On the other hand, the fill made in this way is believed to be heavier, and to have a higher coefficient of friction which gives it additional value as toe material. The practical methods of handling rock fill were worked out by Mr. Hawley and D. W. Albert.

Quicksand Conditions in Dams

When a granular material has its pores completely filled with water and is under pressure, two conditions may be recognized. In the first or normal case, the whole of the pressure is communicated through the material from particle to particle by the bearings of the edges and points of the particles on each other. The water in the pores is under no pressure that interferes with this bearing. Under such conditions, the frictional resistance of the material against sliding on itself may be assumed to be the same, or nearly the same, as it would be if the pores were not filled with water. In the second case, the water in the pores of the material is under pressure. The pressure of the water on the particles tends to hold them apart; and part of the pressure is transmitted through the water. To whatever extent this happens the pressure transmitted by the edges and points of the particles is reduced. As water pressure is increased, the pressure on the edges is reduced and the friction resistance of the material becomes less. If the pressure of the water in the pores is great enough to carry all the load, it will have the effect of holding the particles apart and of producing a condition that is practically equivalent to that of quicksand.

An extra pressure in the water in the pores of such a material may be produced by a sudden blow or shock which tends to compress the solid material by crushing the edges and points where they bear, or by causing a rearrangement of particles with smaller voids. An illustration of this can be seen in the sand on the seashore. Such sand, comparable to dune sand in size, is usually found to be saturated with water for a certain distance above the water level. This condition is maintained by capillarity. If a weight is slowly placed on this saturated sand, there is a slight settlement, the grains of sand coming to firmer bearings and the weight is carried. A sharp blow, as with the foot, however, liquefies a certain volume and makes quicksand. The condition of quicksand lasts for only a few seconds until the surplus water can find its way out. When this happens the grains again come to solid bearings and stability is restored. During a few seconds after the sand is struck, however, it is almost liquid, and is capable of moving or flowing or of transmitting pressure in the same measure as a liquid.

Fine-grained sand in which this condition exists is called quicksand. The properties of quicksand are well known. Fine-grained sand saturated with water and then mixed with an additional 5% of water acts practically as a liquid. It will flow through small orifices or in a pipe at a 5% slope. The sand in a mechanical filter in process of washing is a typical case. When the sand is drained, in the filter, it forms a bed as hard as any sand bed. When subjected to a reverse current of water strong enough to slightly lift it, however, the volume is increased by perhaps 5%, and it becomes liquid. An object can then be pushed through it with scarcely more resistance than would be offered by a liquid of high specific gravity.

The conditions that control the stability or lack of stability in quicksand may also control the stability or lack of stability of materials in dams.

Hazard With Soft Rock

The puddle clay core of an hydraulic-fill dam is physically like quicksand, but with particles one hundred times smaller in diameter and a million times smaller in weight. It has the instability of quicksand in full measure and it retains it for a long time, or perhaps indefinitely.

With the coarse-grained part of an hydraulic-fill dam, that is to say, with rock toes, there may be also, at times, a similar condition. Generally speaking, it would be expected that such coarse-grained materials would have sufficient drainage to let out surplus water and prevent the possibility of an excess sufficient to destroy its stability. With hard-grained materials from glacial drift of New England and the Northern States, it is hard to conceive of a lack of drainage in gravel that would permit the accumulation of an excess of water. With the softer materials of the Pacific Coast, however, the conditions may be different. In the first place, these soft rocks by partial crushing under pressure produce fine material which tends to fill the remaining spaces and to reduce the drainage capacity.

On the other hand, each increment of loading applied to soft-grained material produces a certain compression and settlement; and with it a reduction in voids. This may happen to a toe of soft rock on the upstream side of a dam against which water is being stored during construction. There is first an open condition with ample voids and ample drainage. As the dam is built higher, pressure increases; there is compression and reduction in porosity. Each additional increment of loading and compression means that a certain quantity of water representing the difference between the old voids and the new voids must be expelled. As long as the material remains sufficiently pervious to carry off this excluded water, the process of compression is harmless. The surplus water is pushed back into the reservoir and stability is retained. There may come a time, however, when the compression goes forward so rapidly that the surplus water cannot be carried off fast enough. When that point is reached (if it is reached), there will tend to be an excess of water in the interstices and that excess will transmit some of the pressure that was before carried only by the bearings of solid particles, and the frictional resistance of the material will be less, and perhaps much less, than it was before.

The thought has occurred to the writer, in looking at the material that slid in the Calaveras Dam, that something of this kind may have happened on a large scale—800,000 cu. yds. of fill flowed for a brief space, and then became solid. It was, in fact, so solid that in examining it afterwards, by samples and by borings, it was difficult to see how the material could have flowed—as it certainly did flow.

It may be that after the first movement there was some readjustment of the material in the toe that resulted in producing temporarily this condition of quicksand, and that destroyed for a moment the stability of the material and facilitated the movement that took place.

This will not account for the initial movement; but the initial movement of some part of the material might result in accumulating pressure, first on one point, and then on another, successively, as the early points of concentration were liquefied and in that way a condition comparable to quicksand in a large mass of material may have been produced.

Summary

To summarize briefly the points that the writer has attempted to make and to apply them practically to dam construction:—

1.—It is not well to build an hydraulic-fill dam of material of which any large percentage consists of clay or of particles less than 0.01 mm. in diameter; and in general all such smaller particles may well be wasted and excluded from the dam.

2.—By reducing the construction pool to a minimum, and by controlling it and the quantities of water used for sluicing, the core material may be held to a certain degree of coarseness by wasting all smaller particles. An effective size of 0.01 mm. may reasonably be sought.

3.—To study by borings the actual consolidation of the material, and to adjust the construction of the upper parts of the dam to the demonstrated condition of that which lies below.

4.—To make the toes large enough to resist with an ample factor of safety the whole pressure of the core material as a liquid until there is demonstration of the solidification of the core to a point where horizontal pressure is eliminated.

5.—To increase the weight and solidity of toes by the use of rock fill, placed hydraulically or otherwise.

6.—Stability is increased by compactness. It is worth while to watch voids closely, and to make every effort to