and deltas, where displaced embankments and bridge pilings indicate deep lateral displacement of underlying materials, (3) the concentrations of cracks at corners of buildings, (4) the increasing distances between fracture-bounded blocks toward topographic depressions, and (5) the evidence that lurching and landsliding were not important in producing these cracks — is consistent with the proposition that many ground cracks result from stress generated in the surface materials by lateral displacement and spreading of the underlying sediments. Although these cracks were important in causing damage to railroad and highway embankments, bridges, and buildings, possibly of even greater importance is the fact that they clearly indicate that even on relatively flat areas, where the only topographic relief is provided by a local depression, the depression may cause permanent lateral displacement of both the surface and underlying material for a distance of as much as several hundreds of feet in the adjacent sediments.



48.—Ground cracks localized at the corners of houses on flood plains (1, 2, 4–6), on deltas (3, 7), and on alluvial fans (8–10). All houses oriented with the principal direction of landspreading to the right. Houses 1 and 2 on Portage Creek flood plain; 3, Lowell Creek delta; 4–6, Resurrection River flood plain; 7, Rocky Creek delta; 8–10 on Jap Creek fan (after Lemke, 1967, fig. 15).

The term "landspreading" is proposed for this type of ground movement; first, to describe the spreading within the sediments, and second, to bring attention to the fact that it occurs on flat or nearly flat ground, as opposed to "landsliding," which has the connotation of downslope movement. Probably many of the phenomena ascribed to landspreading resulted primarily from liquefaction within the sediments. However, other mechanisms may have been operating; therefore the term "landspreading" is used, for it includes the effects of liquefaction and all other means by which similar displacements might occur.

CRACKS PRODUCED BY EMBANKMENTS

Embankments produced anastomosing cracks that were subparallel to the embankments, some within the embankment toes, some in the side drainage ditches, and others in a zone about 25 to 30 feet wide in the adjacent sediments. The embankments superimposed this crack pattern across areas of ground cracks on deltas,

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fans, and flat-lying ground in which other cracks were due to lateral displacement of the underlying sediments (pl. 3; figs. 19, 49). The embankments also produced these cracks where there were no other ground cracks.

Similar cracks have been observed in other great earthquakes. Oldham (1899, p. 89) described such cracks in the 1897 Indian earthquake: "A very noteworthy point about the fissures, formed away from and independent of, the river courses, is the manner in which they usually run parallel to, and along either side of, any road or embankment."

It is not clear how these cracks formed. Grossly similar cracks in surface sediments adjacent to an embankment are ascribed to block gliding by Newmark (1965). He believes that the embankment became detached on a buried horizontal glide surface and, in sliding back and forth, produced tension fractures in the sediments at some distance from the embankment. The likelihood that liquefaction occurred beneath the embankments in Alaska and allowed them to oscillate sidewise, as if on a glide surface, makes this mechanism attractive (see p. 75). However, because the surface sediments were frozen, they would have had considerable tensile strength, and seemingly not enough force was available to produce fracturing by this process. For example, in figure 50, the inertial force per linear foot of 3-, 4-, and 5-foot-high embankments are plotted against horizontal gravitational accelerations. The inertias are calculated on the assumption that the embankment underwent horizontal displacement without internal deformation. Seed and Martin (1966) have suggested that this approach may be valid for low, stiff embankments. Also on figure 50, inertias are calculated on the assumption that there was an equal mass of consolidated sediment beneath the embankment that did not liquefy (fig. 54) and whose mass was added to that of the embankment. Even the lower set of these inertial forces probably err by being too large. Furthermore, the peak ground accelerations were probably below 0.3 *g*; for example, Cloud (1967, p. 320) suggests, with reservations, that maximum accelerations in Anchorage may have been 0.14 *g*, and Newmark (1965, p. 142) cites estimates of 0.15 and 0.18 *g*.

A minimum value for the force needed to produce tension fractures in the frozen sediments can be estimated by using a low value (30 psi) for static (rather than dynamic) tensile strength of a granular soil (U.S. Army Corps of Engineers, 1952). Such a frozen layer, with a thickness of 4 feet, would have a tensile strength of 17,280 pounds per linear foot of embankment. This strength far exceeds the probable inertial force developed by the embankment. Thus, even a maximum inertial force and a minimum tensile strength appear insufficient to produce tension failures in the frozen sediments.

In addition, the fact that there were usually several fractures on each side of the embankment also argues that they were not produced by tension generated by block gliding of the embankment, for unless all fractures are formed simultaneously, a single fracture would preclude additional tension fracturing.

A possible explanation for the formation of these ground cracks may be that, as the embankment sank into the underlying sediments, it depressed the immediately adjacent frozen surface,

49.—Ground cracks generated by an embankment in Portage. Note dark areas flooded by ground water. Photograph by U.S. Army.

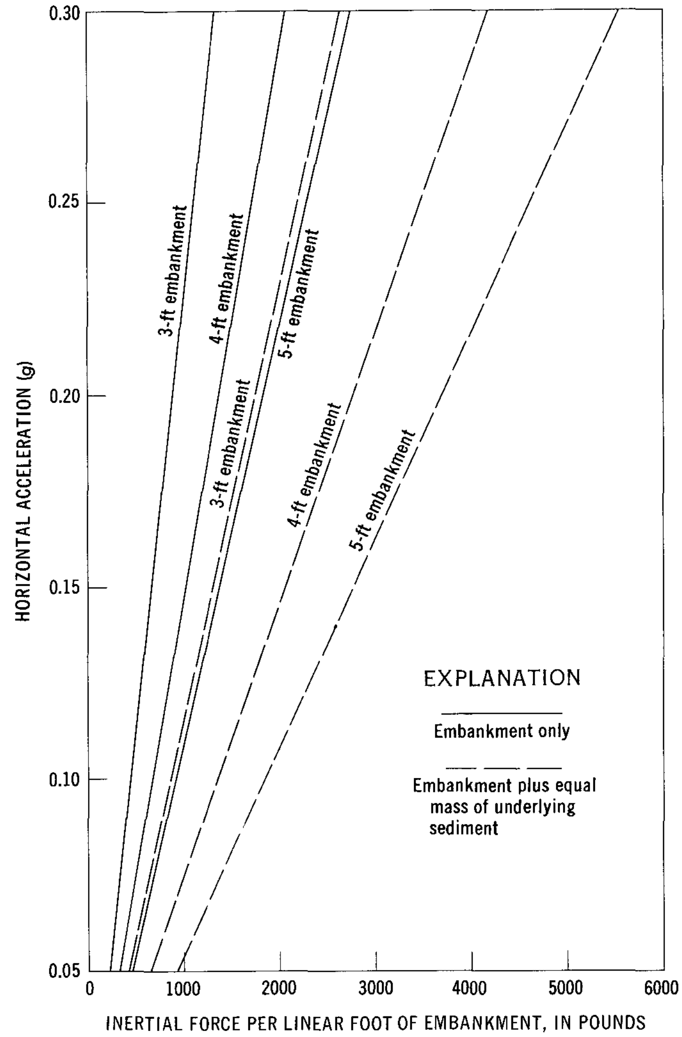
while at some distance the surface was bulged upward slightly by the displaced, possibly liquefied, sediments. The formation of a trough and bulge would have produced a zone of increased stress in the frozen surface sediments approximately parallel to the embankment. Then perhaps with the passage of surface ground waves, and in some areas the development of additional stress due to landspreading, the localized stress may have produced the cracks beside the embankment.

EMBANKMENT AND TRACK DAMAGE

Nearly all damage to embankments and their overlying tracks and ties occurred in areas underlain by water-laid unconsolidated sediments. The only damaged embankment on till or bedrock was along Turnagain Arm, where regional subsidence exposed the embankment to marine erosion. Embankment damage can be divided into three categories:

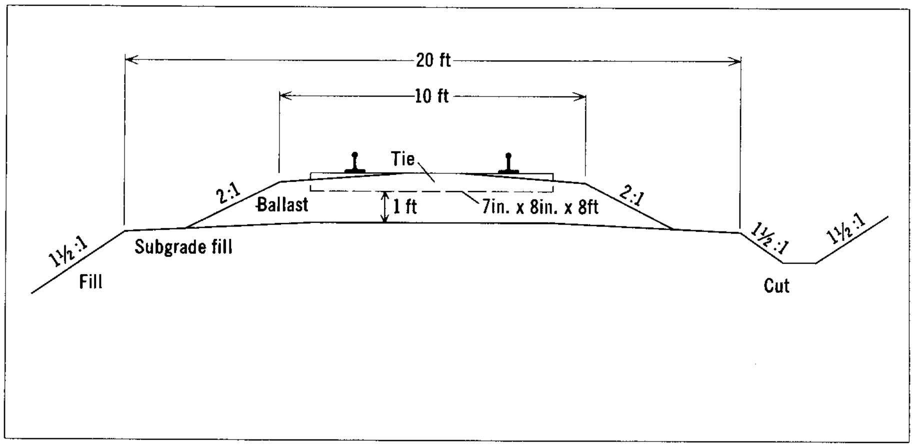
1. Fill failures, in which failure was restricted to the fill.
2. Active failures, in which the embankment played an active part in producing changes in the foundation materials that resulted in damage to the embankment.
3. Passive failures, in which displacement or cracking in the foundation materials produced damage to the embankment which acted passively. It should be noted that the terms "active" and "passive" are used here in the general rather than the specific sense of soil mechanics nomenclature.

Because the types of damage are generally related to the behavior of the foundation materials and these in turn are largely governed by the physiography, it is possible to predict the damage to embankments subjected to a similar seismic condition.



50.—Inertial force per linear foot of 3-, 4-, and 5-foot-high embankments (with and without a comparable mass of consolidated sediment beneath the embankment) at horizontal accelerations of 0.05 to 0.3 *g*.

A typical design cross section of the railroad embankment is shown in figure 51. Most of the embankment was constructed as follows (Cliff Fuglestad, engineer of track, oral commun., 1967): The line was cleared by hand, and the organic layer was left. The subgrade fill was usually side borrow, and it included organic material. Subgrade fill was placed by hand with a Fresno scraper. Berms on the subgrade were fixed by eye, and the side slopes determined by the angle of repose of the subgrade fill. The subgrades were a maximum of 20 feet wide; in the Portage area, they were closer to 18 feet. The ballast was end-dumped and raised, and from Seward to Indian (fig. 1) it is composed of crushed gravel. Most of the embankment was placed prior to 1914; in addition to yearly maintenance since that time, the Seward to Portage line had a major rehabilitation in 1955–56.



51.—Design cross section of a typical railroad embankment.

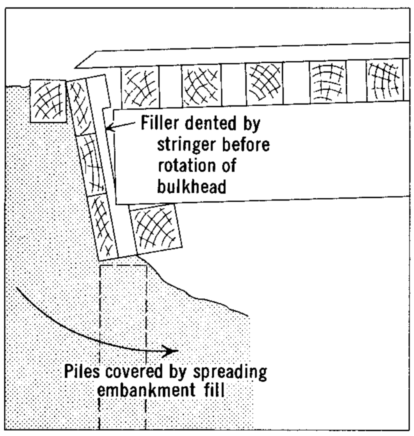
FILL FAILURES

Failures solely within the embankment (not related to shifting of, or interaction with, the foundation materials) were difficult to recognize, for several reasons. There was a virtual absence of easily identifiable discrete surface failures, either rotational or on inclined flat surfaces, that were restricted to the fill. The only rotational failures that affected the embankment, other than the large slides from deltas, occurred at mile 4.6 (see p. D99), where borrow had been removed at the embankment toe, and there the failure surface probably passed into the foundation materials. Other failures on discrete surfaces, although more common than rotational failures, appeared to involve the underlying sediments.

There is some evidence for failure by shear distributed throughout the fill, as shown by spreading of embankments at bridge bulkheads. Commonly, bulkhead fillers, rammed and compressed for the full stringer depth in the early part of the shaking when the bulkhead was vertical, were later rotated, their bases being pushed streamward by the spreading fill during the continued shaking (fig. 52). At several bridges the spreading fill covered the bulkhead piles —which also suggests that movement was distributed throughout the fill.

Spreading may have been more general, but if so it was small, and the lack of strict adherence to design cross sections and the absence of as-built cross sections would have made it very difficult to detect. Where undeniable spreading occurred, it was associated with the displacement of sediments beneath the fill.

According to C. L. Griffith, assistant chief engineer, the seasonal frost within the embankments from Portage to Seward probably extended to a depth of 4 or 5 feet. The lack of failures restricted to the fill, either on discrete surfaces or as distributed shear, may have been due to the increase in shear strength afforded by the interstitial ice.



52.—A bulkhead filler that was rammed and dented by the stringer while it was still vertical. With continued shaking the base of the embankment fill spread over the bulkhead piles and the bulkhead was rotated.

ACTIVE FAILURES

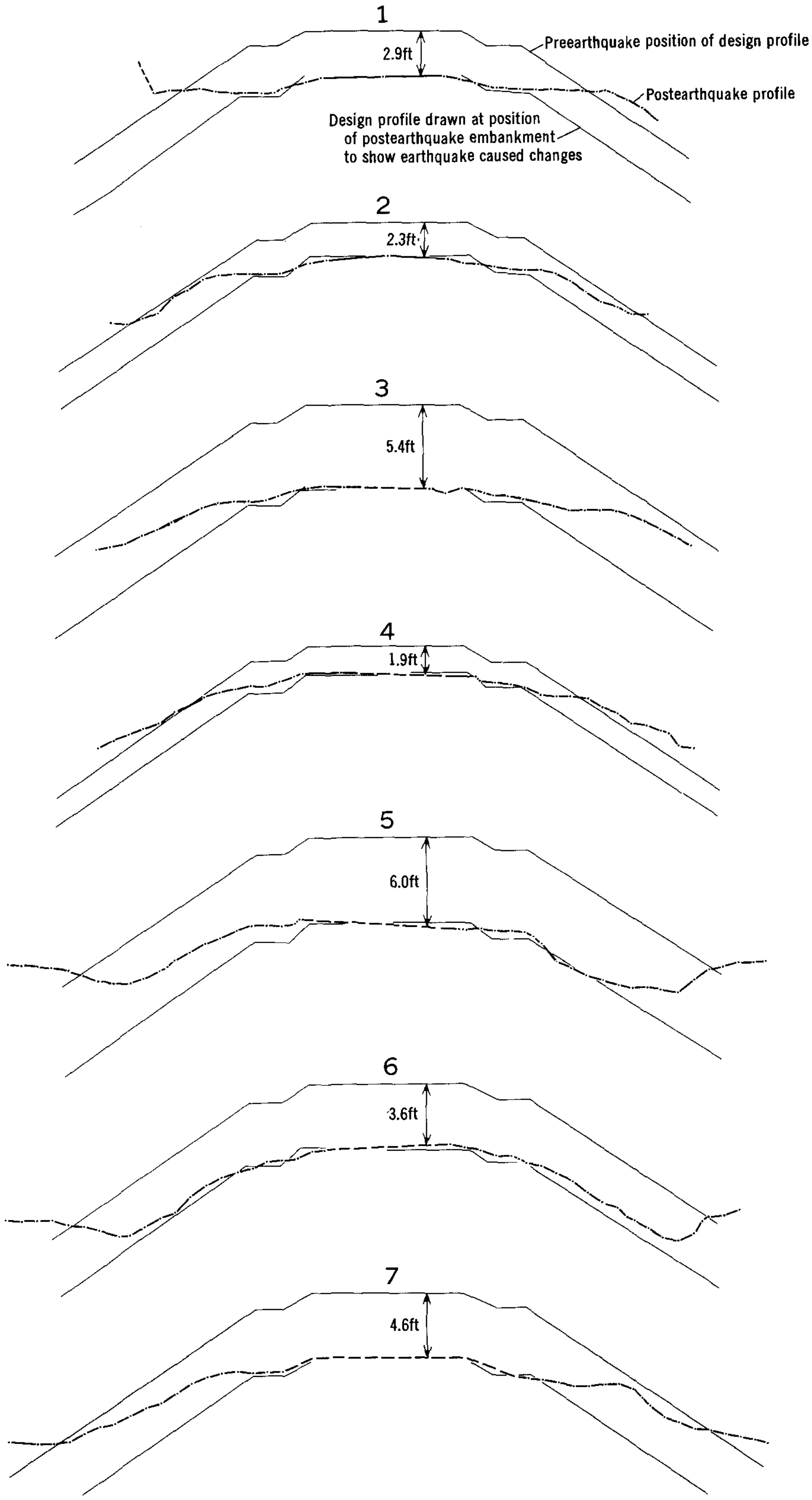
Damage to the embankment from changes in the foundation materials, resulting from the load of the embankment fill, was widespread and severe in areas underlain by wet noncohesive sediments. These failures took several forms. The most damaging was the general and irregular settling of the embankment fill, which lowered long sections of the embankment as much as 6 feet. Cross sections of the embankment in the Portage area made at local dips in the generally settled embankment are shown in figure 53. Each postearthquake profile is compared with design profiles at the preearthquake position and at the height of the postearthquake embankment. The comparisons of the design and postquake profiles show that the embankment fill settled largely en masse. At places there was almost no lateral spreading, and even where spreading was greatest, it does not appear to have been great enough to account for the total lowering.

Settlement was almost universal in areas underlain by wet unconsolidated noncohesive sediments and was greatest in areas of widespread ground cracking, such as active flood plains and the highly fractured margins of fans and deltas. Generally less severe, but locally as large, settlements occurred where the only ground fracturing was produced by the embankment. These latter settlements were in the otherwise unfractured parts of deltas, fans, and inactive flood plains. Settlement was usually accompanied by the expulsion of sediment-laden water from the adjacent ground cracks. A close relationship between the ejection of sediment-laden ground water and settlement was seen in some areas where local extreme settlements occurred where large volumes of sediments, as coarse as cobble gravel, were brought to the surface beside the embankment. (See, for example, mile 16–16.2 p. D103.)

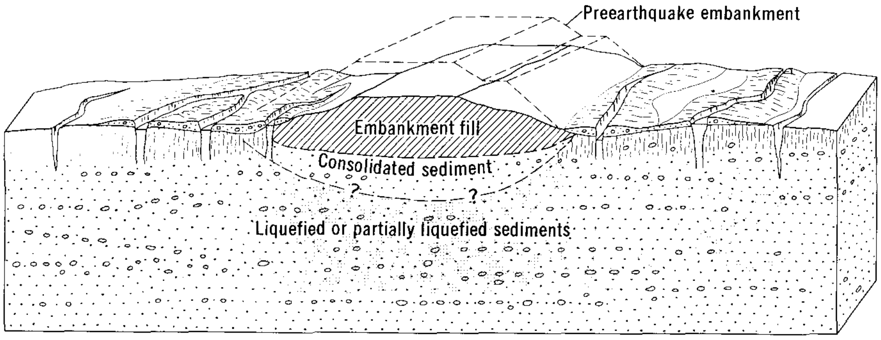
The fact that the embankments were lowered more than can be accounted for by spreading, and that they appear to have settled where ground water was expelled (even where the only ground cracks present were produced by the embankment), suggests that the foundation material became liquefied.

It is of note that in many places where there was no other evidence of liquefaction in adjacent areas, the embankment still settled and produced high pore-water pressures in the underlying sediments. Thus the embankment appears to have been the cause of liquefaction of the underlying sediments. A somewhat similar observation was made by Shiraishi (1968) who reports that during the 7.8 magnitude Tokachioki earthquake in Japan on May 16, 1968 "* * * liquefaction took place only under and around objects such as parked freight cars in a railroad marshalling yard, and not in open areas."

Figure 54 is a hypothetical sketch of liquefaction beneath an embankment. Although the field observations do not determine where liquefaction started, they strongly suggest that the embankments produced the liquefaction, and that sediments beneath the embankments became liquefied.



53.—Transverse profiles of settled railroad embankments in the Portage area measured by M. G. Bonilla and R. Kachadoorian. Each profile is compared with the design profile at the original and postearthquake height of the embankment. Profiles are located on figure 114.



54.—Hypothetical sketch through an embankment underlain by liquefied sediments into which the embankment settled. Cracks formed by the embankment tapped the zone of high pore-water pressure, and sediments were carried to the surface by the escaping water.

Heavy traffic over the roadbed undoubtedly had densified the subfill materials and made them less susceptible to the increased densification needed to produce liquefaction than the adjacent materials. It is possible that inertial differences between an embankment and the adjacent sediments increase the stress locally during shaking and initiate liquefaction adjacent to the fill, in much the same way that differential movements of piles and their enclosing sediments might produce liquefaction locally surrounding the piles (Seed and Idress, 1967). Once high pore-water pressure had been developed in the soil adjacent to the fill, it could propagate downward and laterally, possibly extending under the embankment. With the formation of cracks in the frozen surface sediments adjacent to the fill, some of the high water pressure would be relieved. The close relationship observed between surface discharge and local sags suggests that in some cases liquefaction had occurred beneath the fill at the time of discharge. If it had not, the sinking fill would not have been able to displace the underlying material.

PASSIVE FAILURES

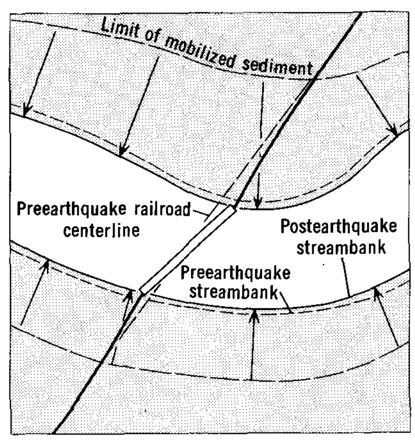
Discussions of embankments subjected to seismic loading commonly consider the distorting forces within the embankment and failures in foundation materials produced by the embankment. Passive failures in embankments that traverse areas in which there was ground cracking or permanent displacement of the ground are generally not considered. However, the widespread cracking and ground displacements that accompanied the Alaska earthquake made passive failures an important cause of damage. Because passive embankment failures depend upon the response of the underlying ground to seismic loading, it is possible to describe these failures in geologic and physiographic terms.

Passive failures are described in detail in Sections 1 to 19 (p. D95–D157), and will only be summarized here, examples being referred to generally by section or specifically by mile.

Passive failures have caused damage in other large earthquakes. For example, Wallace, Phillips, Drake, and Boggs (1907, p. 349) state that in the 1906 San Francisco earthquake "[Railroad] embankments across marshes, or with soft strata underlying them, settled more or less. In some cases the settlement was vertical; in other cases there was considerable horizontal with the vertical movement."

STREAM CROSSINGS

The most damaging passive failures of the embankments were at stream crossings, where landspreading was greatest. Because displacement was generally toward the stream valleys, embankments that approached valleys obliquely were offset horizontally in opposite directions on opposite sides of the streams (fig. 55) and the bridges were skewed horizontally. Horizontal offsets between embankment centerlines on opposite sides of stream channels measured at 27 bridges ranged from several inches to 10 feet (table 1). Twenty-one of these bridges are shown in figure 56; the offsetting of each bridge is described in pages D98–D157. As can be seen in figure 56, offsetting generally occurred as the result of movement toward the stream channels, but it also was produced by movement toward depressions



55.—Bridge skewed by streamward movement of sediments. Landspreading toward stream moved the banks closer together, and railroad grades that crossed streams at acute angles were carried sidewise in opposite directions on opposite sides of the stream, skewing the bridges.

(often wet) beside the embankments (bridges 33.6, 34.8, 37.0, 61.5). In one bridge (62.3), displacement was in the opposite sense, possibly because of local displacement of the high, narrow embankments of this bridge on the low active flood plain. In three large bridges (3.0, 3.2, and 3.3), the bridge ends and adjacent embankments were displaced laterally in the same directions parallel to the contours, offsetting them from the centers of the spans (figs. 29, 31, 32).

The absence of tilting in the displaced bridge piles driven largely through fill (bridges 3.0, 3.3) or the underlying sediments (bridges 3.0, 3.2) demonstrates that lateral shifting was not restricted to the fill, but that the fill was carried passively as the underlying material shifted. The minimal lateral displacement of the bridge centers suggests that movement parallel to the contours resulted from some force on the interstream areas. On the interstream areas the railroad lies adjacent to a large highway fill (fig. 27). Both the highway and railroad fills settled, and as shown by the extensive ground fracturing, expulsion of ground water, and streamward displacement of the foundation materials, the sediments were extensively mobilized by the shaking. The sinking of the large highway fill probably produced an outward flow of foundation materials that carried the adjacent railroad fill sidewise (fig. 57). This outward flow is also suggested by the fact that where the highway swings away from the railroad just north of bridge 3.3, the railroad fill was not displaced laterally (fig. 58). In the middle ground of this same figure, a lateral kink can be seen where the rails crossed a small road (Nash Road, fig. 27). This road fill, lying at right angles to the railroad fill, appears to have resisted the lateral displacement, possibly because of its resistance to longitudinal compression.

In addition to being displaced laterally, bridge approach embankments were broken by fractures in areas where the underlying materials spread toward the stream valleys (pls. 2, 3; figs. 18, 19). The resulting fractures varied considerably in detail, but most were tension fractures that crossed the embankment at nearly right angles. The fractures were nearly vertical, and the block on the streamward side was often downdropped. At many places where the underlying materials were displaced laterally, there was also some horizontal displacement along the fractures. This fracturing is shown diagrammatically in figure 59.

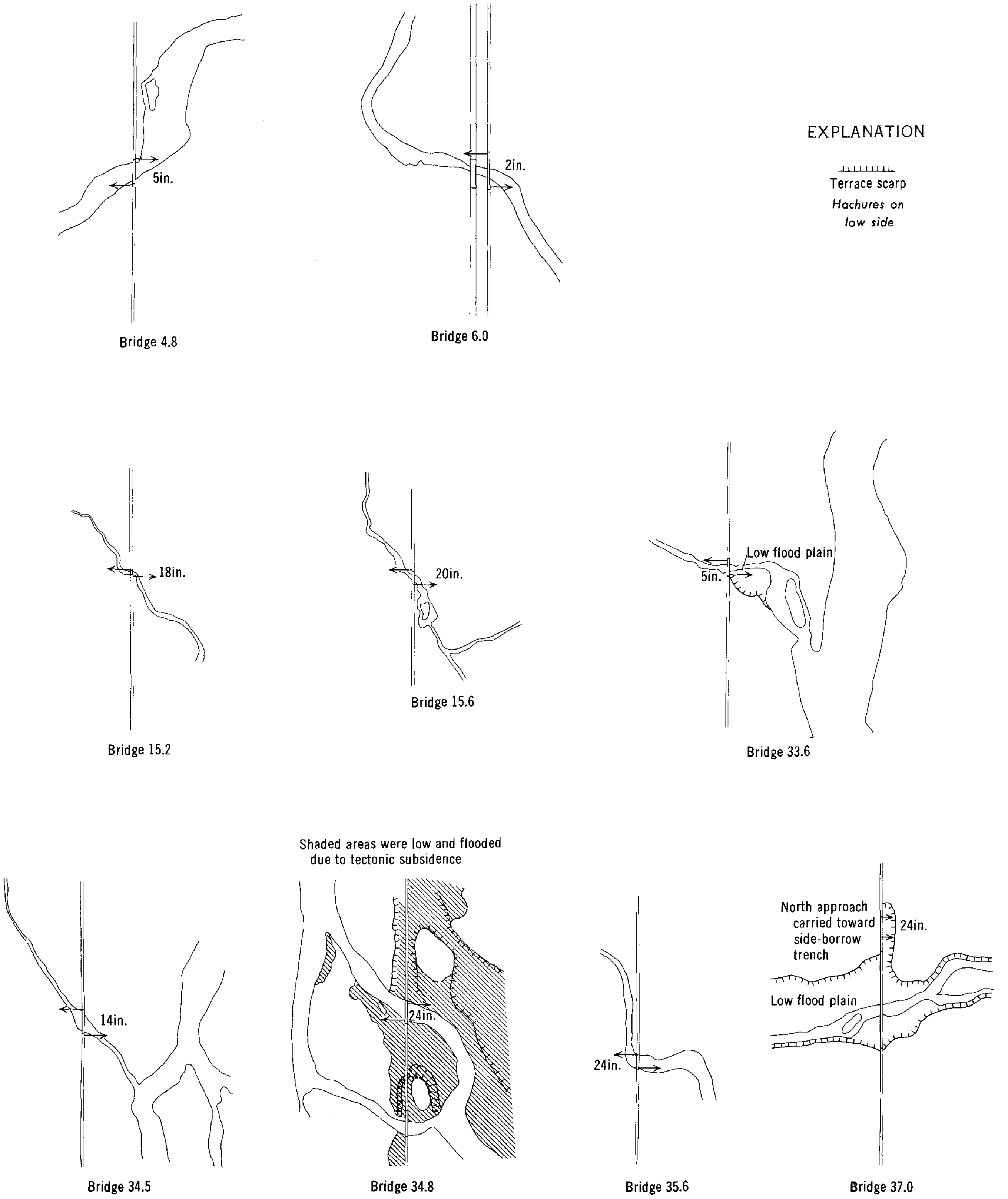
Despite the fact that most of the bridge approaches were put in tension, the ends of the embankments abutting the bulkheads were deformed by compression resulting from the thrust of the compressed bridge decks. Bulkheads, driven back into the fills, bulldozed up the fills, some as much as a foot or more. As a result, the rails were torn from the embankment and either the ties were pulled upward out of the ballast, or, if the ballast was frozen, the rails were torn free of the fish plates that secured them to the ties (figs. 104, 106, 109).

Embankments built over filled-in channels or filled-over bridges behaved somewhat like those at stream crossings. For example, at miles 34.3 and 34.4 embankments were moved toward filled-in creeks and were bulged upward over the old stream channel. The accompanying compression deflected the rails laterally at the bulges and pulled the ties sidewise through the ballast. The embankment settled around filled-over bridges at miles 60.2 and 62.1; at 62.1 the north end of the embankment was offset abruptly 3 feet and the rails were also deflected by compression (fig. 60).

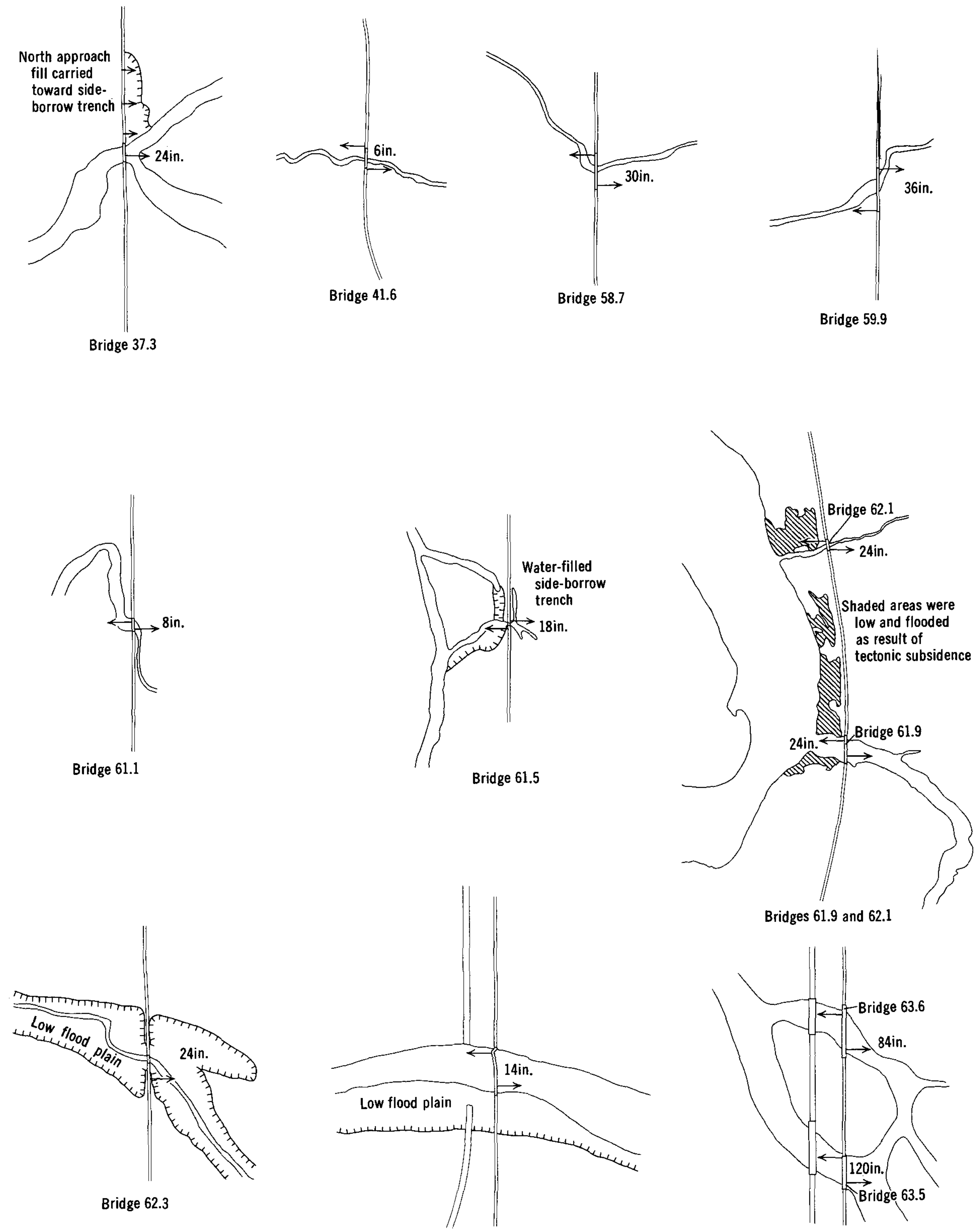
FLOOD PLAINS

Principal passive damage to the embankment on flood plains was caused by permanent horizontal displacements of the underlying flood-plain sediments that carried some embankment sections more than 1,000 feet long out of horizontal alinement. These displacements were as great as several feet and were the rule rather than the exception on active flood-plain sediments. Displacements occurred toward bodies of water, nearby stream channels, borrow pits, areas of low ground, or other topographic depressions. Generally, where the flood-plain sediments were fractured, the embankment was also fractured. Commonly, fractures that approached the embankment obliquely swung normal to the rail line as they cut across the embankment (see, for example, fig. 19).

Rails were occasionally thrown into compressive kinks, even at long distances from bridges (fig. 27). It is possible that the embankment was compressed longitudinally. However, the kinks may have been formed as the result of a transient compression developed during the passage of surface ground waves. That surface ground waves do form compression at the surface is suggested by many eyewitness reports from large earthquakes in which ground cracks open on the crest of a wave and close, often with the ejection of water, as the trough passes.



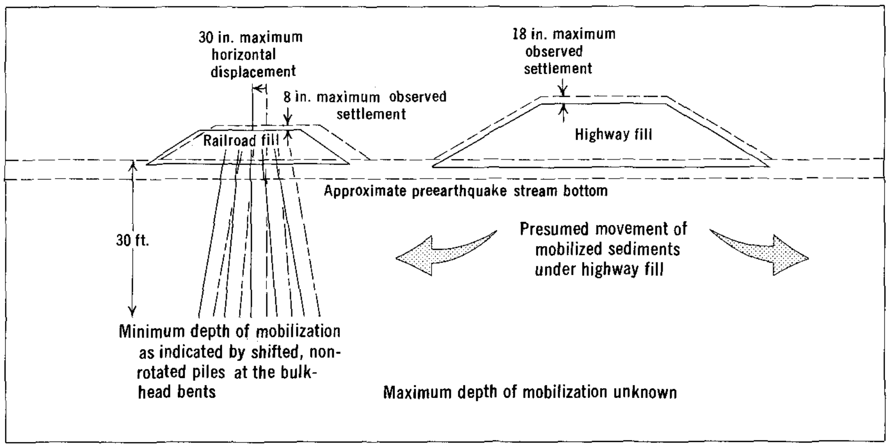
56.—Bridges that were skewed horizontally by landspreading toward stream channels or topographically low areas. All figures oriented with increasing mileage from bottom to top.



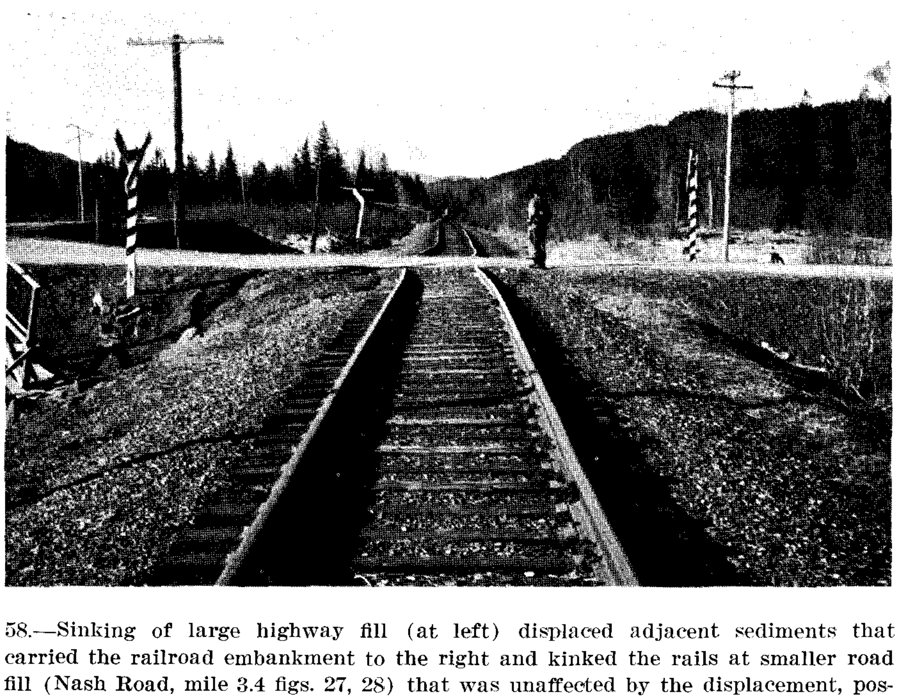
56.—Continued.

DELTAS AND FANS

The unconsolidated materials of deltas and fans spread radially downhill. The overlying embankments were carried laterally as much as 4 feet, and, having little tensile strength, were broken by tension fractures running normal to the embankment. Tension fractures in the embankments were particularly well developed on the margins of deltas and fans, where radial spreading was pronounced. In some places, tensional fractures occurred at about 30- to 50-foot intervals for as much as 1,000 feet. Some of the tension fractures were 1 foot wide. Tension skidded the rails over the ties, opened expansion joints to their extreme positions, and at several places sheared bolts in the angle bars that connect the rails and pulled them as much as 17 inches apart. Bridges on fans and deltas (bridges 20.0 and 21.4) were also pulled apart. Because the distances between the bents was increased, stringers were pulled partly off end bearings and ties and guard rails were split.



57.—Cross section of the railroad and highway fills at Resurrection River (fig. 27). Sediments displaced laterally beneath the sinking highway fill displaced the railroad fill and ends of bridges a maximum of 30 inches laterally, parallel to the contours. The lack of tilting in the bridge piling indicates that the depth of lateral displacement probably exceeded the pile depths. Dashed lines indicate preearthquake positions of embankments and piles.



58.—Sinking of large highway fill (at left) displaced adjacent sediments that carried the railroad embankment to the right and kinked the rails at smaller road fill (Nash Road, mile 3.4 figs. 27, 28) that was unaffected by the displacement, possibly because of its resistance to longitudinal compression. Lateral displacement decreased where the highway turns away from the railroad.

BRIDGE DAMAGE RELATED TO GRAIN SIZE, THICKNESS, AND DENSITY OF FOUNDATION MATERIALS

Almost all damage to bridges resulted from transient and permanent displacements of the foundation materials into which the pilings were driven. Thus, the degree of damage is largely governed by the level of mobility attained by the foundation material and by the length of time during which it moved; these factors in turn are determined by the ease with which a given foundation material becomes mobilized and by the duration and the intensity of the ground motion. In the following discussion, the severity of bridge damage is compared with these variables, by using (1) the dominant grain size of the foundation material into which the piles are driven as a measure of the propensity for mobilization and (2) the total thickness of the unconsolidated sediments at the bridge site as a measure of the duration and intensity of ground motion. These variables are compared in tables 3 and 4.

In these tables the dominant grain size of the foundation material at some bridges is known from adjacent borings (for example, Resurrection River, Portage area, Knik and Matanuska crossings). At others, the grain size of the sediment is based on field examination, the landform in question, and inferences from the surficial geology. Some of the total or minimum sediment thicknesses are also known from borings; others are estimated from a combination of the adjacent bedrock relief, seismic refraction data (near Seward), the areal extent of the unconsolidated sediment, and the geologic history of any given area as outlined in the mile-by-mile description of the damage.

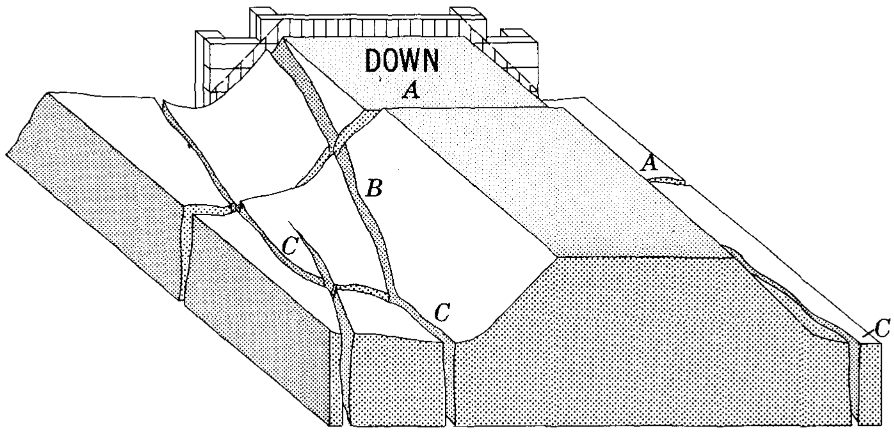
The degree of damage to any bridge is assigned on the basis of the necessary repairs as follows:

Severe—replacements required:
- Entire bridge (or culvert substituted).
- All or some new piling, pile caps, and sway braces.
- All or some new stringers.
- All or some new deck, walkways, and guard rails.
- New abutment backwalls and bulkheads.
- New bearings built on concrete piers and abutments.

Moderate—repairs required:
- Some new piles, pile caps, and sway braces.
- Some to deck and bulkheads.
- Installation of wide caps to carry shifted stringers.
- Steel spans reset on piers and abutments that shifted.
- New anchor bolts for steel spans.

Slight—repairs required:
- Minor repairs to bulkheads and decks.
- Blocking shims added to bents to compensate for vertical pile displacements.
- Minor horizontal readjustments.
- Repositioning steel spans to relieve endways shifting.

In terms of damage to the structures, these divisions represent gradations in the amount of (1) horizontal and vertical displacement of piles, piers, bulkheads, and abutments, (2) ramming of bulkheads and abutments, (3) lateral buckling or rupturing of stringers by compression, (4) lateral skewing of the bridge, and



59.—Typical fractures at a bridge approach. A block of fill was lowered at the bulkhead and along a fracture (*A*) running perpendicular to the embankment. Fractures (*B*) formed on both sides of the embankment and ran diagonally back from the upper edge of the fill and joined fractures (*C*) that were approximately parallel to the fill in the adjacent ground.

60.—Lateral offsetting and compression at the end of filled-over bridge (looking north toward bridge 62.3). Note the ends of pile caps exposed to left of the ties.

(5) endways shifting of steel decks. Where the repairs were not known, the bridge was assigned to one of the divisions in which the observed damage to the structure was comparable.

The comparison of damage to foundation materials in table 3 shows:

1. All bridges damaged by displaced foundation materials (this excludes three bridges on till or bedrock damaged by lateral displacement of decks, not displacement of piers) were built on foundation materials that have the following common characteristics:
   a. All are water-laid sediments.
   b. All are noncohesive (no railroad bridges were built on clay).
   c. All are either modern sediments or are very young geologically.
   d. All have a high water content, the water table lying at or within a few feet of the surface.

   The relation of the distribution of ground cracks to permanent lateral displacement of foundation materials and the distribution of damage to embankments show that little displacement occurred in sediments that are older and (or) drier.
2. The table shows that the severity of bridge damage increases as the grain size of the foundation material decreases. However, the grain size of water-laid sediments commonly decreases away from margins of sediment-filled basins. Thus, sand is more common than gravel where the sediment thickness is great.

TABLE 3.—*Damage to bridges, related to material in which piles were embedded*

Materials in which piles were embedded	Damage to bridges			
	None	Slight	Moderate	Severe
Silt		S M M	M	D
Sand		M D [M] [D]	M D D	D D D D D D D D D D D D D D D [D] [D]
Sand and gravel	M	S S S M M M	S S S S M M M M M D [D] [D] [D]	D D D D D D D D D D D D D D D [D] [D] [D]
Gravel	S (S) (S) [S]	[S] [S] [M] [D]	M M	
Till and (or) bedrock	□ □ □ □ □ □	□ □ ○		

Depth of unconsolidated sediment (to bedrock on glacial drift)
S 0-50′
M 50′-100′
D >100′

Type of bridge
S Open wood trestle
[S] Wood and steel deck or steel on wood and (or) concrete piers
(S) Ballasted wood trestle

The obvious tie between sediment thickness and damage immediately raises the question as to whether the grain size of the material (its propensity for mobilization) or the total thickness (the intensity and duration of the ground motion) is more important in determining the severity of damage to a bridge or embankment (and other structures affected by displacement of foundation materials). By replotting the damage against the sediment thickness (table 4) it appears that there is a stronger correlation between total sediment depth and the severity of the damage. All severely damaged bridges were underlain by more than 100 feet of sediments, and of all the bridges underlain by more than 100 feet of sediment, 88 percent were severely damaged.

The relative dependence of severe damage on the thickness and grain size can be demonstrated as follows: By considering only the grain size of the foundation materials, one would predict that 71 percent (17 of 24) of all bridges on sand and 47 percent (18 of 38) of all bridges on sand and gravel would be severely damaged. However, if one used sediment thickness greater than 100 feet as related directly to severe damage, one could predict that 81 percent (17 of 21) of those on sand and 82 percent (18 of 22) of those on sand and gravel would be severely damaged. The same dependence of damage on sediment thickness is shown in the case of slight versus moderate damage on sand and gravel (table 4). The data available for damage on silt are scant, but they suggest a similar dependence of damage on sediment thickness. Four of the bridges built on silt are along the north shore of Turnagain Arm, where the silt is probably thin and rests on glacial drift that veneers the adjacent bedrock. The one bridge built on silt overlying a thick section of unconsolidated sediments (bridge 63.0) was severely damaged.

The relative dependence of damage on the grain size of the foundation material and the thickness of the underlying sediments can be compared in figure 61. In these graphs open wood trestles on wood piles are distinguished from other bridges. Open wood trestles are built uniformly to a standard design. Thus, one of the major variables—the differences in individual structures—which makes it difficult to evaluate the relation between structural damage and seismic ground response, is largely eliminated. Again, these graphs make it quite clear that the thickness of the sediments is a far more reliable indicator of potential damage than the grain size of the foundation material.

The discussion presented above ignores the density (compaction) of the sediments involved in foundation displacements. Is one justified in doing so? The strong relation of total sediment thickness to damage suggests that whatever the range of the densities of the foundation materials at the sites of the 76 bridges built on waterlaid sediments, it had no great effect on the severity of the damage. However, for design purposes, it is useful to know the range in densities. Densities are sometimes estimated from standard penetrometer resistance values (N values: blows per ft of a 140-lb hammer falling 30 in. on a 2-in.-diameter penetrometer); however, there is some question as to the validity of this approach (Peck, 1967). To avoid the problem of translating N values to densities, only the N values are shown for the two areas in which they are available.

N values determined in six borings in the Portage area are plotted against depth in figure 62, and an estimated average N curve is drawn. As shown by a generalized geologic section, the average N value which is low (15–20) in the upper 10 feet of gravel, increases to a maximum (50) in the underlying sand, and decreases as the section becomes silty near the base.

N values are also plotted from borings along the highway that was under construction across Knik-Matanuska River flood plain at the time of the earthquake (fig. 63). The generalized geologic section (based on 24 borings) shows sand and gravel to a depth of about 40 feet. The base of the sand and gravel is interbedded with silt and fine sand that continue, in beds several feet thick, to some unknown depth below the bottom of the deepest hole (−152

TABLE 4.—*Damage to bridges, related to total sediment thickness at bridge site*

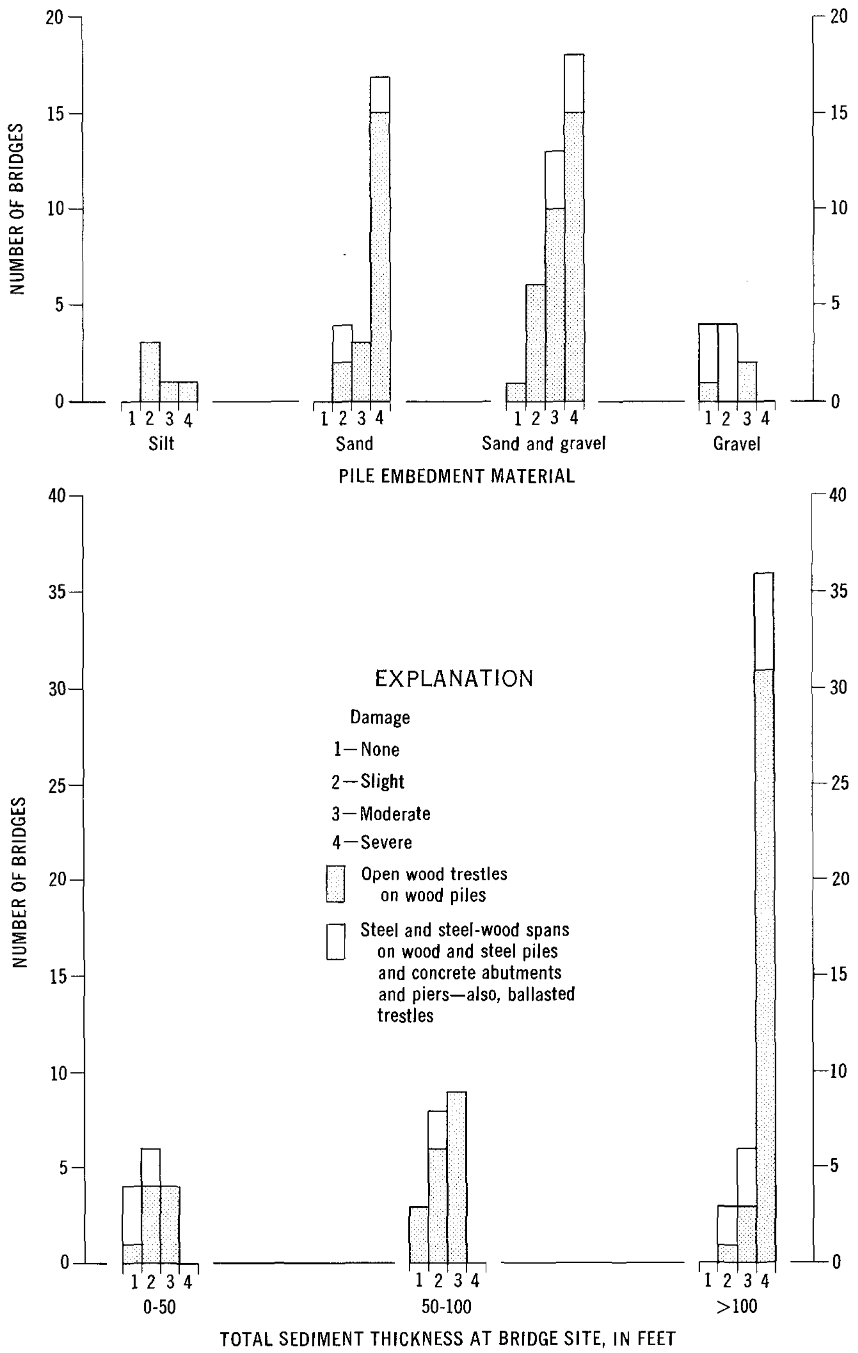
Estimated total sediment thickness at the bridge site (feet)	Damage to bridges			
	None	Slight	Moderate	Severe
0–50′	4 (4) (4) [4]	1 3 3 3 [4] [4]	3 3 3 3	
50′–100′	3	1 1 2 [2] 3 3 3 [4]	1 2 3 3 3 3 3 4 4	
>100′		2 [2] [4]	2 2 3 [3] [3] [3]	1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 [2] [2] 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 [3] [3] [3]

Material in which piles were embedded
1 Silt
2 Sand
3 Sand and gravel
4 Gravel

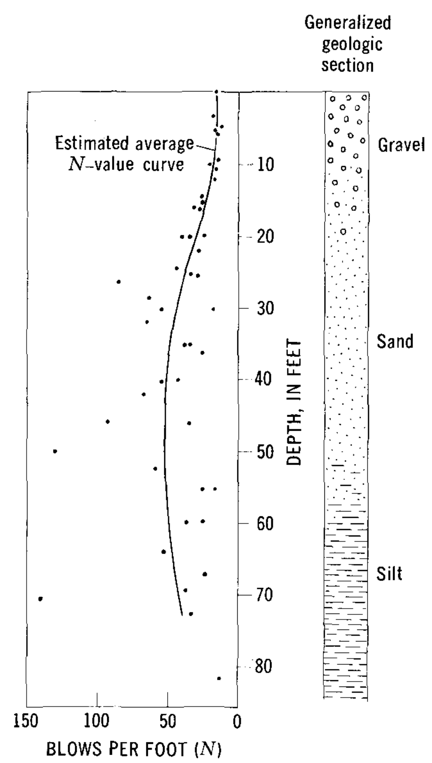
Type of bridge
1 Open wood trestle
[1] Wood and steel or steel deck on wood and concrete or concrete
(1) Ballasted wood trestle

ft). The estimated average penetration resistance increases with depth.

Also shown in figure 63 are the depths of the tips of steel and wood piles in five large railroad bridges. The construction and damage to these bridges are described in table 1, in the discussion of damage to large bridges (p. D49), or on pages D155–D156, and can be summarized as follows: All steel and wood pile-supported abutments and piers beneath steel spans were dis placed streamward. Anchor bolts on steel spans were commonly sheared, and steel spans jammed together, damaging span bearings. Streamward displacement of wood pile bents occurred in those with open wood trestle approach spans (146.4, 148.3). Three of the bridges were severely damaged (147.1, 147.5, 148.3) and the remaining two were moderately damaged. The *N* values at the tips of the piles of these damaged bridges are compared with those of four severely damaged open wood trestles in the Portage area in figure 64. (Damage to the Portage bridges is described in section 12b p. D128, and pile displacements are shown on figs. 7, 8). Each bridge is indicated by a horizontal line that crosses



61.—The degree of damage to bridges compared with the grain size of the material in which the piles were embedded and the total thickness of all unconsolidated sediments at the bridge sites. As shown in table 3 and 4, the severity of the damage appears to be related most directly to the total sediment thickness.

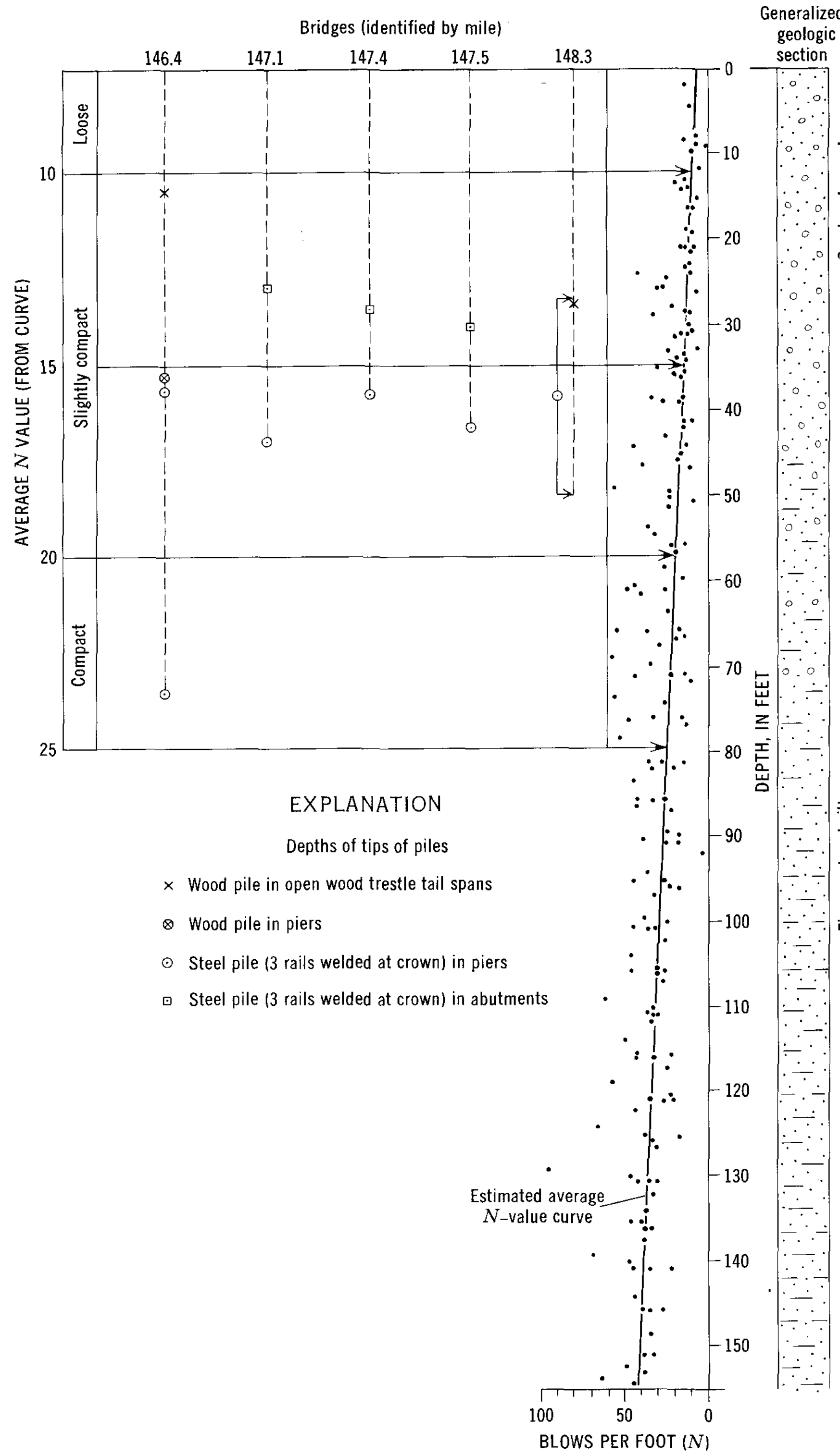


62.—Standard penetrometer values (*N*, blows per ft) and an estimated average *N* curve for six borings in the Portage area. Borings are located in figure 111, and logs are given on figure 112.

its respective average N curve at the average depth of the piles in the bridge. The ends of the horizontal lines indicate the N values at the tips of the deepest and shallowest pile in each bridge.

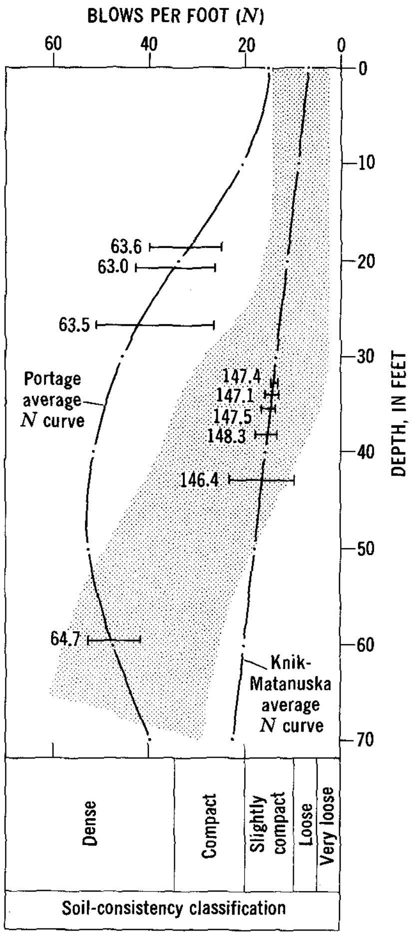
The considerable range in the density of the sediments associated with displaced foundations of these damaged bridges is shown in figure 64; those at Portage lie within the compact to dense range, and those at Knik-Matanuska crossings within the slightly compact to compact range. The more severe damage to bridges in denser sediments at Portage probably is due to the fact that Portage is considerably closer to the area of high strain release (fig. 2). Thus, in these two areas in which the sediments are relatively thick, the large difference in density of the foundation material appears to have had less effect on the degree of damage than the severity of the ground motion.

An informative comparison can be made between these two areas and damage associated with the 1964 Niigata earthquake in Japan. The Niigata earthquake was smaller (magnitude 7.3) and closer to Niigata (35 miles) than either the Portage or Knik-Matanuska area was to any of the large Alaska events. The shaded area in figure 64 is the range of penetration resistance values at the tips of piles under heavily damaged structures in Niigata (Seed and Idress, 1967; Koizumi in Seed and Idress, 1967), and damaged Knik-Matanuska bridges lie within this zone. However, the Knik-Matanuska area is nearly twice as far from the epicenter (65 miles) as Niigata and four times as far from the largest event (event C, magnitude 7.8, fig. 2). The Portage area bridges lie closer to the source of the seismic energy, yet were built in considerably denser



63.—Standard penetrometer values (N, blows per ft), an estimated average N-value curve for 22 borings across Knik and Matanuska River floodplains, and a generalized geologic section based on 24 borings. The average penetrometer values are compared with the tips of piles in five bridges located on plate 1. Six of the deeper borings are located on plate 1 and their logs are shown in figure 137. Data supplied by the Alaska Department of Highways.

sediments than those that were severely damaged at Niigata. These comparisons show that the choice of the magnitude, location, and duration of the "design earthquake" are extremely important when considering the possible behavior of foundation materials.



64.—Range of N-values (horizontal line) at tips of shallowest and deepest piles in damaged bridges in Portage and Knik-Matanuska areas, plotted on their respective average penetration resistance curves. Bridges in less dense sediments, far from the area of strain release at Knik-Matanuska area, were less severely damaged than those in denser sediments, nearer the area of greater strain release at Portage. The shaded area is the range of penetrometer values in sediments under severely damaged pile-supported structures in the 1964 Niigata earthquake in Japan (Seed and Idress, 1967).

In summary:

1. Foundation materials in which damaging displacements occurred were young noncohesive water-laid wet sediments. Bridges on bedrock, till, or older drier water-laid sediments were undamaged by foundation displacements.
2. Severity of the damage increased with the thickness of the sediments, and all severely damaged bridges were on sediments more than 100 feet thick.
3. Severity of the damage appeared to be less influenced by grain size of the wet water-laid foundation materials than by the total sediment thickness.
4. Displacements occurred in foundation materials with penetration resistance values even above 50 blows per foot (dense soil).
5. Of the two areas in which there is data, the proximity to the area of strain release appears to have been more important in determining the severity of the damage than the penetration resistance of the foundation materials.

These observations can be furthur summarized in the following useful generalization: In an area subjected to a large long-duration earthquake, structures on thick water-laid noncohesive wet young sediments that range from silt to gravel and have a wide range in penetration resistance values should be expected to sustain severe damage, either from displacements of the foundation materials or from severe ground motion.

LANDSLIDES

Subaqueous landslides were responsible for a considerable part of the total cost of repairing the railroad. Slides at Seward, Whittier, and Kenai Lake have been described by Grantz, Plafker, and Kachadoorian (1964), Lemke (1967), Kachadoorian (1965), and McCulloch (1966). Subaerial landslides also caused damage at Potter Hill (mile 103-104), in and adjacent to the railroad yards in Anchorage, at mile 138.4 on the main line, and at mile 16.5 on the Sutton Branch.

POTTER HILL SLIDES

Landsliding occurred for about 4,200 feet between mile 103 and 104. The railroad was built in cuts and fills across the face of a bluff at Potter Hill, about 2.5 miles north of Potter (fig. 1). Two sections of embankment and track, totaling 1,550 feet, were carried away by the slides (fig. 65). The following paragraphs summarize the report of an investigation of the slides prepared by the authors for The Alaska Railroad. A longer summary of this report is given in Hansen (1965, p. A31-A33).

At the north end of the slide area the bluff is composed of glacial till resting on glacial outwash, which in turn rests on silt and fine sand. To the south, the till is lower in the bluff, and is overlain by glacial outwash. A water well (well 571, Cedarstrom and others, 1964), 900 feet east of the railroad, penetrated a 20-foot bed of "blue mud," from 2 feet above to 18 feet below mean lower low water, resting on alternating thick beds of sand and blue clay to a depth of 375 feet below mean lower low water. This "mud," sand, and clay may be the Bootlegger Cove Clay, in which the slides occurred in the city of Anchorage.

The scarp along which the railroad gradually ascends is an abandoned wave-cut cliff that was cut when sea level was higher with respect to the land. As the subsequent relative lowering of sea level occurred, the shoreline shifted toward Turnagain Arm and left a wide tidal flat exposed. Coniferous trees growing on this surface show that it is above the highest tides (fig. 65). This flat tidal plain is composed of a sheet of sediments that rest on an erosion surface cut across unconsolidated sediments. The erosion surface slopes gently from the toe of the bluff toward Turnagain Arm. The tidal-plain sediments are probably largely of silt size, as are most of the sediments in modern Turnagain Arm.

Sliding was caused by flowage of material near the base of the bluff. Flowage may have been initiated in either, or both, the fine sand and silt that underlie the base of the bluff, or the adjacent fine tidal-flat sediments which must have underlain some of the embankment fill. The resulting slumping and flowage carried disintegrating blocks of earth, track, and ties down and away from the bluff; some ties and rails were carried as much as 140 feet horizontally. Where flowage occurred, the material was probably saturated, because depressions in the slide debris were rapidly filled with water, and sand craters and mounds were found where water under pressure was driven to the surface of the debris. Because the ground surface was frozen, this water was undoubtedly ground

65.—View of Potter Hill slides. Note the overthrusts in the low-lying tidal flat in the foreground, and dark strata of water-saturated sediments in the slide scarps. Photograph by The Alaska Railroad.

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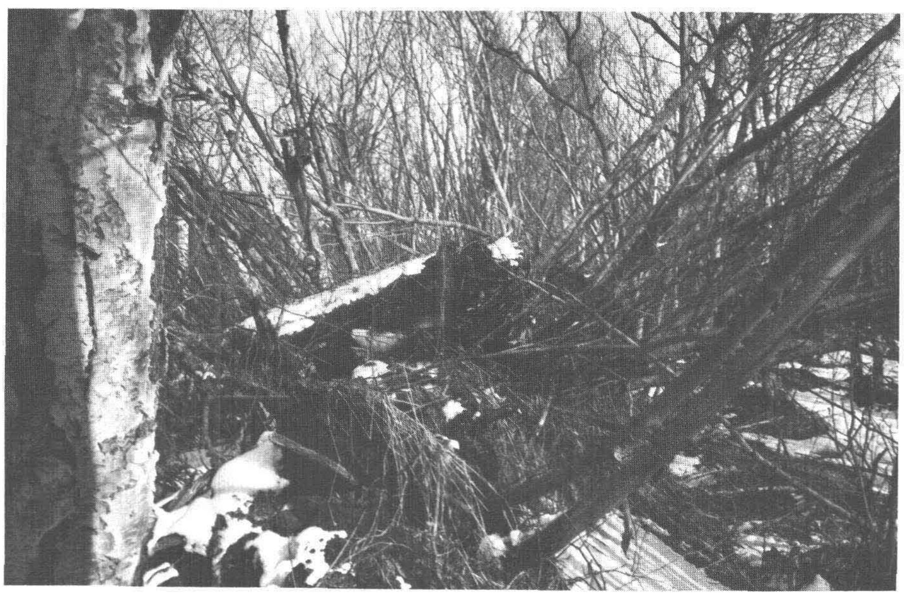
water. Water wells inland from the bluff encounter water from 240 to 30 feet above sea level, and the dark bands of saturated sediments visible in figure 65 show that ground water is discharged along the base and at several levels throughout the height of the bluff. The dark tone of the soil in figure 68 also shows that water was plentiful at the scarp of the slump that cut deepest into the bluff.

Pressure ridges formed within the slide debris and at their margins. In the ridge at the outer margin of the slide, lateral force transmitted through the frozen surface sediments drove the tree-covered frozen sediments up over adjacent trees (fig. 66). Some upper blocks were completely detached at their edges, which suggests that the overthrusting may have been relatively rapid. Lateral thrust in the frozen sediments continued beyond the outer edge of the slides and formed overthrust ridges well out in the adjacent tidal flats (pl. 4; fig. 65).

Comparisons of pre- and post-slide cross sections (pl. 4) indicate that the volume of slide material that accumulated at the base of the slope and adjacent tidal flats was less than the material removed from the slope by sliding. The apparent loss in volume may be due to lateral flowage of the fine-grained tidal flat sediments away from the bluff. The lateral flowage probably occurred beneath and contributed to the thrusting of the frozen surface layer that extended as much as one-third mile beyond the edge of the slides. Marginal cracks formed on adjacent parts of the bluff face, where slumps did not develop. These cracks were approximately parallel to the bluff in natural bank material and in the fill up to the level of the tracks, in the roadbed, and in the drainage ditch between the tracks and the bluff. Near Rabbit Creek, cracks occurred to the top of the bluff face. Cracks from which sand-bearing water was ejected were also observed by James A. Morrison of the Engineering Department of The Alaska Railroad on the surface of the bluff, about 400 feet back from the scarp.



66.—Entirely detached block of frozen soil and uprooted trees that was thrust up over the adjacent tree-covered ground in a pressure ridge at the toe of Potter Hill slide.

After this study was made, Clair A. Hill and Associates of Redding, Calif., investigated the slide area preparatory to designing a new alinement and associated drainage structures ("Potter Hill Slide investigations for The Alaska Railroad," Aug. 1964, 20 p.). Borings were made in the slide debris and undisturbed bank material. Logs of the borings and a topographic map prepared from aerial photographs from this report are shown on plate 4. The aerial photographs were taken after the rail line had been relocated in a cut across the slide area; thus the slide scarp that was mapped earlier appears to lie on a slope.

Borings B 8 and B 6 straddle the northern slide. In the interval of suspected failure (from somewhere below the embankment at an altitude of 82 ft, to somewhere below the bluff base at an altitude of 20 ft), both borings penetrated predominantly sand-size material containing varying amounts of silt and fine gravel. Between altitudes of 10 and 20 feet, both borings penetrated water-bearing strata. The inversion of penetration resistance values in hole B 8 that shows low values between 0 and 35 feet—the interval encompassing the water-bearing strata—suggests that failure might have occurred within this zone. However, blow counts in B 6 give no indication of a comparable zone. It is possible that more closely spaced measurements of penetration resistance in B 6 might have isolated a weak zone.

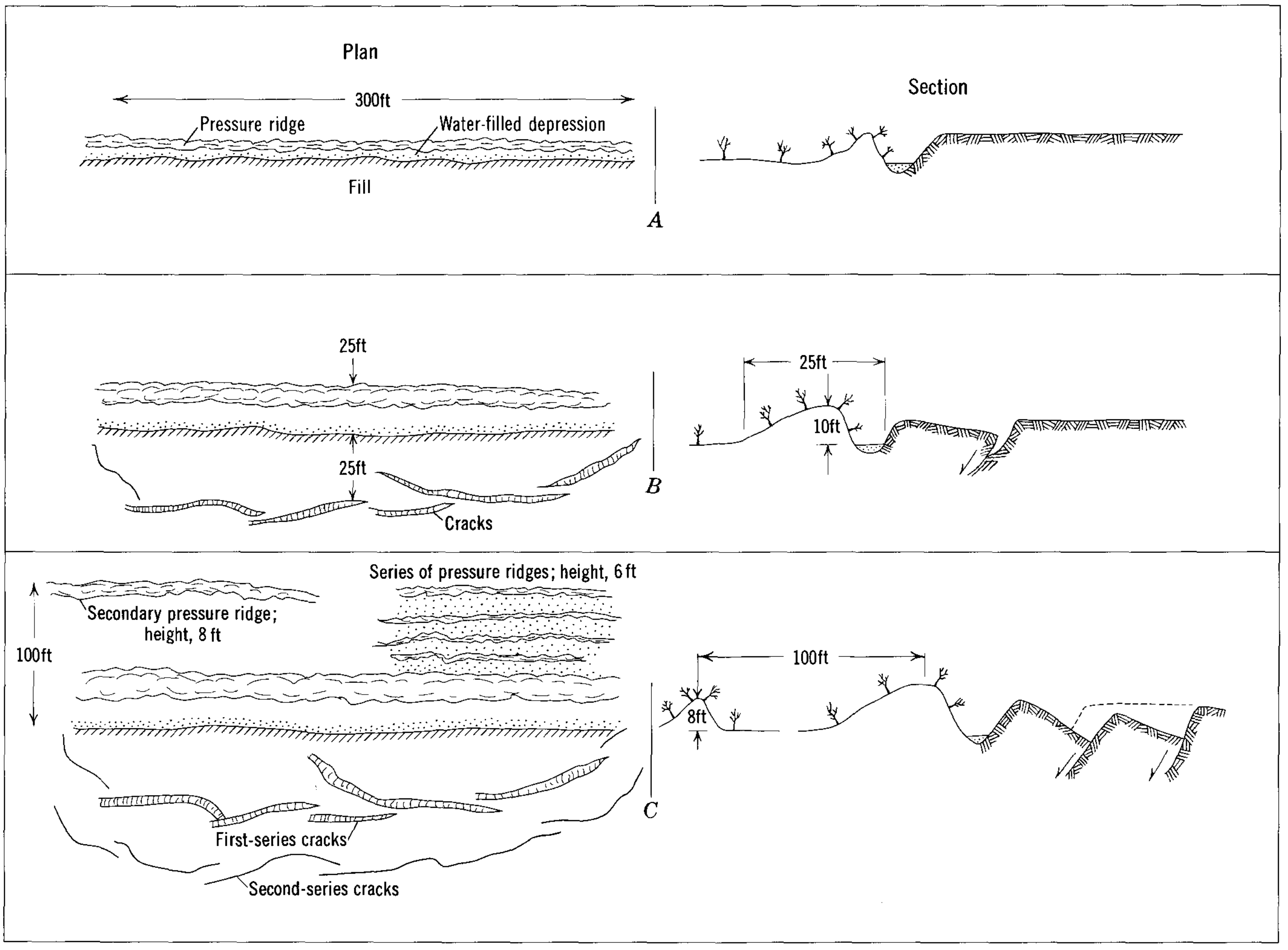
Borings B 1 and B 2 are located just upslope, and B 3 just north, of the other major slide area. Of these three borings only B 3 was deep enough to have penetrated the zone of suspected failure. The partial cementation and very dense consistency of the sediments suggest that no failure occurred in these materials; possibly most or all of the sliding at this location was in fill. No detailed records showing the distribution of cuts and fills are available for this area; however, in the recollection of Mr. Cliff Fugelstad, engineer of track, this was an area of fill. Some unknown amount of fill might also have been involved in the slide to the north, but our field observations showed that natural materials were exposed along the northern part of the slide scarp.

The type and extent of failures in fill placed on the estuarine sediments at the toe of the bluff during reconstruction add some credence to the inference that part of the landsliding involved failures within these sediments where they were overlain by embankment fill. The failures produced pressure ridges separated by water-filled troughs resembling those formed by the landslides. The following account of the failure during reconstruction is from a letter written to The Alaska Railroad on April 24, 1965, by Dan K. Conger, resident engineer for Clair A. Hill and Associates. The letter describes failure associated with a 5- to 12-foot-thick 400- by 5,000-foot spoil area built on the tidal flat adjacent to the toe of the slides.

"A general subsidence is experienced in most areas as evidenced by a 3 to 5 foot depression formed at the forward toe of the earth fill and heaving of the tundra surface beyond [fig. 67*A*].

Water usually appears in the depression, and sizable streams issue from beneath the fill. Cracks form in the fill surface indicating settlement as well as forward movement. Shock waves are felt at considerable distances, and weaving of the surface beneath wheels is common.

Instantaneous slipouts have occurred which were triggered by the earthmoving



67.—Field sketches of successive failures that occurred in a spoil area and adjacent tidal flat at the toe of Potter Hill slides during reconstruction. Sketches redrawn from Dan K. Conger, Clair A. Hill and Associates.

equipment, and required considerable effort to extricate the machine. Of particular note was an occurrence on Monday, April 20, 1965, which will be further described with related reactions of the tundra.

Opposite Railroad Survey Stations 2886 to 2889, a section of the fill approximately 25 ft. by 300 feet, dropped suddenly and started moving out. A short time later cracks appeared about 25 feet further back and a new section was seen to be subsiding and moving toward the tundra [fig. 67*B*].

A characteristic rotation of the blocks of earth was noted, having minor subsidence of the forward edge, with the rear edges continuing to subside during the periods of forward motion. The surface of the first section dipped 45° from horizontal, reaching a maximum settlement of 10 feet. The second section attained a dip of about 30° and experienced somewhat less settlement.

Late in the day a semblance of stability was reached, where the materials rested in a state of uncertain equilibrium, and movements were not readily discernible. Several thousand cubic yards of fill added to the sunken area had not restored the original grade.

Transformations of the tundra occur as a result of the subsiding fills and is evidenced by the formation of pressure ridges, which rise to heights of 6 to 10 feet, a distance of 25 feet in advance of fill [fig. 67*C*]. In the instance cited, a secondary pressure ridge appeared about 100 feet beyond the first, reaching a height of 8 feet, indicating that pressure was being transmitted through the underlying muds to considerable distance. At the northerly end of the section a series of pressure ridges developed, reaching about 5 feet in height, and extending about 100 feet beyond. The intervening troughs filled with water.

Of particular interest was the manner in which the crest of pressure ridges appears to flow beneath the turf. Matted vegetation is first raised, then as the crest moves forward is draped over the back side of the ridge, presenting much the same appearance on both sides. Forward motion of the ridges is not rapid, but is apparent from occasional miscellaneous movements, which continue until some degree of equilibrium is re-established.

This is the third time the section between miles 103 and 104 has been damaged by slides within about a 35-year period. In the late 1920's and early 1930's heavy rains caused sliding; the largest slide removed about 1,000 feet of track (Bert Wennerstrom, chief accountant, The Alaska Railroad, oral commun., 1964). On October 3, 1954, landsliding resulting from an earthquake again destroyed some of the rail line. A report on slides, between mile posts 103 and 104, after the earthquake is on file at The Alaska Railroad Office (James A. Morrison, unpub. data). Since the 1964 earthquake the rail line has been rebuilt close to the pre-1964 alinement in a slightly deeper cut across the face of the bluff.

ROCKY CREEK DELTA

The delta of Rocky Creek (21.4; also called Boulder Creek) on the east shore of Kenai Lake was extensively fractured, and a series of small slumps into the lake trimmed back the edge of the delta as much as 150 feet (McCulloch, 1966, fig. 29). One slump carried away 261 feet of the railroad embankment. The following description of the slumping and fracturing in the deltas is taken in part from a 1964 unpublished report prepared by the authors for The Alaska Railroad ("Report on a landslide at mile 21.4, Kenai Lake, resulting from the earthquake on March 27, 1964").

Fractures in the delta occurred in the pattern typical of fans and deltas—two sets of fractures that intersected at about 60°, to form parallelogram-shaped blocks having long axes parallel to the contours. Single blocks at the edge of the delta were lowered and rotated downward along the fractures; farther up the delta the blocks appeared to have moved downslope without rotation.

Soundings made down the axis of the scarp of the slide that carried away the rail line showed that the water was 9 feet deep where before the track had been 12 feet above the water. The slide scarp sloped at about 32° to a depth of about 100 feet, and then continued to a depth of approximately 375 feet at a slope of 27°.

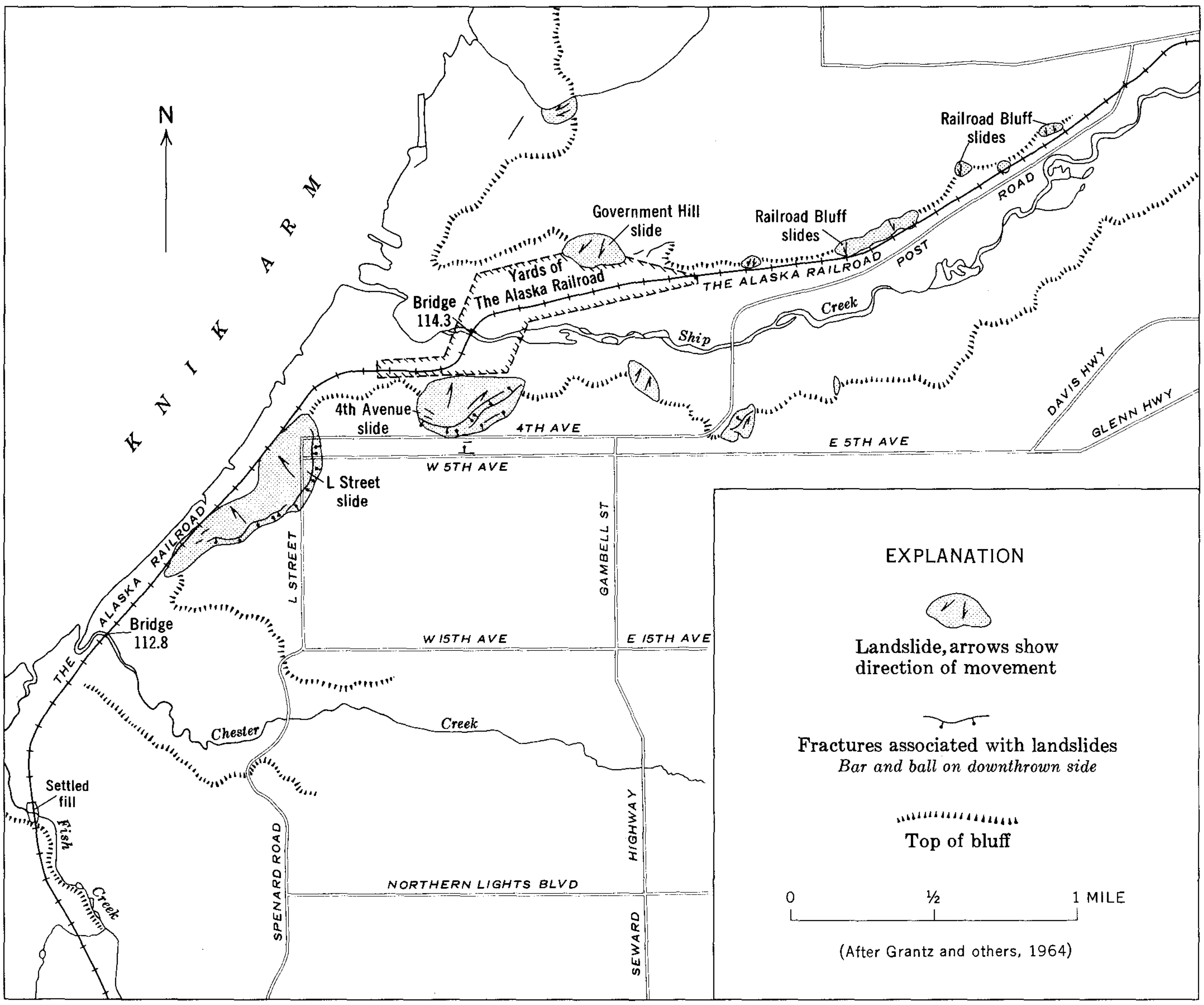
The 1964 report recommended that the rail line be relocated farther up the slope of the delta, not only because of the difficulty of placing and maintaining a fill in the steep slide scarps, but also to avoid the zone of deep fractures at the edge of the delta that might slump in a subsequent earthquake. It was also suggested that heavy traffic, which might trigger a slide, be avoided until relocation was complete. Since the earthquake, 1,500 feet of roadbed has been relocated a maximum of 75 feet upslope of the preearthquake alinement, and the small open wood trestle (mile 21.4) that was pulled apart by the spreading delta sediments was replaced by an 8-foot-diameter steel culvert.

ANCHORAGE

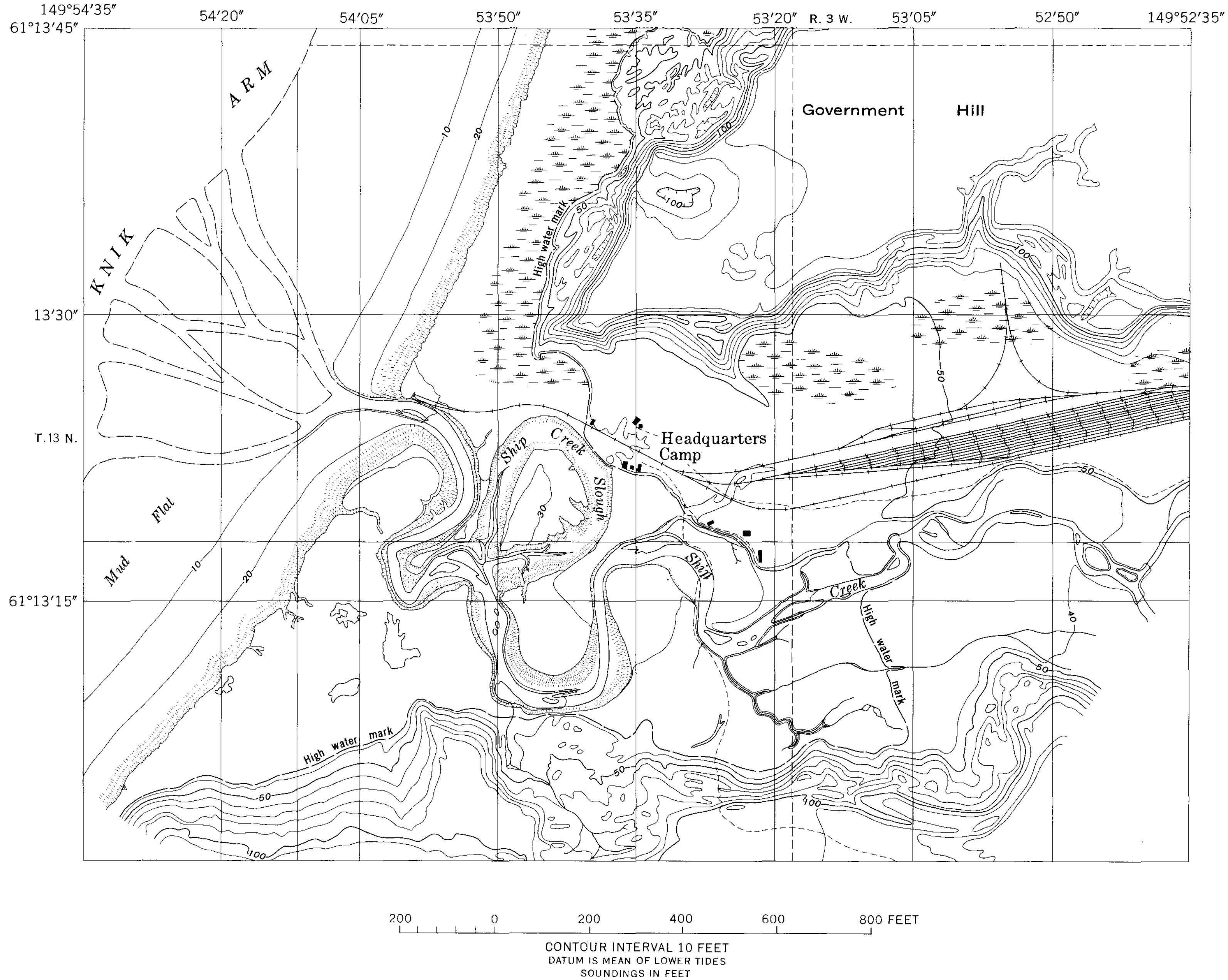
Landslides that occurred along the edges of the high bluffs beside Knik Arm and the valley of Ship Creek (fig. 68) have been described in detail by Shannon and Wilson, Inc. (1964a) and by Hansen (1965). The L Street slide, the Fourth Avenue slide, the Government Hill slide, and some of the slides along Railroad Bluff damaged tracks, buildings, buried utilities, and rolling stock of the railroad (see Section 15, p. D143). Ship Creek valley probably has a long history of landsliding. A 1914 topographic map made by the Alaska Engineering Commission (fig. 69) shows landforms that are clearly landslides along the bluffs surrounding the railyards. Although Miller and Dobrovolny (1959) recognized old landslides along the bluffs in the Anchorage area, these slides are not shown on their map. The 1914 map shows two distinct slides on the northwest side of Government Hill. The northernmost, with a nearly circular toe, appears to have been little modified by erosion and may have occurred not long before 1914. An oil-tank farm has since been built on this landslide. On the south side of Government Hill, just northeast of the present railyard, hummocky side-slope topography and a terracelike form with a linear depression at its back edge that resembles the grabens formed behind many of the 1964 Anchorage slides suggest that there had been sliding in the area in which the 1964 Government Hill slide occurred.

On the south side of Ship Creek there is hummocky side-slope topography along most of the bluff east of the location of the modern railroad depot. Of special interest is the reentrant in the bluff at the position of the 1964 Fourth Avenue slide, in which there is a low hummocky area with a lobate tongue that protrudes out into the adjacent flood plain. As Hansen states (1965, p. A66), several people have concluded that the Fourth Avenue slide occurred in an old slide area:

> The alcove-like area centered at the city parking lot * * * probably also is the scar of an old landslide (Shannon and Wilson, Inc., 1964, p. 39; R. M. Waller, written commun., 1965). The area coincides almost exactly with the Fourth Avenue slide of March 27, except that the Fourth Avenue slide retrogressed farther into the bluff.



68.—Distribution of landslides in the Anchorage area and settled fill on Fish Creek (after Grantz and others, 1964).



69.—Alaska Engineering Commission 1914 topographic map of Ship Creek valley, Anchorage. The landforms indicate two distinct slides backed by elongate grabens. These slides are on the west side of Government Hill, on either side of a topographic depression interpreted as being an ice-kettle hole. Two slides are also discernible on the south side of Government Hill, the easternmost in the position of the 1964 slide. On the south side of the creek, jumbled side-slope topography suggests extensive sliding from the area of the 1964 Fourth Avenue slide eastward for a distance of approximately 2,600 feet.

The topography shown on the 1914 map clearly confirms this conclusion. It also indicates that there was a flowing stream with several tributaries in the slide area. Although the topographer indicated small gullies up the face of the bluff, the fact that this is the only stream that he drew suggests that it was of some consequence. As drawn, the tributary pattern shows that the stream was largely fed from springs located in the slide mass and in the scarp at its head.

Groundwater discharge into this slide area seems to have persisted after 1914, for as Shannon and Wilson, Inc., state (1964a, p. 40),

> At some fairly recent date, the area now occupied by a parking lot between Fourth Avenue and Third Avenue was filled with gravel. Prior to filling, this area was wet and swampy. Early records show a 12-inch drain pipe was installed prior to filling, and that this drain still discharges water just above First Avenue

The persistently high groundwater discharge probably contributed to both the 1914 and 1964 slides.

Landslide damage to the railroad in, and adjacent to, the Anchorage railroad yard (p. D146–D150) can be summarized as follows: The L Street slide carried the embankment and tracks possibly several feet laterally toward Knik Arm. The Fourth Avenue slide (1) broke foundations of unused dormitory buildings on the slide; the buildings have been razed; (2) displaced laterally and heaved up on pressure ridges the buried concrete utilidor along First Avenue and B Street; the utility lines have been rebuilt above ground; (3) contributed to the damage to the office annex building; it has subsequently been razed; (4) displaced foundation piles under a long freight depot north of First Avenue; and (5) may have displaced the depot-office building slightly to the north. The Government Hill slide overran a prefabricated metal Butler building used for on-track equipment storage, destroyed the building, covered adjacent trackage, and damaged some rolling stock. Slides from Railroad Bluff covered the tracks, but did no important damage.

SUTTON BRANCH SLIDE

At mile 16.5 on the Sutton branch line, about 2 miles south of Sutton (fig. 1), a small landslide was dislodged from the bluff along the north bank of the Matanuska River — a bluff that rises steeply above the flood plain on which the rail line is built. The slide overrode about 300 feet of track, but at the time the following observations were made the tracks had been cleared and repaired, and most of the toe of the slide had been removed.

Sliding occurred on the very steep 40° to 45° face of a 150-foot-high bluff cut in outwash sand and gravel. The area affected by the slide was about 700 feet wide and extended to about 100 feet above the bluff base; thus, about 21,000 cubic yards of material were involved. As far as could be determined, the only material in the slide was an approximately 6-foot-thick layer of silty sand that had been blown from the adjacent valley floor onto the face of the bluff. The eolian material was tied together by the root mat of conifers, some deciduous trees, and low shrubs; it may have been frozen at the time of the earthquake. Several large pieces of this root mat tore free and skidded downslope. The movement occurred at the contact with the underlying outwash sand and gravel, and at no place was the sand and gravel seen to be involved in the slide (fig. 70). It is not known if water played any role in the sliding. Some water was seen in the jumbled slide debris at the base of the slope, but none was found above where the outwash was laid bare on the skid surface. Similar slides in which windblown sand was dis-

70.—Root mat development in windblown silty sand that became detached and skidded downslope along its contact with glacial outwash sand and gravel at mile 16.5 on the Sutton branch line.

lodged from a bluff face were studied by the present authors along several miles of bluff between Point Campbell and Campbell Creek southwest of Anchorage (Hansen and others, 1966, p. 56), and are described by Hansen (1965, p. A30–A31).

SLIDE AT MILE 138.4

At mile 138.4 the rail line crosses a small creek, which drains Mirror Lake (fig. 136). The creek has cut a wide reentrant into the edge of the adjacent bluff that rises to about 125 feet just southeast of the rail line. Ground cracks formed in the bluff along the edge of the reentrant as well as on the floor of the reentrant, where water was ponded behind pressure ridges. From about 35 to 525 feet north of the culvert through which the creek discharges, the turf on the northwest side of the rail line was buckled upward in an arcuate pressure ridge. The pressure ridge was hollow. Its walls were made of frozen turf that had been jackknifed upward 3 to 8 feet, and it was possible to walk in the hollow under the center of the pressure ridge, beneath the roof of frozen turf (fig. 71). Adjacent to the pressure ridge, 450 feet of embankment was displaced laterally and lowered irregularly as much as 5 feet. The sliding appeared to have been shallow, and was probably produced largely by flowage of material beneath the surface, because there was neither a scarp at the head of the slide nor an upthrust, or upbulged toe, which might suggest rotational failure. The upward buckling of the frozen turf probably was produced by the resistance of the frozen surface to lateral transport of the flowing sediments below, in much the same way as the overthrusts in the frozen sediments beyond the edges of the slide at Potter Hill.

This area appears to have a history of sliding, for there are old pressure ridges and hummocky slide topography on the floor of the reentrant southeast of the tracks, which clearly predate the 1964 movement. Although no pre-1964 slides are recorded, this section of track has required considerable maintenance to keep the line at grade level. It is also notorious for "glaciering," that is, the growth of ice out over the tracks which suggests that ground water is discharged through the shallow slide debris. The excess ground water undoubtedly contributed to the instability of the slide by increasing whatever propensity the sediments had for sliding.

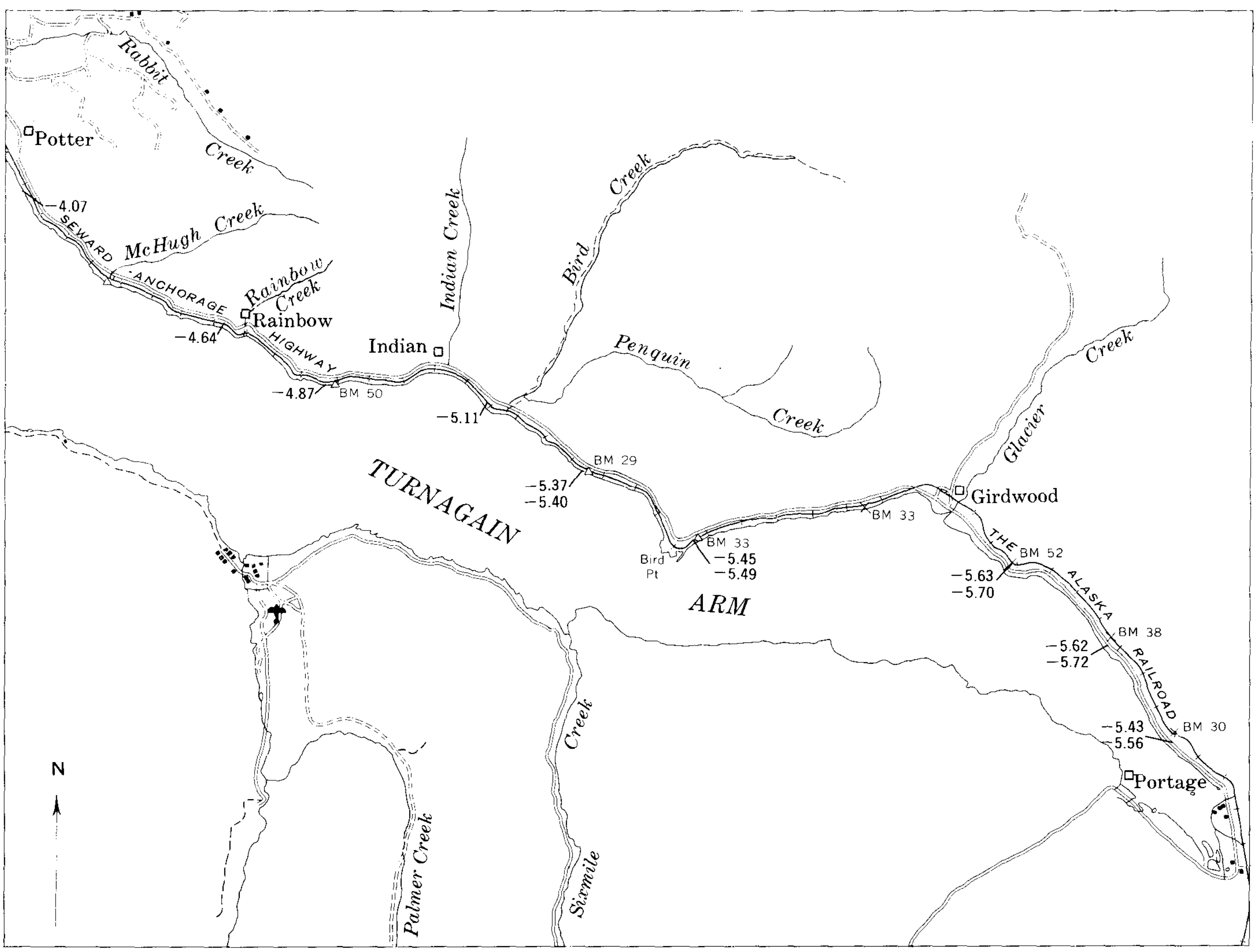
71.—Frozen turf arched upward in a hollow pressure ridge at the toe of the slide at mile 138.4. The hollow center can be seen where the ridge is broken by an extension fracture. The slide lies behind the viewer.

DISTRIBUTION OF REGIONAL TECTONIC SUBSIDENCE AND ITS RELATED DAMAGE

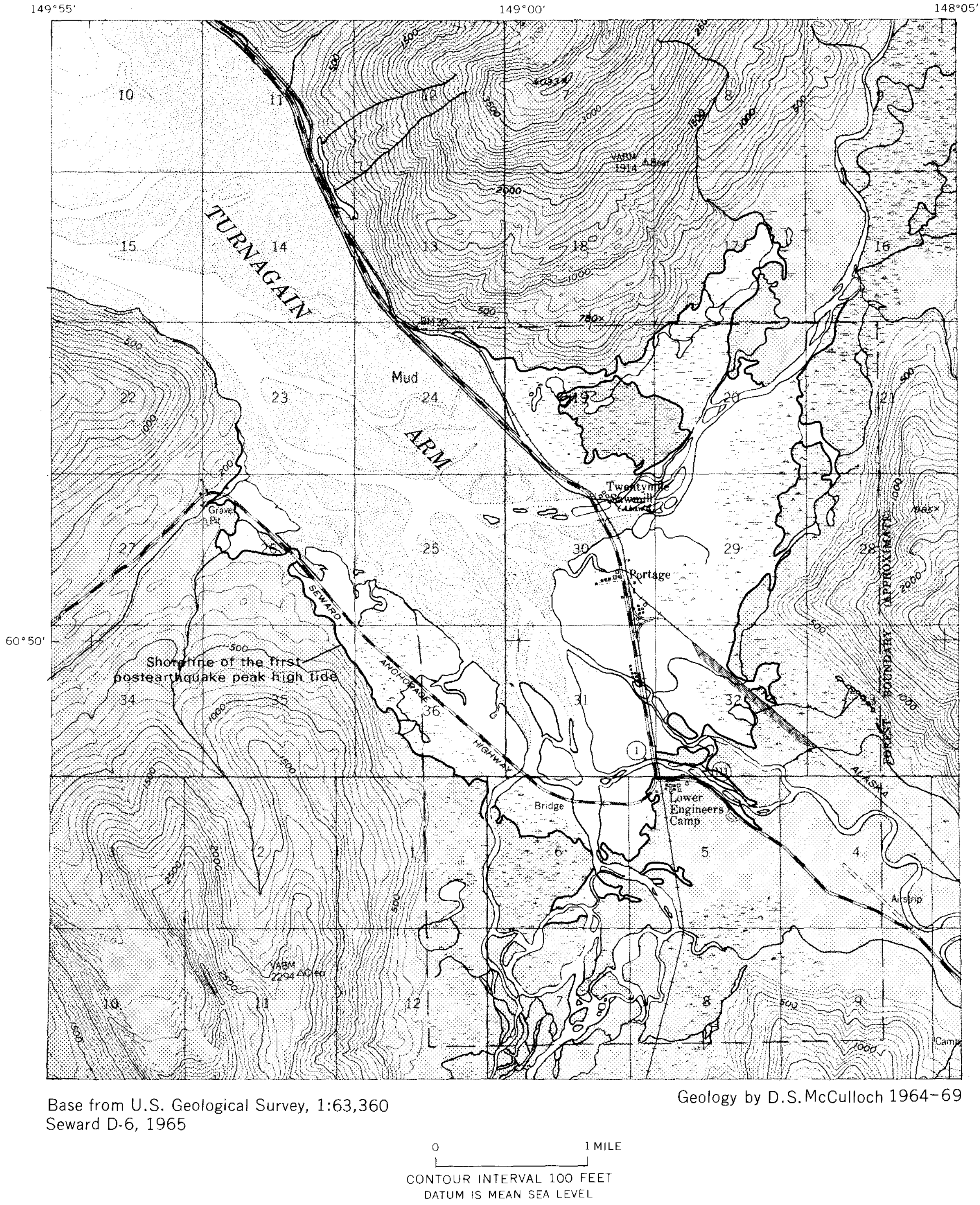
Turnagain Arm and Portage lie in the area of regional subsidence (fig. 2). The lowering of bench marks on bedrock relative to their 1923 altitudes is shown in figure 72. Elevations measured in two surveys in May to October of 1964 (Wood, 1966, table 11, p. 124) indicate that the maximum subsidence occurred between Girdwood and Portage and may have been as much as 5.72 feet.

In the Portage area, the shoreline of the first period of high tides in late April after the earthquake was as much as 2 miles inland from the preearthquake mean high water shoreline (fig. 73). The town of Portage was inundated and covered with a blanket of silt. Both the railroad depot, which had been severely damaged by ground cracking and seismic shaking, and a microwave building, just across the track from the depot, were flooded. At high water, parts of the embankment and most of the marshaling yards on the Whittier branch were submerged. Much of the highway, which was at a lower altitude than the railroad, was covered by water, and all transportation between Seward, Whittier, and Anchorage was halted. Large blocks of ice carried ashore by the wind and incoming tides were left stranded on the highway and townsite as the tides retreated (fig. 74) and the outgoing water, which was channeled beneath the bridges, eroded the approach fills and gullied the highway fill between the broken blocks of pavement.

Throughout the Portage area, and to the west along Turnagain Arm, local settling of the embankment into unconsolidated sediments, which themselves also underwent some unknown and variable amount of compaction, combined with the regional tectonic subsidence to lower the railroad grade (fig. 75). Adding the 5.49 feet of regional subsidence to local lowering due to compaction and settling in the Portage area generally lowered the grade about 8.5 to 9.5 feet; local dips were as much as 11.5 feet. The amount and distribution of lowering northwest of Portage, where repairs were made before the line was surveyed, are not so well known. The pre-and postearthquake top-of-rail profiles are compared in figure 75, and the total lowering of the grade is compared with the regional subsidence shown by lowering of bench marks on bedrock. Where apparent lowering was less than regional subsidence, the line had been regraded prior to the surveying; lowering in excess of regional subsidence was due to local settling and compaction. There may be errors in the survey, for at mile 80.77, where the grade and bench mark are both on bedrock, lowering exceeded regional subsidence.



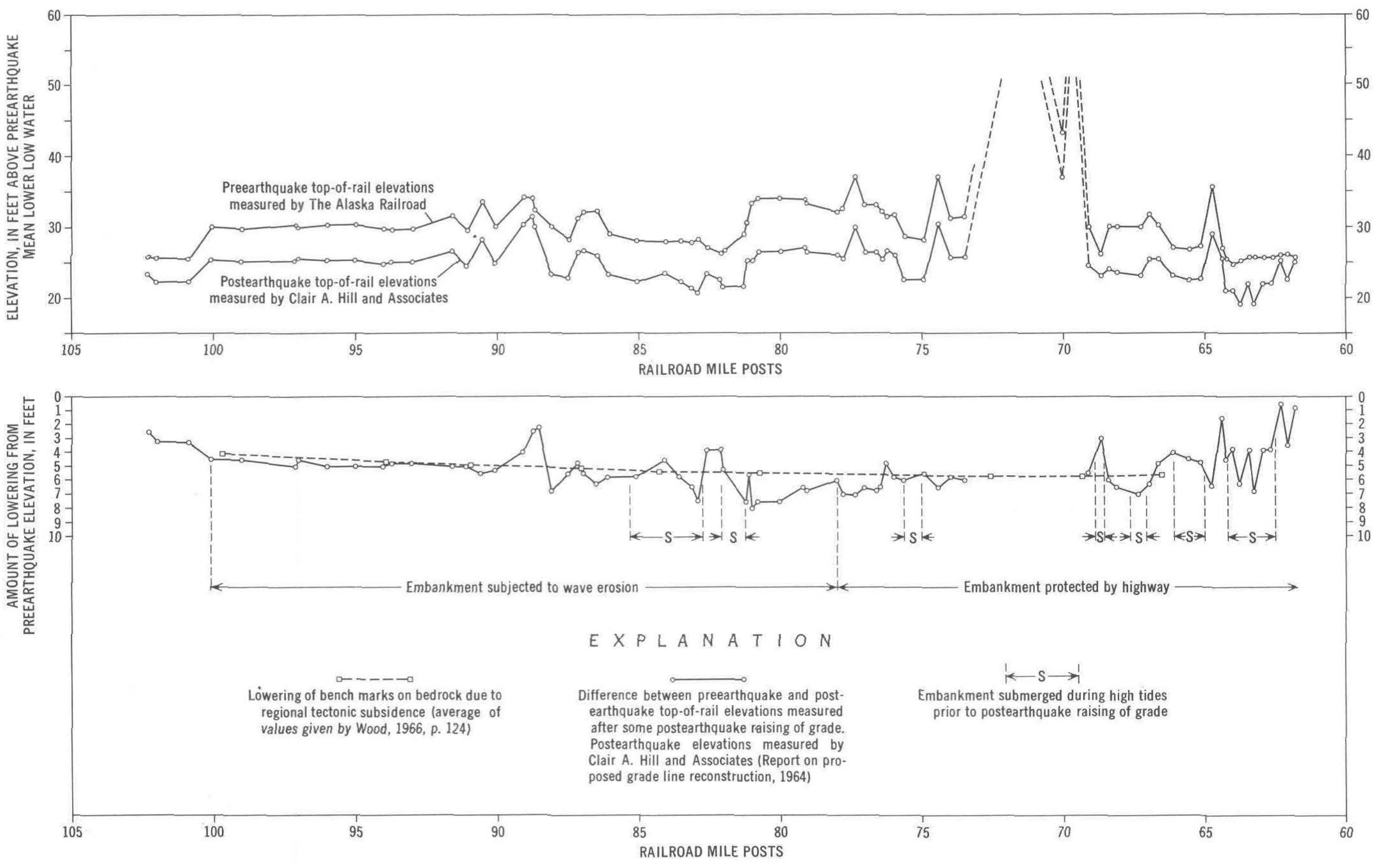
72.—The amount of lowering of bench marks on bedrock due to tectonic subsidence along Turnagain Arm, as determined by two U.S. Coast and Geodetic Survey level lines (Wood, 1966, p. 124). Single and top elevations were measured on a survey along the highway; bottom elevations east of Bird Creek were measured on a survey along the railroad.



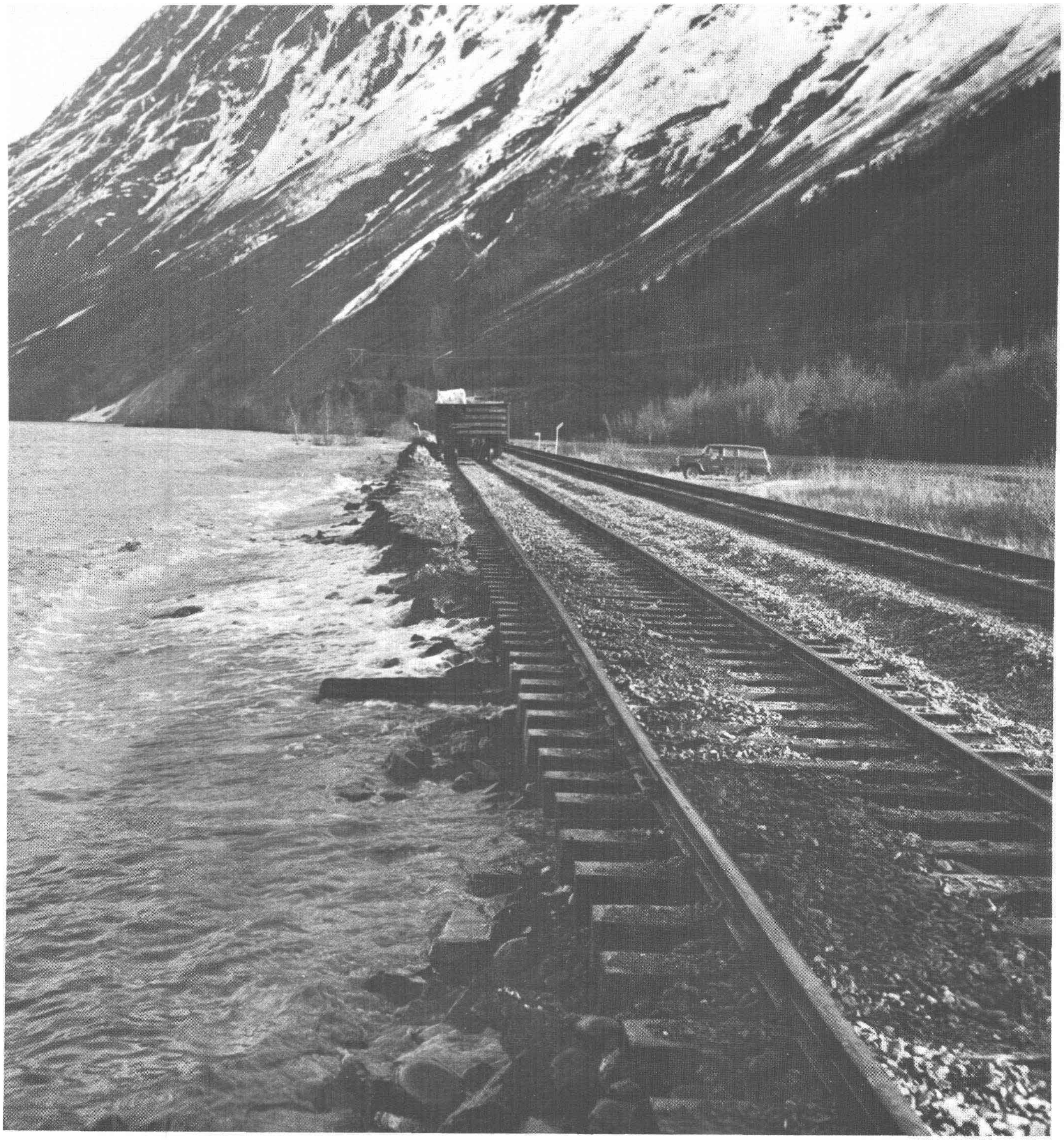
73.—Shorelines of the preearthquake mean high water and the first postearthquake peak high tides in the Portage area. The postearthquake high-tide limit is drawn from photographs by Air Photo Tech, Inc., Anchorage.

When lowered, long sections of the embankment were submerged and subjected to erosion by swift tidal currents (fig. 76). These currents accompany the large diurnal tide range of as much as 33 feet (measured at Sunrise, U.S. Coast and Geod. Survey, 1964.) Grass-covered tide flats at the waters edge that had protected parts of the embankment were rapidly eaten away by the currents. Waves driven by the notoriously high winds that blow from the northwest up the arm also attacked the rail line west of mile 78, where it was not protected by the highway embankment. Winds of 80 to 100 miles per hour have been recorded here for periods of 3 hours or more, and winds of

74.—View south over Portage after the postearthquake high tide had left ice blocks strewn over the townsite and a small house stranded on the railroad embankment (at left).



75.—A comparison of the as-built top-of-rail profile and the postearthquake top-of-rail profile from mile 62 to mile 102.5 along Turnagain Arm, and a comparison of the lowering of the rail line and bench marks on bedrock.



76.—Waves eroding the railroad embankment lowered by tectonic subsidence along Turnagain Arm. Photograph by The Alaska Railroad.

150 miles per hour have been observed for shorter periods (Clair A. Hill and Associates, "Report on proposed gradeline reconstruction" for The Alaska Railroad, Dec. 1964, 92 p.).

All along Turnagain Arm, railroad personnel waged a day-and-night battle to save the embankments from the late April high tides. They were fighting to keep the line open to Whittier from which material and provisions were brought for the repair and rebuilding in Anchorage. In all, 1,086,000 cubic yards of common fill were placed on this part of the line — some 200,000 cubic yards worked by off-track equipment, and 886,000 cubic yards hauled by train. The pressing need for fill necessitated using materials that would not have been used under normal circumstances. Just east of Bird Creek, bluffs of glacial till and outwash were mined with on-track equipment; outwash gravel west of Girdwood and talus aprons behind a small lagoon 1½ to 2 miles east of Bird Point were worked by off-track equipment. A new bedrock quarry was opened on Bird Point; it provided 865,000 cubic yards of rock to armor the embankment.

Plafker and Rubin (1967) have shown that there is clear and widespread evidence that tectonic subsidence occurred in zones that had previously been uplifted and depressed—that is, long before the 1964 earthquake. At Girdwood in Turnagain Arm (fig. 72), Karlstrom (1964, pl. 7) collected wood 2½ feet below the Girdwood datum (1953 high tide) that has a radiocarbon age of 700 ±250 years (W–175) and wood from a buried peat 15 below the Girdwood datum that has a radiocarbon age of 2,800 ±180 years (W–299). These dates suggest that this part of Turnagain Arm has been subsiding. There is, however, some evidence that sea level may have been somewhat higher with respect to the land in this area at a fairly recent time.

Linear elongate traces approximately parallel to the shoreline visible on preearthquake aerial photographs of the Portage area may be old shorelines cut during a period when sea level was relatively higher (fig. 103, p. D137). The postearthquake shoreline (fig. 73) lies along a section of this possible old shoreline at the south end of the arm, and lies inland but parallel to it east of the town of Portage. To the north, along the shore near and north of Potter Hill, old tide flats adjacent to steep wave-cut bluffs may have been elevated above high-tide level prior to the earthquake. Small stands of spruce and shrubs had established themselves on the flats (fig. 65) and water no longer reached the base of the wave-cut cliffs.

Alternatively, prograding may have caused the seaward displacement of the shorelines in both these areas. However, until the evidence is evaluated the possibility remains that sea level was recently relatively higher along this coast.

COST DISTRIBUTION OF DAMAGE

Damage to the railroad can be divided into five major categories, and the distribution of this damage, expressed as the geographic distribution of the cost, reflects the geologic control of the earthquake damage. In table 5, the cost per major category is shown for 10 geographic areas. The total cost of $22,300,880 given in table 5 is less than the full cost of the damage, which was approximately $26,784,000. The difference includes the cost of new purchases, upgrading of equipment, and temporary repairs to docks, buildings, roadbed, and track. Not considered in this total cost is the loss of property, which in Seward alone is estimated to have been approximately 8.5 million dollars, the loss of income during the rehabilitation, and the loss of future freight haulage resulting from the development of Anchorage as an all-weather shipping port (Eckel, 1967).

TABLE 5.—*Cost of damage to the railroad, by geographic distribution and category*

[Cost figures from I. P. Cook, chief engineer, memorandum of Feb. 4, 1966. Progress report of earthquake repairs to Feb. 1, 1966; and F. Weeks, accountant. Disaster recovery projects expenditures, Dec. 31, 1966]

Area	Bridges and culverts (steel and wood)	Roadbed and track (fill, armor, new rail, realinement)	Slides (removal, regrading, land purchase)	Buildings and utilities	Port facilities (piers, yards, buildings)	Cost	
						Per area	Percent of total
Seward					10,900,053	10,900,053	48.88
Seward to Portage	941,158	763,961	59,096			1,764,215	7.91
Whittier		18,755			1,202,172	1,220,927	5.47
Whittier to Portage	21,626	302,946				324,572	1.45
Portage				71,515		71,515	0.32
Portage to Anchorage	247,416	4,121,976	977,599			5,346,991	23.98
Anchorage				1,927,796		1,927,796	8.64
Anchorage to Matanuska	142,645	277,342	99,893			519,880	2.33
Matanuska to Sutton	16,166		95,400			111,566	0.5
Matanuska to Fairbanks	89,183	24,132				113,315	0.5
Total	1,458,194	5,509,1[illegible]2	1,231,988	1,999,3[illegible]1	12,102,225	22,300,830	
Percent of total	6.54	24.70	5.52	8.96	54.27		

Damage in each of the major categories can be summarized as follows:

1. Bridges and culverts:
   - (a) Steel bridges (work done on 52 bridges) — $497,892
     - Reset 72 sets of span and bearings.
     - Install new concrete piers and abutments.
     - Reestablish two girder-span bridges.
     - Repair 52 damaged piers and abutments on 15 bridges.
     - Replace one concrete pier shaft.
     - Encase broken concrete pier.
     - Raise and install new concrete foundations on two bridges (elevate deck to clear tide water and ice).
     - Install three new steel-span bridges on concrete piers and abutments to replace wood trestles.
   - (b) Wood trestles (work done on 73 bridges—617 spans, or 9,255 lineal ft) — $808,610
     - Redrive or make major repairs to 648 wood pile bents.
     - Replace stringers and decks on 273 spans (4,095 lineal ft).
     - Fill in or replace with culverts 108 spans (1,620 lineal ft).
   - (c) Culverts — $151,692
     - Install 110 culverts to replace damaged culverts or filled-in bridges, or to accommodate drainage changes associated with land-level changes.
     - An additional 65 culverts still to be repaired or replaced as of February 1966 (40 from Portage to Anchorage, 25 from Anchorage to Matanuska).

   Total, bridges and culverts — $1,458,194

2. Roadbed and track:
   - (a) Load, haul dump, and place the following fill:
     - 1,356,000 cu yd common material to restore approximately 70 miles of track to original grade line south of Anchorage, and to raise grade above tidal reach along Turnagain Arm
     - 865,000 cu yd rock riprap to armor subgrade from marine erosion along Turnagain Arm
     - 58,000 cu yd common materials and rock to restore approximately 8 miles of track to original grade line north of Anchorage and to protect grade from mile 146.5–148.5 against tidal erosion
   - (b) Place 130,000 cu yd crushed gravel ballast
   - (c) Replace bent rail and shift rail to adjust expansion joints

   Total, roadbed and track — $5,509,112

3. Landslides:

   Damage includes debris removal, engineering studies, land purchase where necessary, temporary repairs, and final repairs. In Anchorage, debris from several slides was removed. The slides crossed the tracks and damaged buildings and rolling stock.
   - Rocky Creek delta, Kenai Lake — $59,096
   - Potter Hill, mile 102–104 — $977,599
   - Mile 138–9 — $99,893
   - Sutton branch slides — $95,400

   Total, landslides — $1,231,988

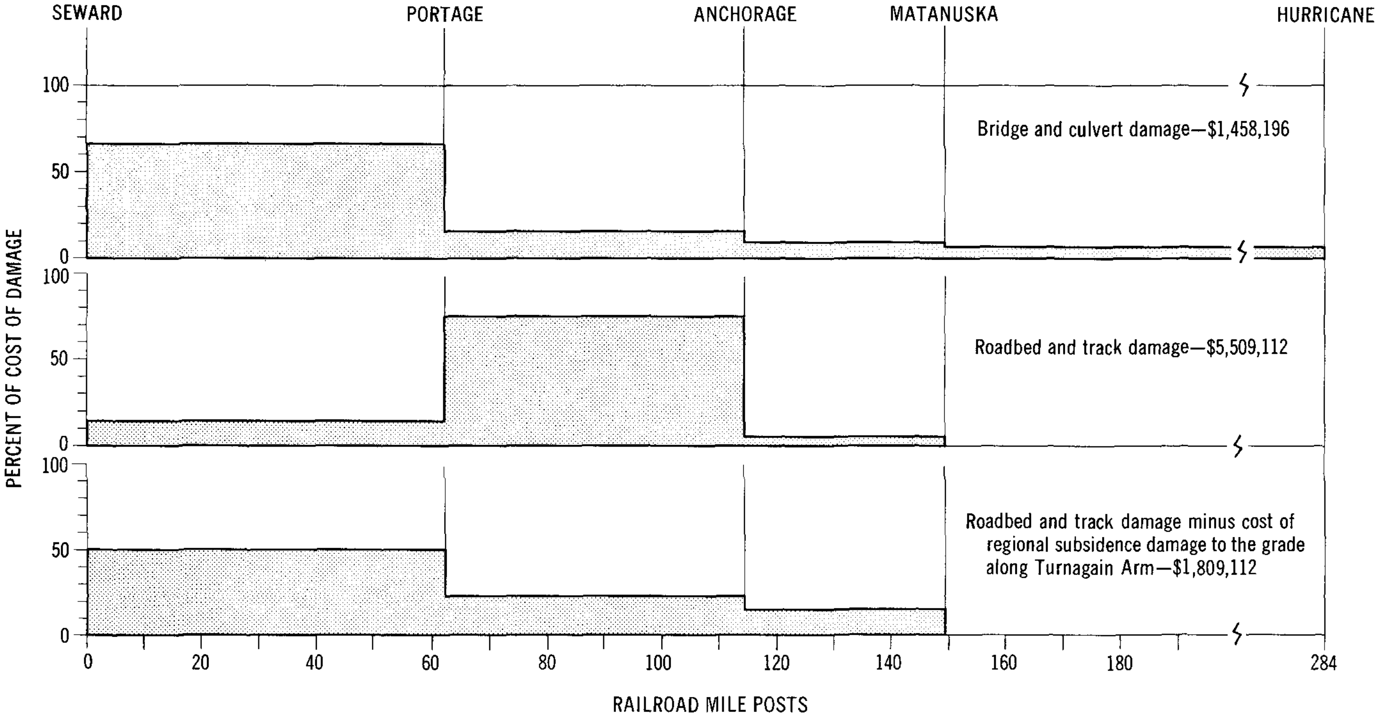
4. Buildings and Utilities:
   - (a) Anchorage (damage to these structures and utilities described in section 15, p. D143
     - Replace office annex building — $300,433
     - Replace wheel shop and mechanical offices building — $381,724
     - Replace east bay of car and coach shop — $621,624
     - Repair heavy equipment-diesel repair shop and general repair shop — $206,775
     - Repairs to various small buildings — $138,240

(b) Portage, section house and dormitory	$71, 515
(c) Utilities, repair and replace steam, water, sewer, and communications system	$279, 000
Total, buildings and utilities	$1, 999, 311
5. Port facilities (includes docks, piers, associated buildings, and rail yards):	
(a) Seward	
Land acquisition and survey	$114, 499
Dredge and build new pier	$8, 000, 000
New transit shed	$260, 000
New engine house	$304, 000
Clear fill and construct new marshaling yards	$970, 000
Underground utilities	
Total, Seward port facilities	$10, 900, 053
(b) Whittier:	
Replace car barge slip	$545, 699
Repair marginal wharf and transit shed	$399, 000
Repair depot building	
Repair composite shop building	
Repair deck and approach of De Long pier	
Repair Hodge building (Kachadorian, 1965)	
Total, Whittier port facilities	$1, 202, 172
Total, port facillities	$12, 102, 225

By far the most damage to the railroad was done on the fan deltas of Seward and Whittier, where slides, slide-generated and seismic seawaves, burning petroleum, ground cracking, and lateral displacement largely destroyed or damaged concentrated and expensive structures, rolling stock, and trackage. Although of great importance to the railroad, this damage is probably of less interest generally than the more widespread damage to bridges and culverts and to the roadbed and track, on flat or nearly flat areas, because the former is a specialized physiographic situation while the latter has applications to many areas.

In figure 77, the distribution of some of the damage is shown diagrammatically to emphasize the geologic control. Bridge and culvert damage (the uppermost graph) increased dramatically to the south, 83 percent of all such damage lying south of Anchorage. As shown in a preceding discussion and in the detailed descriptions of damage and geology later, this distribution is largely due to a combination of two circumstances: (1) South of Anchorage the rail line is built on several bedrock basins filled with young wet unconsolidated sediments, and (2) the seismic energy increased to the south.

Regional subsidence played the greatest role in controlling the cost of roadbed and track damage — 75 percent of all such damage occurred in the section along Turnagain Arm. Again, nearly all such damage (95 percent) lay south of Anchorage, and, where not caused by regional subsidence, it was due to the mobilization of foundation materials and their attendant loss of bearing strength, surface cracking, and horizontal displacements. The lowermost graph (fig. 77) is an attempt to show the distribution of roadbed and track damage due solely to mobilization of foundation materials by eliminating that part of the cost resulting from regional subsidence of the roadbed along Turnagain Arm. In this graph the cost of armoring the grade with rock riprap and three-quarters of the cost of raising this 35-mile section of roadbed between 3 and 5 feet (total $3,700,000) have been removed. One-quarter of the cost of raising the grade has been maintained to allow for local settling. With this estimated adjustment, the distribution of roadbed and track damage resembles that of bridges and culverts, and reflects the geologic control and the distribution of the seismic energy.



77.—Geographic distribution of the cost of the damage to bridges and culverts (top graph) and to roadbed and track (middle graph), Bridge and culvert damage increased to the south, toward the area of maximum strain release, but the cost of roadbed and track damage was greatest in the area of subsidence along Turnagain Arm. Eliminating costs due to regional subsidence (lower graph) shows that the roadbed and track damage also increased to the south, toward the area of maximum strain release.

SUMMARY AND CONCLUSIONS

THE EARTHQUAKE

The great 1964 Alaska earthquake consisted of a series of large discrete bursts of seismic energy released over a period of about 70 seconds. These were produced when a large part of the earth's crust beneath Prince William Sound and the adjacent land tore loose from the underlying mantle and was thrust southward up a gently dipping rupture surface. Epicenters of the discrete seismic events lie in a linear zone approximately 150 miles long that runs southwest from the first epicenter 80 miles east of Anchorage to about 40 miles southeast of Seward. This zone is subparallel to the rail line for about 150 miles. As a result, this portion of The Alaska Railroad was subjected to a long period of severe ground motion. Timed strong ground motion lasted 3 to 4 minutes from Anchorage to Seward. This long duration of strong motion is three to four times that reported in other large earthquakes and was responsible for much of the damage that resulted from changes in natural foundation materials—changes that are time dependent and cumulative.

DAMAGE COST

The total cost of the damage to The Alaska Railroad including the loss of preearthquake facilities was in excess of $30,000,000. The total cost of rebuilding and repair, and some minor upgrading of equipment, was $26,784,000. The cost was distributed among five major categories as follows: rebuilding port facilities at Seward and Whittier (54 percent), roadbed and track damage (25 percent), rebuilding and repair of buildings and utilities (9 percent), repair and replacement of bridges and culverts (7 percent), and landslide removal and repair (5 percent).

KINDS OF DAMAGE

The destructive agents that caused this damage took many forms. Landslides were dislodged from the edges of deltas on which the deepwater ports of Seward and Whittier are built. Portions of the railroad port facilities were carried away by the slides and most of the remaining facilities were overrun by extremely destructive seismic sea waves and waves generated by the slides. Landsliding also carried away a short section of track on Kenai Lake, and landslides overran and destroyed several miles of roadbed or damaged buildings and rolling stock at seven other localities. Regional tectonic subsidence of as much as 5½ feet made it necessary to raise and armor approximately 22 miles of roadbed that was made susceptible to marine erosion along Turnagain Arm. Most of the remaining damage — the damage to which this study is addressed — resulted from a general loss of strength in wet water-laid noncohesive granular sediments that allowed embankments to settle and enable the sediments to undergo flowlike displacements in a downslope direction, or more commonly toward topographic depressions, even on relatively flat surfaces. The term "landspreading" is proposed for these lateral displacements. Landspreading may have been due largely to liquefaction of the sediments. Failures produced by landspreading were extensive, sometimes affecting areas of several tens of square miles.

LANDSPREADING AND BRIDGE DAMAGE

The amount and direction of sediment displacement that occurred as a result of landspreading are clearly shown by the pattern of damage to the rail line, track, embankment, and bridges; by the damage to highway embankments, bridges, and utility pole lines; and by the patterns of associated ground cracks. Mobilization of the sediments appears to have been initiated at the edges of streams and other topographic depressions. As shaking continued, the width of the mobilized area increased; in some places it extended several hundreds, or as much as a thousand, feet away from the streambanks. The mobilized sediments moved streamward and produced zones of surface extension beside the streambanks in which railroad rails at right angles to the streams were pulled apart, railroad and highway embankments were broken by tension fractures on which there was horizontal separation, and telephone lines and powerlines were pulled taut. Bridge piles were carried toward the centers of the stream channels; although all piles were displaced streamward, the fact that distances between those near the bridge ends were usually increased suggests that the extension flow observed adjacent to the streambanks continued beneath the edges of the stream channels. In stream centers, the distances between piles were generally decreased, showing that the sediments had undergone compression. Piles and piers of railroad bridges were displaced with little or no vertical rotation — which indicates that flowage occurred to depths in excess of the pile depths. Displaced piles averaged less than 35 feet deep, but sediment displacements affected some piles driven as deeply as 125 feet. Streamward movement of the sediments was usually accompanied by some upward component of movement of the sediments under the stream channels that carried the central piles upward relative to piles near the ends. As a result, many bridges were arched upward in the center. The vertical displacements were independent of the length of pile penetration, which indicates that arching was due to flowage of the sediments rather than to differential compaction.

Bridge superstructures were subjected to compressive forces when streamward flow of the sediments decreased stream widths — by as much as 6½ feet. Compression was released as stringers drove into bulkheads and bulldozed up approach fills, or in more extreme cases, drove either entirely through or over the bulkheads into, or onto, the approach fills. Some deck stringers were buckled laterally and broken. Compression probably made little or no contribution to the upward displacement of piles or arching of the superstructure at stream centers because: (1) the connections between the superstructures and piles were commonly broken by lateral displacement of the piles, (2) even if the connections were not broken they were considerably weaker than the upward pull needed to overcome the skin friction of the outward-battered piles, and (3) arching due solely to pile displacement occurred in bridges in which there was no evidence for compression of the superstructure.

Movement of the unconsolidated sediments in flat-lying areas was directly toward the adjacent stream channel or topographic depression, as shown by the horizontal displacement of railroad and highway embankments and utility pole lines. As a result, bridges that crossed streams or even small gullies at an oblique angle were skewed horizontally as embankments on opposite sides of the stream were offset. The largest measured horizontal offset across a stream was 10 feet.

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MODEL OF SEDIMENT DISPLACEMENTS

Sandbox models of a stream channel were made to examine the pattern of sediment displacement that occurs beneath stream channels during shaking. The sand used was rounded, well-sorted quartz of medium grain size (average diameter approximately 0.35 mm). Single and multiple horizontal layers and a vertical grid of 100-mesh carborundum powder were placed in the sand. The sand was saturated and compacted. Then water was withdrawn to the depth to which a flat-bottomed channel was cut. Water was again added until it covered the channel bottom, and the edges of the model were raised a few inches and dropped onto a table until visible surface deformation occurred. The model was drained and sectioned vertically, perpendicular to the channel, and the pre- and postshake positions of the horizontal layers and vertical grid were compared. During shaking the channel banks were lowered, and bank-to-bank distances decreased. Sediments moved toward the channel centers and produced zones of extension beside and under the edges of the channel, and sediments in the channel centers were compressed. Sediments also moved upward from considerable depth beneath the channels and raised channel floors to above the preshake positions. The displacements of sediments observed in the models are similar to those observed or inferred from field observations.

GROUND CRACKS CAUSED BY LANDSPREADING AND EMBANKMENTS

The large size of areas affected by landspreading was indicated by the ground cracks that occurred in patterns consistent with the orientation of probable stress fields that would be formed in the ground surface by movement of the underlying sediments toward streams or other topographic depressions. Cracks approximately parallel to streambanks resulted from nearly unidirectional stress on straight or concave streambanks. Cracks intersecting at 45° to 70°, and probably representing failure by shear, formed on convex banks where principal stress directions were parallel and perpendicular to the streambank. Cracks on small islands or on the insides of meander bends, where spreading was nearly radial and stress nearly omnidirectional, became orthogonal (rectilinear or curvilinear cracks with right-angle intersections). Ground cracks with these three patterns commonly occurred for widths of as much as several hundred feet, and in some places as much as 1,000 feet back from the edges of rivers and streams.

In areas of ground cracking attributed to landspreading on deltas, fans, and flood plains, ground cracks commonly radiated outward from the external corners of houses. These cracks also suggest that tension was generated in the ground surface, for stresses should be concentrated at the external corners of holes in sediments that are subjected to tension.

Lurching and shallow block-glide landsliding at or above stream bottoms, both commonly described in earthquakes, do not appear to have been important contributors to movement of sediment or to production of cracks at stream margins. If lurching or block-gliding had been important, the surface materials would have moved farther toward streams than the underlying materials. The generally close agreement between the amount of longitudinal compression of the bridge superstructures and the net horizontal compression of the underlying piles shows that the surface sediments were carried passively toward the streams, rather than undergoing independent movement.

A second principal type of ground cracking that affected the railroad was that generated where embankments settled into the underlying sediments. The cracks formed within embankment toes and in an adjacent zone several tens of feet wide on flood plains, tidal flats, deltas, and alluvial fans. Sediment-laden ground water was commonly ejected from the cracks. The cause of this cracking is not clear. It probably was not caused by horizontal block-gliding of the embankments, for the inertial force developed by embankments during horizontal acceleration is considerably smaller than the static, and far less than the dynamic tensile strength of the adjacent frozen sediments. It is suggested that the cracks formed as the result of stresses generated as the sinking embankments depressed the immediately adjacent frozen surface, while at some distance the surface was bulged upward by sediments displaced from beneath the embankments.

TRANSIENT HORIZONTAL COMPRESSION OF BRIDGES

Many bridges over a wide area were subjected to transient horizontal compression that pounded superstructures repeatedly against bulkheads and abutments. The transient compression appears to have started early in the shaking and to have persisted throughout the period of lateral displacement of the foundation materials. The force of the transient horizontal compression varied considerably, from bridges in which there was evidence of only minor pounding to a 105-foot wooden bridge, the deck of which was repeatedly arched from, and dropped back onto, its piles. The repetitive arching was recorded by multiple drift-pin holes punched into the pile tops. A minimum estimate of the compressive force on this bridge (treating the deformation as static, rather than dynamic) ranges from about 255,000 to 200,000 pounds for initial arches of 1 to 40 inches; the force delivered to the bulkhead by the embankment ranges from about 23 to 18 pounds per square inch for this same range of initial arching. The rate at which pounding occurred probably varied considerably. At one bridge a series of dents made by a falling pebble that was repeatedly caught between pounding bridge members indicates that the transient compression had a rate of between 2 and 7 cycles per second.

HORIZONTAL BRIDGE ACCELERATIONS

Evidence for high horizontal accelerations in bridges is made ambiguous by similar damage that resulted from compression produced by streamward movement of foundation materials. However, at one wooden bridge where the stringers appear to have been driven rapidly through the bulkhead timbers, the force needed to overcome the static resistance to penetration of the bulkhead timbers is approximately an order of magnitude larger than the force needed to produce Coulomb failure of the fill behind the bulkhead. It is suggested, therefore, that penetration may have been rapid and that resistance was offered principally by the inertia, rather than by the shearing strength, of the fill. The minimum horizontal acceleration of the bridge deck needed to produce rapid penetration (using the dynamic strength of the bulkhead timbers and the superstructure deadweight) would have been between about 1.1 to 1.7 *g*. It is suggested that the high acceleration is the result of amplification of ground motion by the bridge structure.

EMBANKMENT DAMAGE

Embankments suffered four general types of damage. Approximately half the cost of all embankment damage resulted from the necessity of raising and armoring about 22 miles of embankment along Turnagain Arm where regional tectonic subsidence of about 4 to 5½ feet, consolidation of tidal sediments beneath the rail line, and sinking of the embankment into the underlying sediments exposed the embankment to erosion by waves and swift tidal currents.

Second most important kind of embankment damage were those failures (called active failures) in which the weight of the embankment and the shaking produced a loss of bearing strength, flowage, and high pore-water pressures within the underlying and adjacent sediments into which the embankment fills sank nearly en masse. Sinking of several feet was common and at many places was accompanied by the expulsion of sediment-laden water from embankment-generated ground cracks. Local extreme settlement occurred where ejected sediment volumes were large. Settlements (and the associated embankment-generated ground cracks) were largest and most extensive in areas where there was evidence of landspreading. However, the fact that settlement and the associated cracking also occurred in areas where there was no such evidence suggests that the fill produced the mobilization of the underlying materials. Settlement was nearly universal in areas underlain by wet unconsolidated young waterlaid noncohesive sediments on flood plains, deltas, tide flats, and alluvial fans.

Landspreading was the third greatest cause of damage. This damage (called passive failure) included lateral and longitudinal displacement and cracking of the embankment as the underlying sediments moved toward lakes, gullies, abandoned river channels, borrow pits, streams, and marine shorelines. Sections of embankments more than 1,000 feet long were displaced as much as several feet horizontally, and, as noted previously, embankments that crossed streams obliquely were offset on opposite sides of the streams. Radial downhill spreading on deltas and alluvial fans produced passive failures that carried the rail line downslope several feet and subjected it to tension which broke the embankment and pulled rails apart endways.

Of least importance were failures entirely within the embankment fills (called fill failures). The infrequency of this type of failure may have been largely due to the presence of interstitial ice in the frozen embankments that afforded additional shear strength to the fill materials.

BRIDGE DAMAGE AS RELATED TO GRAIN SIZE AND THICKNESS OF SEDIMENTS

The severity of damage to many similar bridges was compared with the grain size of the material in which the piles were embedded and the total thickness of the unconsolidated sediments at each bridge site. Foundations of bridges on till or bedrock were not displaced. Bridges on young unconsolidated wet water-laid noncohesive sediments suffered increasing damage as the grain size of the embankment material decreased. However, a stronger correlation was found between the severity of the damage and the total thickness of the underlying unconsolidated sediments. It is suggested that the difference in the propensity for mobilization, probably controlled by the grain size of the pile-embedment material, was less important in controlling the amount of damage than the severity and duration of ground motion which are related to the total sediment thickness.

Limited standard penetrometer data for two areas show that away from the area of maximum seismic strain energy release (that is, the belt generally defined by the epicenters of the multiple seismic events that occurred during the earthquake) foundation displacements occurred in sediments classified as slightly compact to compact, whereas closer to the area of maximum strain release more severe displacements occurred even in denser sediments classified as compact to dense.

GEOLOGIC CONTROLS OF DAMAGE

The geographic distribution of the severity of the ground response and the degree of mobilization that occurred in geologic materials beneath many miles of the railroad line are grossly reflected by the geographic distribution of the cost of repairs to the roadbed and track and the bridges and culverts. If expenditures arising from regional tectonic subsidence are omitted (raising and armoring the grade along Turnagain Arm), the costs of both of these types of damage increase dramatically to the south, that is, toward the area of maximum strain release.

When the distribution of these and other kinds of damage (especially those caused by landspreading) is considered in more detail (as it is on p. D98–D158), it is apparent that the local geology and physiography strongly controlled the kind, the distribution, and the severity of the damage. This point merits considerable emphasis, for it provides a basis for predicting the kinds and severity of damage and ground response that should be expected in these and similar areas in large earthquakes. Surficial geologic-physiographic maps made for most of the rail belt along which there was damage show that only a few easily distinguishable geologic-physiographic units need be mapped to isolate areas of damage. These units and the related damage sustained are as follows:

1. Bedrock and glacial till on bedrock.— Embankments and open wooden trestle bridges on wood piles were undamaged. Steel superstructures on bridges were either unmoved or slightly shifted (often with a rocking motion) on piers and abutments. There were no permanent displacements of piers, piles, or abutments, no ground cracking, and no evidence of landspreading. Limited observations of damage to buildings and the shifting of steel bridge superstructures suggest that ground motion was relatively strong, especially toward the area of maximum strain release.
2. Glacial outwash terraces. — There was little or no damage to the railroad on glacial outwash terraces which were undissected, were well drained, and had a water table well below the surface, or which consisted of relatively thin deposits lying on till or bedrock. Embankment settlement, ground cracking, and landspreading — especially along terrace margins that abut lower modern flood plains—increased as the height of the outwash terrace surface decreased to that of the flood plain and as the water table approached the surface. These relationships are clearly shown by the fact that there was less severe damage on glacial outwash terraces close to the area of maximum strain release than on glacial outwash terraces considerably farther away (Knik and Matanuska River valleys, 40 miles northeast of Anchorage), where there was a relatively thick section of unconsolidated sediments (probably well in excess of 200 ft), a shallow water table (about a 10-ft maximum depth), and considerable dissection by stream channels.
3. Inactive flood plains.— Landspreading and its associated ground cracking, and lateral displacement, settlement, and embankment-generated ground cracks were severe on inactive flood plains that lay adjacent to

lower active flood plains or other topographically lower areas. Farther from topographically low areas landspreading largely disappeared, but almost universally there was settlement of embankments accompanied by embankment-generated ground cracks and the expulsion of ground water. Landspreading also decreased as the depth to underlying bedrock or till decreased.

4. Active flood plains.—As the rail line passed from areas underlain by till or bedrock onto adjacent valley floors, the active flood-plain sediments, being closest to the modern stream channels and generally lying at or within a few feet of the ground-water table, were the first to show evidence of a general loss of strength and flowage by landspreading. Thus all the associated damage caused by ground cracking, lateral displacement, settlement, and the ejection of ground water was most extreme in these areas. Even within these most unstable sediments, there is an obvious increase in the damage with increasing depth to till or bedrock.
5. Fan deltas.— Damage on alluvial fans was similar to that on deltas in many respects, the major difference being that landslides commonly occurred at delta margins. These two units are mapped together because tidewater or lakes commonly lie close to mountains along the rail belt, and the distal parts of many alluvial fans are deltaic where deposited in water. Mobilized sediments spread radially downslope on fans and deltas. Railroad embankments were carried as much as 4 feet downslope and were broken by tension fractures; rails were pulled apart endways and the wires on utility poles were pulled taut. Spreading extended to some depth and increased distances between piling driven as deeply as 30 feet under railroad bridges that were pulled apart longitudinally. Radial downhill spreading also produced a fringe of ground cracks at fan and delta margins. Cracks were orthogonal (common on low-slope deltas where spreading was omnidirectional) or shear fractures intersecting at about 45° to 70° (on fans and steeper deltas where principal stresses were oriented downslope and parallel to the fan or delta margin). Cracking of the fringe of fans and deltas appears to be related to the depth to the ground-water table. For example, ground water was commonly ejected only from cracks at the downslope edge of the cracked fringe. The fact that cracking extended only a short distance upslope from the cracks that expelled ground water suggests that when the water table exceeds some critical depth below the surface, the sediments do not undergo sufficient mobilization and landspreading to generate cracking surface stress. However, upslope of the cracked fringe, railroad embankments did produce mobilization, usually underwent settlement, and usually generated cracks from which additional sediment-laden water was ejected. Additional ground cracks that expelled ground water were formed on flood plains, just beyond the toes of the fans. These cracks were irregular but generally were parallel to radii of the fan.

PRINCIPAL GEOLOGIC CONTROLS OF DAMAGE

The foregoing observations can be generalized by defining six principal geologic controls on the damage produced primarily by the mobilization of natural materials. Arranged in decreasing order of apparent importance these are:

1. The difference in foundation materials.— In areas of exposed till and bedrock, there was no damage, and in areas of young unconsolidated water-laid noncohesive sediments, all mobilization damage occurred.
2. The total thickness of the sediments.— Other things being equal, damage increased dramatically with sediment thickness. For example, damage to railroad bridges was slight on sediments less than 50 feet thick, moderate on sediments 50 to 100 feet thick, and severe where sediments were more than 100 feet thick.
3. The depth of the ground-water table beneath the surface.— In the most severely damaged areas the water table probably was about 10 feet or less beneath the surface.
4. The distance to a topographically lower area.— The amount of lateral spreading increased toward stream channels, gullies, borrow pits, or adjacent lower terraces.
5. The slope of the ground surface. — Steeper slopes, such as those on deltas and fans have a greater propensity for spreading.
6. The proximity to the area of maximum strain release.— The closer to the source of the seismic energy, the stronger was the ground motion.

CONSTRUCTION IN AREAS OF POTENTIAL LANDSPREADING

There was a general pattern to the deformation of a wide textural range of granular sediments during the earthquake. Thus some general recommendations may be made concerning construction in areas underlain by granular sediments where safety demands, and economics permit, the building of structures that are to survive a large earthquake with minimal damage. It would be ideal to avoid problem sites for schools and hospitals, for pumping, generating, fire, and radio stations, and for all other structures that involve public safety or public investment. Unfortunately this option is not always available, and thus the following recommendations are offered to reduce damage in these areas:

1. Structures that cannot withstand distention or cracking of their foundations (or foundation materials) should be built where landspreading is least likely to occur — well away from topographically low areas, where the water table is well below the surface and where the unconsolidated sediments are thinnest, or where depth to bedrock is least.
2. Landspreading may be reduced by the elimination of surface depressions; however, this may not eliminate landspreading because some occurred toward filled channels. Conversely, artificial waterways or other artificial depressions may increase landspreading.
3. The practice of side-borrowing to build embankments promoted lateral displacement and should be avoided.
4. Narrow linear fills (railroad and highway), although well compacted, should be expected to settle and form ground cracks for a width of several tens of feet on either side of the embankment, both within and outside of the area of landspreading.
5. Narrow railroad fills settled largely en masse. In wider highway fills, the outward flow of sediments was greater from under the edges than the center, with the result that the edges of the highway fills were lowered in relation to the middle, and tension failures occurred down the embankment centerlines. Thus, in a given area subjected to a given earthquake, there is some finite width of embankment or fill from under which the underlying materials have time to flow. Accordingly structures that are placed on wider fills and kept well back from the edges of the fills, will stand less chance of being damaged by this sort of failure. However, even wider fills will be subject to ground cracking in areas of landspreading and to lowering by the compaction of the underlying materials.
6. The width of the zone of embankment-generated ground cracks (commonly several tens of feet wide on either side of the embankments) is more than doubled beside adjacent parallel fills. Thus, if such fills were combined into a single fill, the width of the cracked zone (and the width of sediments mobilized by the fills) probably would be substantially reduced.
7. Utilities buried within or adjacent to linear fills will probably be subjected to tension and compression resulting from differential settlement of the fills or to shear in the zone of embankment-generated ground cracking. In such areas, damage may be substantially reduced by decoupling utilities from the ground.
8. Because ground cracks commonly radiate away from the corners of buildings in areas where there is landspreading, damage to buried utilities, paved walks, and driveways may be reduced if they are not placed close to building corners.
9. Given the option, the toes of alluvial fans and deltas, which were severely fractured, and on which radial downhill spreading was marked, might be avoided. If such areas must be crossed, the older, higher, better drained upper segments of fans and deltas will probably be more stable.
10. Adjacent to topographic lows and the lower parts of fans and deltas where landspreading might occur, damage to pipelines and similar structures might be minimized if the structures are built on the surface and if some provision such as the use of expansion loops is made to accommodate longitudinal tension.
11. Similar provisions in structures at the edges of stream channels (or other topographically low areas) would accommodate both the compression that develops as streambanks moved closer together and the horizontal skewing that usually accompanies compression.

12. Culverts beneath embankment fills were subjected to crushing loads where landspreading displaced foundation materials toward streams and even shallow drainage ditches. Such loads might be anticipated in culvert design.
13. Bridge construction. Although the following recommendations are based on observations of damage to Alaskan bridges, some of these construction details have already been incorporated in the design of existing bridges in Japan and the United States (Eng. News-Record, 1945; Japan Soc. Civil Engineers, 1960, p. 95-104).

(a) Single spans supported only on the ends would avoid arching due to the differential vertical displacement of foundation materials that drives piling upward under the centers of bridges.

(b) Longitudinal compression (commonly 20 inches but as much as 6½ feet) of superstructures could be accommodated by wide abutment-bearing surfaces that support telescoping end sections and by bridge bearings that will allow considerable end travel.

(c) If several spans are used and the spans are simply butted at the piers or bents and have no through-going structural member, spans could be kept from falling by safety connections that join the spans together. The Alaska Railroad has installed such safety links on some of its bridges since the earthquake.

(d) Many highway bridges built with multiple concrete deck sections that butted on wood pile bents were destroyed when deck sections lost their end bearings and fell, sometimes becoming impaled on piles driven through the concrete decks. By contrast, almost every adjacent wooden railroad bridge, all of which have continuous superstructures and more closely spaced piles to carry heavier transient loads, could, and in some places did, carry auto traffic after the earthquake—despite the fact that the piling in these bridges had undergone considerable longitudinal displacement. The addition of through-going structural members to the superstructure, and an increased number of more heavily braced bents that would maintain their integrity and therefore their support of the superstructure, would probably have permitted use of many highway bridges after the earthquake.

(e) Provision for longitudinal movement of the tops of piers and piles beneath superstructures should prevent their being tilted as their bases are displaced by streamward movement of the foundation materials. Concrete piers held stationary at their tops were commonly rotated inward at the base and broken at the ground line; many wood pile bents were torn loose from their pile caps and thus escaped rotation and breaking.

(f) Lateral skewing of bridges, which was common and as large as 10 feet, could be avoided or reduced by crossing water courses or other topographically low areas parallel to the direction in which streambank sediments are likely to move. This direction is generally at right angles to the stream course.

(g) Concrete piers were broken along joints between successive pours. Careful attention should be given to such joints during construction.

DISTRIBUTION OF DAMAGE AND ITS RELATION TO SURFICIAL GEOLOGY AND PHYSIOGRAPHY

There is a direct relation between (1) the type and severity of the damage to the railroad and (2) the underlying physiography and the materials of which the landforms are composed. This relationship is so marked that a geologic map can be used as a damage-distribution map. To demonstrate this connection, the following description of damage to the rail line and some adjacent areas is divided from south to north into 19 sections. Those between Seward and Portage are characterized by a specific geologic-physiographic environment. North of Portage some of the sections are geographic units, in which there is some variation in the geology and physiography but in which the damage, or lack of damage, is similar in kind and severity.

The description has other important applications. Damage to manmade structures often provides the only quantitative or even qualitative measure of ground motion or behavior of the sediments that occurred within specific areas during an earthquake. Such observations become extremely important in planning the development of these, or similar, areas. For example, systematic descriptions of damage from the 1906 earthquake to manmade structures, roads, and railroads on uninhabited land surrounding San Francisco Bay would now be invaluable in this rapidly developing area. The lack of such observations has led to considerable uncertainty and controversy as to how these materials will behave during another large earthquake.

Further, the record given here is in sufficient detail that (1) a comparison can be made with effects of future large earthquakes in the region, and (2) the influence of differences in focal distance, direction, duration, and pattern of energy release can be evaluated.

These descriptions also document the damage to bridges, embankments, and buildings, and the behavior of foundation materials; they therefore constitute evidence for some of the conclusions drawn in earlier parts of this report. In addition, they provide a discussion of the surficial geology and physiography, and in doing so they form a series of site studies.

The surficial geology at Seward, Whittier, Portage Pass, the Anchorage area, and the Matanuska Valley has been mapped (Lemke, 1967; Barnes, 1943; Kachadoorian, 1965; Miller and Dobrovolny, 1959; Trainer, 1953, 1960, 1961). The balance of the geology from Seward to Portage was interpreted from aerial photographs and limited field observations.

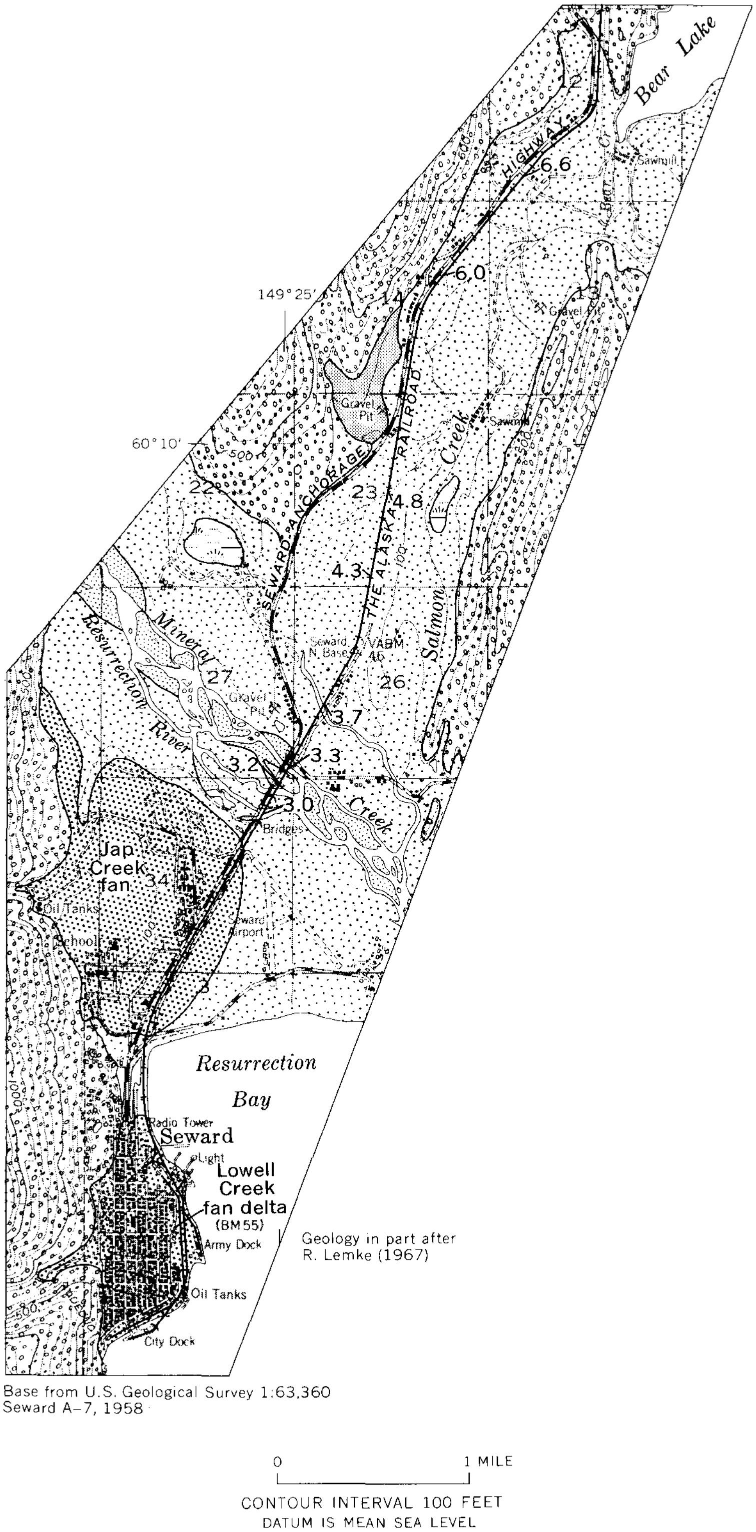
For this study, the following geologic-physiographic units were mapped (see fig. 78):

1. Till on bedrock—On steep valley walls, till is usually thin or absent. On more gentle slopes till is often thicker, and in some places the entire bedrock surface is covered. Hachured lines through these areas define old ice-front positions, as shown on steep valley walls by ice-marginal drainage channels, discontinuous fragments of lateral moraines, the upper limit of ice-carved bedrock, and accumulations of talus. On gentle valley walls and valley floors, hachured lines often define well-developed morainal ridges (see fig. 101).
2. Glacial outwash terraces.—Flat-surfaced outwash terraces composed of horizontally bedded sand and gravel often lie above inactive flood-plain surfaces. They are found downstream from old moraines or modern glaciers.
3. Inactive flood plains.—Flood plains not inundated by normal high stream discharges are composed of horizontally bedded sediments containing some fine gravel, but predominantly of sand size. Sediments are generally coarser toward headwaters and finer downstream. Where streams enter standing water, the bedding is deltaic.
4. Active flood plains.—Composition and bedding are like those of inactive flood plains. They usually are entrenched within the inactive flood plain and are subject to flooding during periods of high discharge.
5. Fan deltas. — Alluvial fans, some of which become deltaic where deposited in standing water, are composed of bedded granular noncohesive materials throughout the area of subaerial deposition. Clasts are as large as cobble and boulder size. Deltaic parts are likely to contain generally finer materials, and in some places drilling has revealed beds of silt-sized sediments.

SECTION 1. SEWARD FAN DELTA

At Seward (fig. 78), the southern terminus of the rail line was at docking facilities and a switching and storage yard on the south side of the Lowell Creek fan delta. The rail line then passed north along the shoreline, being built largely on artificial fill placed along the east side of the fan delta. The fan delta is known from borings and seismic profiles (Lemke, 1967) to be composed of glacial drift (till and outwash) on bedrock covered by about 100 feet of fine gravel that intertongues with marine silt along the shoreline. Ground failures and damage to the city and rail facilities, previously described by Grantz and others (1964), Lemke (1967) and Chance (1966), is summarized below.

Landsliding started about 30 seconds after the shaking and took place as a series of slides that removed all the artificial fill beneath the rail line and some of the adjacent natural deltaic sediments from the eastern edge of the delta. These slides carried away most of the port facilities and some railroad line. At about the same time, sliding on the south edge of the delta carried away part of the two large railroad warehouses. During ground shaking, cracks developed, pro-



EXPLANATION

Active flood plain
Horizontally bedded sand and gravel with sand predominating. Surface subject to flooding at high discharges. Usually lies entrenched within inactive flood plain. Water table at or near surface. Usually free of vegetation

Inactive flood plain
Horizontally bedded sand and gravel with sand predominating. Not inundated by normal high discharges. Usually lies a few feet above active flood plain. Water table probably 2 to 10 feet below surface. Commonly supports growth of shrubs and trees

Fan delta
Alluvial fans and fans that become deltas where deposited in standing water. Clasts in alluvial fans are as large as boulder size if stream gradient is steep. Deltaic portions likely to contain finer sediments

Glacial outwash terraces
Generally flat terraces, often above inactive flood plain. Horizontally bedded sand and gravel. Grain size commonly coarser than in inactive-flood-plain terrace

Glacial till on bedrock
Till thin or absent on steep valley walls, thicker on gentle slopes and on valley floors.

Swamp

Contact

3.0
Bridge number
Indicated by railroad mileage north of Seward

78.—Surficial geologic-physiographic map of the rail belt from Seward to Woodrow. Geology in Seward area modified after Lemke (1967, pl. 1).

gressively inland from the delta margin. The ground motion was sufficiently violent to tip railroad cars off the tracks and literally bounce a large railroad gantry crane off the tracks into the water. Landsliding generated local waves that inundated the edge of the delta and carried ashore burning oil from storage tanks which had ruptured and exploded early in the shaking. The burning fuel ignited some railroad tank cars, but these waves were not as destructive as the seismic sea waves that arrived about half an hour later. The seismic sea waves, sweeping in over the delta, carried away the railroad docks and piled rolling stock in a gigantic swash mark along the edge of the town. Other seismic sea waves that arrived throughout the night compounded the damage.

North from the delta on which Seward is built, the rail line crossed a small embayment on an earth-fill causeway to the mainland. Several gaps, the largest 150 feet long, were torn through the causeway by the seismic sea waves, across which tracks were left swinging unsupported.

SECTION 2. JAP CREEK FAN

The composition of Jap Creek fan (fig. 78) and its surface cracking have been described by Lemke (1967). Cracking was restricted to the outer margin of the fan and was especially severe along the north edge (Forest Hills area). The fan is composed of bedded sand and gravel, coarser toward the head and finer toward the toe. In the severely fractured area, lenses or beds of sand 1 to 5 feet thick intertongue with poorly sorted sand and gravel. Occasional silt lenses as much as 2 feet thick are intercalated with the sand. The fan deposits are uncompacted and uncemented, and slump on exposed faces. The depth to bedrock beneath the outer edge of the fan is not known, but it is estimated that it may be several hundred to more than 1,000 feet beneath the surface. Seismic profiles and borings immediately to the south suggest that there may be a substantial thickness of compact glacial sediments beneath the fan deposits (Lemke, pl. 2, 1967).

The rail line leaves the causeway at the head of Resurrection Bay and runs in a wide curve for a distance of 1,100 feet where it is joined by the highway. The rail line and highway fills run parallel for a distance of 1.1 miles across the toe of the fan; their centerlines about 75 feet apart. Cracking along the rail line first appeared where the two fills are juxtaposed. The cracks were minor; some crossed the highway at nearly right angles and broke the pavement, but most paralleled the highway and railroad fills in the toe of the fills or in the adjacent alluvial fan.

The fracture pattern on the fan was typical of those found on fans and deltas, where sediments beneath the surface spread radially downslope (figs. 46, 48). Fractures intersected at angles between 40° and 70°, forming fracture-bounded blocks with elongate axes subparallel to the slope. The railroad and highway fills and two other highway fills farther upslope on the highly fractured part of the fan (Diamond Boulevard and Ash Street, Lemke, fig. 15, 1967) superimposed typical embankment - generated fractures (approximately parallel to the embankments) across the normal fracture pattern of the fan.

SECTION 3. RESURRECTION AND SALMON RIVERS FLOOD PLAINS

Leaving Jap Creek fan, the rail line crosses the flood plains of Resurrection River and its northern channel, Mineral Creek, then passes on to the adjacent flood plain of Salmon River (fig. 78). The thickness of the flood-plain sediments on these valley floors and the composition of the underlying materials are not well known. At the north end of Resurrection Bay, seismic profiles and four bore holes indicate that the alluvium is about 350 feet thick, approximately half a mile west of the mouth of Resurrection River (Lemke, 1967, pl. 2). The alluvium thins eastward over a bedrock surface that emerges to the north; it also thins westward to about 100 feet and lies on compact glacial sediments that may be as much as 1,000 feet thick. At Resurrection River the deepest of borings for highway bridges reaches a depth of 95 feet and does not penetrate the base of the alluvium. (Logs of these wells are given in figs. 30–32).

The alluvium probably becomes thinner to the north as the valley narrows, and bedrock appears at its northern end. The glacier that carved Salmon River valley was smaller than that which filled Resurrection River valley; thus the bedrock may have been less deeply eroded and the sediments may be thinner in Salmon River valley.

Where the parallel highway and railroad fills passed from Jap Creek fan onto Resurrection River flood plain, cracking between the fills was more pronounced and water was discharged along the fractures. These fractures did not seriously affect the fills. However, where the fills lay on the extensively and severely fractured active and inactive flood-plain sediments along the rivers (figs. 27, 28), damage increased. Minor failures occurred within the fills, but most of the damage resulted from lateral displacement and cracking of the underlying sediments. As indicated by damage to the bridges, all of which were so severely damaged that they had to be replaced with entirely new structures, the flood-plain sediments were mobilized to depths in excess of 30 feet. The movement of the underlying sediments carried the railroad fill as much as 30 inches to the southeast, and the grade was broken by tension fractures. The pattern and distribution of cracking in the flood plain sediments are described on page D35.

Severe ground cracking on Resurrection River and Mineral Creek flood plains occurred throughout the area — from Resurrection Bay to about 1⅛ miles upstream of the railroad bridges. Similar ground cracking on the Salmon River flood plain affected an area that extended from about 200 feet west of the Seward-Anchorage highway to about 1,000 feet east of Salmon River. The cracking decreased in severity northward from the rail line; its limit was just north of the highway bridge four-fifths of a mile from Mineral Creek.

Northward from Mineral Creek the rail line crossed the severely fractured flood plains. The pattern of fractures was like that shown in figure 27, but fractures generated by the embankment were wider than those on the south side of Resurrection River. The embankment-generated fractures occurred in a zone a few tens of feet wide beside the toes of the fills, and some joined fractures that ran obliquely up the embankment sides. Few fractures reached the top of the embankment, and none crossed over.

The embankment was most severely damaged about 900 feet north of Mineral Creek bridge, where it crossed an abandoned highway fill, and at the Salmon River bridge approaches. The embankment was shifted about a foot laterally in several places, and its top developed a rolling surface with dips of about 1.5 feet amplitude. Salmon River bridge (mile 3.7), a 105-foot pile-supported open wood trestle, was compressed 5.5 inches, its stringers driving the tops of the bulkhead back into the approach fills. The fills were lowered 4 and 6 inches relative to the bulkhead, and the bulkheads and their bents were lowered several inches relative to the rest of the bridge. The deck was arched upward 6 inches, the crest of the arch being between the fourth and fifth bents. The deck was also deflected sidewise, the fourth and fifth bents moving 6 inches upstream of the adjacent bents. In addition, bents shifted southward and the south approach was displaced 1 inch west of the north approach.

Cracking continued in the sediments along the embankment for about 1,200 feet beyond Salmon Creek. On the east side of the embankment, cracking extended for about 500 feet from the railway embankment, across a drainage ditch and the adjacent dirt road, and into an area of houses.

From here (mile 3.9) to about mile 5.6 there was no general cracking of the flood-plain sediments beside the embankment. Bridge 4.3, a 43-foot 3-span pile-supported open wood trestle was only slightly damaged. The end ties were pressed into the bulkhead fillers and the bulkheads were slightly rotated back into the fills. Total compression was small, and the bridge deck was arched only about 1 inch. However, at mile 4.6 about 200 feet of the embankment was cracked by fractures that broke to the top of the embankment, outboard of the ties, as the embankment shifted about 5 feet laterally toward borrow pits dug immediately adjacent to the embankment toe. Cracking also occurred on the north approach of bridge 4.8 at Salmon Creek. These cracks affected about 600 feet of the embankment and appear to have been produced as the approach was displaced southward toward the riverbank that lies close to the embankment toe. Concurrently with this displacement the bridge (a 105-ft open wood trestle) was skewed horizontally, the north end displaced 5 inches east of the south end. At the south bulkhead the bent and adjacent fill were lowered ¾ to 4½ inches with respect to the bridge. The bulkhead remained horizontal but the bridge deck tilted about 3° down to the east (fig. 79). The deck was arched about 8 inches and the stringers were cantilevered 5 inches above the south bulkhead bent and one-eighth inch of the north bulkhead bent. The bridge was rammed at the north end, as shown by two pebble dents in the fillers, but there was no sign that the stringers were driven into the south bulkhead, despite the fact that there were pebbles present that would have recorded a blow. Beyond this bridge the embankment developed dips of as much as 2 feet and local horizontal displacements of about 1 foot.

From about mile 5 to mile 6.5, where the highway and railroad

79.—View north over arched and compressed bridge 4.8. Sags of about 2 feet and horizontal displacement of about 1 foot can be seen in the roadbed to the north.

fills lie parallel on the flood plain between Lost Creek and Salmon Creek, there was ground cracking between, and on both sides of, the fills. Cracking was not severe, but some sediment-laden water was ejected along the cracks into and onto the snow.

At mile 6.0, a 165-foot pile-supported open wood trestle was compressed 2 inches at the deck level. The stringers were driven into the bulkhead, and the tops of the bulkheads were rotated back into the fills. Piling was shifted toward the sixth bent at the center of the channel, and the first four bents at the south end of the bridge were shifted about 2 inches to the east relative to the rest of the bridge. The bulkhead bents were about 1 inch lower, and the fifth bent about half an inch higher than the remaining bents.

This bridge was the northernmost in this section to be damaged. The bridge at mile 6.6, a foot-long ballasted wood deck on wood piles, was undamaged and there was no evidence of any differential movement between its members.

SECTION 4. WOODROW TO DIVIDE

From half a mile north of Woodrow to 2½ miles north of Divide, the rail line lies on the floor of a glaciated valley that is covered by a thin veneer of till, from which linear glacially smoothed bedrock ridges protrude (fig. 80). About a mile north of Divide, the valley floor is composed of flood-plain sediments of Snow River and its south fork, but the rail line lies to the west of the flood plain on the toe of the western till-covered bedrock valley wall. There was no damage to the rail line throughout this section, either to the embankments or to a 136-foot-long tunnel through bedrock at mile 11.35.

SECTION 5. SNOW RIVER FLOOD PLAIN AND DELTA

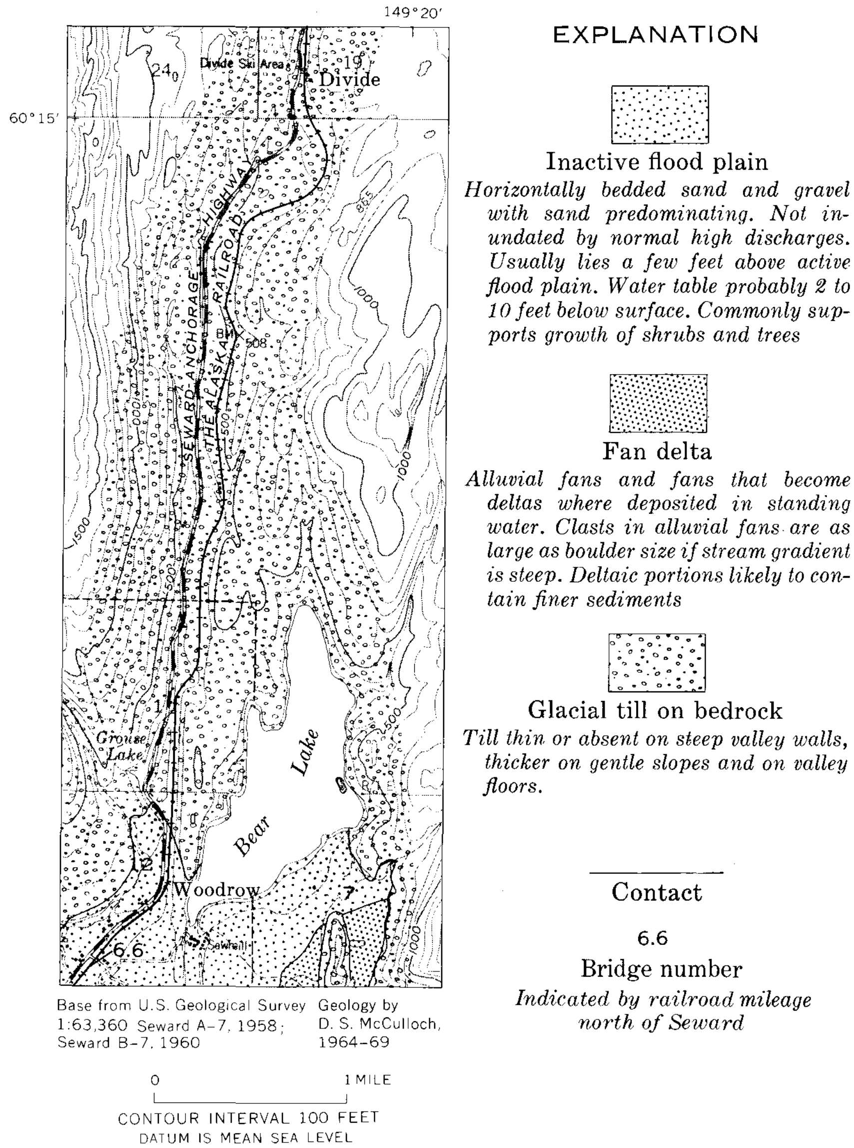
At mile 14.5 the rail line leaves the till-veneered bedrock valley wall and swings out onto the flood plain of Snow River (fig. 81). At mile 14.5 the sediments visible on the riverbed are sand and medium gravel. To the north, where the flood plain becomes a delta in Kenai Lake, the sediments are finer. Four borings by the Alaska Highway Department for a new highway crossing just south of Kenai Lake show fine gravel or pebbly sand to maximum depths of 25 feet. Beneath these deposits to a depth of at least 90 feet, the sediments are described as sand, fine sand, and appreciable thicknesses of silt (Kachadoorian, 1968). The nearly flat floor of Snow River flood plain (slope of 15 ft per mile), the large quantity of silt found at depth in the borings, the steep slope of the valley's eastern wall, and the occurrence of wave-cut bedrock terraces 6 feet above high lake level along the shores of Kenai Lake, all suggest that Kenai Lake was once higher and extended farther south into Snow River valley. The high sediment load carried by Snow River suggests that filling of the lake may have been rapid and that the shoreline may have been well to the south of its present position. Thus a large part of the flood plain may be underlain by fine lacustrine and deltaic sediments.

Railroad damage in this section started where the rail line left the till-covered bedrock valley wall and crossed onto the Snow River flood plain on the long steel and concrete bridge at mile 14.5. Shifting of the concrete piers and abutments, and displacements of the steel spans are discussed on page D44.

The active flood-plain sediments were broken by fractures as much as half a foot wide at the north bridge abutment; others on the adjacent flood plain are estimated from aerial photographs to have been as much as 3 feet wide. The fracture pattern on the active flood-plain sediments was roughly rectilinear, one set of cracks lay in the axes of channels occupied at high water approximately parallel to the river, and a second set of cracks formed at nearly right angles and usually turned somewhat to become normal to the adjacent water-filled river channel. Narrow bars between water-filled channels were broken from bank to bank by cracks running approximately normal to the banks. Individual blocks bounded by fractures were large, and were 100 to 200 feet across. Some fracture-bounded blocks were shifted slightly toward the channels, and sediment-laden water was ejected from some fractures.

The active flood-plain sediments were fractured throughout the entire area visible on aerial photographs. The fracturing extended from 1¾ miles south of bridge 14.5, where the flood plain narrows to about one-third of a mile, continuously and with increasing severity to the north, to the shore of Kenai Lake.

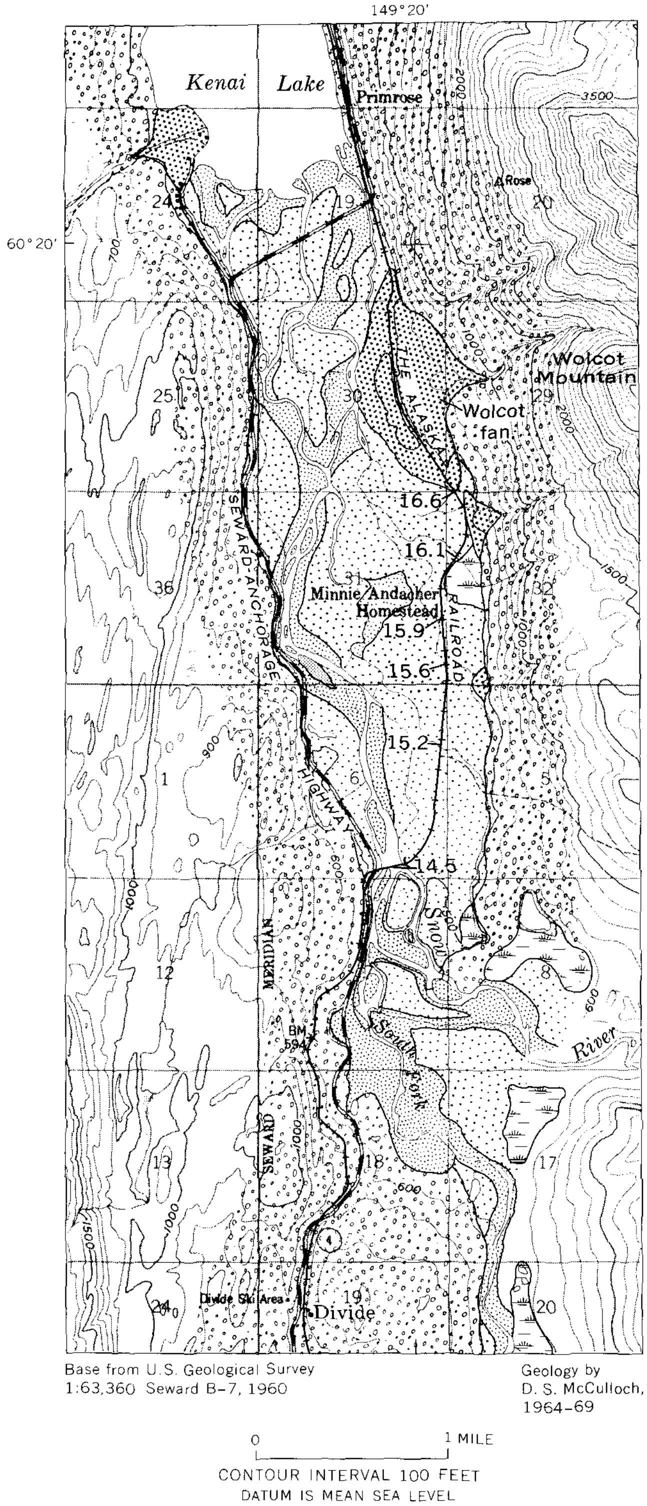
The rail line runs north from bridge 14.5 onto a wooded inactive flood-plain terrace. Several fractures on the terrace crossed beneath the northern end of the bridge at the last piers and at the bulkhead. Long single fractures formed on both sides of the embankment, some in the flood plain and some joining the few fractures that crossed the embankment at nearly right angles. These fractures had little effect on the rail line.



80.—**Surficial geologic-physiographic map of the rail belt from Woodrow (mile 6.5) to Divide (mile 12).**

The rail line proceeds north over the inactive flood-plain terrace to an alluvial fan at mile 16.5. Small bridges at miles 15.2, 15.6, and 15.9 were damaged. The bridge at mile 16.1 was not studied, and the bridge at mile 16.5 was undamaged. Bridge 15.2, a single-span open wood trestle, was compressed 6½ inches, stringers jamming the bulkheads back into the approach fills. The bents shifted streamward without noticeable tilting. As a result, the bridge was skewed horizontally about 1½ feet (fig. 82).

Bridge 15.6, a 45-foot open wood trestle, was also compressed, but only 1¾ inches; its piles shifted streamward and the embankments were lowered slightly with respect to the bridge. As at bridge 15.2, long segments of the approaches were displaced horizontally. As shown in figure 56, the bridge crosses the creek obliquely. About 1,200 feet of the northern approach, to just beyond bridge 15.9,



EXPLANATION

Active flood plain

Horizontally bedded sand and gravel with sand predominating. Surface subject to flooding at high discharges. Usually lies entrenched within inactive flood plain. Water table at or near surface. Usually free of vegetation

Inactive flood plain

Horizontally bedded sand and gravel with sand predominating. Not inundated by normal high discharges. Usually lies a few feet above active flood plain. Water table probably 2 to 10 feet below surface. Commonly supports growth of shrubs and trees

Fan delta

Alluvial fans and fans that become deltas where deposited in standing water. Clasts in alluvial fans are as large as boulder size if stream gradient is steep. Deltaic portions likely to contain finer sediments

Glacial outwash terraces

Generally flat terraces, often above inactive flood plain. Horizontally bedded sand and gravel. Grain size commonly coarser than in inactive-flood-plain terrace

Glacial till on bedrock

Till thin or absent on steep valley walls, thicker on gentle slopes and on valley floors.

Swamp

Contact

14.5
Bridge number
Indicated by railroad mileage north of Seward

81.—Surficial geologic-physiographic map of the rail line from Divide to Kenai Lake.

was shifted westward toward the stream channel that approximately parallels the embankment (fig. 83). About 600 feet of the southern approach was displaced eastward toward a channel that lies between the rail line and the channel shown in figure 56. The straightness of the rails on the displaced segments north and south of the bridge indicates that the displacement was relatively uniform over the long segments. The resulting horizontal offset at the bridge was 20 inches.

The inactive flood-plain sediments along Snow River were broken by an increasing number of ground cracks from the south toward Kenai Lake. The cracking usually occurred near, and at the edges of, the major channels or larger braided overflow channels. From mile 15.2 to 15.4 some of these cracks came within 200 feet of the rail line, but most were considerably farther away. Throughout this entire section on the flood-plain terrace, there were cracks in the toe of the embankment and in the sediments immediately adjacent, but in general no cracks were farther than about 25 feet from the embankment. Thus the embankment appears to have caused the cracking in the flood-plain sediments where no other cracks occurred. Cracking generated by the embankment also occurred from mile 16 to 16.21 where dips in the track of as much as 2 feet formed beside fractures in the sediments. Copious discharges of sand and pebble gravel were ejected from the fractures (fig. 84). As shown in figure 84 this area lies beside a swamp, and the ground-water table is quite high. There was also some ground cracking and discharge of sediment-bearing water onto the snow covering the swamp.

At mile 16.2 a round corrugated-iron culvert about 2 feet in diameter carried water from a small drainage ditch under the embankment. The embankment moved toward the culvert from both sides and compressed the culvert to an oval; the tracks bowed upward and outward off the ties to accommodate the shortening (fig. 85).

82.—View north over bridge 15.2 on the inactive floodplain terrace of Snow River. Approximately 950 feet of the embankment north of the bridge shifted about 1½ feet to the west toward an abandoned stream channel 220 to 230 feet to the west, in the tree-covered area.

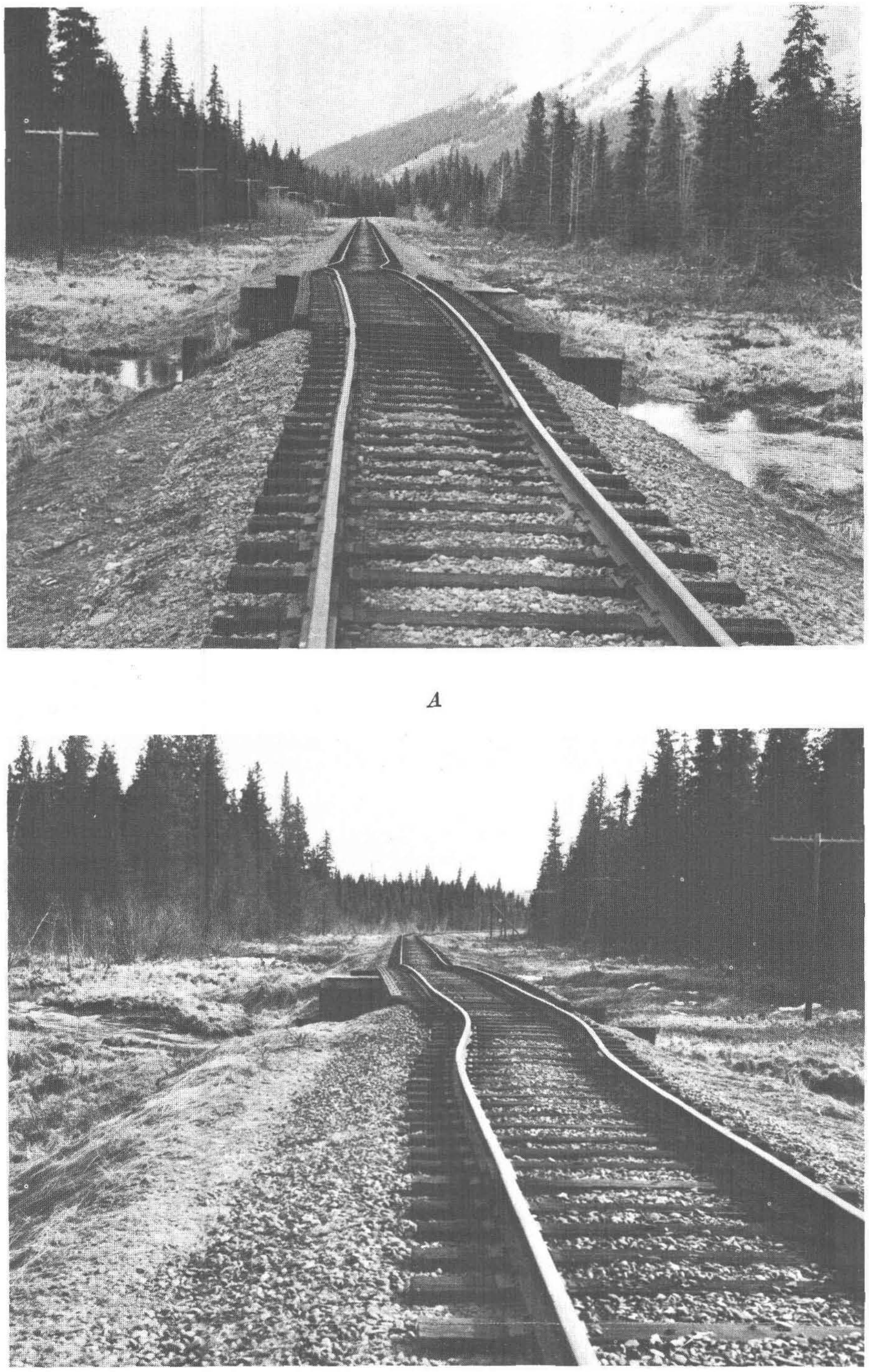
At mile 16.6 a small bridge had only minor cracks in its approaches; however, gravel dikes built to confine the creek both upstream and downstream from the bridge were cracked by longitudinal fractures and transverse cracks.

SECTION 6. WOLCOT MOUNTAIN ALLUVIAL FAN

Northward from mile 16.6 to mile 17.8, the rail line is built across the distal end of the alluvial fan of a small creek that rises from a glacier on Wolcot Mountain to the east of Snow River (fig. 81).

The pattern and distribution of the ground cracks on this fan are similar to those that developed on many other fans and deltas during the Alaska earthquake; on the most distal part of the fan and on the adjacent flood plain, sediment-laden water was ejected from irregularly distributed cracks. Just upslope, the edge of the fan was laced with a network of cracks forming parallelogram-shaped blocks, the long axes of the parallelograms parallel to the edge of the fan. Very little water was ejected from these cracks.

The rail line crossed uphill of most of the cracked zone at the



A

B

83.—Bridge 15.6, a 45-foot wood trestle on the inactive floodplain of Snow River, showing long, horizontally offset embankments. *A*, View north; *B*, view south.

lower edge of the fan, but cracks induced by the embankment broke both the embankment and the fan sediments immediately adjacent.

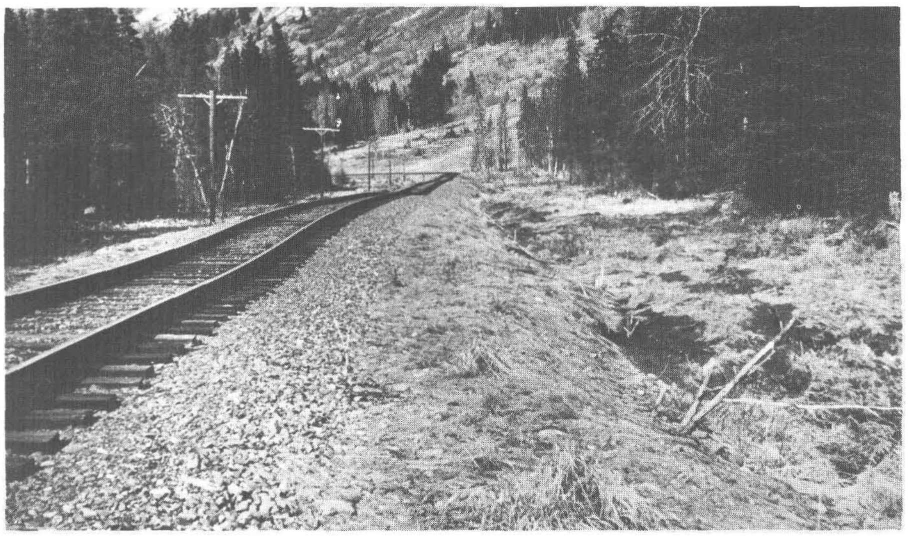
About 1,200 feet of the embankment that did cross the northern cracked edge of the fan sustained additional fracturing. There was some sagging of the embankment on the fan, but, despite large volumes of sand and sandy gravel ejected from the fractures, most of the local sags were less than a foot. Some of the ejected material was relatively course; it measured as much as 3½ by 2½ by 4 inches, and at one place water ejected from a fracture that crossed the embankment excavated a cavity 2 feet deep and 4 feet wide under the ballast (fig. 86).

In addition to developing sags, the embankment was carried irregularly downhill by the valleyward spreading of the underlying fan. Spreading generated tension in the rails, and pulled expansion joints open to their limit. At mile 17.3, on the axis of the fan, tension in the rails was large enough to shear bolts in the angle bars, and the rails were pulled about a foot apart. At the axis of the fan, downhill spreading also produced tension fractures that broke across the embankment at nearly right angles; from mile 17 to 17.5 these tension fractures occurred at nearly regular 40- to 50-foot intervals.

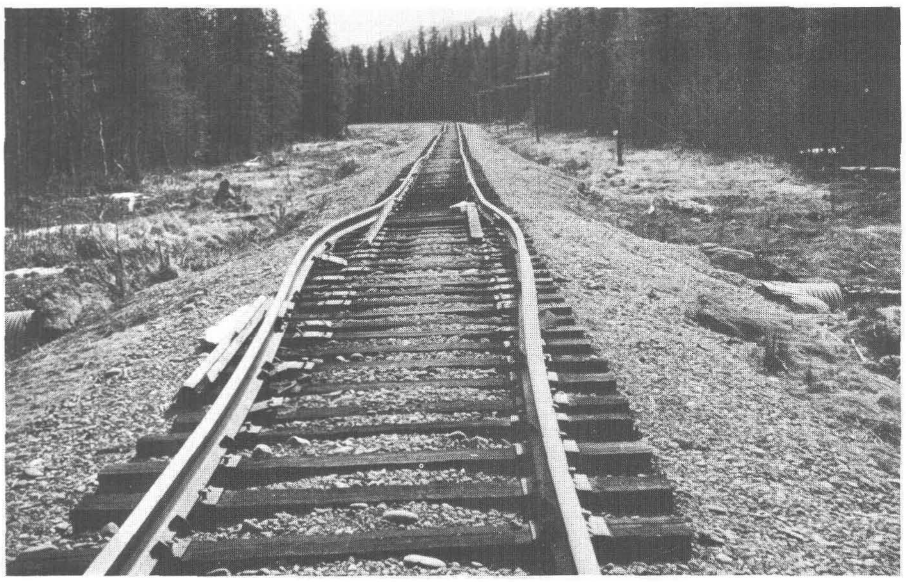
North of the edge of the fan, the active flood plain and delta of Snow River lie immediately adjacent to the eastern valley wall, and the rail line is crowded against the toe of the slope (fig. 81).

The strong contrast between the damage to the highway and the damage to the railroad at this end of the lake directly reflects the difference in the materials upon which they are built. The rail line is built on a low fill in a cut at the base of the slope, and it escaped injury; the highway crossed the delta and was severely damaged. A 900-foot wood deck, a pile-supported causeway, and two small wooden bridges were greatly damaged by horizontal and vertical pile displacements. Where it overpassed the railroad, the causeway had a concrete deck that entirely collapsed and was dropped nearly vertically onto the track (fig. 87). The adjacent highway roadbed was cracked and in some places sank to the level of the delta surface. Postearthquake surveying from one outcrop of bedrock to another across the delta shows that the road and some heavily reinforced concrete piers on 90-foot-long steel piles were displaced as much as 10 feet toward the lake (Kachadoorian, 1968). The piers were tilted, their bases carried farther toward the lake than their tops (fig. 88), perhaps owing to differential lateral displacement of sediments from beneath the adjacent highway fill that settled level with the delta surface.

An additional indication of the fluidity attained by the sediments is shown by the following observation: An open network of orthogonal cracks formed on the flood plain and delta as the sediments spread toward the lake and toward the many distributary channels lacing the delta surface. Ground cracks on the delta face were continuous with cracks in the overlying thick lake ice to which it was probably frozen fast. Sediments were injected into the ground cracks and were driven upward into the cracks between the ice blocks. When the ice melted the sediments were left in reticulated dikes standing as much as a foot above the ground surface. As seen in a 2-foot excavation, one of the dikes was composed of fine to medium sand that had a sharp contact with the pebbly sand of the upper delta sediments (fig. 89). Poorly developed horizontal stratification in the top few inches of the dike suggests that some lateral flow may have occurred while the sand dikes were confined between the ice blocks. Another view of these dikes is shown in Hansen and others (1966, fig. 7).



84.—Mounds of sand and gravel ejected with ground water coincident with local dips in the embankment (foreground and middle ground).



85.—Rails compressed and deflected where sediments moved toward a small ditch under the embankment and crushed a culvert (visible on both sides of tracks).

SECTION 7. KENAI LAKE FAN DELTAS

After leaving the delta, the railroad follows the eastern shore of Kenai Lake for about 5 miles. Except where it is built on deltas at Lakeview, Rocky Creek, and Lawing, it lies in small cuts in bedrock and on minor amounts of shore deposits (fig. 90). The only damage to the rail line occurred on the deltas. There was considerable cracking on Lakeview and Rocky Creek deltas, and subaqueous slides occurred from all three deltas. The cracking and the slides

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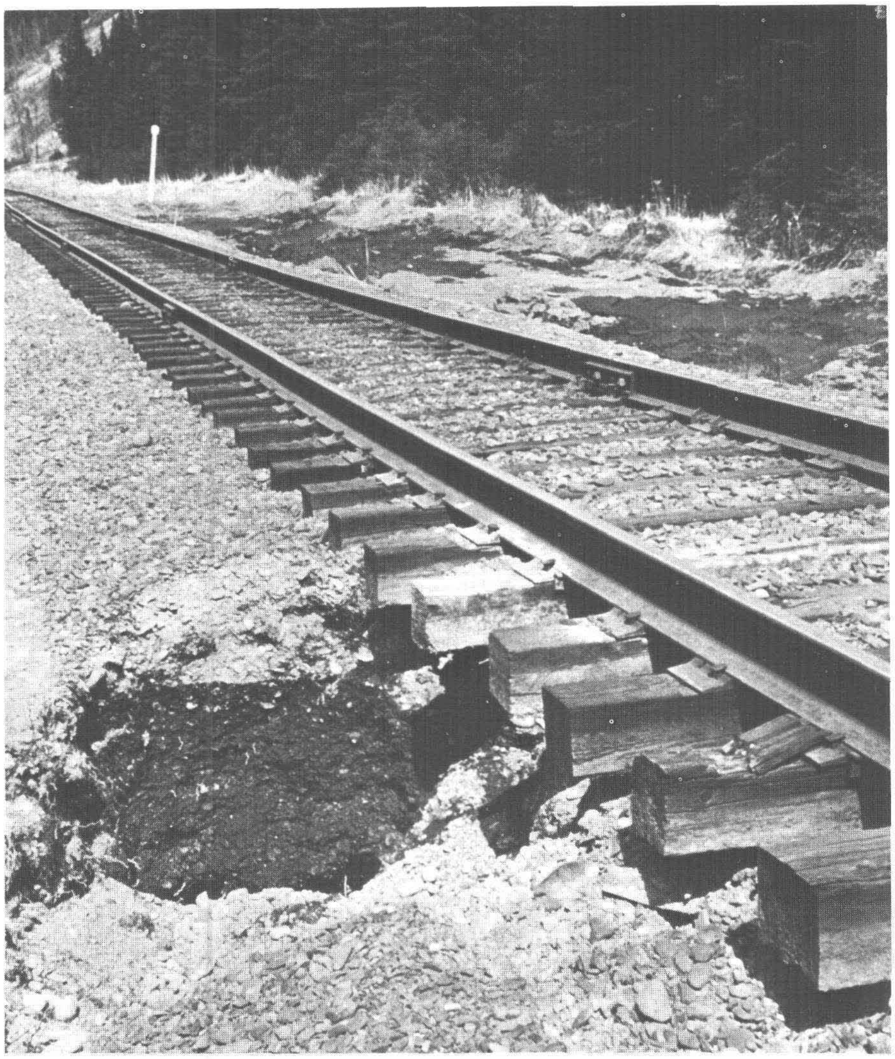


86.—A 4-foot-wide and 2-foot-deep cavity excavated beneath the ties by the forceful expulsion of ground water at mile 17.2.

have been described in detail in McCulloch (1966); only a summary follows.

At Lakeview delta—a delta built of coarse sand and gravel by a high-gradient stream — large slides removed two protruding areas along the delta margin. Cracking along the edge of the delta was of three kinds: (1) arcuate slump scarps with some rotation and downdropping of as much as 5 feet on the downslope side, (2) shallow cracking in the surface materials of the delta produced by lakeward spreading of the underlying materials, and (3) cracks in the railroad embankment and in the adjacent delta surface localized along, and produced by, the embankment. Radial downslope spreading of the delta sediments shifted the rail line toward the lake and put the embankment and the bridge at mile 20 in tension. Rails were pulled apart, shearing bolts in the angle bars; the distance between deeply driven bridge pilings and the bridge bulkheads was increased, and tension fractures, formed across the embankment at nearly right angles, like those on the alluvial fan at mile 17 (see p. D104). Radial spreading also pulled wires taut on pole lines running parallel and at right angles to the tracks.

The delta at Rocky Creek was also severely fractured, and a slide into Kenai Lake from the edge of the delta (see p. D76) carried away 261 feet of railroad roadbed.

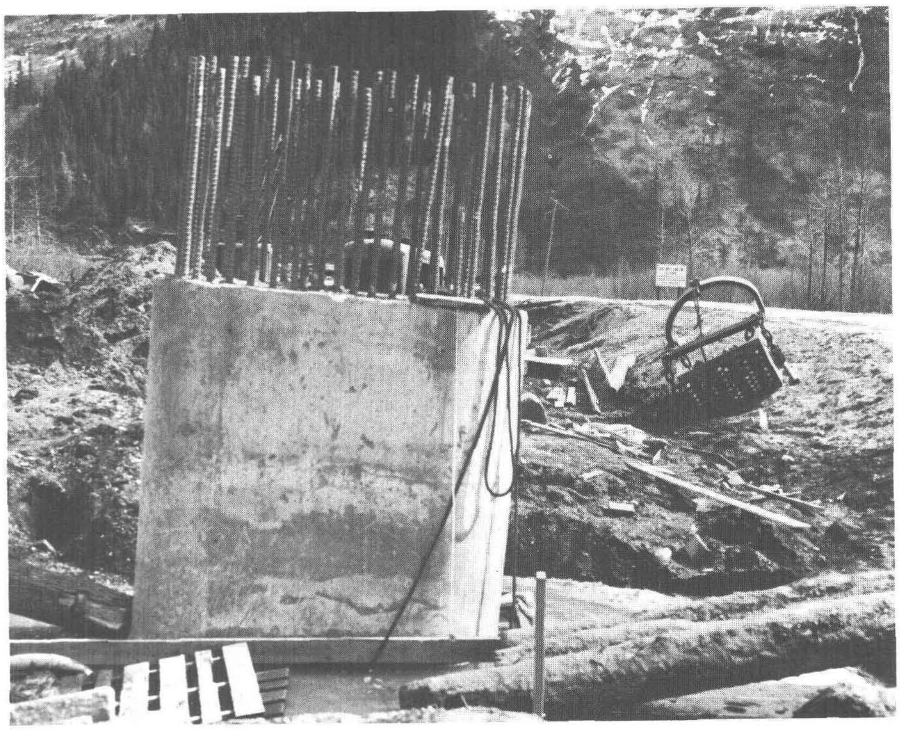
Lawing delta, at the northeast corner of the lake, is a relatively large delta with a nearly flat surface. Except for a small slide that removed a slightly protruding area of young delta sediments near the mouth of Trail River, the delta behaved quite differently from the deltas at Lakeview and Rocky Creek. There was almost no surface cracking and the damage to bridge 23.5 over Ptarmigan Creek was minimal; the north approach fill was lowered half an inch; rails skidded half an inch to the south over the bridge deck, and as indicated by the single dent one-sixteenth of an inch deep made by a pebble caught between the last tie at the north end of the bridge and the filler on the bulkhead, the stringers were driven at least once against the fillers. No vertical or horizontal displacement of the piles was detected.

Because of the severe fracturing on both Rocky Creek and Lakeview deltas, the lack of cracking would not have been predicted for Lawing delta. Its absence probably cannot be attributed to less severe or shorter duration ground motion here than on the other deltas, for eyewitnesses describe relatively strong ground motion. One observer living at the shore of the delta was knocked to the floor of his house by the first shock, and his house continued to shake for several minutes. Another, also living on the delta shore, described shaking that lasted several minutes, during which a car in a garage was seen "swaying tremendously and also sliding back and forth across a concrete floor" (McCulloch, 1966, p. A17). There was minor structural damage to houses, including the collapse of a small garage and a two-story chimney from the side of a house on the south side of the delta.

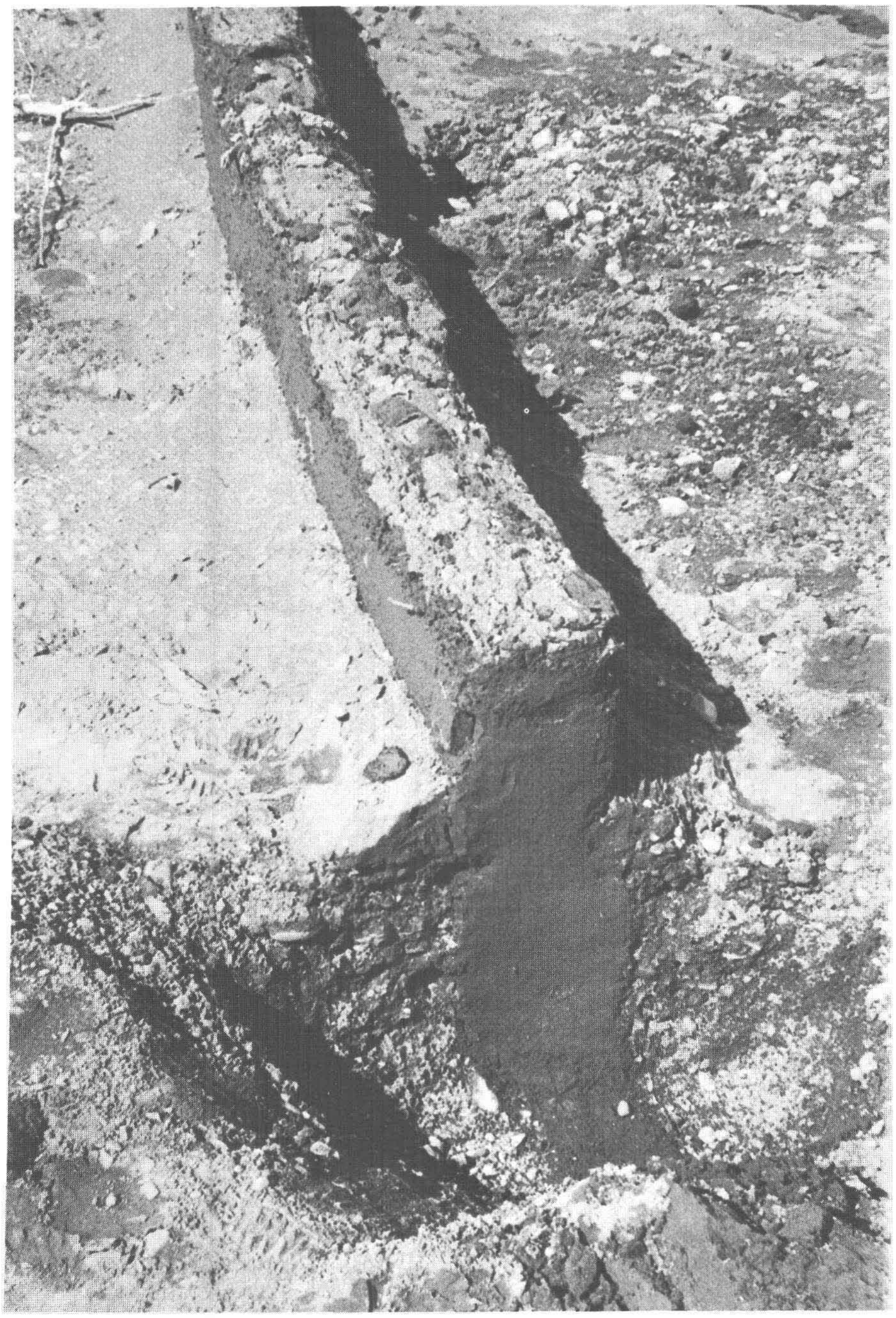
Several factors may have contributed to the lack of surface fracturing on this delta. Beds of rocky clay between beds of sand and gravel, penetrated by eight water wells drilled for the U.S. Forest Service on the delta (John C. Crupper, U.S. Forest Service, written commun., 1967), suggest that the till exposed on the surface of the delta (as shown in fig. 90) is more extensive and is interbedded with the delta sediments in the subsurface. The location of two of the wells is shown in figure 93. At well 1 (25 ft deep), "rocky clay" was found from 12 to 20 feet below the surface overlain by "looser rocks and boulders" and underlain by 5 feet of "water sand." At well 2 (49-ft well at Kenai Lake Work Center), strata of "hard rocky clay" was found at depths from 33½ to 35 feet and from 38 to 40 feet overlain by, interbedded with, and underlain by sand and gravel. Fracturing may also have been reduced by the fact that the surface of the delta is flatter than the Lakeview and Rocky Creek deltas (which would reduce the propensity for downhill spreading) and that the water table in the delta was so low at the time of the earthquake that many wells had run dry (Frank Kraxberger, well driller, oral commun., 1964).

The rail line runs north from the delta on the Trail River flood plain. From 100 to 200 feet south of mile post 25, there was minor cracking directly behind, and re-

87.—The concrete deck of a highway overpass at Snow River delta that collapsed onto the railroad.



88.—A highway bridge pier on deeply driven steel piling at Snow River delta that was under construction at the time of the earthquake. Movement of the delta sediments toward Kenai Lake, to the left, from beneath the highway fill that settled approximately 4 feet carried the pier about 10 feet from its original position (Kachadoorian, 1968) and carried the base of the pier farther than its top; the white plumbline on the pier indicates a tilt of about 5°.



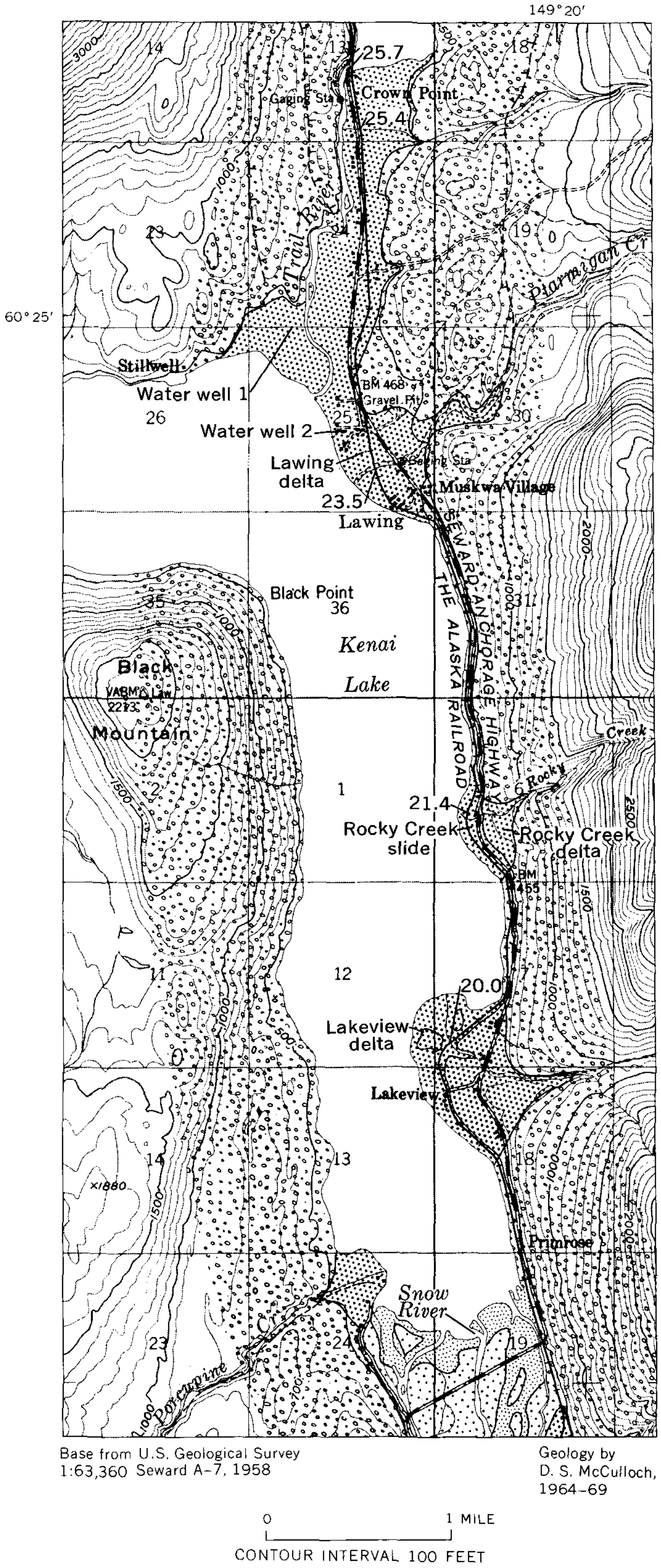
89.—A clastic dike on Snow River delta composed of sediments that were injected into a crack in the frozen delta sediments and overlying lake ice that was frozen to the delta surface. The top of the dike is about a foot above the ground surface.

lated to, a slight slump which lowered the adjacent highway toward a cutbank where the river approached the highway. Minor damage to the railroad bridge at Falls Creek (mile 25.5) was similar to that at Ptarmigan Creek: the south approach fill was lowered half an inch at the bulkhead, multiple pebble dents show repetitive, but not damaging, endways compression. At bridge 25.7, which crosses Trail River at the end of Lower Trail Lake, there was minor cracking on the east side of the south embankment, and the north end of the bridge was displaced slightly toward the lake along a crack which crossed the embankment diagonally. The piles were shifted slightly, and the south approach, bulkhead, and first bent were lowered 1 to 2 inches. The stringers were jammed into the fillers at the south end, shoving the bulkhead back into the fill.

SECTION 8. LOWER TRAIL RIVER VALLEY

At the south end of Lower Trail Lake the rail line leaves the flood plain of Trail River, and for the next 7.3 miles it runs along the shores of Lower and Upper Trail Lakes — lakes that lie in elongate glacially carved bedrock basins (fig. 91). In this section the rail line is built on thin deposits of till that lie in patches between bedrock outcrops on the valley floor; on beach deposits along Lower Trail Lake; and, at the town of Moose Pass, on a lobate landform that may be composed of outwash gravel lying on glacial till. Damage to the rail line was minor throughout this section. There was a short stretch of minor slumping in a narrow strip of sediment resting on bedrock along the shore of Lower Trail Lake from 600 feet south to 400 feet north of mile 26. The slump blocks were lowered and rotated from about 8 to 12 inches, and cracks bounding the slumps were as much as 6 inches wide and 6 feet deep. Slumping may have been the result of slippage of the soft lake sediments on the underlying bedrock, because the bedrock exposed immediately adjacent to the rail line has a very steep slope that probably continues to some depth.

The next damage to the railroad was 3.5 miles to the north at Moose



EXPLANATION

Active flood plain
Horizontally bedded sand and gravel with sand predominating. Surface subject to flooding at high discharges. Usually lies entrenched within inactive flood plain. Water table at or near surface. Usually free of vegetation

Inactive flood plain
Horizontally bedded sand and gravel with sand predominating. Not inundated by normal high discharges. Usually lies a few feet above active flood plain. Water table probably 2 to 10 feet below surface. Commonly supports growth of shrubs and trees

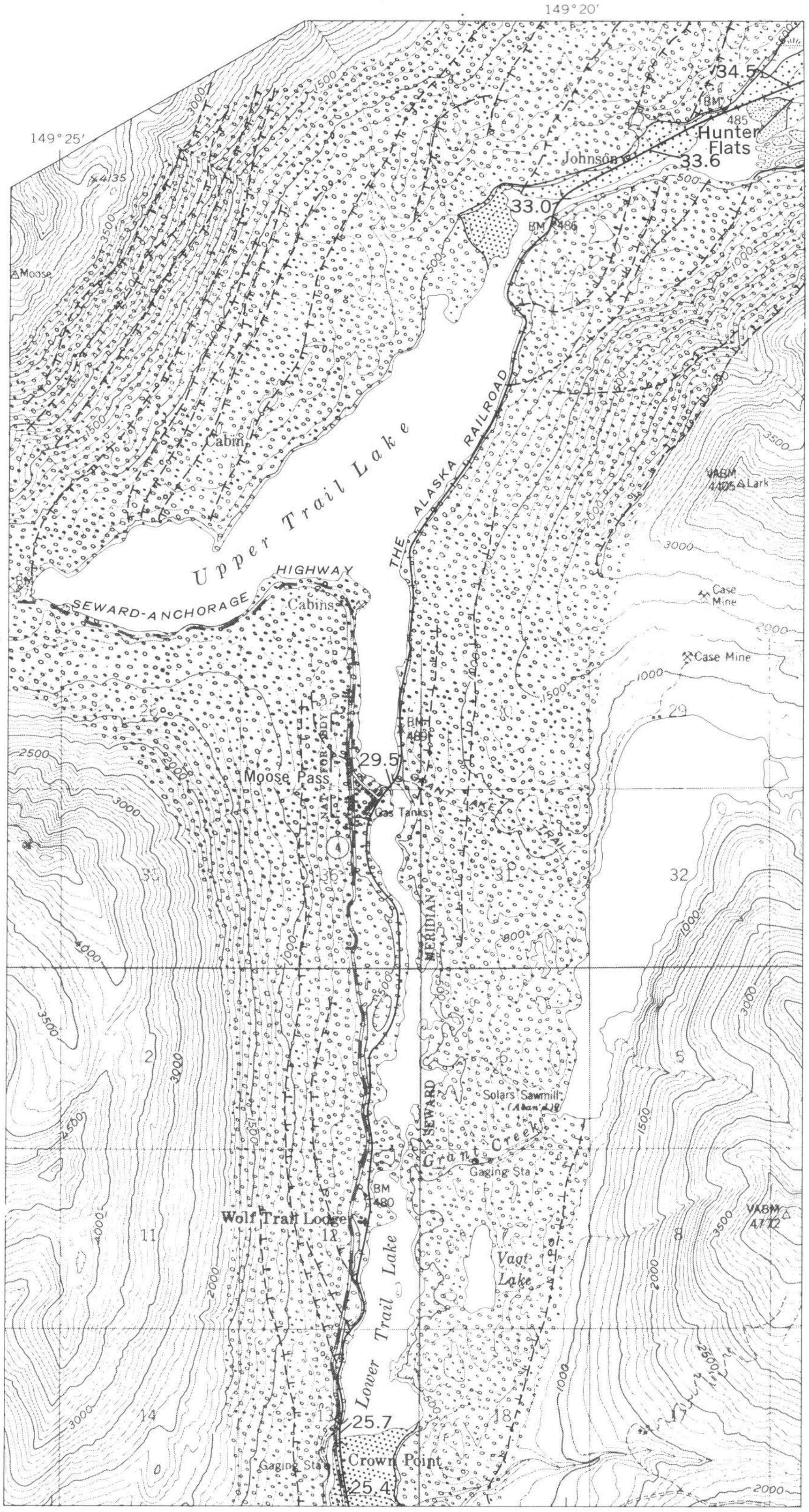
Fan delta
Alluvial fans and fans that become deltas where deposited in standing water. Clasts in alluvial fans are as large as boulder size if stream gradient is steep. Deltaic portions likely to contain finer sediments

Glacial till on bedrock
Till thin or absent on steep valley walls, thicker on gentle slopes and on valley floors. Hachured lines indicate old ice-front still stands as shown by ice-marginal drainage channels, moraines, upper limit of ice-carved bedrock, lower limit of old talus, or well-defined moraines on valley floors. Hachures on ice side

Contact

20.0
Bridge number
Indicated by railroad mileage north of Seward

90.—Surficial geologic-physiographic map of the rail belt from Snow River delta to Lawing.



Base from U.S. Geological Survey 1:63,360
Seward B-7, 1960; Seward C-7, 1959

Geology by D. S. McCulloch, 1964–69

0 1 MILE

CONTOUR INTERVAL 100 FEET
DATUM IS MEAN SEA LEVEL

EXPLANATION

Active flood plain

Horizontally bedded sand and gravel with sand predominating. Surface subject to flooding at high discharges. Usually lies entrenched within inactive flood plain. Water table at or near surface. Usually free of vegetation.

Inactive flood plain

Horizontally bedded sand and gravel with sand predominating. Not inundated by normal high discharges. Usually lies a few feet above active flood plain. Water table probably 2 to 10 feet below surface. Commonly supports growth of shrubs and trees

Fan delta

Alluvial fans and fans that become deltas where deposited in standing water. Clasts in alluvial fans are as large as boulder size if stream gradient is steep. Deltaic portions likely to contain finer sediments

Glacial till on bedrock

Till thin or absent on steep valley walls, thicker on gentle slopes and on valley floors. Hachured lines indicate old ice-front still stands as shown by ice-marginal drainage channels, moraines, upper limit of ice-carved bedrock, lower limit of old talus, or well-defined moraines on valley floors. Hachures on ice side

Swamp

Contact

29.5
Bridge number

Indicated by railroad mileage north of Seward

91.—Surficial geologic-physiographic map of the rail belt from Lawing to Hunter Flats.

Pass. The railroad bridge (29.5) was compressed, its stringers rammed the bulkheads but did no serious damage. On the flat, lobate townsite, cracks as much as 6 inches wide formed from the margins to about 50 feet back from most of the north and northeast shore. The cracking occurred in a sandy gravel, and no vertical displacement was seen. Some minor ground cracks were reported across C Street in the middle of the townsite, but they were not visible when the area was examined 2 months after the earthquake. Some buildings on the flat area were considerably damaged by shaking and movement of their foundations, but, according to Mr. Keith, the school principal (oral commun., 1964), buildings nestled against the bedrock slope at the west edge of town escaped with little or no damage. The school, a combination one- and two-story structure built on the flat area (fig. 91) was badly damaged. The perimeter foundation settled and left a central-bearing partition standing high. As a result there was damage to both floor and ceiling joists. The school's two cement-block chimneys were toppled; both had one-quarter-inch-steel reinforcing at the flue corners and steel webbing between block courses. The tallest, which stood at least 12 feet above the flat roof of the single-story part, fell across the roof but did not even puncture the built-up gravel and tar-paper surfacing. Shaking also tipped over the boiler, bent and tore away its connecting plumbing. A corner was broken from the concrete foundation, but no ground cracks were found adjacent to the school. To the east, across the railroad tracks, the railroad section house, a small one-story structure, lost its chimney, and minor ground cracks radiated away from the northwest and southwest corners of the building. There were also minor ground cracks radiating from the corners of the foundations of the nearby railroad station, and its porch was lowered slightly, possibly as a result of the failure of its foundation. These radiating cracks suggest that there was some spreading of the sediments. The fact that there were few ground cracks at the townsite is probably due to some geologic control, not the absence of strong ground motion. Eyewitness accounts suggest that there probably was strong ground motion on the flat part of the townsite. For example, in answer to a questionnaire Mrs. D. L. Wolfe (postmistress, Moose Pass) wrote that the shaking lasted perhaps 5 minutes. Small objects were thrown down and there were "bushels of china, glassware, and crockery broken and some furniture damage." Heavy objects like refrigerators were overturned or were shifted. Six water heaters were torn loose and overturned. All chimneys laid up in concrete block or rock fell, even if built with reinforcing (poured concrete fireplaces and chimneys were undamaged). The southwest and northeast corners of a single-story 40- by 80-foot cement-block Community Hall were broken open and the junction between the walls and the heavy roof made of railroad bridge timbers was broken.

Just what the geologic controls were that prevented extensive ground cracking are not known. As shown in figure 91, the town lies at about the position once occupied by the end of the glacier that filled the valley, and the townsite may be underlain by till, which was part of the morainal ridge now visible on the adjacent valley walls.

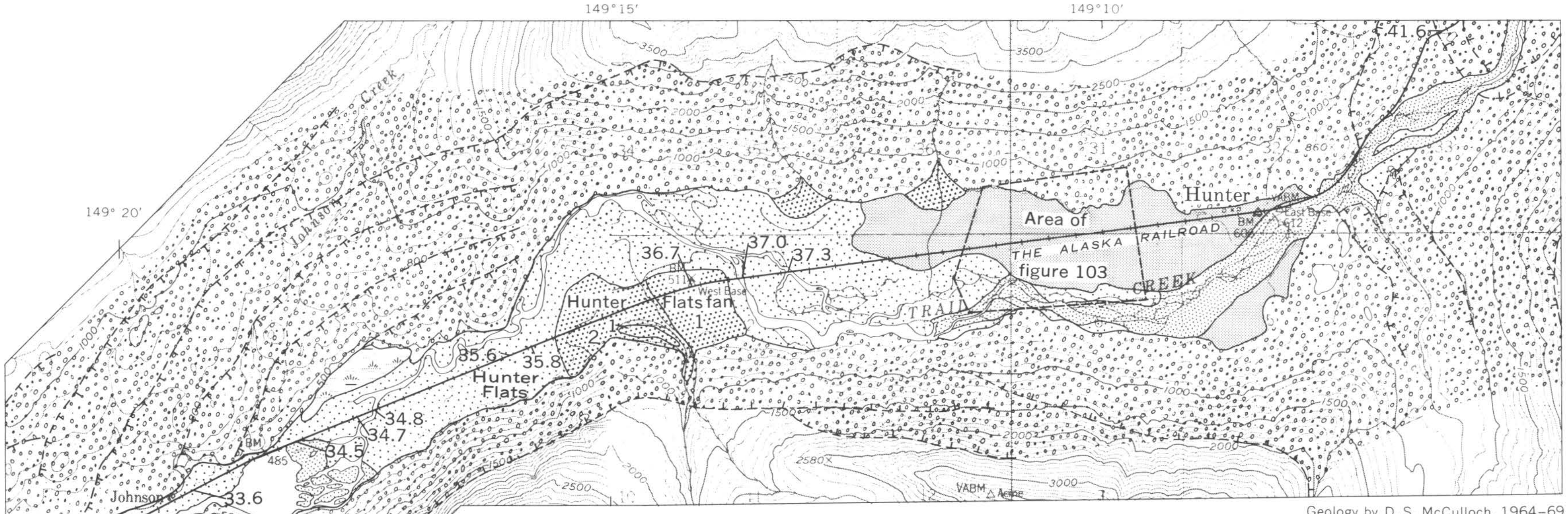
Shaking generated a seiche in Lower and Upper Trail Lakes, as it did in nearby Kenai Lake (McCulloch, 1966). Water surged the long way of the lake basins and shattered the ice at the ends of the lakes and at the sides of rocky protrusions on the shoreline. Sediment-laden water was visible on aerial photographs on the north shore of Moose Pass townsite and was reported to have "squirted" out from under the ice. Ice blocks were also reported to have been heaved up on the shore. The runup of the water at the ends of the lakes indicates that the seiche wave had an amplitude of perhaps 3 feet or less.

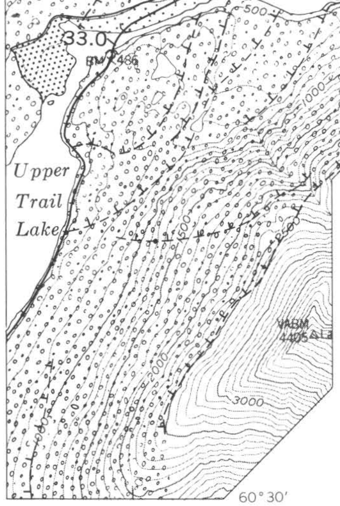
Except for 1,000 feet of minor slumping at mile 26 and the very minor damage at Moose Pass there was no further damage to the railroad as far as the north end of Upper Trail Lake. Throughout this undamaged section north of Moose Pass, the rail line lies primarily on a thin till veneer on bedrock or in small cuts in the bedrock along the lakeshore.

SECTION 9. HUNTER FLATS FLOOD PLAIN

At the north end of Upper Trail Lake the change from till, across which the line had been running, to water-laid sediments is accompanied by the beginning of some of the most severe damage to bridges and embankments (fig. 92). For the next 7 miles where the railroad crosses the flat swampy valley floor, known as Hunter Flats, bridge after bridge was destroyed. Not one of the 11 bridges escaped destruction.

Except for braiding stream channels, most of which are small and shallow, there is almost no relief on the valley floor. Despite the lack of relief, there was a considerable amount of permanent





Base from U.S. Geological Survey 1:63,360
Seward C-6, 1963; C-7, 1959

0 — 1 MILE

CONTOUR INTERVAL 100 FEET
DATUM IS MEAN SEA LEVEL

EXPLANATION

Active flood plain

Horizontally bedded sand and gravel with sand predominating. Surface subject to flooding at high discharges. Usually lies entrenched within inactive flood plain. Water table at or near surface. Usually free of vegetation

Inactive flood plain

Horizontally bedded sand and gravel with sand predominating. Not inundated by normal high discharges. Usually lies a few feet above active flood plain. Water table probably 2 to 10 feet below surface. Commonly supports growth of shrubs and trees

Fan delta

Alluvial fans and fans that become deltas where deposited in standing water. Clasts in alluvial fans are as large as boulder size if stream gradient is steep. Deltaic portions likely to contain finer sediments
1, *older (higher) part of fan*
2, *younger part of fan*

Glacial outwash terraces

Generally flat terraces, often above inactive flood plain. Horizontally bedded sand and gravel. Grain size commonly coarser than in inactive-flood-plain terrace

Glacial till on bedrock

Till thin or absent on steep valley walls, thicker on gentle slopes and on valley floors. Hachured lines indicate old ice-front still stands as shown by ice-marginal drainage channels, moraines, upper limit of ice-carved bedrock, lower limit of old talus, or well-defined moraines on valley floors. Hachures on ice side

Swamp

Contact

41.6
Bridge number
Indicated by railroad mileage north of Seward

92.—Surficial geologic-physiographic map of the rail belt from Upper Trail Lake to Hunter

horizontal displacement of the sediments. Horizontal displacement, especially toward stream channels, distorted the embankments and was the principal cause of bridge damage. Displacements occurred within the sediments to depths sufficient to shift piling with penetration of as much as 30 feet. Horizontal displacements of the sediments were accompanied by a general but unequal settling of the embankment into the underlying material, by extensive ground fracturing, and by the expulsion of great quantities of ground water that flooded large areas of the valley floor. Some of the ground cracks and some of the water-covered areas are shown on plate 2. Despite the large number of cracks shown on this plate, probably more than half were unmapped, for many were obscured in flooded and snow-covered areas. In addition, many cracks were seen in the field at the toe of the embankment and in the materials immediately adjacent, but most of these cracks were not visible on the aerial photographs.

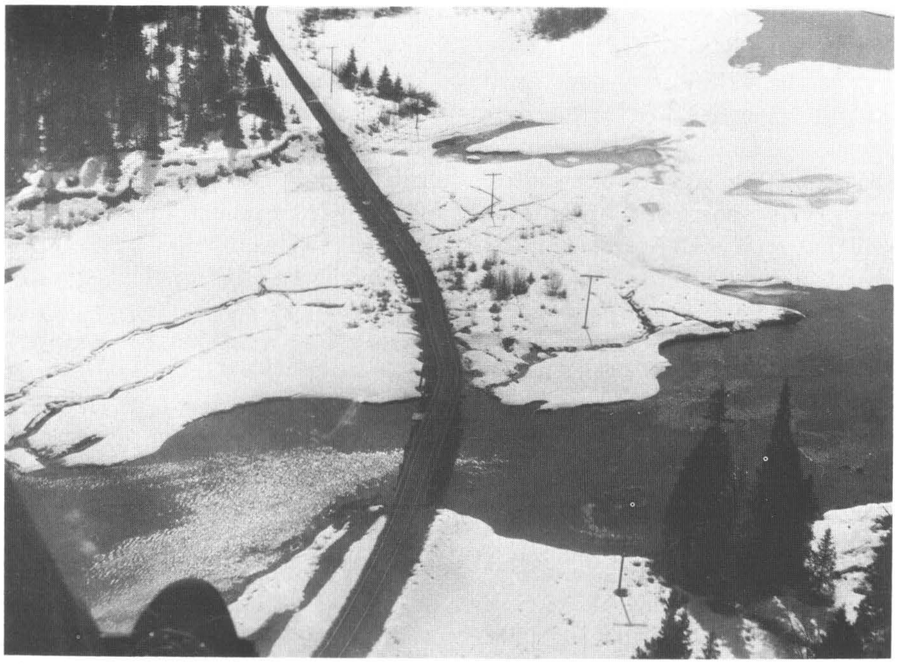
No subsurface data are available for this valley; however, some inferences about the subsurface can be made from the geologic history indicated by the distribution of the surficial deposits and the topography. The steep bedrock valley walls suggest that the bedrock basin extends to some depth beneath the valley floor and that the valley fill may have an appreciable thickness. The floor of the bedrock basin may be overlain by till, but the lack of evidence for a well-developed ice-front stillstand between the mouth of Trail Creek and Hunter suggests that there are probably no well-developed morainal ridges buried beneath the valley fill. The lack of evidence for a well-developed ice-front stillstand in the valley also suggests that ice retreat was rapid and that the lake at the southwest end of the valley may once have extended considerably farther into the valley. Glacial moraines indicate that the ice retreat halted temporarily northeast of Hunter and that melt-water streams filled the eastern 2.5 miles of the valley with sand and gravel (the now inactive flood-plain terrace). If the lake extended into the eastern end of the valley, the outwash sand and gravel may be deltaic in part and interbedded with lake deposits of silt size. Throughout the deposition of the outwash, finer sediments, probably mostly rock flour of silt size, would have been accumulating in the lake. During the subsequent retreat of the ice, melt-water streams would have continued to carry sediments to the valley, and the lake would have continued to act as a trap for the fine sediments, while coarser sediments formed a delta out over the top of the lake deposits. As the delta was built farther into the lake and the streams lengthened, the material carried to the delta would have become progressively finer. This reconstruction is substantiated by the fact that sediments in the present-day stream channels at bridges 34.5, 34.7, and 34.8 are generally fine and are composed of medium to fine sand and silt, whereas at bridges 37 and 37.3 the streambeds are composed of sandy pebble gravel.

Considerable ground cracking, horizontal displacement of sediments, and the expulsion of ground water took place in the southwestern part of the valley where this interpretation of the geology suggests that there is an appreciable thickness of silt interbedded with, and overlain by, fine to medium sand. At the northern end of the valley, where ground cracking was nearly limited to the active flood plain, where bridges suffered less compression from horizontal displacement of sediments and where less of the surface was flooded, there may be little or no silt, and gravel may constitute a large part of the sediments.

At the head of Upper Trail Lake the 495-foot open wood trestle bridge (33.0) across Trail Creek was damaged by compression and vertical pile displacements. The bridge is built on a long curve and runs from south to north over an overflow channel on active flood-plain sediments, a small brush-covered knoll, the creek channel, and finally onto active flood-plain sediments. The flood-plain sediments on both sides of the channel were broken by ground cracks, and on the north side the crack extended across the embankment. Vertical displacements of the piles produced arches of about 1 inch on either side of the small knoll; however, most of the damage was caused by compression that buckled the deck laterally in the downstream direction across the tops of the bents at the channel (fig. 93). The deflecting stringers tore free of most bents, but a few that remained attached were racked sidewise, and their sway braces split.

At mile 33.6, a 70-foot open wood trestle was compressed as the streambanks moved closer together. The stringers jammed 2 inches into the south bulkhead and 5 inches into the north bulkhead, and the top of each bulkhead was driven back into the approach fill. The bents were crowded together toward the center of the stream channel, and vertical pile displacement produced an arch of about 6 inches in the center of the bridge.

From this bridge north to mile 33.9, the rail line crosses tree-covered alluvium on which the embankment settled slightly and



93.—View south over bridge 33.0 at the north end of Upper Trail Lake. Compression buckled the bridge deck laterally. Note the large ground cracks in the flood-plain sediments. Photograph by The Alaska Railroad.

cracks formed beside the embankment (pl. 2). Between mile 33.8 and mile 33.9 the embankment was built at the edge of the lake on lakeshore sediments between two small cuts across rock promontories of the valley wall. The embankment on the lake deposits settled abruptly about 1.5 feet against the bedrock cuts and was displaced irregularly as much as 1.5 feet toward the lake. Two small slumps broke to the top of the embankment near the bedrock cut at mile 33.9. In both places the slumps appear to have been caused by failures within the underlying lake sediments.

North from the bedrock cut at mile 34, the embankment passed onto the delta where it settled irregularly with sags of about 1.5 feet and lateral displacements in both directions of about 1 foot. At miles 34.3 and 34.4, possibly where small timber bridges had been removed and small channels filled in, the embankment bulged upward. At the bulges the rails were thrown into compression and kinked sidewise; at mile 34.4 the deflecting rails dragged the ties laterally through the ballast (fig. 94). This is one of the few places in which there is evidence that the embankment may have been compressed longitudinally.

The 105-foot open wood trestle bridge at mile 34.5 was compressed so severely (2.2 ft) that the stringers jackknifed up off the piles and broke in the center of the span (figs. 13, 95). The piles were shifted toward the stream channel, and sand that had been ejected with ground water from cracks in the streambed covered the bed to a depth of several inches. Details of damage to this bridge are given on page D51.

Between bridges 34.5 and 34.7 the embankment settled with dips of about 3 feet (fig. 96). Bridge 34.7 and the succeeding bridge at mile 34.8, both 105-foot-long open wood trestles, were pulled apart as the underlying sediments were distended. The distance between the bulkheads increased by 1.1 feet at bridge 34.7 and three-quarters of an inch at bridge 34.8. Despite the fact that both bridges were pulled apart, both showed evidence of endways pounding. Bridge 34.7 had two pebble dents between the south bulkhead fillers and the last bridge tie, and the stringers of bridge 34.8 had been rammed into the north bulkhead. Both bridges were arched by vertical pile displacement about 2 feet over the full length of the deck. The crests of the arches were at about the centers of the spans, and the stringers were bearing on all bents but those at the bulkheads, above which they were cantilevered as much as 5½ inches (fig. 97). Sand ejected with ground water from cracks in the floor of the creek beneath the bridge at mile 34.7 formed a mound about 1 foot high (fig. 17).

Between bridges 34.8 and 35.6 there was an area of extensive flooding. The embankment settled probably 1 to 2 feet into the flood plain without developing large local sags; however, about 1,000 feet of the embankment just north of bridge 34.8 shifted approximately 5 feet to the south. At mile 35, longitudinal compression of the rails, possibly resulting from longitudinal compression of the embankment, drove the rails and their attached ties sidewise across the tops of the embankment (fig. 98).

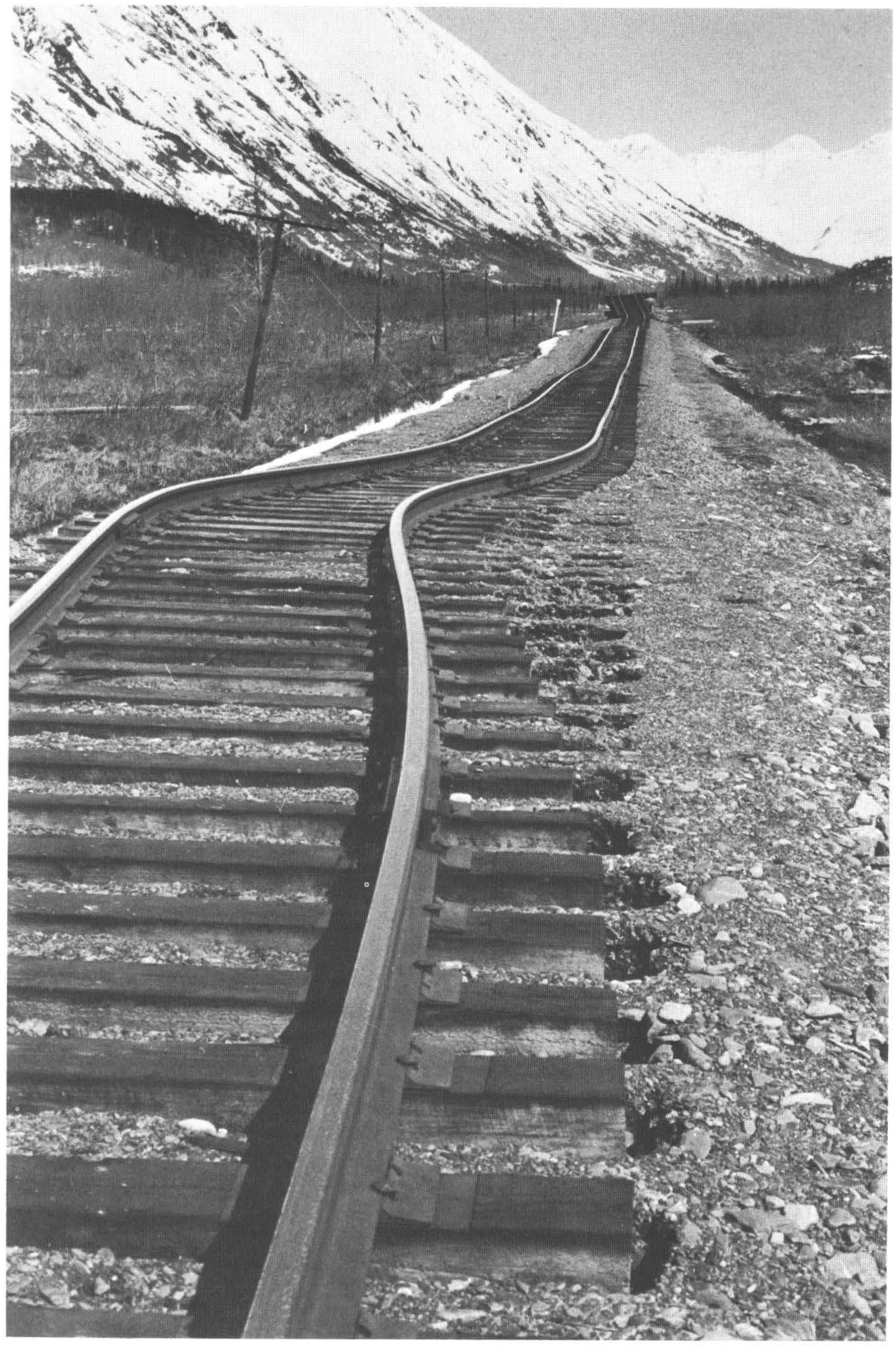
Damage to the 98-foot open wood trestle bridge at mile 35.6 was similar to that at 34.5 and 34.7, in that endways pounding of the bridge drove the stringers into both bulkheads, but the sediments beneath the bridge were distended, and the bulkheads were pulled 4 inches away from the ends of the stringers. Tension resulting from the distension of the sediments sheared bolts in the angle bars and pulled the rails 7 inches apart on the bridge deck. The bridge was arched about 1.5 feet; the crest of the arch was at the center of the bridge, and the stringers were bearing on all but the fourth bent.

The nearby bridge at mile 35.8, an 84-foot open wood trestle, was compressed as the streambanks moved toward the creek. Stringers were rammed into the bulkheads and the bulkheads were driven back into the fills. The piling was displaced both toward the creek and vertically; the displacement produced an arch of 10 inches with its crest at the fourth bent.

SECTION 10. HUNTER FLATS ALLUVIAL FAN

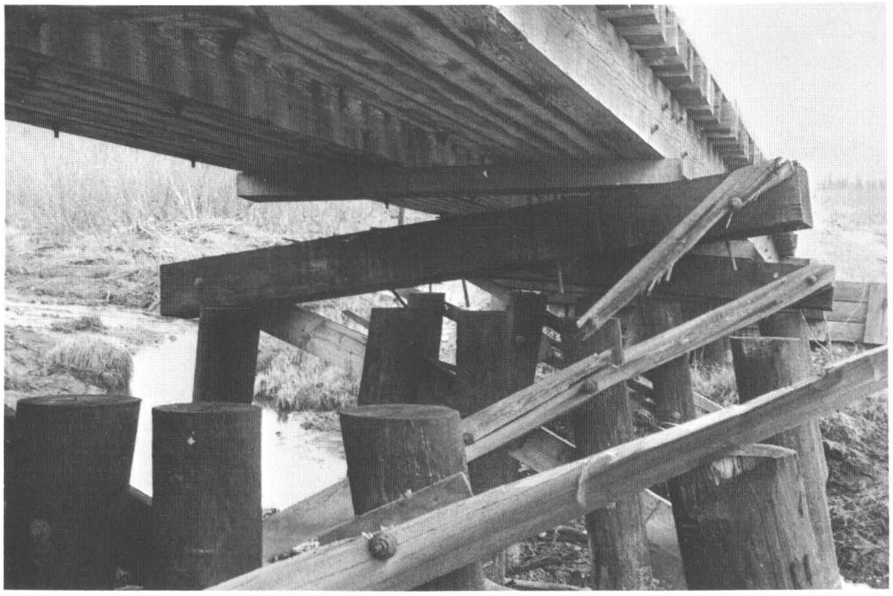
At mile 36 the rail line leaves the flood plain briefly, and is built for a short distance across the nearly level toe of a large alluvial fan. This fan was deposited by a stream that rises at small glaciers high on the southern valley wall. The stream has a gradient of approximately 675 feet per mile for its 4-mile length, and the material in the fan is probably considerably coarser than the flood-plain sediments.

The fan is divisible into a high-standing older and a low-standing younger segment, numbered 1 and 2 respectively in figure 92. The older segment, which supports a heavy stand of conifers, was almost unfractured. The younger segment was fractured in the pattern typical of alluvial fans (pl. 2). Near the margin of the young part of the fan an open network of fractures that intersected generally at about 60° formed elongate parallelogram-shaped blocks with long axes approximately parallel to the contours. Farther downslope, on the edge of the fan and on the adjacent flood plain, water was ejected from irregular fractures that trended generally across the contours.



94.—A lateral buckle in the track at mile 34.3, possibly a result of longitudinal compression of the roadbed fill. Bridge 34.5 is visible in the background.

Where the embankment crossed the zone of cracking on the edge of the fan, it was broken by tension fractures, and a crack as much as 3 feet wide and several hundred feet long formed along the north side of the embankment. Measurements on aerial photographs indi-



95.—Caps pulled from bents and broken sway braces on the underside of the jack-knifed deck of bridge 34.5.

96.—Local settling of the railroad embankment between bridges 34.7 (foreground) and 34.5 on Hunter Flats.

cate that about 1,600 feet of the rail line was offset downslope on the fan, the maximum of approximately 3 feet being in the center of the offset. The stream on the alluvial fan has been diverted against the south valley wall by dikes built by The Alaska Railroad. The dikes (centerlines shown on pl. 2), which are composed of fan sediments bulldozed into ridges, appear to have had little or no effect on the fracture pattern. The northern dike was cracked where it passed into the zone of marginal cracking, but no more seriously than the underlying and adjacent fan.

SECTION 9. HUNTER FLATS FLOOD PLAIN (continued)

Just east of the alluvial fan, at mile 37.0, the deck of a 435-foot open wood trestle was compressed approximately 21½ inches; the compression buckled the stringers 6 feet laterally over a length of 60 feet near the north end of the bridge. The stringers were broken at the points at which they were deflected and at the apex of the bend. Bents that remained attached to the deflected stringers were carried sidewise through the sediments and racked. In figure 99 the outermost pile on the bent near the point of the bend—a pile that originally had an outward batter of 10° (fig. 4)—can be seen tilting slightly under the bridge. There was a general crowding of the piles toward the stream, and about 600 feet of the northern approach fill shifted approximately 2 feet toward a water-filled slough along the embankment toe (fig. 56).

At mile 37.3, a 75-foot wood trestle sustained similar damage (figs. 12, 59). Its deck was compressed 7¼ inches and the stringers buckled about 4 feet to the east at the third bent. Piles shifted toward the channel between the fourth and fifth bents, and the deck developed an arch of about 6 inches. Approximately 400 feet of the embankment north of the bridge shifted toward a wet low area adjacent to the rail line (fig. 12), producing a horizontal offset of about 2 feet between the ends of the bridge.

North and east of the alluvial fan there was extensive ground cracking and flooding in the active and inactive flood-plain sediments that cover the valley floor. Farther to the east a glacial outwash terrace that stands above the flood-plain sediments was much less affected. A few fractures formed along its margins, where cracking in the adjacent inactive flood-plain sediments extended into the outwash terrace. The only cracking of any consequence to the railroad on the outwash terrace was at about mile 39, where the embankment was broken by tension fractures as it crossed a northeast-trending zone of fractures running across the terrace surface (fig. 100).

Shaking dislodged many large avalanches from the steep southern valley wall at the western end of the valley (pl. 2). The avalanche tongues, which were composed primarily of snow, were fractured where they were spewed out onto the valley floor. In some places the fractures in the avalanche debris were continuous with fractures in the underlying valley sediments. The avalanches were probably triggered by the early strong motion reported by eyewitnesses in nearby communities and were later fractured as continued shaking mobilized the underlying valley sediments. One of the avalanches produced an air blast that plastered snow against trees for a distance of about 100 feet beyond the end of the avalanche. Avalanche-generated airblasts that extend beyond the limit of the avalanche deposits and plaster snow on trees are well known (Mellor, 1968, p. 75).

SECTION 11. HUNTER TO SPENCER GLACIER

At Hunter (mile 40) the flat valley floor narrows abruptly and from here to Grandview (mile 45) the rail line is built along the northwestern valley wall in cuts and small fills to the side and above the flood-plain sediments (fig. 101). Ground cracking here was much less than at Hunter Flats, and was virtually confined to the unvegetated active flood-plain sediments, so that the rail line was unaffected by ground cracks. The only bridge (41.6) between Hunter and Grandview is a 70-foot open wood trestle. Eighteen feet of its 20-foot-high northern approach fill dropped about 1.5 feet. It sank as a single block bounded by a crack at the bulkhead and a crack that crossed nearly perpendicular to the embankment (fig. 102). The bridge was compressed and its bents were crowded toward the center of the bridge. There was no other significant damage from Hunter to Grandview.

97.—Stringers of extended bridge 34.7 that were pulled 4½ inches away from the north bulkhead and cantilevered 5½ inches up off the bulkhead bent.

Leaving Grandview the rail line runs north in the narrow glaciated valley of Placer River. Thin discontinuous patches of glacial drift cover the valley floor and a narrow band of alluvium borders the river. At about mile 47.5 the rail line crosses a morainal ridge built by Bartlett Glacier, traverses an outwash plain, and then passes through six tunnels driven through bedrock spurs along the canyon cut by Placer River. Throughout this entire section, from mile 45 at Grandview to mile 52.7, there was

98.—Lateral kinks in the tracks, at mile 35 on Hunter Flats, which may have resulted from longitudinal compression of the embankment.

no damage to the embankment, tunnels, or any of the six bridges. This absence of damage is attributable to the fact that the tunnels and three of the bridges are built on bedrock and the remaining three bridges (46.8, 47.2, and 47.5) and culvert are underlain by only a thin section of unconsolidated materials. Ground motion was nevertheless violent enough to shift the position of the water boilers in the section house at Tunnel (mile 51) and to cause considerable damage to the connecting pipelines.

SECTION 12. PLACER RIVER, PORTAGE CREEK, AND TWENTYMILE RIVER FLOOD PLAINS

In contrast to the absence of damage in the narrow bedrock valley of the preceding section, some damage occurred where the rail line enters the broad flat-floored valley of Placer River that is underlain by unconsolidated sediments (fig. 103). Damage increased markedly northward. Severe damage continued on the adjoining flood plains of Portage Creek and Twentymile River to the north. For example, of the 17 bridges between mile 52.7 and mile 64.7, fifteen are open wood trestles on wood piles. Of these 15 bridges, four were damaged beyond repair, two were replaced with entirely new bridges, and two were replaced with culverts. All or part of the piling of six bridges was replaced, and the decks and stringers of eight bridges were either entirely replaced or extensively repaired. Embankments also sustained considerable distortion.

The only subsurface information available for this section is for the Portage area, but some inferences about the subsurface materials can be made by using arguments similar to those used for the Hunter Flats area (Section 9). The absence of evidence for a well-developed ice-front stillstand within the valley suggests that the large glaciers that filled Placer River valley withdrew relatively rapidly. The steep bedrock valley walls indicate that the bedrock floor of the valley may lie at considerable depth beneath the filling of unconsolidated sediments. Furthermore, a 600-foot-deep well in Portage did not encounter bedrock. After the ice retreated, Turnagain Arm probably extended a considerable way into the valley, as shown by fine-grained estuarine sediments within this well. With time, glacial-outwash streams built deltas and outwash plains over the fine deposits of the arm, until the shoreline reached its present position. If this reconstruction is generally correct, the thickness of the unconsolidated sediments overlying the glacially eroded bedrock floor probably increases and contains more fine-grained material toward the modern shoreline. The details of the subsurface data available at Portage are given on pages D129–D132.

Because Section 12 is long, it is divided into Subsections, 12a, the Placer River valley, and 12b, the Portage area on the flood plains of Portage Creek and Twentymile River.

SECTION 12A. PLACER RIVER FLOOD PLAIN

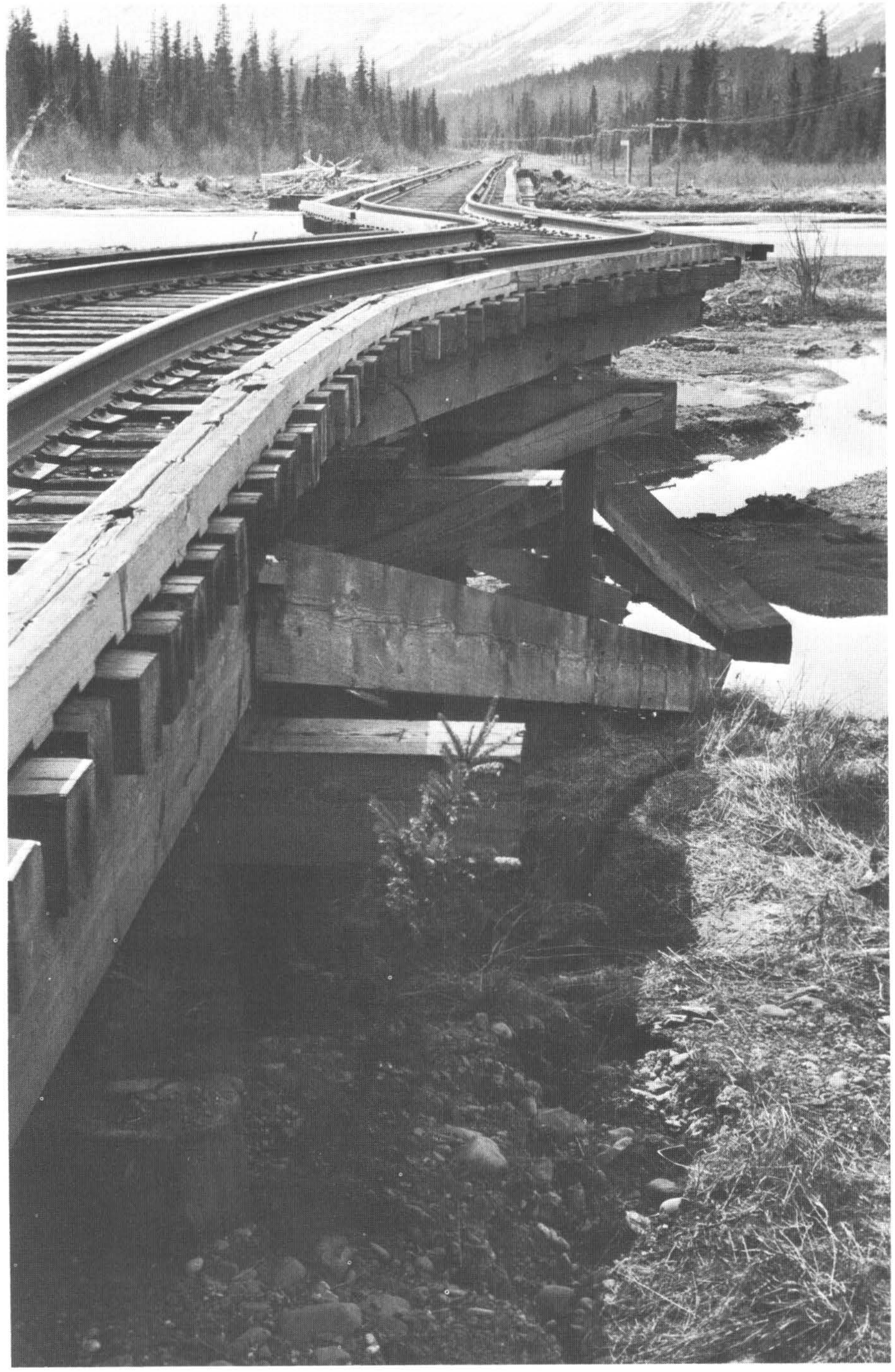
On entering the valley at about mile 52.7, the rail line swings abruptly west along the toe of the slope. A massive snow slide about half a mile wide was dislodged from the slope and covered the rail line, but did no damage. Leaving the edge of the slope, the line turns northeast and crosses Portage River on a morainal ridge. At this point the river is greatly enlarged by the melt water from nearby Spencer Glacier. The bridge across Portage River, a 200-foot steel through truss with two 28-foot wood trestle end spans, was not seen by the authors, but Bruce Cannon, engineer of structures, reports that the only damage was a slight jamming of the spans.

In the southern end of this valley as far as mile 59.6, observations were limited to bridges, because the rest of the rail line was covered with snow. However, the distribution of surface cracking along the rail line is known from aerial photographs. The glacial outwash terrace that lies in front of Spencer Glacier was unfractured. Cracking was greatest in swampy areas near Spencer (mile 55.8 to 57.5) and along stream margins from mile 58.2 to 58.8.

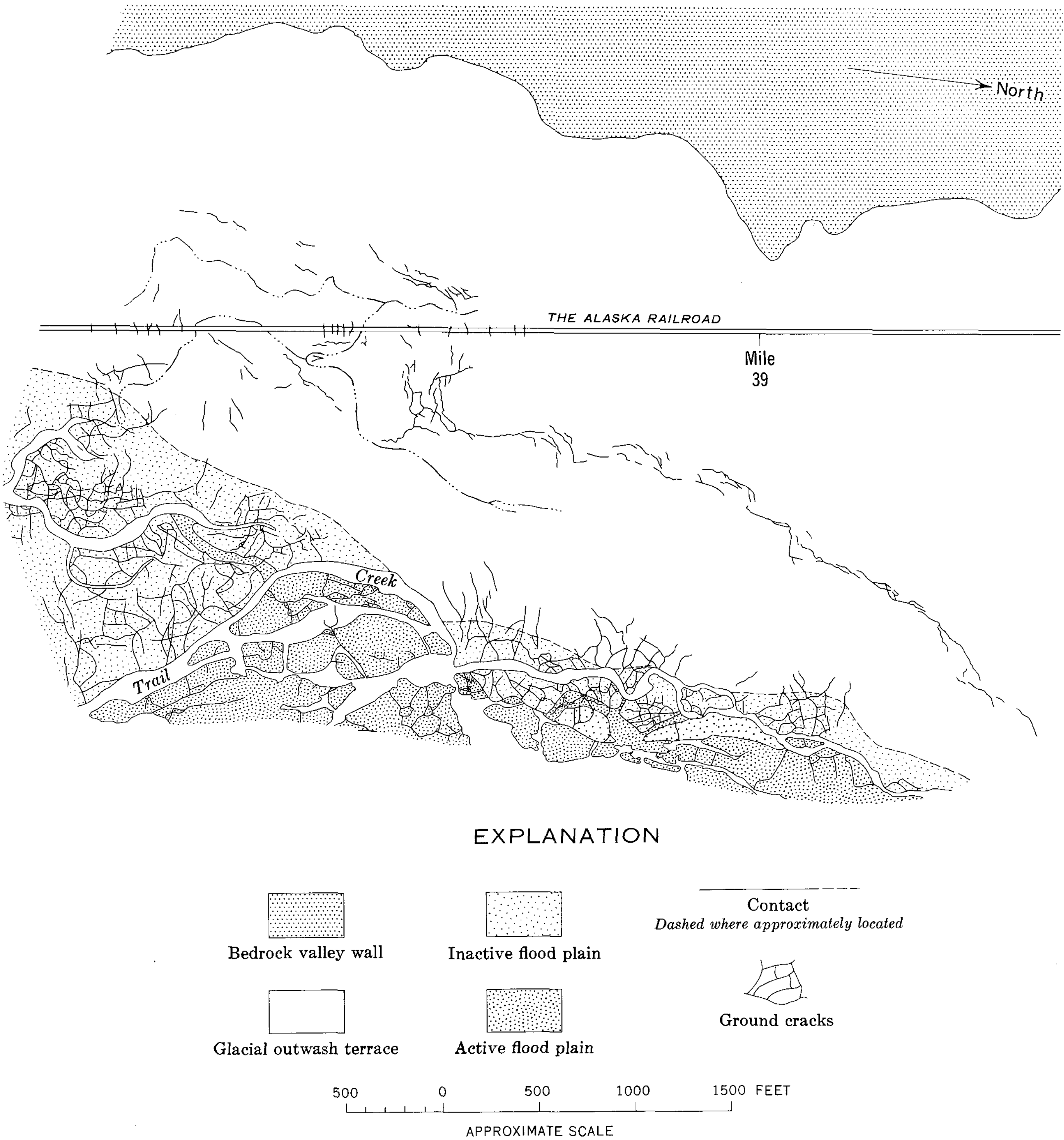
From at least a quarter of a mile south of bridge 59.6 to as far north as bridge 59.9, the embankment, which is built on the flood plain of Skookum Creek, has acted as a dike and has deflected the braiding creek channels through two bridges. In doing so, the embankment has trapped sediments on the eastern uphill side and raised the ground level by perhaps 2 to 3 feet. The water table appears to be nearly at the surface on both sides of the embankment, but there was more standing water on the higher ground. Cracking occurred on both sides of the embankment, but was more extensive in the higher wetter ground.

South of bridge 59.6 the embankment was thrown into swales with amplitudes of as much as 2.5 feet and was shifted irregularly sidewise toward the low ground. At bridge 59.6, a 45-foot four-bent open wood trestle, the approach fill was lowered 1.5 feet relative to the deck (fig. 104). The bridge was severely compressed as the streambanks converged; the stringers were driven 14 inches through the south bulkhead and the piles were crowded toward the stream (fig. 105). The bridge was also skewed, the north end moving 8 inches east relative to the south end. The north approach fill was 4 to 6 inches below the deck, and large cracks parallel to the track formed in the edges of the embankment.

From bridge 59.6 to 59.9 the embankment was generally lowered 1.5 to 2.5 feet below the level of the bridges; superimposed short-wavelength swales had amplitudes of about 0.5 foot. There was also a maximum of about 5



99.—Laterally buckled deck of bridge 37.0, on Hunter Flats. The buckling stringers broke free of some bents and pulled others (at apex of bend) laterally through the sediments.



100.—Ground cracking near mile 39 in the active and inactive flood plains of Trail Creek and in glacial outwash terrace. Most cracks in the active action and inactive flood plains are orthogonal and related to landspreading. The cause of the linear zone of cracks in the outwash terrace is not known. The cracks across the embankment in this zone are tension fractures.

EXPLANATION

Active flood plain

Horizontally bedded sand and gravel with sand predominating. Surface subject to flooding at high discharges. Usually lies entrenched within inactive flood plain. Water table at or near surface. Usually free of vegetation

Inactive flood plain

Horizontally bedded sand and gravel with sand predominating. Not inundated by normal high discharges. Usually lies a few feet above active flood plain. Water table probably 2 to 10 feet below surface. Commonly supports growth of shrubs and trees

Fan delta

Alluvial fans and fans that become deltas where deposited in standing water. Clasts in alluvial fans are as large as boulder size if stream gradient is steep. Deltaic portions likely to contain finer sediments

Glacial outwash terraces

Generally flat terraces, often above inactive flood plain. Horizontally bedded sand and gravel. Grain size commonly coarser than in inactive-flood-plain terrace

Glacial till on bedrock

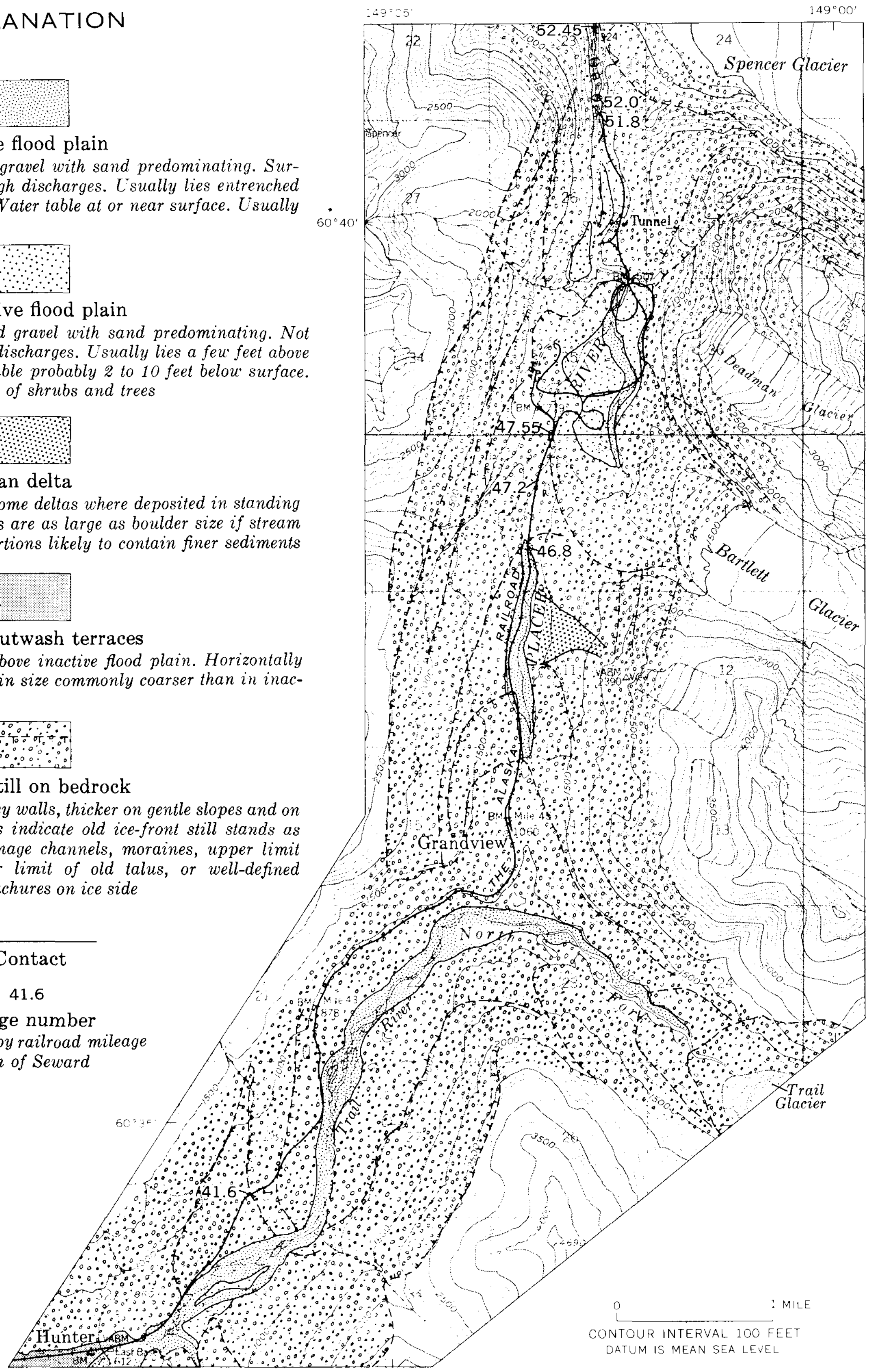
Till thin or absent on steep valley walls, thicker on gentle slopes and on valley floors. Hachured lines indicate old ice-front still stands as shown by ice-marginal drainage channels, moraines, upper limit of ice-carved bedrock, lower limit of old talus, or well-defined moraines on valley floors. Hachures on ice side

Contact

41.6

Bridge number

Indicated by railroad mileage north of Seward



Base from U.S. Geological Survey 1:63,360 Seward C-6, 1963

Geology by D. S. McCulloch, 1964-69

101.—Surficial geologic-physiographic map of the rail belt from Hunter to Spencer Glacier.

102.—View north over bridge 41.6, where 18 feet of the approach fill was lowered about 1.5 feet. Photograph by The Alaska Railroad.

feet of irregular horizontal shifting, again, all toward the low ground west of the line (fig. 104). Cracking was severe, but more severe in the wetter ground to the east, and sand was commonly ejected from the cracks—especially from cracks adjacent to swales in the embankment.

At the south approach of bridge 59.9, a 180-foot 13-bent open wood trestle, long cracks formed parallel to the track in the sloping edges of the embankment, and three cracks crossed the embankment at nearly right angles. The bridge itself was severely compressed, the stringers being driven 15 inches through the planking of the north bulkhead. Piling was crowded toward the center of the stream and the bridge was skewed horizontally, its north end moving 3 feet east relative to the south end (fig. 106). The piles were also carried horizontally toward the center of the stream and sidewise under the skewed bridge deck. The north approach was lowered 31 inches relative to the deck, from which it was separated by a crack. This crack joined large cracks that paralleled the track in the sloping edges of the embankment.

For three-quarters of the way from bridge 59.9 to bridge 60.15, the rail line is built on the same vegetation-free flood-plain surface of Skookum Creek that underlies it from a point south of bridge 59.6. Consequently, there was considerable vertical and horizontal displacement of the embankment accompanied by extensive ground cracking. In the remaining quarter of the way to bridge 60.15, the rail line is underlain by somewhat higher terrace covered with scrub willow. On this terrace, ground cracking was minor and the embankment was little disturbed. At bridge 60.15, a six-bent 75-foot open wood trestle, there was only slight compression, but the deck was arched upward about 10 inches. The crest was located at the third bent from the south end, and stringers on the east side were cantilevered half an inch above the bulkhead bent. The stringers rammed the north bulkhead and penetrated 2 inches into the fillers. Piling was shifted toward the central part of the stream valley. The embankment of the north bulkhead was lowered 2.5 feet along a fracture on the north side of an abandoned bulkhead buried in the embankment fill. The fractures continued out across the edges of the embankment and crossed fractures running parallel to the embankment.

Three hundred feet north of bridge 60.15, a section of the embankment built over a filled-in bridge stood somewhat higher than the adjacent embankment. The bents of the buried bridge were exposed by slight slumping of the western edge of the embankment fill. From the end of the buried bridge to bridge 60.4, long-wavelength low-amplitude swales developed in the embankment, and cracks formed parallel to the embankment in the valley-floor sediments on both sides of the rail line.

Bridge 60.4 crosses a small sluggish creek in a brush-covered area at the west edge of slightly higher, slightly better drained ground. Cracking in the embankment adjacent to the bridge was minor. The toe of the western edge of the embankment on the south side of the creek settled a few inches along a crack that ran parallel to the embankment for several tens of feet back from the bulkhead. There was minor slumping and associated fracturing of the embankment material where it was adjacent to the creek at the north bulkhead. Cracking accompanied by the discharge of sandy water was more severe in the higher valley-floor sediments east of the embankment on both the north and south sides of the creek. Some ground cracks continued across the shallow creek bottom.

The bridge was a 45-foot four-bent open wood trestle. It was compressed as the streambanks moved streamward, and stringers were driven half an inch into the fillers on the south bulkhead and 2 inches into the fillers on the north bulkhead. The deck was arched upward about 4 inches, and piling was shifted toward the center of the stream. The rails at the south end of the bridge were deformed into an S-shape by compression; each bend in the S was displaced about 4 feet from its original position, and the S-bend was about 50 feet long. As the rails were deformed horizontally, they pulled the ties sidewise across the top of the ballast.

The north end of the bridge and about 275 feet of the adjacent embankment were shifted to the east. At the bridge, horizontal displacement was about 4 inches, but to the north it reached a maximum of about 2 feet. The displacement ended at a crack that crossed the embankment at nearly right angles and continued across the valley floor. Horizontal displacement of the embankment was due to the movement of the valley-floor sediments, and not to failure within the embankment fill. Movement of the valley-floor sediments was also evident from a comparable horizontal offset in the pole line 50 feet west of the embankment.

From bridge 60.4 to bridge 61.1, the embankment had no obvious lateral distortion and no local swales developed. Discontinuous minor cracking occurred in the valley-bottom sediments, but it was localized to within about 10 to 15 feet from the edge of the embankment. In the last 850 feet south of bridge 61.1 where the embankment approaches the active flood plain of Placer River, the western side slope of the embankment was broken by fractures running approximately parallel to the rail line, and at the bridge there was minor cracking of the eastern side slope of the embankment. The embankment was lowered approximately 1 foot relative to the bridge deck.

Bridge 61.1, a 60-foot five-bent open wood trestle, was compressed a total of about 16¾ inches, its stringers acting as struts as they were driven into the bulkheads. The stringers penetrated 2 inches into the fillers on the south bulkhead, and on the north they rammed the bulkhead planks off the fillers and carried them back over the top of the fill that was lowered about 18 inches at the bulkhead. The north bulkhead was also lowered about 5 inches, which produced an arch in the bridge.

The stream runs along the east side of the embankment south of the bridge, then turns and crosses under the bridge at nearly right angles; it then turns again and runs north along the western edge of the embankment. Each approach fill moved toward the adjacent creek, the south approach shifted east, the north approach west. Shifting skewed the bridge about 8 inches horizontally. Piling was shifted not only sidewise with the skewing deck but also streamward. Following the usual construction practice, piles at the bulkhead were not connected by sway braces. This allowed the piles at the south bulkhead to move independently; all piles moved toward the creek and the central pile of the bent moved 10 inches more than piles at the ends of the bent.

North of the bridges the embankment was lowered about 1½ feet for a distance of about 65 feet, then about 1 foot beyond. The toes of the fill were lowered along cracks that ran a few feet back from the bulkhead. A crack that formed across the embankment several feet from the bulkhead ended at these cracks in the embankment toes. The fill beside the bulkhead was lowered slightly along this crack, but most of the movement on the crack was horizontal, and the fill near the bulkhead was pulled away from adjacent fill.

Between bridges 61.1 and 61.3 the embankment developed swales with amplitudes of as much as 1 foot. Cracks formed in the toe of the fill and in the adjacent sediments along both sides of the embankment. Cracks along this section of the embankment, which continued for a distance of several miles to the north, are shown on plate 3, a map made from aerial photographs. As can be seen on this plate, cracking increased at the bridges. There was also some lateral displacement of the embankment. North and south of bridge 61.3 the embankment shifted westward, and the maximum displacement occurred at the bridge. This displacement is shown in figure 107 by the misalinement of the right-hand rail in the foreground and background.

Bridges 61.3, a 60-foot five-bent open wood trestle, was compressed 5 inches; the stringers rammed 3 inches into fillers on the south bulkhead and 2 inches into the north bulkhead. Piles shifted streamward, the deck was arched upward approximately 6 inches, and the rails accommodated the compression by pulling free of the ties and bowing outward on the deck. Compression also deformed the rails; on the south approach

EXPLANATION

Active flood plain

Horizontally bedded sand and gravel with sand predominating. Surface subject to flooding at high discharges. Usually lies entrenched within inactive flood plain. Water table at or near surface. Usually free of vegetation

Inactive flood plain

Horizontally bedded sand and gravel with sand predominating. Not inundated by normal high discharges. Usually lies a few feet above active flood plain. Water table probably 2 to 10 feet below surface. Commonly supports growth of shrubs and trees

Fan delta

Alluvial fans and fans that become deltas where deposited in standing water. Clasts in alluvial fans are as large as boulder size if stream gradient is steep. Deltaic portions likely to contain finer sediments

Glacial outwash terraces

Generally flat terraces, often above inactive flood plain. Horizontally bedded sand and gravel. Grain size commonly coarser than in inactive-flood-plain terrace

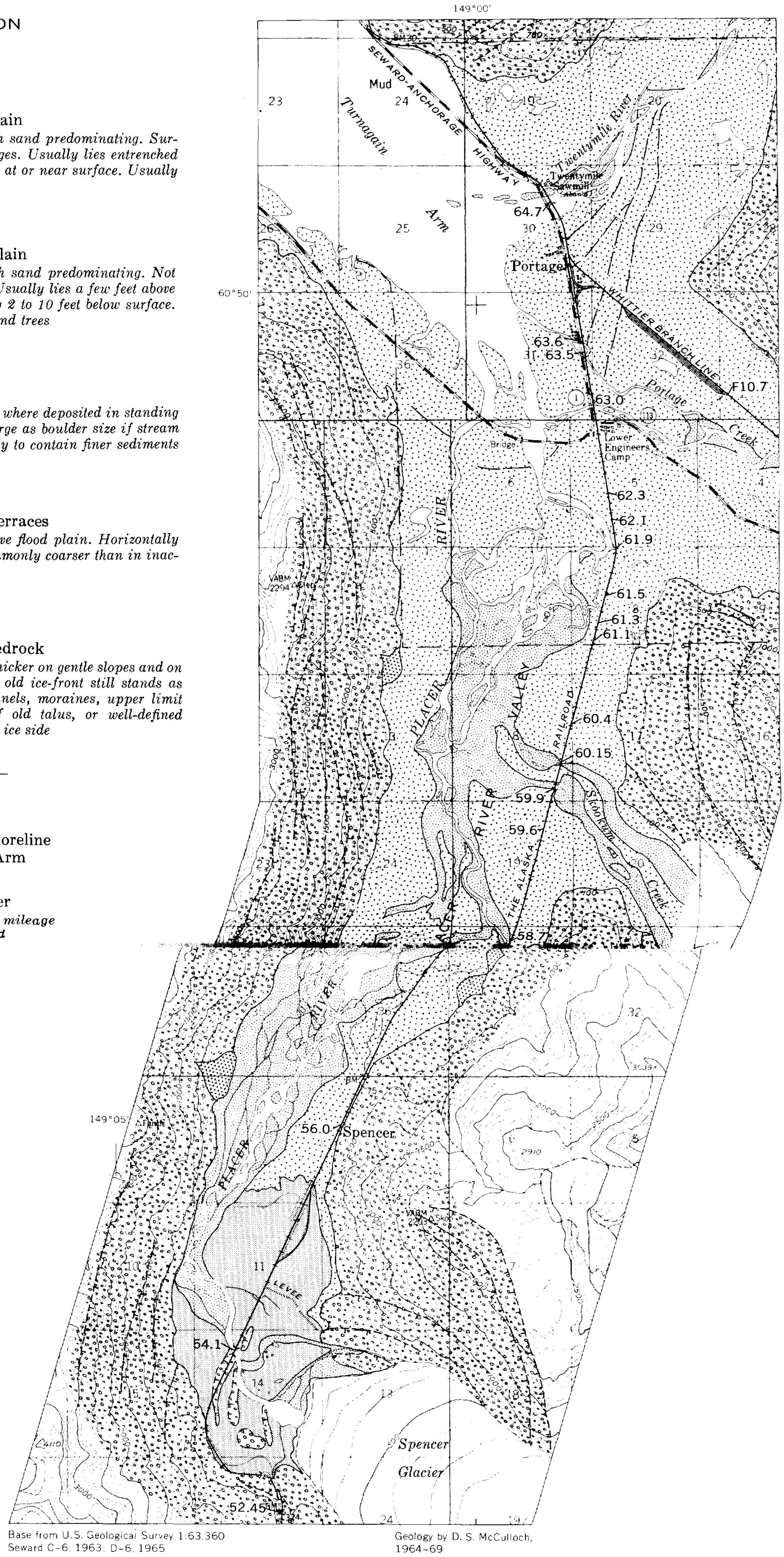
Glacial till on bedrock

Till thin or absent on steep valley walls, thicker on gentle slopes and on valley floors. Hachured lines indicate old ice-front still stands as shown by ice-marginal drainage channels, moraines, upper limit of ice-carved bedrock, lower limit of old talus, or well-defined moraines on valley floors. Hachures on ice side

Contact

Possible former shoreline of Turnagain Arm

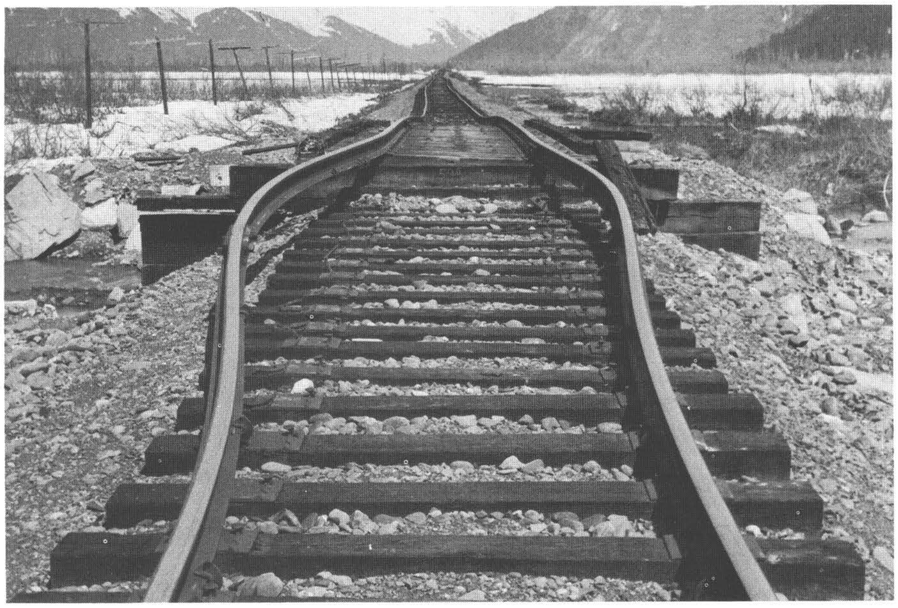
56.0
Bridge number
Indicated by railroad mileage north of Seward



Base from U.S. Geological Survey 1:63,360 Seward C-6, 1963; D-6, 1965

Geology by D. S. McCulloch, 1964-69

103.—Surficial geologic-physiographic map of the rail belt from Spencer Glacier to Twentymile River.



104.—View north over bridge 59.6, showing the lowering of the embankment relative to the bridge, compressive bowing of the rails, skewing of the deck, and horizontal displacement of the embankment toward the low ground to the left of the roadbed. The ties were frozen in the ballast, and the rails pulled free of the fish plates.

fill and the south end of the deck the rails bowed inward, and the west rail was torn free of the ties. On the north approach and northern end of the deck both rails bowed outward and both were torn free of the ties.

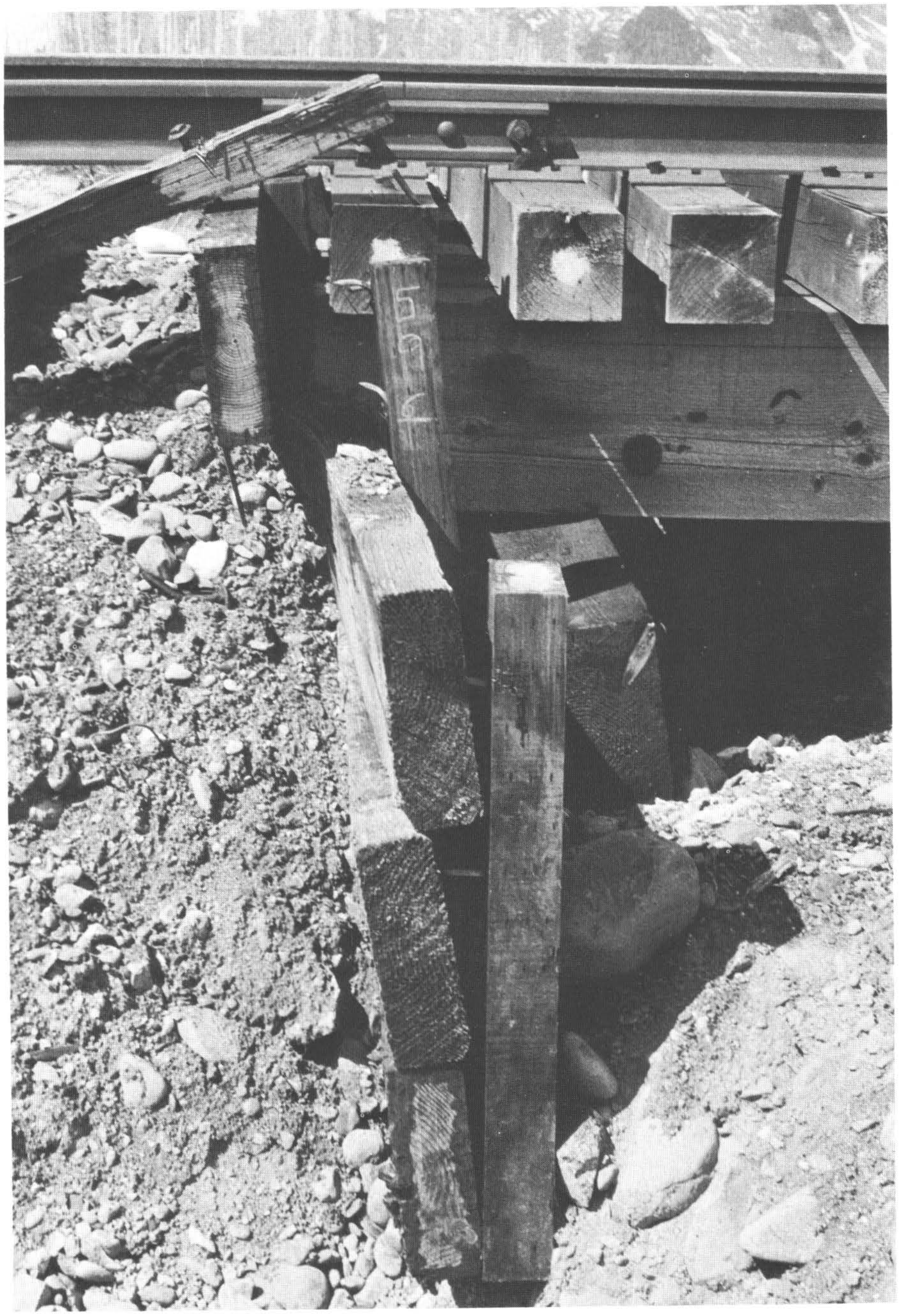
The embankment north and south of the bridge was also lowered relative to the bridge. The unweathered light-colored wood on the bulkhead visible in figure 107 was exposed by this lowering. As can be seen in this figure, lowering of the fill was not localized at the bulkhead.

North of bridge 61.3 the embankment was lowered about 6 inches but stayed relatively flat for about 200 feet. Then to the north, where the embankment has acted as a dam to pond water on the east and raise the level of the ground-water table, it was lowered an additional 2 feet. The embankment continued north at about the same level for 250 feet more and was then shifted laterally to the west over a distance of about 600 feet, with a maximum horizontal displacement of about 2 feet.

As shown on plate 3, the embankment between these bridges runs parallel to a small estuary channel of Portage Creek. Cracking occurred along the margins of this channel as well as the larger channels to the west. In some places, cracks formed continuously for as much as 250 feet back from the channel edges. The plate also shows that the embankment was displaced horizontally in the area where the cracking indicates streamward movement of the flood-plain sediments. Cracks generated by the embankment fill occurred along the embankment sides, in the side slopes of the fills, and on the adjacent valley floor. These cracks are clearly visible in the southern half of the section, where the pattern of the cracking is not confused by cracking related to streamward displacement.

Bridge 61.5, a 13.8-foot two-bent open wood trestle, was compressed by streamward movement of the sediments beneath the bridge and embankments. Compression at the deck was about 4 inches and was absorbed by the crushing of the fillers and the forcing of the bulkheads back into the fill. Compression also deformed the rails; on the south approach and south side of the deck, the rails bowed inward, and the left rail was torn free of the ties; on the north side of the deck and north approach, both rails bowed outward and both were pulled free of the ties (fig. 108). An eastward displacement of about 160 feet of the north approach, toward a backwater slough of the creek that lies adjacent to the embankment, produced an 18-inch horizontal skew in the bridge. After the structure was skewed horizontally, the compressive force of the stringers (acting as struts) was directed at an oblique angle to the bulkhead, and, during the subsequent compression, the top of the bulkhead and the bent to which it was secured were racked to the east.

Both approach fills were lowered below the deck, 6 to 10 inches on the south, 18 inches on the north. Lowering was not localized at the bulkheads, and, in fact, the embankment rose slightly toward the bulkhead (fig. 109). Such a rise was common in bridge approaches, and it appears that the embankments, which were being carried toward the creek by the movement of the underlying material, were bulldozed up against the bulkheads as the stringers resisted compression. This explanation is also suggested by the fact that the piling was commonly carried farther toward the creeks than the bulkheads, which were held back by the stringers.



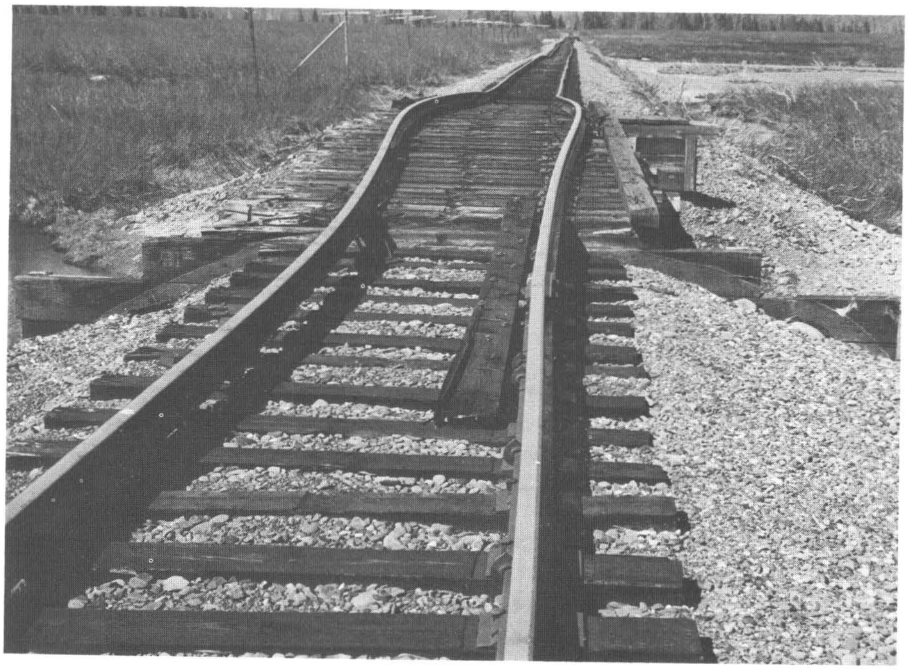
105.—The stringers of bridge 59.6 driven into and through the bulkhead planks.

North from the bridges, the 160 feet of embankment that was shifted eastward toward the slough, was severely cracked on the west side of the fill, but, although lowered about 2 feet below the bridge, the surface stayed almost flat. At the end of this 160-foot section, the grade rose slowly northward, about 1 foot, and maintained a nearly flat surface into the curve shown in the background of figure 108 and plate 3. South of the curve, cracks were formed on the west side of the embankment and appear to have been caused by the embankment.

As the embankment approached the tributary to Placer River at bridge 61.9, it traversed an area of cracking localized by the stream margin that extended 200 feet back from the river. A considerable amount of silt and sand was ejected from the cracks. Four large tension cracks crossed the embankment at nearly right angles in the 200-foot-wide zone of stream-margin cracking. The embankment surface was lowered perhaps a foot, but rose in the last 15 feet south of the bridge to meet the deck. At this same end of the bridge, silt was ejected up through the embankment along cracks that ran diagonally back from the bulkhead toward the edges of the fill. These cracks turned abruptly before reaching the outer edges of the fill and ran parallel to the embankment within the toe of the fill.

Bridge 61.9, a 103.8-foot eight-bent open wood trestle built on a curve, was compressed approximately 20 inches. The stringers crushed fillers on the south bulkhead and smashed through the north bulkhead planks. As noted in the discussion of transient horizontal displacements in bridges (p. D52–D53), the deck of this bridge may have developed a high horizontal acceleration. Penetration into and through the bulkheads released most of the compression on the stringers, but the rails, being restricted endways, reacted to the compression by horizontal deflection. On the south end of the deck, 40 feet of both rails bowed to the west a maximum of about 2 feet. The deflecting rails carried with them the alternate ties that were not secured to the bridge stringers and tore these ties free of the eastern guardrail to which they were lag screwed. Rails pulled free of the ties and bowed a maximum of 5 feet to the west over a distance of about 45 feet (fig. 110).

106.—View north over bridge 59.9 on Skookum Creek flood plain. It shows the lowered embankments, rails buckled by compression, and horizontal displacement of the embankment that produced a skew of about 3 feet in the bridge deck (see fig. 56).



107.—View north over bridge 61.3 on the inactive flood plain of Placer River. The bridge was compressed and arched, and, as shown by the freshly exposed unweathered wood on the bulkhead, the embankment settled at the bulkheads. Approximately 200 feet of the embankment north of the bridge shifted to the left.

As at bridge 61.5, the approach fills were locally bulldozed up by the bulkheads that were held apart by the stringers. At the same time the sediments under the embankment moved streamward and carried the piling toward the stream. There was also considerable lateral movement of the sediments toward the major channel of Placer River to the west of the bridge. The embankments at both ends of the bridge were carried westward. The north embankment, which was somewhat closer to the main channel and bounded by lower ground, was carried farther; thus the north end of the bridge was skewed about 2 feet west relative to the south end. The piling was also carried laterally toward Placer River.

SECTION 12B. PORTAGE CREEK AND TWENTYMILE RIVER FLOOD PLAINS

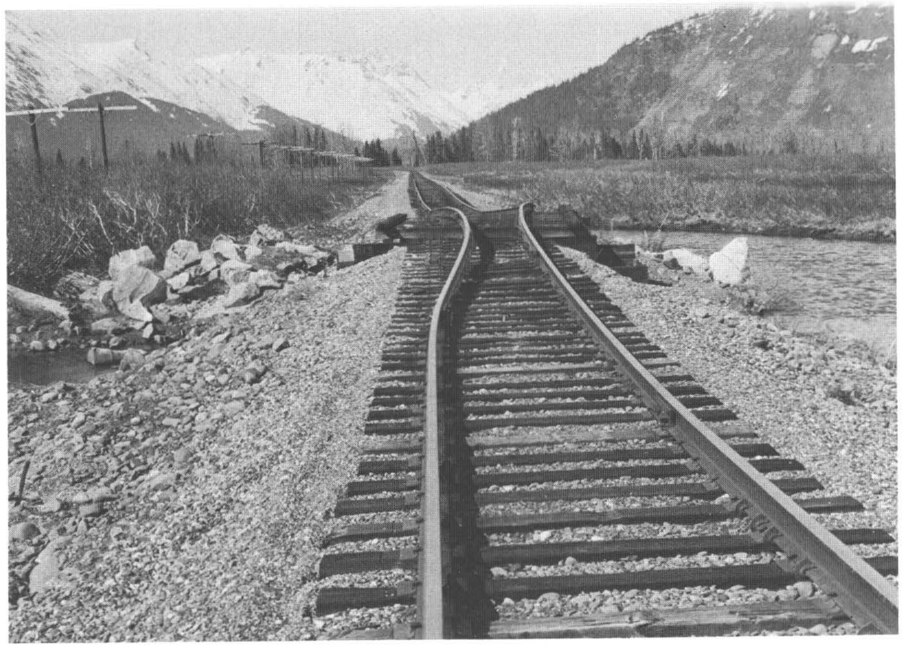
The embankment and bridges in the 3¾ miles north of bridge 61.9 sustained extremely severe damage where the rail line passes over the flood plain of Portage Creek, through the town of Portage, and across the flood plain of Twentymile River. In addition to the damage caused by streamward displacement of flood-plain sediments and settling of the grade into the underlying materials (more marked here than in most areas), regional subsidence of about 5.2 feet, local compaction of the flood-plain sediments, and some spreading of the embankment all contributed to the lowering of the embankment to near or below high-tide level which made it subject to wave and tidal current erosion.

The flood plains of Portage Creek and Twentymile River join at the edge of Turnagain Arm and form a continuous, nearly flat surface dissected by small interconnecting sloughs (fig. 103). The surface is covered by open marshy grasslands bordered by slightly higher, better drained ground that supports small isolated stands of conifer and willow. The surface is generally flat and the total relief is low; the highest part of the combined flood plain is about 20 feet above the shoreline of Turnagain Arm. Local topographic relief is greatest at stream channels, but even here its maximum is only 28 feet on the major channels (bridge 63.5) and considerably less along the smaller sloughs.

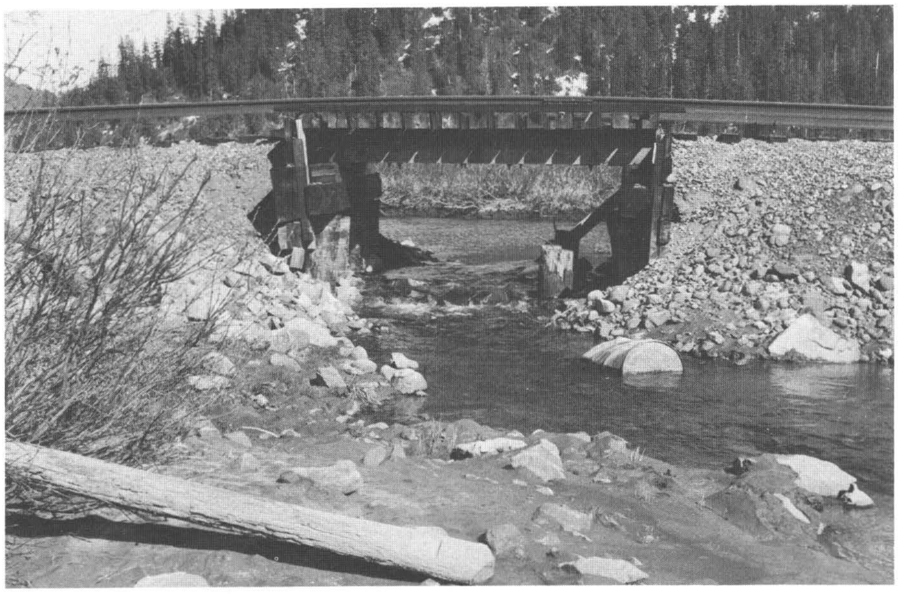
Despite the low relief and the general flatness of the interstream areas, there was considerable spreading of the flood-plain sediments toward topographic depressions.

Some data on the character of the unconsolidated sediments beneath the flood plain are available from two relatively deep preearthquake water wells and 14 shallower postearthquake bridge-site borings made by the Alaska Department of Highways and by Clair A. Hill and Associates (see p. D74). The wells and borings are located in figure 111, and their logs are shown in figure 112. The two deep water wells lie in Portage Creek valley: a 600-foot-deep well at the Union Oil Co. tanks, about 1,500 feet south of the junction of Seward Highway and Portage Highway 35, and a 500-foot-deep well, about 500 feet south of Portage Highway 35, 2 miles east of Seward Highway.

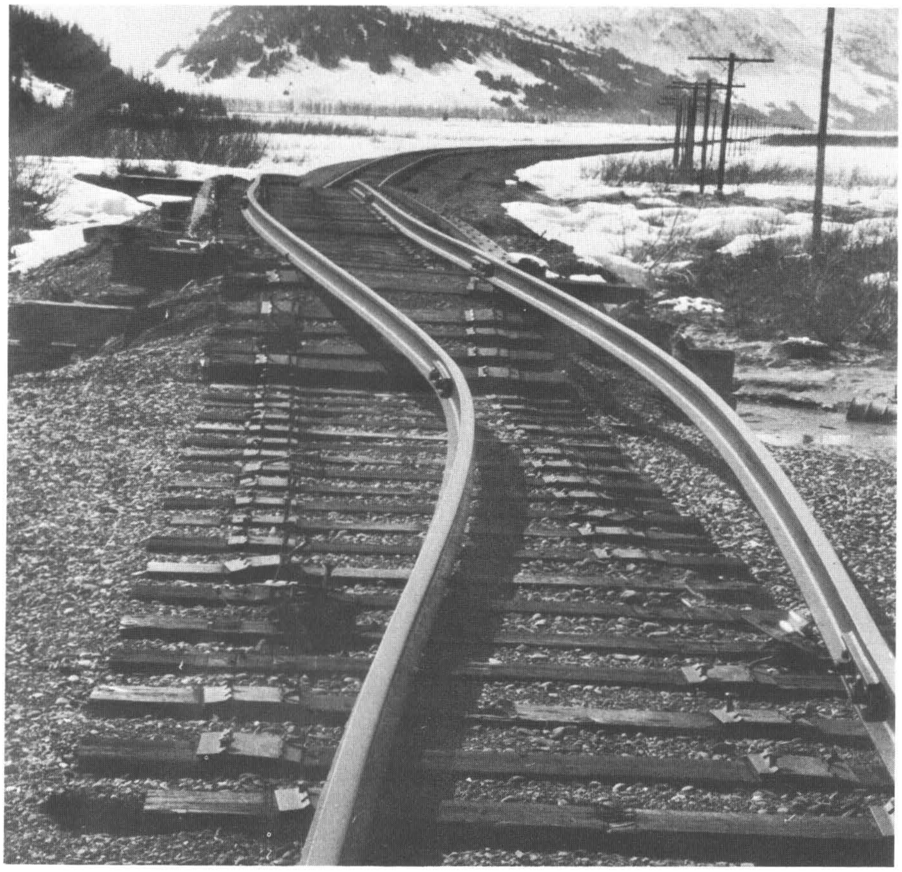
Both deep wells indicate a considerable but unknown total thickness of fine-grained unconsolidated sediments beneath the flood plain. If the field identifications are correct, the sampled sediments are predominantly of clay size near the rail line, and have only about 40 feet of granular material at the flood-plain surface.



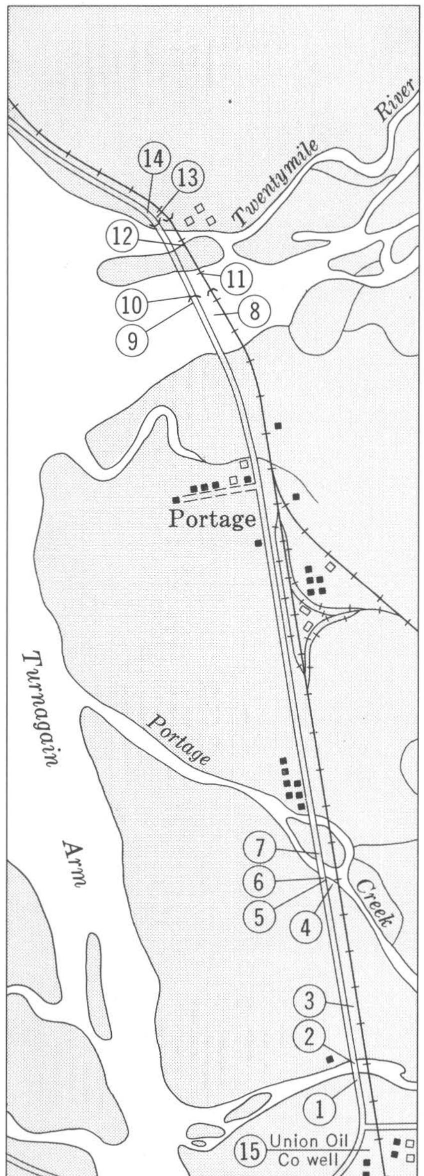
108.—View north over bridge 61.5 on the inactive flood plain of Portage Creek. The bridge was compressed and arched, and the rails pulled free of the fish plates. The north approach shifted to the right toward a small slough, and the south embankment shifted toward the topographically lower active flood plain of the adjacent creek, skewing the bridge 18 inches horizontally (see fig. 56).



109.—View east at bridge 61.5 showing that the embankments were lowered relative to the bridge deck but had risen slightly toward the bridge.



110.—Bridge 61.9 from the south, showing the lowering of the fills and the buckled compressed rails pulled free of the ties.



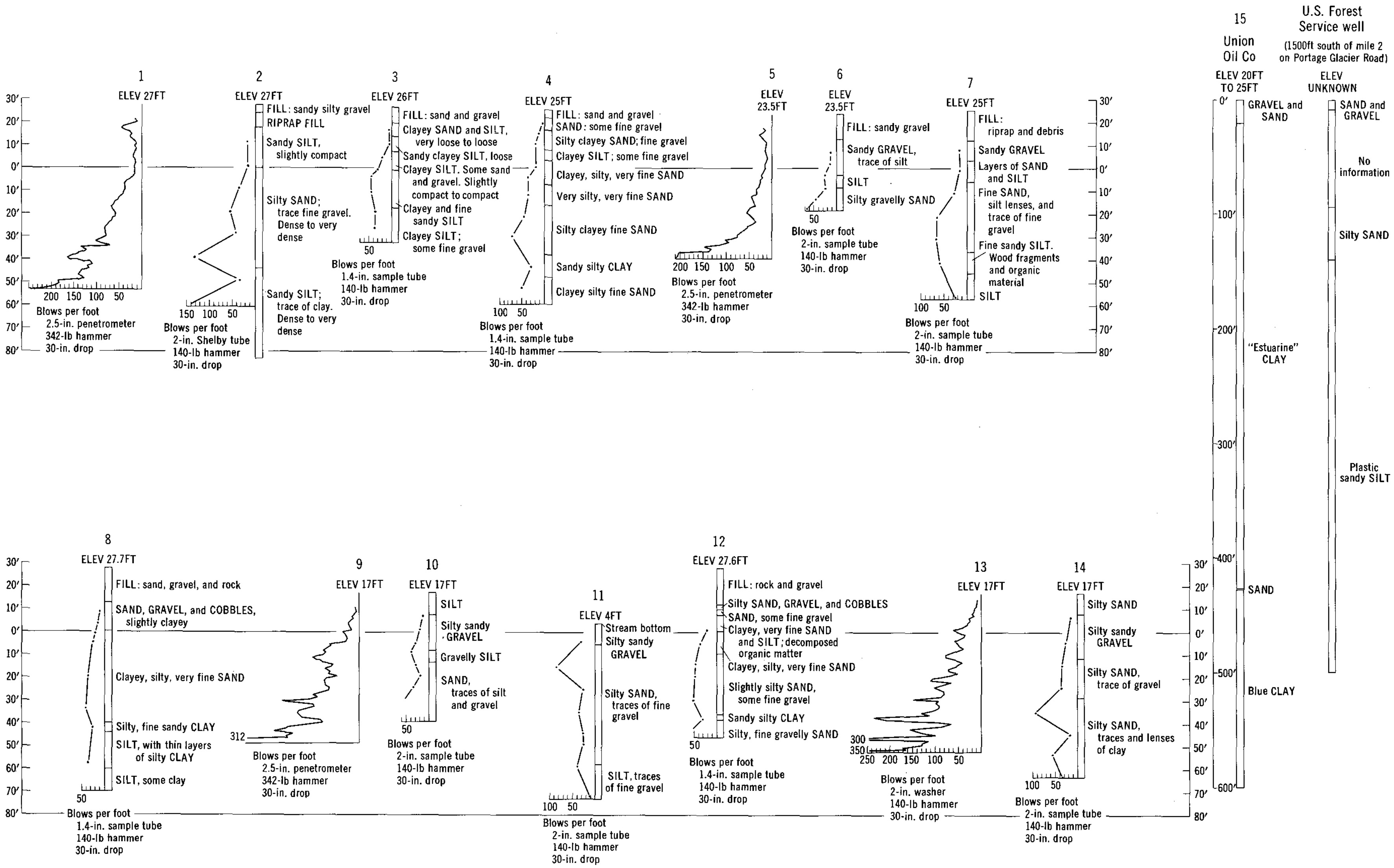
Base from U.S. Geological Survey 1:63,360 Seward D-6, 1965

111.—The locations of bridge-site borings along the railroad and highway and the deep Union Oil Co. water wells in the Portage area.

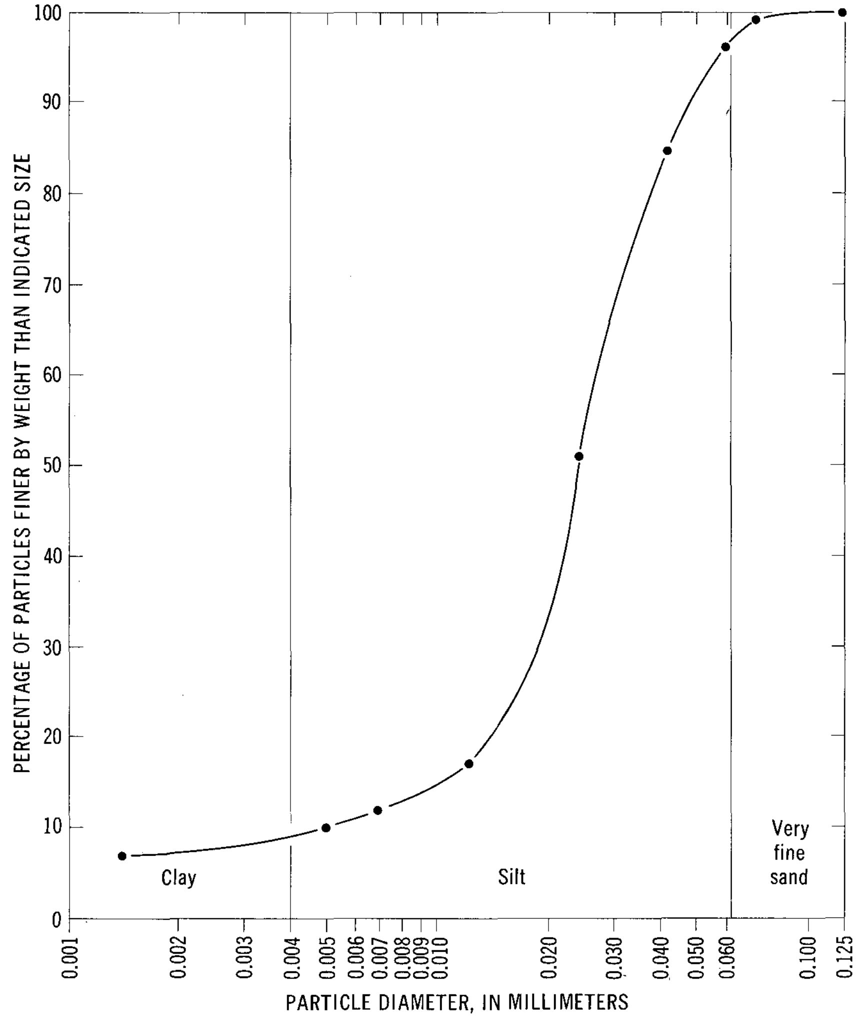
There is, however, reason to doubt the identification of clay in the deep well. Eight hundred feet to the north sediment penetrated in bore hole 1, well below the likely depth of present-day scour, is probably comparable material. In two samples in the lower 40 feet of the well, 87 percent and 74 percent passed the number 200 sieve. This fine material was visually identified as silt with a trace of clay.

A single analysis of the grain-size distribution of a modern surface sample taken nearby on the tide flats of Turnagain Arm shows a predominance of silt with only minor amounts of clay and very fine sand (fig. 113). The modern material is composed largely of glacial rock flour carried to Turnagain Arm from the active glaciers that feed Placer River, Portage Creek, and Twentymile River. It seems likely that the modern material is similar to the older estuarine sediments, and this similarity suggests that the fine sediment in the deep well may be primarily silt, and not clay.

As indicated by the borings, the uppermost hundred feet of sediments are discontinuous units composed primarily of fine sand and silt and minor amounts of fine gravel and clay. This sort of sediment distribution might be expected with the relatively low gradient meandering estuarine streams that occur on the modern flood plain. There is also a general coarsening of the sediments to the north into the valley of Twenty-



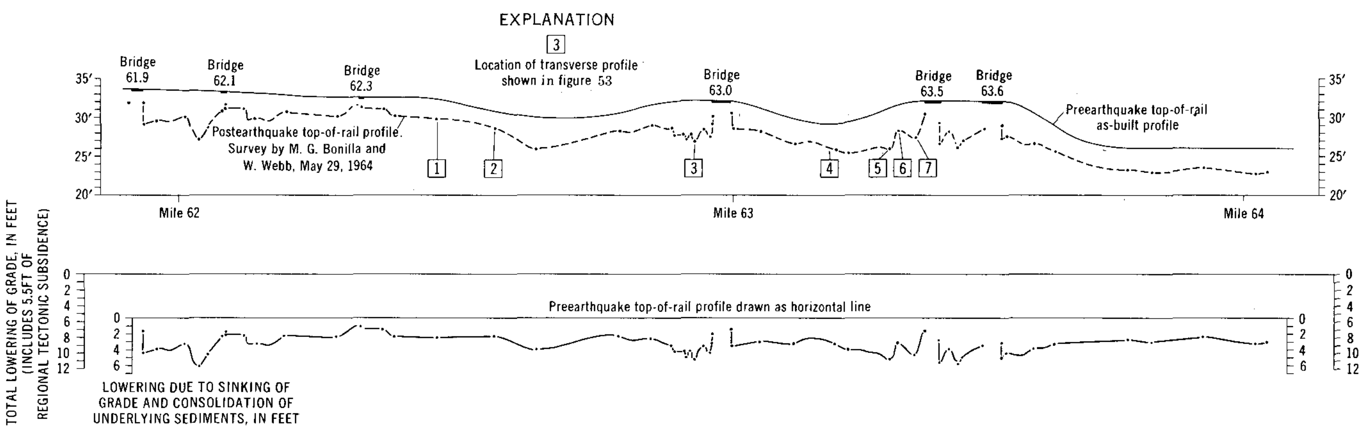
112.—Logs of borings and two deep water wells in the Portage area.



113.—Grain-size distribution curve of modern estuarine sediments on the tidal flat in Turnagain Arm at Portage.

mile River. For example, at the south crossing of Portage Creek silt predominates over sand. At the north crossings, at bridges 63.5 and 63.6, borings show 8 to 16 feet of fine gravel at the top underlain primarily with fine sand. Still farther north, at Twentymile River, 2 to 20 feet of sandy fine gravel is underlain by sand and at many places contains small amounts of fine gravel.

North from bridge 61.9 the embankment was generally lowered about 3 feet where it crosses the combined flood plains of Portage Creek and Twentymile River. The height of the postearthquake embankment is compared with the preearthquake embankment in figure 114, in which the heights of both are referred to the nearest bedrock bench mark (Q 12, U.S. Coast and Geod. Survey, 1929, at mile 66.5). Although there was ground cracking accompanied by the discharge of sediment-laden ground water along much of the embankment (pl. 3), the fact that local sags appeared to be related to larger discharges of sediment suggests that these sags resulted



114.—A comparison of the pre- and postearthquake top-of-rail profiles in the Portage area, neglecting the lowering due to tectonic subsidence, and a plot of the lowering as compared to the preearthquake position and the additional 5.49± feet of tectonic subsidence of the nearest bedrock bench mark (see fig. 72). Numbers indicate the stations at which transverse profiles were measured (see fig. 53).

directly from the expulsion of the underlying material.

Approximately 200 feet south of bridge 61.9 there was a pronounced local sag of about 6 feet in the embankment. There were cracks on both sides of the embankment and a crack across the embankment at the sag joined the side fractures (pl. 3). Areas covered by fine sand and silt that was ejected from these cracks form dark patches on the snow visible on the plate. The grade was lowered and broken by an additional cross fracture 100 feet south of bridge 62.1 but climbed gradually toward the bridge. Both approaches were bulldozed upward against the bulkheads that were held apart by the stringers (fig. 115); this movement partially accounts for the higher grade at the bridge.

The bridge, a 42-foot four-bent open wood trestle, was compressed a total of about 7 inches. The stringers crushed the bulkhead fillers and the deck arched upward about 10 inches. There was also streamward movements of the bents, but of a very uncommon type (fig. 115). The two central bents behaved in the usual way, being shifted horizontally with little or no vertical rotation, but because the bottoms of the bulkhead bents moved farther streamward than their tops, each bent was rotated.

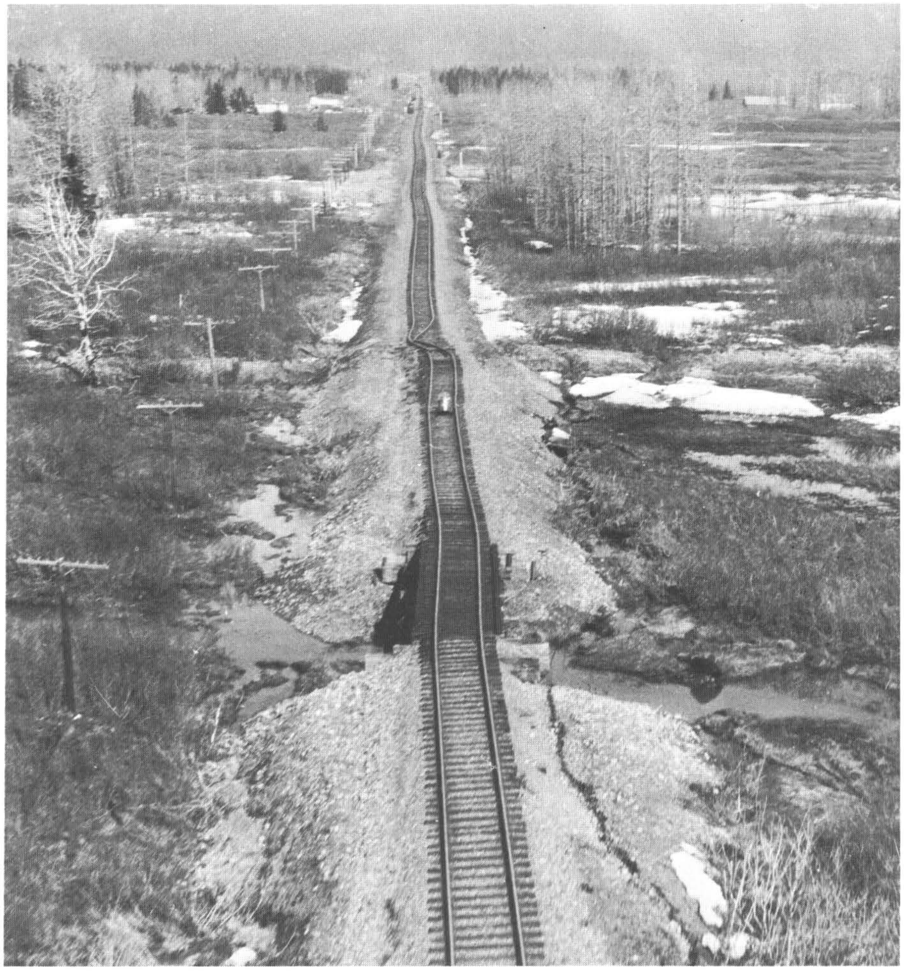
The northern approach shifted about 6 inches to the west toward low ground (flooded by high tide on pl. 3), which skewed the north end of the bridge to the west. Compression must have continued throughout the skewing for, as at bridge 61.5, the stringers were forced obliquely against the bulkhead, and the bulkhead top was racked 3 inches to the east.

North from bridge 62.1 the grade stayed high for about 200 feet over an old buried bridge, partially exposed during the earthquake by slumping of the embankment sides. At the end of the buried bridge the grade dropped abruptly about a foot where the rail line crosses a wide zone of fracturing at the junction of the low flood-plain terrace and a slightly higher older terrace. The cracks formed subparallel with the slope, some on the slope, but most at the back of the low terrace. Where the cracked area was crossed by the embankment, the crack pattern changed to a fine network, and the cracks extended up into the edges of, but generally not across, the fill. This entire section of the embankment throughout the fractured area was displaced about 3 feet westward toward the major channel of Placer River, which suggests that the cracking was related to streamward movement of the material beneath the entire low flood-plain surface.

115.—Approach fills bulldozed against the bulkheads of bridge 62.1. Central bents were displaced horizontally without rotation, but the bulkhead bent was rotated as its base was carried farther toward the channel than its top. This sort of rotation was very uncommon.

As the embankment continued north toward the next bridge it crossed a 150-foot-wide zone of stream-margin cracking. In this zone, cracks formed on the side slopes of the embankment and several tension fractures crossed over the embankment. The rail was put in tension; at one fracture the bolts in the angle bars were sheared, and the rails pulled 6 inches apart. Sand was discharged from a crack that paralleled the east side of the embankment at this pull-apart. At the next bridge, 62.3 (fig. 116), the east side of the approach fill was broken by a common type of fracture that started at the bulkhead and ran diagonally back toward the edge of the fill, then turned and continued on in the toe of the fill. Figure 116 (left foreground) also shows minor cracking of the embankment on the west side; a crack also formed at the end of the toe of the fill on the east side just beyond the bridge.

An uncommon type of ground cracking developed around the margin of a swamp that lies about 400 feet east of the rail line at this point (pl. 3). The swamp measures about 600 by 1,000 feet; its margin is clearly defined by a fine network of cracks, but the middle of the swamp was not fractured. This cracking pattern, similar to



116.—Broken and laterally displaced embankment north of bridge 62.3. Photograph by The Alaska Railroad.

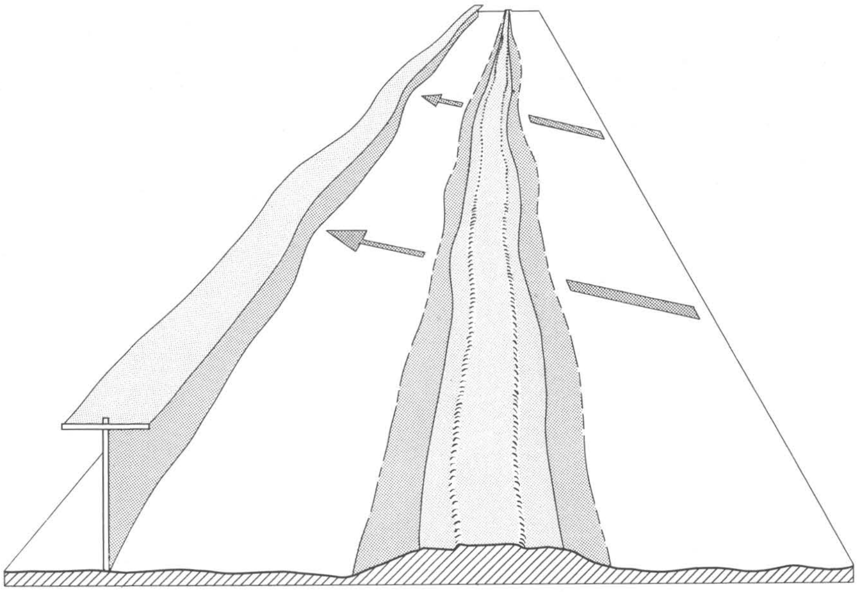
shows both the embankment and the adjacent pole line as drawn from a low-altitude aerial photograph that includes the embankment from just north of the buried structure to the Union Oil Co. tanks at about mile 62.8. The congruent sinuosity developed by both suggests that the lateral displacement resulted from horizontal shifting of the valley floor sediments beneath both the embankment and the pole line. As can be seen on plate 3, there was considerable ground cracking along the southern third of the embankment shown in figure 117. The pattern of the ground cracks and the numerous tension fractures that cross the embankment suggest an east-west spreading of unconsolidated materials beneath the flood-plain surface. The rails responded to the tension in this zone by forming 2-foot-wide pull-aparts, in the left rail 710 feet, and in the right rail 770 feet, north of the bridge (fig. 118). Actual movement of the valley floor sediment was predominantly to the east toward the major channel and the low area in which a small meandering stream flows.

Just beyond the Union Oil Co. tanks, which are situated in an area of dense ground cracking, the railroad crosses Portage Highway at a grade crossing (about mile 62.95). Four cracks at the grade crossing ran from the flood-plain sediments up the junction between the two fills to the flat tops of the fills, where they joined four more fractures that formed normal to each fill. Minor relative downward movement on the normal fractures left the center of the intersection slightly high. There was considerable settling of both the railroad embankment and the highway fill. The railroad grade was lowered about 2¼ feet at the intersection (fig. 114), and a few feet east of

that in the ice on lakes that oscillated during the earthquake (Grantz and others, 1964, fig. 5c), suggests that the swamp behaved like a body of water.

Bridge 62.3, a 45-foot four-bent open wood trestle, was compressed about 8 inches; stringers crushed fillers and rammed the bulkheads. The deck arched upward about 5 inches, which cantilevered the stringers off the south bulkhead bent. Streamward movement of the sediments carried the piling toward the stream. The north end of the bridge and about 200 feet of the embankment built over buried bents of an older structure shifted east relative to the south end of the bridge. The shifting produced a horizontal skew of about 1 foot in the bridge deck. The buried structure behaved somewhat like a bridge; its north end, which lies at the edge of the flood plain of a little creek, was abruptly offset laterally about 4 feet from the adjacent embankment. Offsetting was accompanied by compression that bowed the rails to the west; the right rail bowed about 4 feet, the left rail bowed less because the bolts were sheared in the angle bar at the bend (fig. 116).

Beyond the buried structure, lateral shifting gave the embankment a sinuous form. Figure 117



117.—Congruent lateral displacement of the roadbed and pole line north of bridge 62.3 (drawn from fig. 116) showing that the roadbed and pole line were carried passively as the underlying flood-plain sediments moved laterally.

118.—Tension fracture in the roadbed and a 2-foot pull-apart in the rail at about mile 61.9 caused by spreading of the underlying flood-plain sediments (see pl. 3).

the crossing a corrugated-iron culvert was cantilevered 6 feet off the ground as its buried end was carried down with the settling highway fill (fig. 119). From the intersection with the highway north to bridge 63.0, five sags, with amplitudes of as much as 1 foot, formed in the railroad embankment (fig. 120).

Bridge 63.0, a 194.8-foot 14-bent open wood trestle with 4-foot-wide planked decks lying outboard of the guard timbers, was compressed approximately 7 feet. The compression produced a sharp lateral kink in the deck with a deflection of about 8 feet and the stringers were broken at the apex of the kink. As at bridge 37.0, bents not torn free of the bridge were dragged laterally through the sediments by the deflecting deck, and most bents shifted streamward (fig. 18).

The embankment on both sides of the bridge was lowered, 8 inches at the south bulkhead and about 2 feet at the north bulkhead beyond the few feet of embankment bulldozed up by the deck. The entire embankment north of the bridge was lowered, about 3 feet near the bridge and generally but irregularly increasing to about 5 feet at the next bridge at mile 63.4 (fig. 114).

Six tension fractures lying within, and produced by, the 200-foot-wide zone of stream-margin cracking crossed the embankment north of bridge 63.0. One fracture in the zone, about 35 feet north of the bridge, was about 3.5 feet wide, and the embankment south of the fracture shifted 1 foot to the west (fig. 18).

Cracks produced by the railroad and highway fills, occurring within the toes of the fills or more commonly in the adjacent valley floor, were pronounced north from this bridge for about the next 2 miles, where the highway and railroad lie parallel, with centerlines about 100 feet apart. The total width of the zone of fill-induced fractures is wider (175 to 225 ft) where the two fills lie close together than the sum of the widths (125 ft) of the zones of cracking caused by the fills to the south where they lie farther apart.

As the rail line approached bridge 63.5, it crossed an area of stream-margin cracking in which tension cracks crossed both the rail line and the adjacent highway. On one such crack 400 feet south of

119.—Three-foot-diameter culvert cantilevered upward by sinking of the highway fill just north of the grade crossing at mile 62.9.

120.—Irregular settlement of the railroad embankment between the highway grade crossing at mile 62.9 and bridge 63.0 (see pl. 3).

the bridge, the rails were pulled apart 0.9 foot.

Bridges 63.5 and 63.6, the next two bridges that cross two channels of Portage Creek at a small island, were so severely damaged by large movements of the underlying unconsolidated sediments that the former was replaced with an entirely new bridge and the latter with a culvert. Compression at bridge 63.5, a 149.6-foot 11-bent open wood trestle, was so great that the deck was driven through, and 64 inches beyond, the south bulkhead; the deck rode upward and out over the top of the embankment fill. This overthrusting produced a sag at the south end of the bridge deck, because the fill had not been locally lowered at the bulkhead. Beneath the deck the tops of the piles were progressively higher toward the center of the stream, and where the deck was supported by the piles it was arched upward about 1 foot (fig. 14). At the south end, compression also tore about 56 feet of rails from the ties that were frozen in the ballast and bowed the rails 10½ feet to the west. At the north bulkhead the stringers rammed 2 inches into the fillers. Compression was accompanied by a considerable amount of streamward shifting of the piling, and the bridge was skewed horizontally about 10 feet, its south end moving east relative to its north end.

On the small island between the two bridges, the embankment was lowered and two sags developed, each approximately 5½ feet below original grade. The surface of the island was broken by an open network of orthogonal fractures, like that on other islands and insides of meanders (figs. 19, 46). None of the fractures seriously damaged the rail line, but they separated sections of the adjacent highway pavement, and, during the succeeding high tides that flooded this area, the open fractures channeled the water across the highway, which accelerated erosion of the embankment.

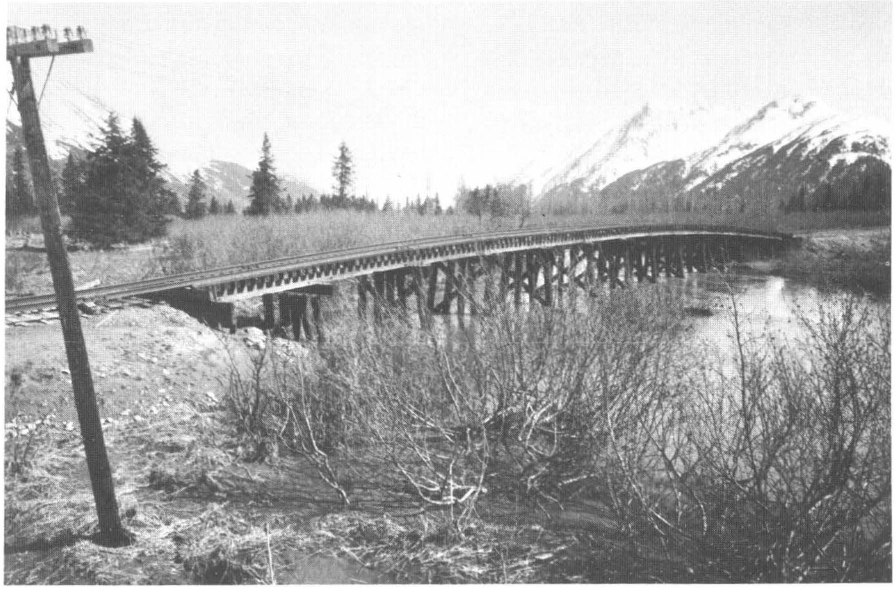
Bridge 63.6, a 208.95-foot 16-bent open wood trestle, was compressed only a few inches, but there was considerable vertical displacement of its piling. The deck was arched upward in a graceful curve with an amplitude of 2.6 feet, yet with few exceptions the stringers rested either on the piles or the pile caps (fig. 121). Vertical pile movement was accompanied by horizontal movement, and the piles were carried sidewise from their original alinement as the bridge was skewed, its south end moving 7 feet east relative to its north end. There was also some streamward shifting of the piles.

Just north of the bridge, the railroad and highway fills were cracked by tension fractures related to the stream-margin cracking. There was also lateral displacement on some of the tension cracks, especially on those that crossed the highway. North from this zone of stream-margin cracking, most of the cracks were produced by the two fills. These cracks were extensive between the fills (pl. 3).

Embankment settlement was pronounced at the junction of the main line with the Whittier branch (pl. 3). The settlement of the accompanying ejection of water produced a water-filled trough that completely submerged 1,500 feet of the main line, 1,400 feet of the branch line, and about 300 feet of the adjacent highway. Where settlement was less pronounced, it was still large enough to produce water-filled troughs at the sides of the embankments.

Cracking of the flood-plain sediments produced by the fills continued north from the junction with the Whittier branch. Where the fills diverge and reach maximum separation north of the railroad station, the cracks had widths of as much as 5 feet and lay between, but close to, the edges of the fills.

Water ejected from ground cracks was ponded where the fills were farthest apart, and from here north, as the fills converged, cracks occurred across the entire area between the two fills. About 200 feet north of the depot, a large crack formed between the present embankment and an abandoned bridge-approach embankment.



121.—A 2.6-foot arch in the deck of bridge 63.6 over Portage Creek. The deck was only slightly compressed, but was offset horizontally approximately 7 feet (see figs. 19, 56).

Settlement occurred along the main-line embankment as it approached Twentymile River bridge. In the last 200 feet south of the bridge, settlement increased abruptly to about 5 feet, where the embankment was severely fractured by cracks that ran approximately parallel to the track in the upper edge of the slope of the fill. These cracks were joined to others in the adjacent flood-plain sediments by cracks running approximately normal to the embankment. Similar cracking, but with more pronounced tension cracks, some of which also had small lateral displacements, occurred in the north bridge approach. Both approach fills rose abruptly at the bridge abutments, having been bulldozed by the abutments.

Bridge 64.7, 419 feet long, constructed of seven steel deck trusses on pile-supported concrete abutments and piers, was damaged but was passable (see p. D45). The adjacent highway bridge was destroyed, all but one of its concrete deck slabs were dislodged from their supporting piles. Some piles were driven up through the reinforced concrete deck (fig. 35; Kachadoorian, 1968).

Leaving the bridge over Twentymile River, the rail line runs north along the crest of a linear topographic ridge that is connected to bedrock at its northern end. This ridge may be a spit formed at a time when sea level was higher with respect to the land at Portage (see p. D85). The possible spit controlled the pattern of ground cracking; long fractures formed approximately parallel to the slope (pl. 3). Between this ridge and the shore line to the west, beyond the influence of the topographic ridge, landspreading was less unidirectional, and the crack pattern became a reticulated net.

SECTION 13. WHITTIER TO PORTAGE

The preceding sections are restricted to a single geologic environment, but Section 13 and most that follow are more heterogeneous and are geographic, rather than geologic, subdivisions. The geology along the rail line is shown in figure 122. The eastern 6.5 miles has been mapped by Barnes (1943) and Kachadoorian (1965), and the western part is interpreted from aerial photographs and limited field observations.

The Whittier branch line joins the all-weather deep-water port of Whittier to the main line at mile 64.2 in Portage. Damage was severe to bridges and embankments at the Portage end of the line and to the port facilities. Rapid repair of this short line (12.4 miles) enabled the first train to reach Whittier by April 20, but obscured and altered the effects of the earthquake. The following observations are therefore primarily from aerial photographs and from notes on bridge damage made by Bruce Cannon, engineer of structures.

The port facilities at Whittier were built largely on the sandy gravel fan delta of Whittier Creek, on the north side and near the head of Passage Canal (fig. 122). Damage to the port facilities has been described by Kachadoorian (1965) and is summarized in part in the following paragraph.

A car-barge slip, which is a tilting platform between two counterweight towers, used to on- and off-load trains from barges, and a 450-foot-long combination office-intransit storage building at the back edge of the marginal wharf were damaged by large waves that rolled ashore over the top of the wharf and reached an altitude of about 20 feet in this area. The waves also tore away the northeastern end of the railroad depot. Some of the waves in the western end of Passage Canal might have been generated by submarine landslides (mapped by McCulloch and L. R. Mayo; Kachadoorian, pl. 3, 1965); however, waves that damaged the railroad structures may have been generated by the lateral displacement of the land that accompanied the earthquake (Plafker, 1968).

A small submarine slide occurred just off the marginal wharf. Postearthquake soundings by The Alaska Railroad personnel show that the water deepened considerably at the car barge slip; this increase in depth suggests that the submarine slide extended under, and was the primary cause of damage to, the outermost counterweight tower.

In addition to wave damage, there was ground cracking and differential settlement of the sediments that displaced and deformed the rails in the 2,400-foot-long railroad marshaling yards that lie near the outer margin of the fan delta. Cracking also occurred in the fill underlying the marginal wharf and the intransit storage shed. Buried utilities were damaged by the cracking and settlement.

Seismic shaking caused slight or moderate damage to other large buildings farther up on the fan delta, including a fire station, composite shop, the communications building, and the station-storage warehouse.

From Whittier (mile F 0) the rail line runs west across bedrock to the coalescing fan deltas of creeks flowing from Portage Pass and from Shakespeare and Learned Glaciers. Bridge F 2.1, a 211-foot 15-bent open wood trestle that spans the creek from Portage Pass on the upper end of the fan, was undamaged. About 1,400 feet farther west the rail line enters the first of two tunnels cut in graywacke, slate, and argillite. These rocks dip steeply north and northwest and have been cut by small faults and minor shear zones that parallel the northeasterly structural trend (Barnes, 1943). The first tunnel is 13,000 feet long, the second 5,000 feet long. Both are unlined but are timbered near the portals, and both are built with the cross section shown in figure 123. A rock weighing about 2½ tons fell in one of the tunnels.

Arthur Kennedy, of the U.S. Forest Service in Anchorage, was one of a party of five engaged in making water-depth measurements on Portage Lake at the time of the earthquake (Waller, 1966, p. A5-A6). The earthquake generated a seiche in the lake with an amplitude of 5 to 10 feet. After about 2 hours of exploring routes to shore, the party made its way to safety across the rising and falling broken ice adjacent to the center of Bear Valley (fig. 122). At about 7:50 p.m. the party considered walking through the western tunnel but decided not to after hearing some small rocks fall just inside the entrance.

Between the two tunnels, the railroad is built on glacial outwash that accumulated behind a dam of glacial moraine on the floor of Bear Valley (fig. 122). Mr. Kennedy (written commun., 1965) reports that, having walked east from the entrance of the western tunnel to a section house near the east edge of Bear Valley, he noted that "* * * there were cracks running perpendicular to, and across [the] tracks. Snow drifts on both sides of the tracks were cracked away [by] cracks running parallel to tracks." The bridge over Placer Creek, in Bear Valley at mile F 5.7, is a 196-foot 15-bent open wood trestle. It was compressed, and three bents at the east and two at the west were crowded toward the center of the bridge.

From the western tunnel the rail line runs northwest on the flood plain of Portage Creek, on the north side of the creek. About 200 feet from the tunnel portal, 300 feet of the track was covered by a snow avalanche which continued south by another 400 feet and crossed Portage Creek. Eastward from the edge of the avalanche, for about 2,400 feet to Portage Lake, the creek overflowed its banks, possibly owing to seiching in the lake or to being dammed behind the avalanche.

As the line proceeds northeast, the material in the cuts decreases in grain size from coarse gravel to fine sand and silt. The decrease in grain size was accompanied by increased fracturing and increased damage to the embankment and bridges. From mile F 8 to F 8.4 the embankment settled and shifted a few feet toward a bend in the creek that lies about 50 feet to the south. There also appeared to have been minor lateral displacements toward borrow pits dug at the toe of the embankment from about mile F 9.2 to F 9.6. Water filling the marginal drainage ditches throughout this area of lateral shifting suggests that the embankment also settled.

The bridge at F 9.4, a 56-foot 5-bent open wood trestle, was compressed, and its deck arched. The bridge was skewed horizontally, its eastern end shifted 1 to 2 feet north relative to the west end. West of the bridge, for about 700 feet, the embankment shifted south toward a borrow pit. The lateral shifting was accompanied by tension fractures normal to the embankment. Lateral displacement of about 2 feet also occurred near mile F 10, where the embankment moved toward the edge of the stream channel about 16 feet south of the track. At bridge F 10.7, which crosses a small creek at an angle of about 60°, there was considerable stream-margin cracking. The eastern bridge approach shifted north, and the western approach shifted south; the bridge was skewed 8 to 10 feet horizontally. The bridge was also arched and probably compressed.

Just beyond the bridge, the rail line crosses an area of extensive fracturing. The fractures were accompanied by the discharge of ground water that flooded large sections of the valley floor. The predominant crack pattern was an open network, but fractures in the embankment were primarily perpendicular to the tracks or lay parallel to the tracks within the fill and in the adjacent flood-plain sediments.

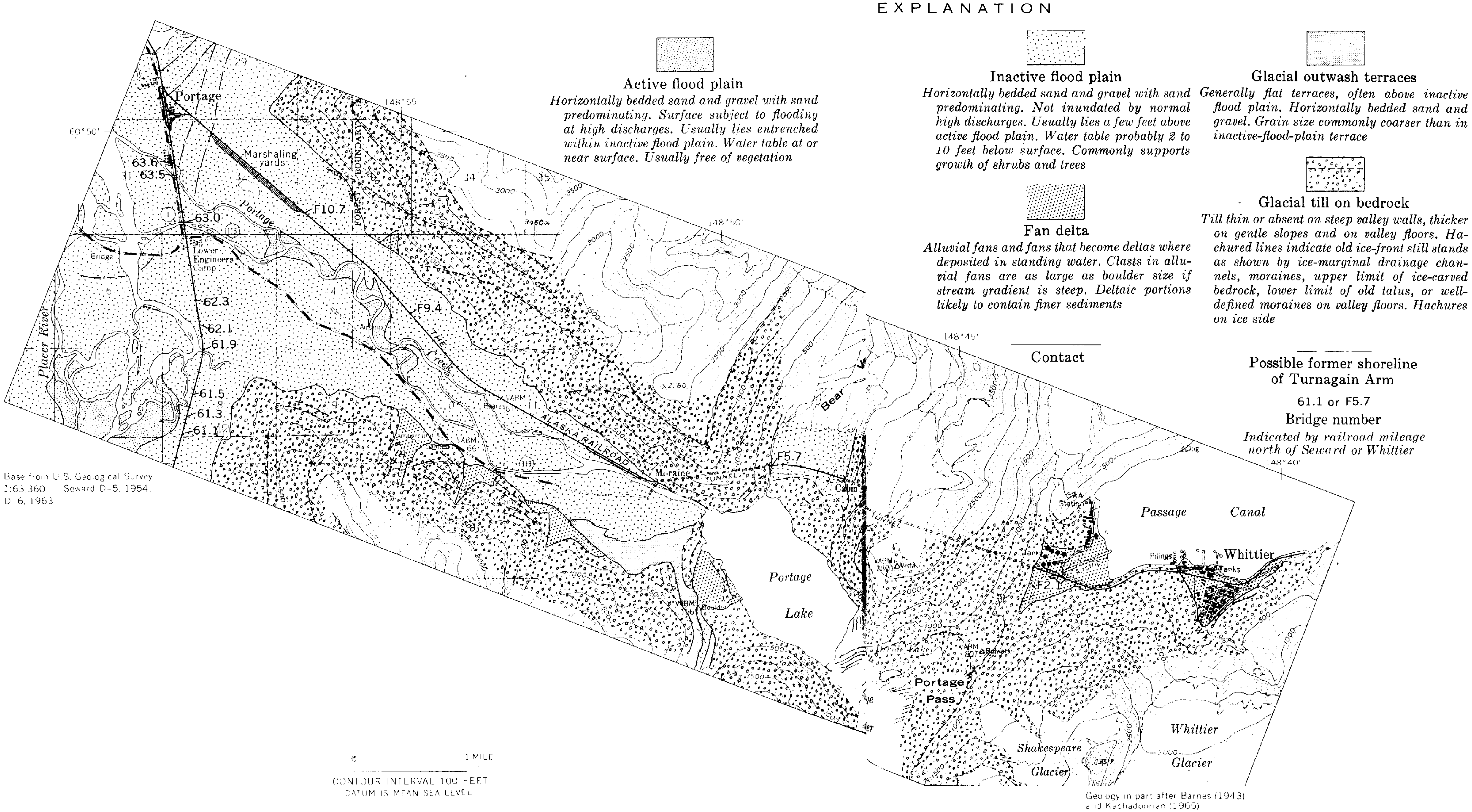
The six-track-wide marshaling yard between mile F 10.75 and F 11.75 lies partially within this zone of fracturing. The fill, which was laid as a single pad, spread laterally about 10 feet where it crossed a small creek near mile F 11.15. Spreading carried the outside tracks 4 to 5 feet out of line and produced tension fractures several feet wide running both between, and normal to, the tracks. Even where not crossing depressions the fill spread laterally; two water-filled fractures about 2 feet wide occurred on the outer side of the central two rails and divided the fill into three approximately equal segments (fig. 124). Distances scaled between tracks in figure 124 show that the crack width is approximately equal to the increase in distance between the tracks. This indicates that although the lower part of the fill may have failed by spreading, the surface of the fill failed in tension. No measurements were made, but undoubtedly there was significant settlement of this fill, as there must have been over a considerable part of the embankment. As shown on plate 3, cracking continued along the embankment to the junction with the main line, where settlement was so great on the Y-junction that parts of the grade were entirely submerged by discharged ground water (see p. D137).

SECTION 14. PORTAGE TO ANCHORAGE

Northwest from Portage along Turnagain Arm, the rail line is built on cuts in till or glacial outwash that veneer bedrock, on small fills underlain by unconsolidated estuarine silts, and on the flood plains and deltas of several creeks that lie in valleys once occupied by glaciers that were tributary to the massive ice tongue that filled Turnagain Arm.

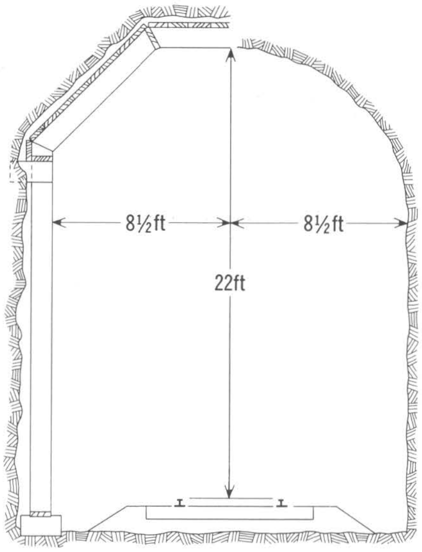
Regional subsidence combined with local settling of the embankment made a considerable part of the rail line along Turnagain Arm susceptible to marine erosion. In order to minimize the loss of roadbed, reconstruction of this part of the rail line was started very soon after the earthquake, and earthquake damage to the rail line was rapidly repaired. Thus, observations of embankment damage was minimal; however, because the bridges were not made impassable by the earthquake, and were not immediately repaired, some of the bridge damage was recorded.

The few observations that were made of the embankment can be generalized as follows: There was little or no settling of the grade where it was built in bedrock cuts or in cuts in till and outwash deposits that rest on bedrock. Settling was common, however, on fills underlain by the estuarine sediments. As the grade passed



122.—Surficial geologic-physiographic map of the rail belt from Whittier to Portage. Geology at Portage Pass and Whittier modified after Barnes (1943) and Kachadoorian (1965).

Figure 122—Continued.



123.—Typical cross section of The Alaska Railroad tuunels, showing timbering used near portals.

124.—Tension fractures between tracks on the Whittier branch marshaling yards. The subgrade fill failed by lateral spreading and the ballast failed in tension.

from fills on the estuarine sediments of Turnagain Arm to cuts on small bedrock promontories, the change in grade was abrupt and at many places was marked by a fracture at the edge of the bedrock along which the fill on the sediments had been lowered. In addition to being lowered, the embankment was commonly displaced laterally along this fracture as it was carried toward Turnagain Arm on the shifting estuarine sediments (fig. 125).

At Potter (mile 100.5, fig. 1) at the mouth of Potter Creek, the embankment swings out into Turnagain Arm and is built on the crest of an old barrier beach, now separated from the mainland by a wide marsh. The embankment fared quite well on the beach ridge except at the approaches to bridge 102.5 at Rabbit Creek, where for 400 feet south and about 600 feet north of the bridge the embankment was broken by both transverse tension fractures and fractures running parallel to the tracks within the fill outboard of the ties. Water was ejected up through the

125.—Highway embankment along the north shore of Turnagain Arm that settled abruptly on tidal sediments adjacent to a bedrock promotory. Similar settlement occurred on the railroad embankment. Embankments on tidal sediments also were shifted toward the arm and offset horizontally.

embankment on both the transverse-tension and the embankment-side fractures. Water was also forced up through the fill on cracks running back 100 feet from the south bulkhead, and about 25 feet north from the north bulkhead. The bridge was skewed horizontally, its north end moving about 3 feet west of its south end.

The beach ridge swings in to shore just south of Potter Hill. Here several slides carried away about 1,550 feet of roadbed that was built in cuts across the face of a bluff formed of unconsolidated sediments (see p. D72–D76).

North from Potter Hill, the rail line runs for about 8 miles across the somewhat irregular topography of a pitted outwash plain, ground moraine, glacial fluvial deposits, and swamps (Miller and Dobrovolny, 1959, pl. 1) before reaching Bootlegger Cove on the shore of Knik Arm a few miles southwest of Anchorage (fig. 68). The only damage of any consequence occurred at the two crossings of Fish Creek, where a 4-foot-diameter concrete culvert at mile 11.6 was broken, and at mile 111.98, where a 5-foot-diameter concrete culvert failed and 280 feet of the overlying embankment settled several feet across the full width of the valley. As it settled, the embankment fill spread laterally, and cracks as much as 200 feet long and 5 feet wide formed approximately parallel to the tracks. The embankment was also dropped downward about 2 feet along a fracture across the embankment at the south edge of the valley.

Having reached the shore at Bootlegger Cove, the rail line runs northeast and crosses the 2,000-foot-wide flat-floored valley of Chester Creek at mile 112.8 on a 192-foot bridge. This bridge was constructed of two 56-foot open wood trestle tail spans and a central 80-foot steel deck girder supported on wood pile piers. The bridge was compressed slightly, and the pile pier at the south end of the steel span shifted from 2 to 4 inches streamward. There was also evidence of slight pounding at the south end, and the southern approach fill was lowered 10 inches below the bridge deck.

Northwest from Chester Creek the rail line lies on a fill at the toe of the abandoned wave-cut cliff in the estuarine-marine Bootlegger Cove Clay. Where the rail line crosses the toe of the L Street slide that developed in this bluff, it was displaced laterally about 8 feet toward the water; most displacement occurred between the extension of Seventh and Eleventh Avenues. An aerial photograph of this displacement is shown in the report of Shannon and Wilson, Inc. (1964a, p. 53).

SECTION 15. ANCHORAGE

Shops and office buildings of The Alaska Railroad in the yards at Anchorage (fig. 126) were damaged by seismic shaking and compaction of underlying materials. In addition, buildings and utilities that lay in the path of landslides dislodged from the adjacent bluffs were also subjected to ground displacement, and one building was overrun by slide debris.

Most of the buildings damaged by shaking had heavy masses at some height above the ground floor, such as heavy concrete second floors, or large overhead cranes that ride on tracks secured to the building frame. The inertia of these large masses undoubtedly increased the racking forces that produced most of the damage. Where damage was severe, it can be attributed to a lack of reinforcement and ties between masonry walls and building frames, inadequate or total lack of sway bracing, or weak connections between structural members.

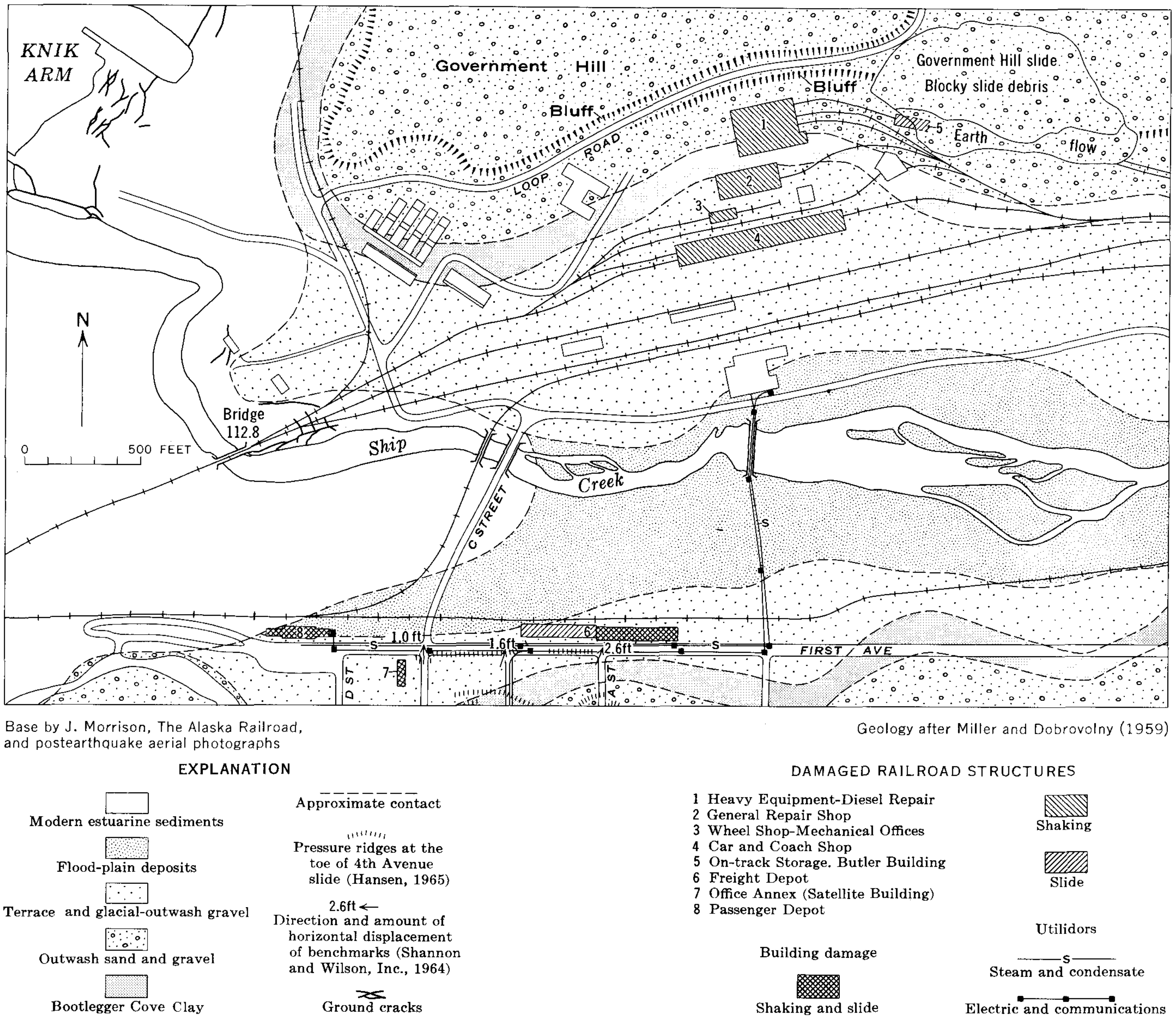
The Wheel Shop, Car and Coach Shop, and General Repair Shop lacked adequate sway bracing and only the General Repair Shop had any at all. The Diesel Shop was well designed in all respects.

The heavily damaged Wheel Shop-Mechanical Offices Building, and the less severely damaged Car and Coach and General Repair Shops are built on a low terrace veneered by glacial outwash gravels (fig. 126; Miller and Dobrovolny, pl. 1, 1959). The gravel was deposited by Ship Creek at the time when melt water from glaciers to the east enabled the creek to cut its valley down through the outwash and the underlying Bootlegger Cove Clay that form the adjacent bluffs. The Heavy Equipment-Diesel Repair Shop lies on the clay and high outwash gravel.

South of Ship Creek the Freight Depot is also built on the low terrace of outwash gravel; the depot to the west is on younger deposits of the meandering Ship Creek.

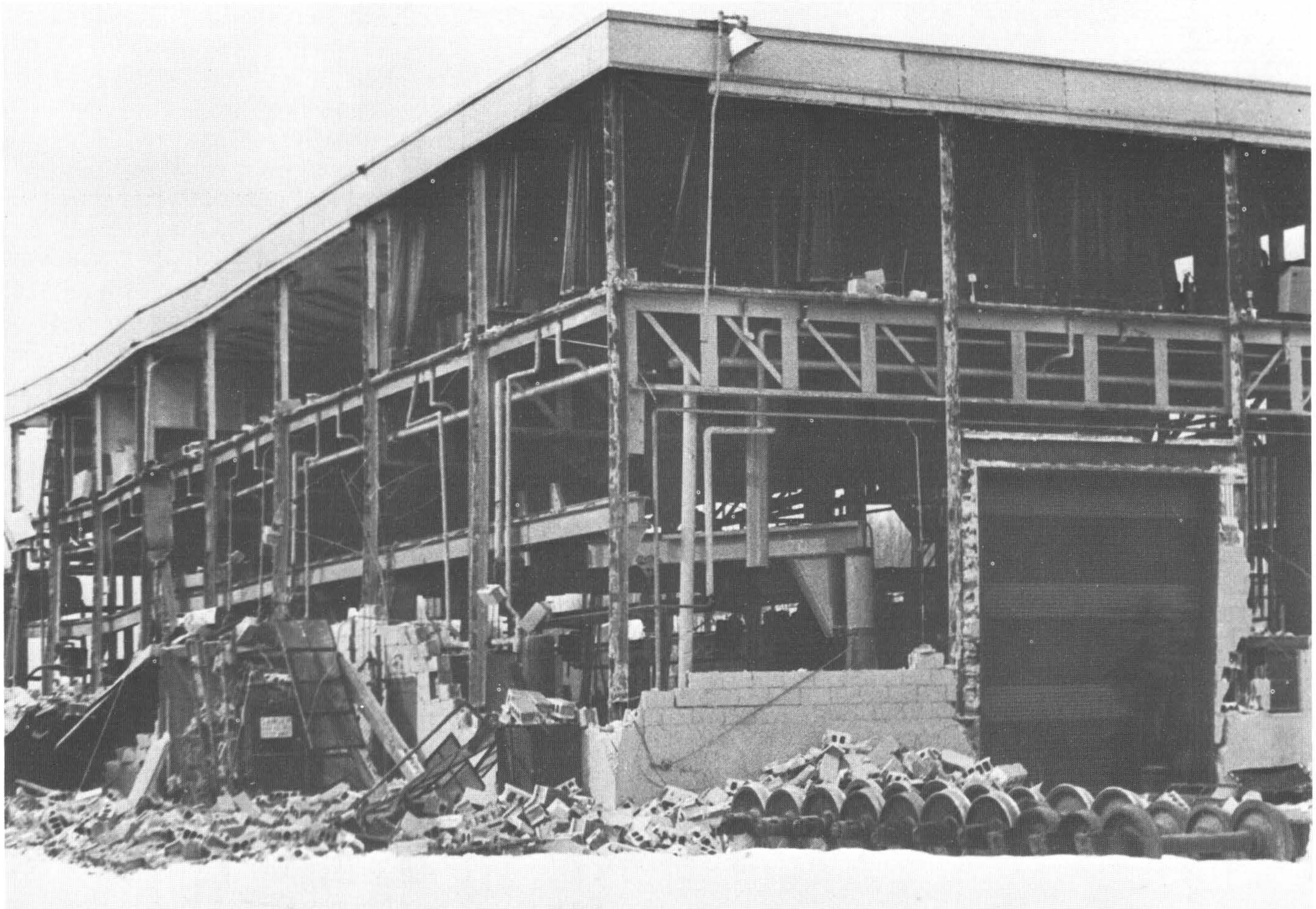
A topographic map of the Ship Creek area made in 1914 by the Alaska Engineering Commission (fig. 69) shows the area north of Ship Creek (now the site of most of the rail yard) as "tundra." C. L. Griffiths, assistant chief engineer, remembers that this flat marshy tundra area consisted of several feet of peat, silt and muskeg, and a few lenses of gravel. In preparing the area for construction, the organic material was removed, and at least 3 feet of fill was placed on the stripped surface. The fill was compacted by traffic.

The Wheel Shop and Mechanical Offices (No. 3, fig. 126), located in the lower and upper stories of a two-story steel-frame concrete-block building was so



126.—Map of the railroad buildings and buried utilities, surficial geology, and landslide features in the Anchorage railroad yards in Ship Creek valley. Map of the railroad facilities after J. Morrison of The Alaska Railroad; geology modified after Miller and Dobrovolny (1959, pl. 1); landslide features after Shannon and Wilson, Inc. (1964b, pl. 8.2) and Hansen (1965, fig. 38).

severely damaged that it had to be razed (fig. 127). The building, constructed during the Second World War when material was scarce, was built largely of salvaged materials. The steel frame consisted of columns of two welded L's cast into a high perimeter foundation wall (fig. 128). The columns were welded to modified Vierendeel trusses at the second floor, and to a light steel framework supporting a joisted wood roof with a built-up surface. The ground and second floors were reinforced concrete, the latter reinforced with ⅜-inch bars 10 inches on center in the top, middle, and bottom of the slab. The exterior walls were cement block. The only reinforcement in the walls was steel K-webbing on each third course; there was no vertica reinforcing iron or concrete filling in the cells. The block, was butted against the columns and window and door frames with a mortar joint, and there were no ties from the frame to the block. The absence of diagonal bracing in the steel frame allowed the racking forces, which were undoubtedly augmented by the mass of the

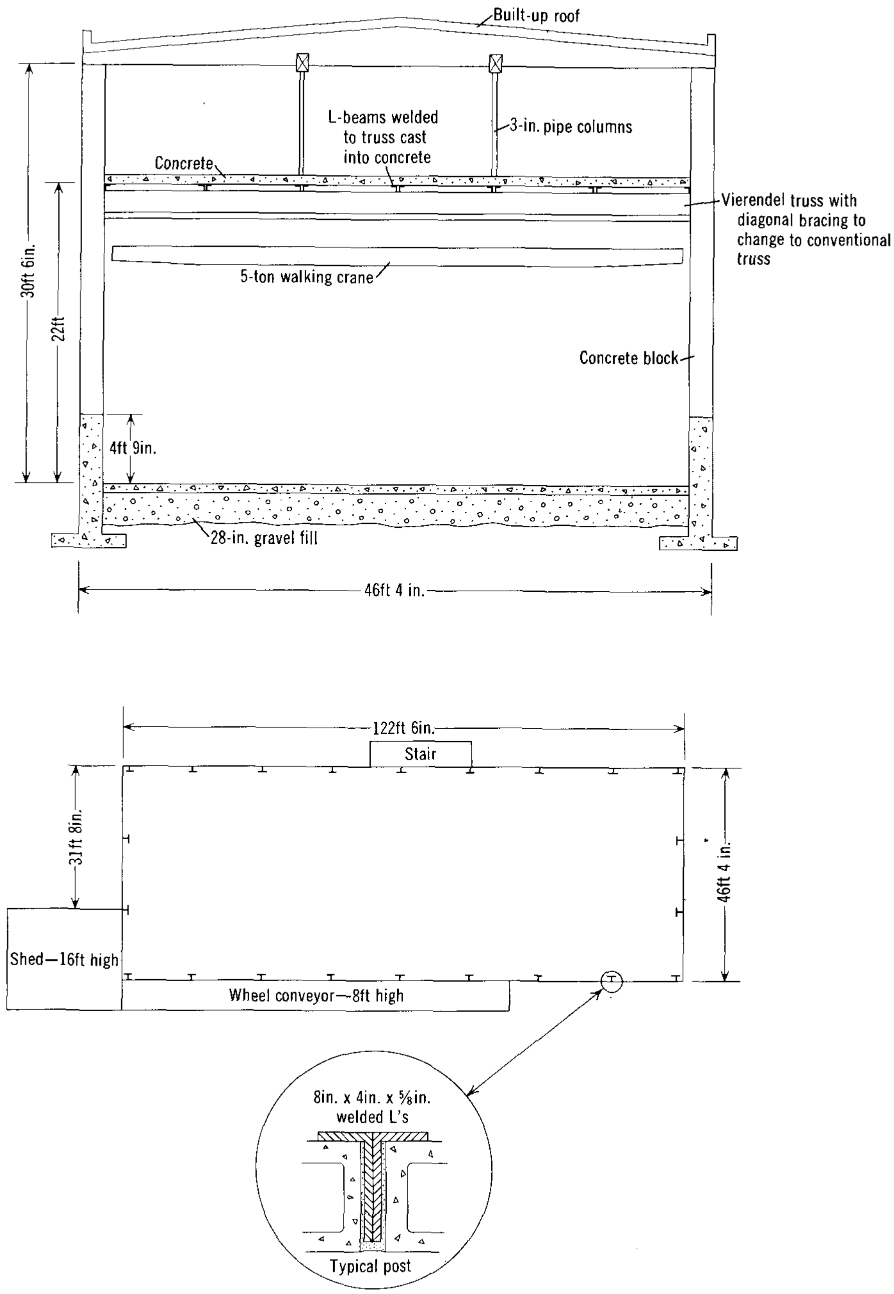


127.—Postearthquake view of the Wheel Shop-Mechanical Offices, showing the steel frame exposed by the collapse of the concrete block walls. Photograph by The Alaska Railroad.

concrete second floor, to be delivered to the block walls. As a result, the unreinforced walls were shed from the sides of the building. The irregular roof-line and floor-line visible in figure 127 suggest that there were also some foundation failures.

The Car and Coach Shop (No. 4, fig. 126) just south of the Wheel Shop was also damaged by shaking. The structure was 738.5 feet long, built with a steel frame of vertical H-columns to which were attached metal roof trusses supporting wood partitions and a wood roof deck (fig. 129). The building was sheathed with insulated metal sandwich panels (Robertson panels) welded to the frame. During the shaking the roof trusses on the two long low bays on the south side of the building were torn from the H-column to which they had been attached by shelf brackets. The roof trusses dropped to a steampipe which then supported the roof. The two low bays were separated by a higher bay (section *B–B′*, fig. 129) in which there was an intermediate-level concrete floor supported on 27-inch-deep I-beams that were welded full height to the H-columns. There was no damage to the floor or to its supporting beams. In this section the central columns were made of two structural channels connected by welded diagonal round rods. The rods buckled (fig. 130) as the building swayed. Swaying also stretched some of the bolts anchoring the H-columns to the concrete pedestals (Berg and Stratta, 1964).

The Heavy Equipment and Diesel Repair Shop (No. 1, fig. 126), originally the Forge Building of the Denver Kaiser Steel Plant, Denver, Colo., had been reassembled in the rail yards with no structural changes. The building is 230 feet wide, 500 feet long, and 56 feet high at the central gable; it has two lower side bays, with outward-sloping shed roofs, that run the full length of the building (fig. 131). The steel frame consists of H-beam columns bolted to concrete pedestals at the floor

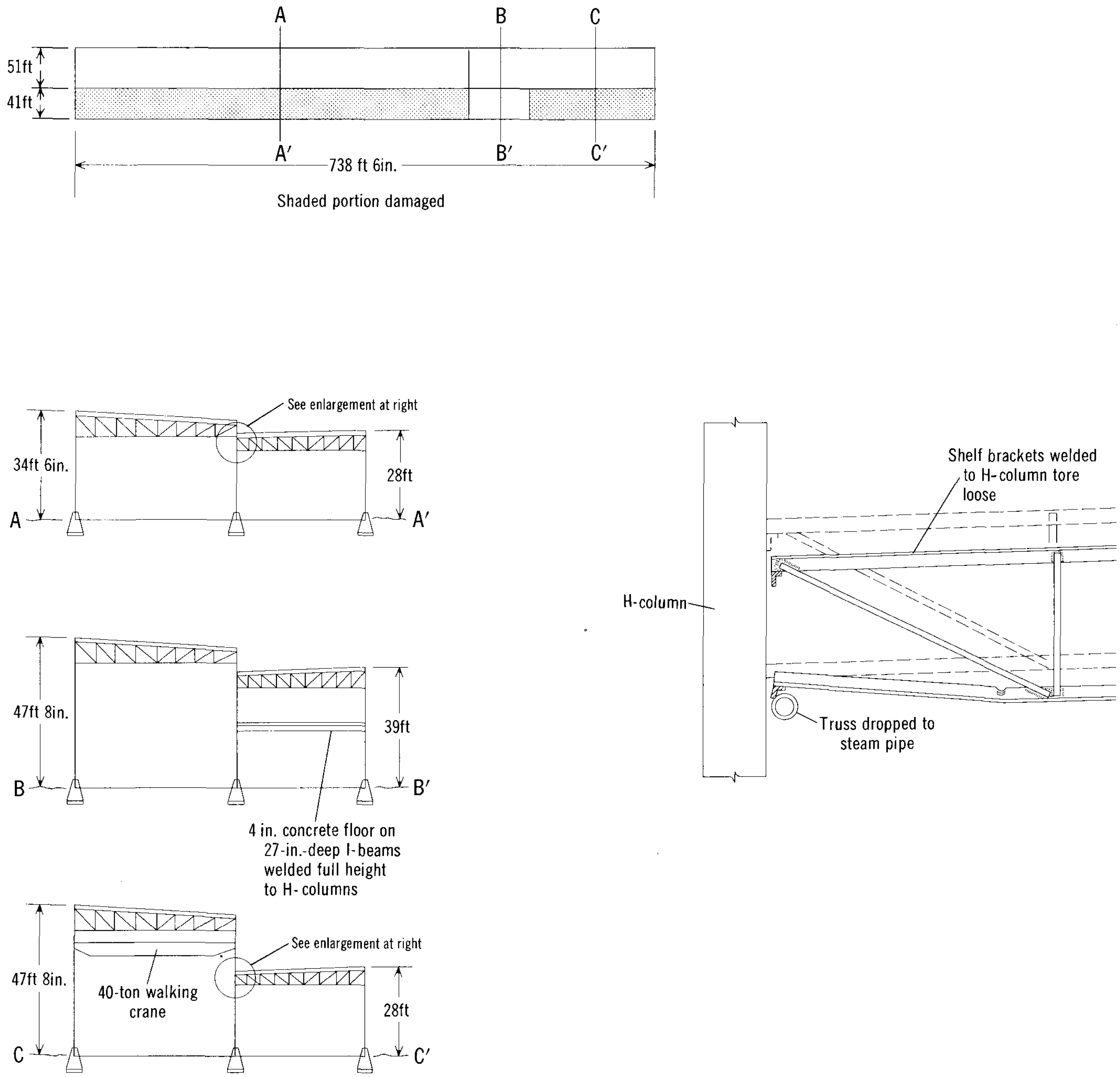


128.—Construction of the Wheel Shop-Mechanical Offices building.

line, the pedestals being supported on steel piling. Metal trusses connected to the columns support a roof of welded-metal panels overlain by rigid insulation and a built-up surface. The exterior steel frame is diagonally braced by ¾-inch tie rods between columns at the ends of the building and at four intermediate positions. It is also braced by metal X-bracing in the interior walls between the bays. Shaking racked the building and stretched some of the column anchor bolts. Sags developed in the 6-inch-thick reinforced concrete floor poured on 3½ feet of compacted gravel fill.

The General Repair Shop (No. 2, fig. 126) is similar in construction to the Diesel Repair Shop, having a central gabled bay and two low side bays with shed roofs, but the shed roofs of this building pitch inward. The northern bay contains a 5-ton crane, the central bay a 60-ton crane, and the southern bay a 7.5-ton crane, all of which run overhead on track attached to the walls. The steel frame of the building consists of H-beam columns spaced 10 feet apart on interior and exterior walls. The column bases are bolted to concrete piers, and the columns support metal roof trusses decked by 2-inch T- and G-sheathing, 2-inch rigid insulation, and a 5-ply built-up roof surface. The exterior walls are rigid insulation covered with metal sheathing welded to the frame. Damage was minor, and was caused by swaying. A few concrete piers were cracked, and racking tore some welds in the metal sheathing. Diagonal ¾-inch tie rods in the exterior walls were stretched or broken, and column anchor bolts were elongated.

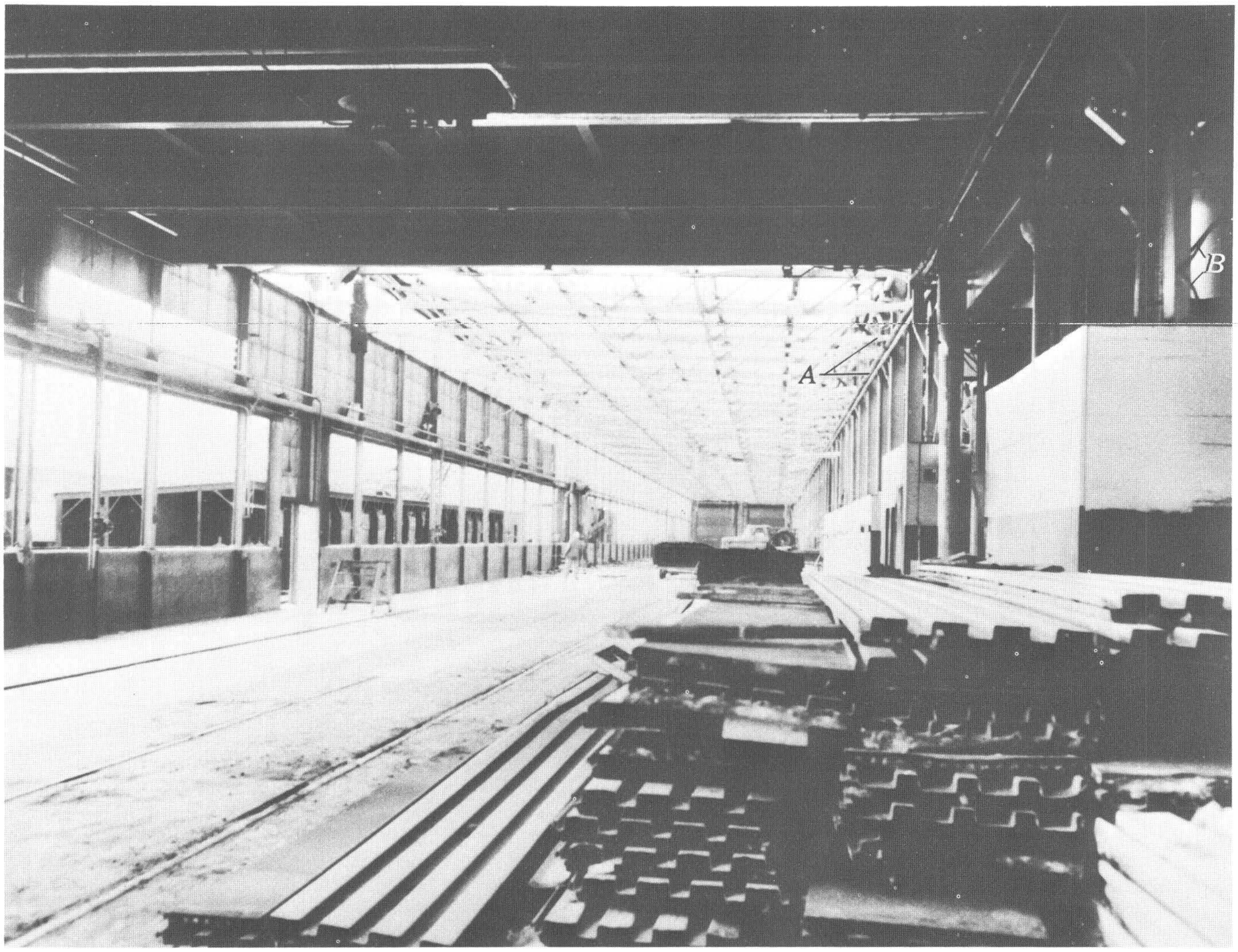
The Office Annex (Satellite) Building (No. 7, fig. 126) lay within the area affected by the Fourth Avenue slide. A pressure ridge formed at the nearby intersection of C Street and First Avenue, and a survey monument at this intersection was shifted 1 foot horizontally toward Ship Creek (fig. 126). The two-story building was 120 feet long, 36 feet wide, and 18 feet high (fig. 132). It had concrete floors, the second floor carried on 8-inch stran steel joists divided into three spans supported by 12-inch I-beams welded to columns of 3-inch standard iron pipe. Joists were 16 inches on center, and the end of every fifth joist was anchorbolted to reinforced concrete lintels in the side walls. The concrete block exterior was reinforced with vertical ¾-inch iron in concrete-filled cells on a maximum 6-foot spacing and steel



129.—Construction of the Car and Coach Shop.

K-webbing on each third course of block. The vertical reinforcing iron passed through the reinforced concrete lintels. This building had no structural continuity around the corners.

The building was shaken with sufficient violence to overturn filing cases and furniture on the second floor. The ground floor, a concrete pour on a fill, was undamaged, but the second floor concrete slab was broken on an east-west crack. There was a vertical crack nearby in the west wall. The north and south end walls were badly broken by shear (C. L. Griffiths, oral commun., 1967). The top two courses of block of the parapet on a small bay on the northwest side of the building were dislodged. Some damage that occurred at the south end of the building (fig. 133), where insufficiently reinforced blocks were pulled apart at mortar joints or ruptured, may have been produced by a pressure ridge. This building was razed and was replaced by a new building constructed across

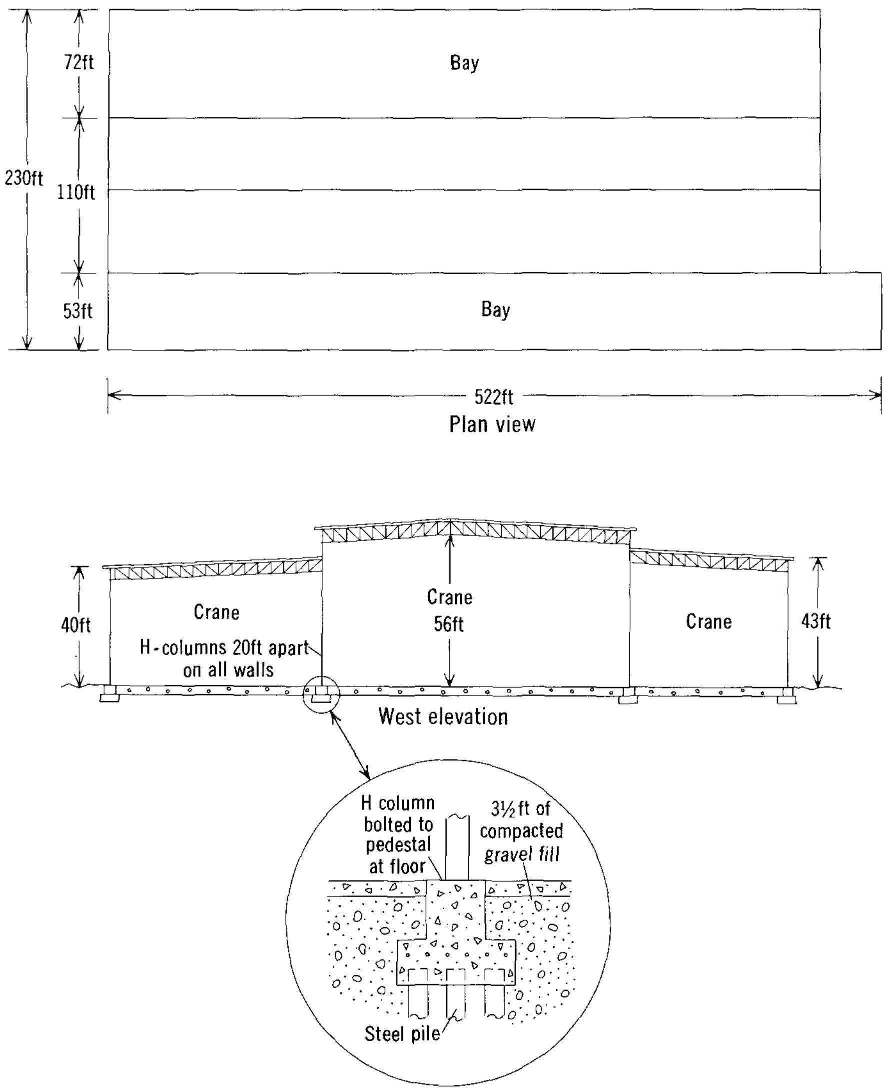


130.—Interior view of the south bay of the Car and Coach Shop showing *A*, the roof trusses resting on a horizontal steampipe and *B*, buckled rods between H-beam columns. Insulated sheathing panels removed during repairs. Photograph by The Alaska Railroad.

First Avenue, off the toe of the slide.

The Depot (No. 8, fig. 126), a four-story reinforced poured-in-place concrete structure on wood piles, performed very well. There was minor cracking in the stairwell and in the east wall of the waiting room, located on the east end of the ground floor. Furniture was shifted about by the shaking, and fluorescent light fixtures were torn from the ceilings. Fractures at right angles to the building broke the black-top surface of the platform lying along the north side of the building. These fractures were suggestive of extension cracks found on the toes of slides, and they suggest that the building was shifted northward by the Fourth Street slide.

Several blocks to the east, the long narrow single-story wood-frame Freight Depot (No. 6, fig. 126) was damaged by ground displacement related to the Fourth Avenue slide. Wood piles, nearly the entire length of the south edge of the Freight Depot, were carried north, as were the supporting legs of a stair (*A′–A′*, fig. 134). A pressure ridge that developed in the middle of First Avenue bulged the asphalt up about 5 inches, and cracks with right-lateral movement of 1 to 4½ inches formed normal to the pressure ridge. The railroad tracks were deflected northward, and the southern edge of the pavement was broken and overthrust 6 to 8 inches. Near the middle of the street, the concrete well of a sewer manhole was shifted to the north and tilted. The



131.—Construction of the Heavy Equipment and Diesel Repair Shop.

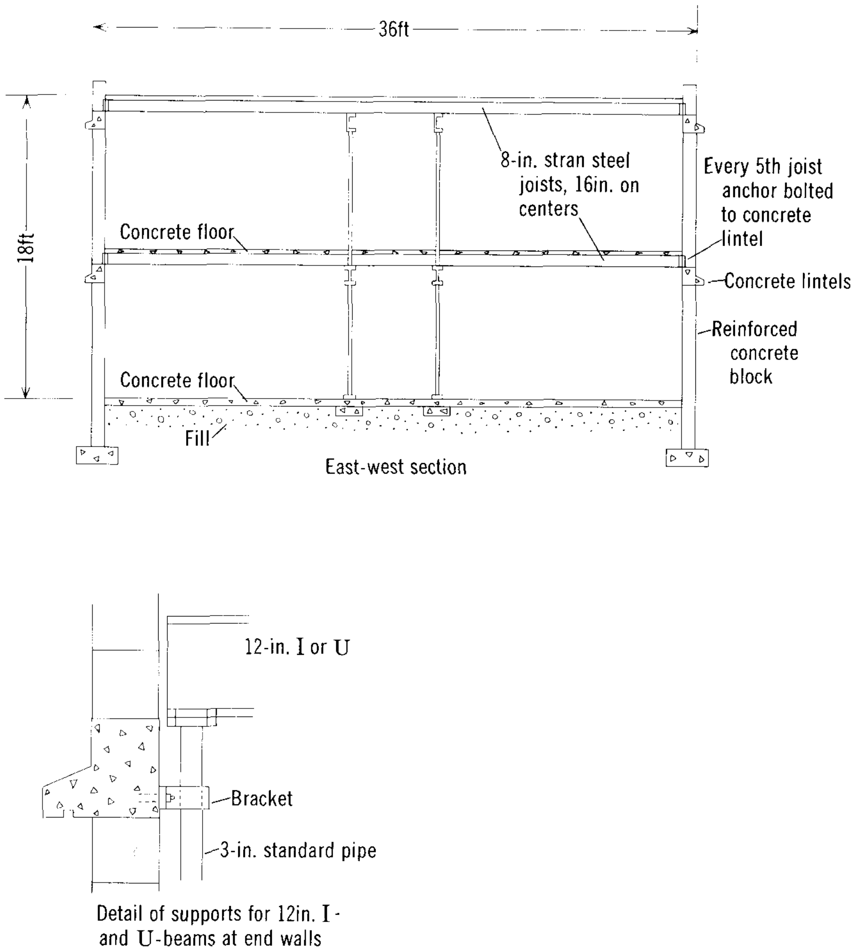
concrete was displaced 6 inches from the steel collar that was embedded in the asphalt road surface. The displacement between the manhole and its collar and the compression features in the asphalt suggest that the ground moved north beneath the overlying pavement. Possibly the pavement became detached from the underlying ground and was held back by the adjacent pavement.

Horizontal displacement of the ground must have stopped under the building, because horizontal shifting of the piles decreaseed to the north, and those at the north edge of the building were not disturbed.

Relative movement between the ground and the building is also shown by the fact that a buried steampipe, from the utilidor under the street, was thrust 16 inches northward into a concrete well in the building (fig. 134). According to the maintenance crew in the building, the movement occurred about April 22, nearly a month after the earthquake. This evidence for movement so long after the earthquake conflicts with the statements of Shannon and Wilson, Inc. (1964a), who, from measurements of the displacements of monuments made (p. 39) "* * * within a period of several weeks" after the earthquake, concluded (p. 1) "* * * that there has been no significant movement subsequent to the middle of April, and it is believed there has been none subsequent to the end of the quake."

Ground displacement at the toe of the Fourth Avenue slide also damaged about 1,800 feet of the steam, condensate, electrical, and communication lines of The Alaska Railroad that were carried in two buried utilidors (fig. 126). The utilidors consist of eight 4-inch-diameter fiber conduits (set in plastic separators) cast in a concrete envelope 17 inches high and 30 inches wide. Steam and condensate lines were cracked and electrical and communication lines sheared as the utilidors were displaced northward near the intersection of First Avenue and A Street. A break also occurred in the electrical-communications utilidor near the pressure ridge halfway between B and C Streets, and water had to be pumped continuously from this utilidor at the manhole southeast of the Depot. An abandoned section of the electrical-communications utilidor that ran up B Street was heaved upward and broken where it crossed a pressure ridge. Since the earthquake, all utilities previously carried by the utilidors along First Avenue have been installed above ground.

A steel-framed metal-sheathed Butler building (No. 5, fig. 126) used for on-track equipment storage was overrun by an earth flow that occurred at the toe of the Government Hill slide (fig. 135).



132.—Construction of the Office Annex (Satellite) building.

Some yard equipment and rolling stock were destroyed or damaged as the flowing earth covered about 850 feet of track. This slide is described by Hansen (1965).

In addition to damage to buildings and utilities, there was a considerable amount of shifting of the rails within the yard, which made realinement and resurfacing necessary (C. L. Griffiths, oral commun., May 1964).

SECTION 16. ANCHORAGE TO KNIK RIVER

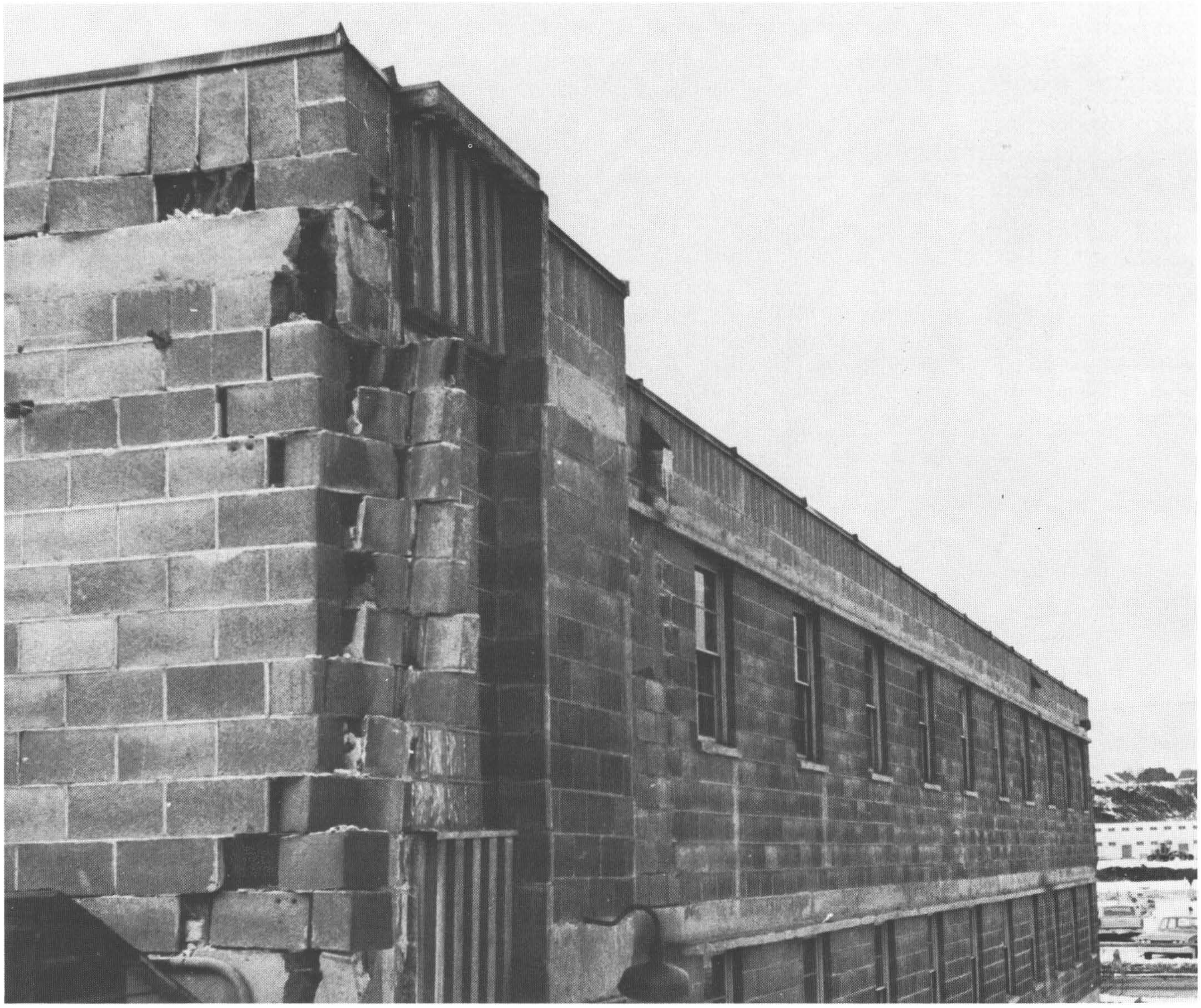
From the Anchorage yard, the rail line runs northeast on the low gravel terrace in Ship Creek valley, along the toe of the high bluffs of Government Hill. Several landslides that occurred along the edge of the bluff (fig. 68) have been described by Hansen (1965) as being primarily rotational and as having inferred failure surfaces extending down into the Bootlegger Cove Clay under the valley floor. There was some flowage and extrusion of material at the toes of the slides. The toe of one slide overrode the rail line and crossed two sets of tracks, but did no damage.

About 3 miles from the yard the rail line turns northward, leaves the valley of Ship Creek, crosses the outwash plain that forms the flat surface on the bluffs, then climbs the axis of an alluvial fan to the top of the northeast-trending ridge of the Elmendorf moraine. The rail line generally follows the moraine to the north, leaving it only from mile 122 to 124.3 as it crosses several kame fields but passing back onto the moraine as it approaches Eagle River (fig. 1). There was no reported damage between the rail yards and Eagle River. The bridge at Eagle River, 308 feet long and constructed of five steel through-deck girders on concrete piers and abutments, was only slightly damaged. Bruce Cannon reported that the only damage to the bridge was 4 to 5 inches of arching. All foundations but the southern abutment and the northernmost pier are reported by the railroad to have been built on bedrock.

From Eagle River, the rail line runs northeast on a plain of ground moraine adjacent to the Elmendorf moraine, and near Birchwood (mile 136.4) it turns eastward and follows the shore of Knik Arm (fig. 136). The low ground-moraine plain is separated from Knik Arm by a low terrace. The sediments on the terrace are primarily estuarine, and the terrace is widened by deltas at the mouth of Peters Creek and the large delta of the Eklutna River, which crosses the rail line at mile 140.8. Northeast from the mouth of Fire Creek, south of Birchwood, the low terrace and delta surfaces were broken by cracks, many of which discharged sediment-laden water.

From 1 mile north of Peters Creek to half a mile south of the small creek draining Mirror Lake, the rail line is built near the terrace edge, but is far enough from the edge not to have been affected by long fractures that occurred in, and just above, the terrace scarp.

Near mile 138.4, about 500 feet of the rail line was irregularly lowered as much as 5 feet and car-

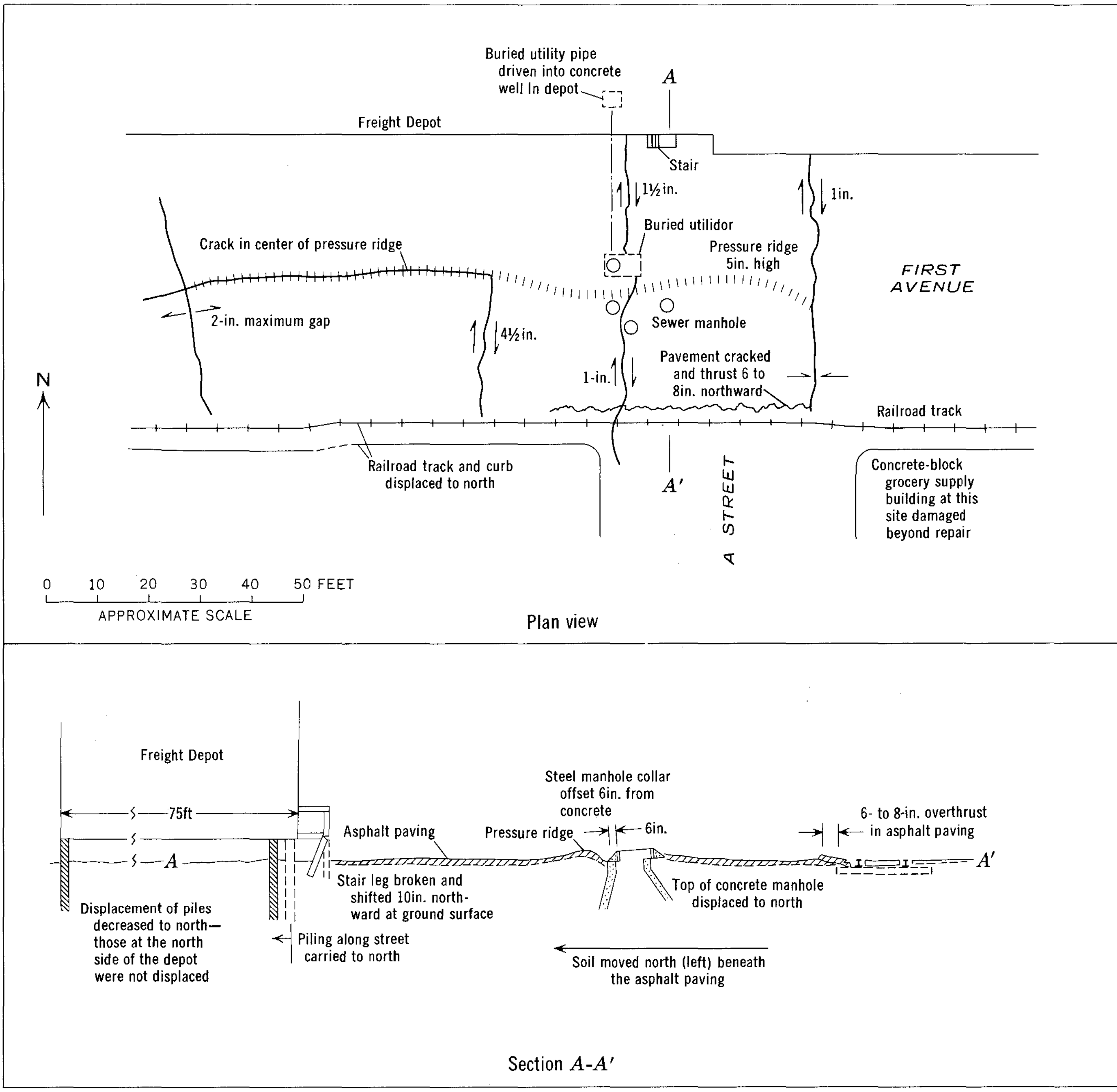


133.—View of the southeast corner of the Office Annex building, showing the rupturing of the block and mortar. Photograph by The Alaska Railroad.

ried laterally toward Knik Arm on an earth flow. This slide is described by Hansen (1965, p. A43–A49).

Continuing northward the rail line is built along the toe of the bluffs, above the Eklutna River delta. The delta has an upper surface covered with shrub and bush and a lower vegetation-free surface. The surfaces are separated by a low scarp (fig. 136). On the lower surface, south of the Eklutna River, cracks formed in the axes of abandoned channels running approximately parallel to the delta edge. There was also some discharge of sediment-laden water from these cracks, but considerably greater discharges occurred from a myriad of small fractures running in, and between, the braided channels of the Eklutna River. South of the Eklutna River the upper delta surface was also fractured, and a minor amount of water was discharged. Just east of the creek draining Edwards Lake some of these fractures extended into the toe of the bluffs on which the rail line lies in a small cut. About 450 feet of roadbed was affected by the slumping that accompanied the fracturing. No details of the effects on the embankment are available.

The rail line crosses the Eklutna River at mile 140.8 with a single-span 80-foot steel through girder



134.—Field sketches (plan and cross section) of landslide features on First Avenue along the south edge of the railroad Freight Depot. Sediments beneath the pavement moved to the north, displacing the concrete well of a sewer manhole and the porch support and wood pile foundation of the Freight Depot. The pipe from the utilidor (plan view) was thrust 16 inches into the concrete well under the depot.

135.—The toe of Government Hill slide that overran an on-track storage building and some rolling stock on the north side of Ship Creek valley

supported on concrete abutments with large wing walls that protect the approach fills from shifts in the meandering channels of the river. Bruce Cannon reports that the large abutments moved toward the river and were jammed tight against the steel deck. As seen in the streambed and in shallow bulldozer cuts, the sediments at the bridge are composed of relatively sand-free coarse gravel.

Cracks with discharges of sand and water occurred just east of the towers of a radio station, and still farther east the cracks formed in the axes of abandoned stream channels on the higher terrace. The 112-foot nine-bent open wood trestle at mile 142.9 over the small unnamed creek southeast of the radio towers was compressed and arched about 8½ inches, the crest of the arch being at about the fifth bent. The south bulkhead was also rammed by the stringers.

SECTION 17. KNIK AND MATANUSKA RIVER FLOOD PLAINS

At mile 146 the rail line turns abruptly north and crosses the braiding channels of the Knik and Matanuska Rivers (fig. 1). This was an area of severe ground fracturing, and the railroad bridges were damaged (pl. 1). The surficial geology of this area has been mapped by Trainer (1953, 1960, 1961), and subsurface information is available from 24 logged borings, six penetration tests, and four pile-pulling-resistance tests. This work was performed by the Alaska Department of Highways at the bridge sites along the route of the highway just west of the rail line that was under construction at the time of the earthquake (Foundation Study Report, Knik River and Matanuska River Bridges, Project Numbers F 042-1(7), Anchorage District). Six of the deep borings are located on plate 1, and their logs are shown in figure 137. The relief of the area is low; the rivers braid between islands that stand only 8 to 12 feet above the river channels, and, except where cut by abandoned meandering channels, the tops of the islands are relatively flat. Trainer has mapped the islands as outwash derived from glaciers that have since receded many miles upstream. The highway borings indicate that the outwash is about 50 to 80 feet thick and is composed of gray sand and gravel with occasional thin beds of sand and silt. Beneath the outwash, borings penetrated interbedded gray fine sand and silt in 1- to 3-foot layers. These fine sediments were found to the bottom of the deepest boring (−152 feet), and neither their base nor the depth of the underlying bedrock is known.

The sediments transported by the modern river are also sand and gravel, but are somewhat finer than the outwash gravel (Trainer, 1960). Both rivers are made estuarine by the approximately 30-foot range in tide in nearby Knik Arm, and one might not expect the river channel sediments to be coarse; however, both the rivers have discharges high enough to produce scour in their channels to depths sufficient to damage deeply driven piles in the railroad bridges. For example, wood piles with penetration depths of 25 feet have been unstable in the Knik River railroad bridge. In the Matanuska River, transportation of some of the coarse sediments and deep scouring occur during the nearly annual flood when Lake George, a lake formed every year by melt water dammed behind Matanuska Glacier, rapidly cuts its way through or under the glacier and empties within a few days. As much as 1,900,000 acre-feet of water has been released, and discharges up to 360,000 cubic feet per second have been recorded at the highway bridge 10 miles upstream from the railroad crossing (J. H. Feth, U.S. Geol. Survey, written commun., 1967).

Ground fractures formed during the earthquake were abundant and formed an open network in the channel deposits (pl. 1). The islands were less fractured; most open cracks were parallel or sub-

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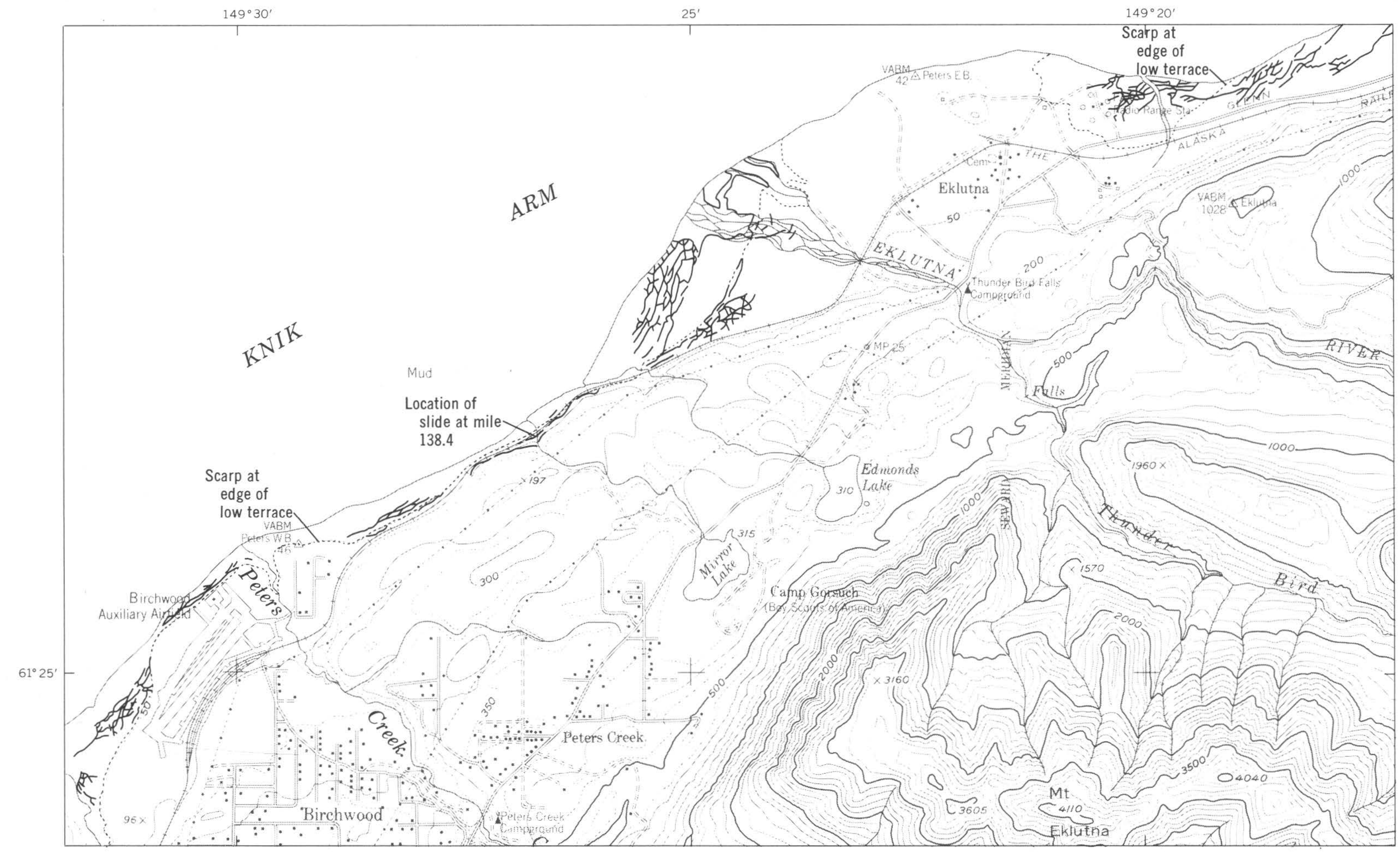


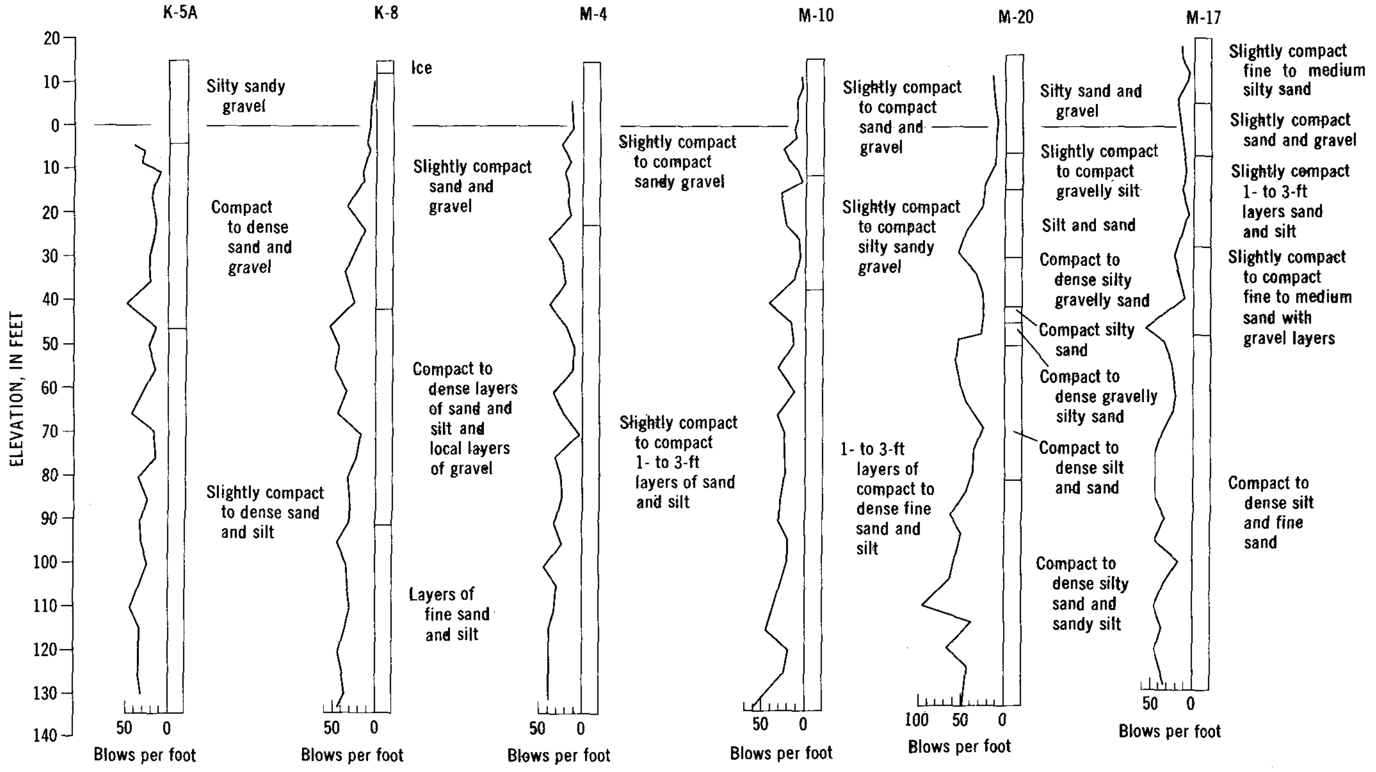
Base from U.S. Geological Survey,
1:63,360 Anchorage B-7, 1961

SCALE 1:63 360

1 ½ 0 1 2 3 MILES

CONTOUR INTERVAL 100 FEET
DOTTED LINES REPRESENT 50-FOOT CONTOURS
DATUM IS MEAN SEA LEVEL
SHORELINE SHOWN REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER

136.—Ground cracking in deltaic and estuarine sediments along the shore of Knik Arm. Cracks mapped from aerial photographs taken by Air Photo Tech, Inc., Anchorage.



137.—Logs and penetration-resistance (blows per ft. 2-in. penetrometer, 140-lb hammer, 30-in. drop) of highway borings across Knik and Matanuska River flood plains. Borings located on plate 1. Data supplied by Alaska Department of Highways.

parallel to the island margins, and many lay in the axes of abandoned meander channels. Less water was discharged from cracks on the islands where ground water lies at a depth of about 10 feet than from cracks in the channel deposits that lie within a foot or so of the water table.

As indicated by the damage to all five railroad bridges that cross the braided channels, the profuse ground cracking was accompanied by permanent horizontal displacement of the sediments. The damage to the 856-foot-long bridge (bridge 146.4), the southernmost across Knik River, is of interest because the south end of the bridge is built on bedrock, and the remainder is built on channel deposits (see fig. 39 and p. D49). The south end of the first of ten 80-foot steel through girders is carried on a concrete abutment. The concrete in the pads under the bridge shoes was in very poor condition before the earthquake; much of it could be crumbled in the hand, and it showed the vein-like texture characteristic of an alkali-aggregate reaction. The concrete on which the pads rest was in good condition. The remaining steel spans rest on cribbing supported by heavy wood-pile piers sheathed with planking. Four 14-foot open wood trestle spans on wood-pile pads join the northernmost steel span. Measurements of the movements between the steel girders and the pile piers indicate that there was a general crowding of the piers toward the center of the bridge, one pier moving perhaps as much as 9⅛ inches toward the river. There was, however, no movement between the southernmost steel span and the concrete abutment that is built on bedrock, or between this span and the pile pier at its other end. Absence of movement here is surprising, because it might have been expected that the difference in the seismic response of bedrock and the adjacent channel deposits would have been sufficiently large to produce damage where the structure passed from one foundation material to the other. The lack of damage probably cannot be attributed to the lack of ground motion, for the profuse cracking, ground-water discharge, and horizontal displacement of the nearby unconsolidated deposits are typical of areas in which ground motion was strong and of long duration. Furthermore, as indicated by the shaking damage to the Eklutna hydroelectric powerplant, 3 miles to the east (Logan, 1967), and by the report of David Drage (oral commun., 1964), who was on duty at the controls in the powerplant during the earthquake, the ground motion on bedrock was also large.

Mr. Drage recounted that the earthquake started with a rolling motion for 10 to 15 seconds "like an ordinary earthquake," lessened in intensity, then was violent for possibly 2 minutes. He said he had the sudden fear that the mountain which rises steeply above the powerplant was going to tip over. The motion was so severe that he did not dare approach the control panel to shut down the plant for fear of hitting the wrong control. Furniture within the plant was shifted, and the large overhead cranes used to maintain the hydroelectric generators rolled back and forth on their tracks.

About 500 feet north of the bridge, 300 feet of embankment was damaged when the bank of the small channel on which it is built cracked and moved toward the creek. The repaired embankment shows as a dark area on plate 1.

The next bridge to the north, built across another channel of Knik River at mile 147.1, is 420 feet long, with three central 125-foot steel through trusses and single 25-foot steel-beam spans at each end. All the spans are supported on concrete piers that were displaced toward the river during the earthquake. The anchor bolts in the short end spans tore free and spalled away the concrete, and the steel was jammed against the adjacent large steel spans. The third pier which, like the others, was reinforced with one-half-inch vertical bars 18 inches on centers was sheared off near its base along a fracture that followed a pour joint most of the way across the pier. The buried base of the pier was displaced about a foot south toward the river. The displacement tilted the upper part of the pier about 8 inches and produced an offset of about 4 inches at the break (fig. 138).

138.—Shearing at a pour joint of a concrete pier at bridge 147.1, Knik River.

The end spans of bridge 147.5, a 666-foot-long steel bridge on concrete piers and abutments, were jammed streamward against the central spans. Piers and abutments were also displaced horizontally; the north abutment and pier shifted about 1 foot west and the third pier moved about 1 foot south, toward the channel.

To the north, 575 feet of the approach embankment to the bridge over the main channel of the Matanuska River (148.3) was heavily damaged by ground cracks. Partial repairs had been made at the time this area was visited, but large cracks are reported to have crossed the tracks diagonally, and the embankment was lowered at least 4 feet. Severe cracking also occurred in the wide bank of channel deposits at the south end of the bridge. According to Bruce Cannon, the cracking "demolished" the 48th through the 59th wood-pile bents. This is the only railroad bridge in which the wood-piles were broken by ground cracks. Figure 139, taken after channel deposits had been bulldozed to replace the destroyed bridge, shows that some of the cracks were several feet wide. Mr. Cannon also reports that the anchor bolts in the adjacent 70-foot through girders shown at the left of figure 140 were sheared.

SECTION 18. MATANUSKA TO WASILLA

North of the Matanuska River the rail line leaves the highly fractured outwash and river-channel deposits and passes abruptly onto a nearly unfractured flat low-lying surface underlain by estuarine silt and clay (fig. 140). The estuarine deposits are relatively thick; Trainer (1960, p. 52) reports that a well drilled by The Alaska Railroad near Matanuska penetrated estuarine silt and clay to a total depth of 200 feet (175 ft below sea level) without reaching the base of the estuarine sediments. The estuarine sediments grade nearly imperceptibly into glacial-outwash

139.—Cracks in the active flood-plain sediments at the south end of bridge 147.5 at Matanuska River. An earth fill has been bulldozed in to replace a section of trestle in which cracks sheared wood piles at the ground and offset the trestle.

sand and gravel along the northern edge of the surface.

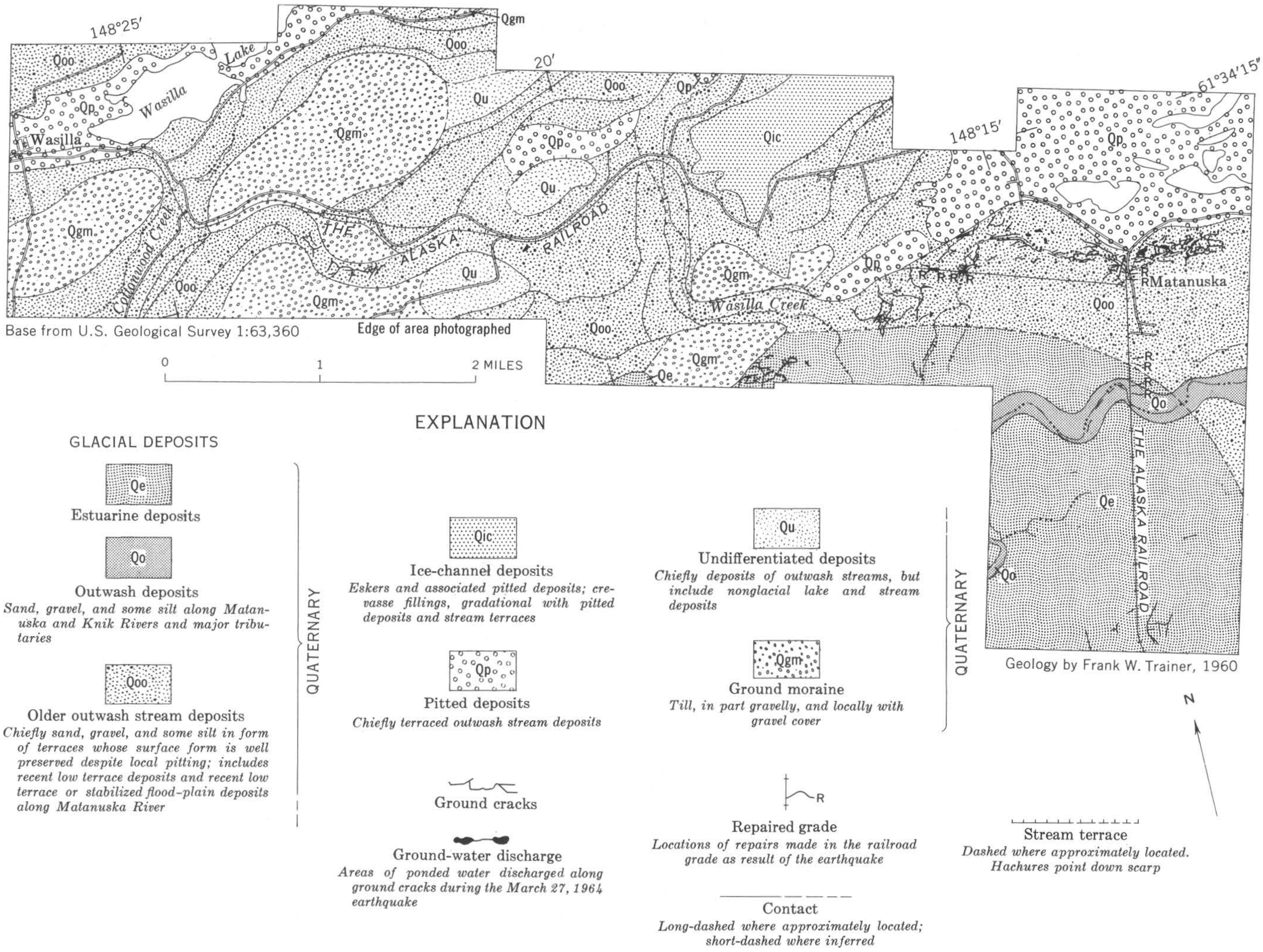
About a quarter of a mile north of Matanuska the rail line divides, the Sutton-Palmer branch swings off to the east and the main line turns west to Fairbanks (fig. 1). As shown on figure 140 the Fairbanks line proceeds west through deposits of glacial moraine and outwash sand and gravel; outwash in old ice-channel fillings, in terraced outwash stream deposits, or in older outwash deposits. Despite the wide variety of materials and the abrupt slopes shown by the scarps on figure 140, the only cracking that was visible on aerial photographs occurred in swampy areas along the modern streams that lie in the older outwash and in the estuarine deposits. The selective cracking probably was related to a very shallow, or at-the-surface, water table.

In addition to the ground cracking there was some slight damage to the railroad embankment (indicated by R) in the area on figure 144, and Bruce Cannon reports that piling was displaced 2 to 3 inches under the pile caps at the open wood trestle bridges (152.1 and 152.3) just west of Matanuska.

North of this area (fig. 1) the only damage to the railroad was minor and was restricted to bridges. At mile 264.1 the 504-foot through girder that spans the Susitna River rocked about 3 inches on its rocker bearings and the bearings had to be reset (C. L. Griffiths, oral commun., 1964). The steel in the Indian River bridge at mile 266.7 was jammed by streamward movement of its abutments, and at Hurricane Gulch, at mile 284.2, two deck truss spans were jammed against the central arch span. The damage to the Hurricane Gulch bridge was the northernmost damage to the railroad.

SECTION 19. SUTTON BRANCH LINE

The Sutton branch line runs northeast from Matanuska across a pitted outwash plain that rises from an altitude of about 100 feet near Matanuska to about 250 feet at Palmer. Sand and silt blown



140.—Ground cracking in the area of Matanuska. Most cracks are in young stream deposits lying in old glacial-outwash channels, where the water table is at, or just below, the ground surface.

from the flood plain of the Matanuska River have accumulated on the outwash in a blanket that thickens to about 20 feet a mile or so north of Palmer (Trainer, 1961). Just beyond Palmer the rail line drops down across the steep river bluffs onto the flood plain of the Matanuska River and continues north on the flood plain at the toe of the bluffs to Sutton. The flood-plain sediments and the islands and low terraces composed of glacial outwash sand and gravel (Trainer, 1961) were as severely fractured here as at the mainline crossing to the southwest (fig. 141). The rail line is built at the

141.—Large and continuous ground cracks in low terraces of glacial outwash and flood-plain sediments in the Matanuska River valley.

toe of the steep bluffs and was not affected by ground cracking.

About 2 miles south of Sutton, at mile 16.5, a small landslide that was dislodged from the steep river bluffs overrode several hundred feet of the tracks (see p. D79 for description). There was no other damage to the Sutton branch line.

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