Effect of Water Movement on Soil

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Introductory Remarks by the Chairman

Much has been said in this symposium about the effect of the geometry and the physico-chemical character of the surfaces of the solid soil constituents on the movement of water through a soil system. It is well to supplement this by taking a different perspective, namely, to consider the effect of water movement on the soil. This Mr. Barber has done in his present paper which deals not only with microscopic, but also with macroscopic effects and their consequences as regards engineering structures. We are grateful to Mr. Barber for condensing into precise and lucid statements so much of his large research and practical engineering experience.

● MOST OF the problems of soil engineering are concerned with soil and water, rather than with dry soil.

Surface reactions are often important, especially if they have an opportunity to affect the dispersion or aggregation of the soil particles before compaction or consolidation. However, many effects of water movement are explained by mechanical reactions on a scale much larger than colloidal sizes.

WEATHERING AND EROSION

Water seepage often causes weathering at depths beyond the reach of surface temperatures and organisms. Figure 1 indicates how rainwater charged with carbon dioxide infiltrated to the water table whence it went horizontally and leached lime from a clayey shell layer resulting in very soft material along its path of flow to springs. A soft arkosic silt near Alexandria, Virginia, was found below 10 ft of firm gravel. While it had once been loaded by over 100 ft of gravel, it had apparently been weathered after most of the load was removed by erosion.

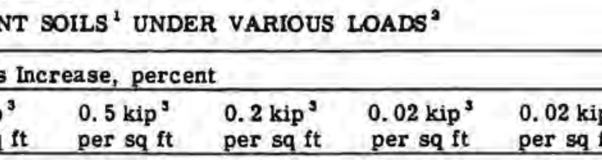

Figure 1. Softening of calcareous soil by solution—Yorktown.

Water erosion begins with the impact of raindrops followed by sheet erosion and gullying where water concentrates. Cohesion retards the beginning of erosion but fine soil is easily carried away once it is displaced. Weakly cemented soils, such as loess and volcanic ash, may

TABLE 1

MAXIMUM SWELL FOR DIFFERENT SOILS[1] UNDER VARIOUS LOADS[2]

Soil	Thickness Increase, percent							
	8 kips per sq ft	4 kips[3] per sq ft	2 kips[3] per sq ft	1 kip[3] per sq ft	0.5 kip[3] per sq ft	0.2 kip[3] per sq ft	0.02 kip[3] per sq ft	0.02 kip per sq ft
A-1	-0.4	-0.3	-0.1	0.0	0.1	0.5	2.1	11.8
A-2	0.0	0.6	1.0	1.4	2.0	2.7	6.6	13.1
A-3	0.0	0.0	0.2	0.2	0.3	0.3	0.6	0.4
A-4	0.8	1.9	3.2	4.3	5.7	7.4	12.9	22.5
A-5	0.5	2.1	2.9	4.6	6.2	7.8	15.1	17.1
A-6	12.2	13.9	16.0	18.2	23.1	-	38.4	70.7
A-7	1.4	4.7	5.5	6.6	7.6	9.0	13.2	21.4
A-8	10.1	12.9	15.6	16.4	17.4	19.1	63.5	98.7

[1] Air-dry soil compacted under 500 kips per sq ft.
[2] In kips per square foot.
[3] After swelling under previous load.

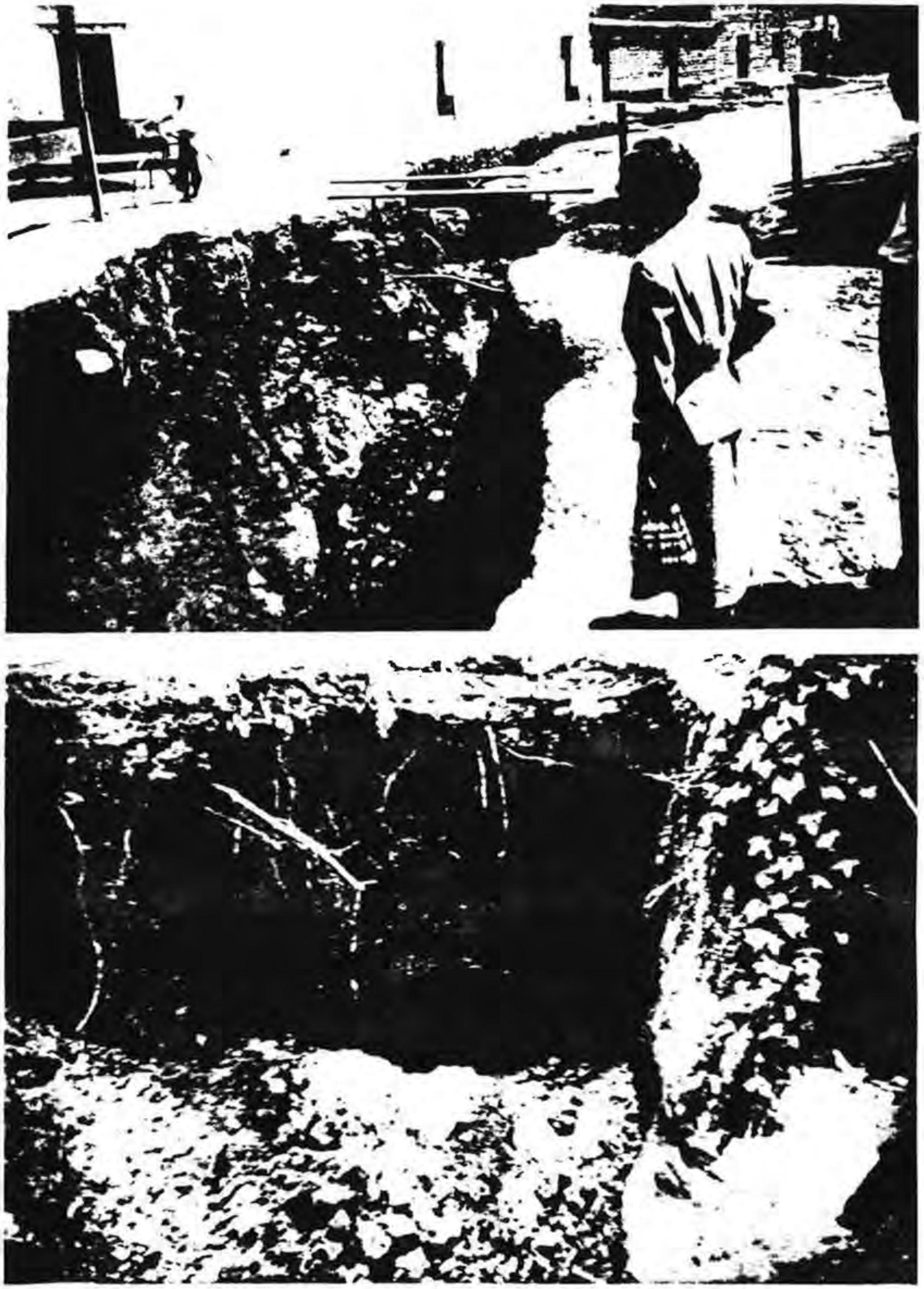

Figure 2. Effect of subsurface erosion in Guatemala.

stand undisturbed on very steep slopes, but are extremely erodible when placed in a fill after the cohesion is destroyed by manipulation.

Internal erosion may also occur. Where surface drainage is lacking, infiltrating water may flow laterally through pervious strata and cause backward

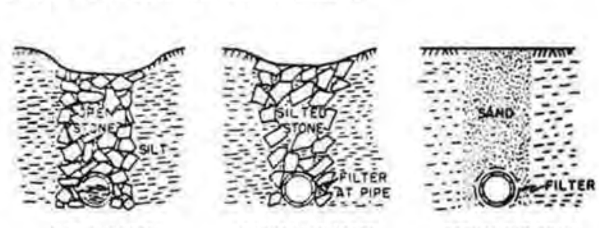

Figure 3. Intrusion of silt into drains.

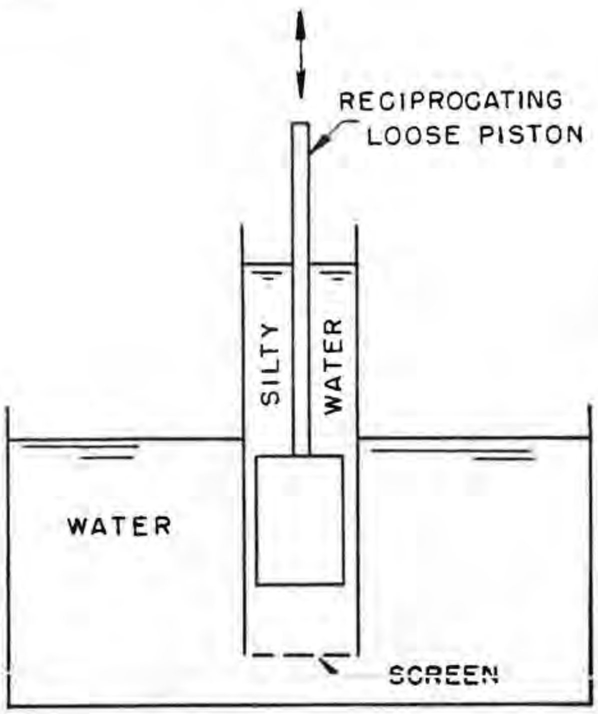

Figure 4. Soil pumping.

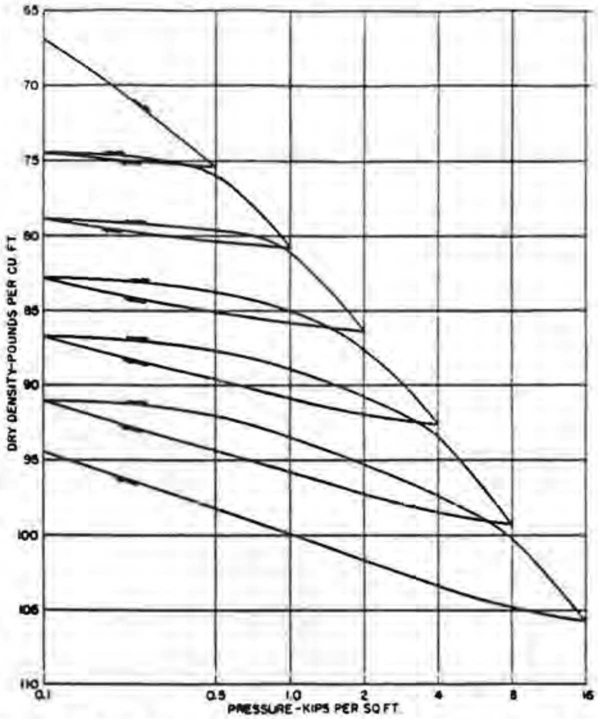

Figure 5. Hysteresis in consolidation of Tuxedo clay from liquid limit.

erosion or piping from an outcrop in a depression. Figure 2 shows the result when the roof of a piping tunnel collapsed. The tunnel is seen in the middle of the bottom picture showing a hole where a house had been.

Similar internal erosion causes failure of subdrains as shown in Figure 3, unless sand is placed between the pipe and the soil. Unless porous or perforated pipe is used to prevent open joints, a supplementary filler is required around the joints.

The displacement of soil and water from beneath concrete slabs deflected by heavy loads is a type of erosion. In addition to the splashing effect, the reciprocating vertical movement can actually pump water upward as demonstrated by the device

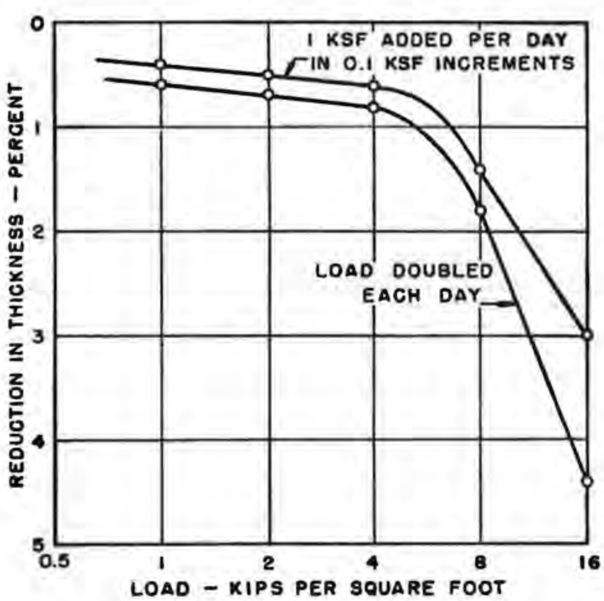

Figure 6. Effect of slow loading on consolidation.

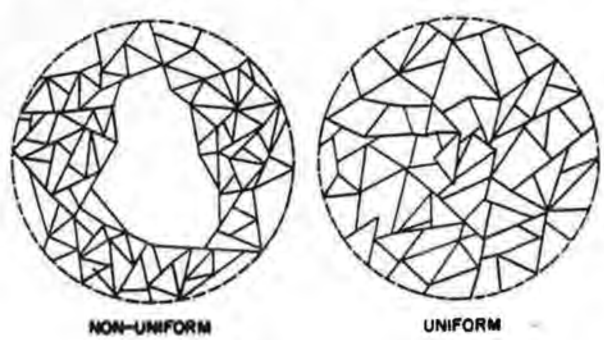

Figure 7. Soil structure.

Figure 8. Slaking due to sudden wetting.

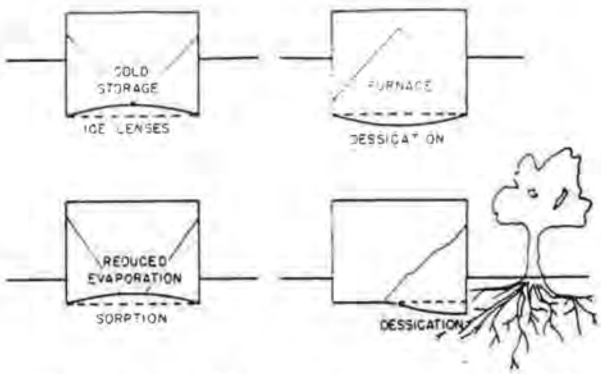

Figure 9. Volume change of clay under buildings.

shown in Figure 4. The soil particles in the water act as valves on the screen which represents the subgrade.

CONSOLIDATION AND SWELL

When a load is applied to a confined clay soil, the volume decreases due to slipping and bending of the plate and needlelike particles. When the load is removed, unbending causes an increase in volume but the slipping is inelastic so the soil is only partly elastice. If the same load is reapplied, friction between particles causes a hysteresis loop as shown in Figure 5. Similar effects are obtained with drying and wetting where the mechanical load is replaced by stresses balancing the surface tension of the water.

Slow application of loads may cause less consolidation as shown in Figure 6, possibly due to less slipping of particles.

The rate of consolidation under a given load is controlled by the escape of air and

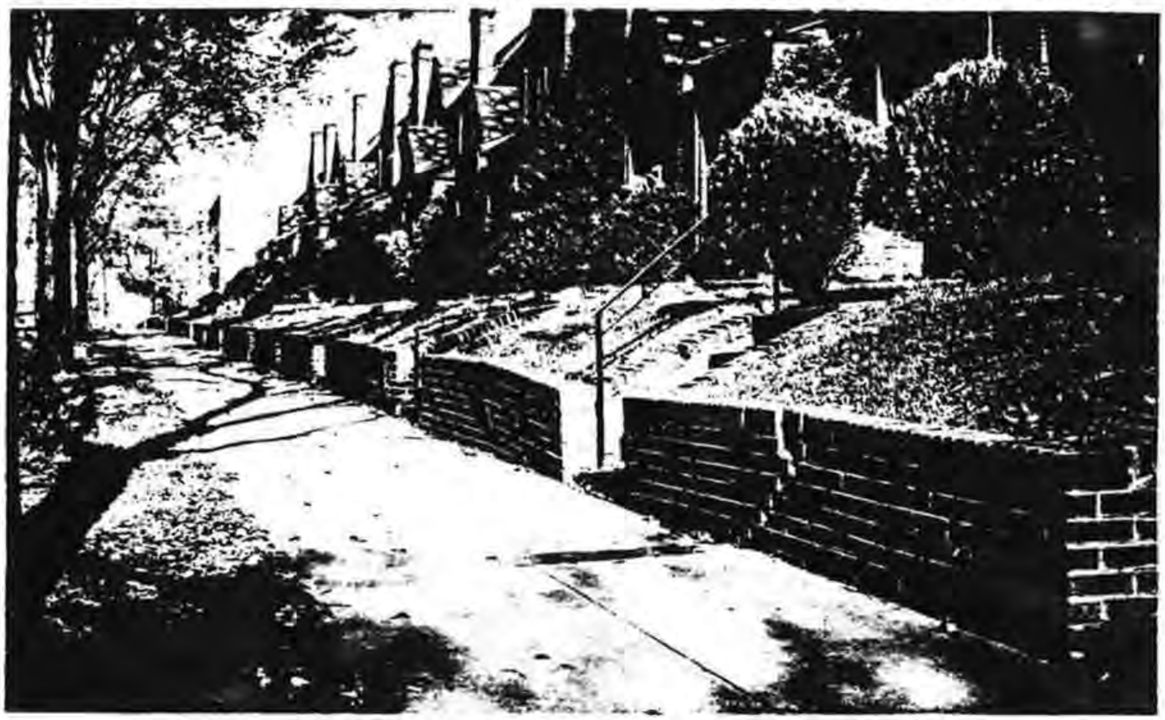

Figure 10. Evidence of bowl-shaped depression by trees.

water and thus depends upon the amount of fluid escaping and the permeability or fluid conductivity of the soil. An additional delay or secondary consolidation evident in cellular material such as peat may be caused by forcing hygroscopic water from the cells.

Both the amount and rate of consolidation depend upon the arrangement of the soil particles or structure. This is the reason for undisturbed sampling of foundation soils but also applies to compacted

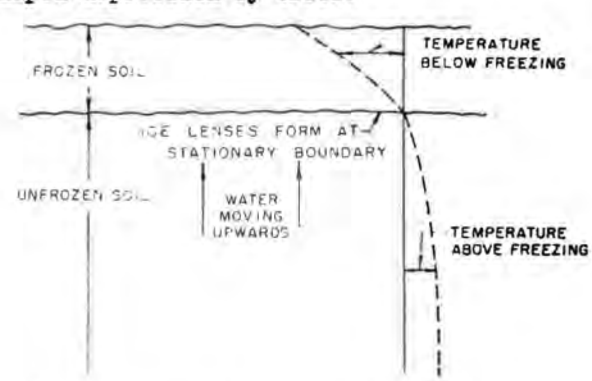

Figure 11. Mechanics of frost heave.

soils. Figure 7 compares the uniform structure of dispersed soils to the non-uniform structure of aggregated soils.

Sensitivity to disturbance increases with non-uniformity of structure. Marine clays may become extremely sensitive or quick if the salt which caused aggregation is leached out.

Compaction with a limited amount of water causes a non-uniform structure since the aggregations due to drying are not dispersed. Table 1 shows the swell or rebound of several soils. Comparison of the last two columns indicates that when swell is retarded, some of the elasticity is lost by dissipation laterally into the less dense parts of the non-uniform structure. This reduction was not found in highly dispersed samples.

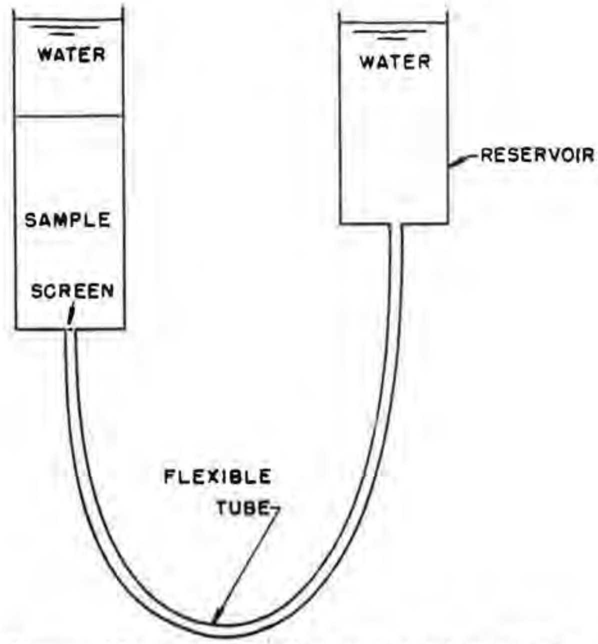

Figure 12. Device for applying vertical seepage force.

It is noted that the A-6 soil swelled 12 percent against 8 kips per sq ft. With no movement, a pressure of 38 kips per sq ft was noted. The sudden release of this energy is the cause of slaking. If dry clay is immersed in water, air trapped in the interior may be compressed and help to disrupt the sample when it escapes. However, slaking will occur if the lump of clay just touches the water as shown in Figure 8 and the air is free to escape upward. If dry clay is permitted to take up water very slowly, it is weakened much less.

Figure 9 indicates some effects of soil volume change on structures. An apartment

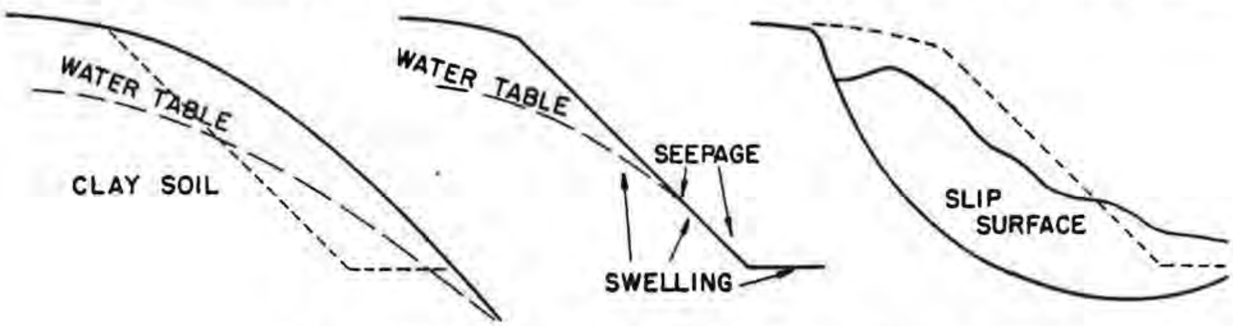

Figure 13. Development of slip in cut in clay.

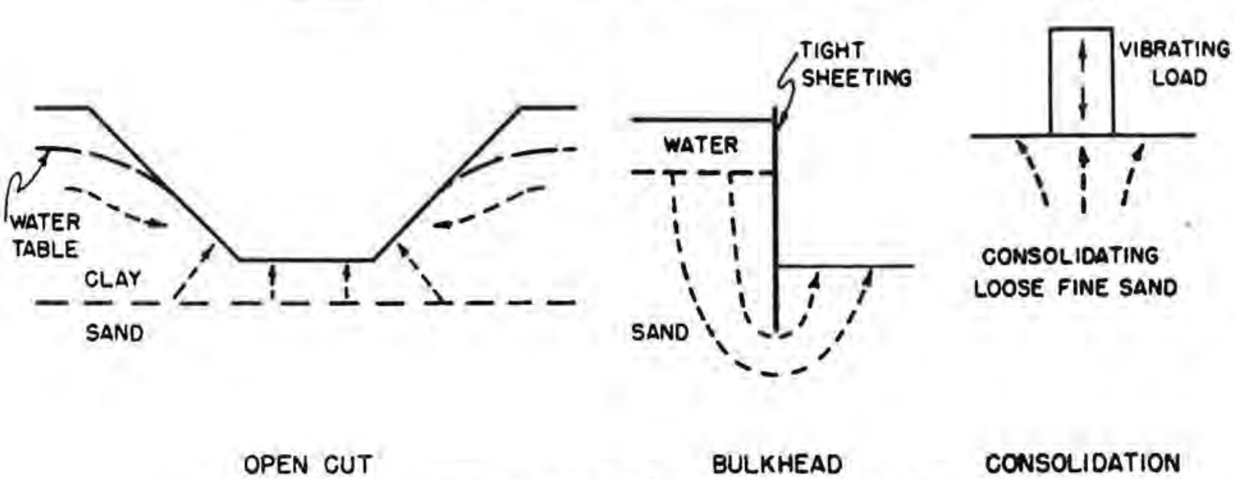

Figure 14. Illustrations of upward flow of water.

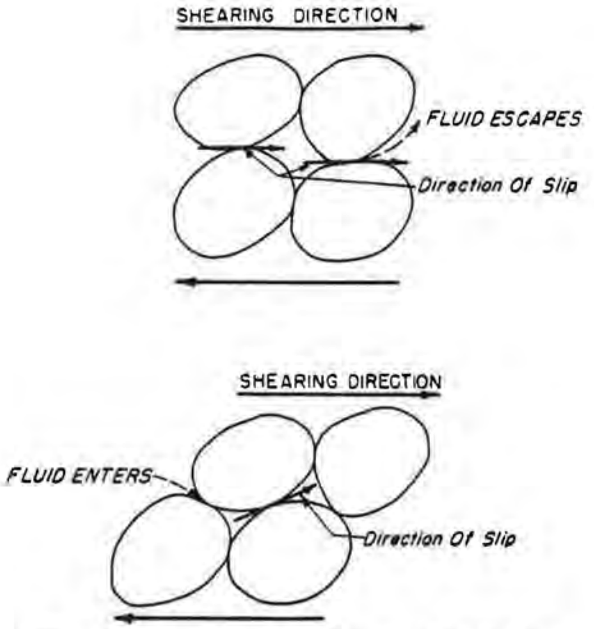

Figure 15. Volume change with shearing.

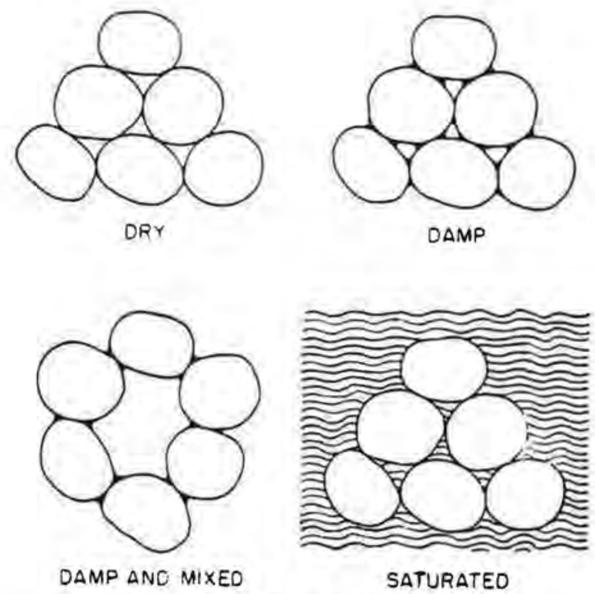

Figure 16. Bulking of sand.

house in Washington, D.C., was disrupted when surface water reached the dry clay supporting a central stairwell. The movement of the wall in Figure 10 indicates the bowl-shaped depression caused by a tree growing in clay. Frost heave under cold storage plants may be prevented by placing heaters below an insulated floor on soil. Figure 11 indicates that ice lenses are formed when the rise of water causes the freezing depth to remain static.

SEEPAGE FORCES

Soil below a static water table is bouyed up in proportion to the water it displaces. If the water table is lowered, the bouyancy is reduced and settlement occurs. This may be demonstrated by the device shown in Figure 12, using powdered mica as the sample and lowering the reservoir to create a downward seepage force. A similar device was used to apply consolidation loads to fluid samples of sediment from Lake Mead behind Hoover Dam. Large settlements in Mexico City have been caused by pumping water from sand below a very compressible clay.

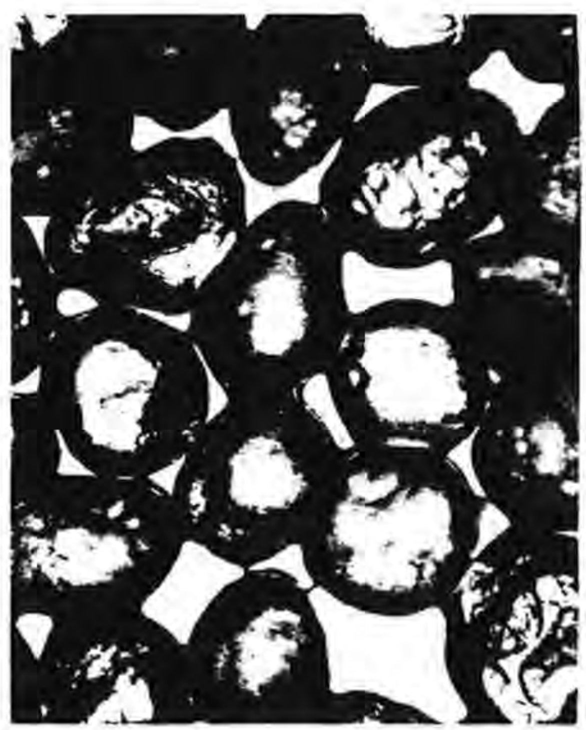

Figure 17. Water menisci between sand grains.

Lateral flow is an important factor in many landslides. The force is not necessarily reflected in the amount of seepage and may be critical only occasionally. In cut slopes in clay, the weakening of seepage is augmented by the gradual swelling of clay which may cause sliding (as shown in Figure 13) sometimes several years after making the cut.

Upward flow of water may cause various difficulties as illustrated in Figure 14. Blowups may be caused by too rapid excavation in clay over sand. The lateral support of sheeting for bulkheads may be

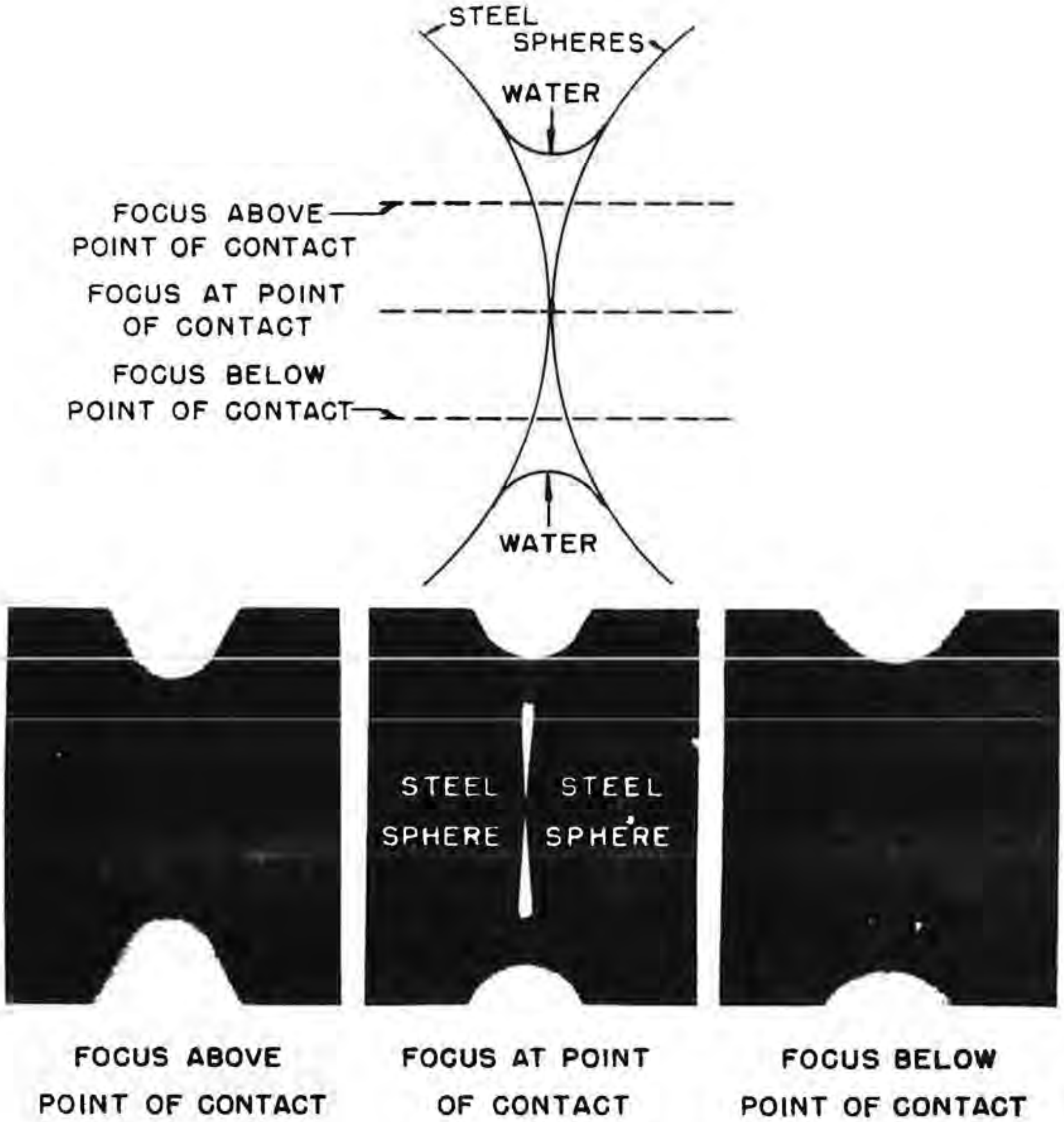

Figure 18. Water menisci around points of contact of steel spheres.

lost if too high an upward gradient causes quicksand. The tendency for a vibratory load to densify a loose saturated sand may cause a temporary quick condition as water is forced upward.

Figure 15 shows the volume changes that accompany shear. A saturated loose material loses strength as load is applied to the pore water; whereas above the critical density, the tendency to increase in volume causes a reduced pore water pressure which gives a temporary increase in strength. The coefficient of interval friction is increased by densification since the direction of slip is in effect uphill. This interlocking effect is added to the friction of loose material.

The bulking of sand when damp and mixed is caused by the surface tension of

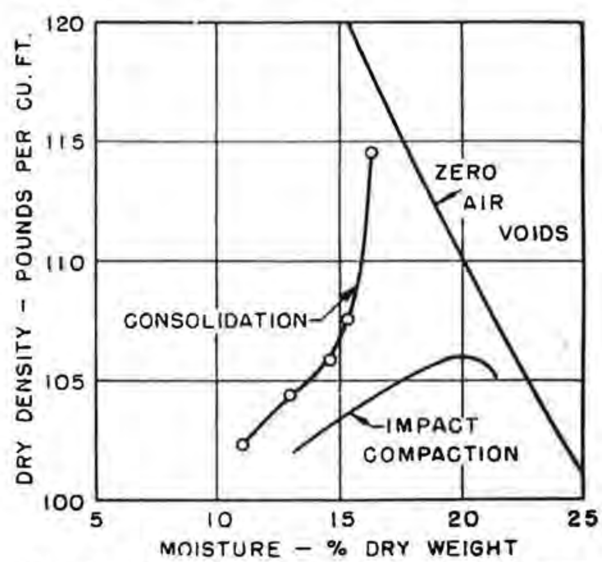

Figure 19. Consolidation versus impact compaction.

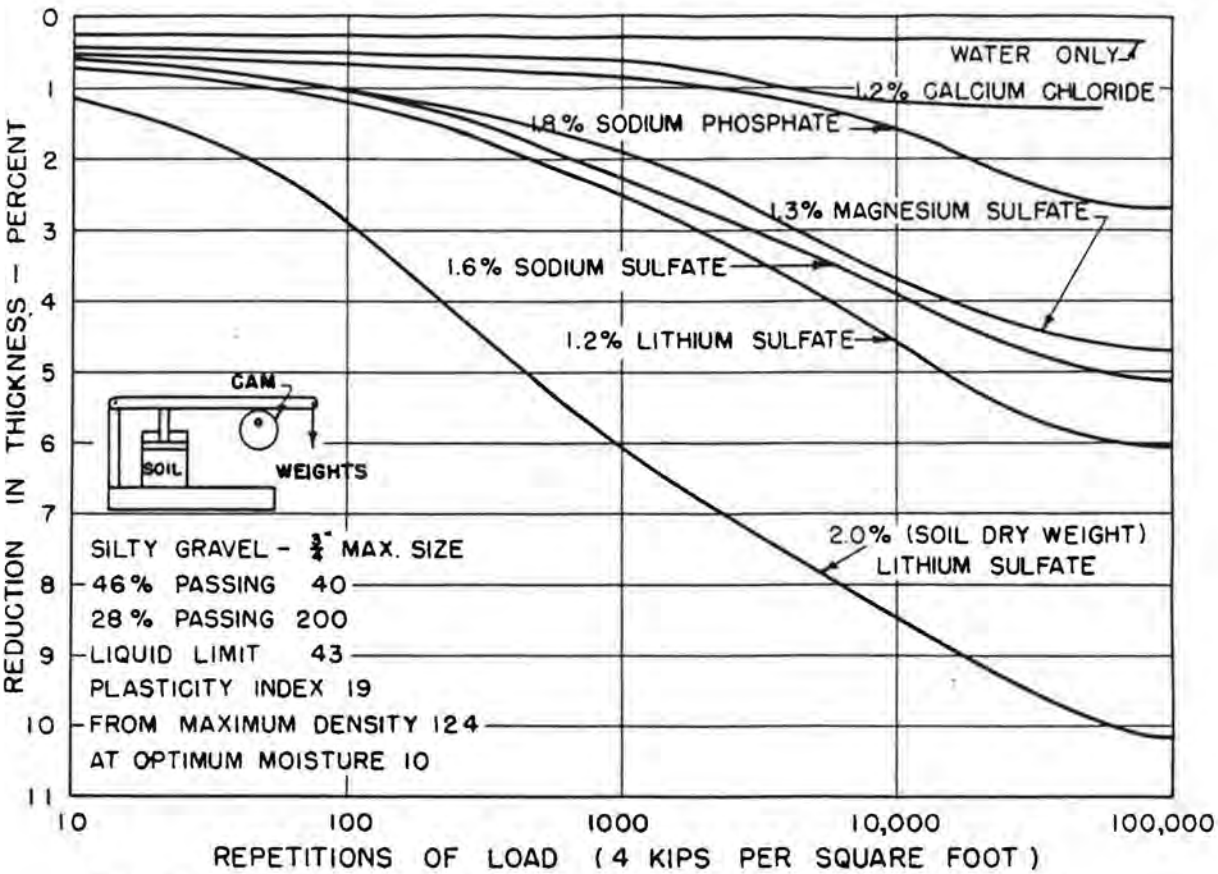

Figure 20. Effect of chemicals on densification under repetitive loading.

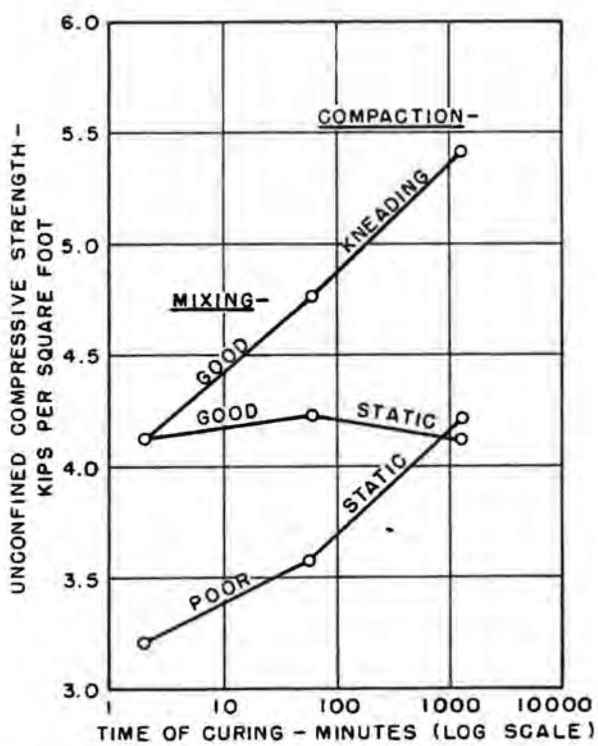

Figure 21. Thixotropy in clay near optimum (17) and maximum density (109).

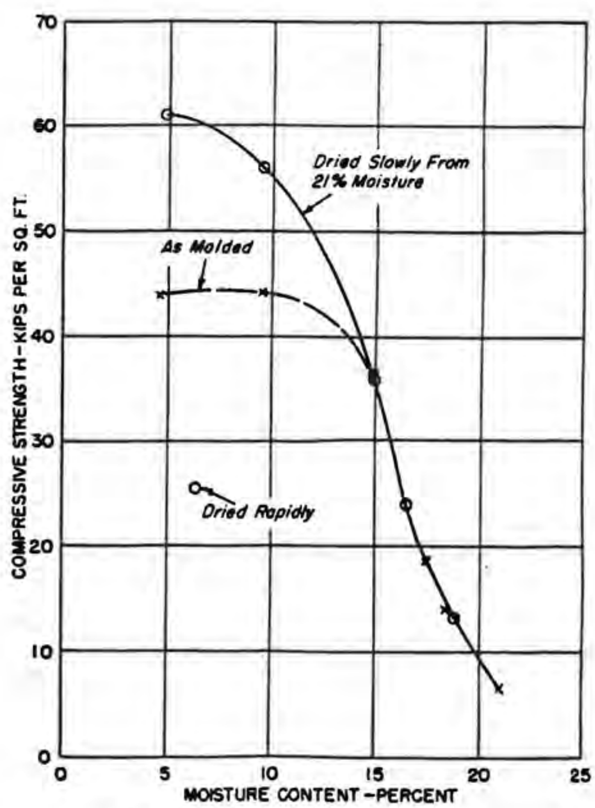

Figure 22. Effect of structure on strength of Tuxedo clay.

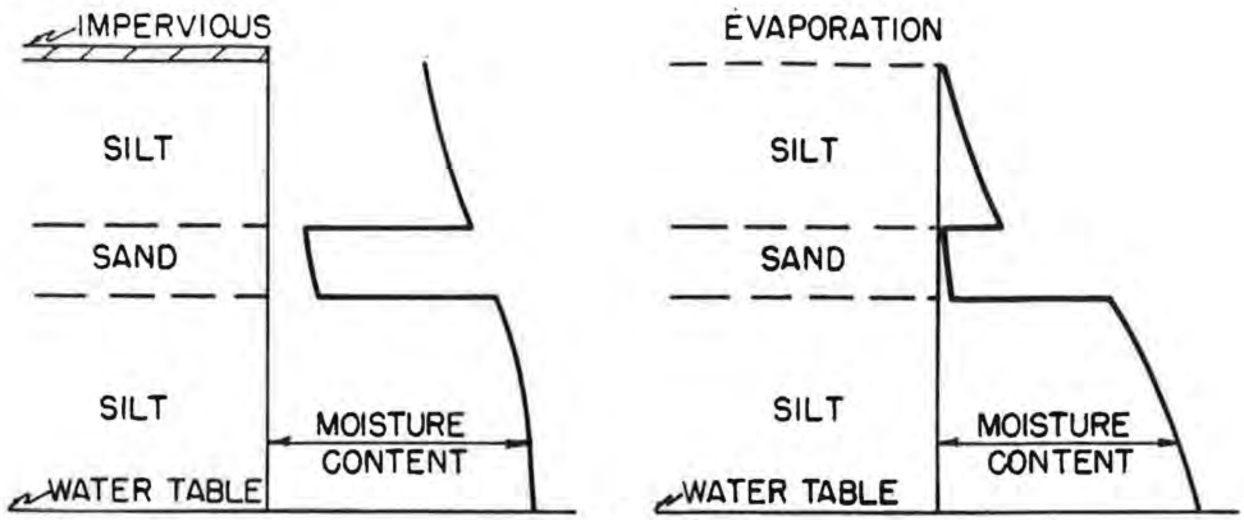

Figure 23. Capillary rise of water.

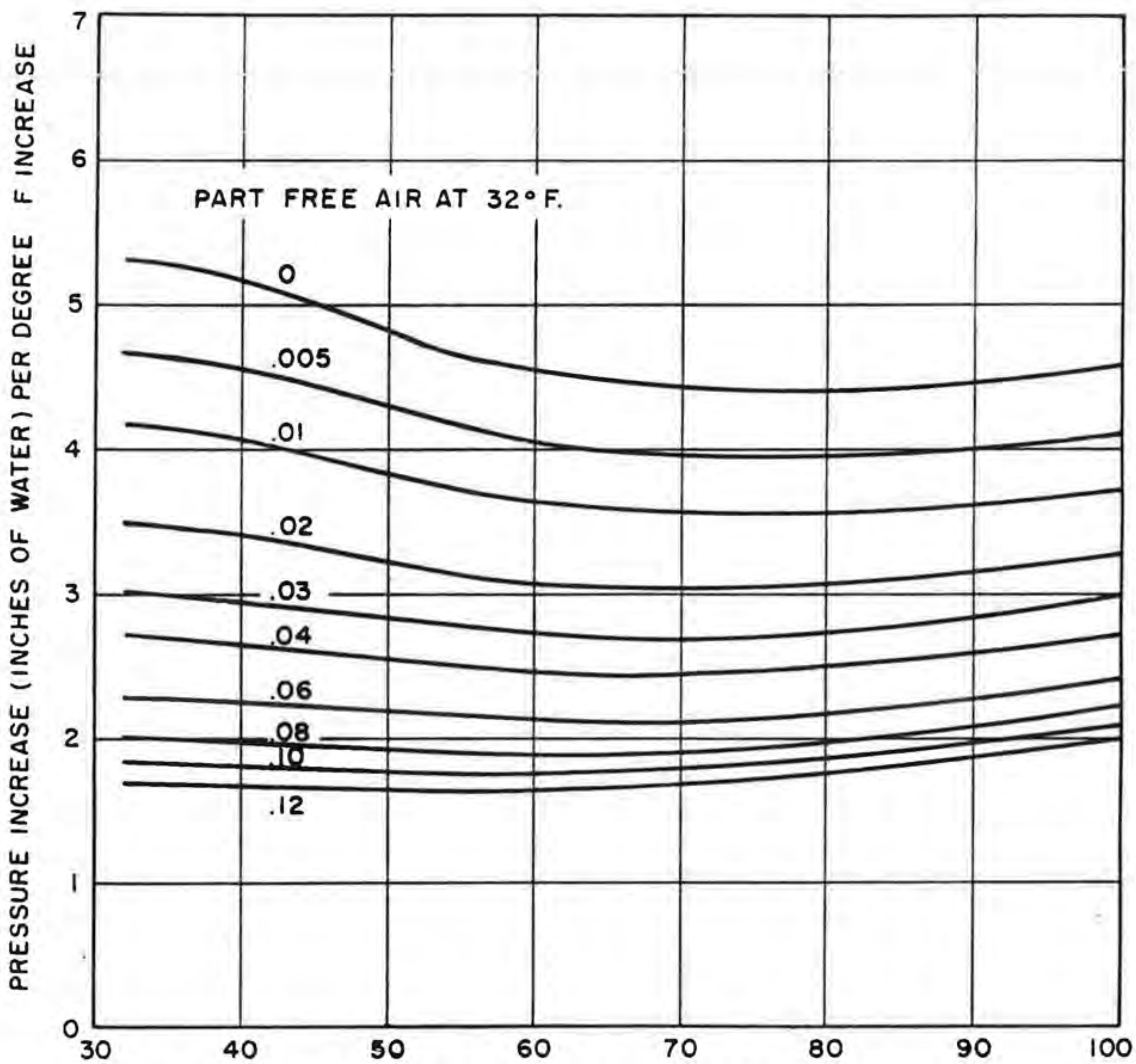

Figure 24. Pressure increase with temperature at constant volume for various air-water mixtures.

water holding the particles together as shown in Figure 16.

Bulking of sand was once wrongly attributed to water holding particles apart. This idea was supported by photographs of damp sand under a microscope as shown in Figure 17. The particles appear to be separated by water because an average focus cannot be at the level of most of the points of contact between particles. This fallacy is illustrated in Figure 18 which shows three photographs of two steel spheres with water around their point of contact. The middle photographs shows the point of contact;

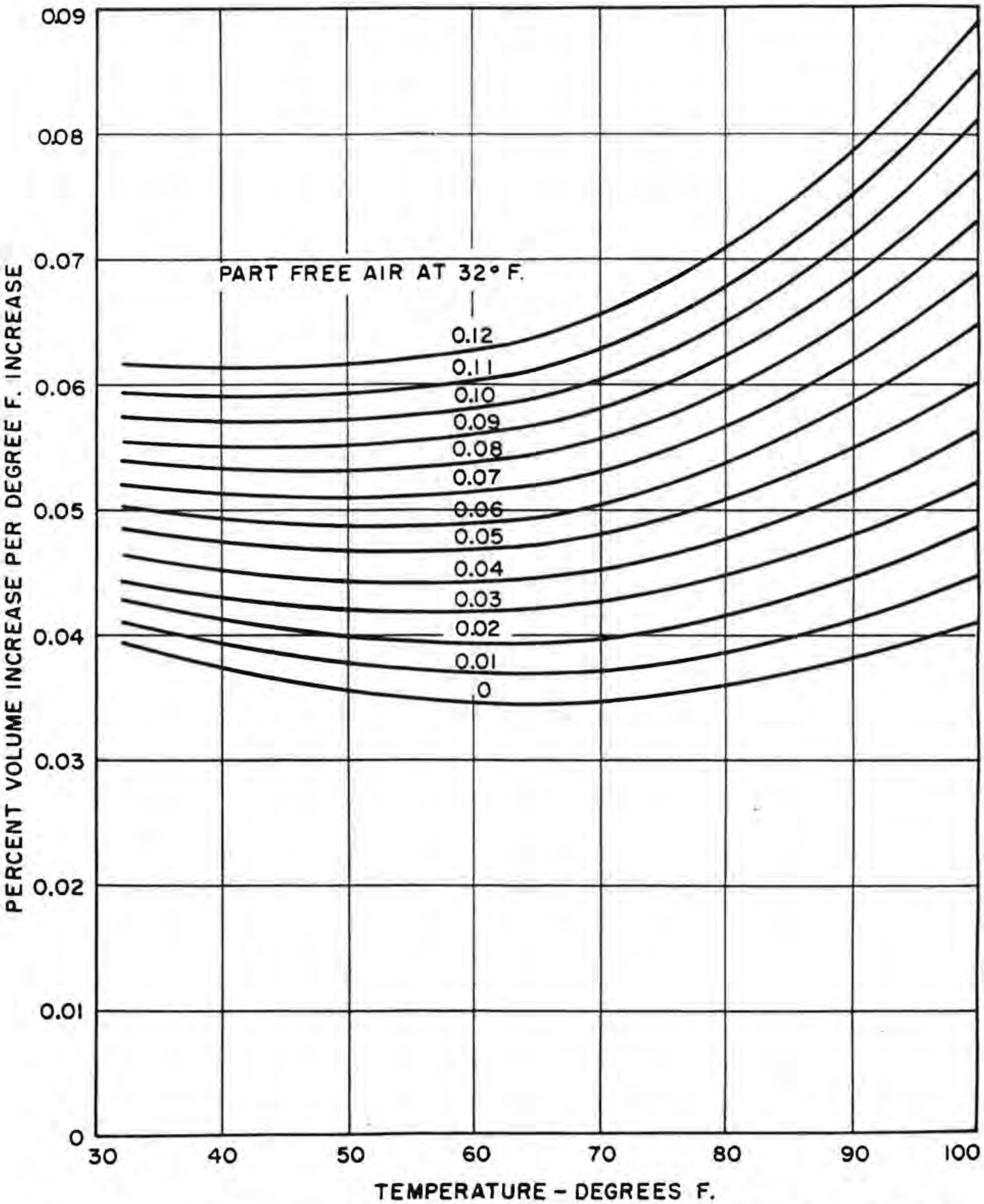

Figure 25. Volume increase with temperature at zero gage pressure for various air-water mixtures.

while in the other photographs the spheres appear to be separated because the focus is above or below the point of contact. (This apparent contact does not preclude separation by a molecular layer.)

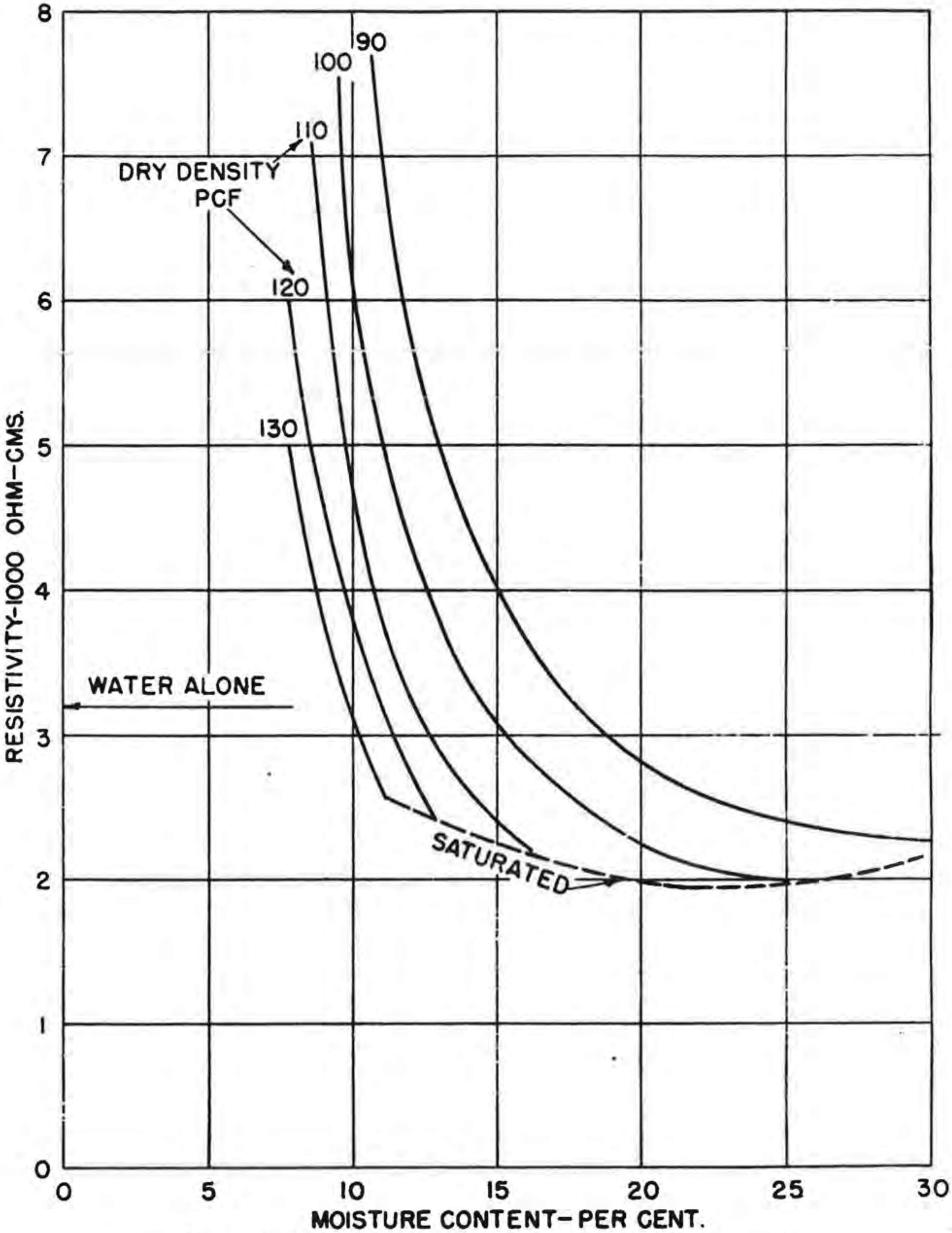

Figure 26. Resistivity of clay at different moistures and densities.

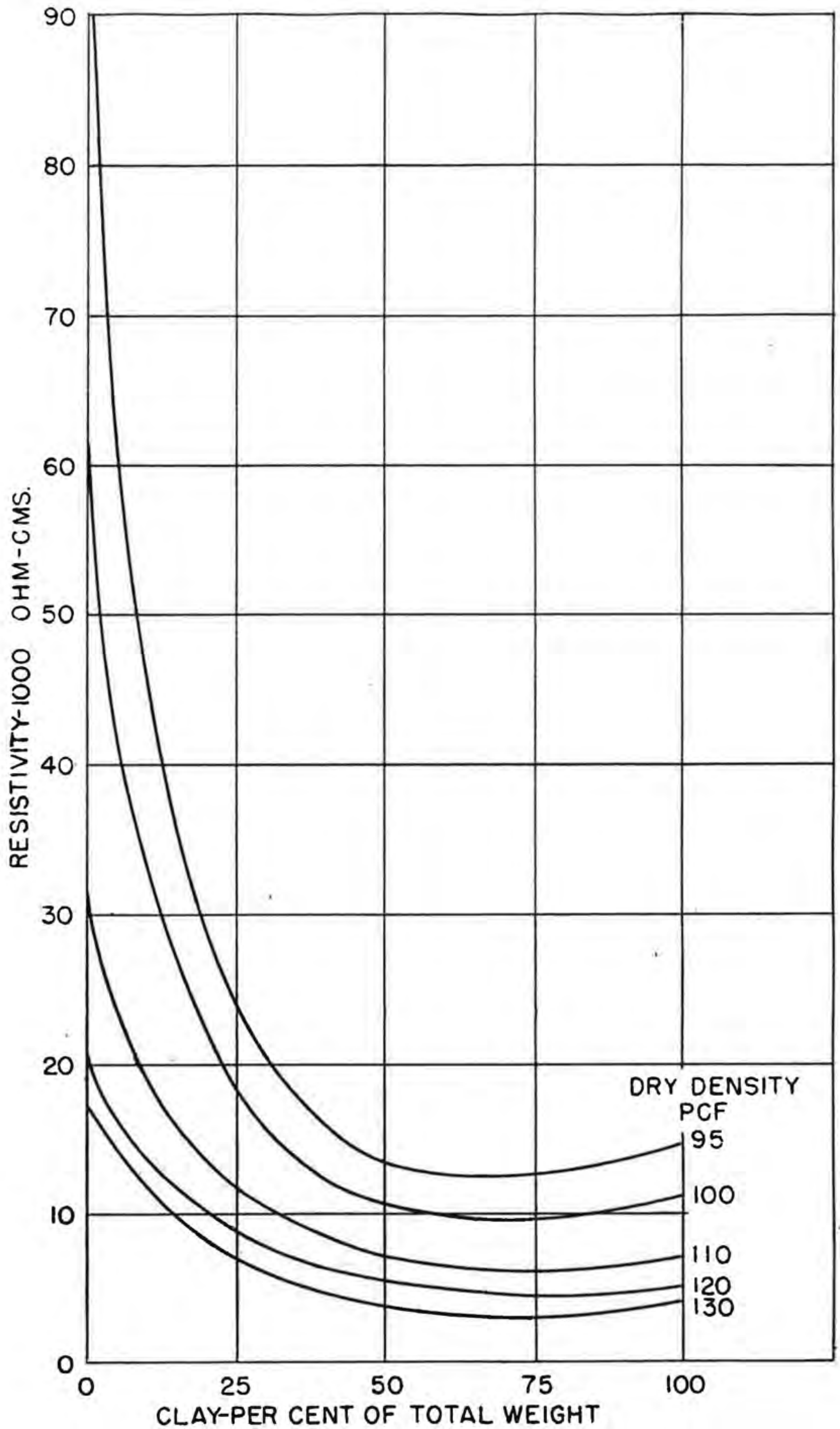

Figure 27. Resistivity of sand and clay mixtures with 10 percent moisture.

COMPACTION

When a given compactive effort is applied to a series of samples (not extremely dry) with increasing moisture content, increased moisture reduces the surface tension permitting rearrangement into a denser structure. If any excess water can escape, there is no optimum moisture. This is true for very permeable materials or for fine soils if the load is left on as shown by the curve marked "consolidation" in Figure 19. For quickly applied loads on fine soils, the density decreases with increased moisture at about 85 percent saturation where the air permeability becomes very small and requires the exudation of water for further densification. Continued impact compaction beyond the optimum causes weakening due to formation of shear surfaces.

Density is increased by repetitions of even moderate loads if there is opportunity for rearrangement of particles—lack of cohesion in sands, water or dispersing agents in clay. Figure 20 shows the effect of several chemicals on densification under repetitive loading.

The distribution of moisture is important to the strength of fine soils. Figure 21 shows the increase of strength with time as the moisture distribution is equalized. Non-uniform moisture distribution may be caused by poor mixing or by expansion on shear planes from kneading compaction. The strength was constant for good mixing with static compaction which formed no shear planes. The thixotropy of undisturbed soils after disturbance also depends upon the redistribution of moisture after shearing.

Figure 22 shows less strength for samples molded with limited moisture than for samples dried from a wet state to the same moisture and density. This is due to the less effective distribution of moisture in the "as molded" samples.

CAPILLARY FLOW

Each soil has a characteristic moisture distribution above the water table for no-flow as shown in the left of Figure 23. If evaporation occurs at the surface, the moisture is reduced, especially if there are sand layers which, at some distance above the water table, have less permeability than fine soils. For downward flow, such a sand layer may actually retard drainage. Many earth roads, with an average condition as shown in the right of Figure 23, failed when surfaced because the moisture increased toward the no-flow condition. Buried bituminous layers have been used to prevent this upward flow. In a few cases parts of fills have been encased in bituminous mastic or sheet plastic.

The upward flow of capillary water has required impervious covers over soil to prevent condensation in unventilated spaces under buildings. Any salts in the soil will be brought to the surface, often causing pavement failures in irrigated arid lands and generally requiring drainage as an adjunct to irrigation. This also causes soluble stabilizers to migrate to the surface to be washed away. Migrating of cementing agents to evaporation surfaces sometimes causes "case-hardening" of cut or natural surfaces.

TEMPERATURE

If a mixture of air and water is heated with no volume change, pressures are developed as shown in Figure 24. For a given temperature change, the maximum pressure is for no air at the freezing point. This may be a factor in spring break-up. The maximum volume change at constant pressure (see Fig. 25) is at high temperatures with a maximum of air as long as the air cannot escape.

These temperature effects have caused water to come up through pavements, reduced the strength of base courses, caused higher soil permeability at lower temperatures, prevented base drainage after a cold rain and caused drainage in fair weather with rising temperatures.

ELECTRICAL

The movement of water through soil by direct current has been used for drainage stabilization, increasing friction of piles, reducing friction of plows and replacing chemicals in soil. When soil settles through water in the hydrometer test, a small voltage may be measured. This streaming potential produces several millivolts in a permeability test (using a lucite cylinder). Such a potential may be used to indicate subsurface flows, perhaps even by water diviners.

Variation in electrical resistivity is used in geophysical prospecting, detection of soluble salts and indication of moisture content where density is controlled. Figure 26 shows the variation of resistivity with moisture and density. Figure 27 shows a minimum resistivity for sand clay mixtures where the limited amount of water is balanced against the conductivity of clay.

CONCLUSION

Without water, the mechanics of soil would be quite simple. Pressure or tension on water in the pores of the soil often controls its strength and volume change. Movement of water may change these pressures as well as cause movement of particles and change the chemical composition. The distribution of water and the arrangement of the particles, that is, the structural arrangement, are as important as the over-all composition and total moisture and density.