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THE ROLE OF ENGINEERING GEOLOGY IN BUILDING THE CALIFORNIA STATE WATER PROJECT

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ABSTRACT

The State of California is blessed with an adequate but maldistributed water supply. Approximately two-thirds of its rainfall occurs in the north, largely during winter months, while the greatest demand for water is in the south. A $2.3 billion water project has been constructed to capture and regulate flood and other surplus waters and convey them to areas of need within the State.

A staff of 128 engineering geologists investigated more than 100 variations of alignment for the 1 100 kilometer aqueduct and the sites for its 21 dams, 6 powerplants, and 22 pumping stations. This paper considers three select studies which influenced the routing of the State Water Project and its design and construction:

(1) the earthquake hazards imposed by the San Andreas and other active faults;

(2) four kinds of land subsidence with which the aqueduct had to contend; and

(3) the development of a procedure for estimating costs of tunnel construction based upon geologic factors.

SUMMARY STATEMENT

The State Water Project of California consists of a complex of reservoirs and aqueduct for the purpose of capturing and storing surplus stream flow in Northern California and conveying it south to areas of deficient water supply (fig. 1). The construction of the initial facilities has included 21 dams and reservoirs, 6 powerplants, 22 pumping plants, and 1 100 km of aqueduct.

The major elements of the project consist of the 235-meter high Oroville Dam (the highest in the United States); A. D. Edmonston Pumping Plant (which boosts more water higher than any plant in the world); and Edward Hyatt underground generating facilities (the largest in the nation). The project is now in the final stage of completion. Its total cost will come to about $2.3 billion. Almost 85 percent of this expenditure will be reimbursed to bond holders through revenues from future water sales.

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FIG. 1. — *Relief map of the State of California showing the State Water Project.*

During the peak period of planning and construction of the State Water Project, 134 earth scientists were employed including 128 engineering geologists, 2 geophysicists, 2 seismologists, and 2 geochemists. Over a period of 21 years, this staff investigated dam and reservoir sites; routes for canals, pipelines, and tunnels;

foundations for power plants and pumping stations; and it conducted studies of related ground water resources. These investigations have entailed extensive geologic mapping, geophysical surveying, foundation drilling, soils and rock testing, and appraising of sources of construction materials.

The exceptionally large staff of earth scientists employed for the State Water Project was necessary because of its enormity, accelerated construction schedules, and complex geology-related problems inherent in the terrain. Throughout the investigation, engineering geologists, seismologists, geophysicists, and engineers were encouraged to participate as teams. Under this concept, the product of each study was the result of a concerted effort in contrast to the practice wherein each discipline undertakes an independent investigation leading to a separate report.

This paper will not attempt to encapsule all engineering geology programs for the State Water Project, but will concentrate on three activities which utilized engineering geologists in more or less novel assignments. Highlights of the following three activities influenced major decisions and policies concerning selection of the route for the aqueduct and the location, design, and operation of major facilities:

(1) Investigations in earthquake engineering;
(2) Studies of areas of potential land subsidence;
(3) Development of a procedure for rapid estimation of tunnel construction costs based on geology.

EARTHQUAKE ENGINEERING PROGRAM

California is one of the most seismically active regions in the United States. Consequently, several of the major technical problems associated with the construction of the State Water Project related to the siting and design of facilities so as to reduce earthquake hazards to life, public property, and project structures.

The dominant source of great earthquakes in California is the San Andreas fault. This great fault trends southeasterly from the coastline north of San Francisco to the Gulf of California, a distance of about 1 050 km (fig. 2). The San Andreas is a rigde-ridge transform fault, which marks the contact between the North American and Pacific tectonic plates. Correlation of formations on either side of the fault indicates an aggregate right-lateral displacement of possibly as much as 560 km since Jurassic time (Hill, M. L., and Diblee, T. W., 1953). The occurrence of occasional contemporary earthquakes attests to its continuing activity.

Any aqueduct bringing water from Northern California into the Los Angeles coastal plain unavoidably must cross the San Andreas fault. Furthermore, important auxiliary facilities such as reservoirs, dams, powerplants, and pumping stations must be located in its vicinity and thus subjected to its future great earthquakes.

Throughout the planning, design, construction, and operation of the State Water Project, earthquake-related hazards have continued to pose the most difficult technical problems to be confronted. Because of California's exceptional seismicity and its numerous faults, it was necessary to construct certain facilities in areas subject to severe shaking and to cross some active faults (fig. 3). Secondary threats such as earthquake induced landslides, reservoir waves, settlement, and tectonic deformation were also considered. The objectives of the Department of Water

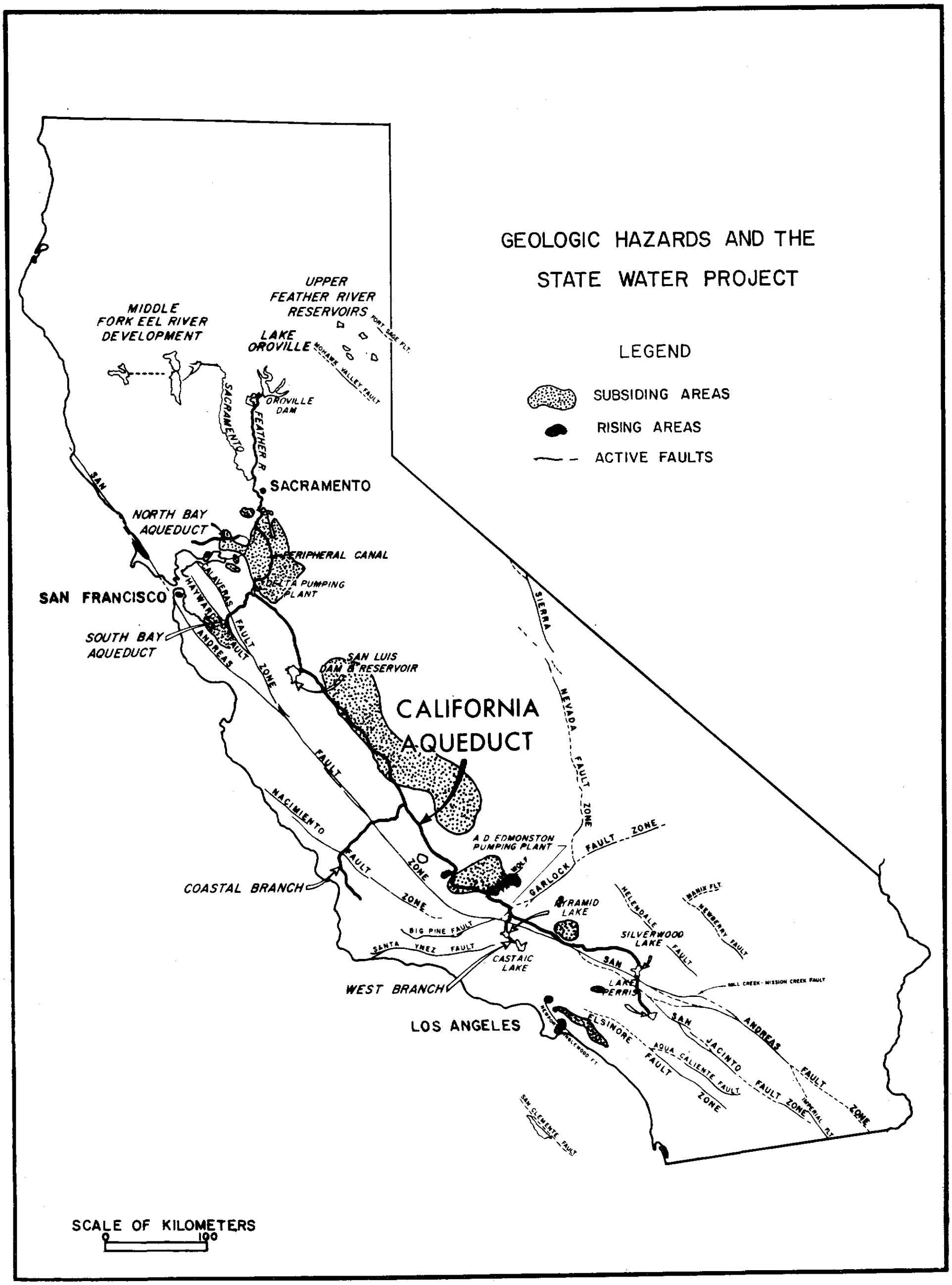

FIG. 2. — *In planning the State Water Project, special investigations were made of earthquake-related hazards and of extensive areas in Central California which are susceptible to subsidence. The San Andreas and other faults, active in the historic or recent geologic past, and actively subsiding areas are shown in relation to the State Water Project.*

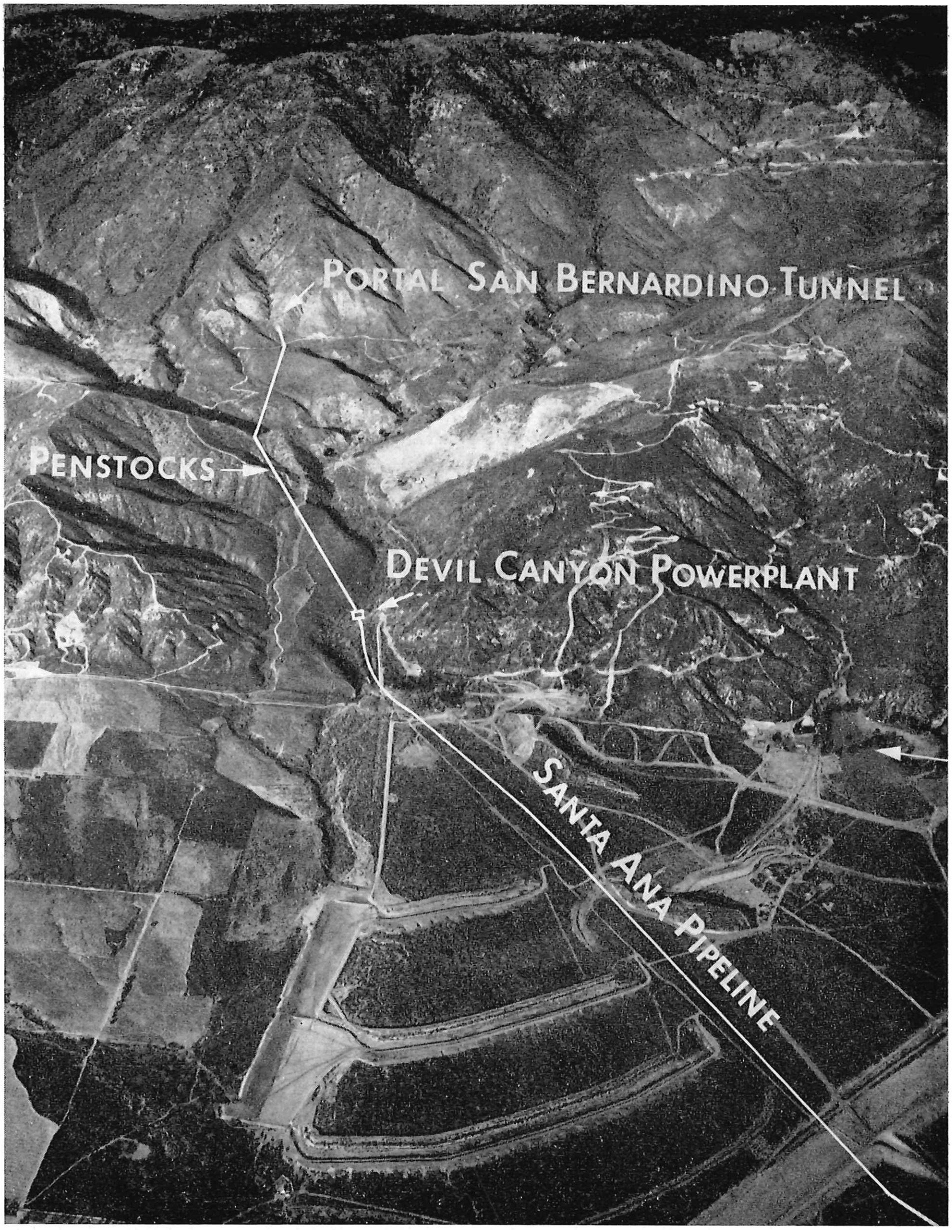

FIG. 3. — *The physiographic manifestations of the fault are evident near the foot of San Bernardino mountains where its trace (marked by arrows) crosses the photo from left to right. A lateral offset of several feet may have occurred on this segment of the fault in 1857. The power plant was located upstream of the fault to avoid a fault crossing in high pressure penstock. An outage in the plant discharge lines due to tectonic movement would result in low pressure discharge which would be captured in flood control facilities located downstream of the fault. Flow can be controlled by a valve at the tunnel portal and by gates near the turbine discharge. All of the facilities shown are part of the State Water Project.*

Resources' earthquake engineering program therefore have been to identify and evaluate the earthquake-related hazards to which the project would be exposed, to develop criteria for the location and design of earthquake-resistant facilities, and to provide for earthquake alerting. The goals of these technical objectives, in order of importance, have been public safety, reliability of water supply, and economy in construction and operation.

In the early stages of project planning, the field of earthquake engineering was in its infancy. At that time, only six severe earthquakes had been recorded by strong-motion seismographs; and, consequently, the nature of the ground motions occurring near the source of an earthquake were poorly understood. Furthermore, the customary practice of basing the design of hydraulic structures on a pseudostatic seismic factor generally on the order of 0.05 to 0.1 g was recognized as highly empirical and in some instances questionable. In view of these shortcomings, the Departement of Water Resources met with representatives of the Earthquake Engineering Research Institute, a nonprofit organization dedicated to the improvement of earthquake design. On recommendation of that group, a 5-man consulting board for earthquake analysis was created, consisting of recognized authorities in the fields of geology, seismology, soil mechanics, foundation engineering, and structural engineering.

Professor Hugo Benioff, seismologist, served as the Board's first chairman and upon his death Professor Clarence R. Allen, geologist, assumed this role. The Board recommended the establishment of an Earthquake Engineering Office to implement needed earthquake-related research and studies. This office was created; and, at the height of project construction, it employed four engineering geologists, two seismologists, one civil engineer, and six electronic technicians. The efforts of this group were devoted largely to studying the habits of the San Andreas fault; developing design earthquakes for planning and design purposes; and the installation and operation of an alerting system to locate with seismographs the epicenters of earthquakes throughout the State, measure their magnitudes, and, in the case of severe earthquakes, assure rapid dispersal of repair crews. The alerting system covers the State Water Project and also 1 100 dams which come under the States' jurisdiction for safety.

Details of the research and special studies conducted by the Department of Water Resources Earthquake Engineering Office are published elsewhere (Calif., DWR, 1968).

Two historic earthquakes generated on the San Andreas fault are noteworthy because of their impact on the planning studies for the project. The first of these earthquakes occurred in 1857 and the second in 1906.

The 1857 earthquake was centered in Southern California. It occurred during the early settling of the State when most of the region affected was only sparsely inhabited. Nevertheless, the shock caused considerable disturbance and was felt throughout the Southwestern United States. Newspaper accounts reported landslides, uprooted trees, damage to the old Spanish missions, and reversal in the direction of stream flow in some areas. The ground surface along the trace of the fault may have ruptured over a length of 320 km. Inspections of offset stream channels indicate that the displacement was in a right lateral sense and on the order of 9 m (Wallace, R. W., 1968). Although the seismograph had not yet been invented, it is generally believed that this shock must have exceeded 8.0 on the Richter magnitude scale. Some geologists contend that it is the strongest experienced in California since civilization of the State. The recurrence of a similar earthquake could disrupt all aqueducts carrying water to Los Angeles where those aqueducts cross the San Andreas fault. For this reason, the Department of Water Resources conducted a study of this fault to determine its characteristics and habits.

The 1906 earthquake is commonly known as the great San Francisco earthquake because of the death and destruction it caused in that city. The crude seismographs of that day indicated that the maximum shock was about 8.3 Richter magnitude. The surface trace of the San Andreas fault was ruptured for 320 km. Displacement was right lateral, the maximum measuring about 6 m (Calif. Earthquake Commission, 1908). Some geologists believe that this earthquake exceeded the 1857 shock in severity.

Four dams and reservoirs of the City of San Francisco located both in and near the zone of active faulting remained intact during this earthquake. The following characteristics of these facilities and the damages they sustained were, therefore, significant to the State Water Project planning (Bardoff and Matsumura, 1973).

Pilarcitos Dam of the City of San Francisco is located about 3 km west of the San Andreas fault. This is an earthfill structure with a puddle core, which was completed in 1867 and raised in 1874. It is 29 m high with a crest length of 158 m. The old drawings indicate that bedrock is close to the surface and that a key was constructed to meet the rock. It suffered no damage during the 1906 earthquake.

San Andreas Dam is located at the San Andreas fault, and its axis trends about 90° to the fault line. This earthfill dam has a puddle core. It is 32 m high with a crest length of 293 m. The San Andreas fault passes through the east abutment of this dam, and a brick-lined spillway tunnel located in this abutment was displaced 2.3 m during the earthquake. However, the earthwork of the dam suffered only minor damage, and water from this reservoir reached San Francisco 62 hours after the earthquake.

Lower Crystal Springs Dam is a concrete masonry structure built in 1887 and raised in 1890 and 1911. When constructed, it was one of the largest dams of its type in the world. It stands 47 m above foundation level, and has a crest length of 183 m. The dam is located within 60 m of the San Andreas fault with its main axis essentially parallel to the fault. It was not damaged during the 1906 earthquake.

Crystal Springs Upper Dam is built across the San Andreas fault and is located upstream from the concrete Crystal Springs Dam. It is an earthfill, puddle-core structure standing 28 m above foundation level with a crest length of 158 m. This dam divides the reservoir impounded by Lower Crystal Springs Dam, and the water level between the two sides of the dam is held constant by open pipes through the fill. Although its axis was offset laterally about 3 m during the earthquake, the embankment remained stable. It is not known if failure would have occurred had one side of the dam been dry.

Lake Honda was the only reservoir of the City of San Francisco that suffered damage. There is no dam at this facility, the entire reservoir being in cuts to a depth of about 11 m. A landslide in the western wall ruptured the brickwork necessitating repairs.

It is significant that the foregoing dams were not constructed to conform with modern standards. Their ability to withstand the 1906 earthquake was therefore encouraging. It indicated that dams conservatively designed, competently constructed, and situated away from the traces of active faults could be expected to resist catastrophic failure during strong earthquakes. The experiences of the San Francisco water supply system demonstrated that California's great earthquakes did not present insurmountable problems and that, by prudent geologic and engineering planning, damage could be minimized and a reasonably safe and reliable California Aqueduct could be constructed.

A particularly important step in the early planning stage of investigation was the selection of the route for the aqueduct through the Tehachapi mountains. This range lies south of the Great Valley of California and separates it from the Los Angeles Coastal Plain as shown on figure 1. Two basically different plans were proposed for passing through these mountains; both involved crossing the San Andreas fault, but each differed in the manner in which that crossing would be accomplished.

One of the alignments was known as the Long Tunnel Route or 1870 Tunnel, 1870 being the elevation of the crossing in feet above sea level. This route included a tunnel approximately 6 m in diameter and 43 km in length. It extended from the southern most tip of the Great Valley to Castaic Reservoir, a terminal storage facility located north of Los Angeles. The long tunnel was aligned to pass beneath the Tehachapi mountains with a maximum cover of 1 197 m. The San Andreas fault would be penetrated at a depth of 550 m. Four other major faults with questionable habits would also be intersected at depth. The formations exposed along the alignment included crystalline igneous and metamorphic rock, sandstones, shales, conglomerates, and limestone.

The southern sector of the proposed long tunnel route passed through formations that earlier had been explored by petroleum companies for natural gas and oil. Although these explorations had proven unsuccessful, the possibility of the long tunnel encountering pockets of explosive gas could not be overlooked. Furthermore, a detailed canvass of its surface alignment disclosed over 180 springs with water temperatures as high as 48 °C. The highest temperature springs were associated with a major fault. The combination of high temperature, springs, and fault zone was interpreted as a portent of extremely difficult tunnelling conditions.

The long tunnel route was explored by detailed areal geologic mapping, limited diamond core drilling, and construction of a test adit 183 m in length. Analyses of the topography and geology suggested that this scheme could be most expeditiously and economically constructed by sinking three shafts in the Tehachapi mountains and driving tunnel from eight headings including two portal headings and six shaft headings. The investigation of the long tunnel route was novel in that the entire study, including the selection of the alignment, construction scheduling, and preparation of the cost estimate for the tunnel and its three access shafts with hoists was undertaken exclusively by engineering geologists. It was estimated in 1954 that it would cost $227 000 000 to construct this tunnel.

The alternative to the long tunnel route was known as the High Line or 3 360 Route, the numbers again reflecting tunnel elevation in feet above sea level. This route included a pumping station of unprecedented size, which would be called upon to lift a flow of 116 cubic meters per second a height of 590 m. The pumps would deliver water to a series of four tunnels driven through the crest of the Tehachapi range, the longest of which would be 6.5 km. Selection of the alignment for these tunnels was based on an extensive program of geologic investigation. The route avoided crossing the San Andreas and other active faults at depth. Fault crossings were to be accomplished at ground surface where repairs to earthquake damage could be made rapidly. Beyond the ridge of the Tehachapi mountains, the high line route would bifurcate—an east branch conveying water to the Mojave desert, San Bernardino, and the eastern coastal plain and a west branch conveying water to Castaic Reservoir (fig. 1). Large amounts of electric power would be required for pumping, only a portion of which could be recovered at power plants to be located at the southern foot of the mountains.

In choosing between the long tunnel and high line routes, capitalized costs of both alternatives were determined and other factors which could not be reduced to cost values were weighed. The principal money-related elements were (1) the cost of driving and maintaining the difficult long tunnel; and (2) the cost of constructing the high line and of pumping the aqueduct flow over the Tehachapi range and its earthquake faults. The major cost-intangible factors were related to earthquake hazards. The alignment and elevation of the high line was governed to a large degree by the requirement that it cross all active faults at ground surface where repairs could be made and service restored quickly in the event of an outage. On the other hand, the long tunnel would be vulnerable to disruption at depth by a future movement on the San Andreas or along one of the other active faults which it would penetrate. Following an earthquake of 1857 severity, a substantial length of the long tunnel could be completely blocked. The effects of the comparatively moderate Bakerfield earthquake of 1952 on a railroad tunnel in the Tehachapi range provided a demonstration of what might happen (fig. 4). Furthermore, repair crews working underground near the source of the earthquake would be subjected to hazards from the strong after shocks that usually continue for several years following severe earthquakes.

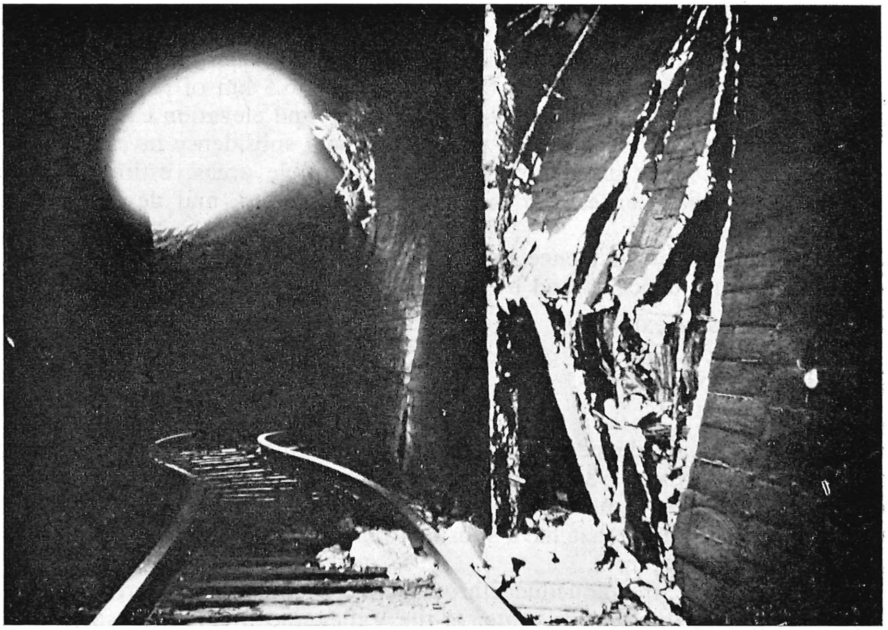

FIG. 4. — *A railroad tunnel in the Tehachapi mountains destroyed by earthquake in 1952 and since replaced by an open-cut excavation. Damage was attributed to movement on an active fault penetrated by the tunnel. In planning the State Water Project, the aqueduct was routed to cross all active faults at ground surface. This policy was adopted to permit rapid restoration of water deliveries following severe earthquakes.*

An additional important consideration affected evaluation of the long tunnel route. Two aqueducts that bring water to Los Angeles had been constructed earlier. These included the Owens Valley aqueduct from the Sierra Nevada mountains in service since 1912 and the Colorado River aqueduct completed in 1934. The Owens Valley aqueduct crosses the San Andreas fault 183 m below ground surface. The Colorado River makes the crossing in a pipe siphon. An offset on the San Andreas fault comparable to that of 1 857 would disrupt these facilities as well as the State Water Project. Thus, all imported sources of water supply for Los Angeles could be simultaneously interrupted at the fault. At such a time, the need for water for fighting fires and other emergencies could be critical. This possibility added to the importance of locating and designing the State Water Project to permit ready access to damaged facilities and provide for reestablishment of water deliveries with a minimum of delay.

The early planning studies led to a decision favoring the high line route. The aqueduct has since been constructed along this route and is now in operation. This decision was governed to a large degree by geological factors, that is, the earthquake hazards and the high cost of tunneling through fault zones at depth. Engineering geologists played a key role in the evaluation of these factors and in the decision making.

LAND SUBSIDENCE ACTIVITIES

Approximately 777 km of the California Aqueduct consists of canal constructed on gradients averaging about 0.3 m of drop for each 6.5 km of reach. Because of this comparatively gentle slope, small changes in ground elevation can significantly affect the aqueduct's performance. A program of land subsidence investigation was therefore undertaken to detect and delimit susceptible areas, estimate ultimate settlements, determine causes and the mechanics involved, and develop effective counter measures.

Four types of land subsidence were recognized in vicinity of project facilities. These included subsidence caused by:

(1) Ground water extraction;
(2) Hydrocompaction;
(3) Oil or gas production;
(4) Tectonic activity.

The most serious subsidence to threaten the California Aqueduct occurs in the Great Valley where about 7 800 km^2 have been affected. Some areas have depressed more than 6 m, chiefly due to ground water extraction and hydrocompaction. The regions in California that have subsided 0.3 m or more from any of the four causes are shown on figure 2.

Three routes for the aqueduct through the Great Valley were considered. One of these passed through the center of the Valley and was located so as to pass to the east of areas identified as susceptible to subsidence. This scheme was rejected on economic grounds largely because it would require installation of an additional pumping station at substantial added capitalized cost. A second route flanking subsidence areas to the west was also discarded due to its excessive length and because of the presence of consolidated formations which would have been costly to excavate. An economic analysis based upon a comparison of capitalized costs indicated that the least expensive route for the canal was one which traversed areas susceptible to subsidence. The conclusion to adopt a route through such areas and live with the subsidence problem prompted an intensive program to develop subsidence counter measures. The cost of geologic investigations for this program including geophysics, drilling, geologic mapping, field and laboratory testing, and experiments was about $2 700 000. The cost of implementing the subsidence preventive measures ultimately developed from the program exceeded $12 700 000 (Golzé, A. R., 1965).

Subsidence Caused by Ground Water Withdrawal

Heavy extractions of artesian ground water for crop irrigation have caused subsidence over several hundred square kilometers of the Great Valley. These depressed regions are not discernible to the eye because of their great areal extent. Such subsidence is generally manifested first by a reduction in the carrying capacities of canals and drainage ditches.

In the Great Valley subsidence due to fluid extraction is a soil consolidation process. The increase in effective intergranular pressure which motivates the process is related to lowering artesian and water table elevations. It consists of downward seepage forces due to the passage of water through the aquicludes overlying the artesian zones supplemented by forces resulting from decreased buoyancy within the shallow aquifers that are dewatered. The net effect has been to squeeze the deep sedimentary deposits, particularly the beds containing abundant clay and silt. The reduction in the thickness of these deposits is reflected on the surface as a depressed bowl. The principal investigations of this phenomenon were undertaken cooperatively over the last 18 years by the United States Geological Survey and the California Department of Water Resources (USGS-DWR, 1972). The development of the compaction recorder by the United States Geological Survey assisted greatly in developing an understanding of the mechanics of the processes and its relationship to hydrogeology. A diagram and explanation of this instrument are set forth on figure 5.

The Department of Water Resources concluded from its investigations that the only practical means of alleviating this type of subsidence was to reduce ground water extractions in vicinity of the aqueduct. The crops in the Great Valley dependent upon well irrigation are valued in millions of dollars, and consequently a mandate restricting pumpage was considered to be economically and politically infeasible. However, it was reasoned that once in operation the California Aqueduct would provide irrigation water at a cost less than the cost of well water and that a curtailment in ground water production would automatically result. Consequently, certain features were included in the design of the canal to compensate for subsidence that might occur during the period in which the switch from ground water to aqueduct water took place. These provisions included constructing additional freeboard in the canal berms and designing the berms so that they could be raised if necessary. Cross-over structures, such as certain roads, bridges, and pipelines, were designed so that they could be lifted by jacks should raising of the berms be required. The validity of this logic subsequently has been demonstrated in that the rate of subsidence has diminished progressively in recent years and is now considered to be negligible.

Subsidence Due to Hydrocompaction

Hydrocompaction has been defined as vertical downward surface displacement resulting from the compaction of underlying low density soils by the application of a sufficient quantity of water (Calif. DWR, 1964). It is the result of compaction and differs from normal consolidation in that a rearrangement of soil particles occurs when water is applied to the susceptible sediments.

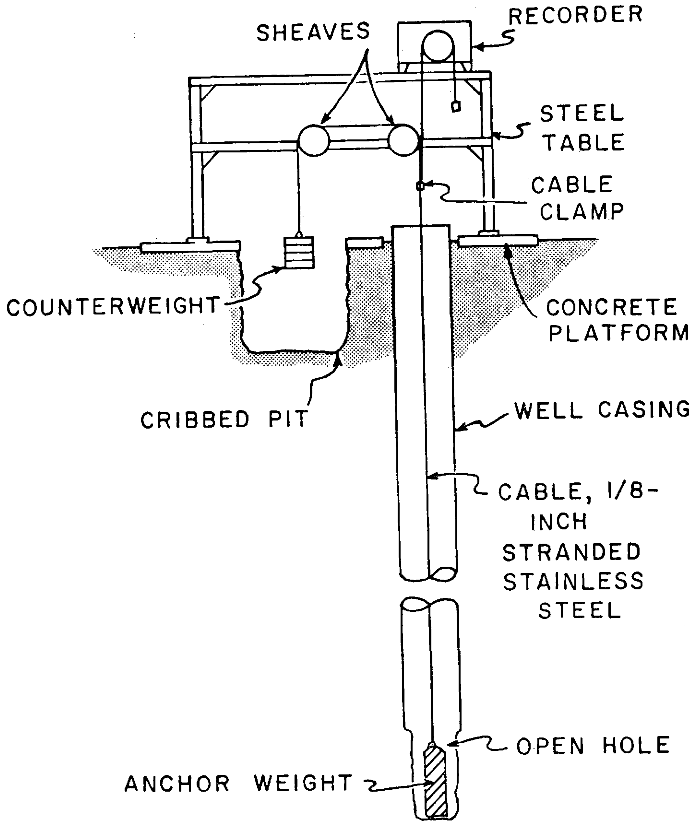

FIG. 5. — *A compaction recorder installation (Courtesy United States Geological Survey). This device is essentially a water stage recorder, which is linked by a wire to an anchor placed at the bottom of a drill hole or abandoned well. Subsidence of the ground surface due to compaction or consolidation of soil layers results in a fore-shortening of the suspended cable. This causes the recorder sheave and drum to rotate resulting in the inscription of a graphic record of the compaction. By installing these devices in wells of different depths, it has been possible to measure the compaction occurring within selected depth intervals. This procedure makes it possible to differentiate between subsidence due to oil or ground water extraction and to determine the degree to which each of these phenomenon may be contributing to subsidence within a region affected by both processes (Poland, J. F., 1972).*

As a general sequence of events, linel canals or concrete pipes passing through regions vulnerable to hydrocompaction will first develop fine cracks as a result of the settlement caused by the slight, unavoidable leakage which occurs through the pores of all concrete linings. These cracks promote further leakage which in turn leads to increased subsidence and enlargement of the initial cracks. Thus, cracking and leakage progressively increase until the system is no longer operable.

Areas susceptible to hydrocompaction were identified in the Great Valley of California on the steep fans of secondary streams where mudflow deposits are common. Such deposits have accumulated to depths up to 60 m in places. It was found that the fans of the principal streams generally do not subside, probably because they have been saturated repeatedly in past by natural stream flow. Hydrocompaction occurs in regions of low annual precipitation. Susceptible areas in the Great Valley experience an average annual rainfall ranging between 13 and 18 cm. This often occurs in torrential downpours resulting in quasi-saturated mudflows.

Laboratory tests and in-place measurements of the shear strength made in the field have shown that most susceptible deposits are strong when in the dry state. However, upon saturation, the chemical and physical bond between particles is diminished and the soil structure collapses. Where water has been ponded on such soils, spectacular cracks and sinks have developed (fig. 6).

The California Aqueduct crosses seven areas within the Great Valley which were determined to be hydrocompactible. The length of canal lying within these seven areas aggregates 155 km.

The subsidable areas were identified by means of aerial reconnaissance, examination of aerial photos, and field inspection. Interviews with local farmers also proved to be fruitful. Although in some instances the manifestations of subsidence had been obliterated by cultivation, the farmers were often able to recall and identify areas that had been affected.

Where the aqueduct passed through susceptible soils, drilling was conducted at intervals to log the soil profile and to obtain samples for testing. Because the significant physical characteristics of these samples would be altered by wetting, it was necessary to develop special drilling techniques in which compressed air was substituted for drilling mud. Holes were drilled to depths up to 103 m. Test plots were constructed on the alignment to study subsidence at specific locations. Details of these plots are given on figures 7 and 8. Fifty-one plots were operated. These tests demonstrated that within the seven susceptible areas hydrocompaction could be expected to cause surface subsidence ranging from 1 to 3.5 m in magnitude.

The geological studies of hydrocompaction were followed by intensive engineering tests of a prototype section of canal. This section consisted of a short length of test canal excavated so that part of its length lay within an area which had been previously subsided by ponding and the remainder within virgin soils susceptible to hydrocompaction. The prism of the test canal was cut to the exact dimensions of the future aqueduct. Part of it was lined with concrete and part left unlined. Its purpose was to determine the effects of hydrocompaction on both lined and unlined aqueduct in native soil and in soils which had been presubsided by ponding. This testing provided the data required for a program for presubsiding the hydrocompactible soils crossed by the aqueduct (Calif. DWR, 1964). A total length

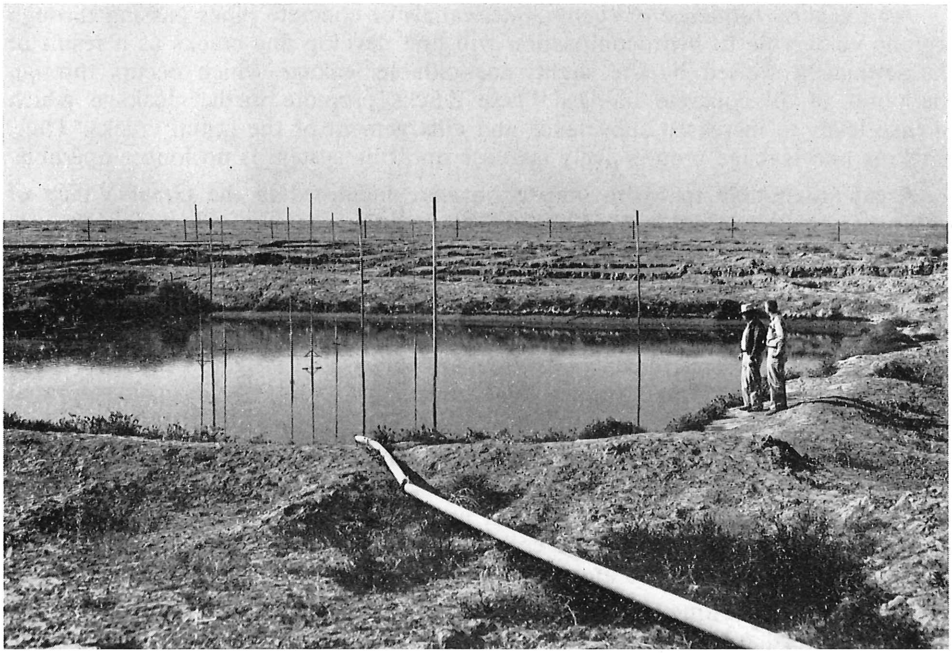

FIG. 6. — *Hydrocompaction caused by ponding. Subsidence due to hydrocompaction occurs when certain soil deposits in the Great Valley of California are saturated. These deposits are often associated with mudflows. This pond was constructed by heaping-up a low berm of earth on the flat plain. After filling with water, the bottom of the pond subsided. Note subsidence scarps. The vertical pipes extend to bench marks located at different depths beneath the floor of the pond. They provide the means for measuring rates of hydrocompaction as discussed in the legend to figure 7.*

of 110 km of aqueduct were presubsided by ponding prior to excavating the prism section for the final canal. The test facilities are depicted in figures 9, 10, and 11.

Subsidence Due to Oil Production

There are 493 oil fields located within the State of California (Munger, A. H., 1967). Subsidence due to oil production has occurred at 27 of these fields ranging from a maximum of 8.5 m at Wilmington field near Los Angeles to a few centimeters at other oil fields (Yerkes, R. F., and Castle, R. O., Unesco, Publication No. 88 AIHS, 1969). The California aqueduct crosses 6 producing oil fields and passes within one mile of 11 other active fields. Although to date no significant depressions have been detected in the oil fields nearest to the aqueduct, a few centimeters of subsidence possibly influenced by oil production have been noted south of Sacramento (fig. 2). Parts of the Great Valley continue to be actively explored for oil, and the consequences of discovering a new oil pool beneath the canal must be considered.

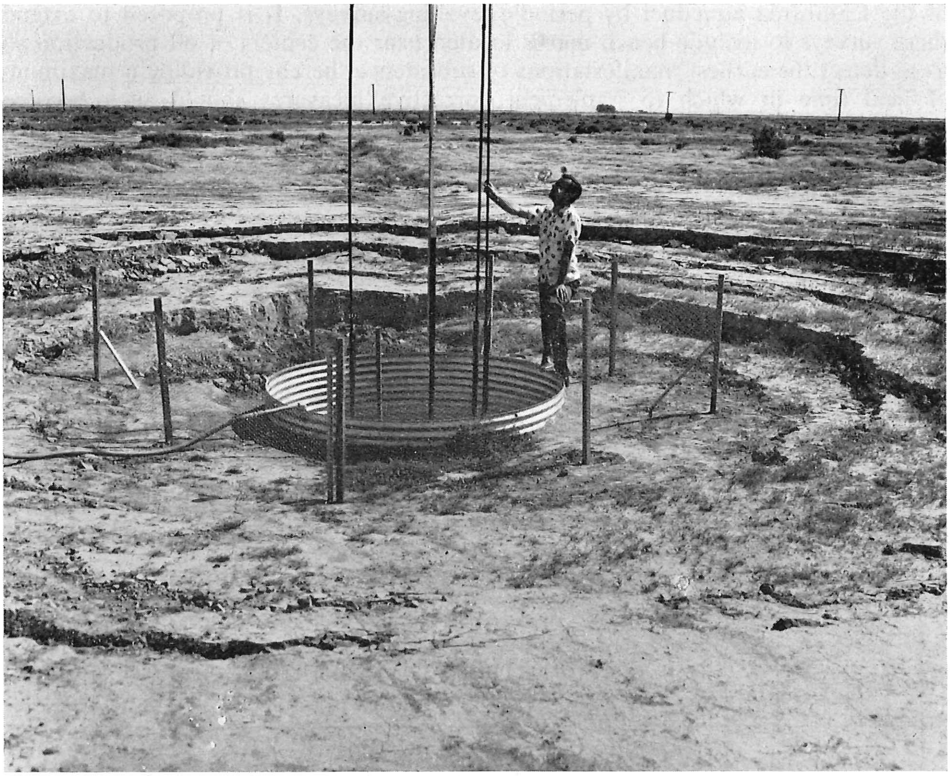

FIG. 7. — *Subsidence test plot. Prior to construction of the canal through areas suspected as susceptible to hydrocompaction, field tests were conducted to determine the extent of the subsidence that would be caused by canal leakage. Twenty-eight test plots similar to that shown were installed along the alignment. Water was maintained in these plots and the resulting subsidence of subsurface bench marks was monitored. The vertical pipe stems protruding from the plot extend from these bench marks. The pipe stems are faced with a scale graduated in tenths of feet, which can be read periodically by a conventional surveying level located several hundred feet from the plot. The numerical difference between readings is a measure of the subsidence that has occurred during the interval between surveys. At one such plot, over 3.5 m of subsidence due to hydrocompaction was measured.*

The two effective counteractions for oil field subsidence consist of (1) curtailment of oil extraction and (2) field repressurization. The second measure is generally preferable in view of current petroleum shortages. Also, repressurization often provides secondary recovery of oil thereby enhancing the production from the field. At Wilmington oil field in Southern California, a carefully planned program of salt water reinjection has effectively eliminated subsidence and increased the yield of petroleum by approximately 50 percent (City of Long Beach, 1969).

The possibilities of future subsidence due to oil extraction have been discussed with the major California oil producers. They are aware of the potential effects on the canal and have stated their intentions to plan their oil field operations accordingly. The Department of Water Resources continues to monitor the profile of the California aqueduct by periodic levelling surveys. It is proposed to extend these surveys to include bench marks located near the centers of oil production so as to detect the earliest manifestations of subsidence thereby providing a maximum of lead time in which to implement corrective measures should such become necessary.

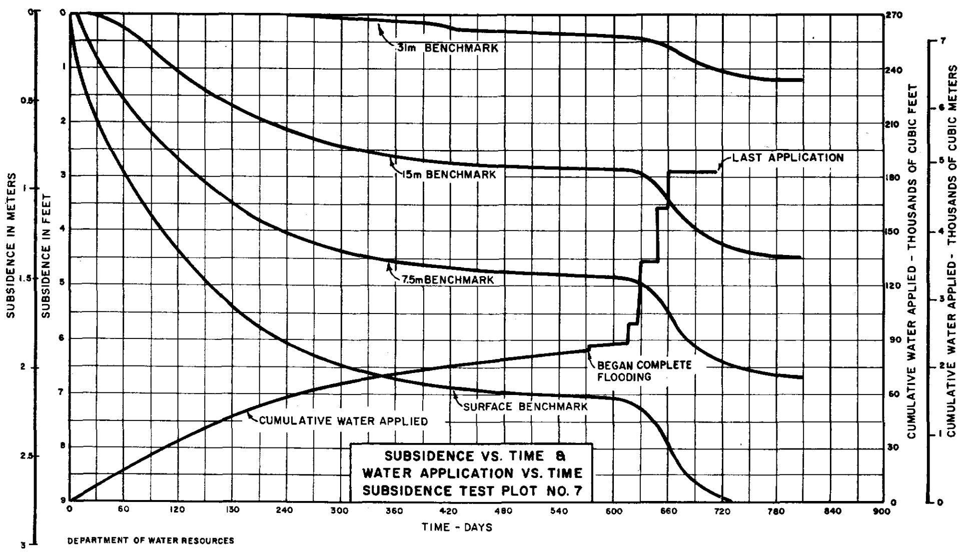

FIG. 8. — *Graph showing subsidence of subsurface bench marks. The results of field testing at Subsidence Plot 7 (fig. 7). The rapid increase in hydrocompaction after 600 days of operation was caused by flooding the entire "crater" of subsidence with water. The graph labelled "Surface Bench Mark" shows the subsidence that occurred at a bench mark located on the floor of the test plot. The graphs labelled 7.5 m, 15 m, and 31 m are for bench marks placed in drill holes at those depths below the floor of the plot.*

Subsidence Due to Tectonic Activity

Subsidence related to crustal deformation has not significantly affected the State Water Project. However, appreciable tectonic uplift has been observed in the region north of Los Angeles that is traversed by East Branch aqueduct. An uplift of about 0.6 m occurred in Tehachapi mountains during the 1952 earthquake (Lofgren, B. E., 1966). A comparison of levelling profiles made before and after the 1971 San Fernando earthquake indicated vertical displacements up to 2.28 m (Burford, R. O., *et al.*, 1971). Tectonic activity in vicinity of the State Water Project continues to be monitored by levelling surveys. During earlier stages of investigation, tripartite tiltmeters were installed and monitored at selected locations (Calif. DWR, 1968). These were later discontinued due to the high costs of maintenance and occasional malfunctioning.

FIG. 9. — *Prototype subsidence test. Note peripheral ground cracks due to hydrocompaction.*

ENGINEERING GEOLOGISTS ESTIMATE COSTS OF TUNNEL CONSTRUCTION

The selection of the aqueduct route involved the comparison of 98 variations of alignment. Because of the pressing need for water deliveries to Southern California, these comparisons had to be completed in the short span of two years. A rapid procedure for estimating the costs of the tunnels was necessary in order to meet this deadline. The development of such a procedure was assigned to the engineering geology staff, as geology was considered the most significant factor influencing the cost of tunnel construction. The goal of this assignment was to provide guidelines from which the approximate cost of a tunnel could be estimated

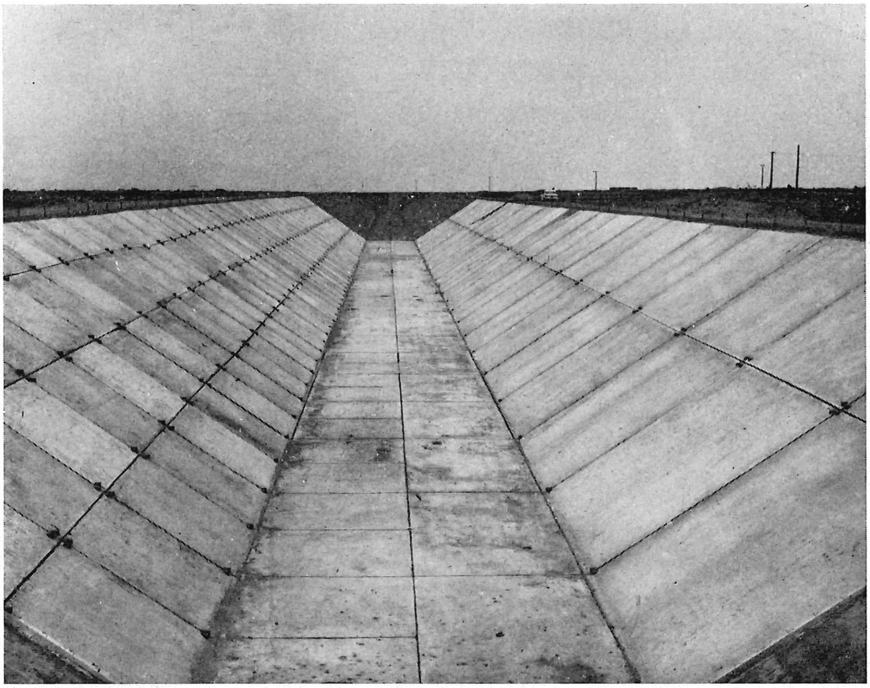

FIG. 10. — *Prototype canal test section prior to filling.*

given a geologic section showing the engineering-geologic conditions predicted throughout the tunnel.

The initial step was to indoctrinate engineering geologists in cost estimating. This was accomplished by study of technical literature, enrollment in university courses on construction procedures and cost estimating, on-site inspection of tunnels under construction, and employment of consultants to provide training and advice with respect to tunnelling techniques. Fortunately, excellent night courses were available from California universities, which provided essential background in construction practices and the mechanics of cost estimating. Tunnel contractors cooperated in permitting staff to inspect on-going projects allowing observation of how geology affects construction progress, tunnel support, and the requirements for materials, such as explosives, drilling supplies, pipe, etc.

Records were compiled of construction progress and problems for various ground conditions. Data for 99 tunnel projects were assimilated from private and governmental agencies, tunnelling equipment manufacturers, explosive companies, tunnel contractors, as well as from technical journals. Consideration was given to all of the major factors which influence tunnelling costs. This information was analysed and correlations established between geologic conditions and the three basic physical elements of a cost estimate, namely the costs for labor, equipment, and materials.

Labor costs were determined based on the size and composition of the crews customarily employed and estimates of the time required to complete construction.

FIG. 11. — *Prototype canal section several weeks after filling. The damaged canal lining had been placed on virgin soil, whereas the unbroken lining had been placed on soil which had been presubsided prior to excavating the canal prism.*

Since these factors depend upon the method of tunnel construction employed, the records of successful projects were examined and criteria established for determining the methods that would probably be used for constructing tunnels of different diameters under a variety of geologic conditions. Tables were prepared based on construction case histories showing the rates of heading advance that could be expected to be attained through ground ranging in physical character from intact rock to incoherent saturated soil. With these guidelines and a knowledge of the geology along a proposed tunnel, it was possible to predict in sequence for any proposed tunnel the most probable construction method, expected rates of heading advance from portal to portal, construction time, and ultimately the total labor costs.

Lists of the equipment commonly used for the different methods of tunnelling and their prices were obtained from manufacturers. On the advice of consultants, the approximate cost for the use of this equipment was determined by utilizing an amortization rate of 15 percent per month which included depreciation and maintenance. This rate was applied throughout the construction period or until the cost of the equipment was written off.

A procedure for estimating the cost of materials required for the construction of tunnels was derived from study of the 99 construction case histories. Relationships were established between tunel line geology and quantities of steel support, explosives, timber, drilling accessories, fuel, and electric energy. The requirements for the first four of these items were found to relate reasonably with ground conditions. The quantities of fuel for diesel equipment and for generation of electric energy were determined to be influenced chiefly by the length of the construction period and consequently were also related indirectly to tunnel geology.

Tables were also compiled for estimating the costs of contractors' overhead and profit. These tables were prepared under the direction of professional cost estimators and were based upon prevailing economic conditions.

Having compiled the basic guidelines for the cost estimating procedure, attention was focused on the role of the field geologist. It was essential that his input be in a usable form with a minimum of extraneous observations. Since this geologist had the greatest familiarity with the tunnel environment, it was important that his judgment of geology-cost relationships be developed and utilized. In his examinations of rock outcrops, he was encouraged to note not only the geologic details conventionally observed but to provide as well an appraisal from the cost estimators standpoint including his estimate of tunnel construction progress, requirements for explosives and support, and a description of any adverse conditions perceived and their probable influence on the construction schedule and costs.

The procedure generally followed by the geologist was to assemble tunnel line geology from all available maps and reports and to supplement this information with detailed geologic mapping. In some instances, holes were drilled to explore geology at tunnel level. Geologic sections were prepared to show conventional geology including petrographic types, formation names, stratigraphy, faults, and other structural elements. Additional sections were drawn showing:

(1) The physical conditions anticipated throughout the length of the tunnel in which ground was classified in nine categories based upon the Terzaghi system (Proctor, R. V., and White, T. L., 1946);

(2) The estimated requirements for explosives and for tunnel support;

(3) The anticipated rates at which the tunnel could be advanced throughout its length.

The engineering geology cross sections and notes provided the information with which to enter appropriate tables and graphs to determine: (1) the probable method of tunnel construction; (2) length of the construction period; and (3) costs of labor, equipment, materials and overhead, and profit. Total construction cost was obtained by adding these cost increments.

An analysis of the 99 case histories studied disclosed that the average cost of tunnel construction excluding overhead and profit was distributed 53 % to labor, 28 % to equipment, 13 % to materials, and 6 % to miscellaneous expenditures. Thus, it was shown that on the average all but 6 % of the actual construction cost is related to geology. The prediction and interpretation of the tunnel geology is therefore a most important element of the cost estimate. Obviously, such prediction and interpretation involves an element of judgment and albeit is subject to error. Nevertheless, someone must exercise this judgment in the preparation of every tunnel cost estimate. The engineering geologist experienced in geologic mapping, structural geology, and stratigraphy and who is also trained and experienced in the principals and practices of construction and cost estimating is certainly as well qualified as anyone to provide this judgment.

The procedure for cost estimating tunnel construction discussed herein has been described in greater detail in previous publications (Calif. DWR, 1959) (Mayo, R. S., 1968). The art of tunnel construction has improved since the writing of these reports, largely through the advent of tunnelling machines. However, the importance of meaningful interpretation of geology remains and the role of the engineering geologist in providing this information is unchanged. Hopefully, some enterprising engineering geologist will undertake the development of a similar cost estimating procedure applicable to machine driven tunnels.

WATER OVER THE MOUNTAINS
(In Retrospect)

Over the past four decades, 263 engineering geologists have been employed for various periods of time by the California Department of Water Resources. The author has had the privilege of serving with many of these professionals on a variety of projects, which have presented problems involving both geology and civil engineering. It was observed that, for the most successful programs, geologists and engineers worked together as well-integrated teams. This interdisciplinary relationship usually prevailed where the geologist members had acquired knowledge of the principles and practices of civil engineering in addition to being competent geologists. With this background, they were able to recognize and appreciate the needs of the engineer planners, designers, and operations staff and to communicate more freely with these people. The geologists who had graduated from accredited universities were generally sufficiently versed in geology but their engineering capabilities had to be developed by on-the-job training supplemented where practicable by evening courses in engineering administered through extension schools of California universities.

That the effectiveness of engineering geologists can be substantially broadened and enhanced through development of this geologist-engineer team capability is regarded as one of the most significant lessons to be learned from the building of the California State Water Project.

References

Bardoff, J. L. and Mutsumura, P. T. (1973). — *Inspection, Maintenance, and Remedial Treatment of Dams of the San Francisco Water Department.* Paper presented at the Engineering Foundation Conference, Asilomar, California, September 1973.

Burford, R. O. *et al.* (1971). — Preliminary measurements of tectonic movement. Appearing in *The San Fernando, California, Earthquake of February 9, 1971.* A report by U. S. Geological Survey and the National Oceanic and Atmospheric Administration.

California, State of, Department of Water Resources (1964). — *Design and Construction Studies of Shallow Land Subsidence for the California Aqueduct in the San Joaquin Valley*, December 1964.

California, State of, Department of Water Resources (1968). — *Earthquake Engineering Programs*, Bulletin No. 116-4, May 1968.

California, State of, Department of Water Resources (1968). — *Geodimeter Fault Movements Investigations in California*, Bulletin No. 116-6, May 1968.

California, State of, Department of Water Resources (1959). — *Investigations of Alternative Aqueduct Systems to Serve Southern California.* Appendix C: *Procedure for Estimating Costs of Tunnel Construction*, Bulletin No. 78, September 1959.

California State Earthquake Investigation Commission (1908). — *California Earthquake of April 18, 1906.*

GOLZÉ, A. R. (1965). — Land subsidence. Why the State is concerned. Published in the *Proceedings for Landslides and Subsidence Geologic Hazards Conference*, Los Angeles, California, May 1965.

HILL, M. L. and DIBLEE, T. W. (1953). — San Andreas, Garlock, and Big Pine Faults, California. *Bulletin, Geological Society of America*, Vol. 64, p. 443-458, April 1953.

LOFGREN, B. E. (1966). — Tectonic movement in the Grapevine area, Kern County, California. Appearing in *Geological Survey Research 1966, Chapter B.* U. S. Geological Survey Prof. Paper, 550-B.

Long Beach, City of, Department of Oil Properties (1969). — *The Mechanics of Compaction and Rebound, Wilmington Oil Field, Long Beach, California*, by D. R. Allen, May 1969.

MAYO, R. S., and Associates, *et al.* (1968). — *Tunnelling. The State of the Art.* U. S. Department of Commerce, National Bureau of Standards, Institute for Applied Technology, January 1968.

Munger Map Book (1967). — *California-Alaska Oil and Gas Fields.* Averill H. Munger, ed., 11th ed., April 1967.

POLAND, J. F. (1972). — Subsidence and its control. *Underground Waste Management and Environmental Implications*, Memoir No. 18, The American Association of Petroleum Geologists.

United States Geological Survey (1972). — *Land Subsidence Due to Ground Water Withdrawal in the Los Banos-Kettleman City Area, California.* Prepared in cooperation with the State of California Department of Water Resources.

WALLACE, R. E. (1968). — Notes on Stream Channels Offset by the San Andreas Fault Southern Coast Ranges, California. *Proceedings of Conference on Geologic Problems of San Andreas Fault System*, Stanford University.

YERKES, R. F. and CASTLE, R. O. (1969). — Surface deformation associated with oil and gas field operations in the United States. L. J. Tison, ed. *Land Subsidence*, Publication No. 88 AIHS, Unesco, Vol. I, p. 55.