Experiences with Subsurface Water

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THIS paper contains a description of personal experiences of the writers in California under particular conditions including (1) cyclical or seasonal climate when a part of the year is rainless and the other exceedingly rainy; (2) young geology with soils often only partly formed from rocks; and (3) predominantly hilly topography.

During the rainy season the upper layers of the earth masses contain seeping water and water pockets, all in addition to possible capillary and hygroscopic moisture. Ground water table itself is anything but horizontal, with ridges, depressions and discontinuities. The location of the ground water is controlled by the geology and topography of the region. In the majority of cases the depressions in the earth surface show the direction of the underground streams; and brooks are generally nothing else than protruding tops of the latter.

Pore pressure in ground water is controlled by local geology and topography. In a typical case ground water close to the foot of a hill under an impervious deposit is artesian.

Planning of earthwork and construction in such localities should be done with due regard to ground-water conditions and sliding possibilities. Unquestionably an adequate study of the local geology and topography is a prerequisite to such a planning. Practice has shown that airphotos often disclose details not noted during a visual inspection. Observations of water-level fluctuations in borings made for planning purposes are of help as indicators of possible pore pressures in the soil. Subsurface water under pressure, including deep ground water and water flowing in the upper layers of a natural slope, causes slides. Places where a steep portion of a natural slope is followed by a lower flat portion, may be favorable for slides. Simple methods of slide repair are discussed in the paper. High water pressures may be reduced by driving oblique tubes 2 to 4 in. in diameter below the slope to permit the water under pressure to escape from its confinement (hydrauger method.)

Grading operations in impervious soils at the foot of a hill chain should be done with great care. Particularly excavations should not be excessively deep to preserve a sufficiently thick cover over the ground water table. Otherwise swampy condition in excavated area develops.

Cases of instability of fills constructed during dry season on sand and gravelly foundations have been observed, apparently due to decrease in shearing strength of the foundation material because of moistening.

● THE portion of California known as the San Francisco Bay region (or Bay Area) covers, geologically speaking, most of 12 counties surrounding the bay and its ramifications. It has an aggregate area of more than 10,000 sq. mi. and includes, in addition to the Central Coast Ranges, also parts of the California Great Valley and Sierra Nevada provinces (*1*). The present configuration of the land is of relatively recent development during which there were strong uplifts and consequent strong erosion of the mountain slopes combined with filling of the valleys. As a result a great portion of the region may be defined as hilly country, located between the mountain ranges and flat valleys.

The hilly topography of the Bay Area is combined with young geology especially with respect to the process of soil formation from rocks. Among the various rocks present shales interbedded with sandstones are common. The predominant soils are loams and clays, both dark and light in color, though obviously other kinds of soils may be found. Exposed shales become half decomposed forming materials which in pulverized and subsequently compacted state may be impervious. In the undisturbed condition, however, they generally offer a relatively easy passage to water through numerous cleavage planes and fissures. A lump of such soil material, if broken by hand in the field, often presents a variety of colors and consistency characteristics but if kneaded with water becomes an amazingly uniform silty or sandy clay, generally gray in color. In making a list of Bay region soils the famed Bay mud should not be forgotten. Essentially this material is similar to organic silt, perhaps with larger clay content, is unconsolidated and has a very low shearing strength. California highway engineers have had considerable experience in accelerating settlement of fills on mud and similar deposits by using sand drains, ("California wells") particularly on the Bayshore Freeway, south of San Francisco (*2*).

A characteristic feature of the region, as of the rest of California and adjacent coastal states, is alternate rainy and rainless seasons. There is practically no rain from the beginning of May till the end of October. Most of the rainfall occurs during the winter months. The average rainfall in San Francisco, for example, is 22.2 in. per year, with an average of 4.54 in. in January, which is one of the most rainy months of the year. The variation in the January rainfall in the past 5 years was wide, however, ranging from less than 1 in. in 1947 to 10.69 in. in 1952. Heavy winter rains are generally followed by a great number of landslides in the area.

Though the observations described hereafter are related to a certain region only, most of them are of general character and may be applied to regions outside of the Bay Area.

SUBSURFACE WATER

Water under a well-defined true water table is ground water. All subsurface water above the true water table will be referred to here as upper subsurface water, or simply, upper water. Besides capillary and hygroscopic moisture the upper subsurface water contains fluids slowly seeping in a horizontal or oblique direction through soil fissures and between particles, especially if forced by a considerable hydraulic gradient. In breaking a lump of clay or clay loam in formation, continuous films of static water on cleavage planes can often be seen, even with the naked eye. Miniature perched water tables and water pockets have also been observed.

The water table, with rare exceptions, is anything but horizontal. The engineer may be misled in his conclusions if he visualizes the water table as a nice horizontal plane as represented on drawings and logs. Generally the ground water is moving and the water surface (water table) slopes in the direction of movement. The profile of the ground water stream in the direction of the flow may have depressions because of intense local pumping for irrigation or industrial purposes, for example.

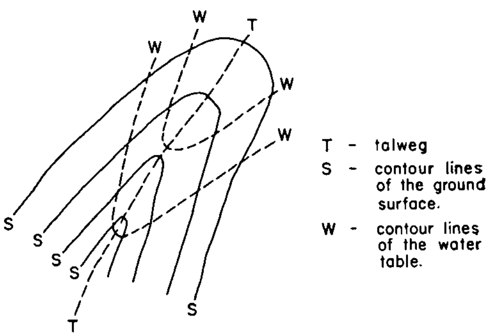

Figure 1. Ground-water flow.

More spectacular are irregularities in transverse cross section where the water table may be concave (for instance, because of seepage from a canal or a ditch) or even discontinuous.

In soil investigating for a structure or for a highway, the direction of the ground-water flow should be determined. In a flat country this can be easily done by sinking three borings and observing the water level in them (*3*). In a hilly country the direction of the ground-water flow in the majority of cases may be determined from the topography of the given locality. The talweg of a valley, or on a smaller scale of a valley-like depression (Fig. 1), is generally indicative of the axis or stem of the ground water flow. The contour lines of the ground surface and those of the water, if the latter is concave, present opposite patterns as in Figure 1. If the talweg is steep, the surface water drains quickly. During the dry season there is no water at the surface of the depression and the ground water flows deep under the talweg. If the latter is flat the depression may become a small valley with a brook. In this case, the brook generally represents the protruding top of a ground-water stream. In the case of two or more depressions distant from each other, there may be a corresponding number of water tables, not necessarily located at identical elevations and possibly with gaps between. Figure 2 represents schematically a similar situation with Water Tables 1 and 2 close to the earth surface and a deep basic Water Table 3. Water Tables 1 and 2 in Figure 2 obviously are peculiar perched water tables. A model of this situation may be visualized in the form of two water flows poured on an inclined plane from two mutually independent sources.

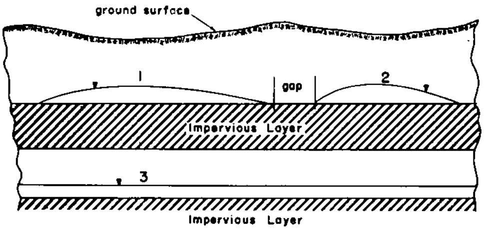

Figure 2. Water tables (1, 2, 3).

A situation similar to that described above was observed by the writers on a construction project occupying a large area south of San Francisco, at a distance about 1½ mi. from the bay. In this case the ground-water flow was carried to the bay by the perched Water Tables 1 and 2 (Fig. 2) and not by the basic Water Table 3 that was many feet below the water level in the bay. In this particular case the presence of two separate perched water tables could be guessed from the local topography. In fact, the ground surface at the given locality situated at the foot of a hill chain was but slightly undulated. In the rear, however, that is in the uphill direction, there were two clearly defined depressions corresponding to the two ground-water streams observed.

If the direction of the ground-water flow in horizontal plan may be guessed from the local topography, as stated above, its location in the vertical plane is almost exclusively a function of local geological conditions, particularly stratification. Physical properties of soil and rock material, particularly impermeability, are of great importance in this connection. For example, Figure 2 suggests that in a simplest case of one impervious deposit surrounded by pervious layers, ground water may flow either above or below that deposit. Figure 3 develops this idea further. Under conditions shown in that figure the ground-water flow during the dry season is constricted in the narrow spaces around Points B and E and, hence, is under pressure (artesian water.) If a boring is made at Point B_3 at the ground surface to reach water at Point B, the water level in the boring will rise to Level B_1 sometimes very rapidly. Distance BB_1 in this case measures the hydraulic head under which water stands at Point B. The same reasoning

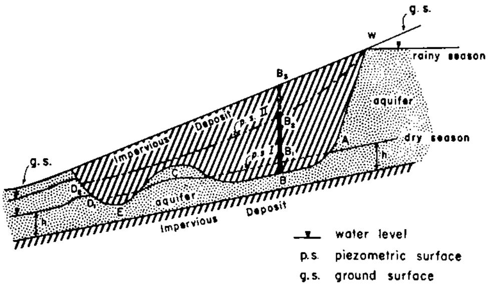

Figure 3. Pore pressure and piezometric surfaces.

is true for any other point in the narrow spaces around Points B and E. The locus of Points B_1 is a piezometric surface (p. s. I in Fig. 3) for the dry season. If instead of borings piezometric tubes driven into the ground are used, the level of water in them will rise to the same elevations as in the borings. At closed spaces such as C, theoretically speaking, even a vacuum may be produced by the fluctuations of the water level. At Points D and D_2 where the water level leaves the impervious deposit there may be some local bulging of the water level. The piezometric surface, (p. s. I, Fig. 3) runs from the intake Point A to the free water surface at D_1.

The highest level that may be reached by water from prolonged rains accumulating in the given aquifer (i.e., water-bearing medium) is the horizontal or slightly rising line through the boundary point W of the impervious deposit (Fig. 3.) This piezometric surface (p. s. II in Fig. 3) starts at Point W and first drops rapidly because of friction concentration in the narrow space around Point B, then flattens out to finally reach Point D_2 at the free-water surface.

SLIDES CAUSED BY GROUND WATER UNDER PRESSURE

Reverting to Figure 3 it should be remarked that if the thickness of the impervious deposit at Region C is not sufficient, and the piezometric surface following heavy rains is occasionally very high, the impervious deposit may be broken through with the occurrence of a slide. Such an occurrence is particularly encouraged when the excavation for a highway or other structure has decreased the thickness of the impervious cover. Though the water flow may be sudden of the type of a "flash pressure," a certain preparatory period is required before a slide of this type occurs. During the dry season the shearing strength of an impervious clay deposit will normally be very high, but it is gradually decreased by the rising and fluctuating ground water from below and by the surface rain water from above. Capillary action is operative in this connection. When the material is soft enough, a sudden high water pressure finally may cause the slide. A part of the slide (generally the shorter one) then would be in excavation and the other part, would consist of the soft material from the area excavated by the slide carried away by gravity and spread along the slope.

The study and rehabilitation of an area that has been subjected to sliding presents difficulties that tax the ingenuity of the engineer. It is practically always true that an adequate study of the area before construction would either have suggested alterations in design that would eliminate the possibility of sliding or would have suggested preventive measures that would have been carried out at a lower cost and with greater chance of success. After a slide has occurred the soil structure is broken down and the soil suffers a considerable decrease in shearing resistance; surface drainage problems are usually aggravated; the rough condition of the surface in the slide area makes the use of drilling equipment for investigations more difficult; and the necessity for rapid repair may not permit time for the proper study of the area which should include a thorough examination of subsurface water conditions. The latter are particularly difficult to delineate, since they may show considerable variation (particularly in California) between the time of sliding and time of investigation and repair. The actual study and repair of a few typical slides undertaken by the writers will be briefly described.

Figure 4 is an aerial photograph of a slide that occurred between two reservoirs which form part of the sewage treatment system for a new suburban community located east of Oakland. This case will be referred to as Case A. The site is on a slope of 16 or 17 percent and lies at the base of Mt. Diablo which rises at an increasingly steeper slope to more than 3,000 ft. above the surrounding area. A brief study of the geology of the area shows that Mt. Diablo has been formed by a piercement of highly contorted Franciscan sediments through later sediments. As a result the sedimentary rocks in the area under study are irregular and have been subjected to considerable folding and faulting (*1*). Sediments at the site of sliding are indicated in the rough section, Figure 6.

The owners of the project, believing that the slide was just a result of the excessive rains at that time, simply tried to bulldoze material back into place. They also placed a lateral drain approximately 10 ft. deep. A second slide (Fig. 5) occurred about two months later, during the same rainy season, carrying out the drain. Again the owners bulldozed material back into place and constructed a second drain in about the same location as the original one. This time the drain was made approximately 20 ft. deep. A third slide occurred in early summer of the same year which carried away a large section of the berm for the upper pond (this is evident in Figure 4). It was at this time that the writers were asked to investigate the condition.

In order to carry out this investigation borings, 6 in. in diameter, were made in the area (Fig. 5). Both disturbed and undisturbed samples were taken from the borings and observations of the water table fluctuations organized. During the course of the repair work eleven vertical shafts 24 in. in diameter (Figs. 5 and 6) were added. The borings indicated that north of the ponds there are deposits of pervious shale and rather impervious sandstone or cemented sand (average coefficient of permeability 1.65×10^{-5} cm. per

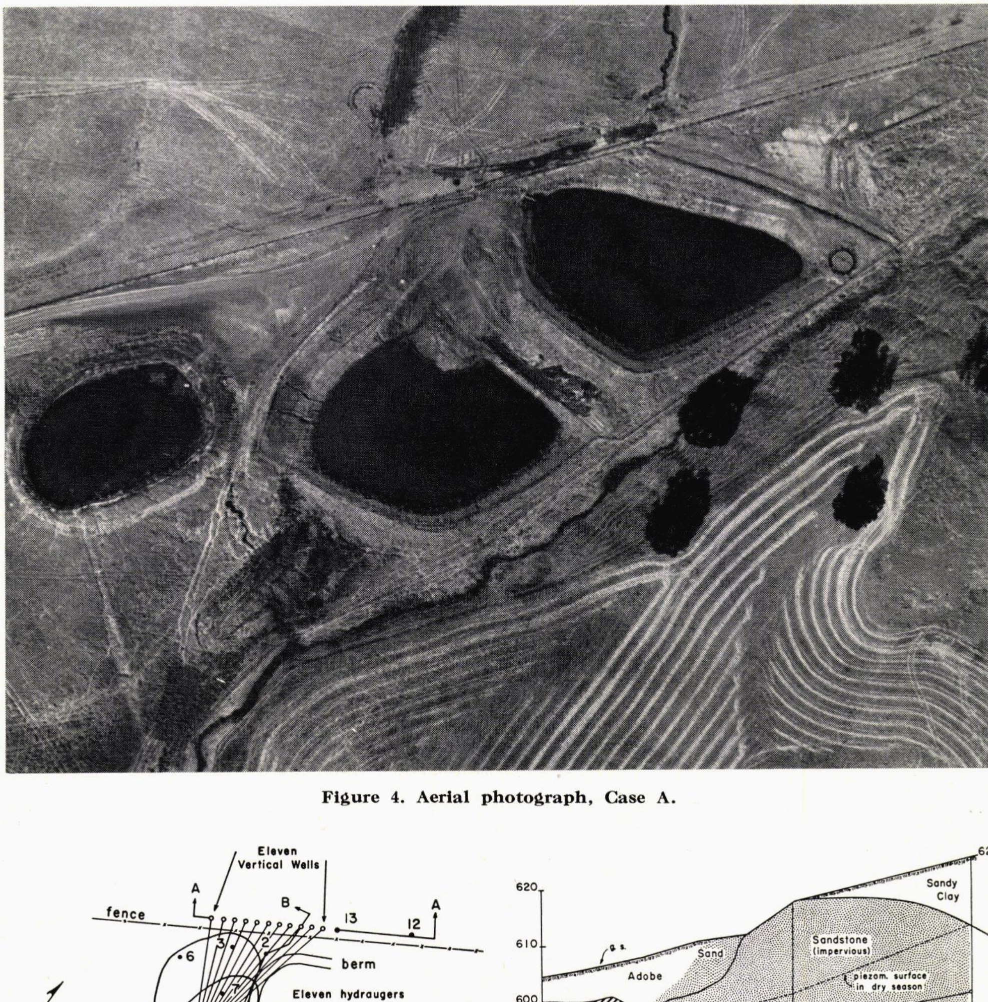

Figure 4. Aerial photograph, Case A.

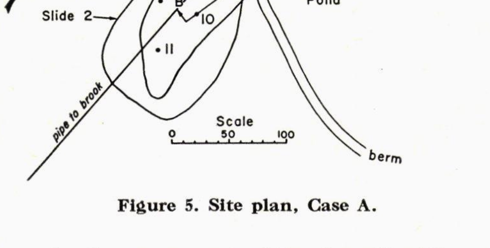

Figure 5. Site plan, Case A.

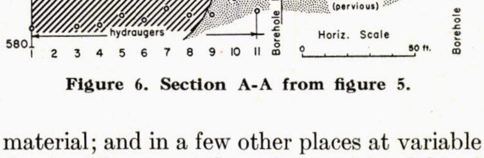

Figure 6. Section A-A from figure 5.

sec. in the upper part of the deposit with an average natural porosity of 27.7 percent). Sandstone was also found at the upper pond which apparently has been excavated in this material; and in a few other places at variable depths. The rest of the soil material bulldozed as it was, represented a mixture of loams and clays of different varieties. An average of representative samples has shown the plasticity index of that mixture at 13.5; the results of the mechanical analysis were (percentages by size): sand, 43; silt, 40; clay, 17 (including

5 percent of colloidal size). These sizes correspond to the U. S. Bureau of Soils triangular classification chart.

In general, the rise of the water level in borings and shafts, if such a rise takes place, may occur either slowly or reasonably rapidly, sometimes in 10 to 15 min., sometimes requiring a day or so. Slow rise may be due to seepage of the upper subsurface water into the boring and in this case is not critical. It may also be due to the fact that the boring is too shallow to completely penetrate an impervious cover. Conversely, rapid rise indicates that under original conditions the ground water at a given spot is kept down by impermeability of the local soil and that when a boring is made water rises to the level of the

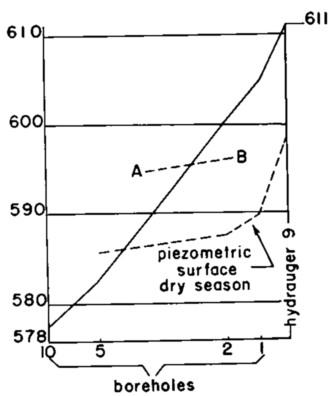

Figure 7. Section B-B, from figure 5.

piezometric surface at the given place. If there is no rise of water table in borings, the water table itself is the piezometric surface.

Figure 7 represents a section through Borings 12, 13, 1, 2, 5 and 10. In this profile are shown elevations of the natural ground, (i.e. those before the first slide) and elevations of the water level after it rose in the borings, the latter elevations being those of the piezometric surface during the time of investigations. Presumably the piezometric surface just before the first or second slide was considerably higher such as shown with a hypothetical line AB in Figure 7.

The fact that all three slides occurred at the same place, suggested that the impervious soil deposit at that place was thin and that the slides were caused by ground water under high pressure (artesian water). In other words, this particular place acted as a safety valve for a boiler with abnormally increased steam pressure. Apparently the grading for the reservoirs had reduced the natural impermeable cover over the ground water to where it was insufficient to withstand the piezometric pressure during the rainy season. The source of the trouble, therefore, seemed to be subsurface water under pressure. It was decided to take steps to decrease the water pressure by increasing the pore area of the material through which the water had to pass. In order to do this plans were made to install a system of underground sloping drains, locally known as "hydraugers" after a machine used for boring nearly horizontal holes.

Hydraugers are extensively used by the California Division of Highways both as corrective and preventive measures for stability of slopes where the presence of artesian water is established. An excellent example of their use is at the site of the large slide that occurred just west of Orinda on State Highway 24, in December 1950. The engineering staff of the City of Oakland has also had considerable practice in the use of hydraugers for rehabilitation of slides (*5*) that are particularly numerous in that area.

It should be noted that the general idea of the hydraugers is not to do away with the artesian pressure completely but simply to reduce it to a reasonable value that would not be able to cause a failure.

In pervious soils the hydrauger drains may simply consist of 2- or 4-in.-diameter slotted pipes placed in the ground to increase the cross section of the drainage area. The slots are about ¼ in. wide and 2 to 3 in. long. About 3 slots per foot of length are ordinarily used for 2-in. pipe; the slots are made with an acetylene torch.

In order to place the pipes a slightly oversized hole is drilled by a machine which is a combination of a drill and wash borer. After the hole is drilled the pipes are jacked into the hole and the sections welded together as the pipe is fed in.

In the particular case under discussion, since much of the material encountered was impervious, these sloping underground pipes were connected at their upper ends to vertical shafts or wells, 24 in. in diameter, spaced 10 ft. center to center and backfilled with coarse rock. The hydraugers were drilled into these vertical wells. A vertical section to approximate scale along one of the hydraugers is shown in Figure 8; Figure 5 shows the collecting and discharge system. The lower ends of the hydraugers were led into a steel standpipe which extends above the finished surface for purposes of observation. This in turn discharges into a 6-in.-diameter pipe which carries the water to a safe discharge point.

The 2-in. hydraugers were drilled beginning with the lowest (No. 1 in Figs. 5 and 6) and continuing in order to the highest (No. 11 in Figs. 5 and 6). In nearly every case water was encountered shortly before reaching the vertical well. The discharge was about 2 to 3 gal. per min. per hydrauger when the hole was first drilled. When all of the holes were completed most of the discharge was coming from the last three hydraugers (i.e., Nos. 9, 10 and 11, Figs. 5 and 6). The total discharge was about 5 gal. per min. and it remained fairly constant before the beginning of the rainy season.

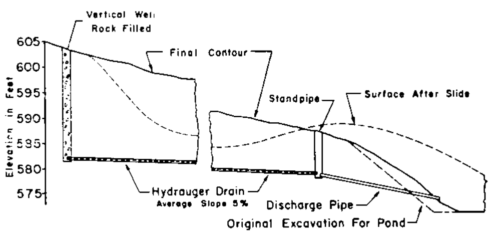

Figure 8. Typical section showing hydraugers, Case A.

After the hydrauger installation was completed it was necessary to reconstruct the berm. This involved the placing of about 3500 cu. yd. of compacted fill with removal of the loose material under the base of the new fill.

An important factor in slides caused by artesian ground water is the decrease of the shearing strength of the earth material by the neutral stress (pore pressure), as is the consensus (*4*). Another possibility of failure is shown in Figure 3 when a part of an impervious deposit is pushed up by ground water under pressure. The writers are inclined to believe that the Case A slide was of this latter type, but are not in a position to affirm it in a definite way because of the disturbance of the ground between slides and consequent loss of evidence.

SLIDES PRODUCED BY UPPER SUBSURFACE WATER

Figure 9 shows a hypothetical case of a long slope in cohesive homogeneous material the upper layer of which is being saturated by the water from rains. The thickness of this layer is designated with symbol z. This upper layer is assumed to be underlain by a firm impervious material or a completely saturated soil layer. Generally the upper layer under consideration has undergone a certain weathering process; it will be termed "weathered layer" hereafter. It is assumed furthermore that in a transverse section of the slope this weathered layer consists of an upper (steeper) portion and a lower (flatter) portion separated by a vertical plane MN (Fig. 9). During a rainstorm water flows on the ground surface and the weathered layer becomes soaked, at least close to the ground surface.

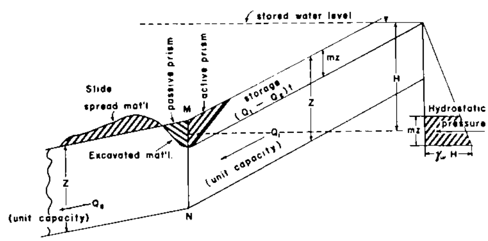

Figure 9. Building up of pore pressure in the upper subsurface water, followed by a slide.

In this way water and air within the weathered layer are practically confined.

The following notation will be used hereafter:

k—coefficient of permeability of the given earth material;

α_1 and α_2—slope angles of the steeper and the flatter portions of the weathered layer, respectively;

Q_1 and Q_2—discharge capacities of the steeper and flatter portions of the weathered layer, respectively, per unit of time and per lineal foot of the slope, and when water level coincides with the ground surface;

γ_w—unit weight of water.

Remembering that if the flow lines are parallel to the ground surface as in this case, the hydraulic gradient may be assumed to equal the tangent of the slope angle, we have

$$Q_1 = k(\tan \alpha_1)(z \cos \alpha_1) = kz \sin \alpha_1 \quad (1)$$

and similarly

$$Q_2 = kz \sin \alpha_2 \tag{2}$$

It appears from Formulas 1 and 2 that the discharge capacity of the steeper portion of the slope Q_1 is larger than the discharge capacity of the flatter portion Q_2 because $\sin \alpha_1$ is larger than $\sin \alpha_2$.

Consider now the beginning of a series of heavy rains causing gradual saturation of the weathered layer. First the amount of flow in both portions of the weathered layer is less than Q_2; but at a certain moment the lower (flatter) portion of the weathered layer becomes fully saturated with water and entrapped compressed air. A certain part of the water coming through the upper (steeper) portion of the weathered layer will be then stored in that portion.

It is natural to believe that when water gradually fills the pores of the weathered layer the flow is concentrated close to the base of the latter. Hence, when the lower portion is saturated excess water is stored at the top of the upper portion the thickness of this storage space being (Fig. 9).

$$z\frac{Q_1 - Q_2}{Q_1} = z\frac{\sin \alpha_1 - \sin \alpha_2}{\sin \alpha_1} = z\left(1 - \frac{\sin \alpha_2}{\sin \alpha_1}\right) \tag{3}$$

For the sake of brevity, let

$$1 - \frac{\sin \alpha_2}{\sin \alpha_1} = m$$

Designation m is also used in Figure 9.

When the stored water reaches a certain critical height H, as measured from the center of storage strip mz thick (Fig. 9) hydrostatic pressure from the upper portion of the weathered layer will overcome the passive resistance offered by its lower portion. In this connection an active and passive prism develop forming roughly angles of 45 deg. with the vertical MN. At failure both prisms are washed out, and the washed material spread downhill. The hydrostatic pressure causing the slide is represented by the cross hatched trapezoid at the right (Fig. 9).

If in the upper portion of the slope there is already a water accumulation that contributes to the water flow in that portion but does not permit the air to escape from the underlying soil-water-air mixture, a slide of the explosion type would occur as soon as the lower portion of the slope is saturated. The phenomenon that takes place in this connection is very similar to the well known water hammer phenomenon caused by a sudden closing of a valve.

An interesting problem (Case B) in rehabilitation of a slide of this type was encountered at another new suburban community a few miles east of Oakland. An excavation for the purpose of constructing roads and streets and developing building areas had been made at the base of a series of hills rising about 300 ft. above the adjacent valley. The slope of the hills averaged 25 deg. The cuts had been made at a one to one slope to depths of 10 or 15 ft.

The next rainy season after this work was done a series of slides occurred. Altogether six separate slides affected the particular community. Some of the slides were on undisturbed slopes and some extended into the cuts. An aerial view of the slides is shown in Figure 10.

Borings disclosed that dense clays were overlain in general by about 5 ft. of less dense, more permeable soil. Some gravel lenses, which undoubtedly serve as underground storage basins during the rainy season, were also uncovered. One of these occurred under the natural basin shown on a plan view of the area (Fig. 11). This collection area was indicated to be responsible to a large degree for slides 4, 5, and 6 in Figure 11.

The borings and visual inspection of the site seemed to indicate that the slides encountered were mainly in the nature of relatively shallow surface creeping. Remedial steps included the placing of hydraugers in slide areas to reduce pore pressures in the critical upper soil layer; release of water from the probable underground storage basins by penetrating them with hydraugers; and reduction of water going into the soil by improving surface drainage. A general plan of corrective measures is included in Figure 11.

Rehabilitation of a slide caused by subsurface water is a difficult problem. Though hydraugers may be very useful in this connection, they are not always fully efficient following initial installation. This is especially true when the slide is caused by "upper" subsurface water, as in Case B. In such instances the engineer has to improve his installation gradually by trial and error, and perhaps combine hydraugers with rock-filled drains or other drainage features.

Figure 10. Aerial photograph, Case B.

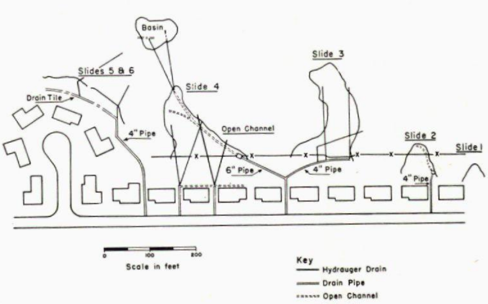

Figure 11. Plan of corrective measures, Case B.

SUBSURFACE WATER AND GRADING

Another example of some effects of subsurface water under pressure was encountered in a new development on the San Francisco Peninsula as discussed hereafter.

The area again lies at the foot of a fairly high range of hills. The particular site in question originally had a maximum elevation of about 20 ft. with a gradual slope towards San Francisco Bay to the east. An excavation was made on the high side and the material was used to construct a fill on the low side of the area. Although the excavation was quite extensive in terms of yardage, it was relatively shallow. The maximum cut varied from about 5 to 10 ft.

A week or two after the cuts were made (in May) water began to appear on the surface in several places. This was particularly evident in street excavations where cuts at the curb were below the surrounding finished grade. The writers were engaged to study the condition and make recommendations.

Test borings indicated the presence of subsurface water under pressure. It was apparent that the impermeable overcover had been made thin enough so that the pressure was forcing water through. Since the cuts at this location were shallow and no particular danger of sliding was apparent, underground open tile drains along and parallel to the base of the cuts were installed. The drains were placed far enough below the surface to go through the impermeable cover; this required a depth of about 5 ft. in most cases.

SUBSURFACE WATER IN THE FOUNDATIONS OF FILLS

Construction of fills in most sections of the Bay Area and adjacent localities must be preceded by a thorough investigation of the foundation. Cases have been observed when subsurface water reaching the foundation of a fill produced a general settlement and cracking of the latter. It is true that such phenomena are not uncommon in loess areas; but the writers know of cases of fills on alluvial soils built during dry seasons in semi-arid areas that have deteriorated when the foundation was moistened. Apparently more studies are required along the lines.

STOPPING SUBSURFACE WATER AT THE SOURCE

In preventing and rehabilitating slides the authors always try to find the original source of the detrimental subsurface water and *stop the trouble at the source* or as close to the source as possible. Particularly in Case B, the system of hydraugers was designed with the purpose of reducing the pressure in the subsurface water especially by tapping possible underground reservoirs or streams under impermeable cover which tend to build up these pressures.

The authors were pleased to discover that the principle of stopping the trouble caused by the subsurface water at the source is successfully used by Swiss engineers (*6*).

USE OF AIRPHOTOS IN THE STUDY OF SLIDES

Special airphotos of a slide where study and rehabilitation are to be made, are of great help as may be concluded from the preceding discussion of Cases A and B. An airphoto facilitates the surveying and may make it unnecessary, wholly or partly. The cost of aërial photography is not high, as it is often believed. The authors' practice has shown that this relatively inexpensive source of information clearly discloses the details of the sliding site, even those that have escaped the attention of the investigator during a visual inspection.

CONCLUSIONS

Planning and construction of earthwork should be based on the knowledge of local topographic and geologic conditions, including subsurface water.

Experiences in California have shown that special attention should be paid to the subsurface water investigations if the proposed earthwork is located at the base of a chain of hills. In this case the piezometric levels may be considerably higher than the actual water tables.

Where an actual failure occurs in earthwork or on a natural hill slope it often takes the form of a slide. Correction of such conditions very often may properly include steps to reduce the pressure in the subsurface water. This can be done by increasing the pore area through which water can travel by the use of oblique tubes, often called hydraugers. These may be used in connection with vertical shafts or wells.

Excavations in impervious soils at the base of a hilly area for highways or area grading require special care. Such excavations should not be undertaken without sufficient knowledge of subsurface water conditions to avoid swampy conditions or sliding.

Design of fills in semiarid areas should be based on the intimate knowledge of the properties of both the fill material itself and that of the foundation of the fill.

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DISCUSSION

A. W. ROOT, *Supervising Materials and Research Engineer, California Division of High ways*, and E. B. ECKEL, *Chief, Engineering Geology Branch, U. S. Geological Survey*—This paper is, in our opinion, valuable because it emphasizes the important part played by subsurface water in causing slides and because it calls attention to the need for more intensive study of subsurface water conditions in prevention and correction of slides. Much is known about the movement of water below the true water table, but pore pressures and other factors related to water above the water table (called "upper subsurface water" by these authors and called "vadose," "mantle," or "perched" water by others) have been very largely neglected by groundwater geologists and engineers alike. The authors have performed a real service in calling attention to this area of relative ignorance; it is to be hoped that they, as well as others stimulated by their paper, will continue research in this field.

Krynine and Woodward stress the hazard which exists *at the base* of a hilly area. Though the geology of the terrain may be such that the base of the slope is critical, we believe that the stability may be just as questionable along the steep slope above the base of the hill. It has been our experience and observation that construction of either embankment or excavation well above the base of steep slopes may be dangerous. For the stratigraphic conditions depicted in the paper the hydrostatic pressure would, theoretically, be greatest near the base of the hill; in reality, excessive pressures may obtain well up on the slope.

There is a reference to flow of sub-surface water similar to the water hammer phenomenon in pipes; the analogy does not seem to be well chosen, as we doubt that the authors intended to imply that the velocity of flow of the ground water is sufficient to resemble water hammer. Throughout the paper we get the impression that the upper subsurface waters tend to move rapidly and along narrow, elongate courses similar to surface streams. We grant that ground waters do move rapidly at times, and even that some of them follow narrow courses, but we feel that these are the exceptions rather than the rule.

It is noted that the term "hydrauger drains" is used throughout the paper. We prefer to describe this type of drains as "horizontal drains"; *Hydrauger* is a trade name for one particular type of drilling equipment; the Hydrauger equipment is used for installing horizontal drains, although not exclusively; other types of drilling equipment are used for the same purpose.

Although some of the above comments appear to be in the nature of fault finding, we do not wish to belittle the value of the paper. In general, we agree with the authors' conclusions as to cause and corrective treatment. We believe also that the paper will promote better understanding of the nature and effects of subsurface water. We heartily agree with their statements which point out the difficulties involved in analysing a landslide and emphasize the desirability of adequate study of questionable areas during design stages.

EARL M. BUCKINGHAM, *Supervising Civil Engineer, City of Oakland, California*—The authors have presented a stimulating paper and have given interesting descriptions of some of their work which involved difficult problems. It is refreshing to read a paper which does not attempt to force all slides into a set of stereotyped patterns, but recognizes each as an individual problem. Case A is an excellent example of this individuality. At first glance this slide seems impossible of solution, as it was necessary both to dry the slide mass and to maintain an unlimited supply of water a few feet away on the upper side of the dam. The existence of the source of water that was causing the trouble could only have been discovered by a thorough and capable investigation not hampered by preconceived generalizations.

The layout shown in Figure 5 is an ingenious adaptation to the site. Had the topography been more favorable it might have been better to drain all wells by a single hydrauger boring from a pit located on the westward extension of the line of the wells. The pit would in turn be drained by boring from a point to the west of the slide. This scheme would have presented several advantages. The footage of hydrauger borings would have been materially reduced, and it would have been possible to increase the number of wells, probably to double the number used, to provide a more complete cutoff. More important, the works would have been entirely removed from the area of the slide. Where borings run through or under the slide mass there is frequently the possibility of leakage from the borings entering the slide, or even of the destruction of the drainage pipes by renewed or deepened slide movement. However the topography did not lend itself to the foregoing treatment, as the required pit would have been excessively deep and would probably have encountered rock too hard for hydrauger boring. The scheme adopted by the authors seems the most suitable for the site.

Where the flow of feed water is concentrated in a well-defined channel, either under pressure or of considerable depth in a pervious body, it may be sufficient to relieve the pressure without obtaining a positive cutoff of all flow. Case A and the Orinda slide mentioned by the authors are examples, as is the Barrows-Holman slide. However, hydrauger borings parallel to the slide motion are seldom effective unless the water is concentrated in a small area at or preferably above the head of the slide. The writer tried borings of this type on the McKillop slide and in the 1940 work on the Simmons Street slide without noticeable effect in either case. The following year the Simmons Street slide was arrested, though not completely stopped, by a system of borings forming a cutoff transverse to the slide, supplemented by longitudinal borings to drain known aquifers. Movement since that time has averaged about 0.02 ft. per year.

In view of this experience, the writer prefers the most positive cutoff that can be obtained. A pipe drain in a continuous rock-filled trench will intercept all flow. If the trench is located

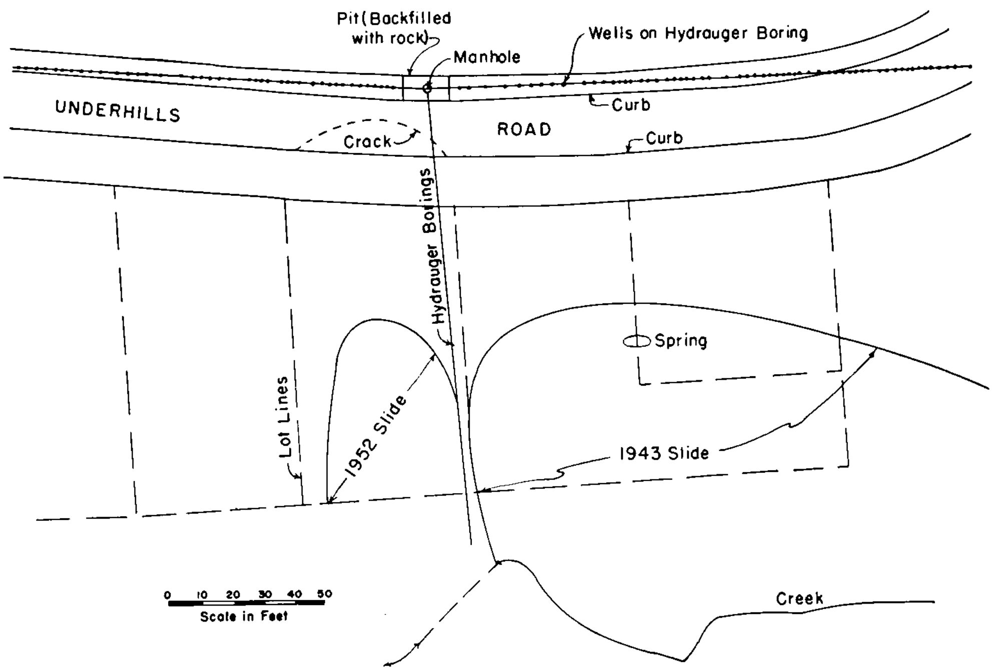

Figure A. Underhills Road slide.

in the slide area it must be of sufficient depth to be below any possible movement. Where the depth is such as to preclude a continuous trench, or where it is not desirable to open a trench across the slide, a reasonably complete cutoff can be obtained by a series of pits drained by a connecting tunnel. Two factors are involved in determining the size and spacing of the pits. It is important that no material flow be allowed to pass between the pits, so the spacing must be close enough to intercept all probable channels. On the other hand, the undisturbed areas should be of sufficient size to provide some support to the slide mass until the pits can be backfilled. Depending on available equipment, pits may be constructed either by conventional excavation with a crane and clamshell, or as circular borings 2½ to 3 ft. in diameter. Because of the rapidity with which borings can be made and cased the clear space between pits can be reduced to as little as 2 or 3 ft., correspondingly reducing the danger of missing an important channel and considerably shortening tunnel lengths.

It is frequently possible to install the horizontal drains in hydrauger borings, eliminating all hand tunneling. In collaboration with Hyde Forbes, consulting engineer and geologist, Palo Alto, California, the writer has just completed such an installation on Underhills Road, in Oakland, as shown in Figure A. The formation involved is a highly sensitive yellow silt clay which has considerable shearing strength in the undisturbed state but is almost viscous when remolded. It was therefore felt that the corrective works should be kept out of the slide mass as much as possible, and that the water must be intercepted before it entered the slide.

The first serious movement of this slide occurred in the early part of 1943, and at that time appeared to involve little more than the topsoil and an old fill which covered much of the area. As this surface material was removed by sliding into the creek rainfall reached progressively lower and the slide involved deeper material year by year. In 1952 an area to the west of the original slide began to move, and a crack opened in the street area. While the original slide seemed to have been caused primarily by direct rainfall, this additional area was obviously fed by an underground source. Meanwhile, the movement of the old slide had uncovered a winter spring which undoubtedly contributed to the movement. Test borings in the street did not locate any large channels that could be tapped by hydrauger borings but did encounter several wet areas at depths ranging to about 30 ft. Below this depth the clay was much harder and apparently practically impervious. The pit shown in Figure A was excavated about 2 ft. into this impervious clay, and a boring made from a point near the creek to the bottom of the pit. Because this boring passed close to or possibly within the slide mass, it was used only during construction to carry away wash water and cuttings from the hydrauger and well borings in the street. The permanent outlet was through a second boring on a flatter grade, some 15 ft. below the bottom of the pit and connected to the pit by a well. Working from the pit, two 12-in. hydrauger borings were made across the head of the slide, and cased with 6-in., perforated, corrugated iron pipe. Seven-inch drainage wells were then drilled to connect to the hydrauger borings, spaced about 2 ft. opposite the crack in the street and where water was found, and about 3 ft. elsewhere, with somewhat greater spacing where obstructions were encountered.

Based on the experience gained on this project, it is believed that a satisfactory interceptor can be constructed by this method. The hydrauger borings should be considerably larger than the casing, and the size of the wells should be increased to at least 12 in. Except for such preliminary wells as may be necessary to locate the hydrauger line, well drilling should proceed from the upper end of the line. As each well is completed it should be filled with fine gravel, sluiced in place. This gravel will advance along the hydrauger pipe and protect it from damage while drilling the next hole. The well drill should be of a type that is withdrawn from the hole to remove cuttings, as there is danger of damaging the pipe if a continuous auger is used.

While slides caused by hydraulic pressure are not unusual, probably a greater number of small hillside slides are the result of simple saturation. These slides may occur on any portion of a slope, depending on such factors as configuration of bedrock, location and volume of feed water, and depth and character of overburden. The writer has observed cases in which direct rainfall caused the surface of a slope to liquefy and flow across a four-lane highway with a depth of only about 6 in.

The initial action of these saturation slides does not involve pore pressure, but consists of lubrication, destruction of capillary cohesion, and increased weight. However the slightest deformation causes an increase in pore pressure, and in some cases almost complete liquefaction occurs very rapidly. On the other hand, movement may continue at an imperceptible rate throughout the entire rainy season. Slides of this type would probably not be corrected by relief of pressure, but would require complete interception of feed water as high on the slide as possible.

It is not ordinarily economical to attempt to stop slides caused by direct rainfall, unless property of unusually high value is involved or the slide can be stabilized by some such means as a nominal retaining wall. Even where the feed is underground it may, in some cases, be desirable merely to remove material from the toe and allow the slide to proceed until it stops itself by daylighting the feed channel and forming a spring. This is the process by which Nature stops her slides, and if given a little assistance, such as the treatment of Slide 2, Figure 11, it is frequently very effective. If the process is left entirely to Nature, movement is likely to be renewed during a subsequent wet period. The basis shown in Figure 11 is an illustration. This depression was formed by an old slide, clearly visible in the aërial photograph (Fig. 10). In all probability the slide progressed until the source of water was exposed at the head and drained in the general direction of Slides 5 and 6. Movement would have stopped or slowed materially, and reconsolidation would have taken place during the next period of dry years. Eventually the escape channel became buried by detritus and the water again moved through the slide mass, which however, remained stable until the excavations were made at the toe, bringing about the conditions described by the authors.

In conclusion, this writer wishes to emphasize that each slide is an individual problem, which can be solved if a way can be found to remove the water that is causing it. While certain generalizations are helpful, the water is still where it is found, and no possible source should be overlooked. The authors have made a real contribution by reporting in detail on a particular type of slide action in which artesian pressure is the dominant factor.

D. P. KRYNINE and R. J. WOODWARD, *Closure*—In response to the interesting and illustrative discussion of this paper, the authors wish to establish certain distinctions concerning various phases of ground-water flow and, at the same time, to clarify the terminology of the latter.

During periods in which no rain falls for a long interval of time, there is a capillary fringe above the water table overlain by a zone of hygroscopic moisture. Occasionally there may be some perched or entrapped water between the water table and the ground surface. The geologic term *vadose water* possibly covers all of these kinds of soil water.

After a prolonged period of heavy rains the situation changes, however, particularly in soil deposits having lower permeabilities. In such cases there is a zone or layer below the ground surface in which water is moving downward toward the true water table. These layers of upper-subsurface water seeping downward through the soil have been observed scores of times by the authors in borings, at a depth from 1 to 5 ft. below the ground surface. The water in these layers is *gravitational* and in many respects similar to that under the true water table. The principal difference between the two consists in the direction and perhaps the velocity of the flow. Presumably, in a general case above and below this layer, there are fringes of capillary and of hygroscopic water that may merge with those located above the true ground-water table. It follows that, in a deep boring intersecting such layers, the moisture contents at various depths may vary considerably, even in a perfectly homogeneous soil material. Moreover, such moisture contents are characteristic for the given place at a given time only, a circumstance that should be seriously considered by those studying the laws of moisture distribution in deep-borings.

A layer of gravitational water as described, located a few feet below the ground surface, may constitute a veritable curtain obstructing the downward motion of additional rain water, since the carrying capacity of the soil pores has already been reached in this zone. The additional water has to move downslope over the curtain. This may cause landslides to occur as described in the body of the paper. If the rain water should fill up all of the soil pores to the ground surface, the surficial and the undersurface flow could merge. If this should occur, the velocity of the undersurface flow would increase because of the drag (shearing stresses in this case) exerted by the upper layer of the combined stream on the lower layers. It is obvious that the "curtain" as described above should approximately follow the surface topography; this is the principal reason for the formation of subsurface-water streams over thinner ground-water layers that may completely disappear during dry seasons.

Though the term *hydrauger* as used in the Pacific Coast area may not be correct, it cannot be replaced by the term *horizontal drains*. In fact, if the pipes termed hydraugers were horizontal, water would not flow through them. The slope of a hydrauger should be greater than the gradient of the ground water; in the authors' practice a 5-percent slope is often used.

Stabilization of Fine-Grained Soils by Electro-osmotic and Electrochemical Methods

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THIS paper gives a brief explanation of the fundamental prolcesses of stabilization by electroösmotic and electrochemical means and cites the work of early investigators. The author investigated the effectiveness of the two methods by laboratory tests on two soils. The first type, a sandy silt, was investigated in the laboratory during development of testing techniques; the second, a medium fat clay, was investigated to evaluate and check the technique and apparatus developed. Tests included grain-size distribution, plasticity, standard compaction, triaxial shear, base-exchange capacity, X-ray diffraction, microscopy, and others. Data include time of lowering of phreatic line by well-point and by electric-potential methods, relative permeability prior to and after electroösmotic treatment. Eight figures illustrate equipment and indicate relationships established in the investigation.

● WITHIN recent years increased importance has been given to the development of practicable methods of stabilizing fine, unstable soils by removal of excess moisture or by the introduction of chemicals into the material in place. Previously, the incomplete knowledge of the physicochemical nature of earth materials was a major obstacle to this development. However, the rapid advancements made in the technology of soil mechanics and in the improvement of techniques of analyses of the mineralogic constituents, crystalline structure, and physicochemical properties of earth materials have opened new fields for soil mechanics engineers.

Two important techniques developed to stabilize fine-grained soils are the electroösmotic and electrochemical processes. These processes produce a movement of liquid through porous material under the influence of an electromotive force. The movement of liquid through porous material was described the first time in 1808 by Reuss (*5, 7, 8, 9, 10*). This movement of liquid results from electrophoresis in electroösmotic phenomenon. Electrophoresis is the transfer of particles in suspension due to the action of the electrical field, created by the flow of the current, on electrical charges carried by the particles.

Electrophoresis and electroösmosis are interpreted from the hypothesis of the "double layer," formulated for the first time in 1861 by Quincke. This hypothesis depends upon the supposition that a spontaneous electrification exists at the contact surface of a solid and a liquid prior to any external electrical action. The surface of the soil is usually charged with a certain electrical layer, and an