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LANDSLIDES IN THE SAN FRANCISCO SOUTH QUADRANGLE, CALIFORNIA

By

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LANDSLIDES IN THE SAN FRANCISCO SOUTH
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INTRODUCTION

Landslides are mentioned in several earlier reports dealing with the geology of the San Francisco Peninsula, but few of them give detailed descriptions of the slides. An unpublished report in the files of the San Francisco City Engineer, written in 1945 by Chester Marliave, contains a map showing some of the landslides north of Thornton Beach State Park. A report by Forbes (1947) includes descriptions of several landslides in the San Francisco South quadrangle.

The field work that is the basis for this report was done intermittently from 1952 to 1959 as part of the U. S. Geological Survey's mapping program in the San Francisco area. Dorothy H. Radbruch of the Geological Survey mapped two of the landslides in the Hunters Point area and I subsequently examined those slides. Conrad R. Appledorn of the Geological Survey operated the planetable during mapping of the Merced formation north of Mussel Rock; the positions of some of the landslides were determined during that survey. Field observations were supplemented by study of three sets of air photos taken in 1943, 1946, and 1956, as well as published and unpublished reports. Information was also obtained from old maps such as the U. S. Coast Survey's 1869 map of the San Francisco Peninsula, on which can be seen the outlines of the large landslides near Thornton Beach State Park and Mussel Rock. Representatives of many public and private organizations cooperated in the investigation; their help is gratefully acknowledged.

The location of the San Francisco South quadrangle is shown on the index map (fig. 1). The quadrangle extends northward from the towns of San Bruno and Sharp Park (see fig. 2), and includes nearly half of the city of San Francisco. About half of the quadrangle has been developed for residential, commercial and industrial uses. The topographic relief is moderate and the highest point, San Bruno Mountain, is slightly more than 1,300 feet above sea level. Mean annual rainfall at the San Francisco airport, which is near the southeast corner of the quadrangle, is 17 inches, and at San Francisco is 21 inches. The rainfall is highly seasonal and most of it occurs in the five months, November through March.

Summary of geology

The most detailed geologic map of the quadrangle that has been published to date is included in the San Francisco Folio (Lawson, 1914). In general, consolidated rocks of the Franciscan formation of Cretaceous and Jurassic(?) age crop out in the northeast and southwest parts of the quadrangle, and unconsolidated rocks of the Merced and Colma formations of Pliocene and Pleistocene age occupy a belt that crosses the quadrangle diagonally from northwest to southeast.

The Franciscan formation in this area consists of the following: interbedded sandstone and shale, hard where fresh and intact, soft where weathered or sheared; hard chert interbedded with firm shale; greenstone, hard where fresh, firm to soft where weathered; and hard to firm schistose, gneissose, or granulose metamorphic rocks. Hard to soft serpentine crops out in the Hunters Point area and near Point San Bruno. Locally the rocks of the Franciscan formation and serpentine have been highly sheared; the sheared rock is generally coherent and firm but is soft in places, especially where weathered.

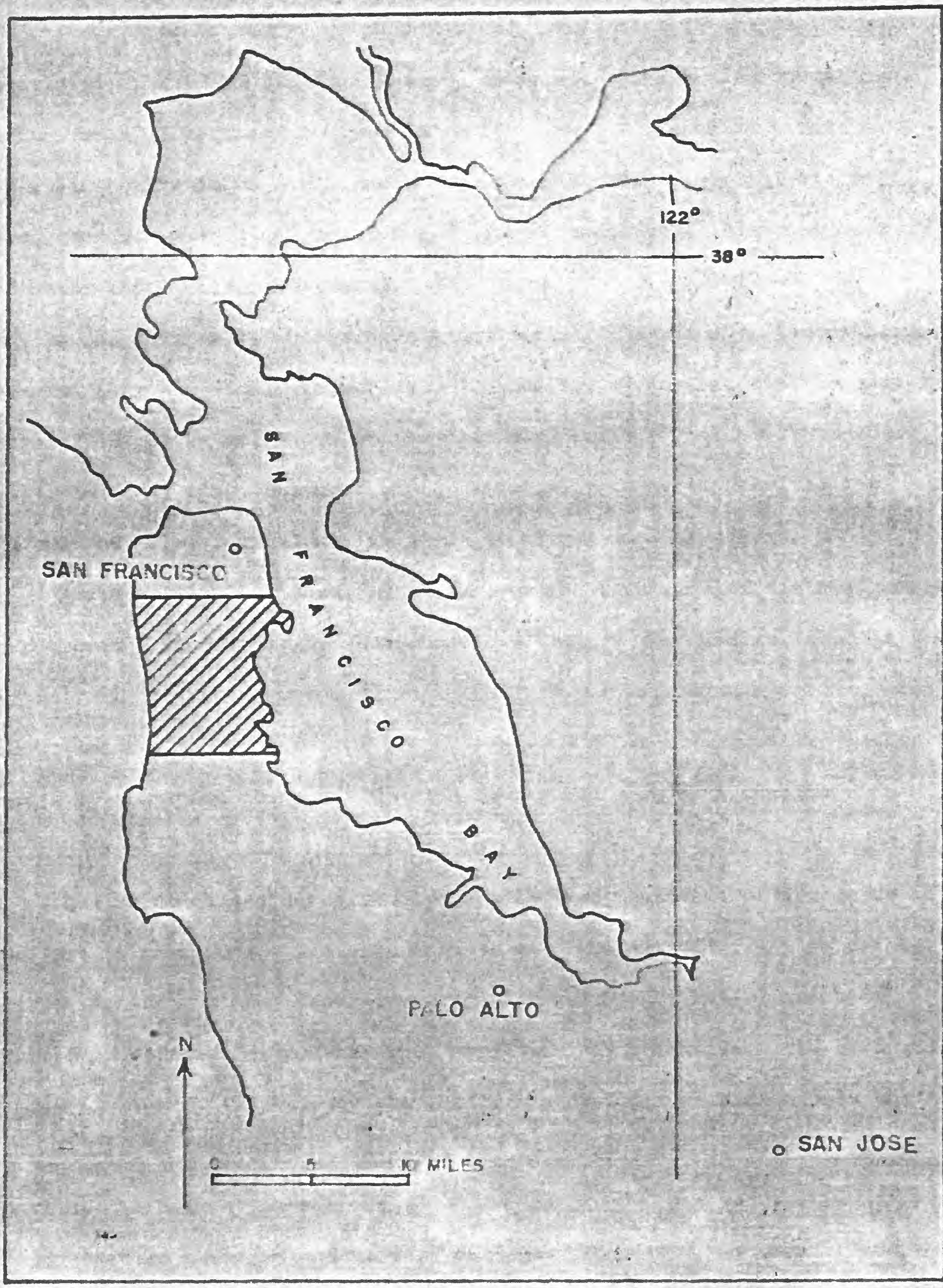


Figure 1. INDEX MAP SHOWING LOCATION OF THE SAN FRANCISCO SOUTH QUADRANGLE

The Merced formation of Pliocene and Pleistocene(?) age consists mostly of friable to firm sand, silt, and clay. The Merced formation unconformably overlies the Franciscan formation and is unconformably overlain by the Colma formation. The Colma formation, of Pleistocene age, consists mostly of friable well-sorted sand, but it has some beds of sandy silt, clay, and gravel.

A map unit called slope debris and ravine fill forms a discontinuous blanket over the older formations. It consists of unstratified or poorly stratified colluvium, alluvium, and residual soils. Most of it is stony silty to sandy clay, but some of it, especially where it overlies the Merced and Colma formations, is silty to clayey sand or gravel.

Artificial fill covers large areas on the east side of the quadrangle, and occurs in small bodies throughout the rest of the quadrangle. The artificial fill is composed of soil, rock fragments, organic matter, and waste materials. Some of the recently placed fills have greater density and stability than the natural soils from which they were obtained.

LANDSLIDES

Landslide damage has probably totalled many hundreds of thousands of dollars in this area. Accurate figures on costs are difficult to obtain, but an estimate of the landslide costs along State Highway 1 north of Mussel Rock indicates the order of magnitude of the damage. The estimate, based on figures supplied by the California Division of Highways, shows that during the last 10 years costs for correcting landslides along that part of the highway have averaged more than $10,000 per year. Damage has been greatest to roads and houses, but many other structures have been affected. Some schools have been endangered, as has the San Francisco aqueduct near Sierra Point (Lauenstein, 1930) and Visitacion Point.

More than 130 slides have been mapped in the quadrangle, or an average of two slides per square mile. This should be taken as a minimum figure, for many observed slides are too small to be shown on the map, and others, whose distinguishing features have been obliterated by natural or human agencies, no doubt went unrecognized. All of the landslides mapped in the quadrangle are shown on figure 2 and are listed in table 1. Table 1 gives the landslide type, the material involved, the length and width, the approximate original slope in degrees, the probable chief causes, and the orientation of the slope. Most landslides are the result of several causes and, as it is often difficult to analyze landslides even after thorough subsurface investigations, some of the causes given in table 1 are no more than guesses. Some of the landslides listed in the table are also described in the paragraphs that follow either because they are typical of certain kinds of landslides or because they have unusual features.

TABLE 1.--LIST OF LANDSLIDES

Type of landslide: S1, slump in rock; S2, slump in soil; BG1, block glide in rock; BG2, block glide in soil; DS, debris slide; RS, rock slide; SR, sand run; DA, debris avalanche; EF, earthflow; SF, sand flow; MF, mudflow; C, complex landslides in which the principal component types could not be satisfactorily determined.

Type of material: Qaf, artificial fill; QTm, Merced formation; KJg, Franciscan greenstone; Qsr, slope debris and ravine fill; KJu, sheared rocks; KJs, Franciscan sandstone and shale; KJc, Franciscan chert; Qc, Colma formation; sp, serpentine.

Length, width, and slope: In most cases these were obtained from the topographic map and are approximate only. Slides 1 through 11 moved into water and total lengths are unknown.

Probable chief causes: E, earthquake; R, removal of material near bottom of slope; L, loading near top of slope; W, water.

Slide number	Type of landslide	Type of material	Length (feet)	Width (feet)	Original slope (degrees)	Probable chief causes	Slope orientation
1	DS	Qaf	75	80	25	E	SE
2	DS	Qaf	100	150	20	E	SE
3	S2	Qaf	100	100	20	E	N
4	S2	Qaf	110	200	35	E	E
5	SF	Qaf	70	80	20	E	E & W
6	[illegible], EF	Qaf	125	120	25	E	W
7	SF, S2	Qaf	80	225	25	E	NE
8	SF, S2	Qaf	100	800(a)	20	E	E
9	S2	Qaf	60	125	25	E	N
10	S2	Qaf	100	100	25	E	W
11	S2	Qaf	60	150	25	E	W
12	S2	QTm	80	100	30	R	W
13A	C	QTm	700	1,800	40	R	W
13B	BG2	QTm	500	2,400	40	R	W
13C	BG2, S2	QTm	300	1,500	40	R	W

Table 1-(continued)

Slide number	Type of land-slide	Type of material	Length (feet)	Width (feet)	Original slope (degrees)	Probable chief causes	Slope orientation
13D	S2	QTm	500	2,600	40	R	W
14	S, EF	QTm	400	160	30	W,E (b)	W
15	S, EF	QTm	350	170	30	W	W
16	DS	QTm	200	300	35	R	W
17	DS	QTm	200	50	40	W,R	W
18	DS	QTm	200	300	40	R	W
19	SR	QTm	120	80	50	E	W
20	DS, SR	QTm	140	100	40	R,E (b)	W
21	DS, SR	QTm	200	120	45	R,E (b)	W
22	DS	QTm	140	120	47	R	W
23	SR	QTm	240	200	50	E	W
24	DS	QTm	110	110	50	R	W
25	DS	QTm	150	100	48	R	W
26	SR	QTm	225	100	35	E	W
27	DS	QTm	120	150	53	R	W
28	SR	QTm	560	450	40	E	W
29	DS	QTm	140	130	48	R	W
30	SR	QTm	140	80	40	E	W
31	DS	QTm	120	70	40	R	W
32	S2	QTm	80	60	40	W,E (b)	NW
33	DS	QTm	150	220	55	R,L	W
34	DS, SR	QTm	140	100	45	R,E	W
35	DS	QTm	150	80	50	E	W
36	DS, EF	QTm	450	100	40	R,W (c)	W

Table 1-(Continued)

Slide number	Type of land-slide	Type of material	Length (feet)	Width (feet)	Original slope (degrees)	Probable chief causes	Slope orientation
37	DS	QTm	120	180	45	R,L	W
38	DS	QTm	200	140	40	R	SW
39	DS, EF	QTm, Qaf	350	100	30	W,L	W
40	S2	QTm	60	100	40	R	W
41	DS	QTm	450	200	50	R (d)	W
42	DA, EF	QTm	700	200	45	R (d)	W
43	C	QTm	2,300	200-2,000	35(?)	R,W,E	W
44	S, EF	QTm	60	70	30	R,W	W
45	S2	QTm	120	200	25	R,W	SW
46	EF	Qsr	80	50	15	W	W
47	EF	Qsr	80	60	40	R	SW
48	EF	Qsr,KJg	200	200	30	R,W	SW
49	EF	Qsr	80	50	25	W	SW
50	EF	Qsr	200	40	20	W	SW
51	EF	Qsr	180	50	15	W	SW
52	EF	Qsr	240	80	15	W	SW
53	EF	Qsr	100	80	25	W	SW
54	DS	KJu	80	100	20	R	SE
55	DS	Qaf,Qsr	150	90	25	R,L	SE
56	DS	KJu	100	75	30	R	N
57	DS	KJu	75	60	30	R	N
58	DS	KJu	120	75	30	R	N
59	DS	Qsr,KJs,KJc	800	350	40	R,W (e)	NE
60	DS	Qaf,Qsr	250	80	30	L,W	E

Table 1--(Continued)

Slide number	Type of land-slide	Type of material	Length (feet)	Width (feet)	Original slope (degrees)	Probable chief causes	Slope orientation
61	DS	Qaf,Qsr	260	100	30	L,W	NE
62	DS	Qsr,KJs	200	100	25	W	N
63	DA	Qsr	380	150	20	W,R	SW
64	DS	Qsr	70	60	35	R	SE
65	DS	Qsr	150	100	25	W	E
66	DS	Qsr	130	60	20	W	NE
67	EF	Qsr	100	60	20	L,W	W
68	EF	Qsr	100	80	20	W	S
69	EF	Qsr	240	90	15	R	S
70	EF	Qc	120	60	15	W,R	SE
71	EF	Qsr	220	80	25	W	SE
72	Sl	KJs,KJc	85	115	50	R,W	SE
73	EF	Qaf	430	100	25	W	SE
74	EF	Qaf,Qsr	150	50	35	R,W	S
75	BGl	KJs	300	150	45	R	E
76	EF	Qsr	230	50	15	W	W
77	EF	KJu, sp	460	85	20	W	NW
78	DS	KJu	180	70	25	W	E
79	DS	KJu	80	60	20	W	SW
80	DS	KJu	370	80	20	W	S
81	EF	Qsr	500(f)	300	20	W	SE
82	EF (g)	Qsr	200	70	20	W	SW

Table I--(Continued)

Slide number	Type of land-slide	Type of material	Length (feet)	Width (feet)	Original slope (degrees)	Probable chief causes	Slope orientation
83	EF	Qsr	200	70	20	W	E
84	EF (g)	Qsr	80	30	15	W	S
85	DA	Qsr	50	30	25	W	SE
86	DS	Qsr	160	40	25	W	SW
87	EF	Qsr	150	50	25	W	SW
88	EF	Qsr	120	30	20	W	SW
89	DS	KJs	170	60	30	W	SW
90	DA	KJs	100	30	40	W	S
91	S1	KJs	70	120	40	R	S
92	S,-EF	Qsr	100	50	23	R	SW
93	S,-EF	Qsr	110	70	23	R	SW
94	S,-EF	Qsr,sp	200	180	25	R,W	NW
95	GB,-EF	KJs,sp	350	100	10 & 40	R,W	S
96	S,-EF	Qsr	100	60	20	W	SW
97	DS	Qsr,Qaf	50	100	40	L,W	N
98	DS	Qsr	40	80	40	R,W	N
99	DS	Qsr	70	60	25	W	W
100	DS	Qsr	200	160	15	W	N
101	EF	Qsr	200	100	12	W	NE
102	DS	Qsr	50	40	30	R	NE
103	DS	Qsr	140	40	40	R	NE
104	DS	Qsr	90	70	45	R,W	E
105	EF	Qsr	280	40	20	W	NE
106	DS	Qsr	100	60	35	R,W	E

Table I--(Continued)

Slide number	Type of land-slide	Type of material	Length (feet)	Width (feet)	Original slope (degrees)	Probable chief causes	Slope orientation
107	DS	Qsr	130	50	30	W	NE
108	DS	Qsr	140	60	15	W	NE
109	DS	Qsr	50	30	40	R	N
110	DS	KJs,Qsr	200	380	25	R	S
111	DS	KJs,Qsr	100	180	30	R	S
112	DS	Qsr,KJu	60	50	35	R	SE
113	C	KJs,Qsr	500	1,000	25	W,R	NE
114	DS	KJs,Qsr	350	180	35	W,R	E
115	DS	KJs	140	90	30	R	NE
116	DS	KJs	220	60	33	R	NE
117	DS	KJs	110	70	33	R	E
118	DS	KJs	130	60	30	R	SE
119	DS	KJs	120	150	33	W,R	SE
120	EF (f)	Qsr	200	120	15	W	E
121	RS	KJs	160	175	33	R	NE
122	EF	Qaf	160	80	20	W	E
123	S, EF	Qaf	120	60	20	W	N
124	MF	Qaf,Qsr	700	70	40	W,L	E
125	MF	Qaf,Qsr	200	50	35	W	E
126	S2	Qsr	80	50	25	W	SW
127	DS	Qsr,KJg	50	60	50	R	SW
128	DS	QTm,Qsr	130	70	20	W	SW
129	EF	Qsr	125	60	15	W	S

Table 1--(Continued)

(a) Consisted of several coalesced slides.

(b) Enlarged by earthquakes.

(c) May be two separate slides.

(d) Removal of support by gullying. Slides may have started in pre-1957 earthquakes.

(e) Has long been stable.

(f) Includes several slides.

(g) Many similar slides nearby.

The landslide classification used in this report is that proposed by the Highway Research Board (Varnes, 1958). The classification is based on two main variables: the type of material involved, and the type of movement. In many ways it resembles the classification of Sharpe (1938). Landslides are grouped on the basis of type of movement into falls, slides, and flow; if more than one type of movement is involved, the landslides are termed complex. Falls and slides are subdivided on the basis of material into those that involve bedrock and those that involve soils. The term soils is used in the sense used by engineers, and includes earth materials that are too soft or too fragmental to be called rock. Rock fragments, sheared or weathered bedrock, and organic matter are considered soils in the Highway Research Board landslide classification.

Slides

Slides include mass movements in which actual shearing takes place along one or more surfaces. Slides make up 54 percent of the landslides mapped. Four types of slides were observed in the quadrangle: slump, block glide, debris slide, and rockslide.

Slump.--Slump includes slides in which the moving material is not greatly deformed and in which the top surface of the slump rotates backward toward the slope. The surface of rupture, which is usually concave upward, is apt to be deeper than in most other types of landslides. The scarp is generally concave downslope in plan.

Thirteen slumps were identified in the quadrangle, or 10 percent of the total number of landslides. Slumps are also involved in most of the complex landslides. About 40 percent of the slumps were along the sea cliffs and involved sand, silt and clay of the Merced formation, and about 40 percent were on the shores of Lake Merced and involved artificial fill. The rest of the slumps involved sandstone, shale, and chert of the Franciscan group.

An example of a bedrock slump is Slide 72 which is in San Francisco on the northwest corner of Powhattan Street and Peralta Street. The slide occurred in February of 1954 and damaged a house. The slide is 115 feet wide along the scarp, and 85 to 100 feet long; the scarp was estimated to extend 35 feet below the original surface.

The slide occurred on the side of an artifical cut that had a slope of 50° and was about 35 feet high. The rock at that site is friable to hard sandstone and chert of the Franciscan formation, is somewhat sheared, and is hydrothermally altered in places. Minor faults dip steeply eastward and the surface of rupture seems to have followed a fault near the south edge of the slide; near the north edge, the surface of rupture is not well exposed but seems to be in hydrothermally altered chert.

When examined in 1954, the slide had only moved a few feet, had moved as a unit, and had rotated toward the scarp. Removal of support by excavation seems to be the principal cause of this slide.

Block glides.--Block glides are slides in which the moving material is not greatly deformed but, in contrast to slumps, the surface of rupture is planar and therefore rotation and backward tilting are absent. Only two block glides were recognized in the quadrangle (Slides 13B and 75) and the identification of Slide 13B is doubtful; slide 13C consists of a combination of block glide and slump. The block glides involve sand and clay of the Merced formation and sandstone and shale of the Franciscan formation.

Slide 75 is a block glide on the side of the inactive quarry that is 2,000 feet south of the Cow Palace. The slide occurred before October 1943; air photos taken at that time show the scarp clearly. The slide is 150 feet wide at the scarp, and about 300 feet long. The slide material is nearly tabular in form and consists of interbedded sandstone and shale of the Franciscan formation, which strikes N. 25° to 75° W. and dips about 50° NE in the vicinity of the slide.

Before quarrying the slope had an inclination of about 35° and after quarrying, about 45°. The scarp of the slide is more than 150 feet upslope from the quarry face. The scarp is about 10 feet high, and judging from air photos, the slide did not move appreciably between 1943 and 1946. The slide seems to be of the block glide type, with the movement nearly parallel with the bedding planes. It seems clear that the cause of the slide was removal of support by the quarrying operation.

Debris slide.--Debris slides occur in soils. Failure is by shearing, and the moving material breaks up into many units or is greatly deformed. The surface of rupture is shallow in most of these slides and is generally located at the top of underlying firmer material.

Debris slides are the most common type of landslide in the quadrangle and constitute 42 percent of the total. Fifty-six debris slides were recognized, of which 7 are doubtful. The material called slope debris and ravine fill is involved in 34 percent of the debris slides. Sand, silt and clay of the Merced formation is involved in 25 percent of the debris slides. Other materials involved, in decreasing order of frequency, are sandstone and shale of the Franciscan formation, sheared bedrock, combinations of materials, and artificial fill.

Slide 33 is a debris slide that occurred between 1946 and 1955. The slide is below Highway 1 on the sea cliffs, 4,900 feet north of Mussel Rock. Little or no sliding is visible on air photos of this site taken in 1946, and at that time a wide bench existed on the seaward side of the highway. By 1955 all the bench had slid away, and the slide had begun to destroy the edge of the pavement. In 1955 the slide was 220 feet wide near the beach and 150 feet from crest to beach (measured in horizontal projection). The slide debris is approximately tabular in form and mantles the slope. In 1955 and 1956 the waves had cut through the debris in a few places and revealed the underlying undisturbed material.

The slope on which the slide occurred is part of the sea cliff about 450 feet high that is being eroded by wave action at its base. Most of the bench that was seaward of the highway was probably composed of artificial fill placed during construction and maintenance of the highway. The slope after sliding was 50°, and judging from adjacent parts of the slope, was about 55° before sliding.

The slide developed in friable silt and fine silty sand of the Merced formation which here strikes N. 50° W. and dips 55° NE. The shoreline trends due north and the beds dip obliquely into the cliff. At the north edge of the slide is a fault that has a right-lateral strike separation of about 200 feet; this fault and several smaller ones adjacent to it strike N. 10° to 20° E. and dip 65° to 75° SE.

In the dry season of the year small springs were seen 500 feet north of the slide but none at the slide. The hydrologic conditions when the slide occurred are not known, but impediment of ground-water movement by the faults may have helped cause the slide. However, the chief cause of the slide was probably oversteepening of the slope by placement of artificial fill at the top, and especially, by wave erosion at the base.

Rockslide.--In rockslides, failure is by shear and the moving material breaks up into many units. Slide 121 is the only rockslide that was mapped but several smaller rockslides were seen. Slide 121, which is west of Visitacion Point, developed on an artificially cut slope inclined at about 33°. The slide destroyed a bench cut in the slope and for a time threatened an aqueduct which is at the base of the slope. The structure and condition of the rock were especially important in the development of this slide. The bedding of the sandstone and shale of the Franciscan formation is inclined toward the cut, and movement of the slide was largely parallel to the bedding. The scarp of the slide was controlled by a fault; closely spaced fractures and hydrothermal alteration further weakened the rock. Slide 121 has been corrected by improving the drainage and reducing the slope to about 15°.

Flows

Varnes (1958, p. 32) says "In flows, the movement within the displaced mass is such that the form taken by the moving material or the apparent distribution of velocities and displacements resembles those of viscous fluids."

Slip surfaces are uncommon in flows but the moving material can have either a sharp or gradational boundary with the stable material.

Twenty-nine percent of the landslides in the quadrangle were classed as flows, including 4 percent which were dry flows. Earthflows are the most common type of flow.

Debris avalanche.--Debris avalanches are rapid, flow-type movements of mixtures of rock, soil and water. The surface of rupture is commonly the boundary between the firm bedrock and the overlying material. In the lower part of the slide, the slide debris commonly flows over and is deposited upon the original ground surface. Debris avalanche deposits are commonly long, narrow, and thin. Only two debris avalanches (Slides 85 and 90) are shown on the map, but numerous smaller debris avalanches were observed in the field or seen on photographs. The debris avalanches involved sandstone and shale of the Franciscan formation, and slope debris. Slide 42, which is a combination of debris avalanche and earthflow, involves silt of the Merced formation.

Earthflow.--Earthflows are slow to rapid flow movements of material that is mostly plastic. The surface of rupture may or may not be well defined. In many cases it is at the contact with underlying firm rock and may be at a shallow or moderate depth from the surface. The scarp is commonly concave downslope in both horizontal plan and longitudinal section. The landslide deposit commonly has a rounded hummocky surface, thicker in the middle than at the sides, and an enlarged toe area.

Twenty-eight earthflows were mapped, or 21 percent of all the landslides in the quadrangle. Earthflows made up part of 13 of the complex landslides. Eighty-two percent of all the earthflows are in slope debris. The other materials involved in earthflows are artificial fill, clayey sand of the Colma formation, and sheared bedrock. The average slope before failure by earthflow was 21° and the range was from 12° to 40°.

Mudflow.--Mudflow is the rapid flow movement of fine-grained material (50 percent or more of sand, silt and clay-sized particles) with a high content of water. Similar flows but with more than 50 percent of coarse material are called debris flows in the Highway Research Board classification. Mudflow deposits are commonly long, narrow, and thin. Natural levees sometimes form on the edges of mudflow deposits.

Only two mudflows were mapped but several were observed in the quadrangle. All of these flows involved slope debris and two of them also involved artificial fill which had been piled on top of the slope debris. Two of the mudflows started on short artificial slopes with inclinations of about 40°, but they flowed several hundred feet on slopes of 15° or so.

A mudflow (Slide 125) occurred on the north side of San Bruno Mountain near the head of Guadalupe Valley sometime between 1946 and 1956. The flow removed material from a triangular prism 15 feet high, 25 feet wide and 55 feet long. The landslide started on a slope of about 35° but the material flowed 200 feet on a slope of about 10° and left a deposit which in most places was less than one foot thick.

The flow involved silty slope debris and artificial fill composed of the same material, both of which were friable when dry and rather porous. The fill was placed on the slope debris during construction of a nearby pipeline. The fill had a slope estimated to be 35° and probably was not compacted. The pipeline is laid in impermeable weathered sandstone and shale of the Franciscan formation uphill from the slide. The flow probably resulted when rainwater flowed along the bedrock surface in the pipeline trench and saturated the slope debris and artificial fill near the bedrock contact.

Sand flow.--Sand flow is the rapid flow movement of saturated sand. Commonly, the sand is liquefied by vibrations caused by earthquakes or by the activities of man. The material involved is usually clean, well-sorted sand of loose structure and saturated with water. The vibrations cause a collapse of the structure of the sand, accompanied by a sudden but temporary increase in the pore-water pressure, and the mixture of sand and water than acts as a fluid. (Terzaghi and Peck, 1948, p. 100-101.) Sudden liquefaction of sand or silt, observed in many parts of the world, can be the result of vibrations caused by blasting, pile-driving, or the passage of streetcars and trucks (Terzaghi, 1950, p. 100; Cogen, 1936, p. 468) as well as earthquakes. The slope of the scarp is generally at the angle of repose of tha sand and the material that has moved is generally spread out on the floor of an adjacent body of water.

The landslides which I have identified as sand flows occurred during or shortly after the earthquake of March 22, 1957. Some of the sand flows were accompanied by slump failure of the adjacent higher and drier sand. All of these sand flows were on the shores of Lake Merced and all involved artificial fill, which consisted of clean, loose, well-sorted sand.

Slide 5 is an example of this type of landslide. It severed the artificial embankment north of the footbridge that crosses the north arm of Lake Merced, as shown on figure 3.

The exact dimensions of the slide deposit could not be determined because it was under water but about 50 feet of the embankment was destroyed. The vegetation displaced by the slide is visible on air photos taken four months after the slide. Measurements made on the photos show that the vegetation on the sides of the embankment moved at least 70 feet both eastward and westward from the original shoreline of the embankment. The material visible in the north end of the embankment was artificial fill composed of clean sand, and as a large deposit of dune sand is found a short distance north of the site, it is probable that all of the embankment was clean well-sorted sand obtained from the dunes. The slope of the embankment above water was on the order of 20^{o}, and under water was presumably less.

The earthquake vibrations probably liquefied the saturated sand at the base of the embankment and the unsupported embankment collapsed and spread over the lake bottom. Slide 8, shown on figure 4, probably started as a sand flow, but removal of support by the flow resulted in slump failure near the head of the landslide.

Sand run.--Sand runs consist of rapid flow movement of dry or slightly moist sand on steep slopes that are near the angle of repose of the sand. The surface of rupture is usually at a shallow depth from the surface and in loose sand is regular. In slightly cemented sand the surface of rupture, including the scarp and flanks, may be irregular owing to joints or greater cementation in some places.

Figure 3. Destruction of artificial embankment on Lake Merced. View looking southeast.

Figure 4. Damage to roadway by landslides along south arm of Lake Merced. View looking northwest.

The deposit formed by sand runs is cone-shaped and in the toe area it usually makes a sharp angle with the surface on which it rests.

Five sand runs, or 4 percent of the total number of landslides in the quadrangle, were mapped. All of the sand runs were in the sea cliffs north of Mussel Rock. Three of the sand runs involved only fine sand of the Merced formation, and two involved sand and silt of the Merced formation. The slope before failure ranged from 35° to 50°. All of the sand runs occurred during or just after the earthquake of March 22, 1957. At the time of the earthquake the seasonal rainfall was about 4 inches below normal. No rain had fallen for several days and the materials in the sea cliff were in a dry state.

The sand involved in these sand runs is slightly coherent, rather than loose as in the more idealized type of sand run. Some of the sand runs undoubtedly began as debris slides, and the material broke down into sand-sized particles as it moved downslope. A few landslides which contained numerous moderately large fragments were classified as combination debris slides and sand runs. One of these complex landslides (Slide 34) occurred 10 months after the March 22 earthquake, when no aftershocks were recorded.

Slide 28 is a sand run that occurred along the sea cliff 4,300 feet south of the intersection of Alemany Boulevard and Skyline Boulevard. The slide started during the main shock of the earthquake of March 22, 1957 and three hours later, when the photograph (figure 5) was taken, the slide covered the full width of Highway 1. Shortly after the picture was taken, an aftershock enlarged the landslide and small clouds of dust arose from the dry sand during the movement. The

Figure 5. Landslides blocking State Highway 1 on March 22, 1957. View looking northward. Slide 28 in foreground.

aftershocks increased the length of the slide by upslope movement of the scarp and, after the debris spilled over the highway, by downslope movement of the toe. The scarp eventually reached the top of the cliff and the toe reached the bottom of the cliff, at that time the slide was 560 feet long and 450 feet wide.

Air photos show that sliding occurred at the site of Slide 28 shortly before October of 1943 but that in 1946 and 1956 the slope was nearly stable and sparsely covered with the vegetation. The slope on which Slide 28 occurred was a little more than 40°, a result of natural cliff recession and artificial excavation for the highway.

The slide probably began in friable medium to fine sand, undermined an overlying silty clay about 8 feet thick and spread into adjacent very fine sand and silt. The slide debris was mostly loose sand but contained blocks of friable sand several inches in diameter.

The beds of the Merced formation here dip about 60° to the northeast and the outcrop of the beds trends diagonally up the slope. The diagonal trend probably is the reason for the asymmetry of the slide in plan (see fig. 2). The shape of the slide debris, the appearance of the failure surface, and the type of debris indicate that the slide was principally a sand run. The slide debris above the highway was removed by maintenance crews and pushed over the highway toward the beach.

Complex landslides

Complex landslides consist of combinations of two or more different types. The shapes of the landslide deposit, of the scarp, and of the surface of rupture are complex because of the combination of different types of movement and materials. Twenty-two landslides, or 17 percent of all in the quadrangle, were complex. Nearly half of the complex landslide were combinations of slump and earthflow. Slope debris, either by itself or combined with serpentine, was involved in most of the slump earthflows; sand, silt and clay of the Merced formation and artificial fill were involved in the remainder of the slump earthflows. The average slope before failure was 25° for the slump earthflows. Other complex landslides were of the following combinations: sand flow and slump, debris slide and sand run, debris slide and earthflow, debris avalanche and earthflow, block glide and slump, and possibly block glide and earthflow. Of the complex slides other than slump earthflows, sand, silt, and clay of the Merced formation were most often involved. Artificial fill, and mixtures consisting of artificial fill, silt of the Merced formation, sheared sandstone of the Franciscan formation, and serpentine were involved in the remainder of the slides. The average slope before sliding of the complex slides, other than slump earthflows, was 33°.

The most complex landslide in the quadrangle is the Mussel Rock slide (Slide 43) which lies immediately northeast of Mussel Rock. This landslide can be seen clearly on large-scale topographic maps, including the 1869 U. S. Coast Survey map. This slide is active and the highway that crosses it must be repaired at frequent intervals. The main slide probably started as a slump earthflow but no convincing evidence of backward rotation was found. At the base of the main scarp, a block about 100 feet wide and 200 feet long has an even surface dipping eastward toward the scarp, but the dip of its surface may be due to erosion before the slide occurred rather than rotation.

The surface of the landslide deposit is irregular; most of it is hummocky and supports intermittent ponds. Material is added to the landslide from the main scarp and flanks by slumps, debris slides, and erosion of gullies. Where cut by a deep gully near the north side, a slump-earthflow has developed in the landslide material, and where the waves erode the landslide deposit, slumps with multiple scarps, earthflows, and mudflows have occurred. On the beach, wave erosion has exposed the surface of rupture of one of the subsidiary slides. The surface of rupture is irregular, and is marked by black clay gouge a few inches thick. Movement of the landslide produces small soil falls at the beach. The main surface of rupture probably extends well below sea level.

Slide 34 occurred above Highway 1 on the sea cliffs 4,900 feet north of Mussel Rock about 1:00 p.m. January 22, 1958, and blocked both lanes of the highway. The slide was approximately 100 feet wide and 140 feet long, and the top of the scarp was estimated to be 200 feet above the highway. The debris had the shape of a cone and its volume was about 5,000 cubic yards.

The general slope of the sea cliff is about 40° but is steeper in the cut above the highway. Air photos taken in 1943 and 1946 show fresh landslide scars there, and during the earthquake of March 22, 1957 a debris slide removed part of the cut above the highway. As a result of the artificial cut and the earlier landslides, the slope was probably 45° or more before Slide 34 occurred.

The slide involved friable silty very fine sand of the Merced formation, which at that place strikes N. 55° W. and dips 65° NE.

After sliding, about 90 percent of the debris consisted of loose sand and the rest consisted of lumps of friable sand a few inches in diameter. Newspaper reports stated that the slide occurred "about 1:00 p.m.," so one may assume the slide movement was rapid. The failure probably began as a debris slide but the material quickly disintegrated and the movement changed to a sand run.

Slide 113 is above Bayshore Highway at Brisbane; it started sometime before 1943 and has been intermittently active since then, causing uplift of the pavement. The slide area is 500 feet from scarp to toe and measures more than 1,000 feet in greatest width.

The slide is in sandstone and shale of the Franciscan formation, covered in many places by thin colluvium and alluvium. The southern part of the scarp, which is 35 to 40 feet high, is a well-defined fault that dips 80° NE. and has slickensides and grooves that plunge 35° to 70° S., 40° E. The footwall of the fault shows irregular hydrothermal alteration. The central part of the scarp is 5 to 15 feet high and most of the sandstone exposed there is also hydrothermally altered. A crack 10 to 15 feet deep, 10 feet wide at the top and 3 feet wide at the bottom was seen at the base of the scarp. Only part of the total depth of the crack was visible because the lower part was filled with debris from the walls.

Most of the hillside had a slope of about 25° before sliding, but the slope was as much as 55° along parts of the highway cut. Study of large scale topographic maps made by the U. S. Coast and Geodetic Survey suggest that the slide did not exist before 1857; presumably the slide started after artificial cuts were made for the railroad and the highway sometime between 1915 and 1939.

At the head of the slide, the movement has been almost vertically downward, but farther downslope it has a strong horizontal component. Along some parts of the toe, movement of the slide has displaced the pavement upward.

Thornton Beach State Park is in an area of landslides which extends along the coast for 1½ miles and extends inland about 700 feet. The area is made up of four or five distinct landslides, including slumps, slump-earthflows, and probably a block glide. The slide that is in line with Alemany Boulevard (Slide 13D) has been studied in detail. A distinctive horizontally bedded ash bed associated with silty clays is exposed in the scarp and in the landslide debris near the beach. An inclined topographic surface at the base of the scarp dips 25° toward the scarp, and its inclination is probably due to rotation during the sliding. However, the ash bed near the beach dips 55° toward the scarp and in addition the ash bed is much farther below the original ground surface than it is in the scarp. These relationships indicate that two slumps occurred here. To test this, an analysis was made using the Swedish method of slices as described by Baker and Yoder (1958, p. 191-195). Several assumptions were made for the analysis: 1) that the toe of the slope before sliding was in line with the coastline north and south of the area; 2) that the slope of the sea cliff was the same as it is north and south of the area, namely 40°; 3) that the surface of separation would intersect the scarp now visible above the slide; and 4) it was assumed that the position of the water table would not greatly influence the analysis. The last assumption had to be made because no reliable information is available on the position of the water table.

Results of tests made by the developers of the nearby Westlake housing project were used to estimate values of the angle of internal friction and cohesion for sediments of the Merced formation. The analysis showed that the surface of rupture would not intersect the observed scarp if the sliding surface were entirely in sand of the Merced formation, but it would if the sliding surface were mostly in silt and clay beds in the Merced. Using zero for the angle of internal friction and 2,350 pounds per square foot for the cohesion of silt and clay, the centers of rotation with the smallest safety factors were found. By making small cardboard models and suspending them from those centers of rotation, the attitudes of both the inclined topographic surface and the ash bed were reproduced closely (see fig. 6). Thus the occurrence of two slumps seems demonstrated. The deepest part of the surface of rupture of the main landslide, according to this analysis, extends 140 feet below sea level.

The sea cliffs both north and south of the Thornton Beach slides are made up of the same types of materials as in the slide area itself. All are in the Merced formation and all are mostly sand with thin interbeds of silt and clay. The attitude of the bedding, however, is not the same everywhere. In the area of sliding, the dip is only 5° to 10°, whereas south of the sliding area the dip is about 45° NE, and north of the sliding area, the dip is 25° to 45°. With respect to slumps and block glides, the Merced formation is apparently unstable in cliff exposures where the dip is low, but stable where the dip is moderate to steep and into the hill.

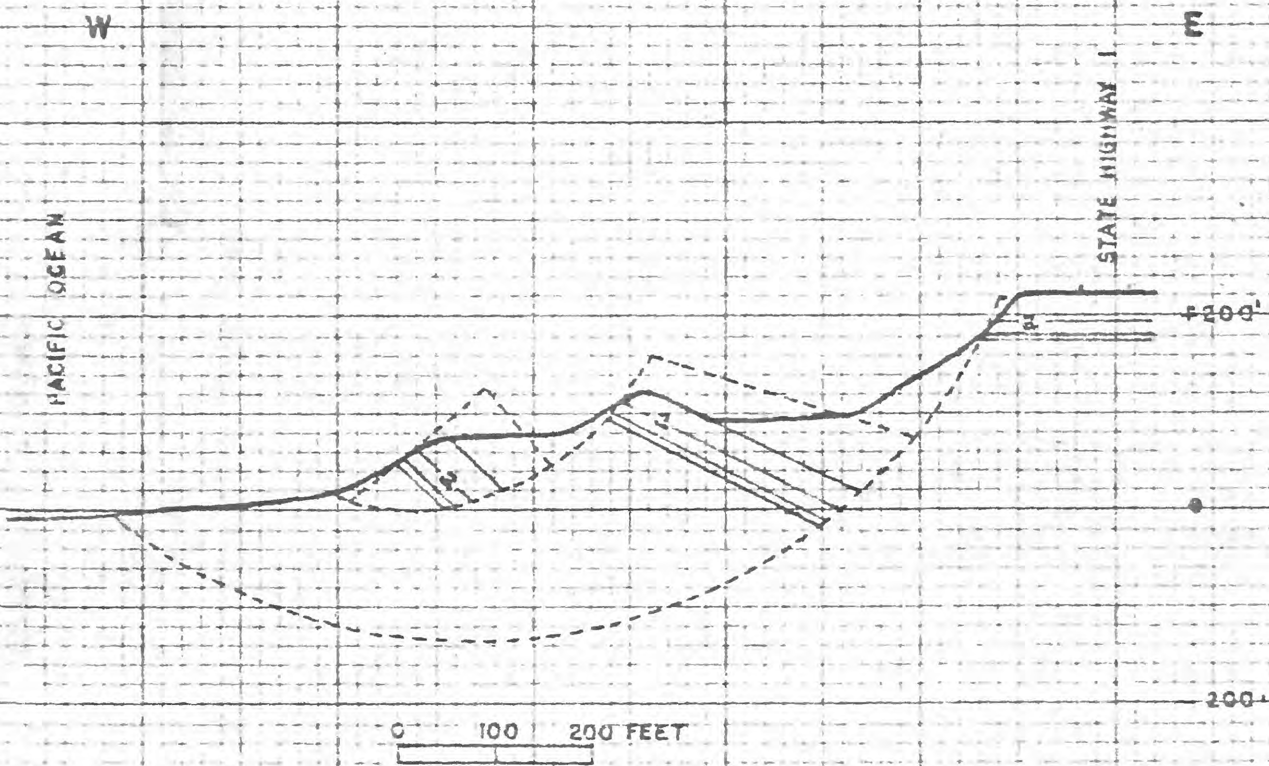


Figure 6. COMPARISON OF CALCULATED AND OBSERVED FEATURES OF SLIDE 13D

Solid lines show profile, bedding, and position of displaced topographic surfaces as determined from surface exposures; dashed lines show calculated positions of rupture surfaces and topographic surfaces. Ash bed indicated by letter "a".

Other landslides

Some alluvial fans on the south and southeast flanks of San Bruno Mountain have boulders as much as 8 feet in diameter resting on their surfaces. These boulders may have been deposited by debris flows. In addition to the soil fall mentioned in the description of the Mussel Rock slide, soil falls occur along steep streambanks where the stream undercuts firm silty terrace material. Rockfalls are rare in the quadrangle because steep natural slopes cut in bedrock are not common. The few rockfalls are limited almost entirely to quarries. Failure by lateral spreading, rock fragment flow and loess flow were not recognized in the quadrangle.

Corrective methods

A full treatment of corrective methods is beyond the scope of this report. The remarks that follow are based mostly on field observations, supplemented by limited discussions with individuals concerned with landslide problems, and published and unpublished information. The term "corrective methods" as here used includes measures taken to restore the usefulness of damaged structures or to prevent further damage.

Several corrective methods have been used in this area. Excavation, drainage, use of restraining structures, avoidance of the slide and replacing the material that has slid are the more common methods of dealing with slide problems. Simple removal of slide debris that obstructs roadways is the most common corrective method, and was frequently used on State Highway 1 north of Mussel Rock. Other excavation methods, less commonly used, are removal of the head of the slide, benching of slopes, flattening of slopes, or entire removal of the slide.

Most of the slides that occurred along the shores of Lake Merced during the 1957 earthquake were corrected by replacing the material that had slid with more stable material, including rock fragments. This method of treatment ranks next to excavation methods in frequency of use for correcting slides.

Improvement of surface and subsurface drainage has been used in attempting to correct many local landslides. Ditches, pipes, and bituminous treatment have been used to improve surface drainage. Tunnels, horizontal auger holes, trenches, and closely spaced shafts or drill holes connected with short tunnels have been used for subsurface drainage. Drainage is commonly used in connection with other corrective methods and in most cases the slides have been successfully controlled.

Restraining structures are not commonly used as a method of correction. Some retaining walls built below landslides have been overtopped by flow movement of the slides. Slide 119 near Sierra Point has been successfully controlled by removal of part of the head of the slide and construction of a masonry wall alongside the highway. Earth fills have been constructed near the toe of some slides to counterbalance the moving material and prevent uplift in the toe area. In one case (Slide 113) the fill is only a few feet thick and the highway has been rebuilt upon the fill. An attempt was made about 30 years ago to stabilize the Thornton Beach slides by constructing timber groins along the beach. The purpose of the groins was presumably to retard erosion and, by trapping littoral drift, to add weight to the toe of the slides. Of the 22 groins originally constructed, only six are now visible and those are largely ineffective in trapping longshore drift.

Some slide problems have been dealt with by avoiding the slides. This method has been used on Highway 1 north of Mussel Rock and accounts for some of the sharp curves in that part of the highway. In many places the remedy resulted in more sliding uphill from Highway 1. In one housing tract, a few lots were not built upon because slides developed in the early stages of the construction.

Horizontal drains were unsuccessful in stopping the movement of the Mussel Rock slide. In the last few years, rather than import fill to maintain the highway at its former level, the road has been allowed to move downward with the slide. This expedient avoids the expense of hauling fill and avoids adding weight which would increase the shearing stress in the slide.

SUMMARY OF RESULTS

The landslide conditions in the San Francisco South quadrangle can perhaps be considered representative of landslide conditions that may be encountered as other parts of the California Coast Ranges become more densely populated. The climate is intermediate between the more humid region to the north and the more arid region to the south. Most of the common Coast Range rock types are exposed in this quadrangle, and all but three of the landslide types in the Highway Research Board classification have been observed here.

Frequency of landslides by type

In terms of numbers, debris slides are by far the most common, accounting for 42 percent of all the landslides (see fig. 7). Earthflows are next most common, and constitute 21 percent of the total, excluding the earthflows that are part of the complex slides. Aside from the landslide types that were not represented in the quadrangle the least common types are rock slide, block glide, mudflow, debris avalanche, and sand flow.

Geologic controls

As shown on figure 8, slope debris and ravine fill was involved in the greatest number of landslides. About 35 percent of all the slides were in this material. Landslides in the Merced formation were the next most common, but almost all of these landslides were in the steep sea cliffs cut in the Merced. The decreasing order of frequency of slides in other materials, including combinations of materials, is as follows: sandstone and shale of the Franciscan formation, artificial fill, sheared rocks, serpentine, greenstone and

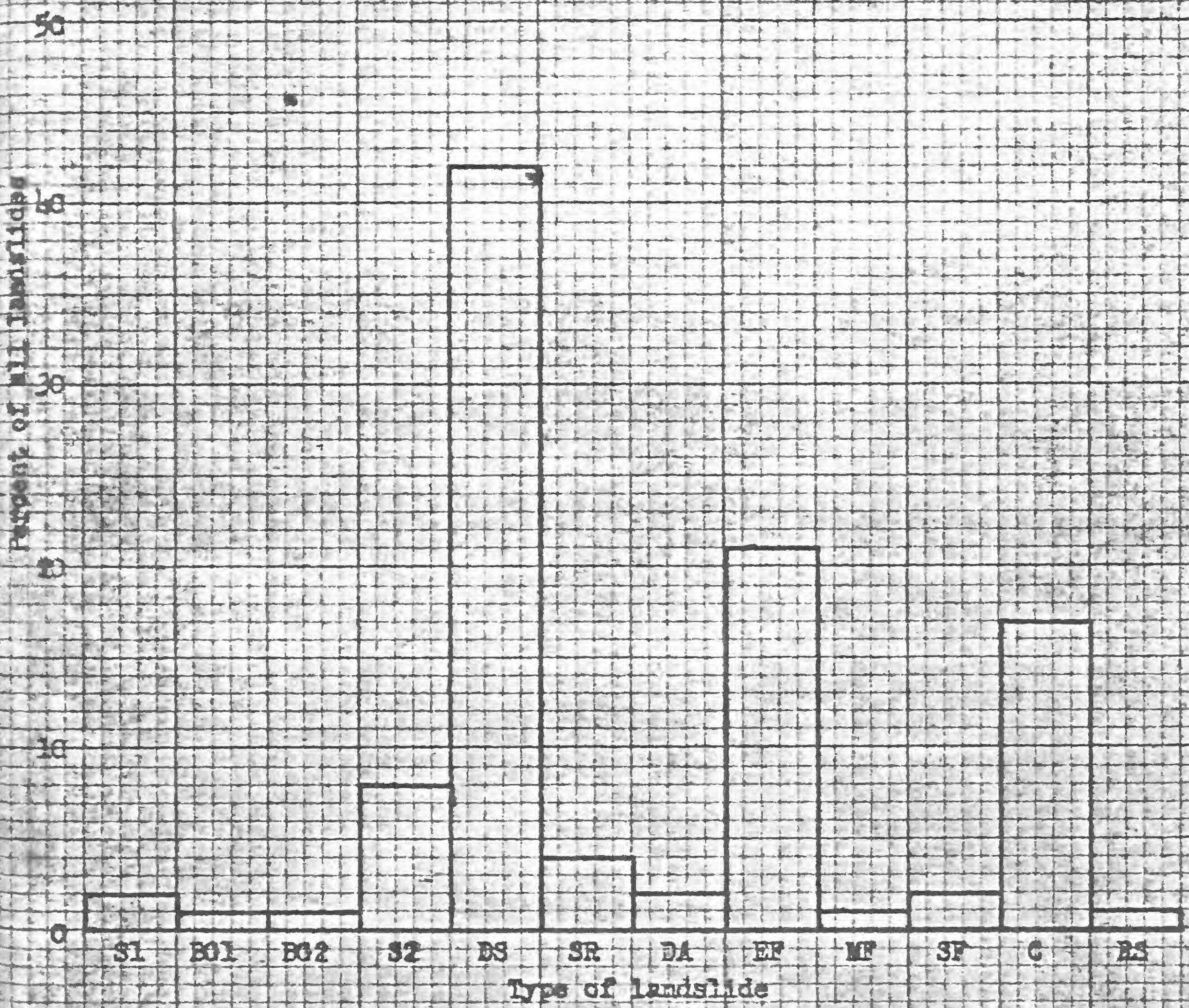


Figure 7. FREQUENCY OF LANDSLIDES BY TYPE
Key to types: S1, slump in rock; BG1, block glide in rock; BG2, block glide in soil; S2, slump in soil; DS, debris slide; SR, sand run; DA, debris avalanche; EF, earthflow; MF, mudflow; SF, sand flow; C, complex; RS, rock slide.

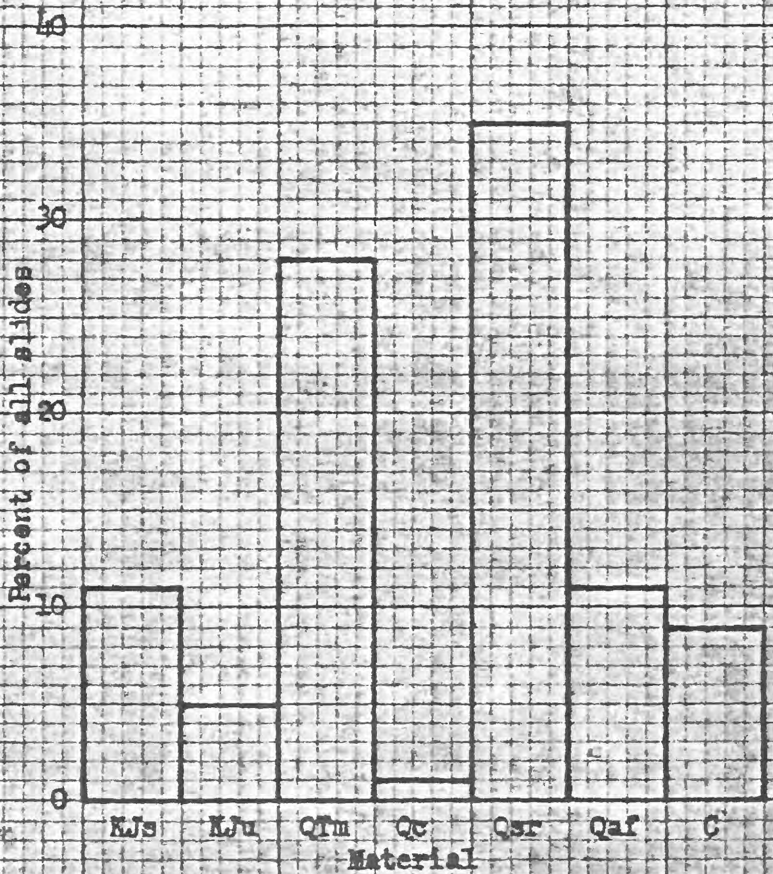


Figure 3. FREQUENCY OF LANDSLIDES BY MATERIAL
Key to type of material: KJs, Franciscan sandstone and shale; KJu, sheared rocks; QTm, Merced formation; Qc, Colma formation; Qsr, slope debris and ravine fill; Qaf, artificial fill; C, combinations of material. Included under "C" are six slides involving greenstone and chert of the Franciscan formation, and serpentine.

chert of the Franciscan formation, and Colma formation. No slides were seen in metamorphic rocks of the Franciscan formation. Several other rock units were not involved in sliding, probably because they are seldom exposed in steep slopes. These are Quaternary alluvium, beach deposits, sand dunes, marine terrace deposits, and bay mud. Damage to one marine installation, however, was probably due to failure in the bay mud.

Topographic controls

Inclination of a slope before failure was in most cases assumed to be the same as adjacent slopes that have not failed. Most of the slopes were determined in the field but some were obtained from the topographic map, which has a scale of 1:24,000 and a contour interval of 25 feet. In figure 9 the slope angles have been rounded off to the nearest 5°.

Figure 9A shows that most of the landslides occurred on slopes of 25°, and almost as many occurred on slopes of 40°. The peak in figure 9A at 40° is the result of including data from the long sea cliff which has a slope of about 40°. In figure 9B the slope figures for the sea cliff have been omitted and the histogram gives a more significant picture of the general relationship over most of the area of the quadrangle, between landslides and inclination of slope. The peak at 25° rather than at a higher slope is the result of the interaction of several factors, none of which is easily evaluated. The most important factors are probably (1) the relative abundance of slopes of a given inclination (a rough estimate suggests that most of the surface of the quadrangle has a slope of less than 20°);

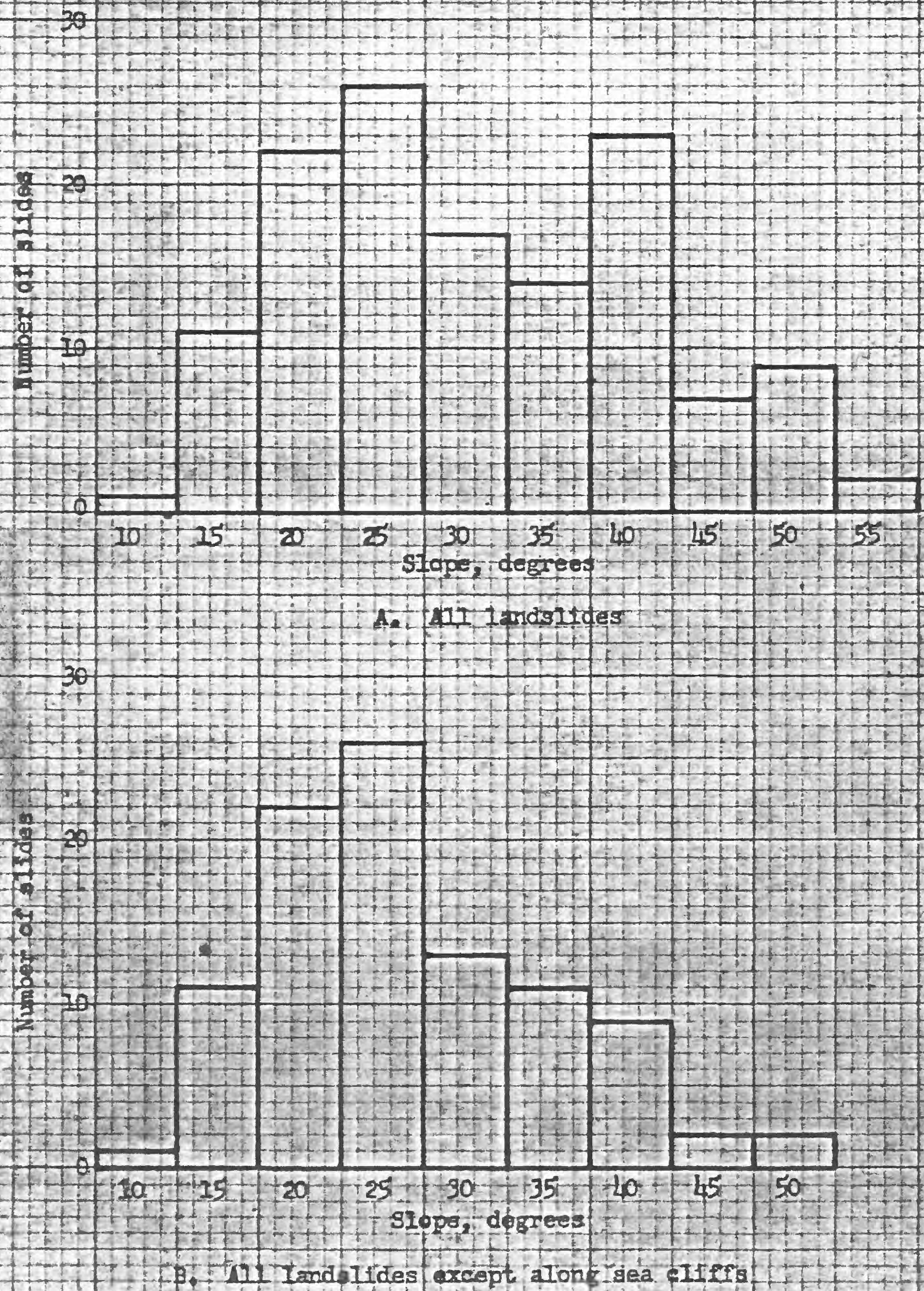


Figure 9. SLOPE INCLINATION BEFORE FAILURE

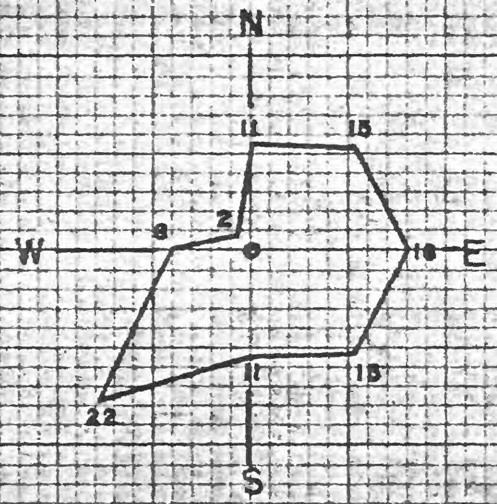
(2) the distribution of the most troublesome material (slope debris) on gentle to moderate slopes; and (3) the fact thatinfiltration of rainwater is less on steep slopes than on gentle slopes.

In a recent study Beaty (1956) found a preponderance of landslides on north-facing slopes in areas east and north of Berkeley. However, most of the landslides in the San Francisco South quadrangle are on west- and southwest-facing slopes. Most of the landslides on west-facing slopes are on the long sea cliff. Because the cliff covers a small proportion of the total area of the quadrangle, and in order to permit a better comparison with Beaty's results, landslides along the sea cliff have been omitted from figure 10A. This figure shows a small peak in the southwest direction.

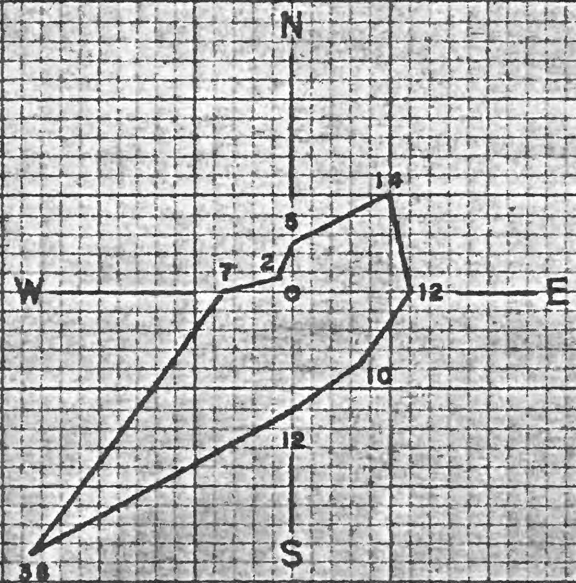
If direction of slope influences the incidence of landslides, the cause is probably related to the moisture conditions at shallow depths in the soil; therefore debris slides, debris avalanches, and earthflows, all of which typically involve surficial materials with a high-water content, should be influenced most by direction of slope.

Figure 10B includes all debris slides, debris avalanches, and earthflows except those probably caused by wave erosion or artificial changes in slope or drainage. Although figure 10B includes only 42 landslides, it is probably more meaningful than figure 10A, which includes 96 landslides of varied types and causes.

Assuming that the shape of figure 10B is significant and not merely a result of insufficient data, most shallow, wet landslides occur on southwest-facing slopes and fewest occur on northwest-facing slopes. Because the structural trend is northwest in this area, more



A. All landslides except those on sea cliffs



B. All debris slides, debris avalanches, and earthflows except those on sea cliffs or caused by artificial changes in slope or drainage

Figure 1c. PERCENTAGE OF LANDSLIDES ON SLOPES FACING IN THE INDICATED DIRECTIONS slopes face northeast and southwest than face northwest and southeast; a plot of landslide frequency should therefore be elongated in a northeast-southwest direction. According to figure 10B, however, more than twice as many landslides of the specified types occurred on southwest slopes as occurred on northeast slopes.

The western slopes of mountain ranges on the Pacific Coast receive more rainfall than the eastern slopes but the effect of small topographic features on total rainfall is not clear. Orographic lifting, which is important in controlling the distribution of rainfall on the slopes of mountain ranges, is of little importance in small topographic features. On small features, however, the trajectory of the raindrops may be important, as the amount of rain that falls can vary with the sine of the angle of incidence. For example, if the rain is falling toward the northeast at 60° from the horizontal, a 30° slope inclined to the northeast would theoretically receive only half as much rain as a similar slope inclined toward the southwest. Precipitation stations are not spaced closely enough in this area to show whether small-scale topographic features receive more rain on southwest than on northeast slopes.

Between periods of rainfall, transpiration, solar radiation, and wind act to remove moisture from the soil. Although vegetation removes moisture by transpiration, vegetation also increases infiltration of rainwater, and the net effect is not easily evaluated. Solar radiation is of course greater on southerly slopes, and in this area the prevailing winds are westerly so that the soil on southerly and westerly slopes should dry more rapidly, more frequently, and more deeply than the soil n other slopes. Cracks formed by drying of clayey soil reduce ts shearing strength and permit rainwater to enter the soil. ntermittent drying of the soil might thus control the formation f shallow landslides, but field examination revealed only very mall and seemingly insignificant cracks. More facts are needed o explain the preponderance of landslides on southwesterly slopes.

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