General and Engineering Geology of the United States Air Force Academy Site Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 551

Prepared in cooperation with the Air Force Academy Construction Agency

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By DAVID J. VARNES *and* GLENN R. SCOTT

With a section on GROUND WATER

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A study of the relation of geology, engineering, and water supply to the planning and construction of the U.S. Air Force Academy

UNITED STATES DEPARTMENT OF THE INTERIOR

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GENERAL AND ENGINEERING GEOLOGY OF THE UNITED STATES AIR FORCE ACADEMY SITE, COLORADO

by DAVID J. VARNES and GLENN R. SCOTT

ABSTRACT

The United States Air Force Academy, about 11 miles north of Colorado Springs, is very close to the center of Colorado and includes 28 square miles of the Great Plains east of the Rampart Range.

Precambrian Pikes Peak Granite forms the mountains of the Rampart Range at the west edge of the Academy area and is separated from Paleozoic, Mesozoic, and Tertiary sedimentary rocks of the foothills and plains by the Rampart Range fault, a high-angle reverse fault. The oldest sedimentary rock exposed within the Academy area is the Fountain Formation of Pennsylvanian and Permian age. Small slivers and fragmental sections of most of the Mesozoic formations of central Colorado are present within or just east of the Rampart Range fault. The predominant bedrock within the Academy area is Dawson Arkose of Cretaceous and Paleocene age. The Dawson locally is tilted to a high angle next to the fault, but to the east its dip flattens rapidly to a prevailing 3°–4° E. or NE. The Dawson Arkose consists about equally of coarse arkosic sandstone and of interbedded lenticular siltstone and clay.

Several stages of downcutting and alluviation have produced gravel-covered bedrock surfaces at three levels. Remnants of these pediments that trend eastward from the mountain front form narrow fingerlike mesas at two levels and broader valleys at the third and youngest level. These ridges and valleys terminate at the principal line of drainage, Monument Creek, which flows southward through the eastern part of the Academy grounds. The area east of Monument Creek is a gently undulating gravel-covered surface of the third level, underlain by Dawson Arkose and trenched by southwest-flowing streams. The valleys of Monument Creek and of its tributaries contain three more sets of alluvium-covered terraces and a narrow modern flood plain.

In planning the Air Force Academy, for which the geologic studies were made as an aid, the topographic and geologic environments were considered so that the required facilities would be arranged attractively and efficiently. All the geologic units upon which the Academy facilities are constructed are predominantly granular in texture, except silty and clayey sections in the Dawson Arkose and peaty facies of the Husted Alluvium; hence, no very serious engineering geologic problems were presented by the original plan or were encountered during construction. The airfield was necessarily located in the more nearly level southeastern part of the site. The large structures of the cadet and academic areas were placed on a mesa toward the north and near the western border of the site. The gravel cover on this mesa also allowed a large volume of grading to be done economically, and the underlying Dawson Arkose furnished a suitable foundation for load-bearing caissons. Valleys in the west-central part of the site were used for two large housing developments and the mesa between them for community facilities. Service and supply buildings were placed near the airfield and highway and next to the major rail lines along Monument Creek. The whole Academy is served by a road system consisting of a peripheral highway and an interior network of roads.

The need to balance cuts and fills—particularly along roads, in the academic area, at dams and reservoirs, and at the airfield—required that thorough exploration and classification of the geologic materials be made so they could be used with a minimum of haulage and waste. Route and site investigations made by the architect-engineer preceding design included many hundreds of borings and thousands of tests on soil and rock samples.

The architect-engineer carried out two extensive test programs—the experimental fills at the airfield and the caisson load test program in the academic area. The airfield test-fill program showed that the increase in density upon rolling increased (1) with the number of coverages by the roller up to six, (2) was more or less independent of water content within the narrow range of 5–8 percent moisture employed, (3) decreased with lift thickness, and (4) could not be correlated with minor variations in grain-size distribution. California Bearing Ratio increased slightly with increased compaction-water content in the range of 4–9 percent and increased progressively with the number of roller coverages. Modulus of subgrade reaction increased with average density and number of coverages and correlated well with the California Bearing Ratio. Full-scale caisson load tests on sandy gravel in the academic area showed that settlement rates could be correlated roughly with blows per foot of standard penetration equipment. Some settlement tests at first very nearly followed Andrade's law of creep; most tests later on approached a rate at which settlement varies linearly with the logarithm of time. Extrapolation of the tests to 100,000 minutes indicated a nonlinear relation between the log of the load and the log of the settlement, with settlements in the range of ¼–¾ inch at design loads. Similar tests on the underlying Dawson Arkose indicated negligible time-dependent settlement at design load, and all caissons were footed within firm bedrock.

Prior appropriation of surface-water rights required that irrigation water be derived from underground sources. The two principal aquifers in the area are the sandstone beds of the Fox Hills Sandstone and the Laramie Formation, which are here considered as a single water-bearing unit (the L–F aquifer), and the sandstone beds of the Dawson Arkose. The greatest depth of a well in the L–F aquifer is 1,493 feet, and the greatest depth of a well in the Dawson is 826 feet.

Data from 12 wells tested on and near the Academy grounds indicate that the Dawson is substantially more productive than the Fox Hills and Laramie. The nine Academy

wells should yield approximately 3⅓ million gallons per day continuously for 30 days; the yield may decline if they are pumped for longer periods.

More water could be obtained from the aquifer by adding more wells, but if the spacing between wells is less than half a mile for those tapping the Dawson and less than a mile for those tapping the Fox Hills and Laramie, individual yields might be substantially reduced.

Chemical analyses show that the water from the Dawson is less mineralized than that from the Fox Hills and Laramie and that water from both aquifers probably is suitable for domestic and irrigation use.

INTRODUCTION

The United States Air Force Academy is a new small community. It presents, on a reduced scale, many of the common problems of municipal planning together with those special features connected with the dominant purpose of the Academy—that of educating Air Force cadets.

The area chosen for the Academy site was not heavily populated or well developed; yet it contained major rail and highway routes. The problems encountered in planning, therefore, could be attacked without man-made restrictions imposed by existing use of the land or by prior municipal works, and they could be handled with complete freedom in anticipation of future needs. An ideal plan could be made in which the best solution for each problem took into account the topography and geology of the site, and each phase of planning and investigation could be done in logical sequence prior to design. The planning of this new community reflected the physical nature of the site itself more obviously than the more common and extremely complex planning necessary for alteration or enlargement of existing urban centers.

PURPOSE AND SCOPE

Geologic studies of the Air Force Academy site were undertaken at the request of the Air Force Academy Construction Agency (AFACA) to the U.S. Geological Survey under contract 33(600–55–4089).

Most of the geologic mapping was done between October 26 and November 28, 1954. A descriptive text and the geologic map were completed December 3, 1954, and incorporated into the first plan submitted to the U.S. Air Force by the architect-engineer, the firm of Skidmore, Owings, and Merrill (SOM). The U.S. Geological Survey furnished services until November 1956, mostly in connection with the performance and interpretation of pumping tests on water wells. The part of the Academy that lies south and southwest of Pine Valley was acquired after the original geologic mapping was completed. This area was mapped by Scott in December 1959.

The main purpose of the present report is to show some of the ways in which prior knowledge of the physical environment, particularly of topography and of the distribution and properties of the geologic materials, influenced the various phases of planning, investigation, design, and construction of a variety of engineering works at the Academy. Additional knowledge was gained during progressive development of the Academy facilities; where possible, therefore, some distinction is made between foresight and hindsight. For example, if exploration and construction disclosed unforeseen conditions or unexpected engineering properties of the geologic materials, these differences are described in the appropriate places in the text.

The site itself is not one of unique geologic interest. For this reason, and because the time allowed for geologic investigations preceding design and construction was very short, the emphasis of this report is placed less on theoretical geology than on the use to which the knowledge of the rock and soils was put. Because the area is in many respects typical of the foothills belt along the mountain front in Colorado, within which heavy construction may be expected to continue, collation and analysis of some of the extensive test results obtained by the architect-engineer are given in some detail.

Much more attention is given to the Dawson Arkose and Quaternary surficial deposits than to pre-Dawson bedrock units, for the younger units are more widespread and were inevitably the ones most prevalent at construction sites. On the other hand, some pre-Dawson sedimentary rocks that do not crop out on the Academy site but that are exposed nearby are briefly described as a matter of general interest for Academy personnel and for others who may have occasion to study the local geology.

METHODS AND TECHNIQUES

Mapping by the U.S. Geological Survey was done on aerial photographs at a scale of 1:12,000 and transferred by means of a stereoplotter to a sepia print of the topographic map of the site, also at a scale of 1:12,000 and with 5-foot contour interval. Both the aerial photographs and the topographic base were furnished by the AFACA. The geology was later recompiled on a simplified version of the general development plan as of January 1, 1958.

Although the geologic investigations were to be used as an aid in planning engineering works, the units chosen to map are geologic units rather than engineering-soils units. Some consideration was given to preparing a map in which the units would follow the Unified Soil Classification System (U.S. Army, 1953), but the early stages of fieldwork showed that a detailed map made according to the system would take considerably longer to prepare than a conventional geologic map based upon lithology and genesis of the units. Moreover, most of the geologic units, particularly the surficial deposits, were believed to have a fairly definite range in physical properties. The basic mapping and lithologic descriptions of the geologic units, together with notations on the expected ranges in terms of the Unified Soil Classification System, appeared more likely to provide the most information for the largest area in the least time. Timing was of the greatest importance; to be of maximum use, the geologic map had to be available prior to the preliminary designing of the Academy facilities.

The geologic map varies somewhat in accuracy depending on the specific geologic units involved. Some contacts are gradational and some are sharp, but in mapping no distinction was made. Surficial deposits are generally not shown unless they are 5 feet or more thick—thus, bedrock with a cover known to be less than 5 feet thick is shown as bedrock. If no information was available concerning the thickness of a surficial unit, it was mapped if it was present to the bottom of a pit about 18 inches deep.

The methods and techniques employed by the architect-engineer in investigating ground conditions at the site are discussed in more detail in later sections of this report. In general, the operations consisted of field reconnaissance and preliminary layout of sites or road alinements, followed by detailed investigations of the sites or routes by borings and soundings and supplemented with physical tests of samples. Most of the tests were made at a well-equipped laboratory on the site; a few special tests were made by the Colorado Department of Highways or by commercial laboratories. As required, special consultants were retained by the architect-engineer to advise on certain phases of the soil-testing program and on the development of ground-water resources. All the accumulated data were then used by SOM to arrive at the recommendations for design submitted to the AFACA.

The few laboratory analyses of samples taken by the U.S. Geological Survey were made as nearly as possible according to standards of the American Society for Testing Materials. The samples themselves were certainly not representative of the large geologic units from which they came, but the analyses were intended only to give a rough approximation of what might be expected.

ACKNOWLEDGMENTS

The geologic field party consisted of David J. Varnes, Glenn R. Scott, George Rozanski, and Paul P. Orkild, occasionally assisted by Roger B. Colton, Robert M. Lindvall, and J. Mark Cattermole. Water resources investigations were undertaken by W. D. E. Cardwell and Edward Jenkins, of the U.S. Geological Survey. Cretaceous fossils were identified by William A. Cobban, of the U.S. Geological Survey.

It is a pleasure to acknowledge the support and assistance given by J. P. Huebsch, deputy director of AFACA at the time the studies were begun, by Colonels A. E. Stoltz and J. A. Barnett, successive directors of AFACA, and their staffs, and by C. L. Tyler and E. A. Merrill, general manager and chief engineer, respectively, of the Colorado Springs office of SOM, and their staff. File material supplied by both AFACA and SOM has been freely used in preparation of this report. Field and laboratory investigations by the SOM soils laboratory reported herein were made under the direction of Robert L. Novak.

PREVIOUS GEOLOGIC STUDIES

The region that now includes the Air Force Academy site was first mapped geologically by Richardson (1915) and Finlay (1916) as part of the geologic atlas of the United States. The only other published work pertaining to the site is a geomorphic reconnaissance of the Colorado Springs area by Tator (1952).

GEOLOGIC AND GEOGRAPHIC SETTING

LOCATION AND PRINCIPAL PHYSICAL FEATURES

The Air Force Academy is about 11 miles north of Colorado Springs, in El Paso County, Colo. (fig. 1). It is roughly trapezoidal in shape and includes about 17,900 acres in the foothills and plains at the east base of the Rampart Range (pl. 1.)

The change from plains to mountains is the most abrupt transition of the region, not only in topography but also in underlying rock units and geologic structure. To the west of the Academy grounds and partly within them are mountains of hard Precambrian granite. Within the Academy grounds are dissected plains whose mesas, valleys, and broad, even slopes are underlain by softer and much younger sedimentary rocks that dip gently to the northeast and are of predominantly Cretaceous age. The Rampart Range fault at the foot of the mountains separates these two geologic provinces. Along this fault the much older granites have been thrust upward so that they stand thousands of feet higher than the sedimentary rocks, and the younger sedimentary rocks along the fault have been turned up, overturned, or much broken.

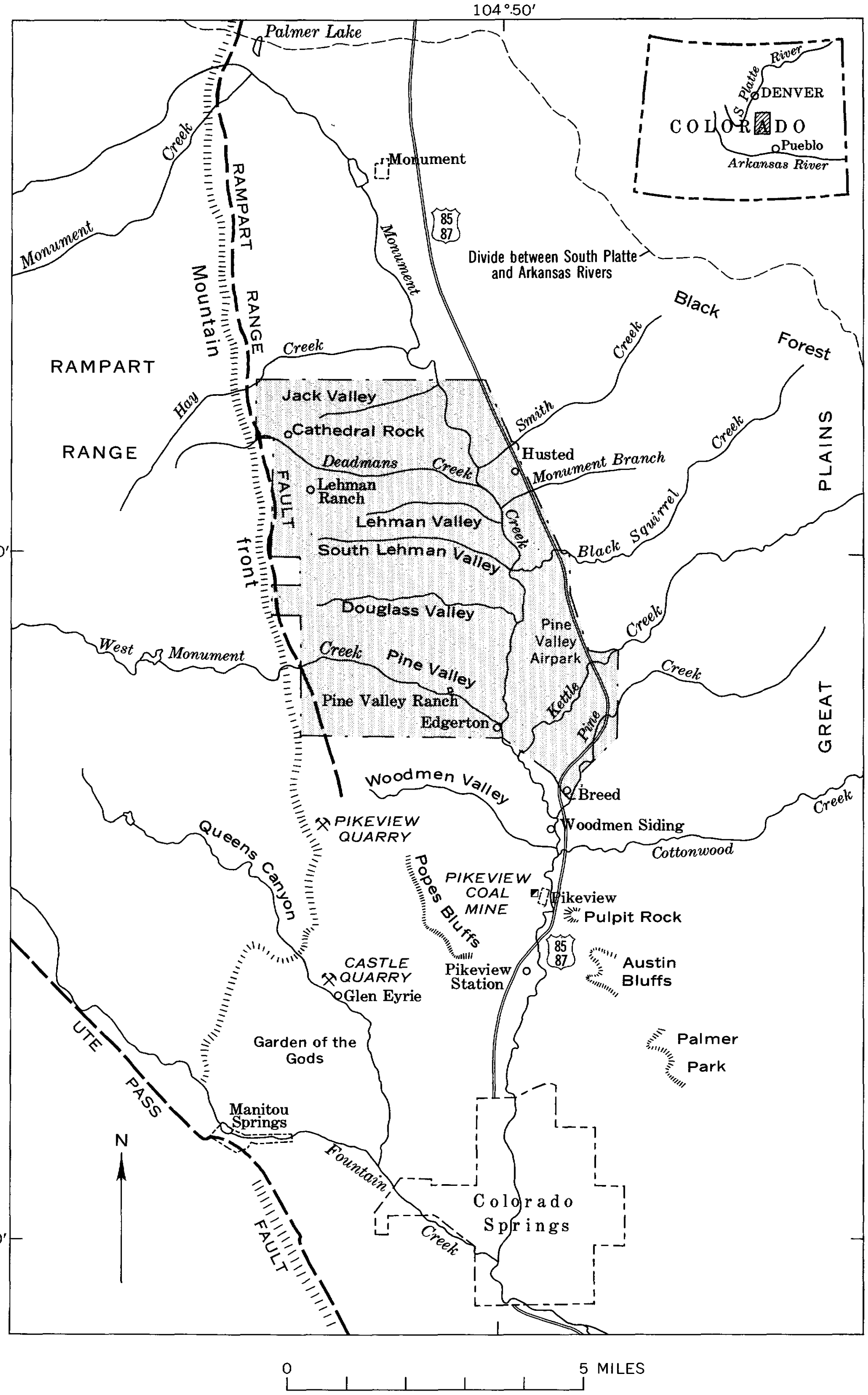

FIGURE 1.—Map showing location of U.S. Air Force Academy, El Paso County, Colo., and vicinity.

Five distinct types of landforms occur within the site: (1) the steep lower slopes of the Rampart Range on the west, (2) ridges of sedimentary rock parallel to the range, (3) mesas and foothill ridges separated by broad valleys extending eastward from the base of the mountains, (4) the valley of southward-flowing Monument Creek, and (5) an even to gently rolling area that slopes southwestward toward Monument Creek. The mesas and ridges west of Monument Creek are remnants of dissected gravel-covered pediments; the land east of Monument Creek is a gravel-covered pediment that rises gradually to the higher area of the Black Forest. Monument Creek and its major tributaries flow in valleys incised into the lowest pediment surface (fig. 2).

RELATION OF LANDFORMS TO GEOLOGY

The Air Force Academy lies between the two principal rivers of eastern Colorado, the South Platte and the Arkansas. The divide between the rivers is a ridge trending eastward from the town of Palmer Lake, El Paso County; all the drainage on the north side of the ridge flows to the South Platte River and all the drainage on the south side, including that from the Academy grounds, flows southeastward to the Arkansas River. Thus, the main drainage to the Arkansas River is parallel to the mountains rather than away from them. The position of two tributaries to the Arkansas—Fountain Creek and southward-flowing Monument Creek—was influenced in the Colorado Springs area by the soft

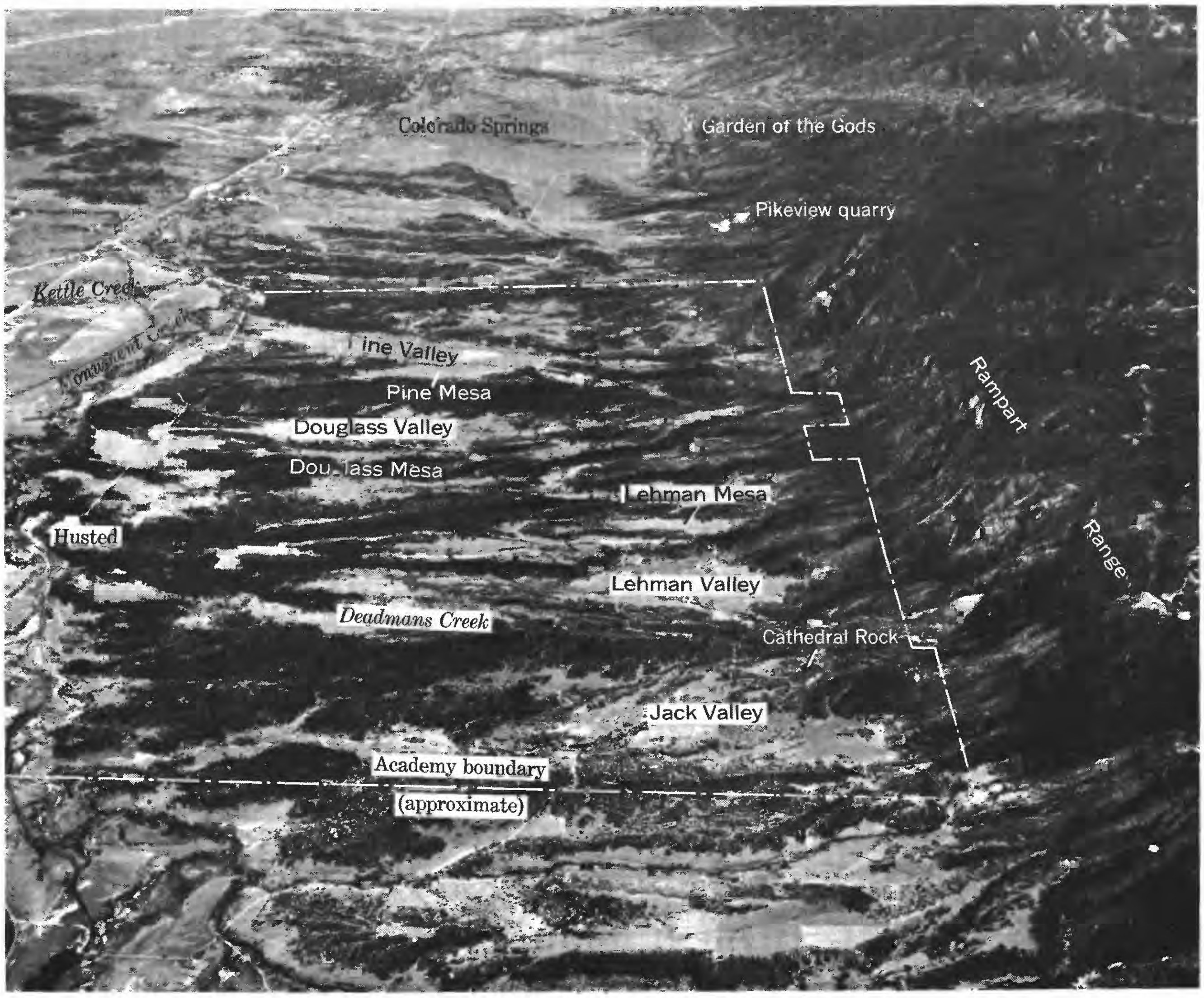

FIGURE 2.—Oblique aerial photograph, looking southward toward Colorado Springs, of the Air Force Academy site prior to construction. Most of the large installations are in the belt of eastward-trending mesas and valleys between the foot of the Rampart Range and Monument Creek. Lehman Mesa was chosen for the cadet academic area. Photograph by U.S. Air Force.

Pierre Shale. The lateral boundaries of the Pierre Shale gradually converge toward the mountain front as they are traced northward toward Colorado Springs. The shale underlies Monument Creek as far north as Pikeview Station. Northward from Pikeview Station for 3 miles, Monument Creek cuts across the southeast-trending structure of harder sedimentary rocks, and northward from Woodmen siding it more or less follows the strike of beds in the Dawson Arkose to the Platte-Arkansas divide.

The modern drainage pattern appears to have been formed by capture. During Tertiary time, streams probably flowed eastward from the mountains across the area called the Black Forest (fig. 1), but were captured in early Pleistocene time by small streams having steeper gradients, such as Monument Creek, that were cutting headward from the Arkansas River. As Monument Creek was cutting headward across the area, small streams from the east and west were cutting surfaces on bedrock at a gradient to meet the newly formed Monument Creek.

These surfaces, called pediments, are the result of a stable base level that prevailed for a long time along the major streams. The stable base level allowed the small streams to meander laterally and widen their valleys. Lowering of base level, probably as a result of climatic change, resulted in downcutting. At least six cycles of this change of stream regimen from lateral to downcutting are recorded in the dissected pediments and terraces of the Academy site. Because the gradients of the streams flowing from the west were steeper than those of the streams flowing from the east, the stages of pedimentation west of Monument Creek never were completed, and ridges were stranded as most of the energy of the streams was concentrated on downcutting. Streams on the east side apparently completed at least the last stage of pedimentation and possibly also the earlier stages. No ridges or remnants of the older pediments can be found for 3–4 miles east of Monument Creek along Kettle Creek and Black Squirrel Creek. The amount of coarse alluvium added to Monument Creek from the mountains on the west far exceeded the amount of fine alluvium from the Black Forest on the east; therefore, Monument Creek was forced to migrate eastward during the successive stages of downcutting. It now impinges on bedrock at many places along its eastern valley wall, but rarely exposes bedrock along its western valley wall.

The difference in grain size between alluvium composed of granite boulders west of Monument Creek and alluvium composed of sand from the Dawson Arkose east of Monument Creek makes a difference in the shape of the pediments west and east of the creek. Small buried ridges on the west side were protected from erosion by a mantle of boulders or by trains of boulders in ancient stream valleys. Longitudinal irregularities on the pediments thus resulted from the inability of the small intermittent streams to move the boulders. On the east side of Monument Creek the streams were not restricted by such obstructions; they flowed freely, cutting a smooth gently sloping pediment whose extent was controlled solely by the amount of time available.

CLIMATE AND WEATHER

The Air Force Academy lies in an area where a continental-type climate prevails; the summers are long and warm, and the winters are short and occasionally quite cold. The atmospheric pressure is about 76 percent of that at sea level and the humidity averages about 53.5 percent. The prevailing climate is characterized by limited and erratic rainfall, high winds in the late fall and early spring, and high evaporation. Because of the rain-shadow effect of the Continental Divide, weather is changeable and difficult to predict. Extremes of temperature, as shown in the table of weather data (table 1), can take place within 24 hours

TABLE 1.—*Weather data*

[From Third Weather Group, U.S. Air Force, Ent Air Force Base, Colorado Springs, Colo., calculated for Air Force Academy site from data gathered at Colorado Springs, Glen Eyrie, Husted, Monument, Auldhurst, and Peterson Field. Data for Glen Eyrie, Husted, and Auldhurst are for years prior to 1931. Data for Colorado Springs and Monument are for periods both before and after 1931. Peterson Field data are for years after 1942]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Precipitation averages:													
Inches	0.40	0.60	1.10	2.20	2.50	1.80	2.90	2.70	1.10	1.00	0.60	0.60	17.50
Number of days	4	3	5	9	10	9	13	12	3	4	3	2	77
Snow, inches	4	8	13	17	4	0	0	0	1	5	6	8	66
Temperatures, °F.:													
Extreme maximum	68	70	74	78	87	97	97	95	91	86	75	71	----------
Mean daily maximum	42	43	47	56	65	75	80	79	73	62	51	43	----------
Mean daily	27	29	34	42	51	59	65	64	57	46	36	28	----------
Mean daily minimum	12	15	20	28	37	44	50	49	41	30	20	13	----------
Extreme minimum	−26	−27	−13	−8	16	24	33	36	17	−9	−16	−25	----------
Humidity averages (percent):													
Local time:													
0600	60	65	65	70	70	60	70	70	65	65	60	60	----------
1200	40	40	40	45	45	35	40	40	35	35	40	40	----------
1800	55	50	45	50	50	40	50	45	40	45	55	50	----------
2400	55	60	65	65	70	60	65	70	60	55	60	60	----------

but extended periods of subzero weather or of temperatures above 100° F are not common. Because the academic area of the Academy lies so close to the escarpment of the Rampart Range, the sun goes down about 20 minutes earlier there than it does at the airfield.

The average date of the last killing frost at Colorado Springs is April 27, and of the first October 14. The ground becomes frozen about November 30, but the depth of frost penetration depends on the exposure and altitude. The frost goes deeper and stays longer on north-facing slopes. According to J. W. Fox, nurseryman for the U.S. Forest Service at Monument, the ground freezes to a depth of 2 feet in an average winter and rarely to 4 feet. Waterlines 5 – 6 feet below the surface in the nursery have never frozen.

Precipitation is barely more than the 15 inches a year that is considered to be the boundary between a semiarid and a humid climate, but it is ideally distributed because nine-tenths of it falls from March to October inclusive. The winter snows are preserved on the north-facing slopes until the warmer spring days when the water soaks into the ground before plant growth begins. Seeps and boggy places are most evident at this time.

SURFACE-WATER RUNOFF

The eastern foothills region of Colorado is subject to cloudbursts. These storms are generally short and confined to small areas, but the precipitation is so heavy and the runoff so rapid that the storms may be very destructive.

Because the Academy site was known to lie within the area subject to such storms and because destructive storms have actually occurred on the site, we have gathered some notes on the problem of runoff.

According to several employees of the Denver and Rio Grande Western Railroad and the Colorado Highway Department, at least four floods have destroyed property during the last 20 – 30 years. The first was on May 30, 1935, and was the most disastrous of all floods within local knowledge. Eighteen inches of rain fell in a small area in the headwaters of Monument Creek between 6 a.m. and 6 p.m.[1] The railroad tracks were undercut intermittently from Monument to Pikeview. Water was 22 feet deep in both Kettle and Pine Creeks. A lake formed back of the Santa Fe railroad bridge over Pine Creek, and the water that went through the arches washed out the highway bridge immediately downstream. The highway bridge over Kettle Creek was overtopped but not destroyed, although water cut behind the abutment. Water ran in a sheet over the surface of the ground near the site of the former Pine Valley Airpark and was 1 foot deep at the break in slope north of the Kettle Creek bridge. Water as much as 6 inches deep has run over the pediment-gravel surface, road, and airfield several times since 1935 during less severe storms, carrying with it sand and occasional boulders. The water does not sink into the pediment sand and gravel as rapidly as might be expected. Rosa[1] stated that the infiltra-
weather data (table 1), can take place within 24 hours
tion rate for the Kettle Creek-Pine Creek drainage area is 0.91 inch per hour under present conditions. He also described an isohyetal map prepared by the U.S. Army Corps of Engineers that shows the extent and concentrations of rainfall in the May 30, 1935, storm.

In 1942 or 1943 the Denver and Rio Grande Western Railroad bridge across West Monument Creek was undermined and in jeopardy for 3 days because of a cloudburst in the mountains near the Colorado Springs reservoirs. The surface of the stream did not rise much, but the stream scoured 8 – 9 feet into its sand bed.

A flood in 1945 took out a bridge 1 mile south of Husted that was constructed of stone and had a high narrow cross section. It was not founded on bedrock; so water undercut the abutments. Vibration of a freight train caused one abutment to collapse and about five freight cars were derailed. Three similar bridges were later equipped with concrete aprons upstream. The storm produced combined rain and hail which fell in a 1-mile-wide strip embracing Husted. Water ran in a sheet about 1 foot deep across the small terrace at Husted, overflowed a culvert having a 4- by 5-foot cross section, and probably would have filled a culvert twice as large. The area drained by the culvert comprises only about a city block.

The railroad tracks at the mouths of Douglass Valley and West Monument Creek have been washed out. A washout at Edgerton in 1947 was caused by plugging of the opening of the bridge across West Monument Creek by brush and trees. Several people who were interviewed emphasized that the main causes of failure of bridges, trestles, and culverts were the accumulation of brush and trees in the openings and resultant damming of the water and failure to dig a deep foundation, preferably founded on bedrock. In flood the streams may scour twice the depth that the water rises in the channel.

The Denver and Rio Grande Western Railroad protects embankments along Monument Creek with riprap. Two types of material are used: slag from Pueblo, Colo., and granite from a quarry near Echo at the west end of the Royal Gorge, Fremont County, Colo.

[1] Rosa, J. M., 1954, The hydrology of upstream flood prevention, upper Arkansas River, Colorado; U.S. Forest Service, unpublished data on file at U.S. Geol. Survey, Denver, Colo.

WINDS

The site of the Air Force Academy has long been swept by strong winds. In late Wisconsin or early Recent time, the wind swept sand off the pediments west of Monument Creek and out of the valleys that separate the pediments and deposited it in longitudinal dunes or barchans on the pediment slope east of Monument Creek. At the same time the wind polished large and small stones which it could not blow away. Some well-polished ventifacts were observed at the east ends of Pine, Douglass, and South Lehman Valleys and along the east side of Monument Creek. The direction of these ancient winds, as inferred from the trend of the sand dunes, was from the southwest. Apparently the wind came down the east slope of the Rampart Range, funneled down the valleys between the pediments, crossed Monument Creek, and swept eastward across the Black Forest.

During the period of fieldwork in the late fall of 1954, there were many days of strong winds from the west. Hurricanes and tornadoes are not known in this area.

VEGETATION

The Air Force Academy site can be divided into four major plant habitats, each of which supports a different plant community. The types of plants in each community vary as a result of local differences in soil and microclimate, but the plants of one community overlap those of other communities to some extent.

The most widespread habitat is on the tableland or pediment. Short grasses predominate, especially buffalo grass and blue grama; fringed sagebrush, yucca. and prickly pear grow on well-drained areas. Ponderosa pine, Gambel oak, and mountain mahogany grow in small groves where the Dawson Arkose is close to the surface.

A south or southwest slope is the habitat most favored by ponderosa pine, Rocky Mountain juniper, Gambel oak, mountain mahogany, yucca, and prickly pear. Needle-and-thread, blue grama, and little bluestem are the most abundant grasses on these sunny slopes and are associated with James eriogonum, fringed sagebrush, pasqueflower, and Indian paintbrush. A small but thriving stand of pinyon pine was seen at the Castle quarry south of the Academy at an altitude of about 7,200 feet on the sunny southeast-facing slope. Soil is poorly developed on the south-facing slopes because of the high evaporation loss and slight plant cover.

A north- or northeast-facing slope is the habitat of plants that require more water and less sun. Douglas-fir, common juniper, bearberry, and many shrubs grow on these shaded slopes. Quaking aspen and Colorado blue spruce grow in the wetter places at the base of the slope along the mountain front. Soil is well developed on the north-facing slopes. The thick plant cover, slow runoff, and small evaporation loss allow the leaves to remain where they fall and a thick duff layer to accumulate and rot to a soft rich organic soil.

Flood-plain habitats in the lower part of the area support broadleaf cottonwood, sandbar willow, New Mexican locust, cattails, sandbur, and needle-and-thread. Some ponderosa pines grow along streambanks where the Dawson Arkose is exposed. Flood plains in the upper part of the area contain narrowleaf cottonwood, wild rose, and Gambel oak.

ECONOMIC GEOGRAPHY

Originally the Academy site was served only by a black-top road from U.S. Highway 85–87 into Pine Valley, a gravel road along the west side of Monument Creek connecting with U.S. Highway 85–87 at Husted, and by dirt roads into Jack, Lehman, South Lehman, and Douglass Valleys, and the upper part of Pine Valley. Jeep trails crossed the west ends of the pediments and connected most of these roads along the mountain front. Several gravel roads enter U.S. Highway 85–87 from the Black Forest east of the site.

Tracks of the Denver and Rio Grande Western Railroad Co. and the Atchison, Topeka and Santa Fe Railway Co. follow Monument Creek through the eastern part of the site.

An airport for small planes, called the Pine Valley Airpark, formerly lay west of U.S. Highway 85–87 and north of Kettle Creek a short distance southwest of the present site for the Air Force Academy airstrip.

The area was thinly settled, and commercial development consisted only of a small factory one-half a mile north of Breed, three service stations, several motels, a clay pit, and one tavern. Four or five large ranches occupied the largest part of the site, and there were about 50 residences along Monument Creek from Husted southward, the largest concentration being near Breed.

SEISMIC ACTIVITY

REGIONAL SEISMIC ACTIVITY

No destructive or near-destructive earthquakes have been recorded in Colorado; in the period 1882–1946, 6 earthquakes of moderate to fairly strong intensity were listed (see following table) for the State, a small number in consideration of its large area of high mountains (Heck, 1947).

The Rossi-Forel scale of intensities ranges from 1 to

Year	Date	Locality	N. lat	W. long	Area (sq miles affected)	Rossi-Forel intensity
1882	Nov. 7	Laramie-Cheyenne, Wyo., to Georgetown, Colo.	40	105	11, 000	6
1895	Mar. 22	Steamboat Springs, Colo			1, 500	5
1901	Nov. 15	Buena Vista, Colo	38. 8	106. 2	Local	6
1913	Nov. 11	Southwest Colorado	38. 2	107. 7	7, 500	6
1928	Apr. 20–May 10	Creede, Colo	37. 8	107. 0	Local	4–5
1944	Sept. 8	Montrose, Colo			3, 000	6

10 (descriptions of intensities 1–3 and 8–10 here omitted):

4. Feeble shock. Felt by persons in motion; disturbance of movable objects, doors, windows; cracking of ceilings.
5. Shock of moderate intensity. Felt generally by everyone; disturbance of furniture, beds, etc.; ringing of some church bells.
6. Fairly strong shock. General awakening of those asleep; general ringing of church bells; oscillation of chandeliers; stopping of clocks; visible agitation of trees and shrubs; some startled persons leaving their dwellings.
7. Strong shock. Overthrow of movable objects; fall of plaster; ringing of church bells; general panic, without damage to buildings.

In the period 1947–61, 14 light to moderate shocks were felt in the State. Two of these originated in adjacent States; epicenters of most of the others were in the northwest, southwest, and southeast parts of Colorado. The maximum reported intensities on the Modified Mercalli scale were VI for shocks in 1955 and 1960 in the Creede-Silverton-Ouray area.

The tremors near Derby in the Denver area during the period June 1962 to February 1966 also have had a maximum intensity of about VI on the Modified Mercalli scale. The maximum magnitude on the Richter scale has been 4.3 (Healy and others, 1966).

The Modified Mercalli intensity scale of 1931 ranges from I to XII:

V. Felt by nearly everyone, many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop (5–6 on Rossi-Forel scale).

VI. Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight (6–7 on Rossi-Forel scale).

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motorcars (8 on Rossi-Forel scale).

LOCAL SEISMIC CONDITIONS

Along the western edge of the Academy site the Rampart Range fault of large displacement locally has thrown the old granite and slivers of old sedimentary rocks on the west up in contact with the relatively young Dawson Arkose to the east. This fault zone apparently has been long inactive. No scarps in the pediment gravels were observed that would indicate movement in Recent geologic time, and no seismic activity has been recorded along this fault zone, which extends all along the base of the Rampart Range.

Perhaps the most convincing evidence against the occurrence of significant earth tremors in the past in this area is the abundance of balanced rocks, topheavy pedestal rocks, and thin upright monumentlike erosional remnants standing in and near the Academy site.

GENERAL GEOLOGY

STRUCTURE

The significant structural features of the site are the Rampart Range fault and the monoclinal fold of the sedimentary rocks along the west side of the site. As the Rampart Range was forced upward during the Laramide Revolution, the latest episode of mountain building, the sedimentary rocks on its flanks were bent in a monoclinal fold. Hogbacks that are the remnants of rocks folded in this manner may be seen at the Garden of the Gods a few miles south of the Academy. Upward and eastward pressure of the mountains overturned the monoclinal fold and finally ruptured it, forming a long, high-angle reverse fault or zone of closely spaced faults along which the Pikes Peak Granite was forced up and over the sedimentary rocks. The fault zone lies along the western boundary of the Academy site and probably dips steeply to the west. The maximum stratigraphic throw is west of Douglass Valley, where the Pikes Peak Granite lies in fault contact with the Dawson Arkose. In some places along this contact, the bedding in the Dawson Arkose is vertical; elsewhere, it is nearly horizontal. Available information indicates that the dip of unfaulted Dawson Arkose in the southern and central part of the Academy site is 2°–4° NE. A small block of pre-Dawson sedimentary rocks in the northwest corner of the site was torn off during faulting and dragged up into the fault zone between the granite and the Dawson Arkose. These rocks generally dip to the west but are extremely contorted and fractured. Limestone beds are well preserved in the fault zone even though the sandstone and shale beds that formerly separated them are cut out by branches of the fault.

In the southwest corner of the area, the Rampart Range fault trends obliquely across northward-striking rocks. The fault decreases in stratigraphic throw from 10,000 feet to only about 2,000 feet within 2 miles. Where the fault has the greatest throw the Dawson Arkose lies against the Pikes Peak Granite; where it has the least throw, the upper part of the Pierre Shale lies against the lower part of the Pierre Shale. Beds on both sides of the fault dip as steeply as 85° W.

BEDROCK

ROCKS OLDER THAN DAWSON ARKOSE

Rocks older than Dawson Arkose crop out in areas totaling about 0.6 square mile along the western edge of the Academy grounds. Some lie within the boundary (pl. 1); others lie outside the boundary. (See Richardson, 1915, and Finlay, 1916, for outcrop patterns of rocks of the Castle Rock and Colorado Springs quadrangles, respectively.) A generalized stratigraphic column of the bedrock units in and near the Air Force Academy is shown in figure 3.

Construction plans indicated that none of the older rocks that crop out within the boundaries of the site would be involved in construction, either as foundations or sources of material; however, some of the rocks outside the site, such as the Manitou Limestone, were used as sources of material. These older rocks are briefly described here, from oldest to youngest.

PIKES PEAK GRANITE

The Pikes Peak Granite of Precambrian age crops out in two small areas along the western margin of the Academy site. A steeply westward dipping fault zone locally forms the boundary between the granite and younger sedimentary rocks. The granite is moderate reddish orange and coarse grained and consists of crystals of microperthite ½–1 inch in diameter, somewhat smaller flakes of black mica, and crystals of quartz about half the diameter of the microperthite. The granite is massive and homogeneous. Joints are prominent in the granite, and their trend and inclination are consistent over many miles of outcrop.

One- to six-inch veins of quartz and granite pegmatite cut the granite. The crystals in the pegmatite commonly have a maximum dimension of 3 inches. Some of the pegmatite also contains cavities into which project well-formed crystals of quartz and microline. These cavities and the surfaces of the veins are coated with iron oxide. Pieces of the quartz veins and crystals are mixed with the colluvium and alluvium on the slopes at the western edge of the site.

The granite weathers mostly by mechanical disintegration rather than by chemical decomposition, and therefore releases individual mineral grains or aggregates of grains. The disintegration starts along the joints and gradually invades the blocks, which are commonly weathered to a depth of 15 feet or more. Softened granite and iron stains along the joints reach a depth of more than 50 feet. Rounded cubical knobs of fairly fresh granite project through the residuum and probably supply the large boulders that are so abundant on the slopes at the western edge of the Academy site.

SAWATCH SANDSTONE

At the head of Deadmans Creek, west of the Academy area, the Sawatch Sandstone of Late Cambrian age overlies the Pikes Peak Granite and underlies a prominent triangular slope of Manitou Limestone (fig. 2).

According to Richardson (1915, p. 3), the sandstone is 115 feet thick (25 feet thick in the Academy area) and is composed of fine-grained quartz sand, cemented by calcium carbonate, and colored red, greenish, or white. Some of the beds contain glauconite.

MANITOU LIMESTONE

The flatiron of Manitou Limestone of Early Ordovician age at the head of Deadmans Creek was the only outcrop of this formation observed north of the Pikeview quarry. The largest outcrop of the formation lies south of the Pikeview quarry between the Castle quarry north of Queens Canyon and the Ute Pass fault west of Manitou Springs (figs. 1, 2).

The limestone is purplish gray, pink, or maroon; it is fine grained and fairly homogeneous within each bed but varies in texture and composition between beds. The lower part of the formation, which is about 50 feet thick at Deadmans Creek, is thick-bedded sandy limestone; the upper part is thin-bedded dolomitic limestone. Marine fossils are abundant in both parts.

FOUNTAIN FORMATION

The Fountain Formation crops out only in the northwestern and southwestern parts of the Academy site. It consists of moderate-reddish-brown arkosic conglomerate, coarse yellowish-gray arkosic sandstone, and thin layers of pale-green and dark-reddish-brown shale. The Fountain Formation is of Pennsylvanian and Permian age and contains the coarse alluvium that was eroded from an earlier range of mountains that stood in about the same place as the Rampart Range. The formation has been greatly thinned by faulting. Colluvium and alluvium thinly cover all but three or four small outcrops of the formation. To the south of the site the Fountain Formation forms some of the attractive monuments in the Garden of the Gods.

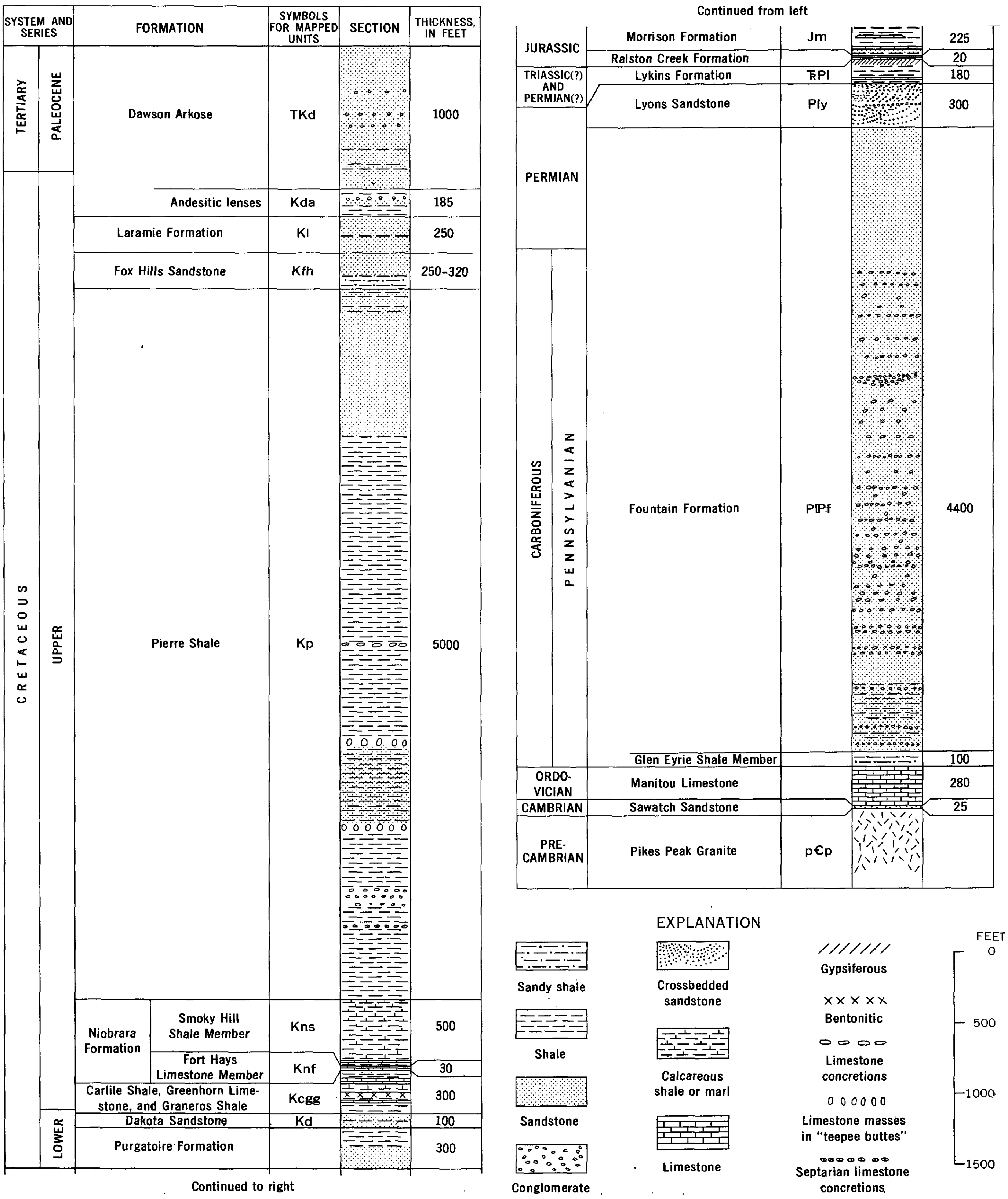

FIGURE 3.—Bedrock exposed in and near the Air Force Academy grounds, Colorado Springs, Colo.

LYONS SANDSTONE

The Lyons Sandstone of Permian age crops out in a belt several hundred feet wide east of the Fountain Formation at the head of Jack Valley and in the southwest corner of the Academy area. The few scattered outcrops that were seen either are fine-grained yellowish-gray friable to loose sandstone that is thin bedded and well laminated or are fine-grained massive sandstone that weathers irregularly to masses of pellets one-sixteenth inch in diameter. Continued weathering has broken down these masses and has strewn the pellets over the ground around the outcrop. The light-colored friable sandstone is more typical of the upper part of the formation. The lower part is cemented by iron oxide and forms the huge vertical sheets of maroon sandstone in the Garden of the Gods.

LYKINS FORMATION

Two small outcrops of the Lykins Formation of Permian(?) and Triassic(?) age were observed east of the Lyons Sandstone in the northwest corner and in a thin belt in the southwest corner of the Academy area. At the west end of Jack Valley the Glennon Limestone Member of the Lykins Formation of LeRoy (1946, p. 31) consists of about 30 feet of very pale orange crystalline limestone containing cavities filled with calcite crystals and irregular veinlets of quartz and chert. The limestone is thinly laminated, and the laminations are intricately folded and faulted. The faults are filled with calcite crystals. The other outcrop, west of Cathedral Rock, consists of thin-bedded finely laminated gray sandy limestone. Maroon shale was observed in the belt at the southwest corner of the area.

RALSTON CREEK FORMATION

The Ralston Creek Formation of Late Jurassic age crops out at the west end of Jack Valley in a thin faulted unmappable slice.

The bed exposed is a grayish-brown fresh-water limestone about 2 feet thick that is made up of stems of characeous algae and nodules of jasper. This limestone lies near the top of the 50-foot-thick Ralston Creek Formation of the Denver area. The lower part of the formation near Denver contains other fresh-water limestone beds and greenish-gray siltstone or white gypsum.

MORRISON FORMATION

The Morrison Formation of Late Jurassic age crops out in the southwest corner of the Academy area and is well exposed at the eastern edge of the Garden of the Gods. It contains thin lenticular brown sandstone beds, greenish-gray siltstone, and light-gray fresh-water limestone beds containing algae.

PURGATOIRE FORMATION

The marine Purgatoire Formation of Early Cretaceous age is not exposed on the site of the Academy, but at Colorado Springs both the Lytle Sandstone Member and the Glencairn Shale Member are exposed. According to Finlay (1916, p. 8), the Lytle contains massive sandstone in the lower part and pebble layers and lenses of red or green claystone in the upper part. The Glencairn consists of dark shale, claystone, and friable fine-grained sandstone beds.

DAKOTA SANDSTONE

The Dakota Sandstone of Early Cretaceous age crops out in a small faulted lens on the ridge between Jack Valley and Deadmans Creek and in a small outcrop in the southwest corner of the Academy area.

The outcrops are yellowish-gray and moderate-brown fine-grained friable sandstone about 15 feet thick that contains hollow ironstone nodules. This sandstone is probably the upper bed of the Dakota. At Colorado Springs the middle part of the formation contains refractory clay beds, and the lower part contains a massive sandstone.

GRANEROS SHALE, GREENHORN LIMESTONE, AND CARLILE SHALE

These marine beds of Early and Late Cretaceous age crop out on the small north-trending ridge at the west end of Jack Valley and in the southwest corner of the area.

The map units are, in ascending order, the Graneros Shale of Early and Late Cretaceous age, the Greenhorn Limestone (which contains the Lincoln Limestone, Hartland Shale, and Bridge Creek Limestone Members), and the Carlile Shale (here represented by the Fairport Chalky Shale, Blue Hill Shale, and Juana Lopez Members) of Late Cretaceous age.

The Graneros Shale is faulted out in the northern part of the site; elsewhere it contains hard black siltstone at the base and olive-black clayey shale having iron-stained concretions and bentonite beds in the upper part.

The Greenhorn Limestone is well exposed on the site. Calcarenite beds about 5 feet thick of the Lincoln Limestone Member and of the Hartland Shale Member of the Greenhorn Limestone crop out at the west end of Jack Valley. The yellowish-gray slabby calcarenite, a sandstone composed of shell fragments, is predominantly composed of prisms of *Inoceramus* shells and tests of Foraminifera. *Inoceramus pictus* Sowerby, *Calycoceras canitaurinum* (Haas), and *Ostrea* sp. were identified. About 20 feet of light-gray fine-grained limestone of the Bridge Creek Member overlies the calcarenite beds. The Bridge Creek contains about eight dense limestone layers separated by soft platy shaly limestone. A 6-inch-thick limestone at the base contains the fossils *Sciponoceras gracile* (Shumard), *I. pictus* Sowerby, and *Worthoceras* sp. The fourth limestone above the base contains abundant *I. labiatus* (Schlotheim) and *Watinoceras coloradoense* (Henderson). The upper limestone beds also contain abundant *I. labiatus* (Schlotheim).

The Fairport Chalky Shale Member of the Carlile Shale is cut out by faulting on the site, but at Fountain Creek to the south it is platy or blocky yellowish-gray chalky shale. The Blue Hill Shale Member is well exposed at the head of Jack Valley where it is an olive-black silty shale that weathers soft and flaky. Selenite crystals lie on the freshly exposed shale. No concretions or fossils were seen. The Juana Lopez Member also is exposed and together with the Fort Hays Limestone Member of the Niobrara Formation makes a low hogback. The Juana Lopez is a dark-yellowish-orange calcarenite. *Prionocyclus wyomingensis* Meek, *Scaphites whitfieldi* Cobban, and *Inoceramus* cf. *I. cuvieri* Sowerby were found in the upper platy part of the member, which is only 3 feet thick.

NIOBRARA FORMATION

Fort Hays Limestone Member

The Fort Hays Limestone Member of the Niobrara Formation of Late Cretaceous age and the underlying Juana Lopez Member form a small hogback at the west end of Jack Valley and another in the southwest corner of the area. The limestone is yellowish gray and fine grained. In the outcrops in the southwest corner of the area, the lower part is thick bedded, hard, and massive; the upper part is thin tabular bedded and soft. The limestone in Jack Valley is broken by a fault, so that bedding is not conspicuous, and the limestone weathers in 4- to 6-inch irregular fragments. Casts of *Inoceramus deformis* Meek and *Ostrea congesta* Conrad were found in the limestone.

Smoky Hill Shale Member

Small outcrops of the Smoky Hill Shale Member of the Niobrara Formation occur on the slopes of the ridge at the northwest head of Jack Valley. Much larger outcrops were found in the southwest corner of the Academy area.

The member is composed of thick slabby beds of chalky limestone separated by thick layers of yellowish-gray fissile chalky shale. A very pale orange ridge-forming limestone lies near the middle, and a yellowish-orange ridge-forming limestone lies at the top of the Smoky Hill. The chalk slakes to a sticky limy clay. *Inoceramus platinus* Logan was found covered by the shells of *Ostrea congesta* Conrad in the slabby chalk.

PIERRE SHALE

The Pierre Shale of Late Cretaceous age crops out at the head of Pine Valley in the southwest part of the Academy area. This is the northernmost exposure of Pierre Shale in the vicinity of the Academy. From this point southward, less and less of the formation is cut out by the Rampart Range fault, and its outcrop rapidly widens to a belt 4½ miles wide at Colorado Springs.

The formation is probably thicker than the 2,500 feet given by Finlay (1916, p. 8). Logs of oil wells east of the Academy area show intervals of the shale between 3,750 and 5,200 feet thick. The lower part, at the Academy site, consists of olive-gray clayey calcareous shale, a thin ridge-forming sandstone, and silty noncalcareous shale that contains ironstone nodules. A soft shaly yellowish-brown sandstone is about one-third of the thickness above the base; this is overlain by clayey shale that contains large irregular gray limestone masses that weather into conical mounds called tepee buttes. Another dark-gray shaly sandstone is about two-thirds of the thickness above the base; this also is overlain by clayey shale that contains many thin layers of fibrous aragonite and cone-in-cone structure. The top 300–400 feet of the formation is soft olive-brown sandstone that contains layers of black phosphatic pebbles. Calcareous concretions, which are characteristic of the formation, contain well-preserved fossils.

FOX HILLS SANDSTONE

The Fox Hills Sandstone of Late Cretaceous age was observed only in the southwest corner of the Academy area. The formation crops out from Pine Valley southward on the western slope of the ridge formed by the Laramie Formation. At the northern end of Popes Bluffs, the lower part of the formation consists of a friable marine sandstone 150 feet thick that is olive brown in the lower and upper parts and light olive gray in the middle, where it contains small sandy limestone concretions. Near the top it contains many phosphatic pebbles that have been perforated by worms. The fossils *Ostrea* sp., *Modiolus* sp., and *Terebratula helena* Whitfield were found in the top inch of the sandstone. Above the sandstone is 100 feet of sandy thin-bedded friable light-olive-gray shale that contains small lenticular sandy limestone concretions and rusty sandy layers which have phosphatic pebbles. The shale becomes soft, sandy, and more massive in the upper part.

LARAMIE FORMATION

The Laramie Formation of Late Cretaceous age is exposed in the fault zone at the head of Jack Valley and in the southwest corner of the area. Fine-grained friable yellowish-gray sandstone containing iron-stained dark-yellowish-orange streaks and coaly layers is exposed in fault contact through a thickness of about 20 feet above the Niobrara Formation. There are small sandy ironstone nodules within the sandstone.

The Laramie Formation is best exposed south of the Academy area along and to the west of Monument Creek near the Pikeview coal mine and on Popes Bluffs to the northwest. At Popes Bluffs it consists of about 120 feet of massive yellowish-gray sandstone at the base, overlain by soft gray siltstone and claystone that contains coal beds, overlain by a persistent bed of sandstone about 28 feet thick, overlain by a 95-foot-thick series of thinner nonresistant sandstone beds containing lenticular coal beds. This series of thin sandstone beds locally is massive and resistant to erosion, as at the south end of Popes Bluffs where it constitutes the most prominent part of the bluffs. A thin olive-green blocky claystone lies at the top of the exposure.

DAWSON ARKOSE

Distribution.—The bedrock that underlies the surficial material almost everywhere within the Academy area is the Dawson Arkose. It crops out over about 25 percent of the Academy area. The widest band of outcrop is around the remnants of the oldest pediment; the next widest outcrop is around the flanks of the next younger pediment. Small outcrops are exposed along most of the stream valleys. A fairly accurate picture of distribution of the Dawson may be had from the pine trees of the area; because of the water-holding capacity of the Dawson, the trees appear to grow only in areas where the arkose is within 15 feet of the ground surface.

Topographic form.—The topographic form of the Dawson Arkose is varied. It crops out in steep slopes, but not cliffs, along the edges of the mesas under the gravels. It underlies alluvium in the valleys west of Monument Creek at shallow depths and its upper contact is a planed surface that is cut locally by eastward-trending modern channels. Along Monument Creek and the larger tributaries entering from the east, the Dawson forms steep to vertical valley walls as much as 30 feet high, as shown in figure 4. In places the Dawson erodes to pedestal and monumentlike forms; Cathedral Rock, shown in figure 5, is an example of the latter form.

Lithology and age.—Arkose is a variety of sandstone that contains a significant proportion of feldspar, at least 25–30 percent, in contrast to sandstone, which consists almost entirely of quartz grains. The name Dawson Arkose was applied by Richardson (1912, p. 271) to the series of arkosic sediments that unconformably overlie the Laramie Formation of Late Cretaceous age and are overlain unconformably by the Castle Rock Conglomerate of Oligocene age. Approximately the lower 500 feet of the Dawson is Late Cretaceous in age; the remainder is Paleocene. The total thickness of the formation is about 2,000 feet, of which perhaps 1,000 feet is present in the Academy. The Dawson Arkose is a continental deposit derived from adjacent granitic highlands and laid down by rivers and streams and in small bodies of standing water. Its lithology changes greatly from place to place.

The Dawson Arkose in this region contains two beds of andesitic material. The lower bed, exposed only south of the Academy boundary, makes up the lowest part of the Dawson and contains more than 100 feet of olive-gray or olive-brown andesitic claystone, sandstone, and conglomerate. A higher, possibly lenslike bed lies above typical arkose along Kettle and Pine Creeks inside the east boundary of the Academy area and is shown on the geologic map (pl. 1). This upper lenslike andesitic bed is similar to the lower andesitic

FIGURE 4.—Massive bed of Dawson Arkose along the east bank of Monument Creek. Interbedded arkose and siltstone lie above the massive bed, and clayey siltstone and clayey arkose form the slope below. Seeps issue from the upper part of the clayey zone in the shallow cave.

FIGURE 5.—View eastward past Cathedral Rock toward the valley of Monument Creek and the Black Forest beyond. Although this erosional remnant of Dawson Arkose is within 2,000 feet of the thrust-fault zone along the foot of the Rampart Range, the gentle eastward dip of the beds is undisturbed. Photograph by R. B. Colton.

bed but contains a larger proportion of claystone and more ironstone. It apparently lies at least 250 feet above the base of the Dawson.

The upper part of the Dawson, which underlies most of the area of the Academy is arkosic conglomerate, sandstone, siltstone, and silty claystone. These beds are light gray, pink, or light reddish brown. Individual beds vary in thickness and lithology and rarely are traceable for more than a few hundred feet. The two most common types of rocks are very light gray coarse, somewhat micaceous sandstone and light-reddish-brown and light-green sandy siltstone and claystone. Nearly every hand-dug shallow test pit and many natural exposures along the flanks of the pediments showed one or the other of these two types of material. Probably not more than half of the Dawson in the Academy area is composed of the arkosic sandstone. Quartz is the predominant constituent of the sandstone, and kaolinized feldspar is the next most abundant. Particles in the upper part of the Dawson range in size from clay to cobbles. The average size seems to be that of sand, in subrounded to subangular grains. Grain size in the formation in general decreases to the east away from the source area. The typical texture of the arkosic sandstone is shown in figure 6. Figure 7 shows a fresh exposure of light-colored arkose over blocky clayey siltstone.

FIGURE 6.—Typical texture of coarse arkosic sandstone of the Dawson. The gray fragments are quartz, and the white grains are kaolinized microcline feldspar.

Some of the claystone lenses in the Dawson Arkose swell upon exposure and produce a loose-textured crust as much as 3 inches thick, as shown in figure 8.

Sandy ironstone beds in the upper part of the Dawson range in thickness from 2 to 18 inches. They commonly cap pedestallike erosion remnants or form the top layer of cliffs of more friable arkose, which they have protected from erosion. The surface of the Dawson Arkose beneath pediment gravels is gently undulating and has many almost flat places that were cut as the eastward-flowing streams meandered across a broad flood plain. Some longitudinal channels a few tens of feet deep cut this gently sloping surface, but their distribution is almost unpredictable.

FIGURE 7.—Fresh exposure of Dawson showing light-colored arkose overlying blocky clayey siltstone. Pick at contact near middle of photograph indicates scale.

Places favorable to examine typical lithologies of the Dawson Arkose are: interbedded sandstone, siltstone, and silty claystone in the walls of Kettle Creek valley and in the Pueblo Brick Co. clay pit at coordinates 428,700 N., 2,188,630 E.; andesitic shale in the lowermost Dawson on the banks of Cottonwood Creek south of the mapped area around U.S. Highway 85–87 bridge; higher lens of andesitic shale in the valleys of Kettle Creek and Pine Creek at the east boundary of the academy; and many exposures along Monument Creek and along the flanks of the pediments west of Monument Creek.

LABORATORY ANALYSES

Several thin sections of arkose were prepared, to determine the source of the clayey material that appeared in the mechanical analyses and to determine the degree of alteration of the feldspar.

The volume proportions of various minerals and of void space for two samples, as determined by the point-count method, are shown in the following table:

Sample	Volume percent				
	Quartz	Microcline and other feldspar	Clay, chlorite, or other very fine-grained material	Muscovite mica	Void space
AFA-24(1)	43	29	13		15
(2)	46	23	11		20
AFA-25(1)	44	35	9	Trace	12
(2)	47	28	16		9

Samples AFA-24 and AFA-25 taken along the old road at the east end of Pine Valley.

FIGURE 8.—Loose open-textured crust produced upon exposure of a lens of swelling claystone in the Dawson Arkose in a roadcut along Route 10.

The grains of quartz and feldspar are subrounded to subangular; many are cracked. A few quartz grains are shattered at points of contact with other grains. The feldspar grains show some degree of alteration to clay minerals, particularly along cleavage planes. Some feldspar grains are so altered and soft that they could not have been transported in their present state. The chemical weathering of the feldspar therefore must have taken place or at least continued, after deposition of the arkose. The clayey material derived by washing the arkose occurs in coatings around the grains, as shown in figure 9.

The fine-grained material washed from samples of the arkose was analyzed in an X-ray diffractometer by A. J. Gude 3d; mineral content was:

	AFA-24	*AFA-25*
Kaolinite	Abundant	Very Abundant.
Illite	Minor	
Quartz	do	Trace.
Feldspar	do	(?).
Dolomite	Trace	
Chlorite	(?)	
Montmorillonite		(?).

FIGURE 9.—Camera-lucida drawing from a thin section of Dawson Arkose. Grains of quartz (Q), microcline feldspar (F), interstitial clay, and void space (V).

Figure 9 indicates that the arkose sample has an open structure, but all grains actually may be in physical point contact with their neighbors. In any one plane, such as the thin section shown, only a few such point contacts would appear.

The greenish friable clayey sandstone, which is the dominant material in the andesitic lens of the Dawson Arkose, is notably different mineralogically from normal white Dawson Arkose. Two samples of fine-grained matrix of this material, collected south of the Academy area near U.S. Highway 85–87, were also analyzed by Mr. Gude, and were found to contain:

Mineral	AFA-18	AFA-29
Quartz	Minor	Trace.
Potassium feldspar	do	Minor.
Montmorillonite	Major	Major.
Kaolinite	do	Trace.
Illite	Trace	Do.

Many laboratory and field tests were performed on Dawson Arkose by the SOM soils laboratory. The general size-distribution characteristics of the Dawson Arkose, as compiled from these tests and exclusive of the andesitic unit, are shown in figure 10. The dots represent the weight percent of a sample smaller than the indicated sizes at the top of the left-hand edge of the columns of dots. The suite includes 52 samples for which the percent smaller than the No. 4, 10, 40 and 200 U.S. Standard sieves and 0.02 and 0.005 mm were recorded. Large dots represent five samples. A median line is drawn through points at which 26 of the samples exceeded that percent passing at a particular size. Because most of the complete size analyses were made on materials of special interest in construction, the more troublesome siltstone and claystone are probably represented more frequently among these tests than the equally common arkosic sandstone. The extremes of a few partial analyses of coarser material are shown by crosses.

The plasticity index versus the liquid limit for samples of Dawson Arkose is plotted in figure 11. All samples, except AFA–29 from the montmorillonite-bearing lens of andesitic Dawson, fall close to or above Casagrande's "A" line, an empirical boundary commonly drawn on plasticity charts that generally separates cohesionless soils and inorganic clays of low to high plasticity in the region above the line from silty and organic soils below the line.

The liquid limit increases rather uniformly as shown in figure 12 by increase in the ratio of percentage of material finer than 0.005 mm to percentage passing the No. 40 sieve. This ratio is in effect the proportion of clay in the material upon which the liquid limit test is made.

A summary of some other physical tests of Dawson Arkose performed by the SOM laboratory is given in table 2.

TABLE 2.—*Summary of physical tests of Dawson Arkose*

	Tests	Average	Range
Specific gravity g per cc	15	2.64	2.59–2.70
Dry field density lb per cu ft	19	116.3	104.3–124.2
Maximum density, Am. Assoc. State Highway Officials modified compaction lb per cu ft	22	126.1	113.0–134.3
Optimum moisture percent	22	8.9	5.6–15.4
Laboratory California Bearing Ratio at—			
90 percent of maximum density	5	19.4	8–29
95 percent of maximum density	10	32.2	5–60
100 percent of maximum density	10	71.3	20–135
Field California Bearing Ratio	3	18	7–27.5
Modulus of subgrade reaction lb per cu in	3	216	200–225

SURFICIAL DEPOSITS

About three-fourths of the Academy grounds is covered by unconsolidated deposits of silt, sand, and gravel of Pleistocene and Recent age. Local geo-

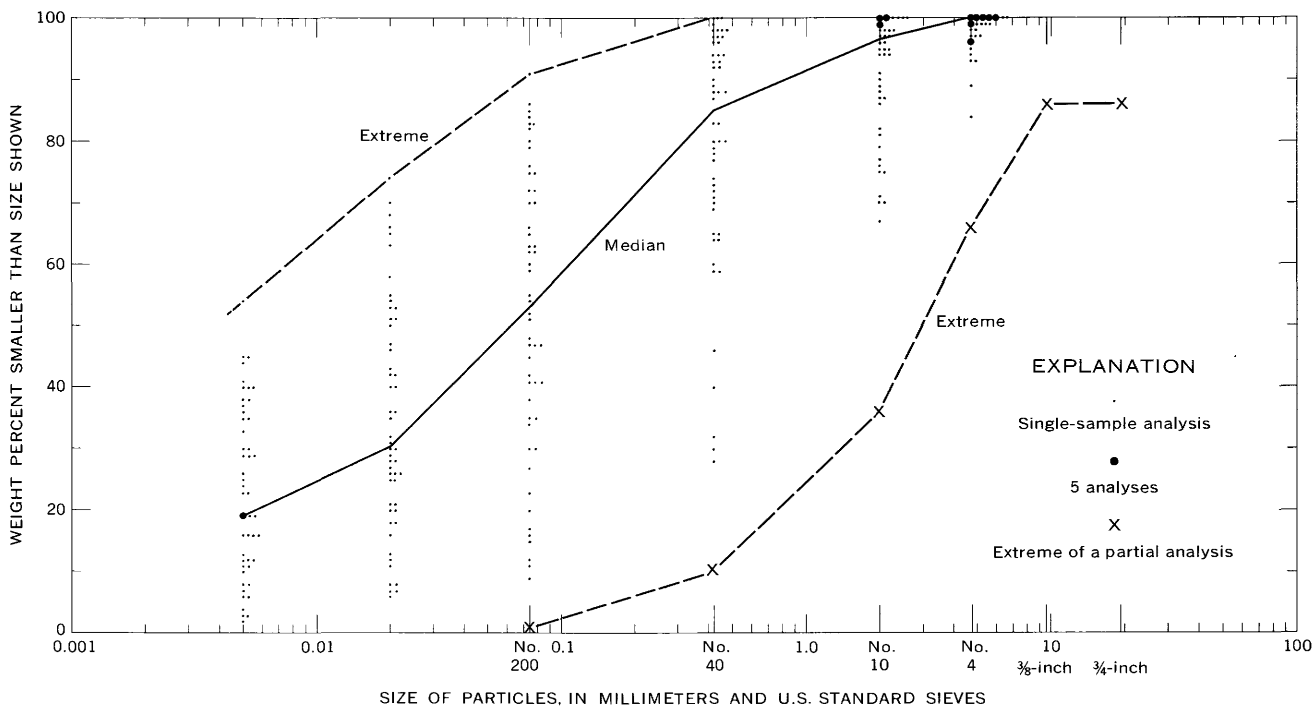

FIGURE 10.—General size-distribution characteristics of Dawson Arkose.

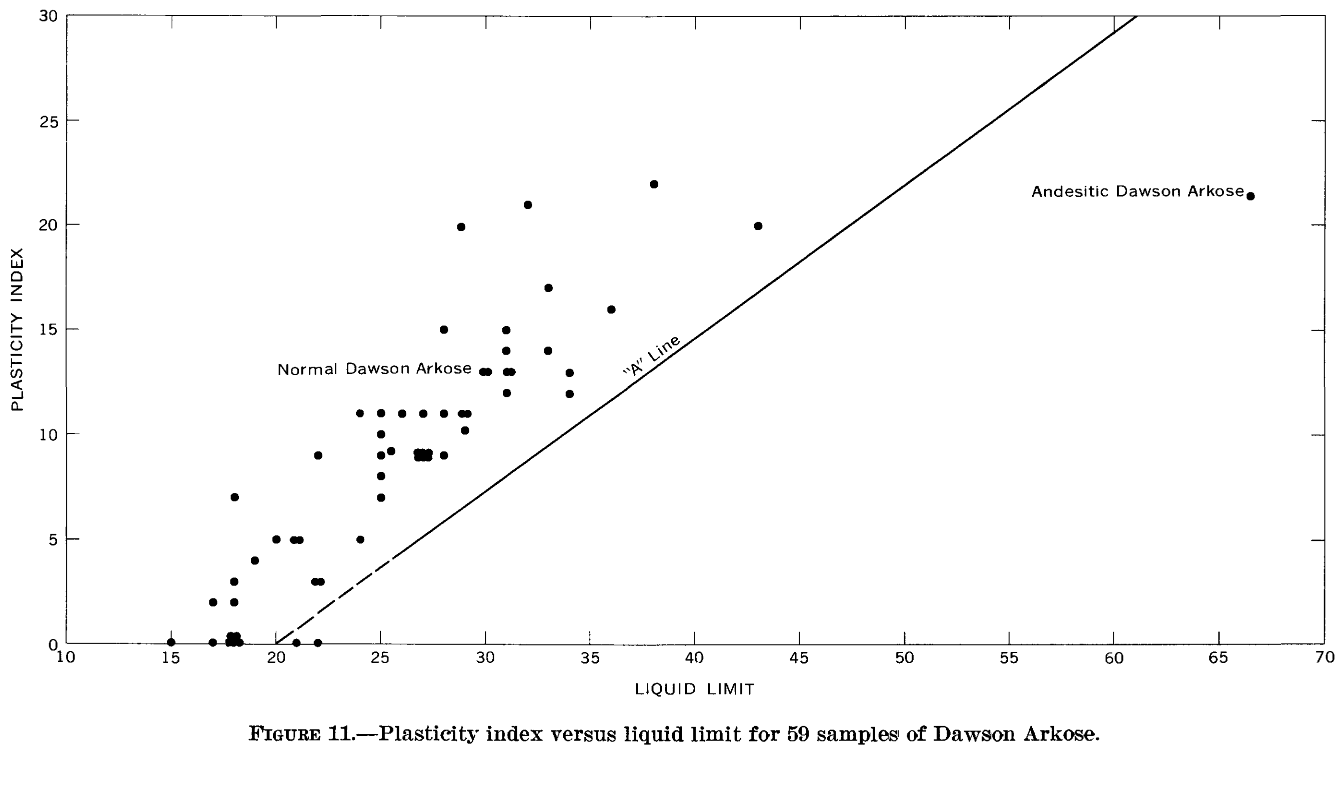

FIGURE 11.—Plasticity index versus liquid limit for 59 samples of Dawson Arkose.

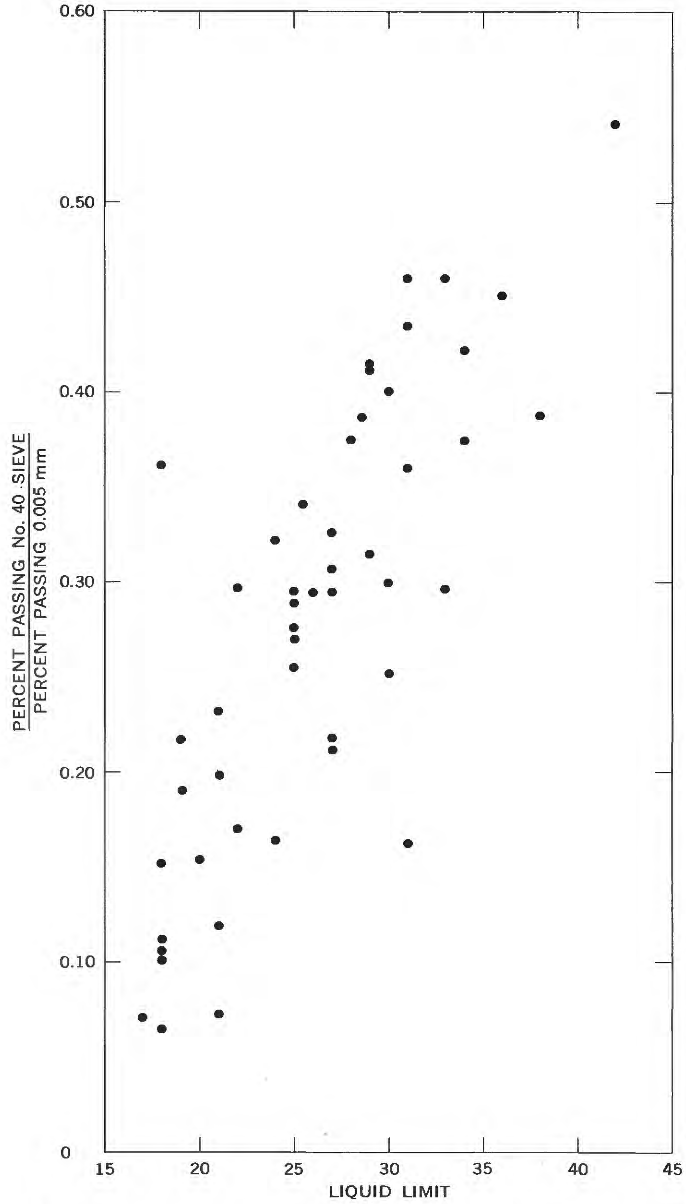

FIGURE 12.—Liquid limit versus ratio of percentage of material finer than 0.005 mm to percentage passing No. 40 sieve for 49 Dawson Arkose samples.

graphic names were assigned to the deposits of different genesis and age so that each deposit could be easily identified in reports and in discussions among the geologists, engineers, and contractors. Another set of names has since been assigned (Scott, 1960, 1963), on the basis of contemporaneous mapping, to surficial deposits near Denver, Colo. The Denver area names are based on detailed soil studies, fossils, a marker ash bed, and other criteria that allow the names to be more widely applicable to the surficial deposits in eastern Colorado than to those of the Academy area. Indeed, the Denver area names have now been used as far north as Longmont and Fort Morgan and as far south as Pueblo, Colo. The original intention was to use the Academy area names in an informal sense, but they have become so widely used in the soil terminology, engineering drawings, and reports of the AFACA and the architect-engineer that it has become necessary to adopt them formally for use only in the area of the Air Force Academy. Correlation of these names with the formal stratigraphic names used near Denver is included in the discussion of each formation.

The three oldest deposits are stream alluvium laid down on ancient pediments that were graded to Monument Creek. Stream alluvium of four younger ages lies in valleys cut into the pediments. Colluvium, which consists of material that was eroded off the hills, underlies intermediate slopes and grades into the stream alluvium at the edge of the valley bottoms. Sand was blown out of the stream bottoms and off the hills by westerly winds and was deposited on the east side of Monument Creek in long low dunes. The topographic relations of the surficial deposits are shown in figure 13.

PEDIMENT GRAVELS

Pediment gravels of three ages crop out in the Academy area. From oldest to youngest they are the Lehman Ridge Gravel of Nebraskan or Aftonian age,

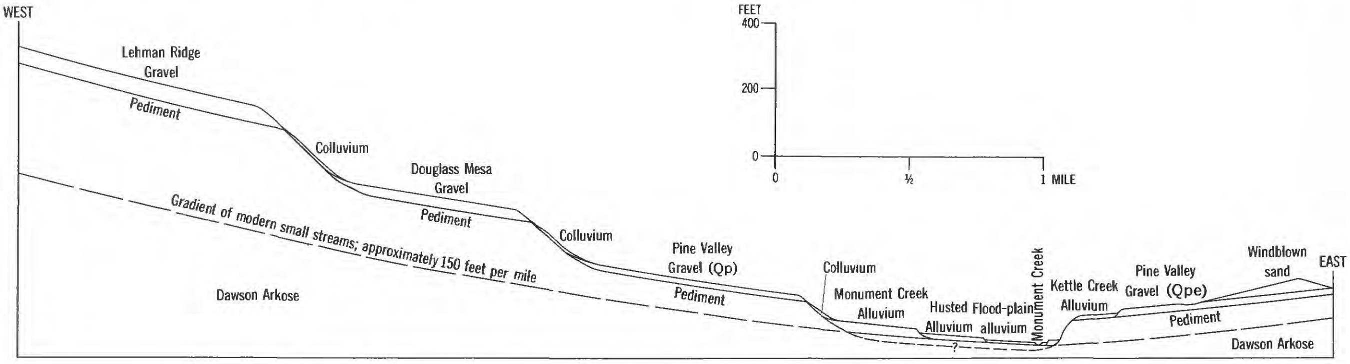

FIGURE 13.—Diagrammatic section showing topographic relations of the surficial deposits.

the Douglass Mesa Gravel of Kansan or Yarmouth age, and the Pine Valley Gravel of Illinoian or Sangamon age. Pine Valley Gravel east of Monument Creek was differentiated from the formation of the same age west of Monument Creek because it is much finer grained and has obviously different engineering characteristics.

LEHMAN RIDGE GRAVEL

Distribution—The gravel of the highest pediment in the Academy area, here named Lehman Ridge Gravel, crops out on the ridge north of Jack Valley, on Lehman Ridge (designated as the type locality), and on the highest pediment remnants north of Pine Valley.

Topographic form.—The Lehman Ridge pediment is the oldest and highest in the area. Remnants lie about 380 feet above adjacent modern streams; consequently, it is the most dissected pediment, and only ridges and knobs remain of the once-extensive surface. The original pediment slope based on these dissected remnants is probably eastward at 200 feet to the mile. Figure 14 shows Lehman Ridge Gravel on Lehman Ridge.

Lithology.—The gravel is composed of reddish-brown fragments of Pikes Peak Granite ranging in size from silt to boulders 20 feet in diameter. Pebbles of quartz and feldspar ¼–1 inch in diameter probably make up the bulk of the gravel. Boulders are both more numerous and larger nearer the mountains. The concentration of boulders may have resulted from washing out of the finer material during erosion of the Lehman Ridge deposit. Milky quartz fragments and smoky quartz crystals from the Pikes Peak Granite, chert fragments from the Manitou Limestone, and ironstone fragments from the Dawson Arkose are minor constituents of the gravel. The Lehman Ridge Gravel is generally more than 25 feet thick and in several places appears to exceed 50 feet. The gravel is very poorly bedded and sorted, as though deposited by streams during times of flood.

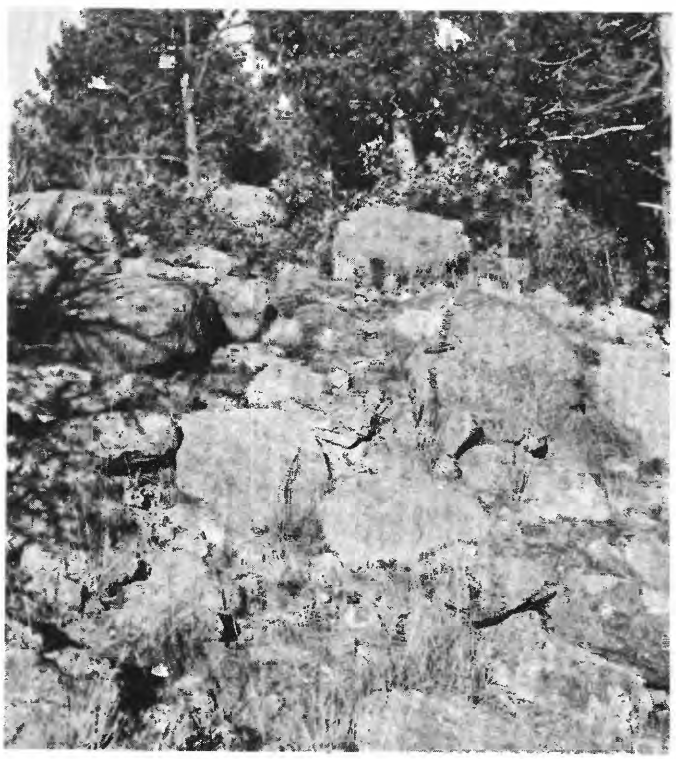

FIGURE 14.—Lehman Ridge Gravel on Lehman Ridge.

Age and correlation.—The Lehman Ridge Gravel is correlated with the Rocky Flats Alluvium (Scott, 1960) of the Denver area, which is considered to be Nebraskan or Aftonian in age on the basis of its stratigraphic and physiographic position. The Lehman Ridge pediment may be the same as the lower of Tator's (1952, p. 260) Deadman Canyon surfaces.

DOUGLASS MESA GRAVEL

Distribution.—The gravel on the intermediate-level pediment, here named Douglass Mesa Gravel, crops out on knobs at the east end of Jack Valley, on a southeast-trending spur in Lehman Valley, on Lehman Mesa, at the type locality on Douglass Mesa, on Pine Mesa, on ridges west of the mouth of Kettle Creek, and as a thin deposit on a low rolling area east of Monument Creek and north of Breed.

Topographic form.—Although the Douglass Mesa pediment has been dissected, many nearly flat, gently eastward sloping remnants indicate its former extent. The slope of the pediment is about 130 feet per mile to the east, and it lies 190–200 feet above adjacent modern streams. Dissected side slopes of the remnants are very steep. Many of the larger remnants have along their centers shallow boulder-filled valleys which trend eastward. The gravel has been completely removed from the east end of many of the pediment remnants, but the underlying Dawson Arkose still lies above the level of the next younger and lower pediment.

Lithology.—The Douglass Mesa Gravel is composed of reddish-brown fragments of Pikes Peak Granite ranging in size from sand to boulders 6 feet in diameter, and of varying amounts of silt and clay. One-fourth-inch pebbles of quartz and feldspar probably form the bulk of the gravel. Boulders are apparently more common in the upper few feet of the deposit and are larger and more numerous near the mountains, but not as numerous as on the Lehman Ridge pediment. Linear concentrations of boulders or "boulder trains" crop out on several of the larger areas of Douglass Mesa

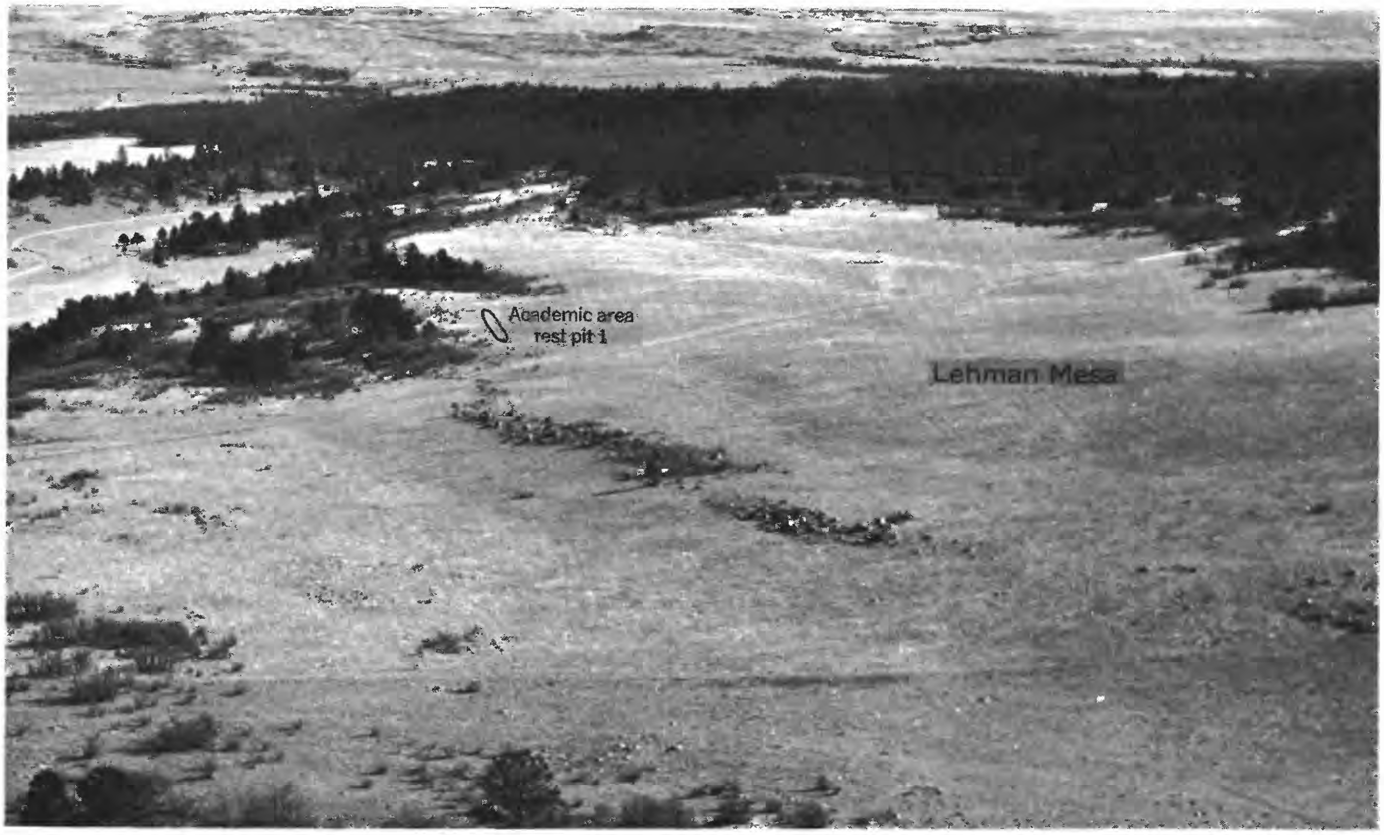

FIGURE 15.—Oblique low-altitude aerial photograph, looking east, of Lehman Mesa, the site of the academic buildings. Note the boulder train on the surface of the mesa. Photograph by R. B. Colton.

Gravel. A boulder train on Lehman Mesa is shown in figure 15. Although boulders are common in the pediment gravel on Lehman Mesa, the prediminant material shown in test pits and borings is sand and fine gravel. Typical Douglass Mesa Gravel at test pit 1 on Lehman Mesa is shown in figure 16. The gravel is almost free of boulders near the east ends of the mesas.

Locally, and especially at a depth of 3–10 feet, the sand and gravel contain enough silt and clay to form a firm binder; and the clay forms an aquiclude where the shallow ground water is under an artesian head. A poorly developed soil from the grass roots down to a depth of 2 feet was observed at several places. An exploratory pit at the hospital site showed that the upper 6 inches of the soil contains humus, and that a lower harder layer about 10 inches thick contains reddish-brown clay leached from the overlying sediment. At the base is a loose layer that is mottled by calcium carbonate.

The thickness of the Douglass Mesa Gravel ranges from 5 to more than 50 feet and probably averages about 30 feet.

MEASURED SECTIONS

Three sections were measured in backhoe excavations in Douglass Mesa Gravel.

Qd–1. Backhoe pit site 2 on top of mesa east of Mr. Lehman's house and north of his access road, coordinates 430,000 N., 2,176,800 E.

Unit	*Description*	*Depth (feet)*
4	Sand, soil, and cobbles,[1] gray-brown, gravelly; grades into unit 3	0–1. 5
3	Cobbles, gravel, and sand,[1] red-brown, firm; grades into unit 2	1. 5–3. 0
2	Gravel[1] having binder of fines; very firm	3. 0–4. 5
1	Gravel, sandy, uniform, loose, damp, and very slightly plastic; maximum diameter of pebbles, 1½ in	4. 5–10. 5

[1] In units 2, 3, and 4, cobbles 4 in. in diameter were common; 2 boulders 18 in. and 24 in. in maximum dimension were removed.

Qd–2. Backhoe pit site 2B, coordinates 430,380 N., 2,176,620 E., about 30 ft lower in elevation than site 2

Unit	*Description*	*Depth (feet)*
3	Silt, dark-gray, gravelly	0–3
2	Sand, gravel, and boulders, dark-red-brown, very firm; silt binder	3–5
1	Sand, light-red-brown, gravelly; clay binder, tough; contains occasional cobble 6 in. in diameter	5–10. 5

Qd-3. Backhoe pit site 3 on Lehman Mesa, coordinates 428,840 N., 2,173,860 E.

Unit	Description	Depth (feet)
3	Soil, dark-reddish-brown	0–2.5
2	Boulder gravel, brown, rudely stratified; maximum diameter, 3 ft	2.5–6.0
1	Sand and gravel,[1] well-stratified; maximum diameter, 1½ in	6–10

[1] Sample AFA-1 of unit 1 taken between 7 and 8.2 feet.

Age and correlation.—The Douglass Mesa Gravel is correlated with the Verdos Alluvium (Scott, 1960) of the Denver area which is considered to be Kansan or Yarmouth in age on the basis of a contained volcanic ash that is identical to the Pearlette Ash Member of the Sappa Formation of Nebraska (Powers and others, 1958, p. 1631). The Douglass Mesa pediment may be the same as Tator's (1952, p. 262) Rock Creek surfaces. Almost all the surfaces that he designated "low level" and most that he designated "high level" are remnants of the Douglass Mesa pediment.

Laboratory Analyses

The results of some of the field and laboratory tests performed on Douglass Mesa Gravel by the SOM soils laboratory, are summarized in figure 17, which shows the general distribution of grain sizes; figure 18 which shows a plot of the plasticity index versus the liquid limit; figure 19 which shows the linear increase in the liquid limit with the increase of the proportion of material finer than 0.005 mm; and table 3, which shows other physical properties.

Figure 16.—North face of test pit 1 on Lehman Mesa in Douglass Mesa Gravel. Pit is about 22 feet deep; bottom of pit is at the edge of shadow. Note pick on one of the larger boulders.

Table 3.—*Summary of physical tests of Douglass Mesa Gravel*

	Tests	Average	Range
Specific gravity g per cc	8	2.64	2.56–2.72
Dry field density lb per cu ft	45	109.2	95.5–130.0
Maximum density, Am. Assoc. State Highway Officials modified compaction lb per cu ft	31	129.5	121.0–134.1
Optimum moisture percent	31	7.95	6.0–11.5
Laboratory California Bearing Ratio at—			
90 percent of maximum density	8	19.9	12.0–32.0
95 percent of maximum density	8	52.4	19.0–88.0
100 percent of maximum density	8	89.3	30.0–135.0

PINE VALLEY GRAVEL

Distribution.—The gravel of the lowest pediment in the Academy area, here named Pine Valley Gravel, occupies the eastern part of Lehman Valley, the eastern part of South Lehman Valley, the eastern part of Douglass Valley, the type locality in a road cut in the SW¼NE¼ sec. 36, T. 12 S., R. 67 W., Pine Valley, a small valley west of the mouth of Kettle Creek, and almost the entire area east of Monument Creek (where it is designated Pine Valley Gravel, east; see pl. 1).

Topographic form.—The Pine Valley pediment is a remarkably flat, very little dissected surface. It forms the floor of several valleys, and despite the fact that several stages of arroyo cutting and filling have taken place since its construction, some intermittent streams still have their floors on the surface of its gravels. Elsewhere streams are entrenched in it; Monument Creek, for instance, has cut downward more than 100 feet since the Pine Valley Gravel was deposited. The pediment generally lies 80–120 feet above adjacent modern streams. The Pine Valley pediment east of Monument Creek is a gently rolling surface that slopes southwestward toward Monument Creek, at about 110–120 feet per mile.

Lithology.—The Pine Valley Gravel west of Monument Creek consists primarily of reddish-brown fragments of Pikes Peak Granite, some of which have been reworked from the Lehman Ridge and Douglass Mesa Gravels. Generally the deposit contains a greater admixture of sand, silt, and clay than do the two older pediment gravels. A soil in the upper few feet of the alluvium contains both humic and clayey layers. Long narrow concentrations of boulders follow old stream channels in the pediment gravel. Some of the boulders in these "boulder trains" are as much as 18 inches in diameter. Most of the rocks that lie on the surface of

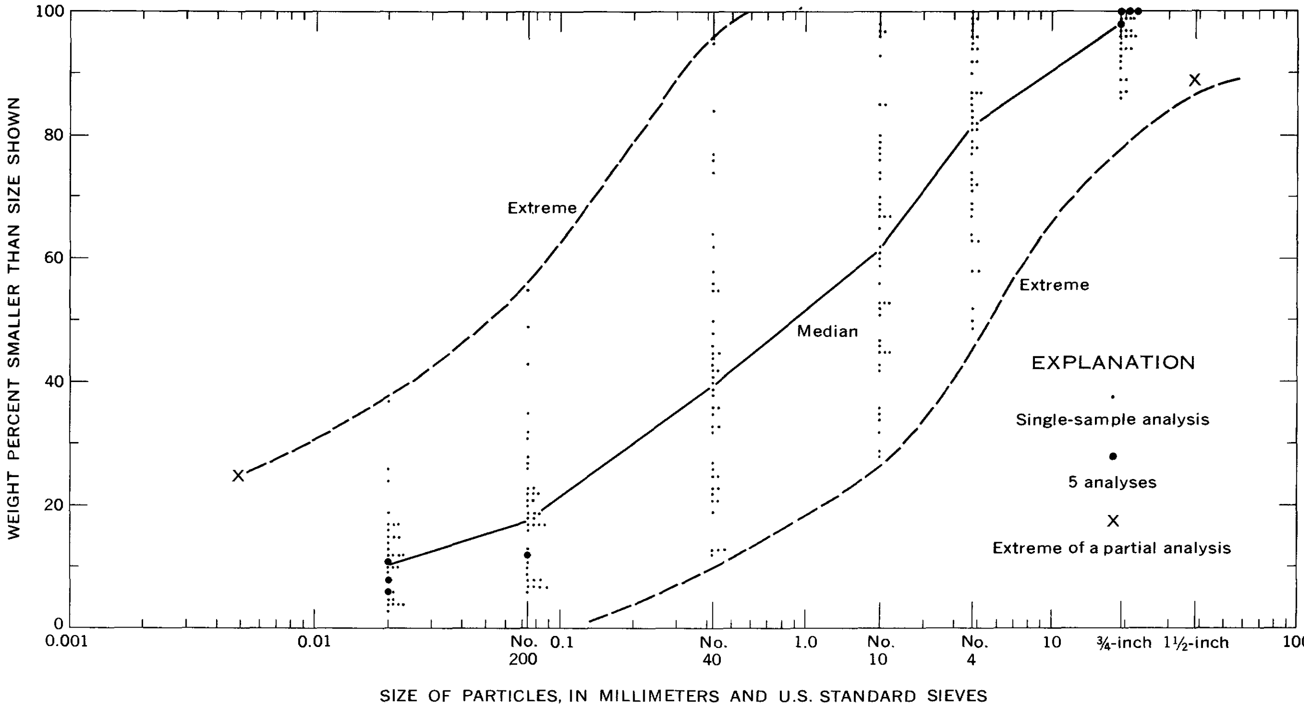

FIGURE 17.—General size-distribution characteristics of Douglass Mesa Gravel.

the Pine Valley Gravel are faceted and polished by the abrasion of the windblown sand, which overlies the pediment gravel and was probably derived from it.

The Pine Valley Gravel east of Monument Creek was derived largely from Dawson Arkose which crops out to the east of the Academy site. It therefore contains no material larger than 1½-inch pebbles. For this reason it was mapped separately from the deposit of the same age west of Monument Creek. The contrast between the two types of material can be seen in photographs of exposures of the two gravels (fig. 20, 21). The thickness of Pine Valley Gravel ranges from 5 to about 30 feet. The thickness east of Monument Creek appears to average about 20 feet; that west of Monument Creek may be somewhat less.

MEASURED SECTION

Qpe–1. Pediment gravel on south side of Kettle Creek about 500 ft east of old U.S. Highway 85–87 bridge, coordinates 412,570 N., 2,196,670 E., in area shown on figure 21.

Unit	Description	Depth (feet)
	Top of pediment.	
4	Sand, grayish-brown, fine, structureless, friable; contains humic material and sparse pebbles as much as ¾ in. in diameter; slope vertical	0–2. 6
3	Sand and gravel, brownish-black, structureless, friable; contains humic material and a few pebbles as large as 1½ in. in diameter; slope vertical	2. 6–4. 5
2	Sand and gravel, light-brown; loose, thin-bedded to indistinctly stratified beds of medium and coarse sand alternate; contains some humic material in upper part; 1-in. pebbles sparse; 2½-in. pebbles very sparse	4. 5–26. 5
1	Dawson Arkose	26. 5–39
	Bottom of arroyo.	

Age and correlation.—The Pine Valley Gravel is correlated with the Slocum Alluvium (Scott, 1960) of the Denver area which is considered to be Illinoian or Sangamon in age on the basis of its stratigraphic and physiographic position, mollusks, and the pre-Wisconsin soil that is developed on it. The Pine Valley pediment was not mapped by Tator, although many well-preserved remnants of it can be seen in the area he mapped.

ALLUVIUM

Alluvium in each of three terraces was given a name, from oldest to youngest; Kettle Creek Alluvium, Monument Creek Alluvium, and Husted Alluvium. Alluvium in the lowest terrace and along the streams is included in flood-plain alluvium.

KETTLE CREEK ALLUVIUM

Distribution.—Alluvial sand, here named Kettle Creek Alluvium, is not a widespread deposit, but crops out only along Monument Creek, Black Squirrel Creek,

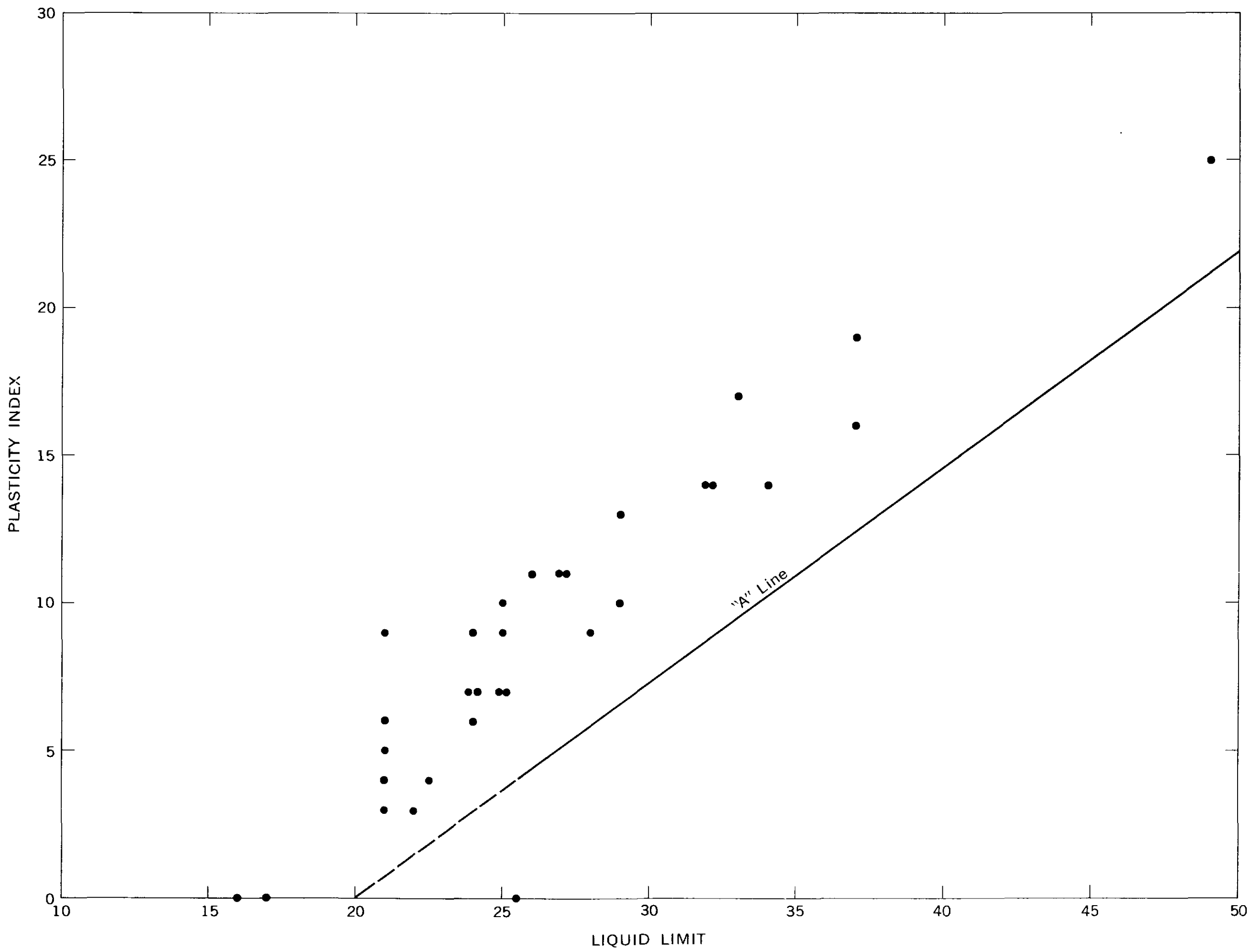

FIGURE 18.—Plasticity index versus liquid limit for 31 samples of Douglass Mesa Gravel.

and Kettle Creek, in the NW¼NW¼ sec. 6, T. 13 S., R. 66 W., the type locality.

Topographic form.—The top of the alluvium forms a terrace 35–40 feet above stream level. Along Kettle Creek and Black Squirrel Creek, the top of Kettle Creek Alluvium is 10–12 feet below the top of the Pine Valley Gravel.

Lithology.—Kettle Creek Alluvium consists of unconsolidated olive-gray and yellowish-brown medium to coarse sand. The alluvium is poorly stratified and individual beds are generally less than a foot thick. The top 2 feet is generally more silty and is commonly modified by a soil having an enrichment of clay in the "B" horizon and a concentration of calcium carbonate in the parent material. The thickness of the alluvium is 3–15 feet. The Pleistocene Kettle Creek Alluvium appears to be mostly a remnant of reworked sand from the Pine Valley Gravel after part or most of the Pine Valley Gravel was stripped off by erosion in Wisconsin time.

Age and correlation.—The Kettle Creek Alluvium is correlated with the Louviers Alluvium (Scott, 1960) of the Denver area which is considered to be early Wisconsin in age on the basis of a diagnostic group of vertebrate and invertebrate fossils.

MONUMENT CREEK ALLUVIUM

Distribution.—Stream deposits of pebbly sand, here named Monument Creek Alluvium, occur along most of the streams flowing into Monument Creek from the east, but principally within the valleys of Monument Creek, the type locality, and Kettle Creek.

Topographic form. — Monument Creek Alluvium forms the second major terrace above the modern flood plain. The terrace surface is nearly flat to gently rolling, and slopes toward the mouth of the stream that cut it at about the same gradient as that of the present stream. The top of the terrace is 20–25 feet above the stream.

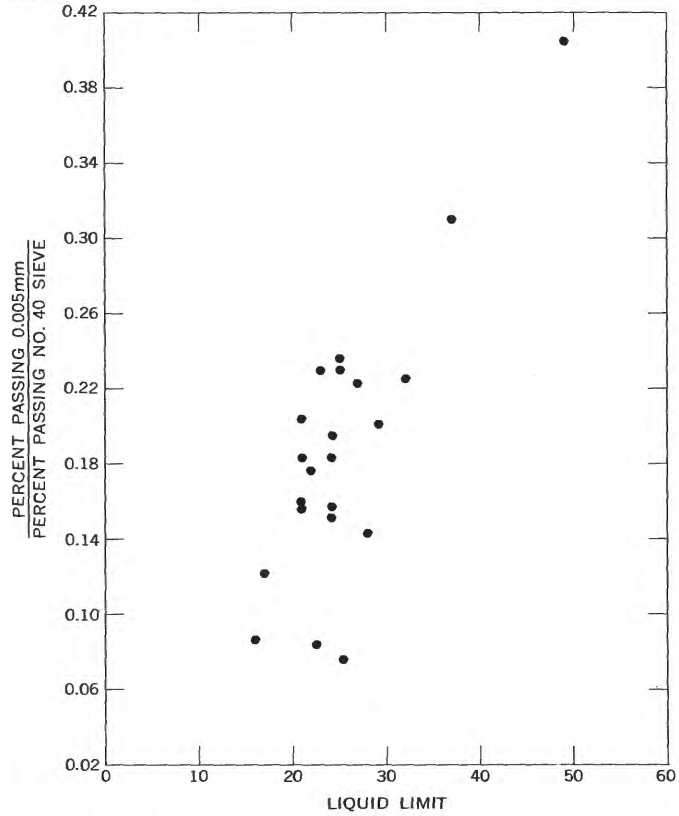

Figure 19.—Liquid limit versus ratio of percentage of material finer than 0.005 mm to percentage passing No. 40 sieve for 22 samples of Douglass Mesa Gravel.

Figure 20.—Pine Valley Gravel (Qp) overlying Dawson Arkose (TKd) in roadcut at east entrance to Pine Valley.

Figure 21.—Pine Valley Gravel (Qpe) overlying Dawson Arkose (TKd) exposed along south side of Kettle Creek about 500 feet east of old U.S. Highway 85–87 bridge.

Lithology.—The terrace is underlain by a bedrock surface. Locally, this bedrock surface is even and at a fairly uniform elevation above the stream; elsewhere it is irregular and channeled. Thus, in some places the alluvium is exposed in continuous section from creek level to the top of the terrace, but more commonly 2–15 feet of Dawson Arkose shows at the base of the terrace. The thickness of the alluvium ranges from 5 to 25 feet and averages 15–20 feet.

Monument Creek Alluvium was deposited by the stream next to which it lies. Its lithology depends therefore upon the rocks within the individual drainage basins. Along Kettle Creek, where Monument Creek Alluvium was derived from older pediment gravels and alluvial deposits to the east and from Dawson Arkose that contained considerable amounts of fine-grained material, the alluvium consists predominantly of unconsolidated interbedded fine gravel, sand, gravelly and sandy silt in layers 6 inches to 6 feet thick, and silty clay in layers 4 inches to 1 foot thick. Some of the gravel layers are iron stained orange or brownish red. The maximum dimension of the pebbles is generally about 1 inch. Along Monument Creek, where granitic material from older coarse pediment gravels and bedrock to the west are included in the drainage basin, the alluvium consists predominantly of sand and gravel and contains some cobbles and boulders of granite. The upper 3–5 feet of the Monument Creek Alluvium is commonly an unstratified gravelly silty sand containing variable amounts of humus that give it a gray-brown color.

Measured Sections

Qm–1. Monument Creek Alluvium along west bank of Kettle Creek, 1,000 ft east of old U.S. Highway 85–87, coordinates 414,800 N., 2,196,680 E.

Unit	Description	Depth (feet)
	Top of terrace.	
14	Sand; gray to dark gray from humus, gravelly and silty, not bedded; no calcareous zone; maximum diameter, 1 in.; grades into unit 13	0–1. 5
13	Sand, light-gray, silty, compact; not bedded, very compact at base; fewer pebbles than unit 14	1. 5–3. 0
12	Sand and gravel, granitic; maximum diameter, 1 in	3. 0–3. 5
11	Sand, fine, and silt, well-bedded	3. 5–4. 75
10	Sand, fine to 1-in. gravel	4. 75–6. 75
9	Clay, gray; contains black plant remains	6. 75–7. 4
8	Sand, fine- to medium-grained	7. 4–10. 4
7	Clay, gray	10. 4–11. 4
6	Sand, fine- to medium-grained	11. 4–13. 4
5	Sand, fine, gravelly, and very compact gray gravelly and sandy silt; maximum diameter, 1 in	13. 4–16. 4
4	Gravel, sandy, loose; maximum diameter, ½ in	16. 4–18. 9
3	Clay, gray, silty, plastic	18. 9–19. 25
2	Sand, gray, fine to coarse	19. 25–20. 25
1	Covered	20. 25–23. 25
	Creek bottom.	

Qm–2. In gully on north bank of Kettle Creek just east of Atchison, Topeka, and Santa Fe Railway fill, coordinates 410,300 N., 2,192,690 E.

Unit	Description	Depth (feet)
	Top of bank.	
3	Sand, brown, gravelly and silty; maximum diameter, 2 in.; fairly compact, not bedded, and no calcareous zone; basal 6 in. harder than upper part and has some concentration of fines	0–2
2	Predominantly sand; not bedded in top 4 ft; rudely bedded and contains silt layers for 8 ft; bottom 2 ft is orange-stained gravel	2–16
1	Covered	16–23
	Dawson Arkose.	

Age and correlation.—The Monument Creek Alluvium is correlated with the Broadway Alluvium (Scott, 1960) of the Denver area which is considered to be late Wisconsin in age on the basis of its stratigraphic and physiographic position and of a diagnostic group of vertebrate fossils.

HUSTED ALLUVIUM

Distribution.—Silty alluvial deposits, here named Husted Alluvium, are present in nearly all stream valleys within the Academy area. The type locality is Husted (fig. 1, pl. 1) where the alluvium is typically developed.

Topographic form.—The topographic form of the deposits is variable. Along Monument Creek and its major tributaries, Husted Alluvium generally forms the first terrace above the modern flood plain. The top of the terrace is 9–12 feet above stream level and has been overtopped by major floods. In valley headwaters and in low swales in upland areas, material similar to the stream terraces formed of Husted Alluvium also covers the valley floors, forming characteristic flat surfaces.

Lithology.—The Husted Alluvium consists in large part of material derived from a humic soil developed in the past on all the unconsolidated materials of the region. In part it consists of the soil itself, in place on these materials and mixed with detritus. The thickness of the unit ranges from 5 to about 12 feet. It is made up of poorly consolidated compact dark-yellowish-brown sandy and silty material containing variable amounts of organic matter interbedded with thin beds and lenses of sand, gravel, and cobbles. In some places the alluvium consists of light-yellowish-brown well-bedded sand and silt. In the northwest head of South Lehman Valley ("Silo Valley") the alluvium consists, for at least the upper 2½ feet, of silty and sandy peat.

Measured Sections

Qh–1. Terrace on west side of Pine Creek, coordinates 406,220 N., 2,196,420 E.

Unit	Description	Depth (feet)
	Top of terrace.	
9	Sand and gravel, dark-yellowish-brown, structureless; maximum size, 1 in. in diameter; slope vertical; Unified Soil Classification (USC) GP–GM	0–2
8	Sand and gravel, dark-yellowish-brown; maximum size, 1¾ in.; few fines; slope vertical; USC GP	2–2. 7
7	Sand and gravel, darker than unit 8, structureless; maximum size, 2 in.; some fines; slope vertical; USC GP–GM	2. 7–3. 3
6	Sand and gravel, unconsolidated, unstratified, porous	3. 3–4. 8
5	Sand and gravel, moderate-yellowish-brown, stratified, unconsolidated; maximum size, ⅝ in., bedding regular, slope 40°–45°	4. 8–8. 4
4	Soil zone, mottled dusky-yellowish-brown to moderate-yellowish-brown, sandy, gravelly, homogeneous; moist strength soft to noncoherent	8. 4–9. 7
3	Sand, dusky-yellowish-brown grading to lighter color at base, clayey; contains gravel as much as ½ in.; slope 55°	9. 7–13. 25
2	Clay, light-olive-gray mottled with brown and yellowish-brown, sandy, rusty, unstratified, unconsolidated, soft; probably weathered Dawson Arkose	13. 25–14. 5
1	Dawson Arkose	14. 5–20. 5

Qh–2. Terrace on west bank of Kettle Creek, coordinates 415,050 N., 2,196,590 E.

Unit	Description	Depth (feet)
4	Sand, very fine, and silt; unit light gray tan, well bedded, blocky; dry strength little or none	0–3. 3
3	Silt, light-gray, thin-bedded; contains minor clay; dry strength little	3. 3–5. 3
2	Silt, gray, poorly bedded; dry strength moderate	5. 3–6. 8
1	Sand and silt, tan; top 6 in., tan sand; 6 to 12 in., gray dirty gravelly silt; 12 to 36 in., gravelly sand; maximum size, 1 in	6. 8–9. 8
	Covered	9. 8–12. 0
	Stream bottom.	

Age and correlation.—The Husted Alluvium is correlated with the Piney Creek Alluvium of the Denver area (Hunt, 1954, p. 114) which is considered to be Recent in age because it contains bones of *Bison bison* Linnaeus and artifacts of man. No bones of Pleistocene animals have been found in the Husted Alluvium. A snail, cf. *Succinea avara*, was found in the alluvium along Pine Creek at the eastern boundary of the Academy area.

FLOOD-PLAIN ALLUVIUM

Distribution.—Flood-plain alluvium lies in stream bottoms in almost every valley in the area. The valleys of Monument Creek and its eastern tributaries contain the thickest and most extensive deposits.

Topographic form.—Included in flood-plain alluvium is a thin and discontinuous deposit of sandy alluvium whose top surface forms an indistinct bench 5 feet above stream level. Most of the flood-plain alluvium is at stream level and is irregular, forming thin willow-covered mounds of sand on the insides of meanders where the stream flows on sand; on the outside of meanders the stream cuts into bedrock.

Lithology.—The flood-plain alluvium, generally less than 10 feet thick, consists of unconsolidated sand, pebbly sand, and silty and clayey sand layers, which are interbedded and which lens out abruptly. The sandy and pebbly beds are light yellowish brown, and the clayey, silty, and humus-rich beds are darker brown. Generally the individual beds are less than a foot thick. The alluvium is composed predominantly of fine, medium, and coarse sand but locally contains boulders, pebbles, silt, or clay. Sandbars in Monument Creek contain many cobbles 3 inches in diameter, consisting mostly of granite and ironstone and some chert, quartzite, quartz crystals, and milky quartz. Most of the flood-plain alluvium is saturated and unstable. When one walks on the sand beside the streams, it is not uncommon to sink 6 inches to a foot into a quagmire.

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WINDBLOWN SAND

Distribution.—Deposits of windblown sand form a few low northeast-trending ridges east of Monument Creek and in South Lehman Valley and Pine Valley west of Monument Creek. The deposits are more extensive to the east of the Academy area.

Topographic form.—The windblown sand lies in low dunelike ridges and in irregular patches. Larger dunes east of the Academy area have a characteristic V or arcuate barchan shape and contain blowouts as deep as 40 feet. The dunes within the Academy area are stabilized by a foot or two of humic soil and grass cover; pine trees 20 feet high grow on some of the dunes east of the Academy.

Lithology.—The windblown sand seldom exceeds 30 feet in thickness and is generally less than 10 feet thick. It consists of stratified light-yellowish-brown sand in individual layers 1/16–8 inches thick. The beds are regular and are nearly horizontal; crossbedding is at a low angle. The sand is mostly coarse, but contains minor amounts of fine sand and silt. Quartz is the dominant mineral, and feldspar is common; biotite, dark minerals, and rock fragments are uncommon. The feldspar fragments are in part kaolinized. The quartz and feldspar grains are mostly subrounded to subangular but both well-rounded and angular grains are common. A face of the sandpit near where section Qs–1 was measured is shown in figure 22.

FIGURE 22.—North face of a sandpit one-fourth of a mile east of old U.S. Highway 85–87, coordinates 409,040 N., 2,196,720 E. The material is windblown sand.

MEASURED SECTION

Qs–1. Sandpit, one-fourth of a mile east of old U.S. Highway 85–87, coordinates 409,040 N., 2,196,720 E.

Unit	Description	Depth (feet)
7	Soil, dark-yellowish-brown, sandy, homogeneous, friable; no calcareous zone; small amount of organic matter; quartz plus 10 percent feldspar; maximum size 5 mm in diameter; more than 50 percent on No. 40 mesh, less than 3 percent minus 200; fair distribution of sizes No. 10 to No. 200; USC SW–SP	0–2
6	Sand, grayish-orange, unstratified; maximum size 4 mm in diameter; poor distribution between No. 10 and No. 200; most on No. 40 and No. 50; less than 50 percent on No. 40; less than 1 percent on No. 200; more than 50 percent of feldspar kaolinized; more than 50 percent quartz; USC SP	2–4
5	Sand, grayish-orange, fine to coarse, in layers 1/16–8 in. thick	4–8
4	Sand, grayish-orange, fine, homogeneous, damp; more than 50 percent minus No. 40	8. 4–9
3	Sand, fine and coarse, stratified	9–11
2	Sand, light-olive-gray, coarse, stratified; more than 50 percent plus No. 40; less than 1 percent minus No. 200	11–17
1	Sand, medium to fine	17–21

COLLUVIUM

Distribution.—Colluvium is detritus that moved or was deposited mainly by the action of gravity or rill wash rather than by streams. It is confined mostly to the area west of Monument Creek. Fanlike slopes of talus adjacent to the mountains, the flat gently sloping valley floor in Jack Valley, and the lower parts of the slopes around the pediment remnants are mapped as colluvium.

Topographic form.—Colluvium generally covers steeply sloping areas and forms fan-shaped deposits. Along the lower slopes of the pediment remnants, many small fans overlap and form a continuous beltlike deposit parallel to the streams.

Lithology.—Most of the colluvium is reddish brown and consists of fragments of Pikes Peak Granite and Dawson Arkose. Humic material from ancient soils is abundant in the colluvium. Colluvium is being deposited in the area continuously as gravity and water bring the sediments downslope. The colluvial deposits are very poorly bedded and sorted. Boulders 12 inches in diameter are common in colluvium along Monument Creek; boulders 12 feet in diameter are common in colluvium along the mountain front.

ENGINEERING GEOLOGY

INTRODUCTION

Topography was the dominant factor that influenced early stages of planning of the Academy construction; geology generally entered only indirectly, to the degree that the distribution of rock types and their structure had influenced the development of erosional and depositional landforms. Planning, on a broad scale, could proceed on the basis of topography rather than geology because the geologic units throughout the site were determined to be predominantly granular in texture. Parts of a few units, such as the peaty facies of the Husted Alluvium and the clayey sections of the Dawson Arkose were recognized early as sources of potential trouble in engineering works.

According to Merrill (1956), the Academy facilities needed consisted of seven principal groups:

> * * * A *Cadet Area* for the housing, training and educational facilities for 2,600 Cadets; *Housing* for 400 families of faculty and service personnel plus BOQ's [bachelor officers' quarters] and barracks for the support troops; the *Community Center* with schools, churches and the shopping and recreational facilities for this small city; the *Air Strip* and supporting facilities; the *Supply Area* with warehouses, shops, and related facilities; the *Athletic Fields* for the cadet component; and a *Maneuver Area*. Each of these facilities had its own requirements not only determining size but influencing its position relative to the others. For all of this, expansion to support a 100 percent increase in the cadet component must be provided.

The general area within which the Academy was to be placed had been determined before the architect-engineer was selected, and a size of 15,000 acres had been authorized by Congressional Committee. Part of the architect's job was to recommend the actual boundaries while considering not only the area needed for the facilities but also the proper location and separation of the several elements and their protection from undesirable marginal developments.

Adequate base maps were needed for planning, and as soon as the site was selected the Air Force contracted for preparation of maps of the site by photogrammetric methods. Two sets of maps were prepared, the first of the general area at a scale of 1 inch to 400 feet with 5-foot contour intervals, the second of the actual site at a scale of 1 inch to 100 feet with 2-foot contour intervals. While these maps were being prepared, preliminary design was started using published and advance copies of U.S. Geological Survey topographic sheets, scale 1:24,000 and contour intervals of 20 and 40 feet, enlarged to 1:12,000. The sequence of map development and the use of maps, models, and aerial photographs in the early stages of planning has been described by Merrill (1956).

One of the first steps taken by the architect-engineer was to plot on maps and models the drainage lines and land areas having slopes from 0 to 5 percent and from 5 to 10 percent. In this way the distribution of areas suitable for building was outlined. About the same time, in early November 1954, the U.S. Geological Survey party prepared a reconnaissance map showing thickness of overburden in the part of the site lying west of Monument Creek and giving brief descriptions of the geologic materials as then known. Several test pits about 10 feet deep were dug in the pediment gravels, and a test trench was dug in Dawson Arkose to determine how difficult excavation might be in the bedrock of the site.

The arrangement of the various parts of the Academy was controlled by several factors. First, the location of the airfield was dictated by the terrain. Only the southeast part of the site contains enough level ground for practical construction of an 8,800-foot runway. The orientation of the airstrip was determined by the wind-direction distribution, the need for avoiding the elevated terrain of Austin Bluffs and Palmer Park and the built-up areas of Colorado Springs in the approach zones, and by the air traffic pattern of Peterson Field, 10 miles east of Colorado Springs.

The location of the airfield influenced the location of most of the other elements of the Academy. For example, the service and supply area was located next to the airfield not only because highways and railroads were close by, and the terrain was favorable, but also to place both these semi-industrial units in the same area.

The position of the airfield affected the location of the cadet area to an even greater degree. The academic and housing units were to be placed at least 2 miles away from the activity and noise of the airfield. The cadet area also needed isolation from the main traffic pattern of the Academy, a general shape and gross area sufficient for the academic, quarters, dining, administration, and other principal buildings, and adjacent level ground suitable for parade grounds and athletic fields. According to the master plan prepared by SOM, it was also felt that the cadet area, the key segment of the Academy, should have a special topographic setting:

> * * * A conscious effort has been made to locate the [Cadet] area on an inspiring and dramatic site which will contain the component parts and permit these being related efficiently and practically to one another.

Several locations for the cadet area were studied. The many interrelated requirements were best fulfilled by the area chosen, which includes Lehman Mesa and Lehman Valley in the northwest part of the site. As shown on plate 1, the main buildings are grouped on Lehman Mesa, and the athletic fields are to the north in the broad flat head of Lehman valley.

The location of other principal facilities of the Academy followed from the choice of sites for the cadet area and the airfield. The rest of the site, consisting of eastward-trending valleys separated by ridges and mesas, lent itself well to the planning of semi-isolated activities. The larger housing developments, each with an elementary school, were put into Douglass Valley and Pine Valley, and the high school was located in Pine Valley. The community center—shopping and recreational facilities and churches, designed to serve both residential areas—was placed on broad Pine Mesa between the two residential areas. Jack Valley is relatively isolated and was set aside for the maneuver area and firing ranges. The valley south of the campus (South Lehman Valley) is expected to be developed for recreational purposes; on the next ridge to the south, Douglass Mesa, are the bachelor officers' and visiting officers' quarters. The location selected for a stadium was in the east-central part of the Academy site where it would be well removed from the cadet and housing areas, but adjacent to the main highway within the Academy and about midway between the north and south entrances.

A road net described by Merrill (1956), to serve all the planned facilities, and designed for 30-mile per hour speeds, provides:

> a. Access to the main highway north and south with interchanges at these entrances.
>
> b. A 4-lane route along the easterly side of the site from which the transverse access roads extend to the west. This is designed to handle the stadium traffic.
>
> c. Close relationship between the south entrance and the rail freight facilities in the Supply and Airfield area; between the north entrance and the rail passenger station and bus terminal; and with direct connection between these areas—all without traversing any of the intermediate areas.
>
> d. A perimeter road—mountain type in the western areas—which will permit the casual visitors, with only limited time, to circle the site seeing all of it but without needing to intrude on the privacy of the cadet or housing areas unless they have personal business there.
>
> e. The east-west access roads up to the valleys serving each of these important units at relatively easy grades and providing 4-laned access to the cadet parade grounds, athletic areas, and fieldhouse all of which may be expected to draw traffic peaks for ceremonies and sports.

According to the master plan prepared by SOM, the determination of final site boundaries was made after the locations of the facilities within the site had been determined. The location and orientation of the airfield determined the eastern boundary of the site.

> * * * Minimum clearances from the runway were maintained in relocating the route of Colorado–U.S. Routes 85–87 to a position 1,000 or more feet east of the proposed runway. Because the frontage of the highway requires control, the site boundary is so located as to accommodate and contain the highway and provide a buffer strip along the east side of it. The boundary at the southeast corner of the property encompasses the existing industrial property there and establishes the existing Atchison, Topeka & Santa Fe Railway right-of-way as the severance point and buffer. The southern boundary

follows the top of a ridge between Pine Valley and Woodmen Valley, thus including Pine Valley within the site and preventing visual encroachment upon the Academy from this quarter.

The southwest corner of the property is defined by existing private holdings largely accessible from Woodmen Valley and not necessary to physical development of the Academy. The western boundary abuts the east line of Pike National Forest which is generally established to the lower reaches of the Rampart Range formation. The northern boundary, as does the southern property line, follows a high ridge limiting visual encroachment on the Academy proper from that quarter and continues to the existing location of Colorado–U.S. Routes 85–87.

The boundaries of the site are marked by monuments established by the architect-engineer. This boundary survey is a part of a general system of horizontal and vertical control that was established both for the purpose of checking the accuracy of the photogrammetric maps and for providing a net of points of known location and elevation within the site for use in detailed planning and for use by construction contractors.

The role of the Geological Survey in the Academy site investigations may be summarized briefly. During the principal period of geologic mapping in November 1954, there was a nearly continuous exchange of information with the AFACA and the architect-engineer, by means of conferences and preliminary reports, beginning with a brief resume of the geology and topography that aided the drawing of specifications for a thorough program of exploratory boring. This resume was followed by preparation of a map showing, in the area lying west of Monument Creek, those parts having (1) more than 12 feet of overburden, (2) less than 12 feet of overburden, and (3) an unknown thickness of overburden. This map was useful in the preliminary siting of major installations that would require extensive regrading. At this point it became critical to establish the lithologic character of the pediment gravel that caps the mesas and to determine whether the Dawson Arkose would present serious excavation problems. Sites were selected for test pits in the Douglass Mesa Gravel and for a trenching test in Dawson Arkose. The pits were examined, sections were measured, laboratory analyses were made on the gravel, a log was kept of time, advancement, and behavior of a trenching machine cutting Dawson Arkose, and the results were reported to the AFACA and the architect-engineer. Even firm arkose was found to be easily trenched with conventional equipment, and therefore the possibility of difficult excavation of bedrock within the site was removed as a major consideration in planning.

A geologic map at scale 1:12,000 of the proposed site and a descriptive text, including summary statements on water resources, local aggregate supplies, and availability of building stone, were completed December 3, 1954, and incorporated into the first plan submitted to the U.S. Air Force by Skidmore, Owings, and Merrill. During approximately the next year, many conferences were held with members of the staffs of AFACA and SOM, particularly with Mr. Novak of SOM, and reports or maps were prepared on seismic conditions, overburden thickness, top of bedrock contours, and the location of water wells. As wells were completed, the Survey hydrologists performed pumping tests and evaluated the potential yield of both the Dawson Arkose and the deeper lying Fox Hills Sandstone. Consulting engineers were retained by AFACA and SOM for several phases of planning and design, such as water supply, airfield design, and foundation conditions in the academic area, and the results of the Geological Survey's investigations were reviewed and used where applicable.

The Geological Survey's contract was terminated in November of 1956.

AIRFIELD AREA

LOCAL GEOLOGY AND TOPOGRAPHY

The airfield area is in the southeastern part of the Academy on a broad alluvial slope that is inclined gently to the southwest and crossed by a few shallow gullies and the valley of Kettle Creek. The slope is covered with 10–25 feet of sandy gravel of the Pine Valley Gravel, east, that rests upon Dawson Arkose.

Deposits of younger alluvium occur along Kettle Creek in the airfield area. These, in order of increasing age and increasing elevation above Kettle Creek, are: flood-plain alluvium in the bed of Kettle Creek, a low terrace of Husted Alluvium, a terrace of Monument Creek Alluvium about 30 feet above the creek bed, and a terrace of Kettle Creek Alluvium about 75 feet above the creek bed and 10 feet below the upper surface of the Pine Valley Gravel, east (fig. 13; pl. 1).

Dawson Arkose is exposed along the flanks of Kettle Creek valley. The exposure is more extensive along the southeast bank than along the northwest.

PROPOSED CONSTRUCTION

The plans for the airfield include a 200- by 8,800-foot runway, a parallel taxiway, and the necessary hangars, aprons, fueling, and maintenance areas (pl. 2). The plans also provide for a possible northward extension of the runway and taxiway to 14,000 feet. Some future changes may be made that are not here mentioned. In order for the runway to be 8,800 feet long it must cross the present valley of Kettle Creek. At the chosen site, the valley is somewhat wider than elsewhere and includes, on the northwest side, a broad terrace of Monument Creek Alluvium that is intermediate in elevation between the general level of the high Pine Valley Gravel, east, surface and the level of Kettle Creek.

A fill of considerable height and length will be necessary to carry the runway and taxiway over Kettle Creek (pl. 2, section *A–A′*). The slope of finished grades will be influenced by the landing requirements, the general slope of the land, and by the need for adequate surface drainage. The proposed grade of the runway is about 0.5 percent to the south, except near the north end, where it slopes 0.5 percent to the north. The elevation of finished grade will be largely determined by the cost of cutting and filling and by the need to balance the volumes of cut and fill, including the fill used in construction of Kettle Creek Dam.

The design thus indicates that the runway and taxiway will rest partly on in-place pediment gravel and partly on fill to be constructed from pediment gravel. Cuts for part of the runway adjacent to the east drainage ditch have encountered Dawson Arkose. The main fill will rest on Pine Valley Gravel, east, Monument Creek Alluvium, Husted Alluvium, and flood-plain alluvium. According to the original design, the total excavation in the airfield area will be about 8,800,000 cubic yards, of which 940,000 cubic yards is estimated to be Dawson Arkose. Some of the Dawson Arkose already excavated was used in Kettle Creek Dam and the rest was placed in non-load-bearing fill. The remaining volume of usable fill available is about 6,000,000 cubic yards, which is about the amount required.

FIELD AND LABORATORY INVESTIGATIONS

BORINGS, SOUNDINGS, AND TEST PITS

The architect-engineer engaged the services of the firm Moran, Proctor, Mueser, and Rutledge to aid in the design and interpretation of the airfield test program. Parts of the text to follow are extracted from the firm's report of July 27, 1955, and from reports by the staff of the architect-engineer.

Initial exploration for the airfield, consisting of soundings and borings made with a dry auger, formed but a part of a larger preliminary exploration program for the whole airfield area, which includes the adjoining sites for Kettle Creek Dam and retention basin, the diversion channel to Pine Creek and Pine Creek channel improvement, and the relocation of U.S. Highway 85–87. Nearly all the borings, soundings, and test pits made for this program are within the area shown by plate 2.

Holes were drilled first by the Oklahoma Testing Laboratories (OTL) at about 500-foot intervals along the centerlines of the runway and taxiway to determine the thickness and nature of the pediment gravel and the lithology of the underlying Dawson Arkose bedrock. In the borings, but not the soundings, a record was kept of the blows necessary to drive a standard split-spoon sampler a certain distance. Samples were taken a regular intervals and wherever visible changes in material occurred. Atterberg limits, natural water contents, and gradation of the various materials were determined by the SOM soils laboratory, and the materials were classified in accordance with the Unified Soil Classification System.

Some difficulty was experienced in interpreting the results of the first borings, owing to the type of equipment employed. The head of the auger consisted of a cylindrical shoe which was rotated and driven downward, then withdrawn and emptied. The sample taken contained as much as 30 percent minus No. 200 sieve material and indicated that the material on and of which the airfield was to be constructed might be highly susceptible to frost. However, the U.S. Geological Survey data indicated that the pediment gravel in the airfield area contained only a few percent minus No. 200 sieve material, mostly in the upper few feet. The Geological Survey's conclusion was corroborated by the Colorado Department of Highways from their experience in the construction of U.S. Highway 85–87 through the area. Because of this contradiction it appeared probable that the auger had ground the gravel enough that the samples yielded confusing results, not only as to the content of fine material in the gravel and in the arkose but also regarding the elevation of the gravel-arkose contact. This possibility was very reasonable because the feldspar grains in the arkose and in the gravel derived from it are partly altered to clay minerals, particularly along the natural planes of cleavage, and can be comminuted by severe abrasion.

Several test pits were dug at or near soundings and borings to obtain material for comparative gradation analyses—for example, OTL test pit 3 and boring 54 near the north end of the runway. The comparisons shown in table 4 indicate the material in test pits contains much less fine material than the auger samples. These analyses and others not here reported demonstrated that reliable gradations could not be obtained from the samples collected with the type of auger head then in use. The seven test pits that were opened permitted the collection of many samples at known depths that were free from previous disturbance. In-place density determinations and California Bearing Ratio and plate-bearing tests were made at various depths in the pediment gravel, in the Monument Creek Alluvium, and where deep cuts were proposed in the Dawson Arkose.

TABLE 4.—*Comparison of gradation analyses of samples taken from borings by auger and from test pits in the airfield area dug at or near the same locations*

[B, borings; TP, test pit; --, not determined]

Runway station	Boring or test pit	Depth of sample (feet)	Percent passing U.S. Standard sieves						
			½-in.	No. 4	No. 10	No. 40	No. 200	0.02 mm	0.005 mm
173+25	B-54	4.0-5.0	100.0	95.8	68.8	25.0	8.0	--	--
173+25	B-54	9.0-10.0	100.0	92.5	79.2	21.2	18.5	5.0	3.5
173+60	TP-3	[1] 4.0, 8.0	--	89	62	9	2	2	1
143+37	B-62	[2] 5, 10, 15, 20	100.0	95.9	75.7	31.4	11.2	7.5	5.3
143+40	TP-1	[1] 5, 10, 15, 20	--	89	68	11	4	4	3

[1] Composite sample.
[2] Average of analyses of four samples at 4.0- to 5.0-, 9.0- to 10.0-, 14.0- to 15.0-, and 19.0 to 20.0-ft depths.

Section *A–A′* of plate 2 shows a profile of the centerline of the proposed runway together with an interpretation of the configuration of the top of Dawson Arkose beneath the pediment gravel. The method used was to construct a map showing the top of bedrock contours to give approximate, but topographically reasonable, forms to the erosion surface on the top of bedrock for much of the airfield area. From these contours, the position of the top of Dawson in the section along the centerline of the runway was inferred.

TEST-FILL PROGRAM

The principal problem presented by the airfield was the construction of large fills to support the runway and taxiway where they cross the valley of Kettle Creek. Because pediment gravel was to be used for the load-bearing parts of these fills, a test program was designed to permit evalution of this material as fill and evaluation of the methods of emplacing and compacting it. The airfield test-fill program eventually grew into a very extensive and thorough investigation. The results of the tests are recorded here in some detail because they represent a unique and successful research effort on the problems of compacting nonplastic granular fill, which is so common in semiarid and arid regions. The procedures followed and some of the difficulties that were met in testing this granular material are of special interest to engineering geologists.

Test fill 1 consisted of three units, each formed of four layers, or "lifts," each 9 inches thick after compaction, placed on a subgrade of the same material stripped to the B horizon. Each lift was compacted by 1⅓ coverages of a 50-ton rubber-tired roller with wheel loads of 25,000 pounds and tire inflation pressures of 100 pounds per square inch. A coverage means that every part of the fill has been subjected to one passage of a tire of the roller. Plate-bearing tests and California Bearing Ratio (CBR) tests were made on the subgrade and compacted fill. In-place densities were measured by the balloon device.

The densities measured in test fill 1 could not be related to the compactive work done on the material. Some tests showed the compacted material to have an apparent density less than the uncompacted material. Experiments revealed that the sides of the density determination holes, which had been excavated in loosely coherent material, had sloughed a little under pressure of the balloon so that the balloon did not expand fully to fill the hole. This defect led to apparent densities that were about 15 percent too high. The holes in firmer material did not slough as much; hence, the tests on compacted gravel gave more accurate but lower values for density.

Test fill 2 was constructed to investigate the effect of a greater number of coverages. Densities were determined by both the balloon and sand-cone devices. Only the results of the sand-cone method were accepted. The fill was constructed, as before, of three units. Each unit consisted of four lifts, and each lift was 9 inches thick after compaction. The bottom lift, placed on the uncompacted B horizon of the pediment gravel, was compacted by two coverages, whereas each of the three additional lifts was compacted by six coverages of the roller, loaded the same as for the first test fill. One set of CBR tests and two plate-bearing tests were performed on each of the three units at a depth of 12 inches from the surface in the second lift from the top. The tests indicate that rolling the gravel increased the density from 98–110 pounds per cubic foot in the natural state to 113–115 pounds per cubic foot. There were also significant increases in the CBR values and coefficient of subgrade reaction.

Test fill 3 was constructed so that the effects of lift thickness, water content, number of coverages, compaction by bulldozer during spreading, and loosening and mixing by use of a scarifier between lifts could be evaluated. The test fill consisted of nine units. Units 1–5 were formed of four or five lifts, each lift 9 inches thick after compaction, placed on a stripped subgrade of the same material compacted by four coverages of the 50-ton roller with tires inflated to a pressure of 80 pounds per square inch. Each lift of units 1, 2, 3, and 5 was compacted by six, eight, four, and two coverages, respectively. Unit 1 was exposed to heavy rain during construction, so unit 4 was added to replace unit 1. After the remaining fills had been partly placed, they were protected by heavy paper when they were not being worked on. The top two lifts of units 2–5 were spread by a bulldozer and then scarified before compaction. All other lifts in units 1–5 were spread and rolled without scarification. In-place densities, water contents, and CBR values were determined on each lift of each unit and on the subgrade after completion of the fills. The modulus of subgrade reaction K was determined by plate-bearing tests on the upper lifts of each unit.

In order to determine the effect of lift thickness on compaction, units 6–9 of test fill 3 were each constructed of three loose lifts totaling 42 inches in thickness. The surfaces of these units were compacted by two, four, six, and eight coverages of the 50-ton rubber-tired roller, respectively. In-place densities and water contents were determined by tests in each lift of each unit.

The maximum densities that could be obtained in the laboratory, according to standard procedures, were less than those measured in the compacted fill. Attempts to determine the maximum density obtainable in the laboratory—using a variety of methods of compaction, vibration, various sized containers, and water contents up to complete saturation—yielded results that could not be reproduced consistently. Thus, it appeared that the establishment of specifications for the airfield fill in the usual way—that is, by requiring the fill to be placed at a certain percent of maximum density as defined by a commonly accepted control test—might have to be supplemented by "method specifications" in which the treatment or number of rollings and roller weight necessary to yield the desired bearing capacity, as well as the final density, would be defined.

The range and average of in-place water contents, densities, K, and CBR values for each lift of each unit of test fill 3 and data for test fills 1 and 2 are tabulated on plates 3 and 4. A typical sampling pattern, as used in test fill 3, unit 4, and the details of the test results on this unit also are given in pl. 4. The other units were sampled and tested in the same way.

TEST-FILL DATA

DENSITY

Effect of water content.—The effect of water content upon the maximum density obtainable in the laboratory (Modified AASHO) was determined by tests on pediment gravel derived from test pits. In these tests the optimum moisture content ranged from 2.8 to 7.6 percent and the maximum density from 115.5 to 130.6 pounds per cubic foot. The effect of water content on the densities measured in the test fills is, however, difficult to determine not only because the water content of borrow material for the fills was deliberately kept between approximately 5 and 8 percent but also because parts of some of the fills were subjected to rain or to severe drying conditions during construction. Moisture determinations on some samples may not truly represent the molding water content at the time of rolling. For example, figure 23 shows a plot of density versus water content for unit 5 (two coverages). There appears to be only an ill-defined increase of density with water content among the lifts that were not scarified prior to rolling. Moreover, the average water content of the samples taken for density and water content after placement is somewhat higher than the average water content measured on a few samples taken as the fill was placed. The in-place densities in lifts that were scarified prior to rolling show generally lower values, as may be expected. Apparently there was some loss of water between the time the lifts were placed and the time of sampling for density and water content. Much of this loss may have occurred during scarification. Figure 24 is a similar plot for unit 4 (six coverages per lift). In this test, the number of coverages was sufficient to remove the effect of scarification. No apparent relation exists between water content and density within the rather small range of water content of the samples.

Effect of number of coverages.—The effect of the number of roller coverages upon density of unscarified lifts is masked to a considerable extent by the compacting action of the equipment used to spread and level the individual lifts prior to rolling. This effect was eliminated in the upper lifts of units 2–5 by scarifying the lifts just before rolling. Figure 25 shows that the density of unscarified lifts does not consistently increase with the number of roller coverages. The densities of lifts that were scarified prior to rolling do show a consistent increase in density through six coverages. The pronounced tendency for topmost lifts to be of abnormally low density is probably the result of local shearing under the roller tires. There seems to be no increase in density in scarified lifts upon rolling with more than six coverages; in fact, the average density apparently decreases slightly. The densities obtained with eight coverages show a smaller range, however, than those obtained with less coverage.

Effect of lift thickness.—The effect of lift thickness upon density is shown to some degree by the test results on units 6, 7, 8, and 9 of test fill 3. In these units a 42-inch-thick loose fill was compacted by two, four, six, and eight coverages, respectively, of the rubber-tired roller on the upper surface. These units were actually placed in three lifts but without rolling; therefore the fills can be regarded as being composed

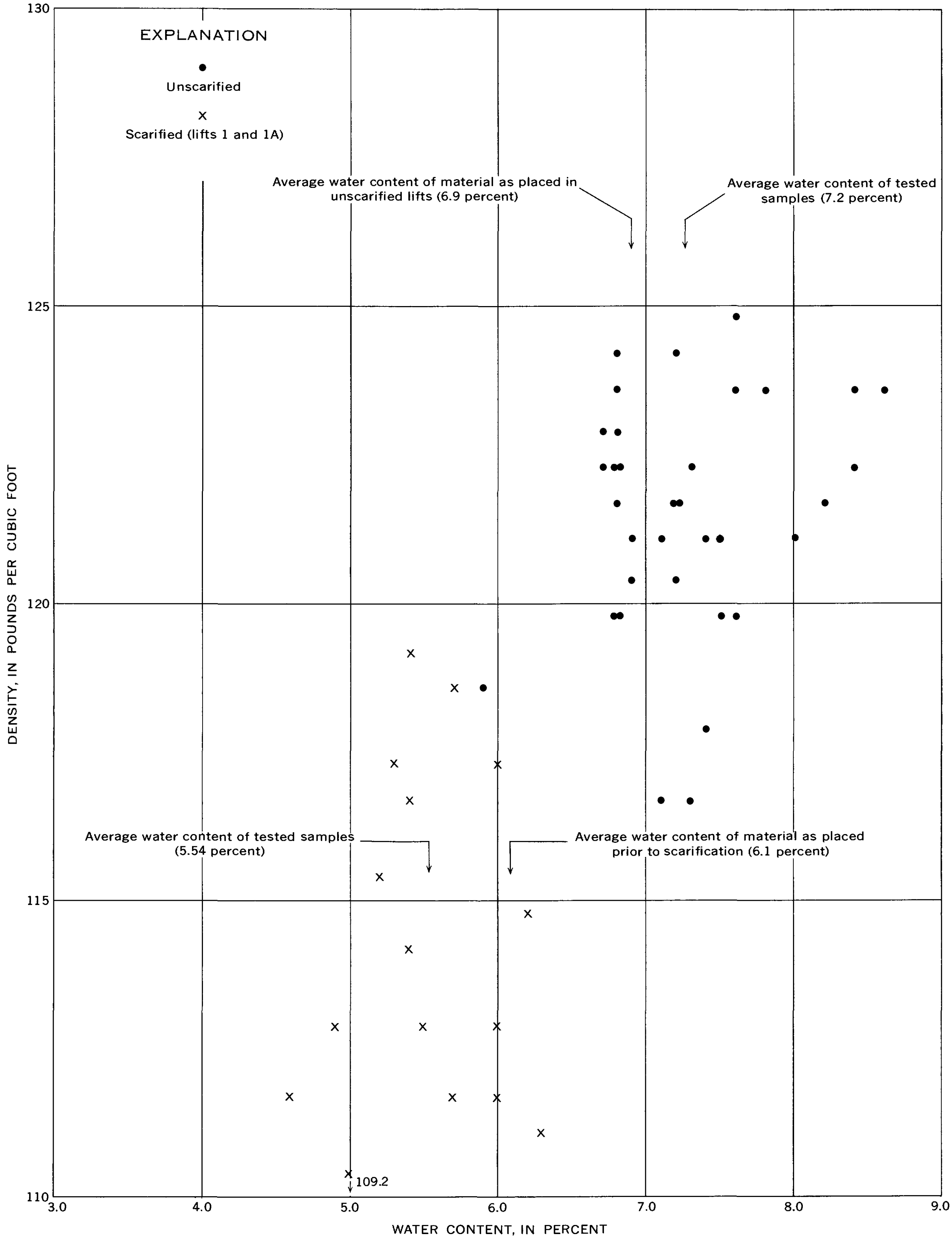

FIGURE 23.—Plot of density versus water content, test fill 3, unit 5 (two coverages).

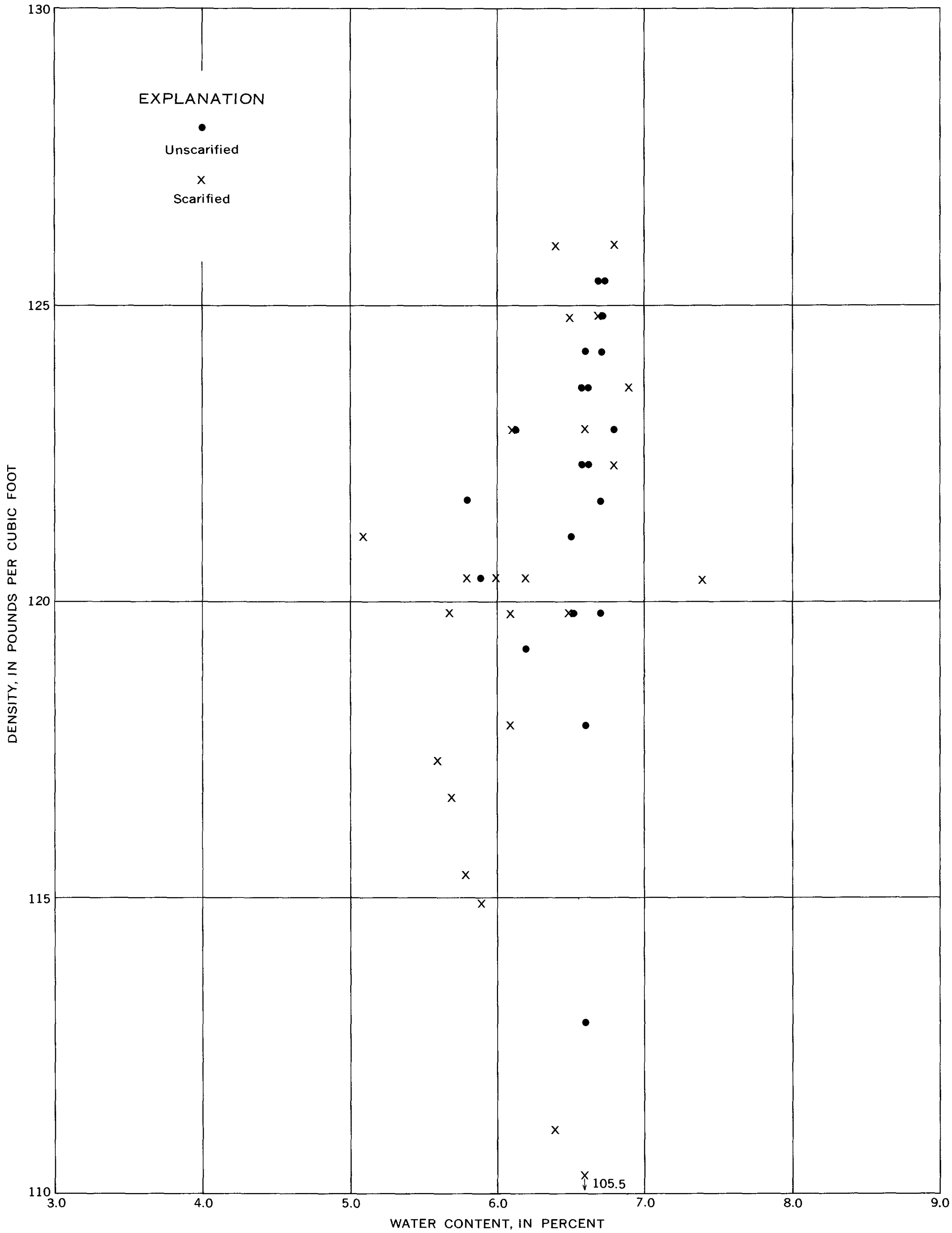

FIGURE 24.—Plot of density versus water content, test fill 3, unit 4 (six coverages).

of a single loose lift having an initial density ranging from 94.8 to 114.2 and averaging 107.7 pounds per cubic foot. The range and average values of in-place water content and density after rolling, for various depths for each unit, are shown in plates 3 and 4. Average densities in excess of 97.5 percent of Modified AASHO maximum were obtained to depths of 18 inches and in excess of 95 percent at 27 inches in units

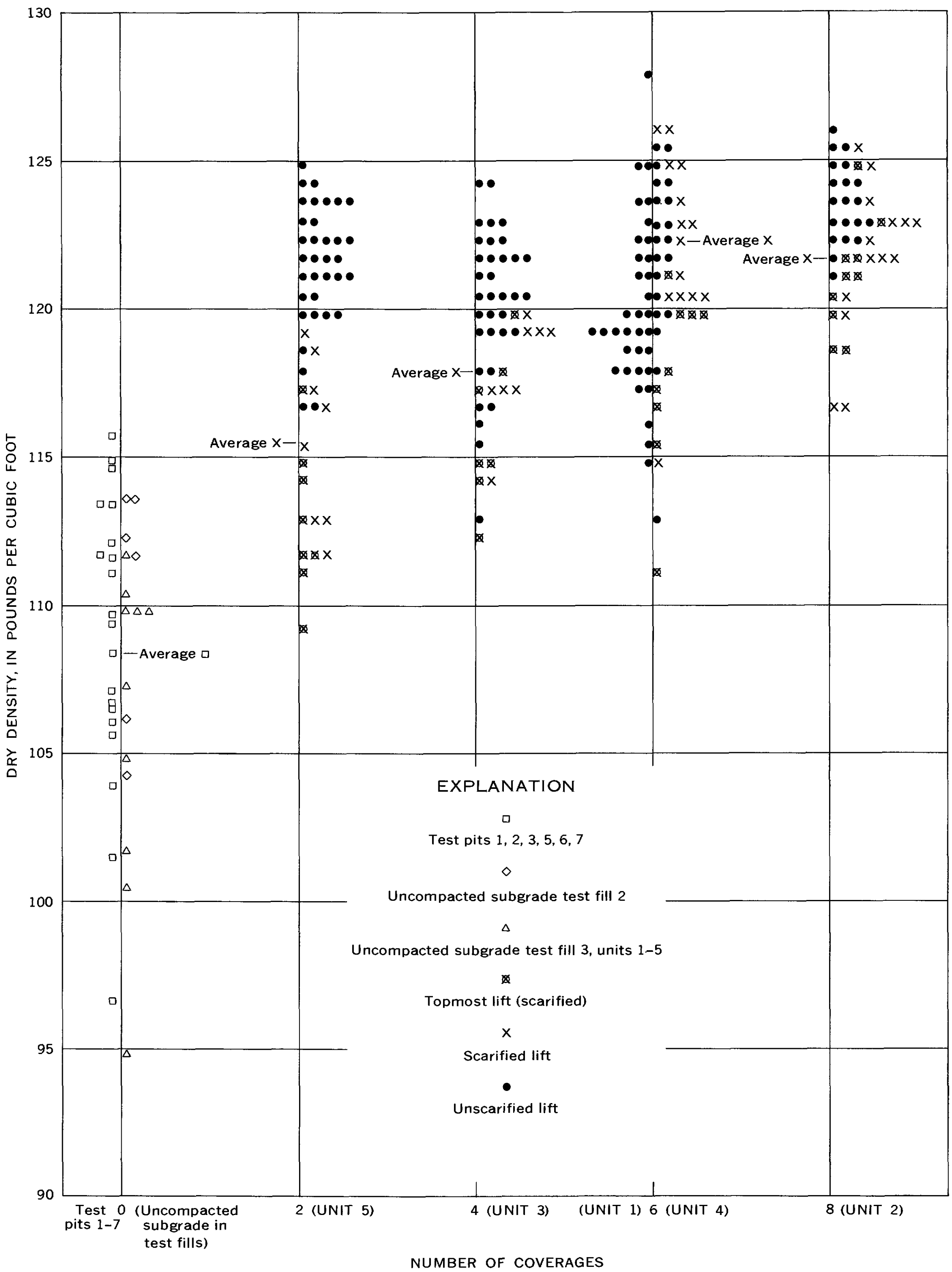

FIGURE 25.—Plot of density versus number of coverages in test pits and test fills.

with four or more coverages. Increases in density of as much as 3 pounds per cubic foot were recorded at depths from 27 to 36 inches.

Effect of gradation

The pediment gravel at the airfield site is a secondary deposit derived from the Dawson Arkose that crops out in the uplands farther east. It is, in effect, reworked Dawson from which most of the clay and silt has been removed. At the test-fill site almost no material is larger than three-quarters of an inch, and generally no more than 4–8 percent smaller than No. 200 sieve. As a whole, the deposit is too well sorted to yield very high densities under compaction. The samples from units 1–5 of test fill 3 fall within a rather narrow range of gradation curves, as shown in figure 26.

We analyzed in some detail the data obtained by Moran, Proctor, Meuser, and Rutledge and by SOM to determine possible correlations between the grain-size distribution of the pediment gravel and the densities obtained in test fill 3. It was thought that the variations in density among samples that were subjected to similar compactive efforts might have resulted, in part at least, from small variations in the distribution of grain sizes.

Seven standard measures of grain-size distribution were compared with the densities obtained in unit 4. This unit was compacted with six coverages and was selected for statistical analysis because the unit contained more samples than the other units, except unit 3, and was compacted by more coverages than unit 3. The standard measures that were compared with density are shown in table 5.

In these formulas D_{75}, for example, stands for the sieve opening in millimeters, at which 75 percent by weight of the grains pass through. The rank-correlation coefficient, r_s, expresses the degree of correlation between the rank of a sample in the series of densities from greatest to least and its rank in the series of values of the particular statistical measure being tested (positive values ranked above negative). If density varies continuously with the statistical measure employed, a value of $r_s = +1$ indicates perfect agreement, a value of -1 indicates exactly opposite ranking, and a value of 0 indicates no rank correlation. Ranks of densities and statistical measures were compared for all 14 samples from unit 4. If the variables are unrelated, the chance that the value of r_s will equal or exceed 0.456 in 14 samples is 1 in 20 (5-percent significance level), and that it will exceed 0.645 is 1 in 100 (1-percent significance level). The rank-correlation

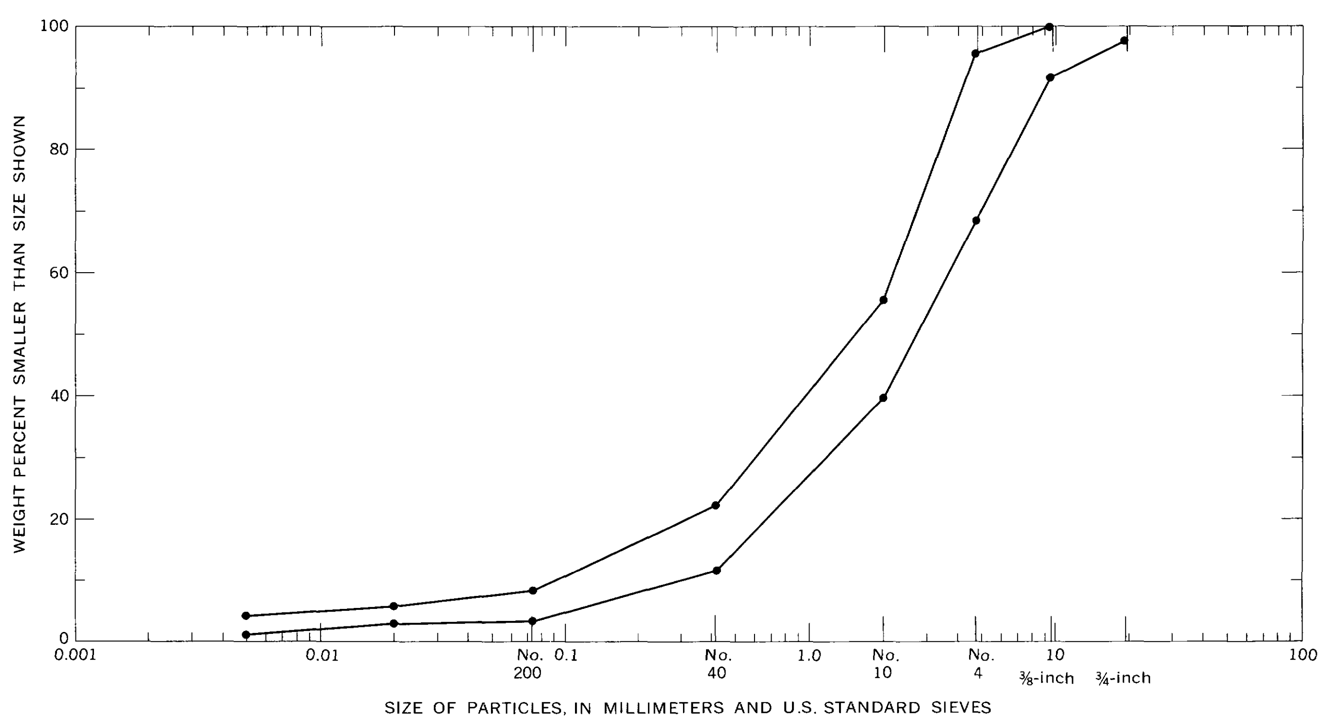

FIGURE 26.—Range of size-distribution analyses of material used in units 1–5 of test fill 3. The lines connect extremes of all percentages of material passing the ¾-inch, ⅜-inch, No. 4, No. 10, No. 40, and No. 200 U.S. Standard sieves, and smaller than 0.02 and 0.005 mm.

TABLE 5.—*Rank-correlation coefficients for relation between density and standard measures of grain-size distribution, test fill 3, unit 4*

Measure	Symbol and definition	Rank-correlation coefficient with regard to density, r_s
Coefficient of uniformity	$C_u=\frac{D_{60}}{D_{30}}$	0.161
Geometric quartile deviation	$QD_g=\sqrt{\frac{D_{75}}{D_{25}}}$	.261
Coefficient of curvature	$C_c=\frac{(D_{30})^2}{D_{10}D_{60}}$	.015
Skewness	$Sk=(D_{50})^{-1/2}(D_{90}+D_{10})$	.035
Arithmetic quartile skewness	$Sk_a=\frac{D_{75}+D_{25}}{2}-D_{50}$	−.013
Geometric quartile skewness	$Sk_g=\sqrt{\frac{D_{75}D_{25}}{(D_{50})^2}}$	.079
Quartile kurtosis	$K_{qa}=\frac{D_{75}-D_{25}}{2(D_{90}-D_{10})}$	.219

coefficients as reported were not corrected for the effect of ties in the ranking of density; this correction is minor and decreases r_s about 0.05 when the uncorrected value is 0.66.

Although the rank-correlation coefficient is a very convenient and easily obtained numerical measure of dependence or independence, it fails to indicate correlation unless one variable continuously increases or decreases as the other continuously increases. It would fail, for example, to show that there might exist an optimum value of C_c that leads to high density. For this reason, scatter diagrams were also drawn in order to help disclose more complex relationships.

The first two measures, C_u and QD_g, each express the spread of grain sizes. The coefficient of uniformity, C_u, is commonly used in soils engineering. The Unified Soil Classification specifies that for a sandy material to be classed as well graded, the value of C_u should exceed 6. The low value of r_s, 0.161, and the randomness of the scatter diagram indicate that, within the narow range of gradations represented by the samples, the value of C_u has no apparent correlation with density. The geometric quartile deviation, QD_g, which is a measure used by sedimentary petrologists, indicates a somewhat higher but still not significant rank correlation, and the scatter diagram did not indicate any obvious trend.

The coefficient of curvature, C_c, is a measure used in soils engineering to indicate the shape of the cumulative size-distribution curve. The Unified Soil Classification System specifies that C_c should be between 1 and 3 for well-graded sands and gravels. The correlation coefficient of 0.015 and the scatter diagram do not indicate correlation between density and C_c among the samples analyzed from unit 4.

The various measures for skewness express, in somewhat different ways, the degree of asymmetry of the size-frequency distribution curves. Of these, only the geometric quartile skewness, because it is formed of ratios, is independent of the units in which particle size measurements are expressed. Skewness was investigated because the work of Tickell, Mechem, and McCurdy (1933) had indicated some correlation between Sk, the first measure of skewness, and the porosity of packed sand. The samples from unit 4 do not apear to show such correlation. The scatter diagrams of density versus arithmetic quartile skewness, Sk_a, and of density versus geometric quartile skewness, Sk_g, exhibited no obvious trend and the rank-correlation coefficients are, respectively, −0.013 and 0.079.

Kurtosis is a measure of bunching of material about the mode, that is, the peakedness of a size-frequency distribution curve. The measure quartile kurtosis, K_{qa}, decreases with increasing peakedness. Apparently no relation exists between kurtosis and density.

The lack of correlation between standard measures of the shape of cumulative size-distribution curves in unit 4 led to the invention and testing of 14 other measures based upon percentages passing at certain sieve sizes rather than the diameters at certain percentages passed. A few measures, for example the percentage retained on the No. 10 U.S. Standard sieve, showed rank-correlation coefficients as high as 0.66, for which the probability that the correlation is due to chance alone is less than 1 in 100. However, where the apparently significant measures for unit 4 were applied to other units in the fill, they all failed to show significant correlation.

In summary, although a few apparently very significant correlations between measures of grain-size distribution and density can be derived for unit 4, these correlations cannot be relied upon for predicting expected densities among a group of closely similar samples such as were taken from the other units. Many investigations have shown that there is a general relation between gradation and maximum density obtained under compaction; but the small variations in gradation among the suite of samples from the units of test fill 3 apparently resulted in such small differences in density that their effect was far outweighed by other factors, such as departures from uniformity in rolling, possible variations in angularity of material, and errors in sampling and testing.

California Bearing Ratio

The California Bearing Ratio (CBR) is the ratio of the pressure required to penetrate a soil mass with a 3-square-inch circular piston at the rate of 0.05 inches per minute to the pressure required for corresponding penetration of a standard material. The pressure is read at 0.1 inch or 0.2 inch penetration, or at both depths, as shown in figure 25. The standard material is a crushed stone for which tables of standard pressures have been prepared. The ratio, expressed as a percentage, is widely used for the evaluation of strengths of subgrade and may be determined on material either in place or on material which has been remolded and compacted in the laboratory.

Effect of water content.—Figure 27 shows the plot of CBR values versus water content for all CBR tests made on units 1–5 of test fill 3, except five tests, all on the first lift, that gave CBR values below 10. The rather ill-defined trend indicates that higher CBR values are associated with higher water content. Scarified lifts have generally lower CBR values than those that were unscarified.

Effect of number of coverages.—The effect of the number of coverages upon the CBR is shown in figure 28. Tests performed upon the topmost lift gave consistently lower values than those made on deeper lifts. If tests on the topmost lift are neglected, the remaining data indicate a progressive increase of CBR values as the number of coverages increases. In general, the CBR values for lifts that were scarified prior to rolling are lower than those of lifts that were precompacted somewhat by the equipment used to spread the material. The CBR values for test fill 2 (six coverages) are not plotted in figure 28; their average is 27.7, close to the average of units 1 and 4 of test fill 3.

Effect of depth.—CBR values generally increase as the depth at which the tests were performed increases. Much of this increase is due to scarification of the upper two lifts prior to rolling. Some increase was noted, however, in lift 4 (the lowest) over lift 3, neither of which was scarified. The CBR values for the lower two lifts approach or exceed those for the underlying subgrade that was compacted by four coverages.

Correlation with density.—California Bearing Ratios cannot be compared directly with densities because the sampling points do not coincide. The average densities of a lift are plotted against the average CBR for the same lift in figure 29. Average CBR increases with average density, and the highest CBR values are generally in the lower unscarified lifts (3 and 4).

Modulus of Subgrade Reaction

The modulus of subgrade reaction, K, is determnied by a plate bearing test and is the ratio p/s, where p is the pressure and s is the corresponding settlement, expressed in pounds per square inch per inch, that is, in pounds per cubic inch.

Effect of water content.—Figure 30 shows a plot of K versus water content. There is only an ill-defined inverse relationship.

Effect of number of coverages.—The plot of K versus the number of coverages is shown in figure 31. Although the data are few and their plot is considerably dispersed, the average value of K does appear to increase with the number of coverages. Most of the tests were performed on scarified lifts; the effect of scarification is evident in the values of K for two, four, and six coverages.

Correlation with density.—Values for density and K cannot be compared directly because the tests were performed at different localities. Average densities for individual lifts are compared with average values of K for the same lifts in figure 32. The rank-correlation coefficient for these data is 0.743, which shows a very significant direct correlation at about the 1-percent level.

Correlation with California Bearing Ratio.—Figure 33 shows the plot of average modulus of subgrade reaction for a lift versus the average CBR value for the same lift. The point representing test fill 1 is an average for the entire fill. As might be expected, the correlation is very evident. The rank-correlation coefficient for all the points is 0.786 and that for data pertaining only to test fill 3 is 0.900. These coefficients indicate that the possibility of such correlation occurring by chance alone is considerably less than 1 in 100.

RECOMMENDATIONS CONCERNING DESIGN

Design recommendations were prepared in 1955 by Moran, Proctor, Meuser, and Rutledge and by the architect-engineer, on the basis of results of the airfield test program. The airfield pavement designs were for a 100,000-pound gear load on dual tires; designs were made for both rigid- and flexible-type pavements in critical areas, such as taxiways, and in noncritical areas, such as the central parts of runways, and for three types of geologic environment: fill sections, cuts in pediment gravel, and cuts in Dawson Arkose. These designs are summarized in plate 5.

Some of the properties of the geologic materials or the average test results that influenced these designs are summarized below.

TOPSOIL

The pediment gravels, terraces along Kettle Creek, and deposits of dune sand all have a thin soil cover consisting of about 6 inches of brown silty sand containing organic material, underlain by a foot or so of a lightly cemented harder B horizon that is somewhat

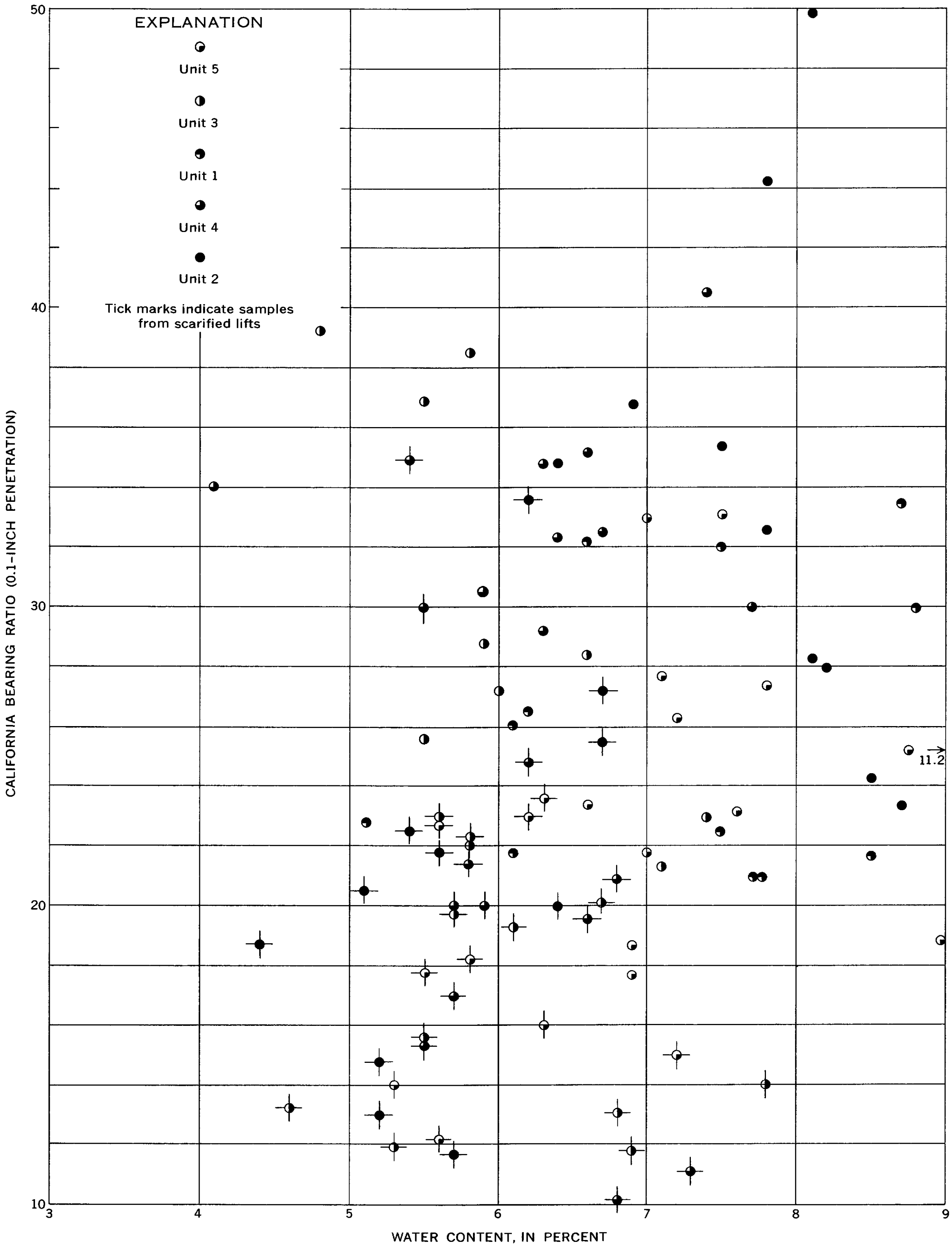

Figure 27.—California Bearing Ratio versus water content, units 1–5 of test fill 3.

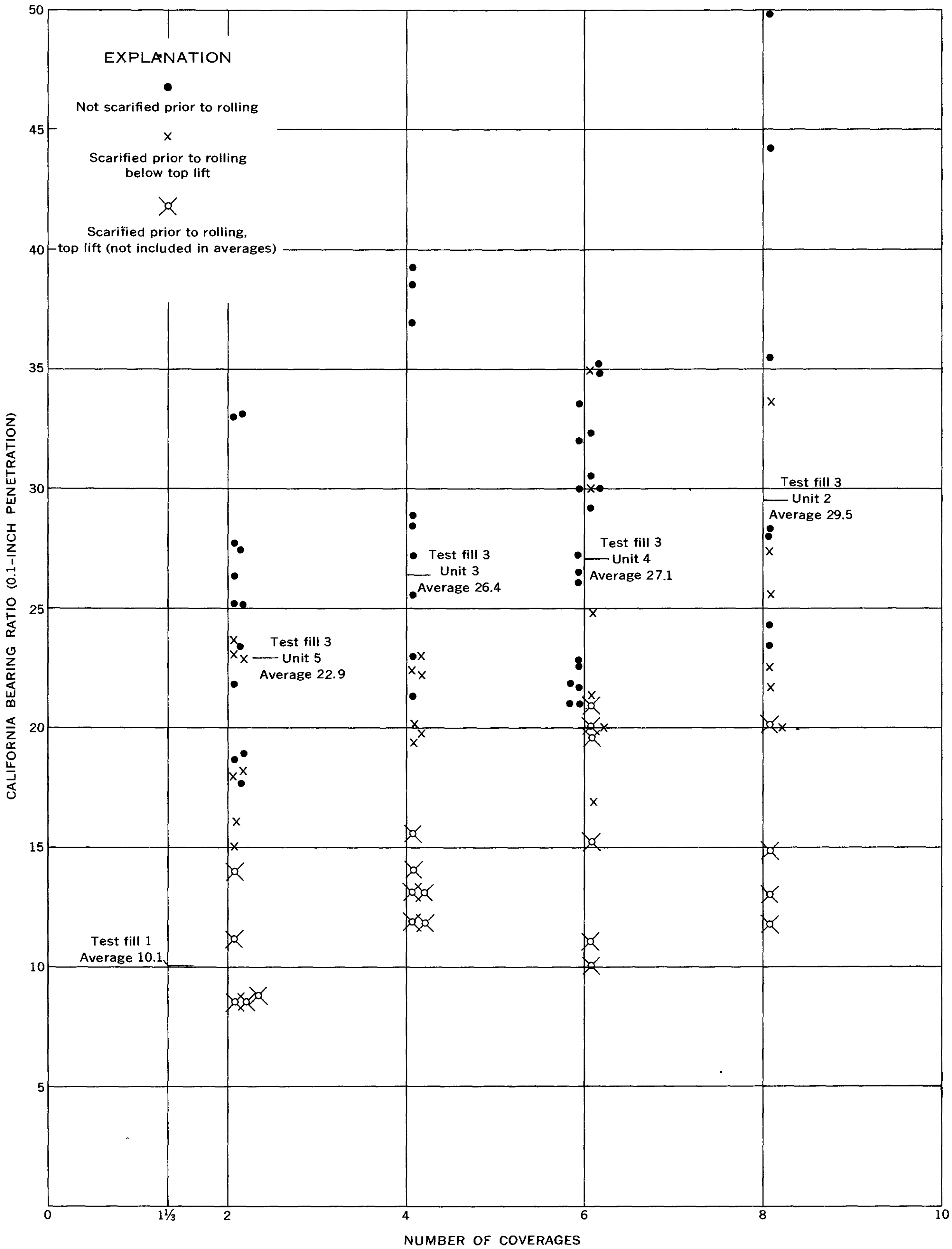

FIGURE 28.—California Bearing Ratio versus number of coverages.

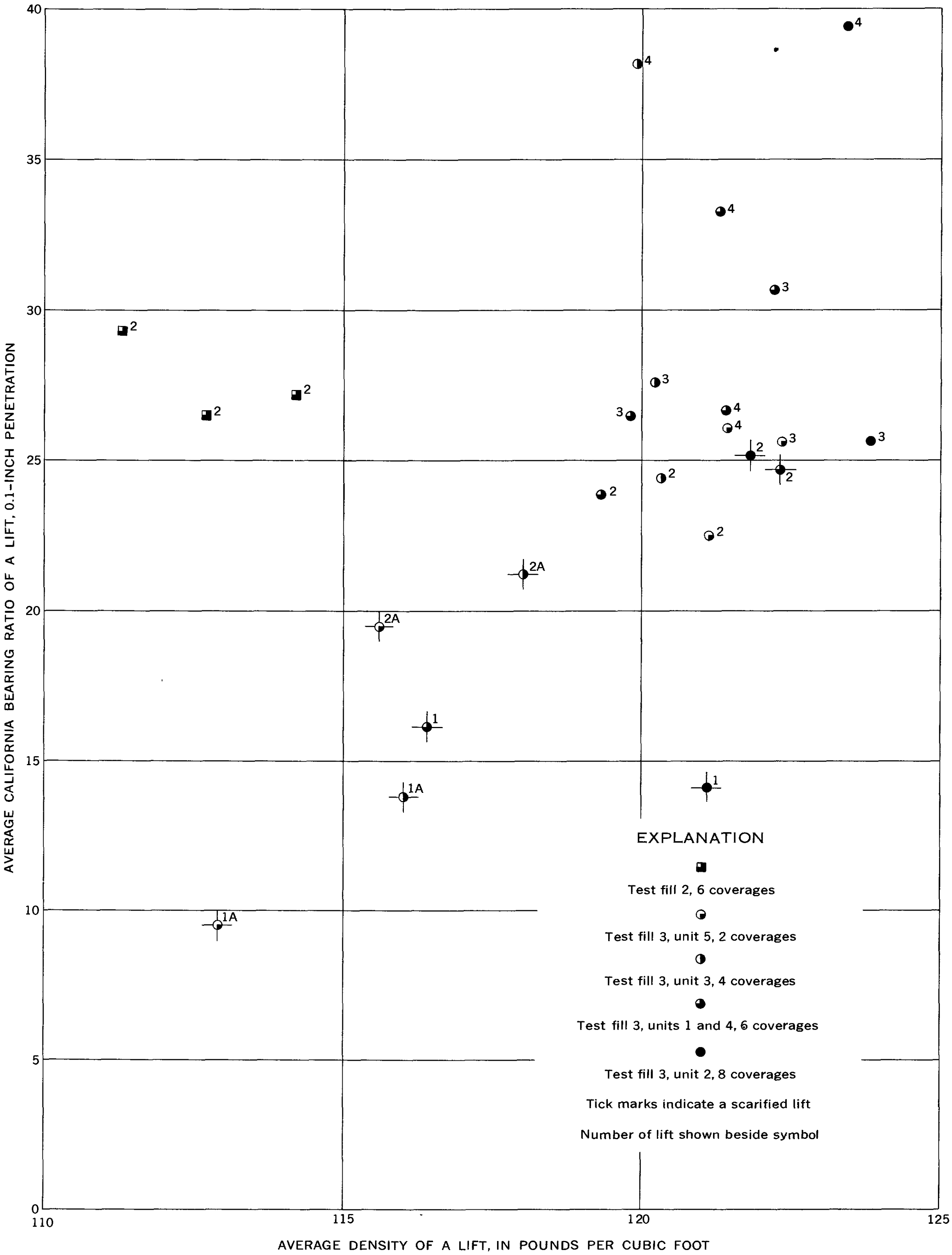

FIGURE 29.—Average density of a lift versus average California Bearing Ratio for the same lift.

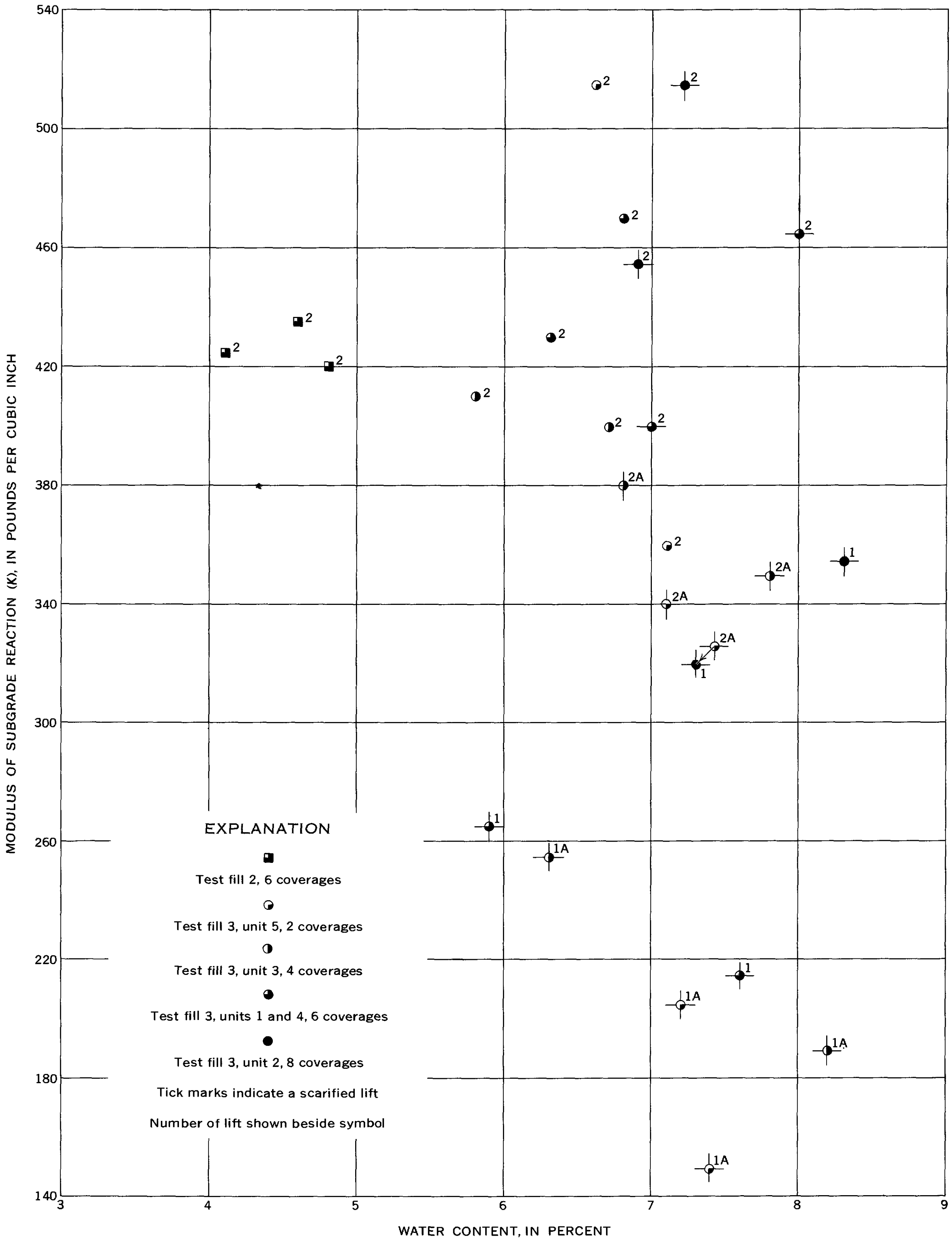

FIGURE 30.—Modulus of subgrade reaction versus water content.

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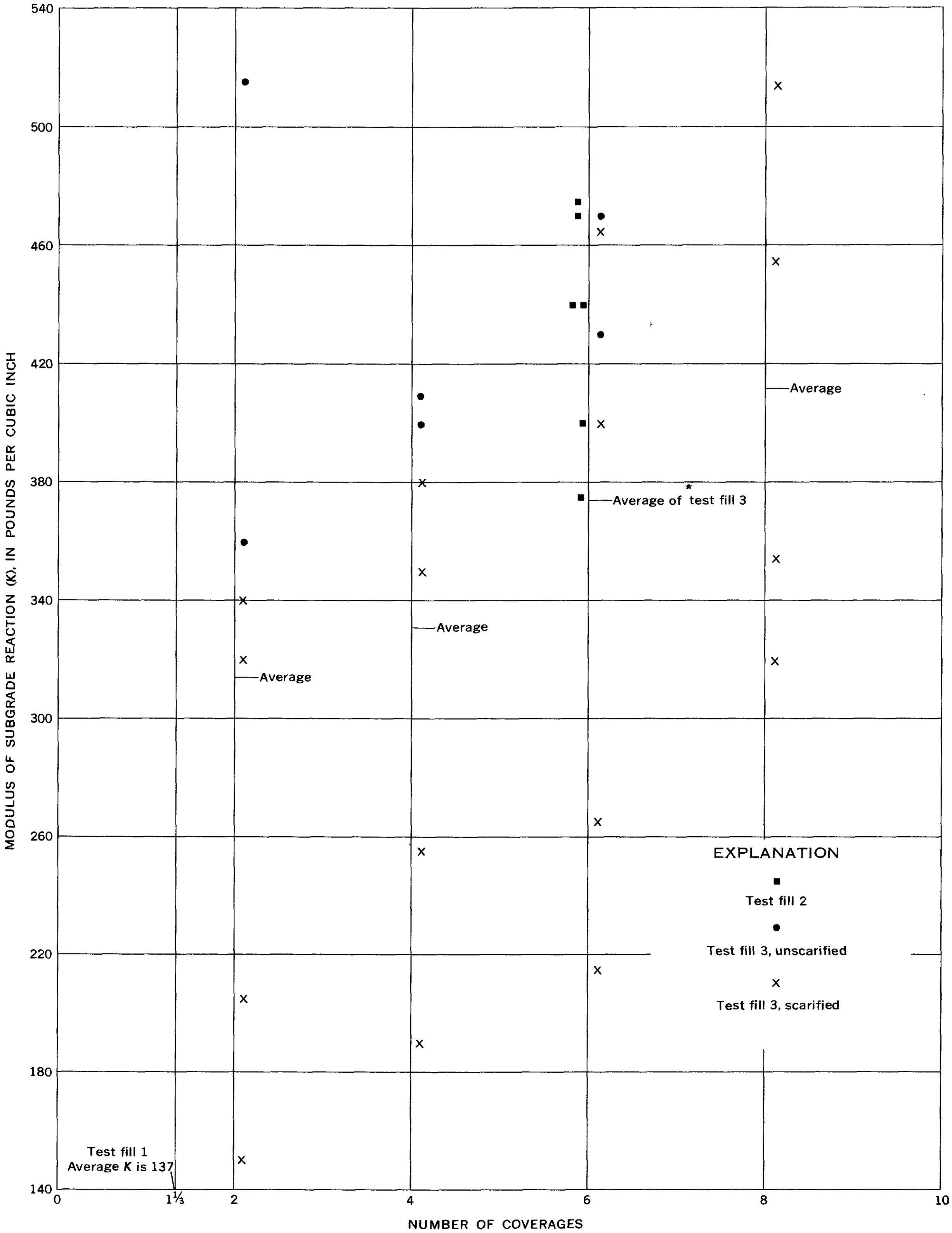


FIGURE 31.—Modulus of subgrade reaction versus number of coverages.

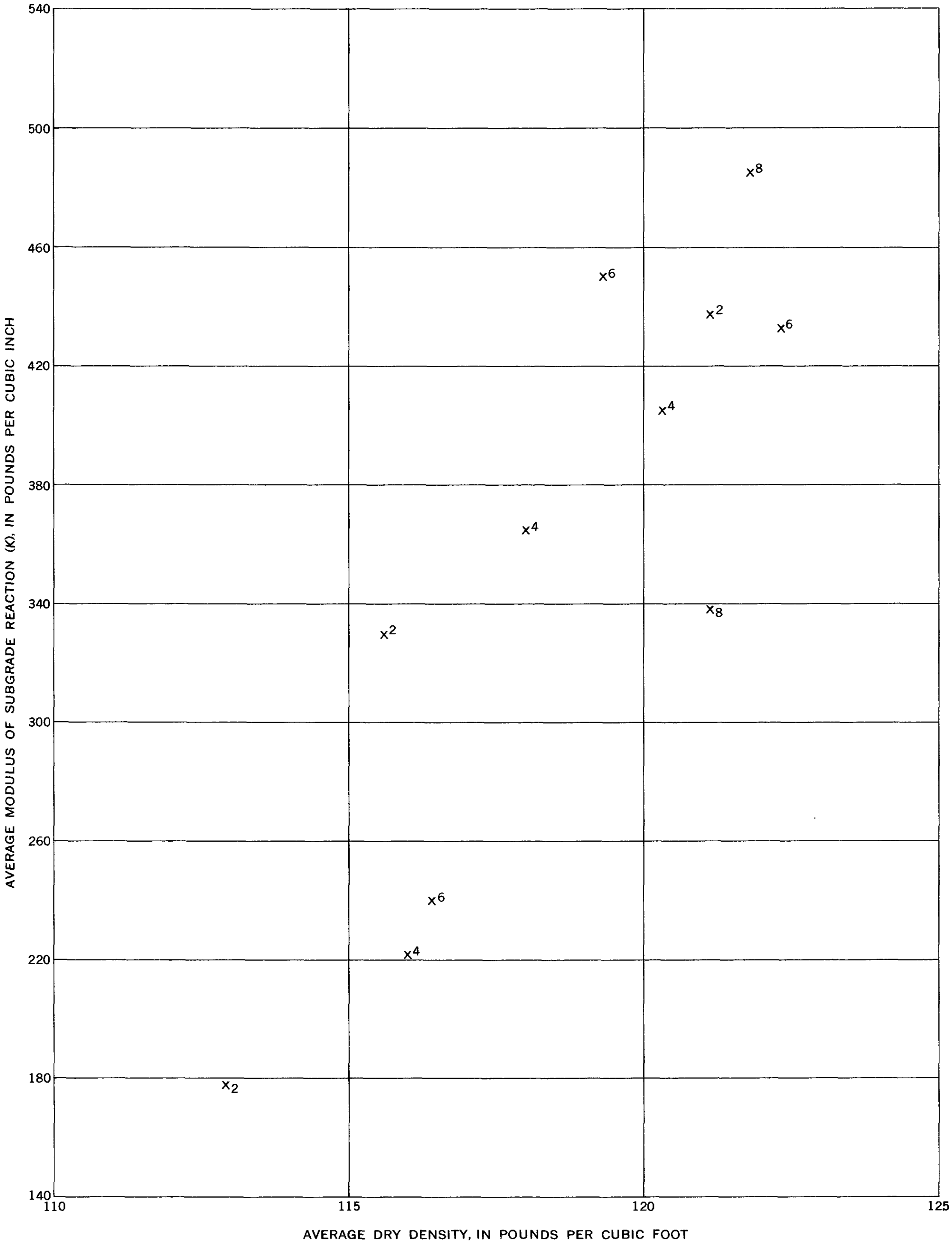


FIGURE 32.—Average density of a lift versus average modulus of subgrade reaction for same lift. Test fill 3 only. Numbers indicate the number of coverages.

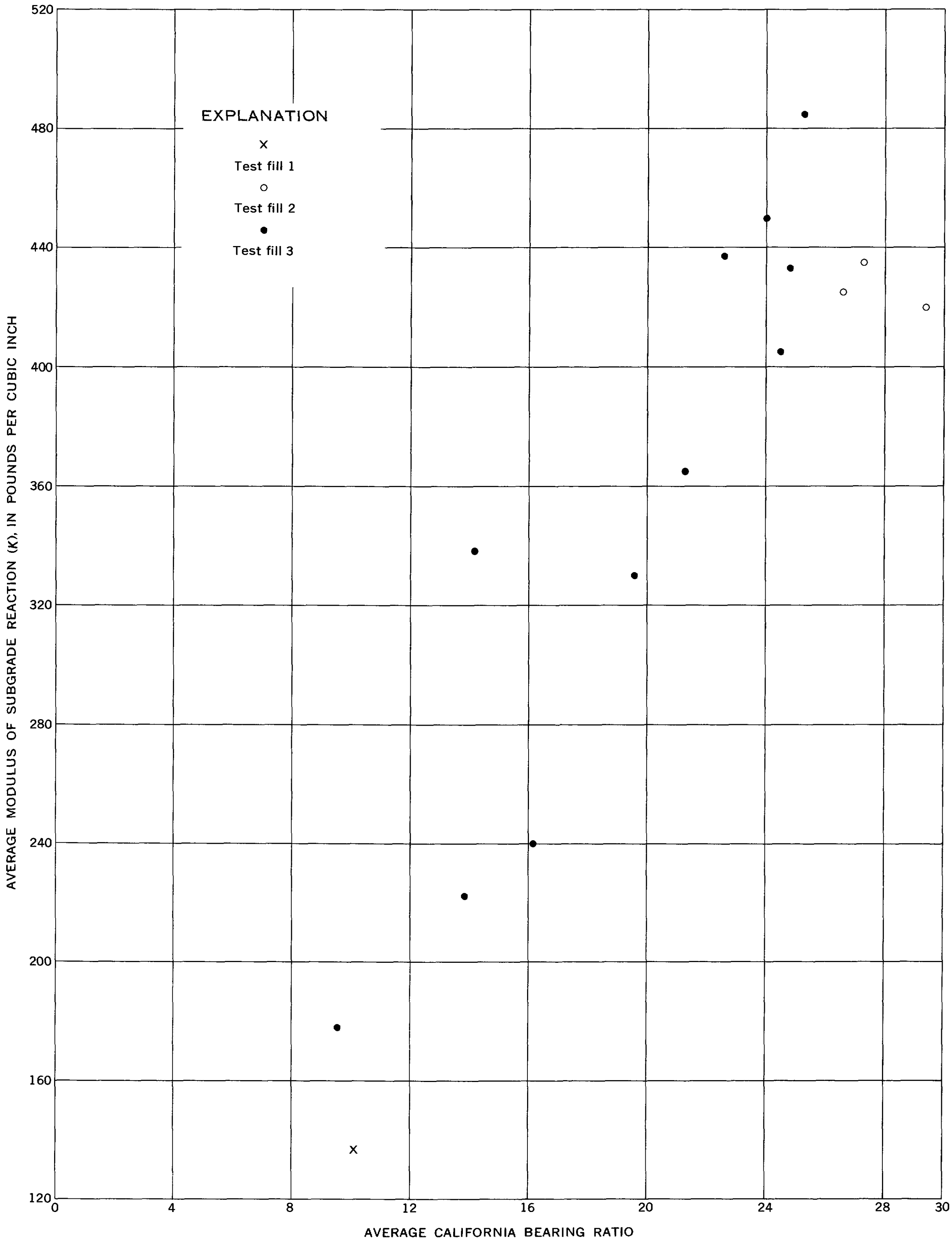


FIGURE 33.—Average modulus of subgrade reaction for a lift versus average California Bearing Ratio for the same lift.

more clayey than the parent material. These soils are regarded as unsuitable for subbase, subgrade, or compacted fills directly beneath the airstrip operational areas and are to be stripped to a depth of 1.5–2.0 feet and stockpiled for use as topsoil or non-load-bearing fill.

PEDIMENT GRAVEL

Grain-size-distribution analyses of the pediment gravel indicated that it was generally a non-frost-susceptible material containing less than 3 percent material finer than 0.02 mm. It is a stream-laid deposit, however, and therefore shows some layering according to grain size. The more silty layers are possibly frost-susceptible, and hence it was necessary to specify that the pediment gravel be mixed and recompacted to eliminate pockets and lenses of finer materials and that the layers be scarified and recompacted beneath load-bearing fills.

The average density of the pediment gravel in its natural state was found to be 108 pounds per cubic foot, or about 92 percent of average Modified AASHO maximum density; the CBR values were variable but averaged about 10 percent; and plate bearing tests gave a range of K (in place) from 73 to 253 pounds per cubic inch, the average being 169 pounds per cubic inch. These values were low but are compatible with the CBR tests and the natural densities. The compaction tests showed that the pediment gravel could be compacted to more than 95 percent Modified AASHO maximum density by six complete coverages of a surface roller in lifts as much as 12 inches thick. The roller should have a minimum wheel load of 25,000 pounds and minimum tire-inflation pressure of 100 pounds per square inch. The placement water content should range between 5 and 8 percent. Thus compacted, the gravel gave CBR values of about 24 percent, and K, the modulus of subgrade reaction, increased to more than 400 pounds per cubic inch.

DAWSON ARKOSE

Mechanical analysis indicated that the Dawson Arkose is a frost-susceptible material. Laboratory swelling tests indicated that the Dawson, here a stiff brown and gray silty clay containing some lenses of sandy clay and sand, was not a highly expansive material but that it swelled a moderate amount upon saturation under reduced loads. In-place CBR tests on the Dawson in test pits gave values averaging about 20 percent; a laboratory CBR test on soaked Dawson gave a value of 4 percent. Plate bearing tests on undisturbed Dawson indicated an average modulus of subgrade reaction, K, of about 210 pounds per cubic inch. The average in-place density was 119.4 pounds per cubic foot, or 95 percent of Modified AASHO maximum.

The need for protection against frost and the rather low modulus of subgrade reaction required that the pavement rest on a blanket of pediment gravel over cut surfaces of the Dawson Arkose. The Dawson derived from cuts was not to be used in fills for the runway and taxiways, but it could be used in the upstream impermeable blanket of the Kettle Creek Dam (see pl. 2, section *B–B′* and *D–D′*), and in non-load-bearing spoil fills.

Major subdrain installations probably will not be needed in the airfield area. Surface drainage is to be intercepted by a ditch on the east side of the runway and led southward to Pine Creek.

Water was present in the valley of Kettle Creek, just east of the old alinement of U.S. Highway 85–87, even after construction of Kettle Creek Dam and the bypass conduit. Apparently this water is percolating through the arkose westward into the valley. Provision for intercepting it and conducting it away from the area will have to be made before the fills are constructed across the valley.

ACADEMIC AREA

LOCAL GEOLOGY AND TOPOGRAPHY

The academic area is on and near Lehman Mesa and occupies about one-fifth of a square mile (pl. 6). Lehman Mesa originally sloped eastward at a grade of about 10 percent from 7,220 feet at the west edge to 7,130 feet at the east. Longitudinal indentations and fingers extended eastward beyond the main mass of the pediment. At the south side of the mesa are some higher remnants of the Lehman Ridge Gravel. Dawson Arkose underlies the whole area and is overlain on Lehman Mesa by the Douglass Mesa Gravel and on Lehman Ridge by the older Lehman Ridge Gravel. The Dawson Arkose contains red, yellow, and gray beds of claystone, siltstone, and friable soft sandstone that lie almost flat or dip slightly to the east. Douglass Mesa Gravel is the most prevalent deposit. It contains many boulders and cobbles in a matrix of pebbles, sand, silt, and clay. Most of the material is derived from the Pikes Peak Granite; the large rocks, therefore, are made up of granite, and the small pebbles and sand consist of individual grains of feldspar and quartz. Boulders are most abundant at the west edge of the pediment but are common also along the north side and in east-trending boulder trains that are partly covered by finer gravel.

CONSTRUCTION AND AREA UTILIZATION

The academic area contains the classrooms and library, cadet quarters, dining hall, chapel, social hall, aeroscience laboratory, physical education, building administration building, and planetarium, as located in plate 6 and as shown partly completed in figure 34. North of these buildings are the athletic facilities, to the east is the parade ground, to the southwest are the rectories, and to the west are Goat Camp Creek Reservoir and the west power substation.

The surface of Lehman Mesa was resloped into four main levels which are, from west to east, the Court of Honor level, at about 7,176 feet (finish elevation), air garden level at 7,163, the lower quarters level at 7,132, and the parade-ground level between 7,100 and 7,050 (fig. 35). Retaining walls were constructed to avoid steeply sloping and potentially unstable ground between the four benches.

FIELD AND LABORATORY INVESTIGATIONS

SOUNDINGS, BORINGS, AND TEST PITS

Field and laboratory investigations of foundation conditions were started as soon as the general site for the group of principal buildings was selected. The purpose of the preliminary investigation was to determine the distribution of the sand and gravel cap on Lehman Mesa and to derive enough information about its thickness and physical properties so that a balanced grading plan could be worked out. As arrangement of the retaining walls and buildings became more definite, the exploratory program was directed more particularly at determining the suitability of the pediment gravel or underlying arkose for foundations of the heavy structures.

The first drilling program on Lehman Mesa consisted of 20–30 small-diameter (4- to 6-inch) holes bored by OTL. Cuttings from these holes gave some qualitative information about the Douglass Mesa Gravel and some idea of its thickness, but differentiation of the pediment gravel from the underlying arkose was often difficult. Most of the borings were at least 30 feet deep. Many were stopped by boulders and only a very few entered recognizable Dawson Arkose.

Both the U.S. Geological Survey and the architect-engineer prepared bedrock contour maps, but the bedrock surface was even more irregular than expected; several deeply buried channels were not discovered until the gravel was excavated.

The exploration program was greatly enlarged as the future locations of the buildings and retaining walls were determined more exactly by SOM. More than 60 holes, 18 or 24 inches in diameter, were drilled to investigate areas of pediment gravel that were to be excavated for use as embankment material. The large-diameter auger removed or passed by most of the smaller boulders, and the holes were generally extended to 5 feet below grade of finished cuts. Extra holes were drilled where retaining walls or foundations were to rest on a cut surface. Three 30-inch holes were drilled through Dawson Arkose and were entered by E. A. Abdun-Nur, a consulting engineer, for visual inspection. Free water was not found in any of the drill holes.

Eight test pits, some of them as much as 22 feet deep, were dug at various points on the mesa. The north side of test pit 1 is shown in figure 16. Most of these pits were paired with borings for which blow counts of penetration of a standard split spoon had been recorded. The pits exposed enough of the pediment gravel to show the approximate proportion and distribution of the larger boulders and some pits exposed Dawson Arkose. The pits also gave an opportunity for in-place density and plate-bearing tests, to be performed for samples to be collected at various depths for sieve analyses, moisture-content tests, determination of moisture-density relations, petrographic examination, and triaxial shear tests. Figure 36 is an example of some of the types of information derived from the test-pit program. Similar tests were performed at other pits in the gravel and underlying arkose.

Triaxial tests were performed on samples taken from the test pits in order to determine the angle of internal friction for design of the large retaining walls. Because the pediment deposits lacked the cohesiveness that is necessary to trim them for the triaxial test they were recompacted at natural water content—some to field density and others to 95 percent and 100 percent of Modified AASHO density. Samples taken from soils having a penetration resistance of 32–42 blows per foot and a dry field density of 106–117 pounds per cubic foot had angles of internal friction ranging from 35° to 44.2° and cohesion ranging from 0.1 to 0.7 ton per square foot. Samples compacted to 95 percent Modified AASHO density (118–134 lb per cu ft) had angles of internal friction ranging from 35° to 49° and cohesion of 0–0.5 ton per square foot. A typical yield envelope, for sample 2063 from test pit 2, is shown in figure 37.

After the test pits and borings had been completed, the results of the exploration and testing of materials in the academic area were evaluated in a report, "Cadet Academic Area, Preliminary Soil Investigation," prepared by the architect-engineer and dated January 9, 1956. This report included a further analysis entitled "Cadet Area, Evaluation of Informa-

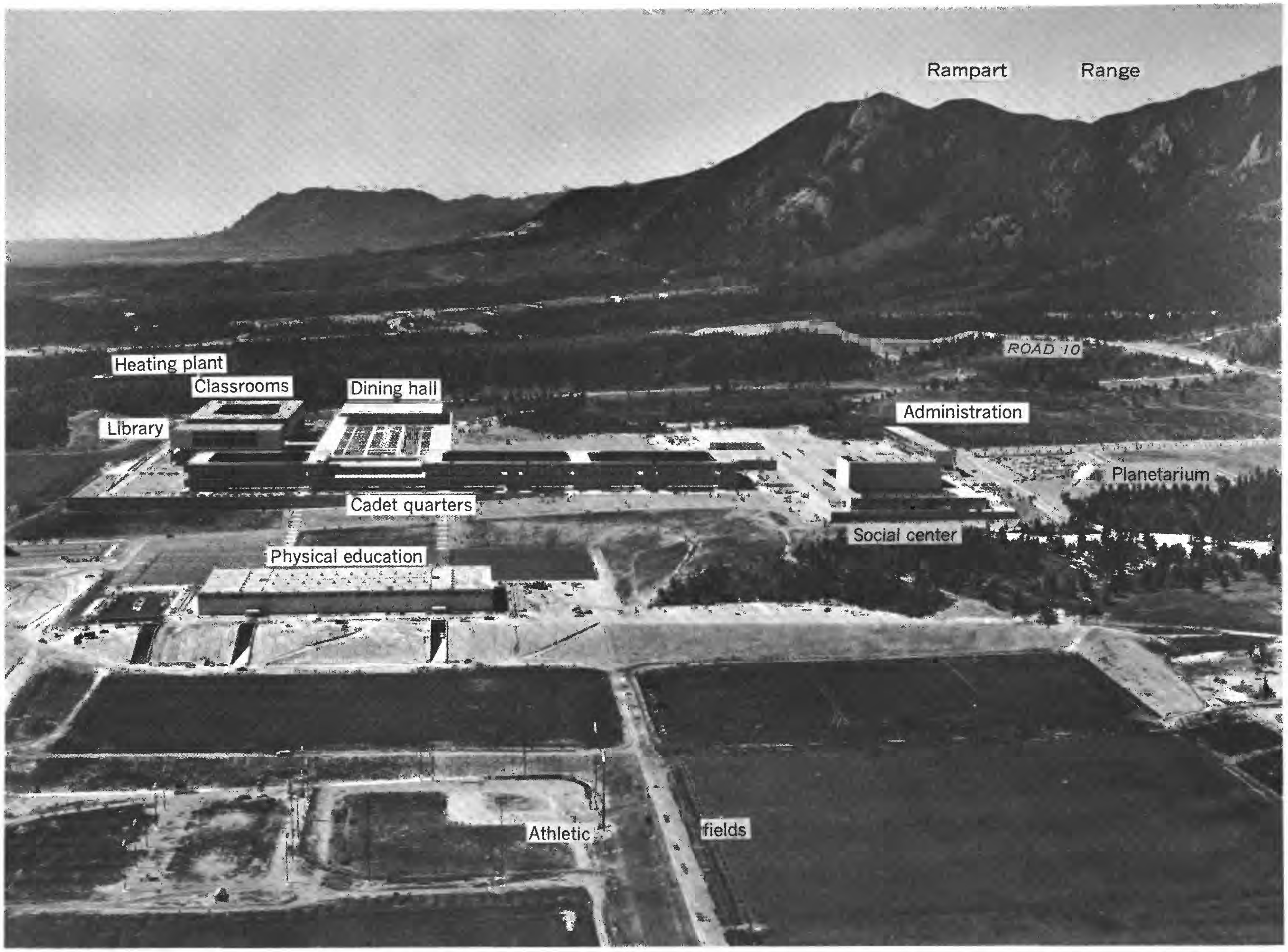
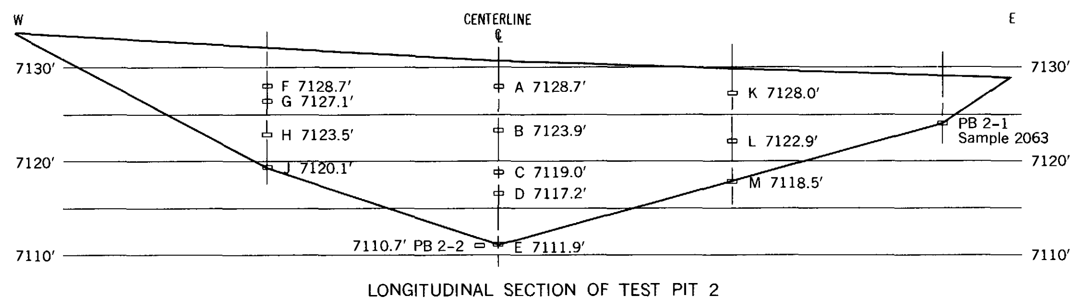
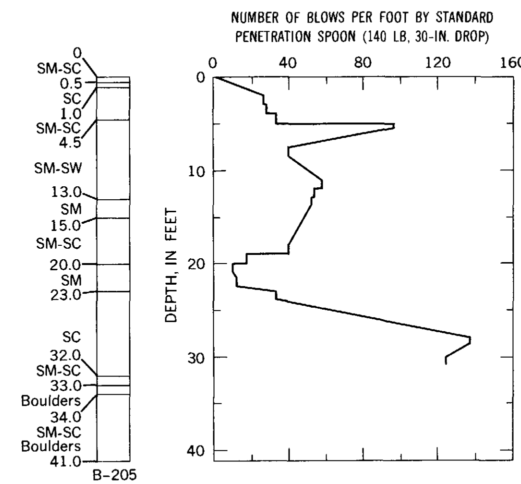
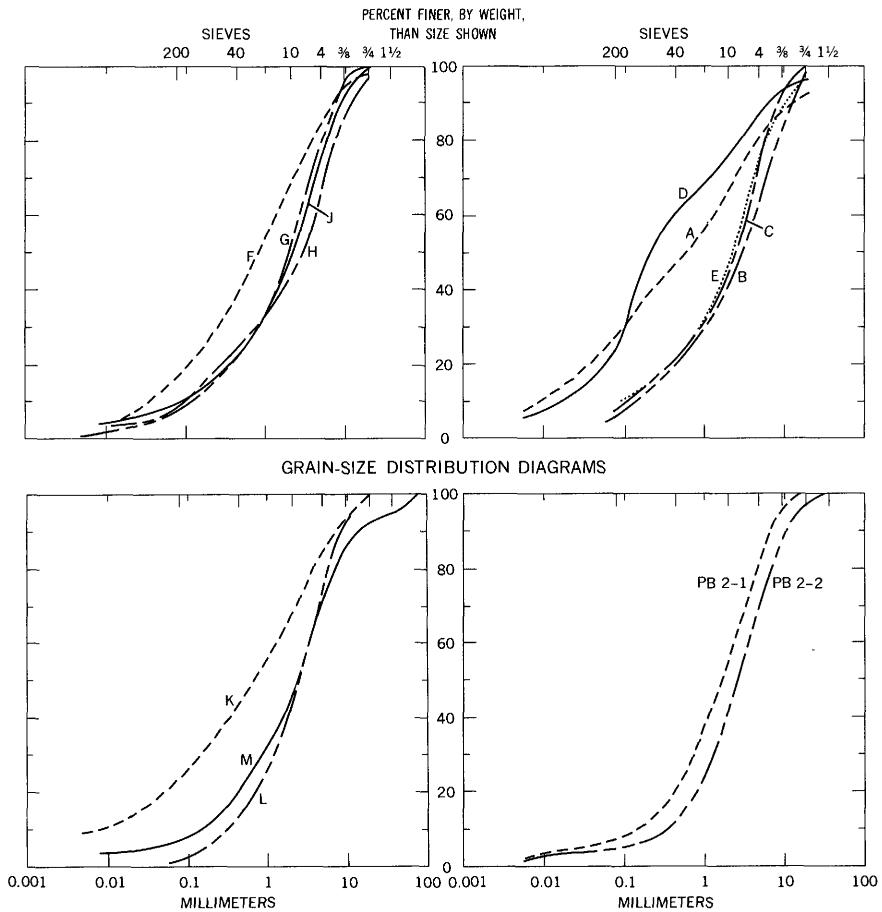


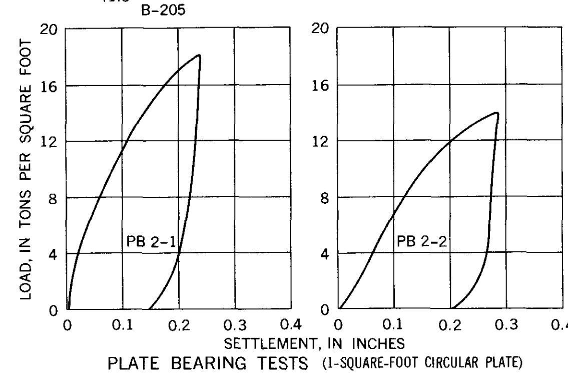
FIGURE 34.—Academic area from the north. Athletic fields in the foreground are largely on Husted Alluvium from which the topsoil was stripped and stockpiled; the underlying material was regraded and recompacted. Goat Camp Creek is carried by conduit northeastward beneath the athletic fields. The physical education building rests on Dawson Arkose; the principal buildings on the higher ground are in an area of regraded Douglass Mesa Gravel but rest on caissons extending to Dawson Arkose. Photograph by the U.S. Air Force, June 10, 1959.

FIGURE 35.—Academic area from the west, showing about the same area as figure 52, 2 years later. The four principal levels in order of increasing elevation, are: the parade ground in the center beyond the buildings, the lower quarters level around the west and north sides and in the courts of the quarters building in left center, the air garden level in the center between the buildings, and the Court of Honor level immediately east of the long administration building in left center. Photograph by the U.S. Air Force, November 12, 1958.



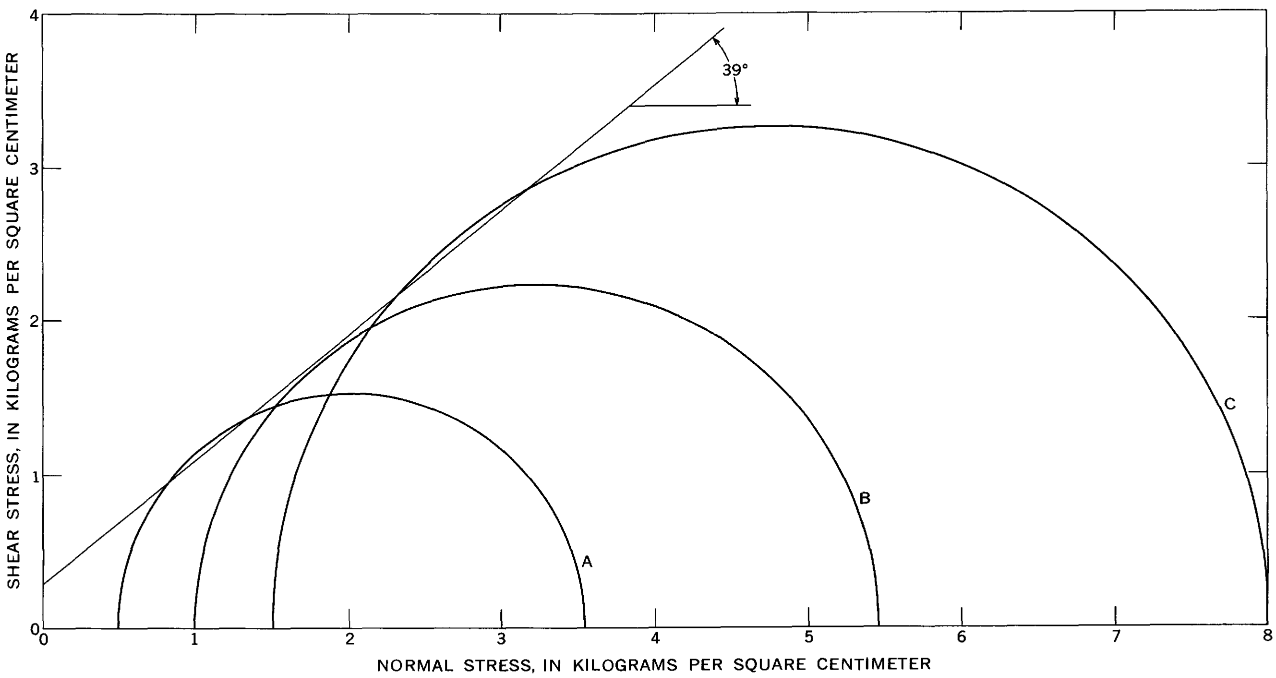






BENCH NO	OFFSET FROM CENTERLINE (FEET)	DEPTH OF STRATUM (FEET)	IN-PLACE DENSITY (LB PER CU FT)	FIELD MOISTURE (WEIGHT PERCENT)	MODIFIED PROCTOR (LB PER CU FT)	OPTIMUM MOISTURE (WEIGHT PERCENT)	LIQUID LIMIT	PLASTICITY INDEX	SPECIFIC GRAVITY	U.S SOIL CLASSIFI-CATION
A	℄	1.0-4.5	103 0	4.3	131.2	8.2	22	7	2.67	SM-SC
B	℄	4.5-11.0	119 8	2.6	128.4	7.9		N.P.		SM-SW
C	℄	11.0-13.0	114.8	3.7	130 7	8.0		N.P.		SM-SW
D	℄	13.0-15.0	109.5	7.4	128 8	8.6		N.P		SM
E	℄	15.0-20.0	110.8	6 6	131 6	7.1	21	4	2 72	SM-SC
F	50 W.	3.5-5 5	108.6	2.9				N.P		SM
G	50 W.	5.5-8.0	114.4	2.5				N.P.		SM-SW
H	50 W.	8.0-11.0	115 4	3.4				N P		SM-SW
J	50 W.	11.0-14.0	117.0	6.9				N.P.		SM-SW
K	50 E.	4.0-6.0	106.4	4.1			21	5		SM-SC
L	50 E.	6.0-11.0	113.0	2.2				N.P.		SM-SW
M	50 E.	11.0-14.0	106.1	3.8				N.P.		SM-SW
PB 2-1	95 E		116.9	3.2	125.9			N.P.		SM-SW
PB 2-2	4 W.							N.P.		SM-SW

FIGURE 36.—Typical report giving information derived from test pit 2, academic area. Source: "Cadet Academic Area, Preliminary Soil Investigation," a report by Skidmore, Owings, and Merrill to the Air Force Academy Construction Agency, January 9, 1956.



Data	A	B	C
Height of sample......cm..	12.09	11.70	11.35
Water content......percent..	2.6	2.8	2.6
Dry density......lbs per cu ft..	118.0	120.0	121.6
Diameter of sample......cm..	6.34	6.34	6.34
σ_3......kg per sq cm..	0.5	1.0	1.5

FIGURE 37.—Triaxial compression test, quick test (drained); cohesion 0.3 kg per sq cm, angle of friction 39°; fine to coarse sand and gravel, some medium-dense silt. Test pit 2, sample 2063, Soil Testing Services, Inc., Chicago, Ill.

tion from Preliminary Soil and Foundation Investigation," by Mr. E. A. Abdun-Nur. The general stratigraphy of the pediment deposit, as shown by the borings and pits and described in the report, is an upper layer of humic clayey topsoil, a foot or less thick, underlain by silty sand and gravel as much as 85 feet thick. The topsoil was stripped and stockpiled for later use in reseeding. The underlying gravel was found to contain boulders several feet in diameter at various depths and generally to become more dense toward the base. Abdun-Nur divided the pediment deposits into two broad types: Type 1 is sandy gravel, mostly in the west half of the mesa, and type 2 is gravelly sand, mostly in the east half of the mesa. Dawson Arkose he designated type 3 material.

Petrographic examinations made by R. C. Mielenz for Abdun-Nur's report indicated that the finer components of the pediment sand and gravel consisted of angular to subangular fragments of fresh to slightly weathered granite, of quartz, and of microcline. The grains are loose or weakly bound by thin films of clay; intergranular spaces are empty. The sand grains are in contact with each other and are not held apart by the clay coating. If unsupported, the clay softens and the sand slakes to loose grains on immersion in water, but if laterally supported, the fabric is retained owing to mutual contacts between the hard grains.

The Dawson Arkose of this area is variable in composition; it consists of weakly cemented arkosic clayey sandstone and sandy and clayey siltstone. Mielenz found that the grains in the clayey sandstone are in point contact but that the intergranular spaces are largely filled with illitic clay, sericitic mica, kaolinite, and a small proportion of montmorillonite. The feldspar grains are weathered and weakened.

The information available from the boring and test-pit program was sufficient to allow the preparation of detailed plans and specifications for the initial grading and for the design of retaining walls, which ranged in height from 3 to about 35 feet. Bids on these items were invited in February 1956. The exploration and testing up to this time had indicated that the granular Douglass Mesa Gravel could support large footing pressures and that the bearing capacity would increase with depth. A cost comparison indicated that a rather deep foundation would be more economical than a near-surface foundation because drilled-in shafts are less expensive than excavations. Furthermore, because the slight cementation between soil grains in the pediment gravel becomes negligible upon wetting, a concentration of surface water probably would cause settling of foundations situated near the ground surface. Speed in construction was also an important factor, and here the subpier-type foundations have a distinct advantage because they can be drilled quickly and concreted with relatively simple equipment. These considerations indicated that a deep, or caisson-type, foundation should be investigated more thoroughly, and for this purpose full-scale load tests, described in the next section, were performed.

CAISSON LOAD TESTS

Four load tests were performed in March 1956 on caissons placed in pediment gravel and Dawson Arkose in the eastern part of the academic area. The purpose of these tests was to aid in selection of the type of foundation and the design bearing pressure for the large buildings around the central campus. The data reported or analyzed here are derived from the architect-engineer's "Report on Caisson Load Tests, Synopsis," of July 1956 and from a drawing "Cadet Academic Area, Test Caisson Program," revised July 25, 1956, to show as-built conditions.

We have examined all the test results and analyzed them in some detail as a matter of general interest, because records of full-scale in-place tests made at such high loads, are rarely available for geologic units of granular texture. Moreover, the data afforded an opportunity to explore empirical time-settlement-load relations in a physical situation where the theory of consolidation could not apply. Actually, the settlements appear to follow laws of creep that have been suggested for a wide variety of metallic and nonmetallic substances and which may have physical bases in statistical mechanics and reaction-rate theory rather than in the classical hydrodynamics of consolidation. Although a discussion of the caisson load tests necessarily goes afield from geology into physics and soil mechanics, it is presented here because the results are pertinent to one of the major engineering-geologic decisions taken by AFACA—that all the caissons upon which the academic area buildings rest were to be bottomed in firm Dawson Arkose and not in pediment gravel. This required specifying that some caissons. such as those at the north end of the library, be longer than 70 feet.

The analyses are also intended to illustrate how difficult it is to extrapolate short-term tests accurately into expected long-term behavior without a firm understanding of the physical process involved.

The locations of the test caissons are shown in plate 6. Information on the subjacent material, available from previous borings, was supplemented where necessary by the architect-engineer with information from new borings. Test caissons 1 and 2 rested in Douglass Mesa Gravel about 65 feet above its base; cassion 3 penetrated the gravel and, according to the auger log, rested on Dawson Arkose about 4 feet below the gravel-arkose contact; and caisson 4 was placed in test pit 4 that had been dug through colluvium into Dawson Arkose. Blows per foot in adjacent borings at the level of the bottoms of caissons 1, 2, and 3 were 45, 20, and more than 100, respectively.

Figure 38 shows the dimensions and loading arrangement for tests 1–3. Test caisson 4 was 48 inches in diameter for the full length and 7 feet rather than 20 feet long. It was not belled at the bottom. All caissons were made of concrete reinforced with steel. The test caissons were cast within forms to provide a free space between the caisson and the soil in order to eliminate skin friction.

Loads of 66, 132, 198, 264, 396, 528, 660, and 800 thousand pounds were applied by hydraulic jacks and kept constant during each test. Both settlement-gage dials were read to the nearest 0.001 inch, generally at times of 0, 5, 15, 30, 45, and 60 minutes, and every half hour thereafter. Level readings to the nearest 0.001 foot were taken on the caisson groups from time to time to check the dial observations and to test for possible upward movement of the tension caissons. The anchor bolts were elongated by the high stresses, but they were not pulled out and no upheaval of the ground was reported.

The tests were run for various lengths of time—usually 60 to 120 minutes at the lower loads and for as long as 5,220 minutes at the maximum load. A few records were made of rebound upon release of the load.

ACTUAL TIME-SETTLEMENT OBSERVATIONS

The settlements of the caissons consist of two parts: The first part occurs at once upon the application of a load or of an additional load increment; the second part increases from time zero at an ever decreasing rate. Curves showing the log of the time versus the total settlement at sites 1, 2, and 3 are plotted in figures 39 and 40. The settlements of test caisson 4 in Dawson Arkose, shown in figure 41, are irregular and much smaller than those of the other caissons.

ACTUAL LOAD-SETTLEMENT OBSERVATIONS

Load-settlement observations during actual testing are shown in figure 42. The instantaneous settlements

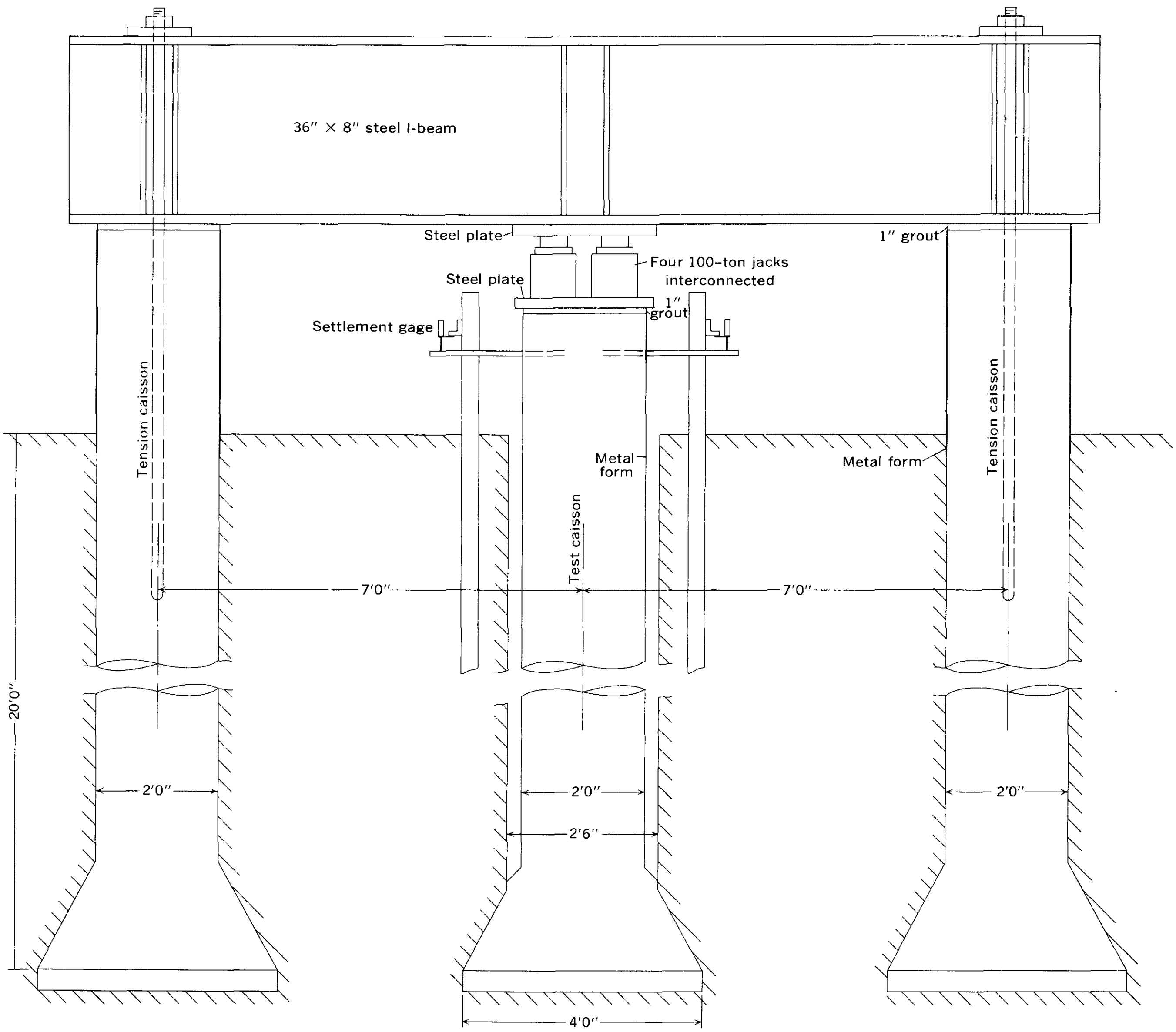


FIGURE 38.—Typical loading arrangement for test caissons.

during application of increments of load are shown here by the sloping segments of the loading curves; the settlements during periods of time at constant load are shown by the vertical segments.

ANALYSIS OF TESTS

The principal purpose of caisson load tests is to form some estimate of the expected settlement of a caisson in a particular type of material, placed under a specific load, during some certain period of time.

The instantaneous settlement associated with each increment of loading is assumed to be the difference between the last gage reading of the previous test and the reading at time zero of the next test. It is further assumed that instantaneous settlements during prior step loading may be added to obtain the instantaneous settlement that would result from immediate application of the full load. In figure 43, the totals of instantaneous settlements, produced by the indicated loads plus instantaneous settlements due to all prior load increments, are plotted on log-log scales. Although there are irregularities, the relations are more or less linear on the log-log plot. The linearity indicates that the instantaneous settlement, S_i, may vary with the load, L, somewhat as follows:

$$\log S_i = a \log L + b$$

and

$$S_i = b'L^a$$

in which b and b' are constants and the exponent a is

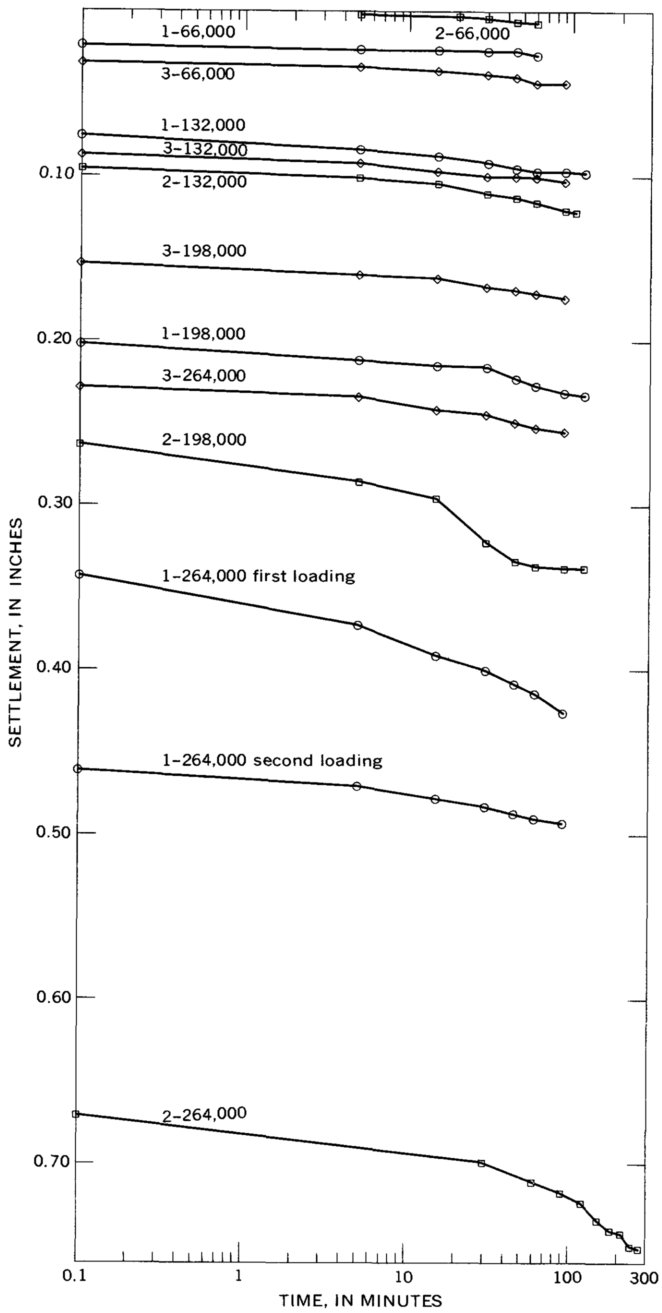


FIGURE 39.—Log time-settlement curves for the tests on caissons 1–3 at low and moderate loads of 66,000–264,000 pounds. Reading at time zero is plotted at 0.1 minute.

about 2 for caissons 1 and 2 and about 1.2 for caisson 4. For caisson 3, the exponent appears to increase from about 1.2 at low loads to about 2 at high loads.

The time-dependent part of the settlements, to be expected at a given constant load and at fairly short times, can be derived from the results of incremental load tests only if the tests show that Boltzmann's principle of superposition is obeyed. This principle states that "the strain at any time *t*, because of the previous application of several stresses in succession—that is, the stress is a series of step functions—is the summation of the strains that would be observed at that time if each of these constant stresses had been applied independently" (Alfrey and Gurnee, 1956, p. 394).

A test of the superposition principle for the transition from an initial load of 66,000 pounds to a load of 132,000 pounds is shown in figure 44. The increment is equal to the initial load. At caisson 2, for example, the load was increased at 60 minutes; therefore the deformation at 90 minutes should be the deformation at 66,000 pounds for 90 minutes, as estimated by projection, plus the deformation at 66,000 pounds for 30 minutes. In all tests the predicted time-dependent settlement derived by this procedure falls short of the actual settlement, even though the projected deformations, owing to the initial 66,000-pound load alone, are assumed to be linear with time and are probably too high. Thus, the principle of superposition does not hold for the first increment of loading. Other graphs for the higher loads, although complicated in places by release of load to repair jacks, by repetitions of loading, or by other irregularities, indicate that, in general, the stress-strain relations are not linear and that settlements cannot be superposed.

The difference between incremental and constant loading probably can be neglected if the data are projected for a long time; that is, if the results of a several-day test at 800,000 pounds are projected to several hundred days, for example, the expected settlement will probably be about the same whether the 800,000-pound loading was or was not preceded by several days of incremental loading.

If the tests have been carried to and beyond design loads, the principal problem is to find a reasonable basis for extrapolating the results far beyond the duration of the actual tests.

The simplest method is to sketch extensions on the time-settlement graphs. Sketching is difficult, however, because the observed settlements generally show fluctuations to either side of an average curve and the average curve itself changes in curvature with time. Extrapolation may thus involve considerable subjective opinion. Were the law that governs the settlement of end-bearing caissons in granular material known, extrapolation would be certain, but the law is not known.

The tool most often used in analysis of settlements is the classical theory of consolidation. This theory is best applied to the consolidation of fine-grained soils, particularly saturated silt and clay. Because the caisson tests were for the most part performed in unsaturated sandy and silty gravel, it appears doubtful that the results could be interpreted by use of the theory of consolidation.

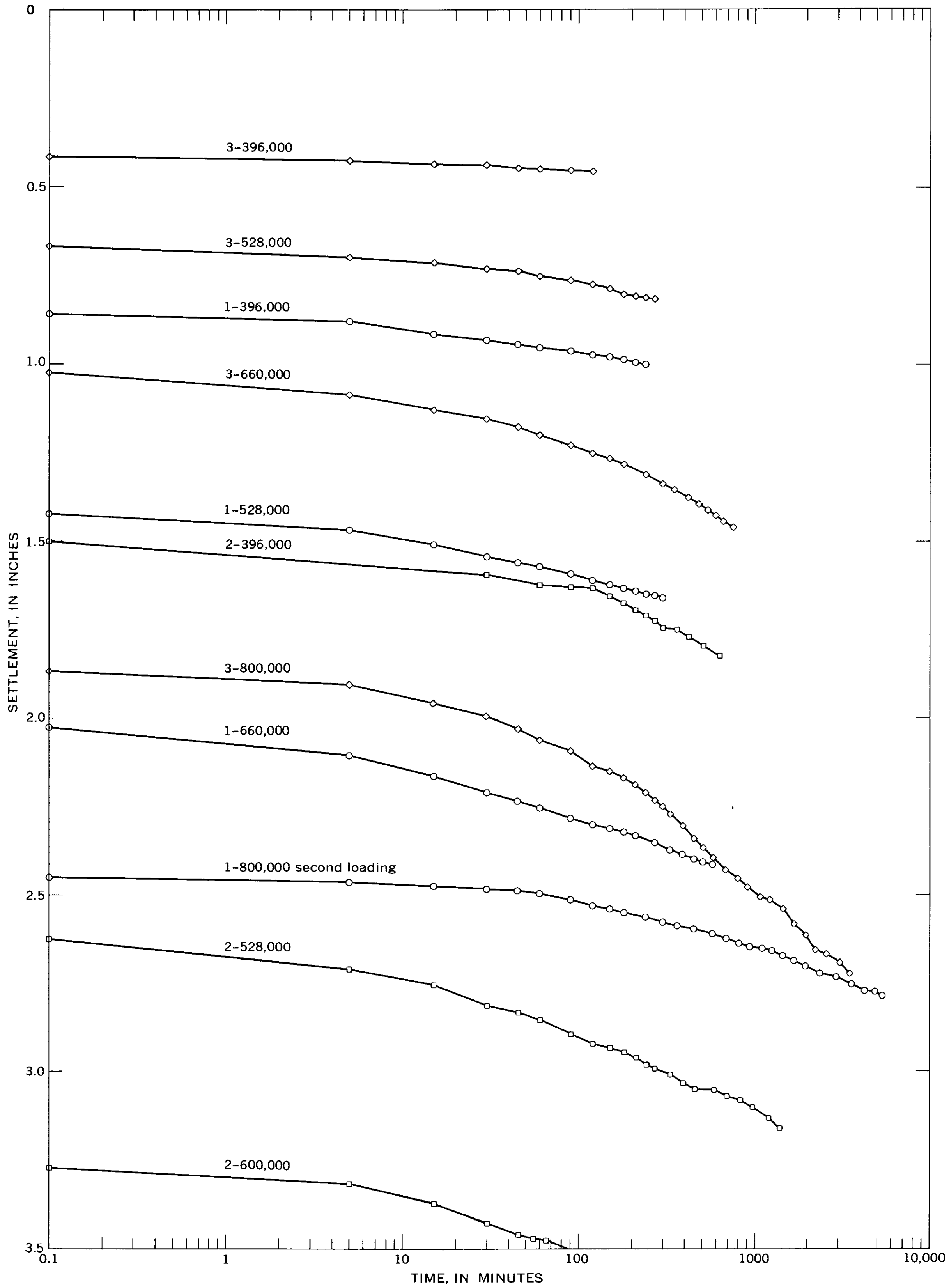


FIGURE 40.—Log time-settlement curves for tests on caissons 1–3 at high loads of 396,000–800,000 pounds. Reading at time zero is plotted at 0.1 minute.

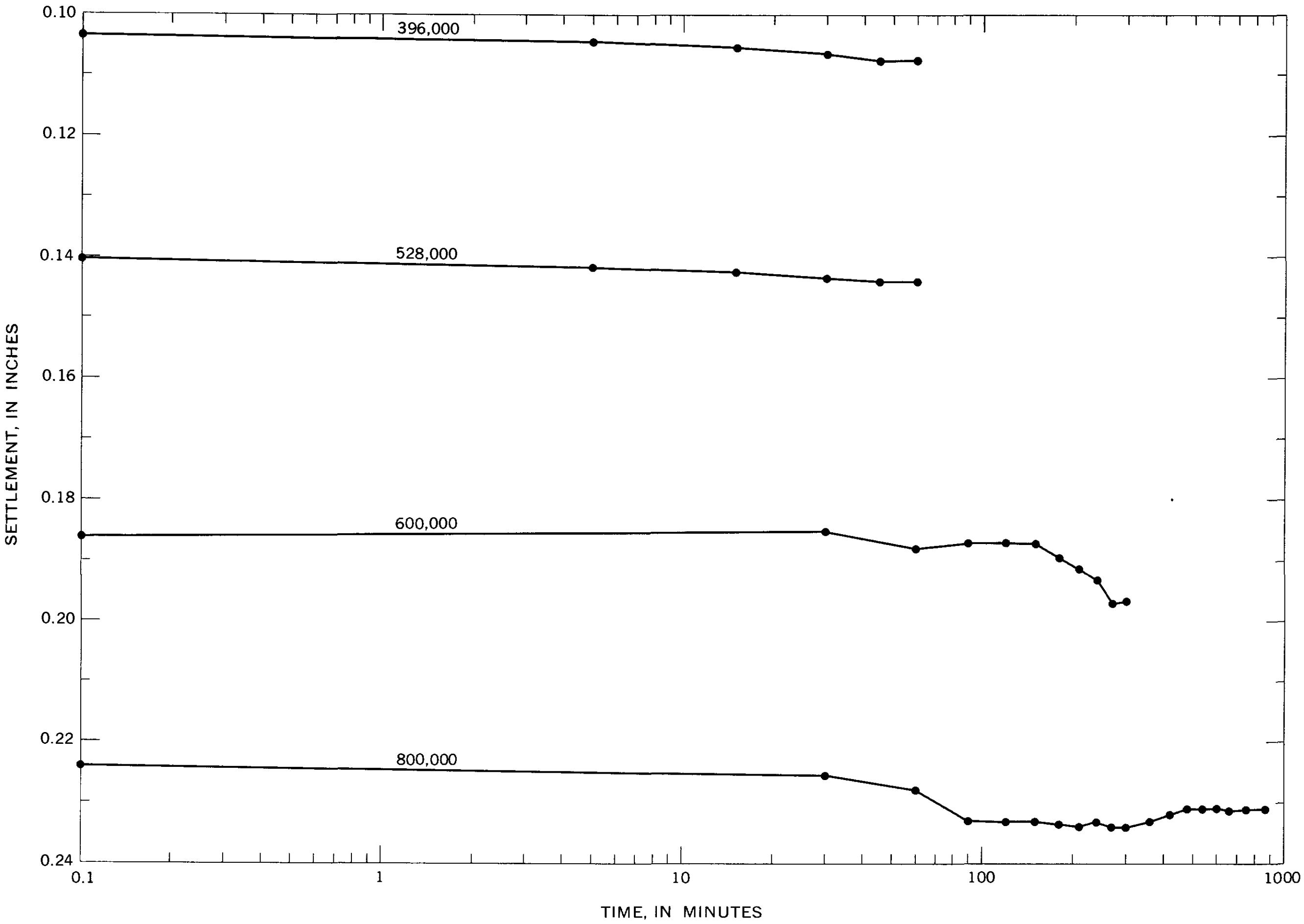


FIGURE 41.—Log time-settlement curves at high loads of 396,000–800,000 pounds on caisson 4. Reading at time zero is plotted at 0.1 minute. Readings at 0 and 60 minutes (end of tests) for lower loads of 66,000, 132,000, 198,000, and 264,000 pounds, which are not plotted, are, respectively, 0.011 and 0.011, 0.025 and 0.031, 0.053 and 0.055. 0.067 and 0.069 inch.

In order to provide a better basis for extrapolation, the settlement data were examined to see if any consistent relations could be found between time, settlement, and load, and if these relations could be expressed quantitatively. At constant load, the log of the rate of settlement was often a linear function of the log of (time plus a constant). This function can be expressed as

$$dS/dt=A(t+B)^{-C}$$

in which S is the dial reading, t is time elapsed since application of the load, and A, B, and C are constants. The constant C, in many instances, is equal to 1. If C is equal to 1, the resulting expression has the form

$$S=a \log (t+b)+c$$

in which a, b, and c are constants.

In other tests, C is between 0 and 1 and the resulting expression has the form

$$S=d(t+e)^f+g$$

in which d, e, f, and g are constants.

Both of these types of relations are common in the test series.

Many other possible expressions were tested against the results, and dimensional analysis was used to some extent in exploring physically reasonable relations. No expressions were found that consistently fit the observations better than the equations just given.

By a combination of trial and error and graphical and statistical methods, time-settlement relations were derived for many of the tests. Correlation coefficients were calculated for the fit of actual observations against the least-squares-adjusted empirical expressions. These coefficients are show in table 6.

Interestingly enough, the exponents of time in several of the power expressions are close to the value one-third. This fact indicates that here there may be some physical mechanism operating that follows Andrade's law of creep (Cottrell, 1952).

Figure 45 shows an example of a time-settlement curve that is well fit by the logarithmic form. Figure

TABLE 6.—*Derived empirical time-settlement relations for caisson tests, correlation coefficients* (r) *between these relations and observed data, and remarks concerning the tests*

[Settlement, S, is in inches; time, t, is in minutes. Notation "irregular" means settlements did not plot into a smooth curve]

Load (pounds)	Length of test (minutes)	Plot of settlement	Empirical formula for time-settlement curve	Correlation coefficient	Remarks
			Caisson 1		
66,000	60	Irregular			
132,000	120		$S=0.00573\ (t+0.1)^{0.345}+0.0734$		Formula fits from 0 to 60 min. No change 60 to 90 min.
198,000	120	Irregular			
264,000	90		$S=0.0184\ t^{0.335}+0.343$		Unloaded and repeated; formula is for 1st test.
396,000	240		$S=0.080\ \log_{10}(t+4)+0.8091$	$r=0.998$	
528,000	300		$S=0.1276\ \log_{10}(t+4.16)+1.3456$	$r=0.999+$	
660,000	570	Irregular 120 to 300 min	$S=0.1663\ \log_{10}(t+2.6)+1.9584$	$r=0.999+$	Tension caissons lifted; value of r is for 0–120 min and 300–570 min.
800,000	(1st) 90				Formula is good after 90 min for 2d test.
	(2d) 5,220		$S=0.1301\ t^{0.169}+2.236$		
			Caisson 2		
66,000	60	Linear versus the log of the time after 30 min.			
132,000	105		$S=0.00971\ (t+5.3)^{0.315}+0.797$	$r=0.998$	
198,000	120	Irregular			Tension caissons may have moved.
264,000	210	Irregular velocity curve			
396,000					Data incomplete.
528,000	1,380		$S=0.229\ \log_{10}(t+10)+2.431$	$r=0.996$	
600,000(?)	70				Time too short to analyze.
800,000					No test.
			Caisson 3		
66,000	90	Irregular			
132,000	90	Irregular before 30 min	$S=0.0116\ \log_{10}t+0.0803$		Formula good for 45–90 min.
198,000	90		$S=0.0166\ \log_{10}(t+6)+0.141$	$r=0.994$	
264,000	90		$S=0.0198\ \log_{10}(t+4)+0.216$	$r=0.993$	
396,000	120		$S=0.0334\ \log_{10}(t+6.5)+0.386$	$r=0.999$	Preceded by 345,000-lb(?) load.
528,000	270		$S=0.0273\ (t+0.7)^{0.33}+0.645$	$r=0.989$	
660,000	750		$S=0.0475\ (t+0.074)^{0.342}+1.004$	$r=0.999+$	
800,000	3,613		$S=0.1466\ (t+4.67)^{0.244}+1.652$		Not very regular.

46 shows a time-settlement curve from another test that is closely fit by a power function.

The coefficients preceding the time terms in the empirical time-settlement relations shown in table 6 may be expected to depend upon the load, the physical properties of the material being tested, the area under load, the shape of the caisson, and, perhaps, many other factors.

The dependence of the coefficients on load, assuming the other factors remain constant, was explored in the following manner: The coefficients of the settlement-$\log_{10}$ time type of relations were multiplied by 0.4343 to convert them to coefficients of natural logarithms; the coefficients were thus made comparable with the coefficients of power of time-type relations. Then in figure 47 the logs of all these coefficients were plotted against the log of the load.

Figure 47 shows that the coefficients for the time-settlement relations derived for caisson 1, whether they apply to the natural logarithm of time or to the power of time type of expression, all fall close to a straight line. The slope of this line, by least-squares adjustment, is 1.663. The line connecting points for the two satisfactory tests on caisson 2 has a slope of 1.679, very nearly the same. Tests on caisson 3, however, yield a plot that is linear to about a 264,000-pound load but strongly concave upward at higher loads. The conclusions that may be drawn from figure 47 are that the coefficients of the time-settlement relations for caisson 1 depend upon load approximately to the 5/3 power, that the relations for caisson 2 are perhaps similar, and that the material under caisson 3 reacted differently. It appears unlikely, from figure 47, that the effect of the load on time-settlement relations could be expressed by mathematical formulas of the same form for all caissons. As noted (p. 53), the auger-boring logs showed that test caissons 1 and 2 rested on pediment gravel and caisson 3 on Dawson Arkose.

The expected time-dependent part of the settlements to 100,000 minutes (about 10 weeks) are extrapolated in figure 48. The extrapolation was done by either sketching extensions to the plotted time-settlement graphs, if no formula was derived, or by computation, if the observed data appeared sufficiently regular to warrant derivation of a formula. As can be readily seen, the results show considerable scatter and do not appear to offer the possibility of predicting the time-dependent settlements over a long period more accurately than to within about half an inch.

The total settlements to be expected at 100,000 minutes for caissons 1–3,—that is, the sum of the instantaneous settlements shown on figure 43 and time-de-

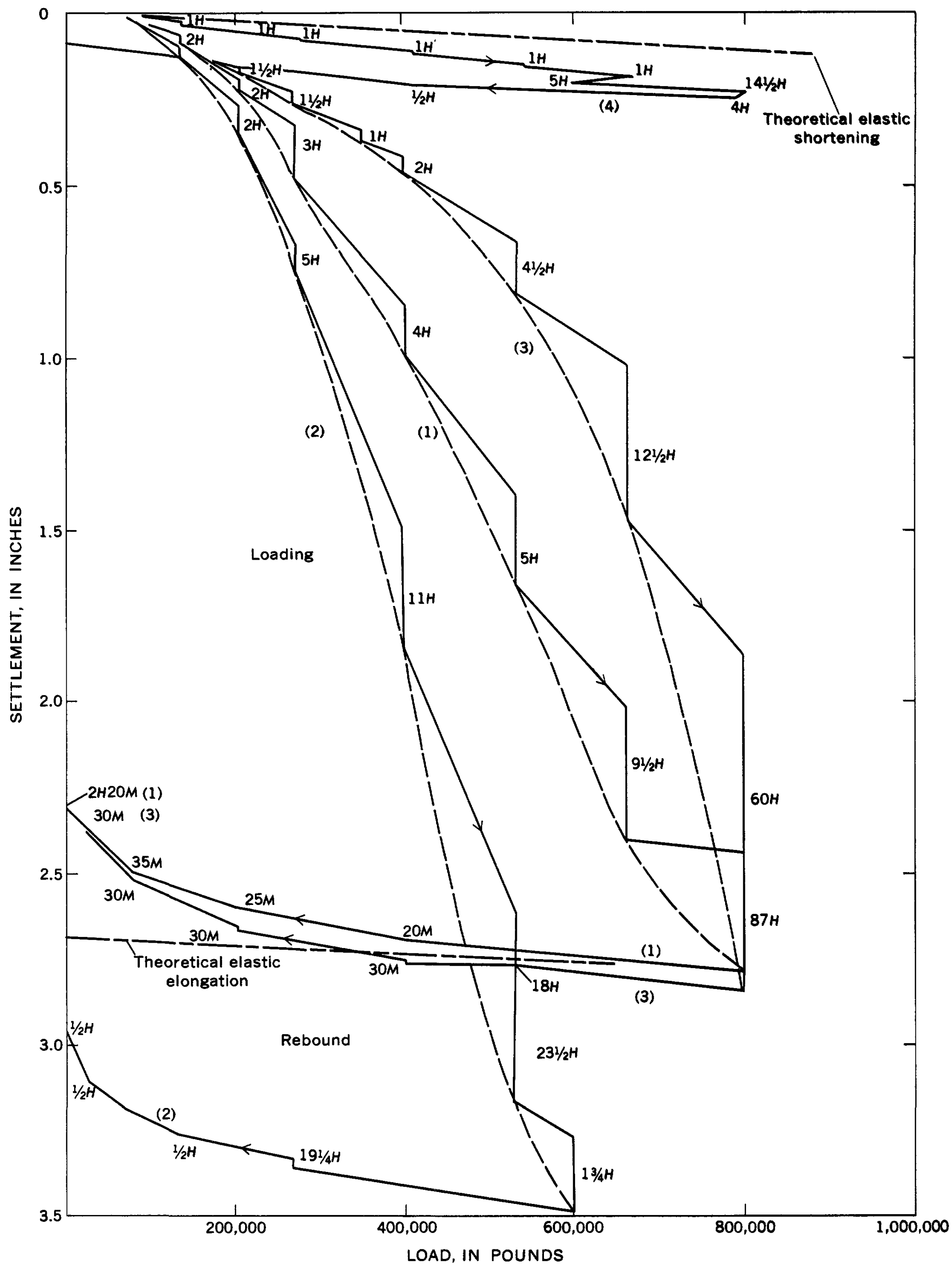


FIGURE 42.—Load-settlement curves for test caissons. Curves (1), (2), and (3) are for caissons 1 and 2 in pediment sand and gravel, and caisson 3 in Dawson Arkose, having penetration values of about 45, 20, and 120 blows per foot, respectively. Curve (4) is for test caisson 4 in Dawson Arkose at test pit 4. Solid lines indicate actual loading and unloading by increments; length of time that most of the loads were applied is shown by hours, *H*, or minutes, *M*. Dashed lines are smoothed curves through incremental loading points. From "Report on Caisson Load Tests Synopsis" by Skidmore, Owings, and Merrill, 1956.

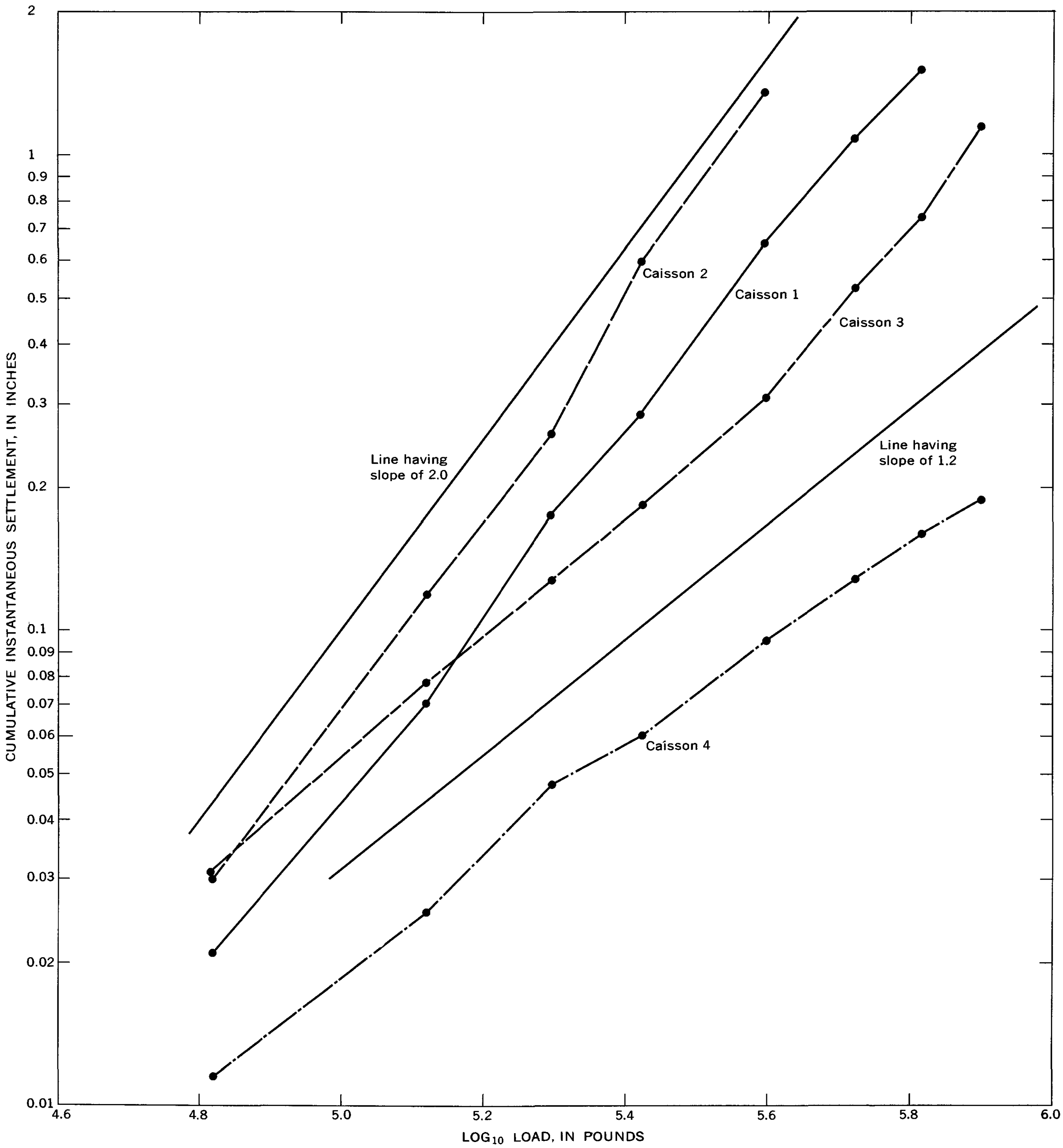


FIGURE 43.—Log cumulative instantaneous settlements versus log loads, caissons 1–4. The instantaneous settlements are those due to the indicated load plus intantaneous settlements due to prior load increments. Initial reading at caisson 2 before any loading is not known; if the instantaneous deformation due to 66,000 pounds is assumed to be 0.03 inch, the resulting plot is shown by the line of short dashes.

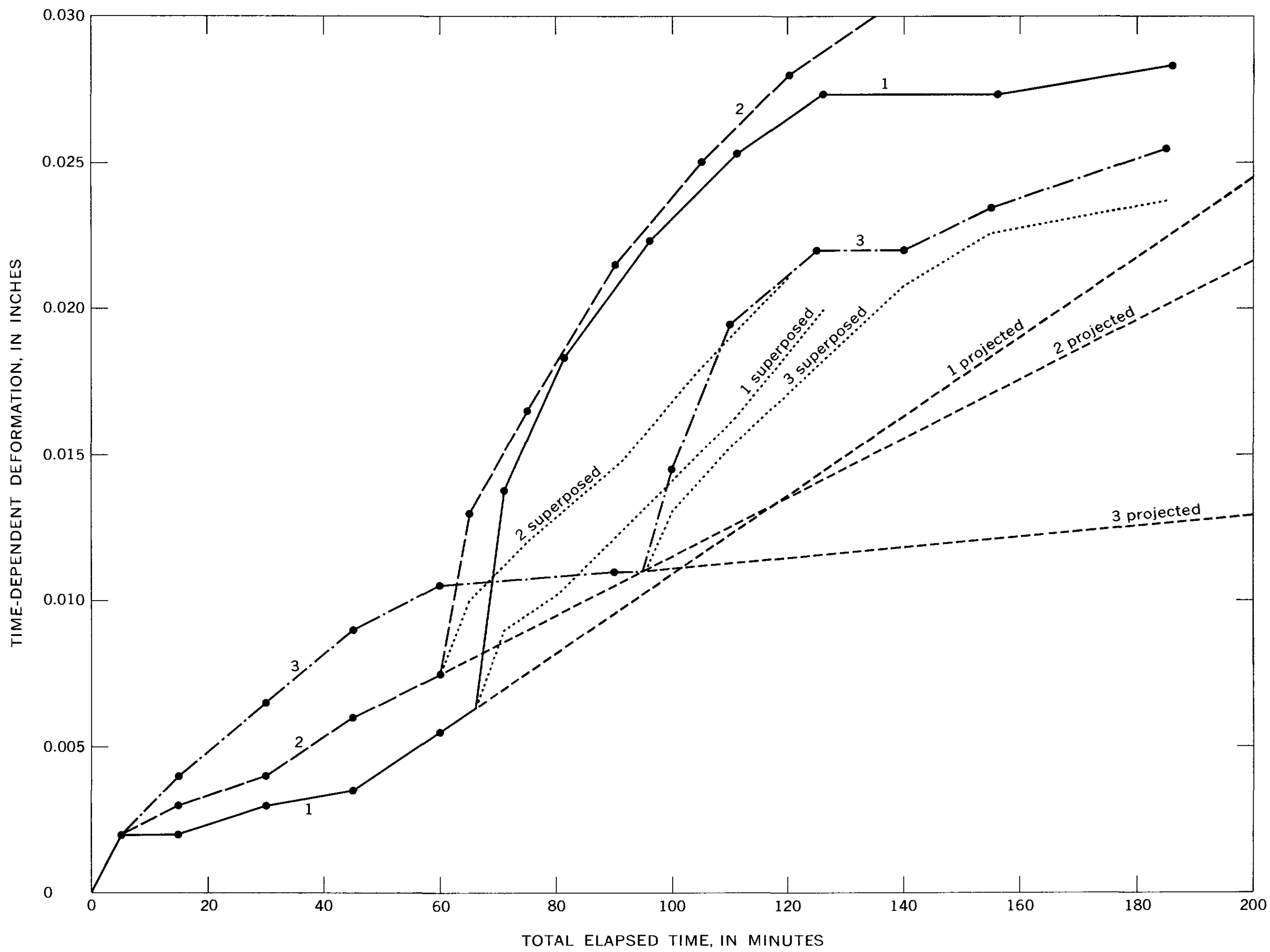


FIGURE 44.—Relation between actual time-dependent deformation and the time-dependent deformation to be expected if the law of superposition held. The actual deformations at caissons 1, 2, and 3, with the instantaneous parts removed, are shown by solid, long dash, and dot-dash lines, respectively. The first parts of the curves represent initial loading at 66,000 pounds and are projected by short-dash lines. The parts of the curves beyond the sharp rise represent actual deformation upon loading with an additional increment of 66,000 pounds to a total of 132,000 pounds. The dotted lines are deformations to be expected if the deformation at 132,000 pounds could be represented by superposition of deformations due to an increment of 66,000 pounds upon those due to the original 66,000-pound load.

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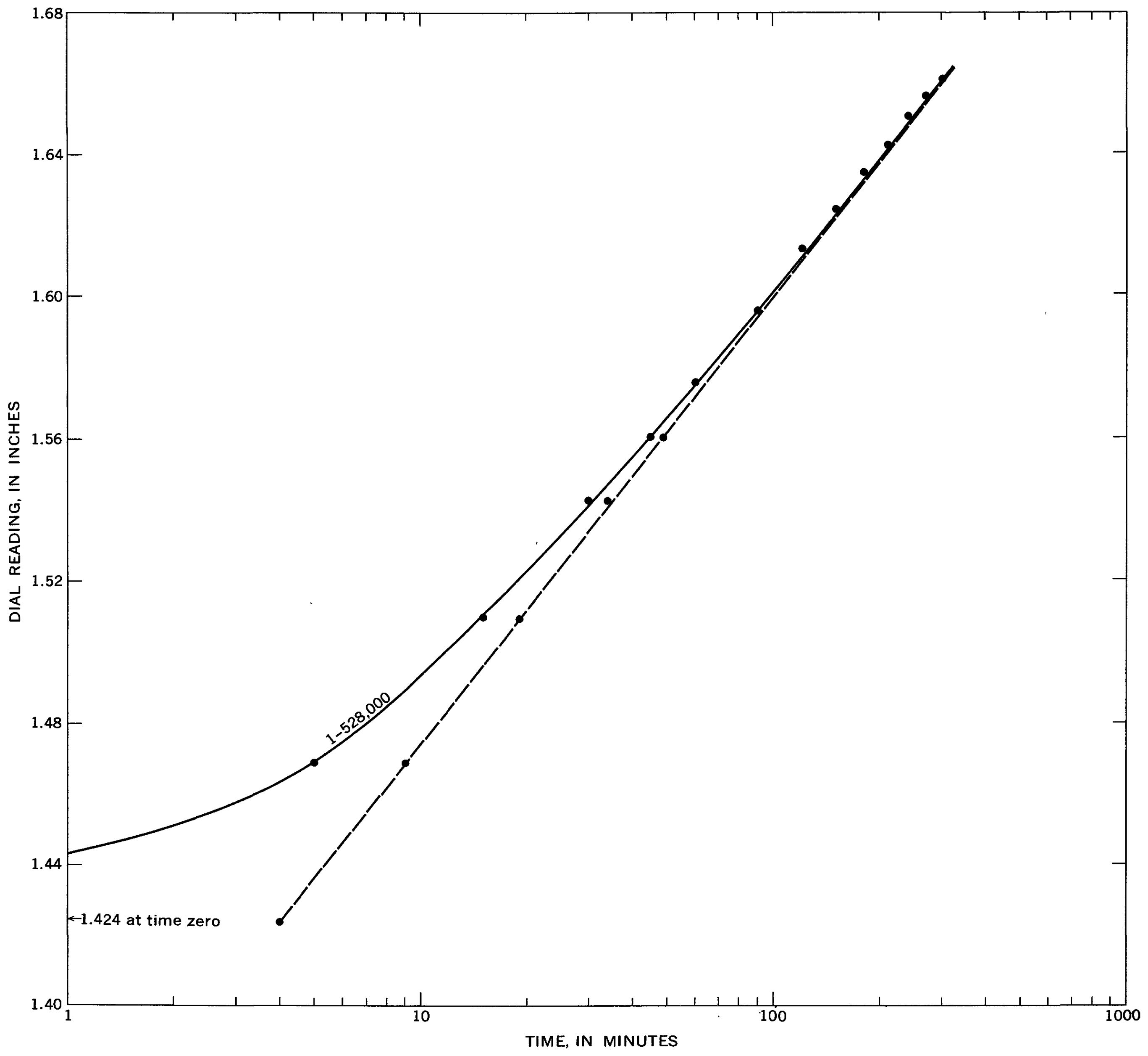


FIGURE 45.—Log time-settlement curve for test at 528,000-pound load on caisson 1. Curve is straightened by adding 4.16 minutes to the actual time of observation, as shown by the dashed line.

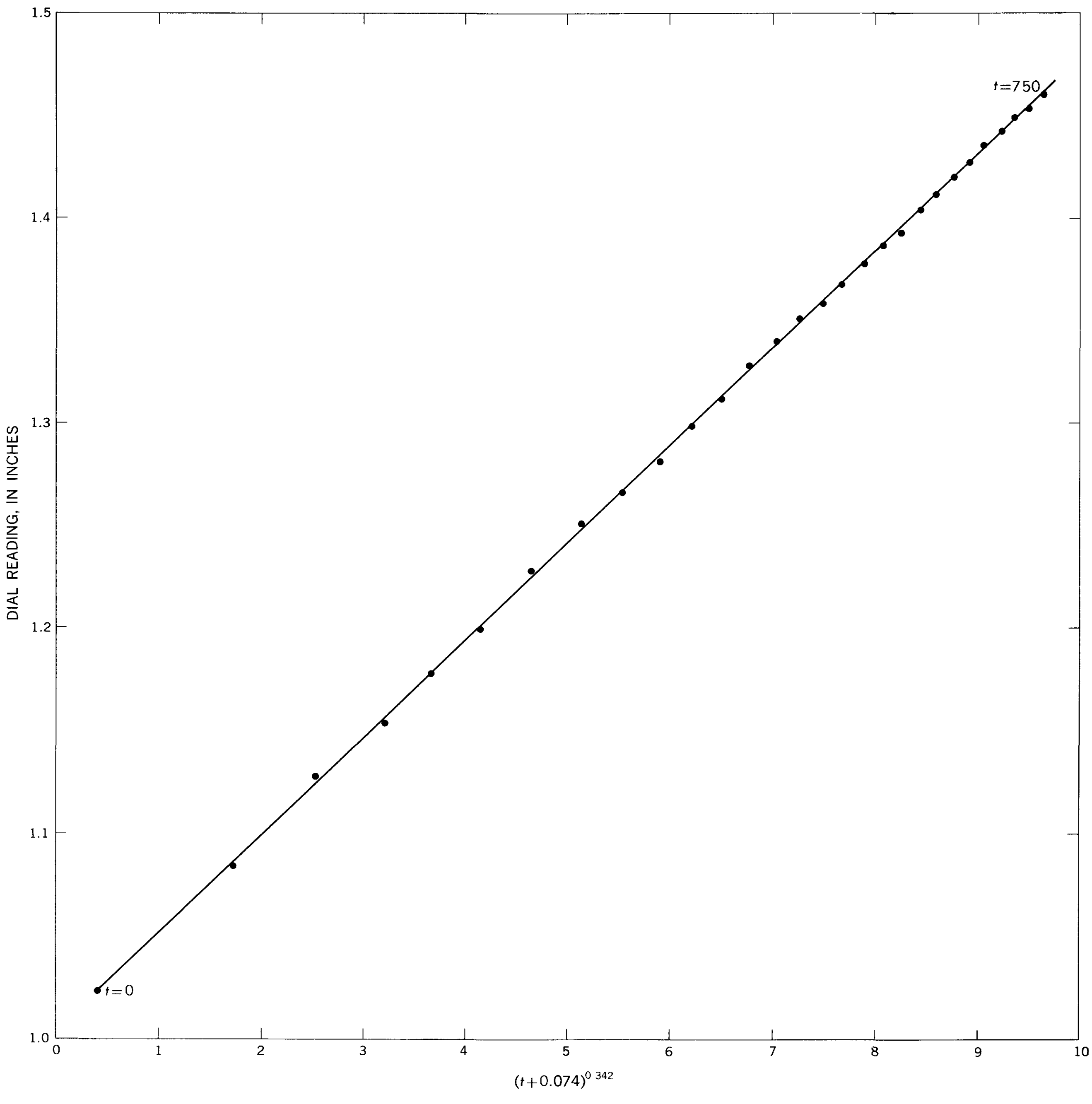


FIGURE 46.—Graph showing fit of the observed settlement of caisson 3 under 660,000-pound load, shown by dots, against the empirical formula Dial reading $=0.0475(t+0.074)^{0.342}+1.004$, shown by the straight line. Time, t, is in minutes. The correlation coefficient is 0.999+.

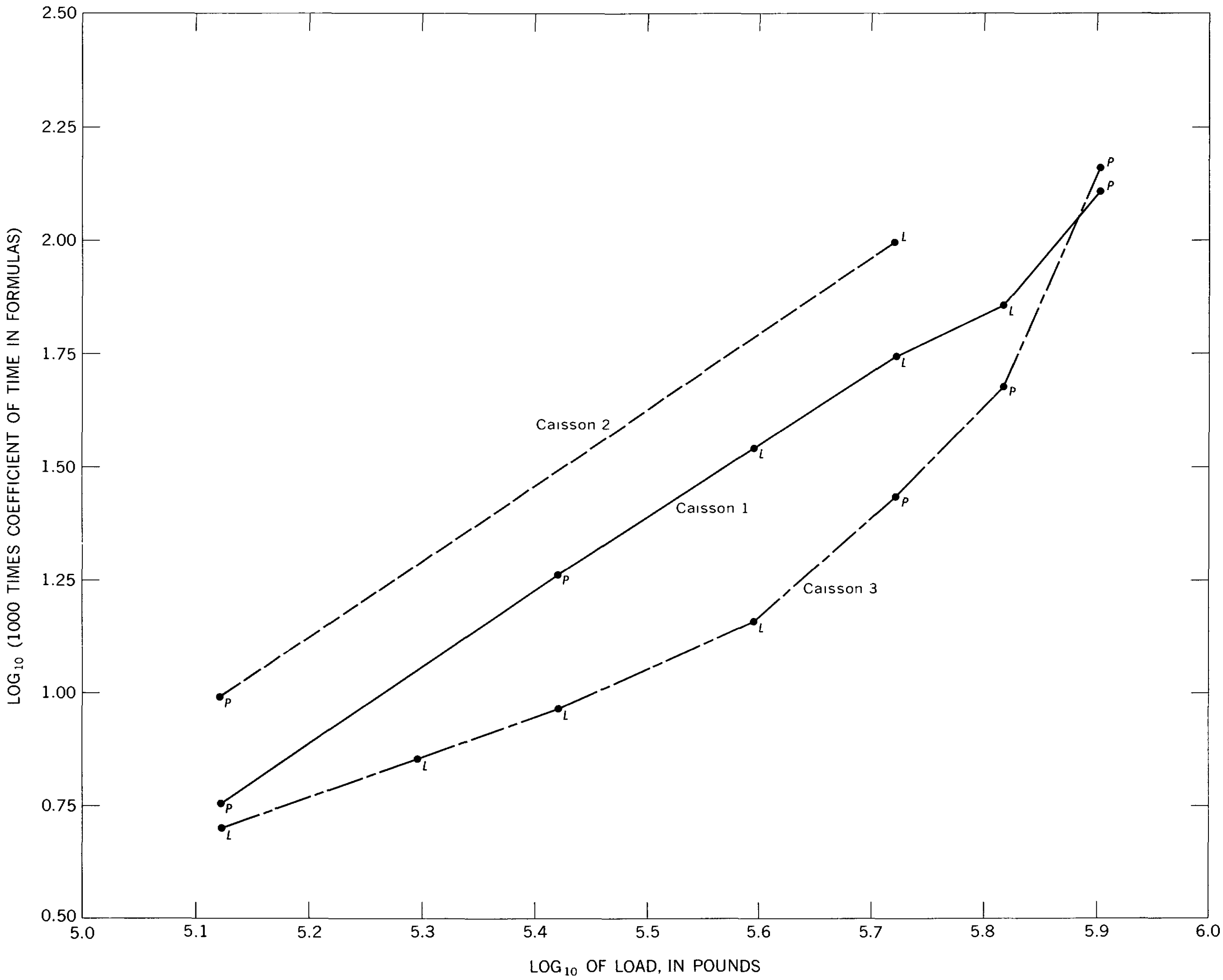


FIGURE 47.—Log_{10} of 1,000 times the coefficients of the time terms in derived time-settlement relations plotted against $\log_{10}$ of load. Letters *L* and *P* indicate, respectively, that the derived coefficients apply to terms of the natural logarithm of time or of the power of time type.

pendent settlements shown on figure 48—are plotted on figure 49. These graphs can be compared with the settlements estimated by the architect-engineer from the same series of tests for particular design loads on materials with various blow counts (Brown and Teng, 1957). The assumed settlement time on which the architect-engineer's estimate was based is unknown. The two estimates agree very well for caisson 1, if an average curve is drawn through the graphed points; they differ by a factor of about two for caisson 2, ours being higher, and they agree almost exactly for caisson 3.

CONSOLIDATION TEST OF DAWSON CLAY

One sample of clay from the Dawson Arkose was subjected to a consolidation test in the U.S. Geological Survey laboratory. This sample, AFA–50, was taken at the Pueblo Brick and Tile Co. clay pit, located at coordinates 2,188,670 E., 428,800 N., from a bed of gray clay about 6 inches thick and 6 feet above the floor of the pit. The location was selected as the best available to obtain large, undisturbed, recently exposed, and representative samples of the clay beds associated with normal arkose of the Dawson Arkose. This location is not in the area of heavy construction on Lehman Mesa; hence the results of this test bear only indirectly on the behavior of clays that may be present in the bedrock beneath the larger buildings.

The plot of the void ratio against the load, presented in figure 50, shows that the clay is heavily preconsolidated, as may be expected, and that even under a load of about 30 tons per square foot, consolidation is

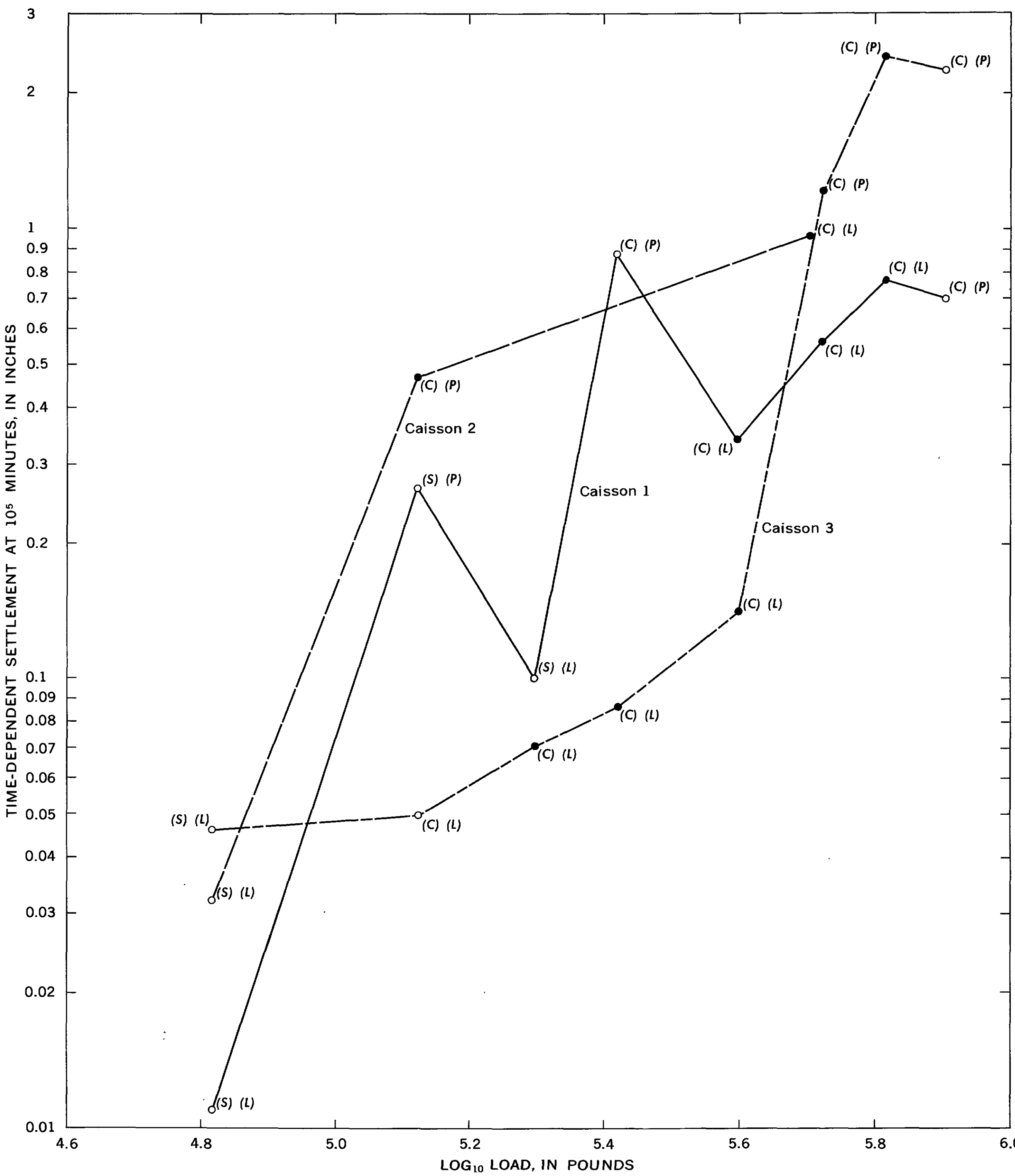


FIGURE 48.—Log of expected time-dependent settlement at 100,000 minutes plotted against log load. The settlements were extrapolated from the tests either by sketching (*S*) or by computation (*C*). The time-settlement functions used were log time (*L*) or power of time (*P*). Points shown by solid dots were obtained from formulas that fit the observed data with a correlation coefficient higher than 0.98.

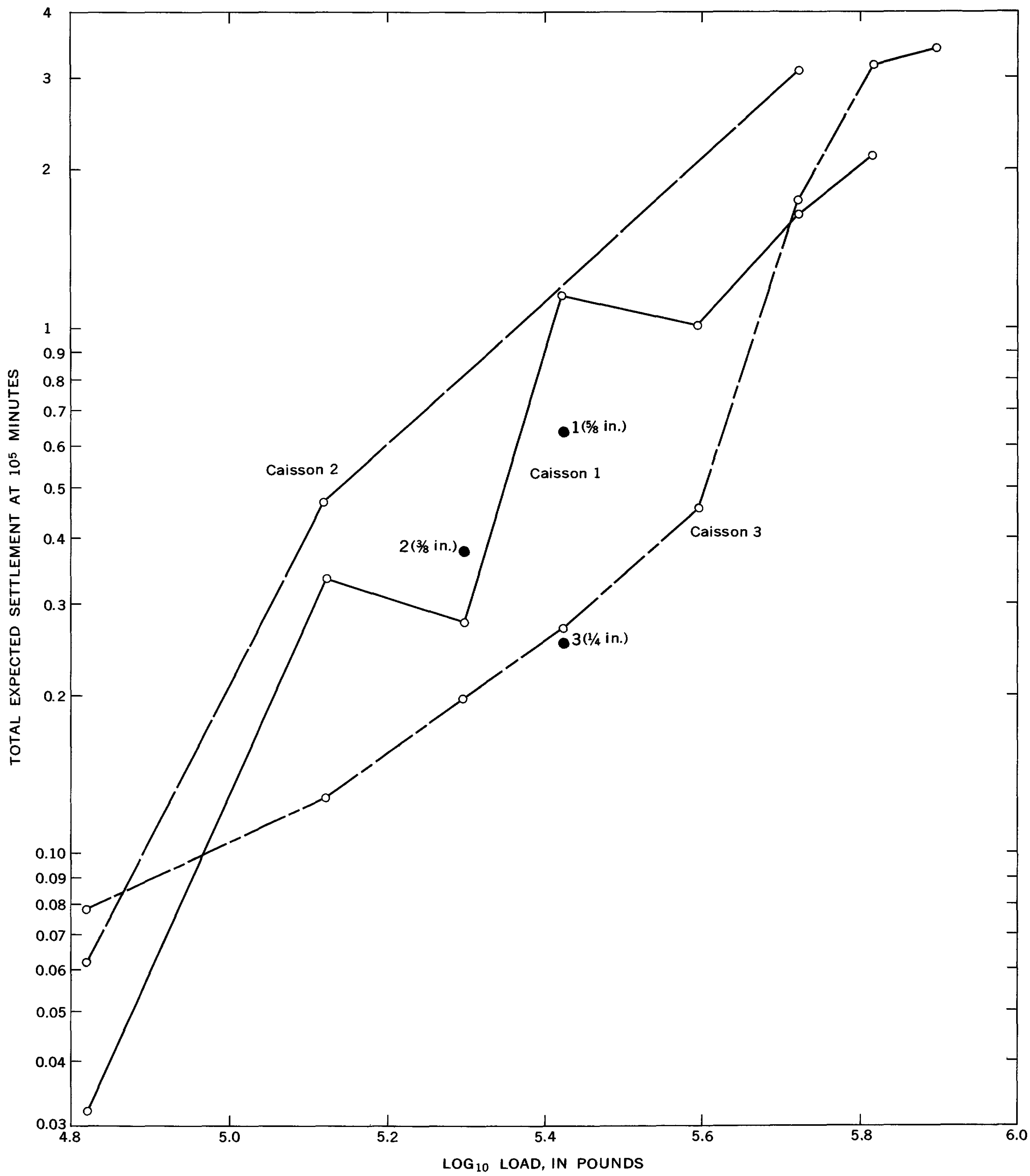


FIGURE 49.—Log expected total settlement at 100,000 minutes (sum of cumulative instantaneous and time-dependent parts) plotted against log load. The solid dots are the estimates of the architect-engineer (Brown and Teng, 1957) for expected settlements at design load in materials corresponding to those at caissons of the indicated number.

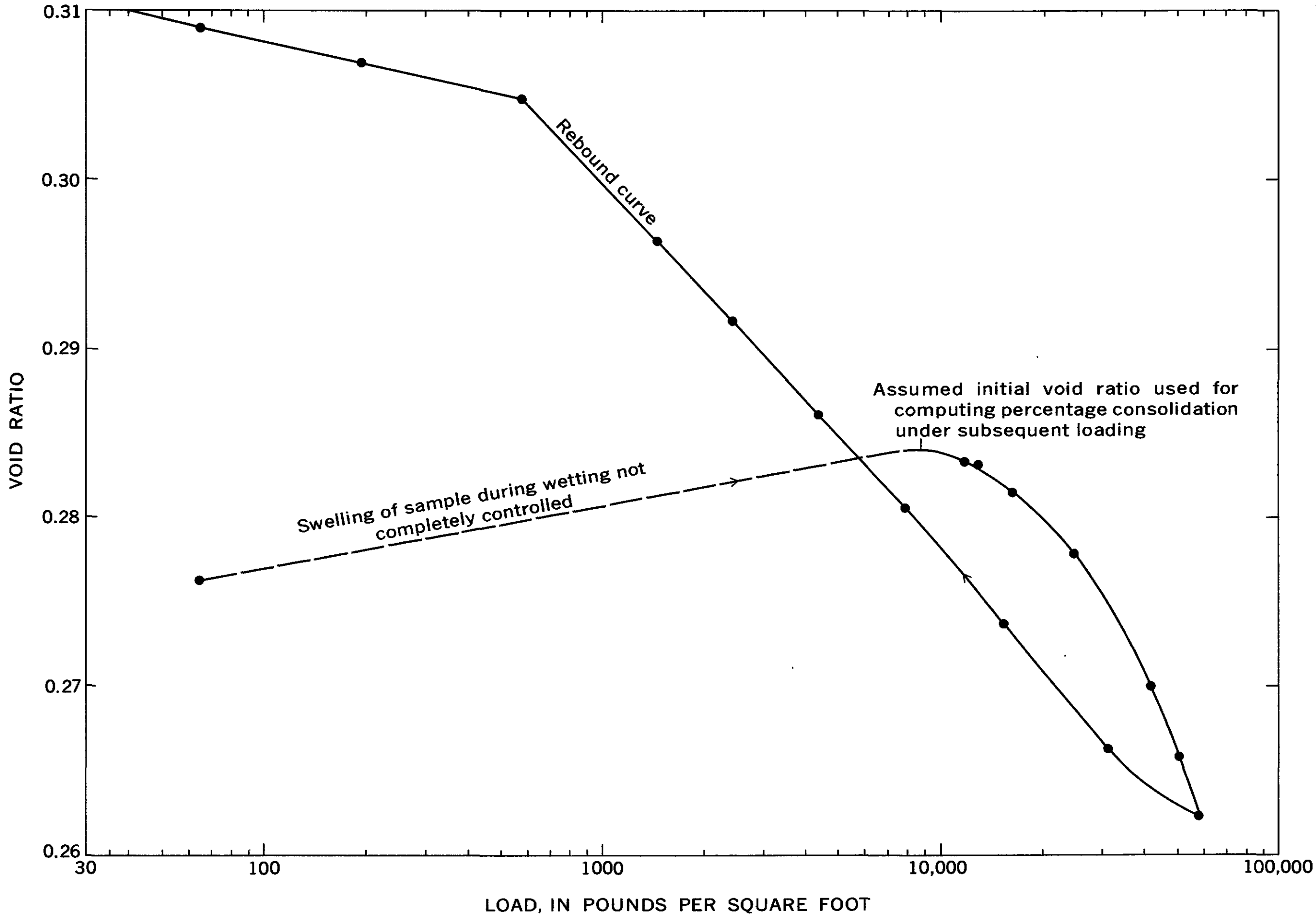


FIGURE 50.—Void ratio plotted against load. Dawson clay from Pueblo Brick and Tile Co. clay pit, sample AFA–50. Void ratio is that attained after load has been applied 24 hours. Diameter of sample, 2.5 inches; thickness, 1.0 inch.

slight. Some difficulty was experienced in keeping the sample (originally air-dry) at constant volume during saturation. Swelling pressure reached about 4 tons per square foot before consolidation began at greater loads. The sample swelled measurably beyond its original size upon release of load, as shown by the rebound curve. The reason for the pronounced flexure in the upper part of the rebound curve is not known.

The void ratios shown in figure 50 are those attained after the load had remained constant for 24 hours. The percentage of consolidation for various loads is plotted against time in figure 51. These plots show that the rate of consolidation, at least for the higher loads, is still appreciable after 24 hours. The plot of the percentage of consolidation versus the log of the time is approximately linear; it shows no consistent flattening of slope with greater time for the duration of these tests.

The sample had a rather high swelling pressure for a kaolinitic clay, which it was assumed to be, and was therefore also examined with the X-ray diffractometer. Montmorillonite was not detected in the bulk sample, but both montmorillonite and montmorillonite-illite mixed-layer clay were found when only the clay-size fraction was examined. Kaolinite is abundant and illite is a minor constituent. The montmorillonite probably accounts for the swelling properties of the clay.

DESIGN RECOMMENDATIONS

GRADING

Many precautions were taken to insure maximum stability and minimum settlement in the load-bearing embankments in the academic area. Specific recommendations were made by Abdun-Nur and concurred with by the architect-engineer on the use of the three types of material described earlier. Type 1 material (sandy gravel) should be placed in the outer shells of embankments—under retaining walls and under the buildings; type 2 material (gravelly sand) should be used in less critical sections of the embankment behind

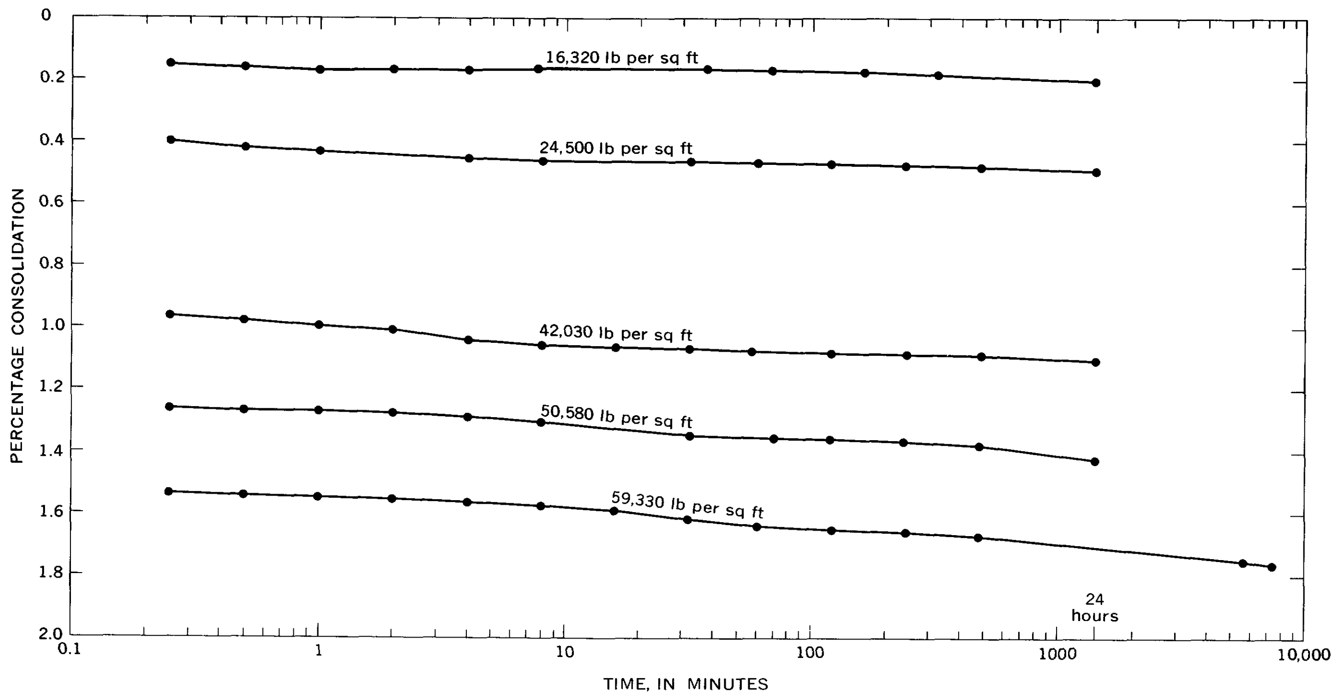


FIGURE 51.—Percentage of consolidation plotted against log time. Dawson clay from Pueblo Brick and Tile Co. clay pit, sample AFA–50. Percentage of consolidation computed from an initial state at which tendency to swell is in equilibrium with applied pressure, as shown in figure 50.

the shell made from type 1, or to replace shortage of type 1; type 3 material (Dawson Arkose) should not be used under structures or in high fills but would be usable as the top layers in the fills because its impermeability would reduce the infiltration of surface waters into the foundation areas. Where the Dawson is not in a laterally confined embankment, slopes should be kept to a minimum. Cobbles and boulders larger than 6 inches in longest dimensions, which constitute about 5 percent of types 1 and 2 material, should be removed before placement in an embankment. Boulders larger than one-half cubic yard should be stockpiled for use as riprap elsewhere. Where fill is to be placed on natural ground having a slope of more than 30°, the natural ground should be benched. About ½–1 foot of topsoil was stripped from all borrow and embankment areas and stockpiled for use in reseeding the construction areas.

Compaction of the pediment gravels was to be carefully controlled, and a minimum density equal to 90–95 percent Modified AASHO, depending on the use of the area, was to be attained. The shrinkage factor was determined to be about 0.85. Abdun-Nur recommended that all material that was not too pervious to benefit should be preirrigated in borrow areas and then be placed in 6- to 8-inch compacted layers. Placement moisture should be kept slightly above optimum moisture content in material types 1 and 2, but slightly below optimum in type 3 to avoid having a "rubbery" fill. All cuts were to be made along the full depth of the face so that the material would be blended. Greater uniformity of embankment leads to easier control of density and bearing capacity.

The final grading program was so planned that at its completion all materials would be placed in their proper locations with as short hauls as possible. Nonload-bearing embankment material from the east end of the cadet quarters was to be used for the parade ground. Load-bearing embankment material from the central part of the academic area was to be used to balance excavation around the main group of buildings. Pediment gravel from the large hill at the west end of the academic area was to be used in the embankment of Goat Camp Creek Dam. Dawson Arkose from excavations for the dining hall, chapel, and aeroscience laboratory was to be used for the parade ground. Excavation was to balance embankment in the athletic fields.

RETAINING WALLS

Two types of retaining walls were built in the academic area, cantilever and counterfort. A modified counterfort design with an anchor bin in the rear was used for the higher walls, as shown in figure 52. The highest wall is 36 feet high and rests on as much as 50 feet of embankment material, which is either recom-

FIGURE 52.—Academic area from the west, showing (1) grading in progress, (2) backfill being placed next to the large counterfort retaining walls around the cadet quarters building, and (3) rows of caissons for the classroom building. The area shown is about the same as that shown in figure 35, 2 years later. Photograph by U.S. Air Force, November 8, 1956.

pacted pediment gravel or Dawson Arkose. Most of the 10,000 linear feet of walls were erected on unexcavated natural soils between the benches. The five principal problems considered in the design of the retaining walls were:

1. Stability of the foundation materials under the imposed load.
2. Settlement under the imposed load.
3. Stability against overturning.
4. Stability against sliding due to backfill pressure.
5. Gradation of backfill materials to assure drainage.

Accordingly to Brown and Teng (1957):

Due to the construction schedule, structural design and stability analysis had to be started before the completion of the soil tests. At that time the following values were assumed, based on the best information available: unit weight of soil, 130 pounds per cubic foot, angle of internal friction, 34°; coefficient of friction between base of wall and underlying soil, 0.42. Using these values, all retaining walls were designed with a minimum safety factor of 2.0 against sliding and overturning. The embankment supporting retaining walls was proportioned to maintain a safety factor of 1.5 against slope failure, pending further soil investigation.

Subsequent triaxial tests on samples compacted to 95 percent Modified AASHO density led to design values of angle of internal friction of 43°–44.2°, unit weight of 130–134 pounds per cubic foot, coefficient of sliding friction of at least 0.67, and an increase in the safety factor against slope failure from 1.5 to more than 2.

The embedment of the retaining-wall foundation slab was to be below the frostline at a depth of 5 feet or more. In both excavation and embankment a maximum footing pressure of 5,000 pounds per square foot was recommended. A settlement of 1.5 percent of the height of embankment is expected in type 1 material and 2 percent in type 2 material. In order to keep settlement to a minimum, Abdun-Nur recommended that the concreting of the retaining walls and the compacting of the backfill behind them be delayed as long as practicable after the completion of the fills. In spite of all precautions, some unequal settlement is bound to take place, particularly where the foundations change from fill to natural ground and where changes between different types of foundation materials take place. Backfill material behind the retaining walls was specified to be a non-frost-susceptible material, either pit-run sand and gravel or cleaner type 1 material which contains less than 10 percent material passing the No. 200 sieve and less than 0.5 percent organic matter. Drainage was required behind the walls. Either weep holes or continuous drains, or a combination of the two, were to be used along with filters to insure continuous operation. A blanket of impermeable material was to be spread on top of the backfill near the walls to reduce the infiltration of surface water.

FOUNDATIONS

The caisson or subpier foundations were to be placed on Dawson Arkose. To design for the number and size of caissons needed in the poorest known pediment gravel would have been more expensive than extending the caissons deeper into Dawson. Although a pressure of 50,000–60,000 pounds per square foot is required to shear granular Dawson, the weathering characteristics of the Dawson made it necessary for the concrete to be placed in the caissons quickly after they were drilled. Clayey Dawson slakes rapidly, as shown in figure 8. Material that has a penetration resistance of 140 blows per foot may soften overnight to a penetration resistance of only 10 blows. The arkosic sands on the other hand caseharden on exposure. To assure that the Dawson at the bottom of each hole had good bearing capacity and was not underlain by unstable material, the bottoms of most of the holes were examined visually and a rod was driven 5 feet below the bottom of the bell in every hole. Several holes had to be deepened to reach stable material. All caissons were carried down to 100-blow material, at least 5 feet into granular Dawson, and at least 14 feet below basement floor or finished grade level, whichever was lower. A bearing pressure of 20,000 pounds per square foot was allowed under the belled-out shaft. The bells were cleaned out and concrete was poured within 90 minutes to avoid air slaking and loss of bearing capacity.

HOUSING AND COMMUNITY AREAS

LOCAL GEOLOGY AND TOPOGRAPHY

The housing and community areas are in Pine Valley and Douglass Valley and on Pine Mesa (fig. 53), Douglass Mesa, and Lehman Ridge. The ground in these areas slopes gently to the east. There are four geologic settings: the Pine Valley housing is on Pine Valley Gravel; the Douglass Valley housing is on colluvium and Dawson Arkose; the Pine Mesa and Douglass Mesa housing and community facilities are on Douglass Mesa Gravel; and the Lehman Ridge housing is on Lehman Ridge Gravel.

PROPOSED CONSTRUCTION

The housing and community areas include:

1. Civilian housing and schools in Pine Valley.
2. Military housing and school in Douglass Valley.
3. Officers' housing in Douglass Valley.
4. Superintendent's and Dean's housing on Lehman Ridge.

FIGURE 53.—View looking south, over the community center, on Pine Mesa in the foreground, to the Pine Valley housing area in the background. The buildings under construction in the community area are, from left to right: support personnel physical education, dormitories, dining hall, dormitories, base exchange, and communications. Photograph by U.S. Air Force, August 15, 1958.

5. Academy staff club and bachelor and visiting officers' quarters on Douglass Mesa.
6. Community area and airmen's dormitories on Pine Mesa.
7. Guest housing—hotel on Douglass Mesa.
8. Academy fire station on Douglass Mesa.
9. Community fire station in Pine Valley.
10. Academy hospital on Douglass Mesa.

EXPLORATION PROGRAM

The exploration program was virtually the same at each of the sites and consisted of making borings and penetration tests to determine the bearing strength of the soil, the depth to the water table, and the amount of boulders. Samples were taken from most of the borings and tested in the soils laboratory of the architect-engineer.

Recommendations were then incorporated in a soil-survey report for each building area. These recommendations included: compaction of embankment to 95 percent Modified AASHO density and control of water content within 1 percent of the optimum moisture content, stripping of topsoil to a depth of one-half a foot, removal of boulders more than 6 inches in diameter from embankments at depths of more than 3 feet below finished grade, and removal of boulders or cobbles more than 2 inches in diameter from the upper 3 feet of embankment. All concrete slabs or footings were to rest on crushed gravel or rock having a plasticity index no higher than 3 and the following gradation:

Sieve size	*Gravel or rock passing (percent)*
1½ in	100
¾ in	40–100
⅜ in	5–40
No. 4	0–15
No. 200	0–5

After the soil survey and the drafting of the general recommendations, specific designs were drawn for grading, foundations, and subdrains. The choice between spread footings and caissons was a matter of cost. Most of the larger structures are on caissons; high loads and the presence of boulders generally precluded spread footings. The medical airmen's building, the nurses' quarters, and many of the community area buildings, however, are on spread footings in Douglass Mesa Gravel. The hospital is on 9½- to 18½-foot caissons in Dawson Arkose. Figure 54 shows the footings, in Dawson Arkose, of the quarters for bachelor officers and visiting officers.

Some of the specific problems that were or may be encountered for the different areas are:

1. The foundations in the community area and at the staff club are partly on Dawson Arkose and partly on Douglass Mesa Gravel. Because of a probable difference in bearing capacity between the two formations, the foundations had to be designed to avoid differential settlement.
2. Husted Alluvium and colluvium should have been mapped by us in greater detail in the area of the officers' housing. Specifically, Husted Alluvium extends farther up the small gullies in the fan-like area at the head of Douglass Valley than our mapping indicated. At one place in the officers' housing area, a series of houses was separated from the main road by one of the small gullies filled with Husted Alluvium. No borings had been made of the driveway alinements; therefore the bearing strength of the subsoil was unknown. When bulldozers and earthmovers crossed the Husted Alluvium, they sank 3–4 feet. Therefore, before the driveways could be built, a thickness of 5–6 feet, or about 13,000 cubic yards, of wet sandy humic Husted Alluvium had to be removed and replaced by stable granular material.
3. In several of the housing areas, especially on the north-facing slopes, the water table not only is high, but it also fluctuates considerably from one season to another. The officers' housing, the community fire station, the military teaching and support-personnel housing, and the gymnasium in the community area had to be subdrained.
4. Surface water may be troublesome to housing situated in valleys. During cloudbursts, which occur about once a year, sheet flow from the valley sides may be several inches deep. Although no houses were built on the main channel of Douglass Valley, some houses may be close enough to require special provisions to handle surface runoff.

FIGURE 54.—Footings, in granular Dawson Arkose, of the quarters for bachelor and visiting officers.

The southeast-trending tributary at the west end of Pine Valley has no well-defined channel where it enters Pine Valley. The tributary occupies a low swale that follows Road 10 eastward past the housing area, but in time of flood the water from the tributary probably would overflow the swale and spread out across the west end of the civilian housing area. The fire station at the mouth of this tributary may be troubled by both sheet flow from the valley sides and flood runoff from the tributary.

5. Colluvium in Pine Valley is more frost susceptible than is Pine Valley Gravel. The colluvium contains 10–40 percent material finer than the No. 200 U.S. Standard series sieve and is generally rather wet. The Pine Valley Gravel contains 5–20 percent material finer than the No. 200 sieve and is generally dryer than the colluvium. The community fire station at the west end of Pine Valley originally was to be placed on colluvium, but because of the fineness of the colluvium and the intermittent springs at foundation level the site was moved onto Pine Valley Gravel.

SERVICE AND SUPPLY AREA

The service and supply area is on the Pine Valley pediment northeast of the junction of Kettle Creek and Monument Creek. The pediment slopes about 125 feet per mile to the southwest and is composed of Pine Valley Gravel, east, which overlies the Dawson Arkose.

Foundation conditions were explored with 4-inch flight augers, 18- and 24-inch helix, and the split spoon. Hard beds of siltstone and the thick lower sandstone of the arkosic Dawson underlie the whole area. More than 250 blows per foot of the split spoon were required to penetrate this material. Overlying the sandstone is thin-bedded humic sandy compressible clay and silt, which contains charcoal, and thin-bedded gray coarse to fine sandstone. Above the Dawson is light-brown coarse to fine sand containing some silt and some pebbles and having penetration resistance of only 30 blows per foot. The upper part of the Pine Valley Gravel is harder and more compact because of more clay enrichment in the soil. After the exploration was completed a selective grading program was laid out. Boulders and cobbles were too scarce to be of any concern. Topsoil to be stripped is thicker on the Pine Valley pediment east of Monument Creek than on the pediments west of the creek. The wet humic claybeds in the Dawson were undercut in all load-bearing areas.

The depth to the water table ranges from 20 feet at the east end of the service and supply area to 33 feet at the west end. The water table in much of this area is perched; locally it is less than 10 feet below ground level. Frost susceptibility is greatly increased by a water source so close to the surface; therefore these soils were classified as F–2, or frost susceptible. Water was so abundant at one of the foundations of the headquarters building that a sump pump had to be installed. Water also was more abundant at the south end of the area where the Dawson is more shaly than at other places. Most of the foundations were installed on caissons resting on Dawson.

HEATING TUNNEL

The heating plant for the academic area is in the upper part of South Lehman Valley south of the academic area (see fig. 55, p. 75). Heat is piped across the intervening area by a tunnel about 800 feet long built through a gravel-capped ridge adjacent to the heating plant and connected to the academic buildings by a covered conduit. The tunnel was drilled in semiconsolidated coarse arkosic sand and clay of the Dawson. Although the material is weakly cemented it is very dense; no penetration could be made in it with the split spoon even though a 348-pound hammer was used. In three borings, one of which was 102 feet deep, no fractures were found and the only soft material was at the portals of the tunnel. No ground water was found in the drill holes.

No trouble was anticipated in the hard sandstone, which was expected to stand unconfined, but the caisson tests in the academic area indicated that the siltstone and claystone might slake upon exposure. The siltstone and claystone also were expected to permit excessive overbreakage in the tunnel.

On the basis of the drill holes and known characteristics of the Dawson, the following recommendations were made by SOM:

1. Because the rock is friable, explosives should not be used under any circumstances, but the tunnel should be advanced by augering, sawing, or other similar methods.
2. Within 8 hours after the rock is exposed, the liner plates should be installed, blocked, wedged, and backpacked.
3. The portals should be supported under the 1–5 feet of overburden and also protected against boulders that might roll off the pediment.
4. Surface water should be kept away from the tunnel.

According to Charles Snodgrass of Armco, the tunnel contractor, this tunnel was easier to drill than most because it contained no hard rock. In actual operations, the contractor was permitted to use explosives and the whole tunnel was blasted in 3- to 7-foot rounds.

The siltstone and claystone were not particularly troublesome. The sandstone was as hard as concrete at the face of the tunnel, but shortly after it was shattered by blasting it slaked to a pile of sand. Overbreakage was easy to control and the 7-foot tunnel was held to no more than 6 inches of overream. The only water that caused trouble came from a spring at the north portal of the tunnel, which probably issued from the contact of the Dawson Arkose and the overlying colluvium. The tunnel was dry, but the clayey materials in it were moist enough to knead in the hands.

The tunnel was advanced by blasting and digging in one 10-hour shift; liner pipe was set in the next 10-hour shift; and grouting behind the liner was done in the last 4-hour shift during the night. By this means the Dawson was confined before slaking could reduce its strength.

DAMS AND RESERVOIRS

Several dams and reservoirs were built on the site for storing potable and nonpotable water and for controlling floods. Potable-water reservoir 1 is in colluvium at the west end of South Lehman Valley; reservoir 2 is on Lehman Ridge Gravel at the west end of Pine Mesa; reservoir 3 is on Lehman Ridge Gravel at the northeast end of Pine Mesa. Nonpotable-water reservoir 1 is on flood-plain alluvium and Pine Valley Gravel overlying interbedded sandstone and claystone of the Dawson at the mouth of South Lehman Valley. Reservoir 2 is in Husted Alluvium, colluvium, and claystone, siltstone and jointed sandstone of the Dawson Arkose in a valley southeast of Lehman Ridge (fig. 55). Reservoir 3 is in Douglass Mesa Gravel between Roads 10 and 50 and east of Road 60. Reservoir 4, or Goat Camp Creek Reservoir, is in colluvium and Dawson Arkose on Goat Camp Creek; the reservoir dam forms the embankment for Road 10. The Kettle Creek flood-control dam is an integral part of the embankment for U.S. Highway 85–87 over Kettle Creek.

The nonpotable-water reservoirs are formed by earth dams, the tops of which are as much as 50 feet above stream bottom. Pervious materials were known to underlie part of every dam alinement. Therefore, along the upstream toes of the dams the stream bottoms were stripped down to an impermeable fine-grained layer in the Dawson Arkose and an impervious blanket of material was laid down on the upstream face of the dams to connect with the impermeable layer of Dawson. The cores of the dams were built of random fill which was compacted onto the scarified existing surface from which all boulders had been removed. A pervious filter of gravel and crushed rock was installed underneath the downstream toes of the dams and up the sides to within 5 feet of high-water level. These filters allow the seepage water which comes through the dams under pressure to escape slowly without displacing the fine soil particles from the embankment. To prevent loss of water from the reservoirs, soil cement was applied in a layer 6–12 inches thick to form an impervious lining over the floor and above the waterline. At reservoir 3 gravel was laid down first because the foundation material was too soft to support the soil cement. The soil cement was made thicker around the edges of the reservoirs at normal pool level because of the greater wave action and greater number of freeze and thaw cycles.

Reservoir 4, or Goat Camp Creek Reservoir, lies downstream from a small upper dam which catches the normal streamflow, for which prior water rights are held, and diverts it into Monument Creek by way of South Lehman Valley; the lower and larger dam retains excess flow, stores nonpotable irrigation water, and is to be used for recreation. Road 10 crosses the embankment of the lower dam, as shown in figure 56. Borings were made every 300 feet across the bottom of the reservoir to determine foundation conditions. The clay beds in the Dawson Arkose were found to be discontinuous. An impermeable clayey core could not be used because it might have caused Road 10 to settle.

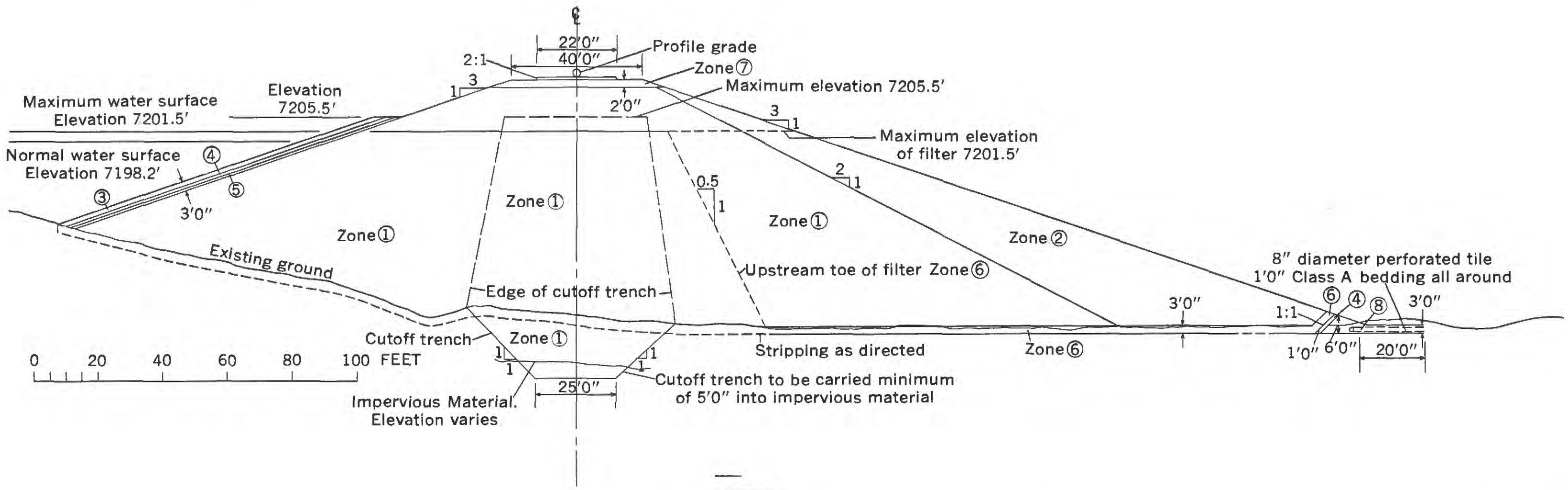
The dam was constructed, therefore, almost entirely from Douglass Mesa Gravel and Lehman Ridge Gravel derived from the academic-area excavations at the west end of Lehman Mesa and from Road 10 excavations The pediment gravel in this area contained a high percentage of fines in the upper 2–5 feet. Permeability and triaxial shear tests performed by the Colorado Department of Highways (table 7) showed this material to be suitable for the body of the dam.

To avoid leakage through permeable lenses in the Dawson Arkose, a cutoff trench was excavated into impervious material around the sides and base of the dam. A pervious filter was placed under the downstream toe of the dam and up around the sides to the maximum level of saturation, as shown in figure 57.

Kettle Creek Dam, shown in figure 58 and plate 2, was built as a temporary storage basin to control floods on Kettle Creek and to protect U.S. Highway 85–87, the airfield, and the service and supply area. The dam was located as far west as possible without interfering with the runway, because a more eastern location would have been complicated by swelling clay in the andesitic Dawson and other adverse economic factors. The dam was designed for a 50-year storm. Flood flows exceeding the 50-year-storm limit will be directed through an emergency spillway and diversion ditch southward past a small dam on Pine Creek and then through a

FIGURE 55.—Nonpotable-water reservoir 2 under construction. Bituminous seal is being placed over the soil-cement lining. Photograph by U.S. Air Force, June 11, 1958.

FIGURE 56.—Goat Camp Creek Dam and nonpotable-water reservoir 4 under construction; view is south. The material for the embankment was derived from excavations at the west end of the academic area on the left and from cuts along Road 10. Photograph by the U.S. Air Force, May 27, 1957.



ZONE	THICKNESS (INCHES)	MATERIAL	GRADATION	PLASTICITY INDEX	COMPACTION	AVAILABILITY
1	Variable	Impervious material	Maximum size 6 in. 25–55 percent passing no. 200 sieve	4 minimum 18 maximum	95 percent (A.A.S.H.O. standard T99-49, modified as per specifications)	Available from Road 10 and academic area excavation
2	Variable	Dawson Arkose	Less than 25 percent passing no. 200 sieve	—	90 percent density	Available from cutoff trench and abutment benching
3	18	Class A riprap	12–18 in. size stones. One dimension 12 in. Minimum size ½ cu ft, average size 1½ cu ft or more	—	Dump and grade off. Small fragments to fill spaces between uniformly distributed large fragments. Hand-placement as necessary	Rocks from excavation within work areas may be used insofar as available
4	12	Class A bedding	100 percent passing 2 in. sieve Less than 25 percent passing no. 4 sieve	—	Not required	Not available within limits of work area
5	6	Class B bedding	Granular, nonplastic, 100 percent passing 2 in. sieve, less than 15 percent passing no. 200 sieve, less than 0.5 percent organic content	—	Not required	Available within limits of work area
6	36	Class C bedding	18 in. sand over 18 in. gravel, graded according to federal specifications SS-A-28 lb. ¾ in. maximum	—	Moisture content 3-10 percent. 6-in. layers compacted to 90 percent density	Not available within limits of work area
7	24	Class B bedding	Same as zone 5	—	95 percent density	Available within limits of work area
8	Variable	Class B riprap	9–12 in. size stones. One dimension 9 in. Minimum size 3/10 cu ft, average ½ cu ft or more	—	Same as Zone 3	Same as Zone 3

FIGURE 57.—Goat Camp Creek Dam. Typical cross section and materials table, from construction drawing AW-4-05-01 sheet 85 and specifications for cadet academic area, site improvement, grading, and retaining walls, Air Force Academy Construction Agency and Skidmore, Owings, and Merrill.

FIGURE 58.—Kettle Creek Dam and new alinement of U.S. Highway 85–87 on the downstream side. Limestone riprap is being placed over the upstream filter bed. The pressure conduit, which will be covered by the fill for the airfield runway and taxiway, terminates at Kettle Creek just beyond the old alinement of the highway. Photograph by the U.S. Air Force, November 8, 1956.

TABLE 7.—*Results of tests on material for Goat Camp Creek Dam*

[From report by Colorado Dept. Highways, Jan. 31, 1956, E. G. Swanson, staff materials engineer]

	SOM laboratory No.		
	1368	1369	1370
Location	Station 340+21, 61 ft right, Road 10, coor. 428,564 N., 2,171,623 E.	Soil sounding S-253, cadet area, coor. 428,732 N., 2,171,198 E.	Soil sounding S-262, cadet area, coor. 428,492 N., 2,173,859 E.
Maximum AASHO density, lb per cu ft	123.8	124.5	127.0.
Optimum moisture, percent	10.8	10.2	9.4.
CDH values (material passing No. 200 sieve), do	41	47	35.
Plasticity index	10	7	2.
Permeability tests[1], cm per sec	1.6×10^{-6}	4.6×10^{-7}	5.1×10^{-6}.
Triaxial tests[2]: Axial stress at failure at lateral loads of:			
0, psi	22	50	32.
10, psi	54	76	58.
20, psi	85	106	100.
30, psi	121	125	134.
Angle of internal friction, degrees	32	28.5	34.
Cohesion, psi	6	14	8.

[1] Falling head method submitted by Sawyer of the Bureau of Public Roads, ASTM Procedures for testing soils' Committee D-18, July 1950 (Method of computation and dimensions of specimen described in CDH report).

[2] Bureau of Public Roads method submitted by Allen and Sawyer, ASTM Procedures for testing soils, Committee D-18, July 1950. Specimens 2 in. in diam., 4 in. long, compacted to 95-percent maximum density at optimum moisture.

new channel that connects the two ends of Pine Creek that were cut off by the relocated highway. Normal runoff from Kettle Creek flows through a pressure conduit under the highway and runway and reenters the channel of Kettle Creek just west of old U.S. Highway 85-87.

The height of the dam is 85 feet. The core is composed of compacted Pine Valley Gravel, which is blanketed with impermeable Dawson clay (section *D-D'*, pl. 2). The base was laid on Dawson Arkose exposed in a 15-foot-wide channel dug through the flood-plain alluvium. Both the upstream face and the spillway were covered with 1-3 feet of riprap composed of granite and limestone boulders. The topsoil that was stripped from the site of the dam and highway foundations was reapplied to all embankments and excavations before seeding.

ROADS

The road network for the Academy consists of two four-lane access roads connected to U.S. Highway 85-87 by cloverleaf interchanges near Breed and Husted, a northwest-trending divided four-lane road that connects the two access roads west of Monument Creek, a two-lane perimeter road, and other two-lane roads that give access to all the facilities of the Academy (pl. 1).

The roads traverse all geologic units except the pre-Dawson. The formations that are crossed most frequently by the roads are the Dawson Arkose, Douglass Mesa Gravel, Pine Valley Gravel, Husted Alluvium, and colluvium.

FIELD AND LABORATORY INVESTIGATIONS

The road network was walked out in a reconnaissance soil survey by the soils engineer and the geologist of the architect-engineer to pick locations for drill holes. Holes were then drilled by a power helix auger driven by a truck-mounted drill rig. The holes were spaced about every 500 feet along the road network. Before this drilling program had been in progress for very long, the AFACA received the geologic map and report from the U.S. Geological Survey. A correlation was immediately observed by the staff of the architect-engineer between their classification of materials in the drill holes and the descriptions of the geologic units as shown on the geologic map. The geologic map then became a useful tool for detailed planning of the drilling program. Additional drilling sites were added to the program to determine more closely the characteristics and variability of each geologic unit and to investigate all stream bottoms and potential seepage areas where drainage structures would be needed. Holes were drilled on an average of about one to every 100-200 feet of roadway and were spaced no farther apart than 500 feet. All the holes penetrated 4 feet below preliminary grade and some were later drilled to greater depth.

On the basis of the geologic maps and the exploration program, some alinement changes were made for geologic or topographic reasons, such as:

1. Road 80 bridge over Monument Creek at the south entrance to the site was moved because artesian water was found at one of the abutments.
2. Road 10 across Silo Valley southwest of the academic area was moved to the west out of a large peat bog. (See pl. 6.)
3. Road 50 was moved out of the middle of a stream channel and up onto the north side of the valley.

Samples taken from the drill holes or from within pits generally were tested for size gradation, Atterberg limits, natural moisture content, in-place density, Modified AASHO maximum density and optimum moisture content, and CBR. The materials were classified according to the Unified Soil Classification System, and records were kept concerning dampness or water in the drill holes, suitability of material for embankments, shrinkage expected upon compaction, amount of boulders that must be removed, and any other feature that might influence the proposed design.

Some of the types of information that were used in the design analysis and preparation of construction drawings and specifications for parts of Road 60 are summarized in plate 7, parts *A–E*. Part *A* shows the plan of the centerline for a segment of Road 60 from station 270+00 to station 347+27, on which have been superposed the geologic contacts from the geologic map. Part *B* is an example of a route description for the same segment, prepared by the staff of the architect-engineer. The description in general is broken into sections that have similar geologic and topographic characteristics. Part *C* shows examples of some of the actual computation sheets for Road 60. Part *D* is a typical construction drawing showing the plan, profile, location, and logs of soil borings and the test results for a short segment of Road 60, which is indicated by brackets on part *A* of this sheet. Part *E* is a mass diagram for the segment described in part *B*, as adapted from construction drawing AW–1–01–04 sheet 77. To avoid negative quantities, the running budgets of materials start at 100,000 cubic yards at the beginning of Road 60 (station 177+35, not on the map), as shown in mass-diagram data sheets. The unsuitable material is very largely silty or clayey Dawson Arkose, which had to be disposed of by being distributed along Road 60 and adjacent roads outside the 2 to 1 slope of load-bearing embankments and underneath more suitable material in deep fills. Paving was done under a later contract. Sources: Design analysis, Roadway facilities increment 2, Skidmore. Owings, and Merrill; Construction drawings and specifications from bid invitations (IFB)–05–613–56–5, AFACA and SOM.

After the original grading of highway cuts at a uniform 2 to 1 slope, erosion was so destructive that many of the excavations were regraded to a 4 to 1 or even flatter slope. The spoil from these larger cuts was put on the outside of the cut to make the backslope more gentle.

After the subbase material was placed, the roads were used during the several years' period of construction at the Academy, long enough to allow any areas of subgrade or subbase requiring repair to show up. Holes about 36 inches deep and 300–500 feet apart were then drilled into the subgrade to determine where the water table was high, the location of surface drainage problems, the location of frost-heave excavation, and the amount of frost-susceptible fine material in the subgrade. Although the engineers drilled both embankments and excavations, they were more concerned about the stability of the natural material under the excavations because the embankments had been controlled during emplacement. The drilling program was conducted at the wettest time possible so that the worst conditions could be observed.

CLASSIFICATION OF FROST SUSCEPTIBILITY

After the amount of fine material was ascertained, the frost susceptibility of the subgrade, based on an assumed frost penetration of 27 inches, was classified for the entire road system according to the Corps of Engineers frost-susceptibility rating system:

Classification	*Frost susceptibility*
F–0	Non-frost-susceptible material.
F–1	Moderately frost susceptible coarse gravel.
F–2	Moderately frost susceptible fine sand.
F–3	Frost-susceptible sand and gravel.
F–4	Frost-susceptible silt and clay.

Many of the F–2 soils were reclassified to F–1, and F–3 soils reclassified to F–2, for the following reasons:

1. The water table is 10 feet or more below the zone of frost penetration; therefore the source of water for ice lensing would be negligible.
2. Because the amount of precipitation on the Academy area is low, the amount of surface water available for the formation of ice lenses in the subsoil is not enough to cause excessive frost heaving.
3. Because the speed limit on the Academy roads is 30 miles per hour and the average traffic density is not high, some frost heaving would not be detrimental to traffic safety.
4. No abrupt changes in soil types were found, and therefore differential heaving would be minimal.
5. Most of the subsoil is well graded, and would be only slightly susceptible to frost heaving.
6. The base course and pavements were designed to be about 40 percent thicker than the standard CBR versus wheel-loads design criteria.

Four types of corrections were made of subgrade or subbase that contained too much fine material or that had not performed satisfactorily under traffic:

1. Subgrade was reinforced with crushed rock.
2. Subbase and subgrade were removed and replaced with more stable material, or subgrade was recompacted.
3. Subbase was thickened.
4. Subdrains or culverts were installed.

The improvement of the subbase and subgrade to an acceptable standard of stability meant that the base course and pavement could be approximately the same thickness everywhere. Considerable saving of money was expected to result from this investigation of subbase and subgrade conditions, not only in original cost, but also in future maintenance, because the pavement and base course could then be designed for the much-improved actual in-place subbase and subgrade conditions, rather than for the worst possible, but unknown, conditions. Subgrade conditions were not investigated in the airfield roads; therefore 3 more inches of subbase was specified for them than for the other roads as a preventive measure.

Some of the recurrent problems in road construction were: (1) the constant need for careful balance of materials to avoid disfigurement of the landscape by unnecessarily deep cuts and large fills and to avoid either large on-site borrow pits or stockpiles of unusable material; (2) preservation of natural stands of trees and removal of topsoil along road alinements, not only because the topsoil formed unsuitable subgrade but also because it was needed elsewhere for planting areas; (3) erratic distribution of large boulders in pediment gravel and colluvium and of clayey layers in Dawson Arkose and pediment gravel, requiring close control in excavation and placement of embankments. and (4) provision for adequate drainage of surface and ground water. Ground water is concentrated principally in the Dawson Arkose and at the contact of Dawson Arkose and pediment gravel.

Bridge foundations were explored by the soils engineer and geologist of the architect-engineer; from 5 to 7 holes were drilled near the locations of planned piers or footings of each bridge. The concrete piers, which are about 4 feet in diameter, all were founded on coarse sandstone in the Dawson Arkose. The bottoms of the holes were probed to make certain that soft unstable material did not lie just below. Artesian water was found at the site for one abutment of the Road 80 bridge across Monument Creek; therefore the location of the bridge was moved southward.

GROUND WATER

By W. D. E. Cardwell and Edward D. Jenkins

INTRODUCTION

During the course of the studies at the United States Air Force Academy, the water-bearing properties of the geologic formations were investigated to determine whether a ground-water supply could be developed that would meet the needs of the Academy. The investigation included an inventory of wells and springs, a study of the surface materials, test drilling, water sampling, and pumping tests. On the basis of the findings, a ground-water supply was developed that now furnishes the Academy with an adequate supply of water of good quality that supplements the supply of potable water obtained from Colorado Springs. Ground water is used mainly for irrigation.

For purposes of describing the water-bearing properties, parts of two formations, the Fox Hills Sandstone and the Laramie Formation, were considered as a single water-bearing unit. This unit and part of the Dawson Arkose constitute the two principal water-bearing units, or aquifers, underlying the Academy grounds.

Test drilling for possible water-bearing formations underlying the Fox Hills Sandstone was ruled out because the formations are deeply buried and because water from them probably is of poor quality. The unconsolidated materials overlying the Dawson Arkose were found to be incapable of yielding the desired supply.

WATER-BEARING FORMATIONS

FOX HILLS AND LARAMIE FORMATIONS

Water-yielding sandstone beds in the upper part of the Fox Hills Sandstone and the lower part of the Laramie Formation constitute the L–F aquifer that is confined above and below by thick intervals of relatively impermeable beds. The contact between the Fox Hills Sandstone and the Laramie Formation lies within this aquifer (pl. 8).

The L–F aquifer can be divided into three units: The lowest unit (about 150 feet thick) is composed of fine- to medium-grained sandstone; the middle unit (about 65 feet thick) is composed of sandy shale interbedded with thin seams of coal; and the highest unit (about 75 feet thick) is composed of well-sorted, fine- to medium-grained sandstone.

Three of the wells near Monument Creek (pl. 8) were drilled through the L–F aquifer. Elevations at the top of the lowest aquifer unit, as inferred from electric logs, show that the L–F aquifer strikes N. 30° W. and dips 2° 48′ NE. Depths to the L–F aquifer range from 400 to 1,165 feet and increase northward as a result of the aquifer's northeastward dip and a rise in surface elevation.

The L–F aquifer is recharged by precipitation and streams where the formations crop out. The water moves downdip through the sandstone beds and is discharged by wells or by springs and seeps. There is no visible natural discharge within the report area; the water is confined under artesian pressure by overlying beds of shale.

The slope direction of the piezometric surface (artesian-pressure surface) of the L–F aquifer could not be computed because one of the three wells tapping it also taps water-bearing sand in the Laramie Formation above the L–F aquifer. The piezometric surface of the L–F aquifer under the Academy area probably slopes northeastward.

DAWSON ARKOSE

The Dawson Arkose is a multiaquifer formation. Typically, it is composed of alternating beds of fine to very coarse grained arkosic sandstone, variegated claystone, siltstone, and shale. The beds are lenticular and differ in thickness and areal extent; thus, correlation of individual beds by use of drillers' and electric logs seldom is possible. The Dawson Arkose is the bedrock at most places in the Academy area and can be seen extensively in outcrop along creeks and on the sides of slopes where surficial materials have been washed away.

Several water wells were developed for the Academy in the Dawson Arkose near Monument Creek (pl. 8). The thickness of the Dawson penetrated by these wells ranged from about 200 to 1,000 feet; it increases northward because of less erosion and possible stratigraphic thickening to the northeast (pl. 8).

Several water-bearing sandstone beds were penetrated while drilling through the Dawson Arkose. The lowermost 125 feet of the formation consists predominantly of claystone and shale and is unsuited for ground-water development All the beds tapped by the wells contained water under artesian pressure.

The permeable beds of the Dawson are recharged by precipitation and streams where the beds crop out. In the outcrop, part of which is within the Academy area, water in the uppermost beds is unconfined, but where the water-bearing beds are overlain by beds of claystone and shale the water is confined under artesian pressure. In some topographically low areas the pressure is great enough to cause wells to flow.

According to computations made from elevations of water levels in wells 3A–5A, the piezometric surface slopes S. 26° E. at 42 feet per mile, a direction and gradient corresponding roughly to that of Monument Creek. The stream is fed by ground-water discharge from the Dawson.

Water is discharged from the formation within the Academy area by wells and, where drainageways have incised saturated beds, by seeps. Where the aquifer is unconfined close to the land surface, water also is evaporated and transpired.

PEDIMENT GRAVEL

The pediment gravel consists of stream-laid deposits of unconsolidated granitic debris that cover more than half the Academy site. Tributaries of Monument Creek have dissected these deposits to form prominent east-trending ridges which lie above the more recently stream-laid alluvial deposits of Monument Creek and its tributaries.

The pediment gravel lies at several levels on bedrock surfaces, each level being defined by a distinct break in slope. According to relative levels, the pediment gravel is designated (highest to lowest) as Lehman Ridge, Douglass Mesa, and Pine Valley Gravels on the geologic map of the Academy site (pl. 1). The gravel is underlain by the Dawson Arkose at most places on the Academy site. Typically, the gravel is poorly sorted and contains material ranging in size from large boulders to clay particles, but overall it becomes somewhat finer and better sorted eastward.

Test drilling by AFACA indicated that the pediment gravel generally ranges in thickness from 10 to 50 feet. In a few places, where it probably is underlain by old bedrock channels, the gravel is thicker.

Any large accumulation of water in the pediment gravel is unlikely; dissection of the deposits facilitates drainage. A large percentage of the recharge is quickly discharged by springs and seeps, generally at the contact with the Dawson Arkose; a smaller percentage percolates through the gravel and into the arkose.

Some wells that yield sufficient water for domestic and stock use have been developed in the lowest deposit of pediment gravel east of Monument Creek. Here, the gravel is better sorted and less dissected than in most places, but it does not yield enough water to warrant development for the Academy.

Several springs discharge at the contact of the low pediment deposits and the underlying Dawson Arkose. The discharges of three springs that are tributary to Cottonwood Creek southeast of the Academy were measured by use of a Parshall flume on November 17, 1954. The discharges were: a spring in the SE¼SE¼ sec. 8, T. 13 S., R. 66 W., was flowing 54 gpm (gallons per minute); two springs in the NW¼NW¼SW¼ sec. 8, T. 13 S., R. 66 W., were flowing 47 and 9.5 gpm, respectively.

ALLUVIUM

Alluvium, as discussed here, consists of the stream-laid deposits in the valleys of Monument Creek and in its tributaries. It lies in the present-day channels and flood plains of the streams and above the flood plains in the form of terraces.

The terrace deposits are named (highest to lowest) Kettle Creek, Monument Creek, and Husted Alluviums (pl. 1). The individual terrace deposits are not present in all the stream valleys. Where all three are most apparent, near the confluence of Monument and Kettle Creeks, the terraced relief is about 40 feet. The deposits of each terrace are from 10 to 15 feet thick.

The alluvium is composed of finer materials than the pediment gravel, and commonly is somewhat stratified. Generally the alluvium lies on bedrock at lower altitudes than the level of the pediment gravel, but locally it overlies the pediment gravel (pl. 1). Particles of the terraced alluvium typically range in size from coarse gravel to clay, but some boulders, cobbles, and pebbles are present. The coarser grained material is more common in the valleys west of Monument Creek, where much of it was derived from the pediment gravel. The fine- to medium-grained material was derived largely from the Dawson Arkose, both east and west of Monument Creek.

Test drilling by AFACA revealed no usable amounts of water in the terraced alluvium. These materials may receive sizable amounts of recharge during infrequent periods of heavy precipitation and runoff, but large amounts of water do not accumulate in them, probably because ground-water losses are high through seepage, evapotranspiration, and percolation downward into the flood-plain alluvium.

AFACA drilled six lines of test holes across the flood plain of Monument Creek, which ranges in width from 50 to 450 feet and averages 250 feet. The alluvium averages about 10 feet in thickness, and consists mainly of fine to coarse sand that contains some boulders, cobbles, and pebbles. The flood-plain alluvium is thickest and most extensive in the vicinity of Monument Creek. Less than 25 percent of the materials were saturated at the time of drilling.

QUALITY OF WATER

Only water from wells tapping the consolidated formations was sampled and analyzed, because water from the unconsolidated formations was not considered to be a potential source of supply for the Academy. Seven wells were sampled; five tap the Dawson Arkose, one taps the L–F aquifer and sandstone in the Laramie Formation above the L–F aquifer (well 2), and one taps the L–F aquifer.

The analyses (table 8) show that the water from the Dawson is less mineralized than that from the L–F aquifer. Water from the Dawson is well suited for irrigation, and water from the L–F aquifer probably is suitable for irrigation if used with caution; water from both aquifers is suitable for domestic use. The properties and constituents of the water from the aquifers were the primary factors that determined the final planned use of the water from each source—either domestic or irrigation use.

Standards set by the U.S. Public Health Service (1962, p. 7–8) for drinking water used on common carriers in interstate commerce are widely accepted as limiting criteria. The suggested maximum concentration of impurities includes the following:

	Ppm
Iron and manganese, together	0.3
Magnesium	125
Chloride	250
Sulfate	250

Permissible fluoride concentrations are now based on the annual average of maximum daily air temperatures; colder areas are permitted higher concentrations of fluoride. The recommended concentration at the Air Force Academy is 0.8–1.3 ppm. Presence of fluoride in average concentrations of more than 2.0 ppm constitutes grounds for rejection of the supply.

TABLE 8.—*Chemical analyses of water from wells*

[Results in parts per million except as indicated]

Well (pl. 8)	Depth (feet)	Geologic source	Date of collection	Temperature (° F)	pH	Specific conductance in micromhos at 25° C.	Percent sodium	Sodium adsorption ratio (SAR)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Silica (SiO_2)	Dissolved solids	Hardness (calculated as $CaCO_3$) Total	Hardness Noncarbonate
1	1,065	Fox Hills and Laramie Formations.	10-28-55	61	7.6	769	7	0.27		107	23	12		130	263	4.0	0.8	0		474	362	255
1A	358	Dawson Arkose	11-11-55	52	6.9	254	12	.29		32	5.4	6.7		65	55	2.0	1.0	.02		134	102	48
2	1,493	Fox Hills and Laramie Formations.	3- 5-56	57	7.6	229	19	.46		27	4.9	9.8	5.0	106	21	2.0	2.0	.3		124	88	0
2A	826	Dawson Arkose	2- 7-56	51	7.0	316	10	.26		42	6.8	7.0	3.0	66	90	2.5	.5	.2	24	184	133	79
4A	672	do	8-30-56	55	7.3	136	13	.24	0	19	2.4	4.2	2.2	65	9.4	2.2	1.0	.4	23	73	58	4
5A	575	do	8-25-56	53	8.0	163	12	.24		21	3.6	4.7	3.0	62	22	2.5	1.2	.7		89	68	16
(1)	600	do	5-29-57	55	6.5	439	23	.79	.04	55	5.8	23	3.0	120	98	6.0	.9	2.4		253	161	62

[1] Location: SE¼SE¼NE¼ sec. 21, T. 11 S., R. 67 W., U.S. Forest Service well.

Dissolved solids should not exceed 500 ppm; however, if such water is not available a dissolved-solids content of 1,000 ppm may be permitted.

Only two samples from wells in the Academy area had constituents exceeding the suggested limits. The single sample of water from the L–F aquifer contained 263 ppm sulfate—slightly more than the suggested limit. Sulfate in excess of the limit, when combined with calcium or magnesium, may have a cathartic effect on some people. The sample from well 2, which taps both the L–F aquifer and water-bearing beds in the Laramie above the L–F aquifer, contained 2.0 ppm fluoride. Fluoride in excessive amounts may cause mottling of children's teeth during the formative years.

The degree of hardness has an effect on the usability of water for laundering and in boilers. Soap consumption and rate of accumulation of boiler scale increase as hardness increases. Samples of water from the Dawson ranged in hardness from 58 to 161 ppm, expressed as $CaCO_3$; one water sample from the L–F aquifer was very hard, 362 ppm $CaCO_3$; the sample from well 2 was relatively soft, 88 ppm $CaCO_3$. An arbitrary classification is commonly used to describe hardness of water: less than 60 ppm, soft; 61–120 ppm, moderately hard; 121–200 ppm, hard; and more than 200 ppm, very hard. Water having a hardness of more than 200 ppm needs to be softened for most purposes.

The classification of water by the U.S. Department of Agriculture (U.S. Salinity Laboratory Staff, 1954) for use in irrigation is based on voluminous data collected from arid and semiarid areas. Factors such as farm management and drainage modify the permissible concentrations of these constituents in water used for irrigation. The tolerance of different crops to the toxic effects of dissolved constituents in water differs widely

Boron is a plant toxicant found in many irrigation waters. The samples collected during this investigation were not analyzed for boron content because water from the two aquifers is not known to contain excessive amounts of this element. Other constituents that may be present in toxic concentrations generally are reflected by the salinity hazard. The salinity hazard (U.S. Salinity Laboratory Staff, 1954, p. 76) is considered low when the conductivity is below 250, medium between 250 and 750, and high between 750 and 2,250. Accordingly, the sample from the L–F aquifer would be classed as having a medium to high salinity hazard, and the samples from the Dawson as having a low to medium salinity hazard.

The sodium hazard (U.S. Salinity Laboratory Staff, 1954, pp. 76–79, 156) is indicated by the sodium-adsorption-ratio (SAR) calculated from the analyses, using the following equation:

$$SAR=\frac{Na}{\sqrt{\frac{Ca+Mg}{2}}}$$

in which the units of the constituents are expressed in equivalents per million. All samples had a very low sodium hazard.

AQUIFER TESTS

Twelve wells drilled on and near the Air Force Academy grounds were tested: two wells tap the L–F aquifer, one taps both the L–F aquifer and sandstone in the Laramie Formation above the L–F aquifer, and nine tap only the Dawson. Nine of these were drilled by AFACA and are within the boundaries of the Academy area. One well was drilled by the U.S. Forest Service, and another was drilled by the town of Monument; these wells are 2½ and 4 miles north of the boundary, respectively. Another well was drilled by the city of Colorado Springs just outside the east boundary of the Academy area (pl. 8).

The aquifer tests were analyzed by nonequilibrium methods, which use the equation developed by Theis (1935, p. 519–524); the results are summarized in table 9. The following terms are used to describe the hydraulic properties of the aquifer and well performance:

"Permeability" and "transmissibility" are used to describe the ability of an aquifer to transmit water. The "field coefficient of permeability" is expressed as the number of gallons of water per day that flows through a vertical section of the aquifer 1 foot thick and 1 mile wide under a hydraulic gradient of 1 foot per mile at the prevailing temperature. The "coefficient of transmissibility" (T) applies to the entire thickness of the aquifer; it is the coefficient of permeability multiplied by the thickness, in feet, of the aquifer.

"Coefficient of storage" (S) is a dimensionless term used to describe the ability of the aquifer to yield water from storage. It is defined as the volume of water an aquifer yields or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface.

"Specific capacity" is used to describe well performance; it is determined by dividing the pumping rate in gallons per minute by the drawdown in feet. Specific capacity will vary with the hydraulic properties of the aquifer, with the duration of pumping, and with well-construction factors.

TABLE 9.—*Records of wells and summary of aquifer tests*

Well (pl. 8)	Owner	Date	Geologic source	Depth of well (ft)	Diameter of casing (in.)	Perforated casing interval (ft)	Saturated thickness of sand (ft)	Depth to water below or above (+) land surface (ft)	Date of water-level measurement	Pumping test data: Average pumping rate (gpm)	Drawdown (ft)	Specific capacity (gpm per ft of drawdown)	Duration of pumping (hr)	Coefficient of transmissibility (gdp per ft)	Coefficient of permeability (gdp per sq ft)	Coefficient of storage	Estimated capacity of well after pumping 30 days (gpm)	Water temperature (°F)	Approximate altitude of land surface (ft)
1	U.S. Air Force Academy.	1955	Fox Hills and Laramie Formations.	1,065	12¾-8⅝-6⅝	700-1,060	223	415.7	10-26-55	83	145	0.57	25½	1,000	4.5	0.005	160	61	6,430
1A	do	1955	Dawson Arkose	358	12¾-9⅝	106-333	206	+20.5	11-16-55	23	19	1.21	25½	1,800	9	.002	200	52	6,430
2	do	1955	Fox Hills and Laramie Formations.	1,493	12¾-8⅝-6⅝	887-1,493	150	131.1	3- 5-56	54	420	.13	24	100	.7		60	57	6,640
2A	do	1956	Dawson Arkose	826	12¾-9⅝-7	87-823	234	38.1	2- 6-56	100	68	1.47	24	1,400	6	.04	300	51	6,640
3A	do	1956	do	654	12¾-9⅝-7	28-610	300	20.6	3- 15-56	150	55	2.73	24	3,500	12	.03	400	[1] 54	6,530
4A	do	1956	do	672	12¾-9⅝	224-672	185	31.7	8- 29-56	210	120	1.75	28	1,800	10	.09	300	55	6,585
5A	do	1956	do	575	12¾-9⅝	102-575	394	78.2	8- 24-56	200	87	2.30	24	3,300	8	.04	400	53	6,559
6	do	1956	Fox Hills and Laramie Formations.	698	12-9⅝-6⅝	407-630	151	340.3	8- 4-56	80	174	.46	24	700	4.6	.003	80	58	6,360
8A	Dr. K. Cogswell (Breed well).	1954	Dawson Arkose	311	18	211-311	31	95.0	10-12-54	100	134	.75	24	1,000	32	.001		56	6,610
9A	U.S. Air Force Academy.	1957	do	680	9⅝	400-675	295	107.7	1- 29-57	175	59	2.97	24	5,800	20	.0005	400	53	6,590
(2)	Town of Monument.	1955	do	985	12-8	211-985	470	87.2	3- 27-55	155	286	.54	24	600	1.3	.10		[3] 53	7,050
(4)	U.S. Forest Service.	1957	do	600	6⅝	250-600	350	138.0	5- 29-57	32	325	.10	11	80	.2	.05		55	6,950

[1] Field determination of specific conductance in micromhos at 25°C=139.
[2] Not shown on map; location: SE¼NW¼NW¼ sec. 14, T. 11 S., R. 67 W.
[3] Field determination of specific conductance in micromhos at 25°C=175.
[4] Not shown on map; location: SE¼SE¼NE¼ sec. 21, T. 11 S., R. 67 W.

The coefficients of storage shown in table 9 are subject to considerable error because only the pumped wells were used in the tests. The only available observation wells were beyond the radius of influence of the pumped wells. It was assumed that the effective radius of the pumping well was identical to the radius of the casing, but the difference between the two may be great. The coefficients of transmissibility probably are much more accurate than the coefficients of storage.

L–F AQUIFER

The coefficient of transmissibility for the L–F aquifer, as determined in three wells, ranged from 100 to 1,000 gpd (gallons per day) per ft and averaged 600 gpd per ft, whereas the coefficient of permeability ranged from 0.7 to 4.6 gpd per sq ft (table 9). The coefficient of storage ranged from 0.003 to 0.005; this range indicates that the water is under artesian pressure. The coefficients determined for well 2 probably are not representative of those for the L–F aquifer. The specific capacity ranged from 0.13 to 0.57 gpm per ft of drawdown and averaged 0.39. Although the sum of the test-pumping rates of the three L–F aquifer wells was only 217 gpm, the results of the tests indicate that they should yield a total of about 300 gpm, or about 0.5 mgd (million gallons per day) continuously for 30 days. Wells spaced at least half a mile apart and pumped intermittently, or a mile apart and pumped continuously, would have little effect on each other.

Figures 59 and 60 show the decline in water level to be expected in an aquifer having the average coefficients obtained from the tests. The graphs are useful in predicting well-field performance.

Well 2, which reportedly taps both the L–F aquifer and the sandstone in the Laramie Formation above the L–F aquifer, has some anomalous characteristics. The water level in the well, the aquifer tests, and the

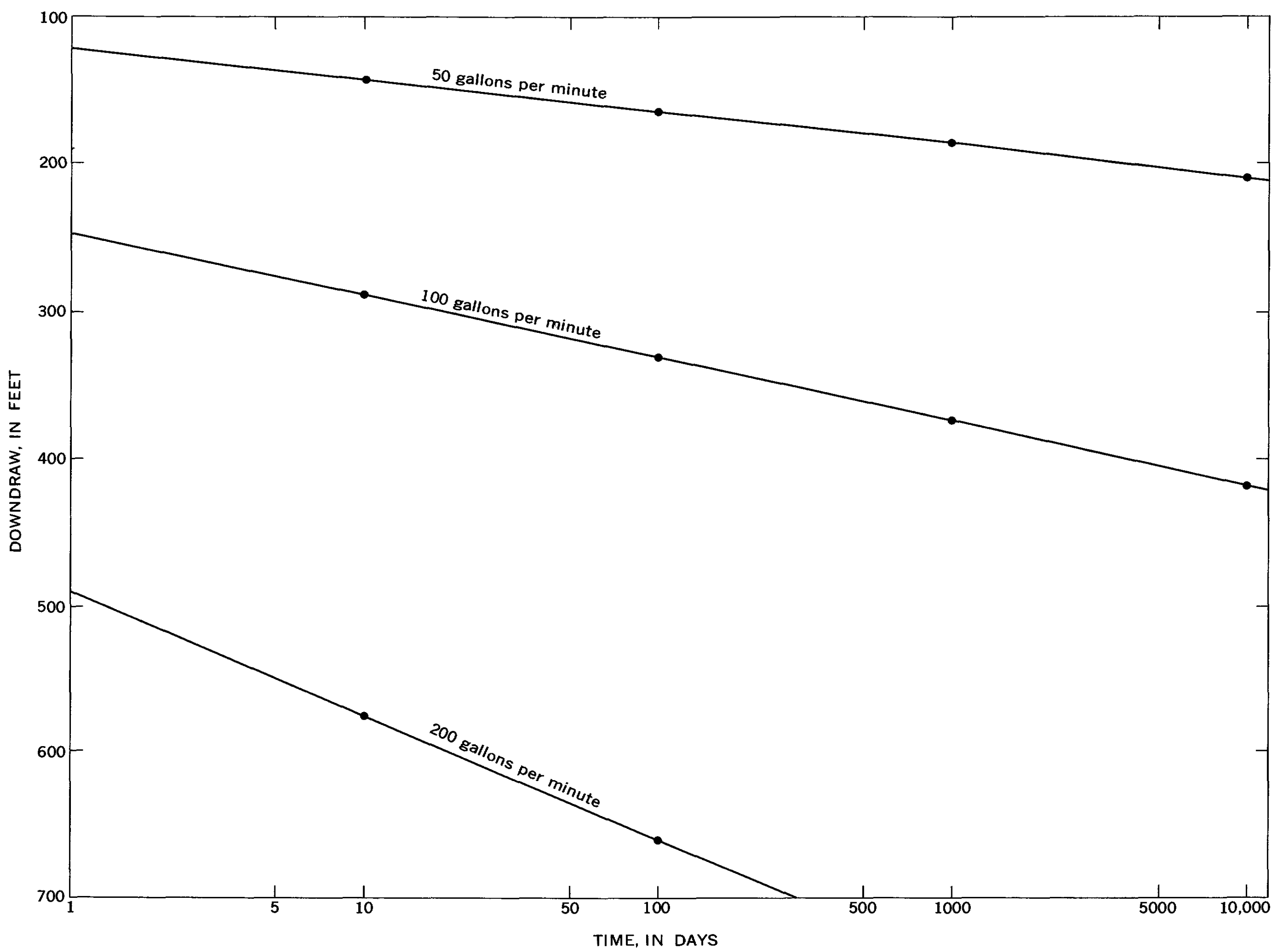


FIGURE 59.—Theoretical declines in water level in a well discharging from the L-F aquifer at the rates of 50, 100, and 200 gpm for periods ranging from 1 to 10,000 days. Assumptions: T=600 gpd per ft; S=0.005.

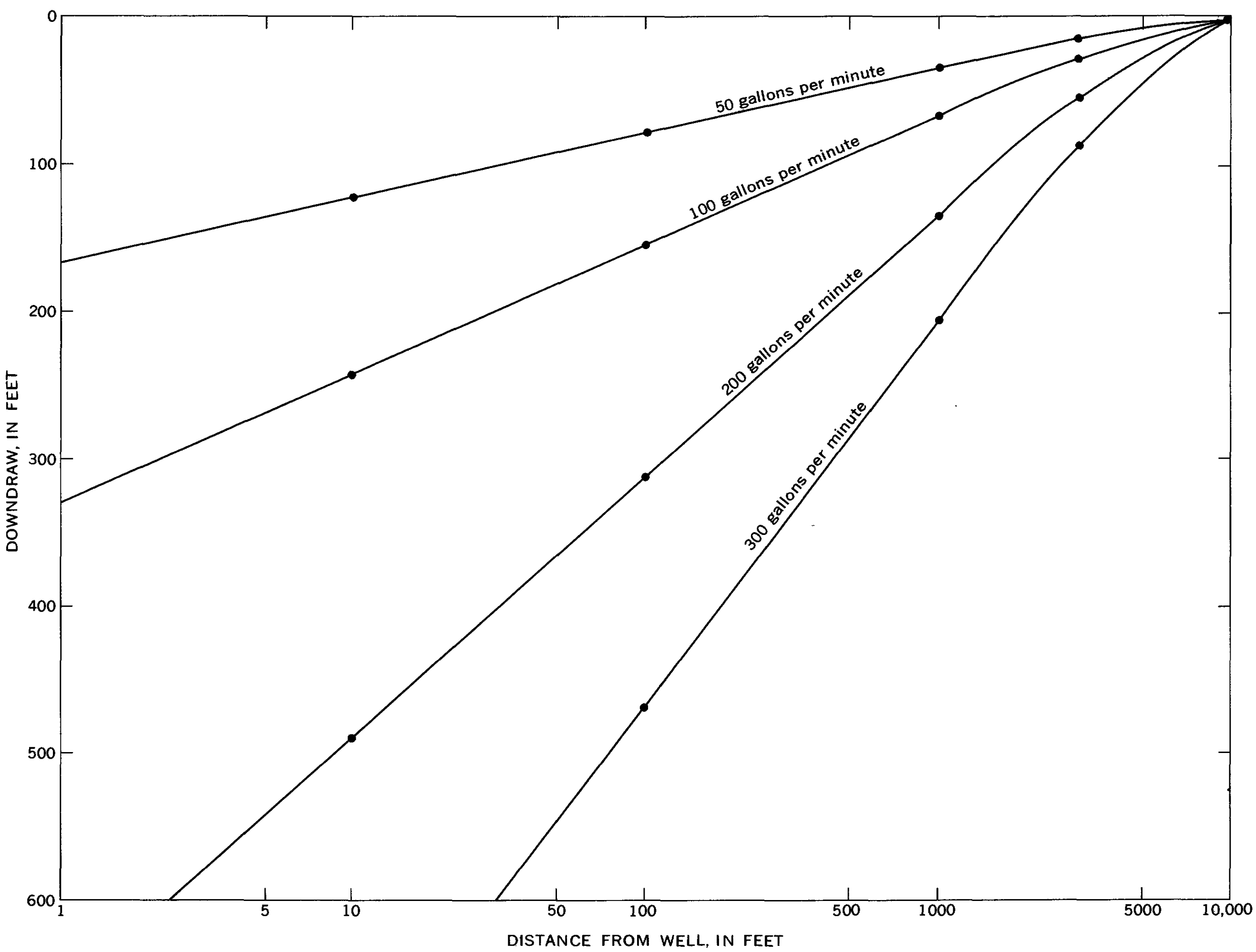


FIGURE 60.—Theoretical declines in water level caused by a well discharging from the L-F aquifer at the rates of 50, 100, 200, and 300 gpm for 1,000 days at distances ranging from 1 to 10,000 feet from the discharging well. Assumptions: T=600 gpd per ft; S=0.005.

analysis of the water indicate that most of the water was obtained from sandstone in the Laramie. The water level in well 2 (table 9) is much higher than would be expected if the well tapped only the L–F aquifer (pl. 8). The coefficient of transmissibility is lower than that in the other wells tapping the L–F aquifer. The water sample from well 2 contained a much higher concentration of fluoride than samples from other wells. Because the well taps sandstone in the Laramie above the L–F aquifer not tapped by the others, the upper part of the Laramie is probably the source of the fluoride. Measurements made in well 2A, which taps only the Dawson and is adjacent to well 2, showed a slight decline in water level when well 2 was being pumped. Well 2 was later abandoned and filled with concrete because of its poor yield and possible interconnection with well 2A.

DAWSON ARKOSE

The coefficient of transmissibility of the aquifer in the Dawson Arkose, as determined by the tests of nine wells, ranged from 80 to 5,800 gpd per ft; that determined by tests of six wells within the Academy boundaries ranged from 1,400 to 5,800 gpd per ft and averaged about 3,000. The field coefficients of permeability of the six tests averaged 11 gpd per sq ft. The lowest coefficients of transmissibility and permeability were for the U.S. Forest Service well, which is outside the Academy area boundary. This well is near the western outcrop of the aquifer. The higher coefficients were obtained farther east, where the saturated thickness of the aquifer is greater. The test of well 8A, known as the Breed well, which taps sandstone beds at depths of 211 to 311 feet, showed a coefficient of transmissibility of 1,000 gpd per ft. The coefficient of transmissibility would be higher if the well were drilled deeper to penetrate the entire aquifer. Academy well 9A, 1½ miles north-northwest of the Breed well, was perforated from 400 to 675 feet; the test showed a coefficient of transmissibility of 5,800 gpd per ft.

The coefficients of storage of the Dawson Arkose ranged from 0.001 to 0.1 and indicated that the aquifer may be subject partly to artesian and partly to water-table conditions.

The specific capacities of the Dawson Arkose wells at the Academy ranged from 0.1 to 2.97 gpm per ft of drawdown and averaged 2.07.

The average test-pumping rate of the six Academy wells was only about 140 gpm; the test data, however, indicate that the wells could yield a total of about 2,000 gpm, or about 3 mgd, if pumped continuously for 30 days. The tests also indicate that wells spaced at least a quarter of a mile apart would have little effect on each other when pumped intermittently and that wells spaced a mile apart, when pumped continuously for long periods, would also have little effect on each other.

The decline in water level to be expected in an aquifer having the average coefficients obtained from the tests is shown in figures 61 and 62. The graphs are useful in predicting well-field performance.

Table 9 shows that the hydraulic properties of the aquifer vary from place to place, and the data suggest that the Dawson is substantially more productive than the L–F aquifer. Although this relation is generally true, the lowest coefficient of transmissibility was obtained from a test of a well tapping the Dawson Arkose (U.S. Forest Service well). The highest was from a test of well 9A, which also taps the Dawson; the coefficient of transmissibility was nearly six times higher than the highest determined from the L–F aquifer.

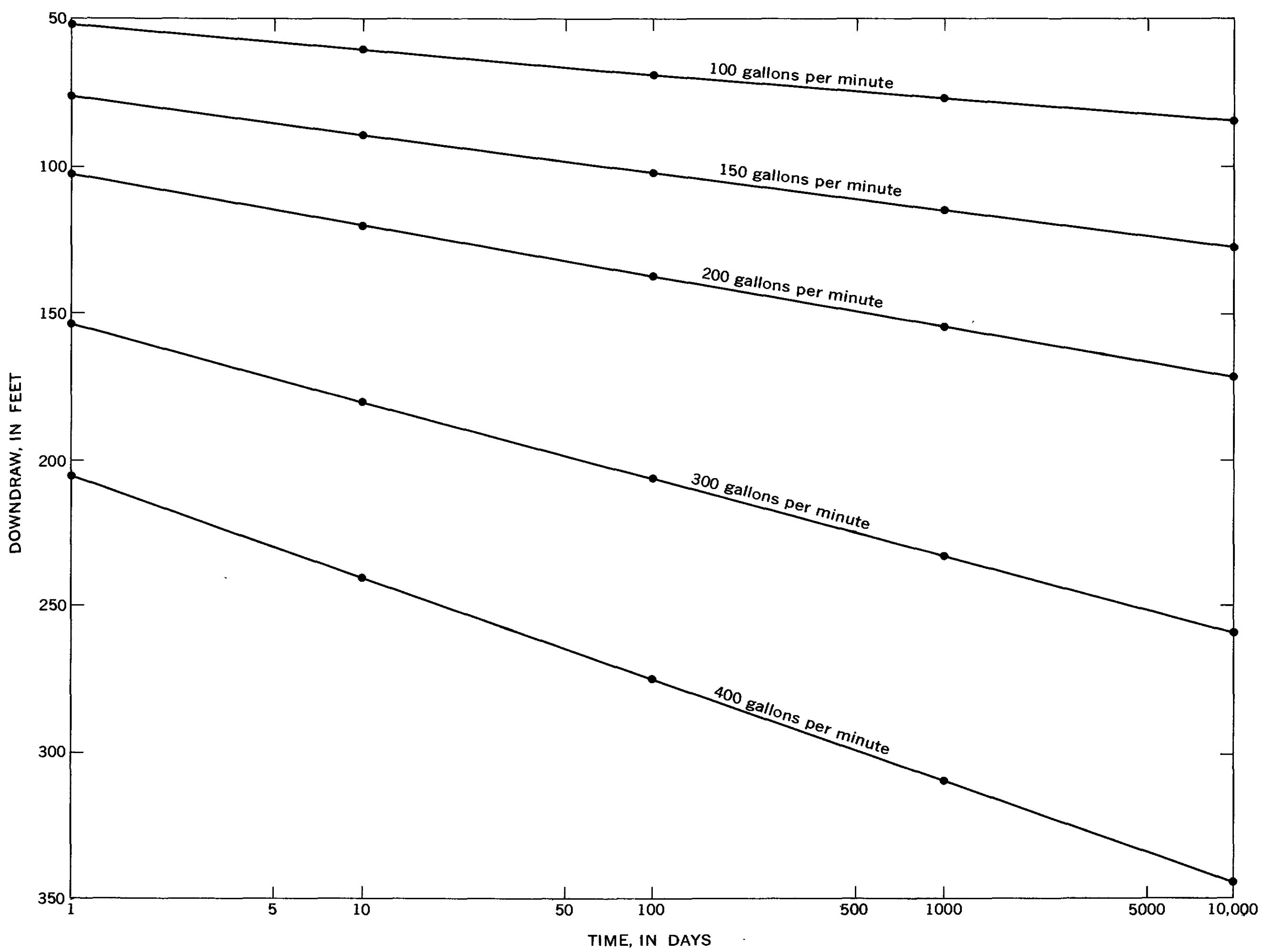


Figure 61.—Theoretical declines in water level in a well discharging from the Dawson Arkose at the rates of 100, 150, 200, 300, and 400 gpm for periods ranging from 1 to 10,000 days. Assumptions: T=3,000 gpd per ft; S=0.05.

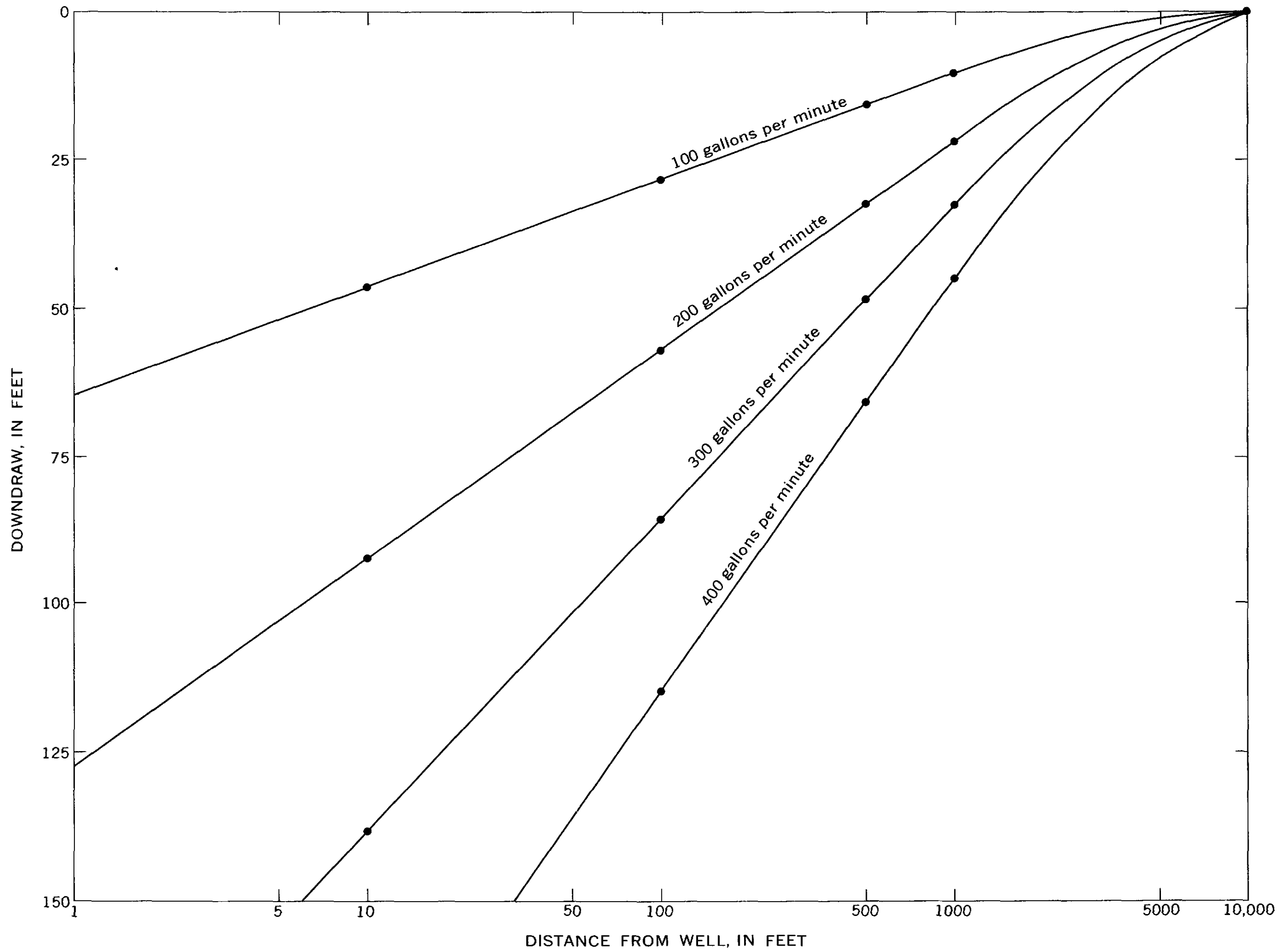


FIGURE 62.—Theoretical declines in water level caused by a well discharging from the Dawson Arkose at the rates of 100, 200, 300, and 400 gpm for 1,000 days at distances ranging from 1 to 10,000 feet from the discharging well. Assumptions: T=3,000 gpd per ft; S=0.05.

CONCLUSIONS

The Dawson and the L–F aquifer are the only aquifers on the Academy property capable of yielding a substantial supply of water of good quality. The tests indicate that the two aquifers are not interconnected—withdrawal from one does not appreciably affect the supply from the other.

The nine wells tested at the Academy are capable of yielding 2,300 gpm (3⅓ mgd) continuously for 30 days. Although the yield might decline if the wells were pumped continuously for longer periods, the rate of decline would be small.

The yield could be increased by pumping from more wells; spacing between them should be considered as the chief factor limiting the number of wells. Spacing of less than half a mile for Dawson wells and 1 mile for L–F aquifer wells would result in interference between wells if pumped continuously for long periods. Wells along the eastern boundary of the Academy are most likely to yield the largest amounts of water.

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