Thorough Geological Investigation is of Prime Importance When Selecting a Dam Site

Strength and Stability of Structure Often Jeopardized by Location Upon Inadequate Foundation which may Superficially Appear Suitable

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TO some readers of this brief article it may appear that unnecessary stress is laid upon considerations that are obvious. The failure of the St. Francis dam, however, is simply the latest of many disasters that have occurred because attention was not given to conditions that should have been clearly perceptible to those responsible for the project.

If rocks were perfectly exposed and entirely homogeneous it probably would be unnecessary to call in a geologist when the construction of a dam is undertaken. The engineers could apply the appropriate tests to the visible foundation and abutment material and determine its fitness to sustain the structure. Such ideal conditions, however, seldom obtain. It is often necessary to determine the changes that may occur in the rocks at various distances and in various directions from the proposed site, to ascertain the structure of these rocks and to learn something of their mineralogical character and mode of origin or formation. These are essentially geological problems and their solution is likely to require the study of a considerably larger area than that which will be occupied by the dam or even by the dam and reservoir.

If a stream is to be dammed, it is manifestly important that the quantity of water carried by the stream and the character of the flow should be known through measurements and records maintained for as many years as possible. Inasmuch as the object usually sought is to confine as large a body of water as possible with a dam of the minimum practicable length and bulk, most dams are built in narrow, steep-walled canyons, above which are more open valleys or basins. This common procedure has in its favor also the probability that such canyons have been cut in harder rock than that of the open valleys, and this rock moreover likely to be comparatively fresh and well exposed.

A geological investigation in connection with a proposed dam commonly comprises two parts—that of the reservoir as a whole and that of the actual dam site.

Failure of a reservoir, where the dam remains intact, is rarely catastrophic. It may, however, mean the loss of valuable water or such large leakage that the reservoir becomes wholly useless. Hardness or strength are seldom important considerations in the rocks of the reservoir as a whole. Even porous rocks, provided that the open spaces are not so connected as to form continuous channels, need cause no concern. Freely permeable rocks and soluble rocks, however, require particular attention and must be considered in relation to the geological structure of the region. Examples of freely permeable rocks are bed of gravel or poorly cemented conglomerate and some volcanic tuffs or breccias. Basaltic lava flows may be so frothy or cavernous, particularly near the top and bottom of each flow, as to permit the passage of large volumes of water. Ordinary compact limestone, altho its solubility under normal conditions and for such periods as need be considered in engineering practice, is usually negligible, is nevertheless geologically soluble, as is plainly shown by such great caverns as those near Carlsbad, New Mexico, and the familiar underground stream of some limestone regions. Consequently, where a proposed reservoir is to be partly or wholly on limestone, it becomes necessary to determine, if possible, whether there are any existing caverns or subterranean chambers through which the water might escape.

Glen Canyon dam site, on the Colorado, near Lees Ferry, Arizona, showing adequate abutments of a soft but massive sandstone.

Wherever freely permeable rocks occur in a reservoir site a knowledge of geological structure becomes highly important. Clearly, for example, a permeable bed which outcrops in the reservoir and, maintaining a regular dip, appears again along the banks of a stream a few miles distant at a lower elevation, would conduct water away from the proposed reservoir, whereas, if the permeable bed is dislocated by a fault or so folded that there is no hydraulic gradient to any lower outcrop, it might not permit any serious leakage.

Presence of Permeable Rocks

Where permeable rocks are present, the position and slopes of the underground water surface, or water table, should be ascertained. In most drainage basins, the water table practically coincides with the topographic surface near

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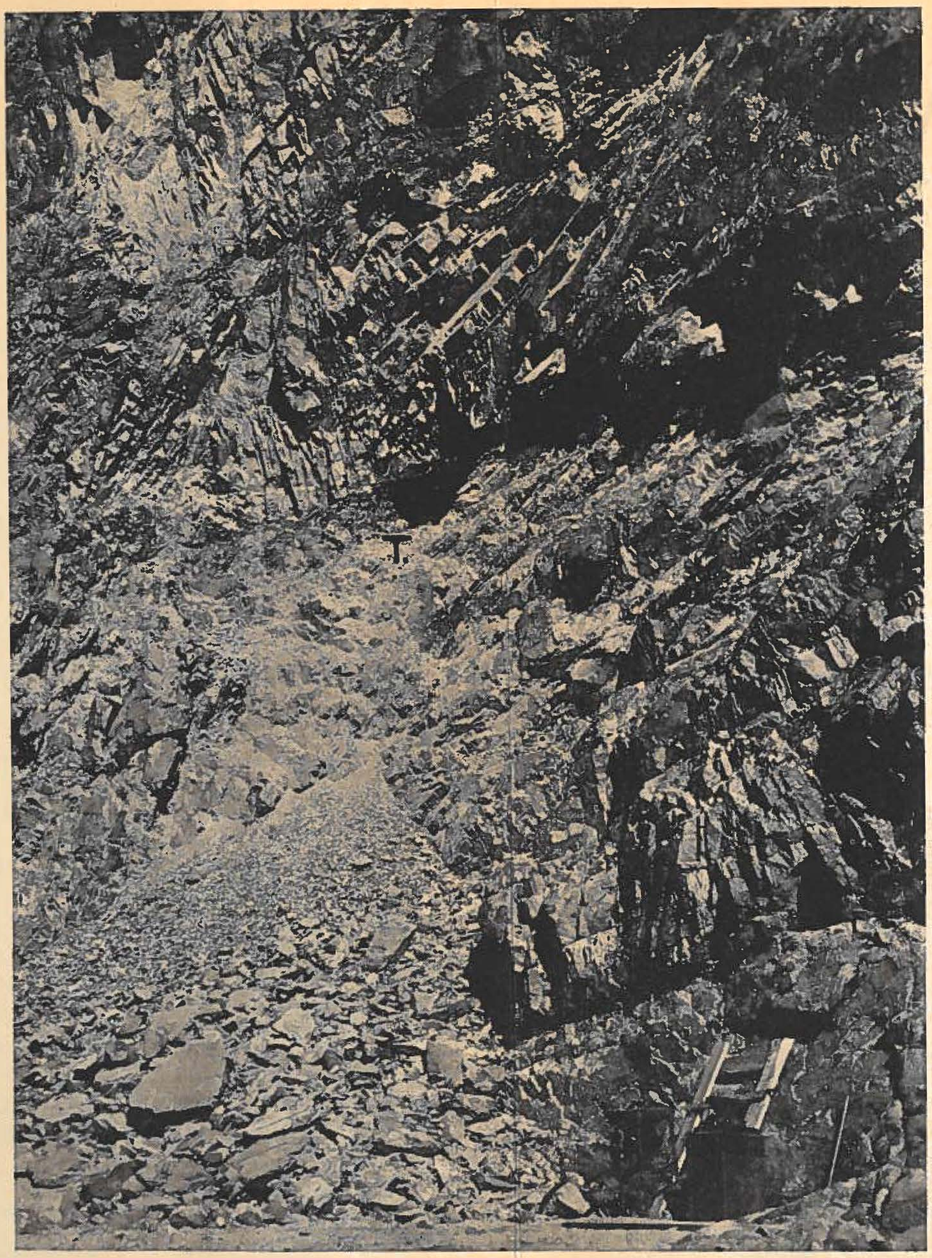

Jointing in granite of the north wall of Boulder Canyon, showing the great number and diversity in direction of the joints. The short tunnel at T shows that these joints become scarcely visible cracks at a distance of less than ten feet from the surface. The tightly fitting blocks between them can be dislodged only by blasting.

the streams and rises towards the ridge crests, although at a lower slope than the surface of the ground. Such a condition indicates that the underground water of the basin is moving slowly towards the streams that drain the basin and consequently that the proposed reservoir will be more likely to receive than to lose water by underground flow. On the other hand, if the water table in some part of the basin is found to be lower than at the adjacent streamways, this indicates that some water is escaping from the basin through underground channels and, consequently, that still more might so escape were the basin converted into a reservoir. Obviously in a reservoir formed merely for flood control, such loss would be immaterial and might even be advantageous.

Among the soluble rocks most likely to require attention in reservoir projects are gypsum and rock salt. The McMillan reservoir, near Carlsbad, New Mexico, is a partial failure because the water escapes in large quantity through underground channels in gypsum and these are increasing in size. On the other hand Willow Lake, another reservoir about 20 miles south of Carlsbad, is enclosed by gymsum but has shown no leakage since the dam was built, some 5 years ago. The difference is probably to be explained by the supposition that in the case of the McMillan reservoir there was initially a small natural solution channel through the gypsum, which the water escaping from the reservoir rapidly enlarged by the solution, whereas, at Willow Lake, no such passage exists and, although gypsum is going into solution all around its shore, this general solution has not led to any leakage. Rock salt is of course, even less trustworthy than gypsum as a water barrier. Thick beds of salt occur in the proposed Boulder reservoir, along the Virgin River, Nevada, but their position is such that they cannot cause leakage. The question that has been raised, whether these salt beds would render the water of the proposed reservoir too saline for use, is a reasonable one and indicates a possibility that should not be overlooked. In this particular case the effect of solution would be to blanket the salt with silt from overlying beds and the quantity of salt desolved would probably be negligible in so large a body of changing water.

The Ideal Dam Site

From the geological point of view, the ideal dam site is one at which the rock is hard and insoluble with strength amply sufficient to carry the load and thrust of the dam, with no planes of weakness, and constituting a homogeneous mass of such horizontal and downward extent that there can be no possibility of water working around or under the dam. A large body of massive granite is a familiar fulfillment of these requirements, although actually no granite mass is entirely free from cracks or joints. Great hardness is not practically essential, for most rocks, so far as their actual substance is concerned, are strong enough to resist the stresses of a dam of ordinary height. It is absolutely essential, however, that the supporting rock should not dissolve, soften or disintegrate, when in contact with water. Gypsum, or clastic rocks with gypsum as the cementing material, have no proper place in a dam site, although occasionally dams of moderate height have been built upon them.

Cracks or, as the geologists call them, joints, are present in most rocks and when rocks are long exposed to the weather, as in canyon walls, these joints become superficially accentuated and give such an alarming appearance of general fragility to the rock mass as has led some engineers and geologists to condemn particular sites. The fine-grained granitic rocks of Boulder Canyon on the Colorado, are in many places dissected by innumerable joints. Yet short tunnels driven into some of the most thoroughly jointed rocks have shown that within ten to twenty feet from the surface the joints become scarcely visible and the blocks into which the granite is divided are so irregular in form and so tightly fitted together that no important leakage could take place. As granite is practically insoluble and unaffected by water, no material could be removed and

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Looking downstream into Boulder Canyon, on the Colorado, illustrating an excellent dam site in hard but minutely jointed granite.

the presence of the joints is, in a practical sense, negligible.

Importance of Joints

Joints are relatively short fractures along which there has been no appreciable movement of one side of the crack past the other. Faults are more extensive fractures along which one side has moved an appreciable distance which may be measured in inches, feet or miles, past the other side. Some faults show no evidence of recent movement; others, as we well know in California, still show capacity for activity. It is rarely possible to determine with absolute certainty whether movement on a fault will recur, although by a study of general history and structure of the region, the geologist can usually decide whether renewed movement is probable. It is obviously better to avoid a dam site that is traversed by faults but this is not always practicable. If a dam is built, however, it should be with knowledge of the existence of any fault through the site, with competent geological advice as to the probability of movement, and with provision in the design of the structure to minimize any possible damage from fault movement.

Other structural features in rocks that demand careful consideration are bedding planes, the laminations of shale, the cleavage of slates and the usually less perfect cleavage or lamination of schists —in short, all structures which by their approximate parallelism produce weakness in rocks when stresses are applied in particular directions. The laminated rocks mentioned may be of ample strength when subjected to stresses acting along lines normal to the planes of lamination but may be extremely weak when the directions of stress are parallel with or make only a small angle with these planes. This rather patent generalization was overlooked in the building of the St. Francis dam, as regards its southeast abutment, where the concrete was poured against the flat cleavage planes of thinly laminated schist, in a cut of inadequate depth. Consequently the rock at this end of the structure offered only slight resistence to displacement of the concrete mass, by slipping along the planes of schistosity. The procedure was like building the dam against the upper surface of a gigantic, inclined pack of cards. The concrete adhered to the top card but there was little to prevent the cards from sliding one over another.

Necessity of Geological Studies

The conditions referred to in this brief article as necessitating the application of geological methods of investigation and reasoning are only a few of those that may be met with in consideration of dam and reservoir sites. The all important point to be emphasized is that no dam of any considerable size should be built without thorough geological examination of the site. The contribution of the geologist to any particular project may be small but on the other hand, he is equipped by training and experience to see and interpret certain facts whose significance may not be plain to engineers who are fully competent in their own calling. The failure of the St. Francis dam is a striking illustration of this truth, as will now be briefly shown.

The St. Francis dam completed on May 4, 1926, by the Bureau of Water Works and Supply, City of Los Angeles, was of solid gravity type and constructed of concrete. It was 200 feet in height and the main dam was 700 feet long. In addition, the structure was continued northwestward by a wing-wall along the crest of the spur that formed the abutment at that end. The dam was curved, on a radius of 500 feet, the convex side being the upstream face.

San Francisquito Canyon, at the damsite has a course of south 60 degrees west. The walls, although steep, particularly on the southeast side, are not precipitous and are covered by the usual brushy vegetation of the Coast Range of Southern California. The bottom of the canyon and the slopes of the southeast

Black Canyon dam site on the Colorado, from down-stream side. An excellent site in hard, moderately jointed volcanic breccia.

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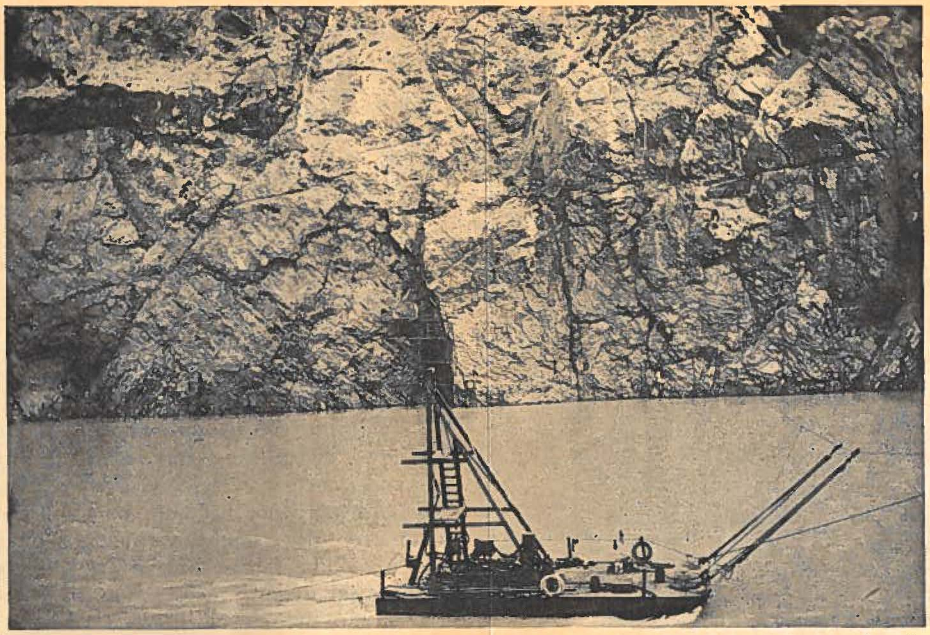


The west abutment of the Black Canyon site on the Colorado. Hard volcanic breccia, dipping upstream. Diamond-drill barge in foreground.

side are underlain by mica schist, which in geological reports on the general region has been, with non-committal caution, designated as pre-Jurassic. The upper northwestern slopes are composed of a reddish conglomerate with sandy and shaly layers, which is probably of Sespe (Oligocene?) age. The contact between the two rocks is a fault which has a course approximately parallel with the canyon and outcrops along its northwest side, about 70 feet above the bottom of the canyon, at the dam. This fault, a rather obscure feature before the tremendous flood caused by the bursting of the dam swept the canyon clean, is now plainly visible, a sharp line separating the dark conglomerate above from the lighter schist below.

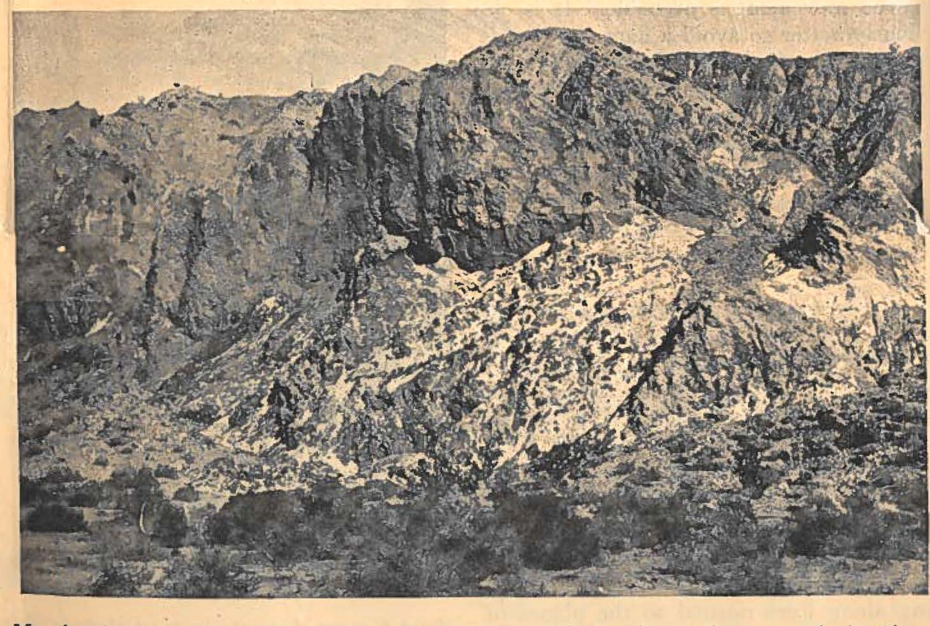
The planes of schistosity, although variable in their altitude, strike, in general, parrallel with the canyon and dip northwesterly at 50 to 60 degrees, or only slightly steeper than the prevalent inclination of the slope. Zones of shearing are numerous and it is evident from the character of the slope, road cuts, and tunnels that the schist as a whole is a fragile rock which readily disintegrates into thin flakes. Cohesion between the laminations is, as a rule, slight.

The conglomerate, probably a fresh water deposit, is composed of poorly assorted schist, granite and sandstone detritus, which ranges from clayey silt to pebbles eight inches or more in length. Bedding is generally rather indistinct and much of the formation is covered with soil. High up the slope, above the dam, may be seen, however, rounded outcrops of conglomerate which suggest that a part of the formation at least, may be fairly hard and moderately resistent to disintegration and erosion. The general dip of the beds is about 45 degrees to the northwest.

The San Francisquito fault has long been known and appears on the fault map of California, compiled under the auspices of the Seismological Society of America as an inactive or "dead" fault. There is no evidence that any recent movement has taken place along it or that it was directly responsible for the failure of the dam. The dip of the fault-plane is to the northwest at 35 to 40 degrees. There is a well-developed clay gouge which is soft and plastic when wet and consists of two distinct portions. Next to the schist foot-wall is a layer of dark gray clay up to eight inches thick, composed apparently of triturated schist. Overlying it is a reddish clay up to 4 feet thick which is plainly ground-up conglomerate, and grades upward into crushed and sheared conglomerate. All of the conglomerate, to an elevation at least equal to the crest of the dam, has been strongly sheared, this shearing being of such intensity that the pebbles themselves are minutely fractured and faulted. The character of movement on the fault is not definitely known. The fact that the younger conglomerate has been brought into a position in which certain of its beds abut against the schist suggests a normal fault. On the other hand, the extensive crushing of the conglomerate and the low dip of the fault-plane are indicative of overthrusting. The fault is probably an overthrust although structure of the region is not well enough known to permit of certainty on this point.

When dry the conglomerate of the dam site is fairly firm, although it is by no means a strong rock. A test, made for the state's investigating commission, gave a crushing strength of 500 pounds to the square inch, whereas the concrete of the dam has a strength of 2000 pounds to the square inch. When wet, however, the rock shows a remarkable change. A piece about two inches in diameter taken from the northwest abutment of the dam at a point directly beneath the former structure, when placed in a beaker of water begins to flake and crumble and in about fifteen minutes slumps to the bottom of the vessel as a loose gritty sediment that can be stirred about with the finger. Evidently the particles of the conglomerate are held together merely by films of clay and when the mass is wet particularly all cohesion is lost. Even the fractured and faulted pebbles fall apart into small fragments.

The conglomerate is traversed by many



Massive bed of rock salt, 50 feet or more thick, overlain by silty sediments. Virgin River, in Boulder reservoir site, Nevada.

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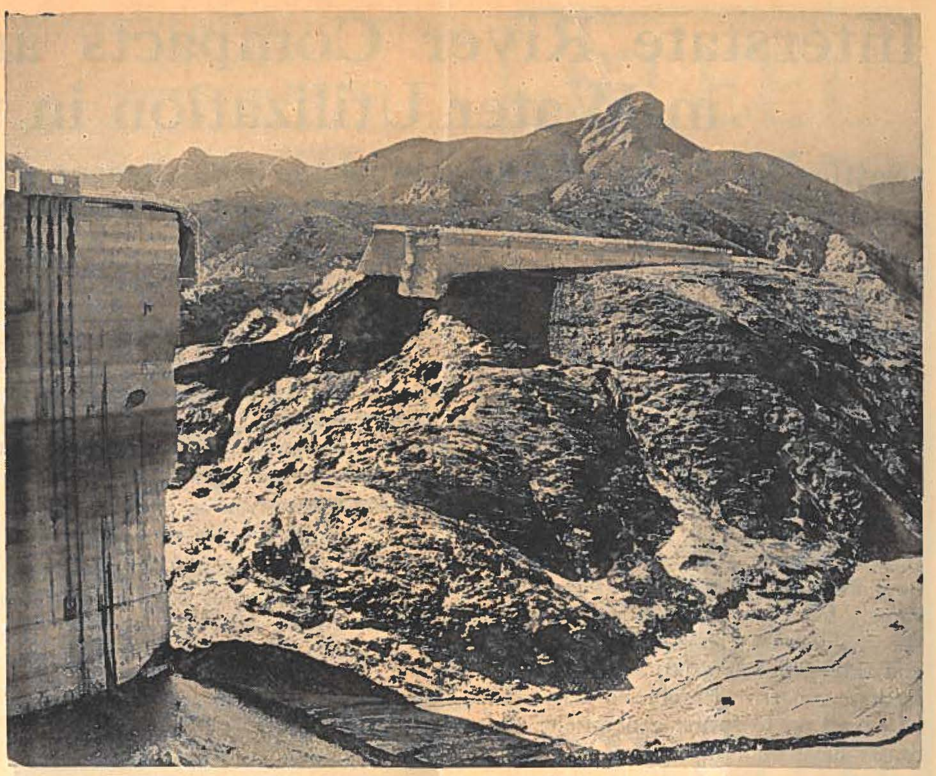
small veinlets of gypsum and it is probable that this mineral constitutes a part of the cement that holds the rock together when dry. The solubility of gypsum is well known and the presence of this mineral probably contributes to the rapid disintegration of the mass when wet.

The dam obviously was built across the fault. The southeast end and the middle section rested on schist. The northwest end, including the wind-wall rested on conglomerate. At the southeast abutment the concrete rested against smooth cleavage surfaces of the schist, and although the concrete adheres to these surfaces the schist itself offered little resistance to stresses that might tend to pull the dam away from its abutment or to move it in directions generally parallel with the planes of schistosity. The middle section of the dam, which is still standing, rests on the edges of the schist, and is obviously on a much stronger foundation than were the end sections. The northwest end of the dam abutted against and rested on a rather narrow spur of conglomerate. As already shown, this material, when wet, provided no better foundation than so much muddy sand.



St. Francis dam after the failure, looking southwest. The fault contact between the schist below and the conglomerate above appears near the center of the slope.

So far as can be ascertained, no geological examination was made of the dam site before construction began and no crushing or immersion tests were made of the conglomerate. How the true nature of this rock failed to become apparent during the progress is difficult to understand.

It is evident from testimony given before the coroner's jury in Los Angeles and from other sources that the conglomerate was mistaken by the engineers responsible for the project for a volcanic agglomerate of somewhat similar appearance, with which they had had some experience. This mistake in identity and consequent misplaced confidence in the material would not have occurred if a proper geological examination had been made.

The reservoir first became full about March 1, 1928. Some seepage was noted through the conglomerate of the northwest abutment and evidently caused some concern to those responsible for the maintenance of the structure. They appear, however, to have had no adequate conception of the full significance of this indication that the conglomerate had become water soaked. Chemical analysis made for the Pasadena Water Department since the dam failed, of water taken from the Los Angeles aqueduct and from places where seepage water from the reservoir was still flowing from the conglomerate, show a remarkable contrast in the soluble constituents. The CaO and SO_3 radicles particularly are many times higher in the seepage water than in the aqueduct water, showing that active solution of gypsum and other constituents was taking place in the conglomerate. This suggests that in future examinations of dam sites, clastic rocks concerning whose cementing material there may be any question should be subjected to leaching tests with chemical analysis of the extracts.

Quite aside from any possibility of movement on the San Francisquito fault, it is plain that the dam, otherwise a well designed and well-built structure was planned without adequate knowledge of the geological features of the site and without proper consideration of the structure and materials of the rocks upon which it was to rest.

It is fairly certain that the dam failed first at its northwestern end. As the conglomerate became water soaked the cementing clay and gypsum was softened and dissolved. The supposed rock on

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St. Francis dam, southeast abutment, showing manner in which the concrete was poured against flat cleavage surfaces of schist.

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Fitz Mining and Milling Company, 512 American Bank Bldg., Oakland, Calif., for 8 c.f.s. from Bath House Creek tributary to Middle Fork of Yuba River. To be diverted in Section 16, T 18 N, R 10 E, M.D. M. for power purposes. 89 Theoretical horsepower to be developed. Estimated cost $1,000.

The state division of water rights at Sacramento, California, received applications for permits to appropriate water from a great many firms during the month of September, the most interesting and important of which are listed herewith:

Permit 3091, Application 5433 (Del Norte County) Issued to Geo. M. Willoughby, et al, Crescent City, Calif., September 6, 1928, for 25 c.f.s. from Coon and Graigs Creeks in Section 36, T 17 N, R 2 E, H.M. for mining purposes. Estimated cost $10,000.

Permit 3092, Application 5462 (Del Norte County) Issued to Geo. M. Willoughby, Crescent City, Calif., September 6, 1928, for 25 c.f.s. from Craigs Creek and Camp Gulch, in Sections 34 and 35, T 17 N, R 2 E, H.M. for mining purposes. Estimated cost $7,000.

Permit 3093, Application 5810 (Trinity County) Issued to Buckeye Placer Mines, Inc., Woodland, Calif., September 11, 1928, for 15 c.f.s. from Buckeye Creek in Section 24, T 37 N, R 8 W, for mining purposes. Estimated cost $6,000.

Permit 3101, Application 5622 (Yuba County) Issued to California Counties Development Corp., Los Angeles, Calif., September 18, 1928, for 220 c.f.s. from Yuba River in Section 26, T 16 N, R 5 E, for irrigation and domestic use on 17,608.78 acres. Estimated cost $400,000.

Permit 3103, Application 5936 (Riverside County) Issued to G. R. Wilkinson, Pasadena, Calif., September 20, 1928, for 0.06 c.f.s. from 2 springs in Section 19, T 5 S, R 3 E, S.B.M. for domestic use. Estimated cost $4,600.

Permit 3109, Application 5919 (San Bernardino County) Issued to H. W. Luetzow, et al, Needles, Calif., September 25, 1928, for 0.25 c.f.s. from the Piute Springs stream and underflow in Section 18, T 12 N, R 19 E, for mining purposes. Estimated cost $10,000.

Permit 3110, Application 5746 (Siskiyou County) Issued to Bull Pine Mining Corp., 1134 W. 39th St., Los Angeles, Calif., September 26, 1928 for 3 c.f.s. from Rogers Creek in Section 11, T 12 N, R 6 E, H.M. for mining and domestic purposes. Estimated cost $5,000.

Permit 3111, Application 5747 (Siskiyou County) Issued to Bull Pine Mining Corp., 1134 W. 39th St., Los Angeles, Calif., September 26, 1928, for 3 c.f.s. from Rogers Creek in Section 11, T 12 N, R 6 E, for power purposes in Section 11. 51 theoretical horsepower to be developed. Estimated cost $5,000.

Dr. Elwood Mead, Commissioner of Reclamation, left the Washington office on August 10 for an extended trip of inspection over a number of the reclamation projects. He expects to be away for several weeks, during which time P. W. Dent will be acting commissioner.

During July 956 visitors were shown through Elephant Butte Dam by the reservoir superintendent.

Importance of Geology in Dam Site Selection

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which that part of the dam rested lost practically all of its strength and became no better suited for a foundation than a mass of wet earth or gritty clay. Seepage through this material probably increased rather suddenly to a jet of water which rapidly attaining appalling proportions washed out the softened conglomerate, permitting the concrete to crack and then to be swept out in huge blocks up to 10,000 ~~pounds~~ tons in weight, which were distributed for half a mile down the canyon. The terrific swirl of water about the toe of the dam undercut the layers of schist at the southeast abutment. Probably within a few minutes of the opening of the first break, the entire southeastern end of the dam slid down into the canyon, the largest fragments coming to rest against the toe of the standing middle segment.

The commission of engineers and geologists appointed by the Governor of California to investigate the causes of the disaster found no evidence of any recent movement on the San Francisquito fault and ascribed the disaster wholly to the unsuitability of the material upon which the dam was built. A commission appointed by the City of Los Angeles and consisting of Robert T. Hill, C. F. Tolman, and D. W. Murphy, while confirming the conclusion of the Governor's commission that the principal cause of the failure was the character of the rocks under the dam, states that a check of the elevation of the standing wing-wall shows it to have risen 0.285 feet since the dam was constructed and suggests that this apparent uplift may have been caused by movement on the San Francisquito fault. This movement, the city's commission believes, may have contributed to the failure of the structure. Whether the engineering data are of sufficient accuracy to prove the small uplift of approximately 0.3 foot is questionable. In any case, however, failure of the dam was inevitable in consequence of the weakness of the conglomerate under its northwestern end. Even had that portion been able to withstand the pressure of the water in a full reservoir, it is highly probable that the schist at the southeast abutment would have ultimately failed.

An inspection trip to American Falls Dam was made recently by Commissioner Mead, accompanied by Senators Borah and Thomas, Representative Addison T. Smith, District Counsel Stoutemyer, B. E. Hayden, reclamation economist, R. E. Shepherd, and Joel Priest and R. A. Smith, of the Union Pacific.