RISK EVALUATION FOR CONSTRUCTION OVER AN ACTIVE FAULT, SYLMAR, CALIFORNIA

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SUMMARY

An investigation was performed to assess the potential for faulting at one of the world's largest proposed water filtration plants designed by Brown & Caldwell-Camp Dresser & McKee for the Los Angeles Department of Water and Power. Filtration capacity is 900 cubic feet per second from the Los Angeles Aqueduct water supply. The site is located near Sylmar, California, an area subjected to ground rupture that accompanied the February 9, 1971, M6.4 San Fernando earthquake.

Site exploration consisted of logging 1,800 feet of trench and determining the minimum age of soil profiles. Four onsite faults were observed and dated by age of soil profile development. One of the four faults was judged active; that is, had displacement in the past 10,000 years (Holocene epoch). Conclusions on this fault were:

- Tectonically generated and not the result of dewatering of alluvial deposits caused by regional seismic shaking.
- East-trending reverse fault dipping north 49° to 78°.
- Displacement increases with depth, indicating multiple events.
- Maximum observed cumulative vertical displacement was 2.6 feet.
- Maximum single slip event was 0.7 feet, occurring as recently as 5,000 years ago.
- The probability that surface displacement of 0.7 feet will occur during time periods up to 100 years is less than two percent.

The study allowed design to continue without disruption of schedule or major design changes.

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LOCATION

The site is located in the San Fernando Valley about 20 miles northwest of downtown Los Angeles, California. The site is within the general area of extensive ground rupture associated with the February 9, 1971 M6.4 earthquake (Refs. 1 and 2)

The San Fernando Valley is in the central part of the Transverse Ranges geomorphic province of southern California and lies athwart the northwesterly regional trend of the Coast Ranges and Peninsular Ranges and faults of the San Andreas system. The Transverse Ranges Province consists of late Cenozoic compressive structural features such as east-west trending tight folds and reverse-slip (thrust) faults of similar trend. The compression is relieved, in part, by reverse and/or left-lateral faults such as the San Fernando, Santa Susana and Sierra Madre faults south of the San Andreas; and the Pleito and White Wolf faults north of the San Andreas.

PURPOSE

The purpose of the trenching and dating soil profiles was to determine (1) the age of faulting, (2) probability of displacement, and (3) acceptability of risk to the facility due to fault rupture.

SITE AREA NEOTECTONICS

The site is bounded on the south by the east-trending, north-dipping reverse San Fernando fault and on the north by the Santa Susana thrust fault.

The south half of the site is in the Alquist-Priolo Special Fault Studies Zone. This Study Zone (Alquist-Priolo Act of 1972) encompasses tectonic breaks associated with the 1971 San Fernando earthquake. The purpose of the Alquist-Priolo Act is to provide for public safety along known active faults subject to surface rupture (Ref. 3).

For the purposes of this paper, an active fault is defined as one which has had surface displacement at or near the ground surface within Holocene time (about the last 10,000 years).

1971 San Fernando Fault Displacements

The Sylmar fault segment of the San Fernando fault (Refs. 4 and 5), located about 5 miles east of the site, produced these maximum known measured displacements: left-lateral strike-slip, 6.2 feet; reverse dip-slip, 4.9 feet; and vertical separation, 4.6 feet (Ref. 6). The ratio of vertical to horizontal displacement was about 1:1.

The Reservoir fault segment of the San Fernando fault is about 1.2 miles south of the site, and experienced these displacements: left-lateral strike-slip, 0.53 feet; reverse dip-slip, 1.25 feet (Ref. 6). Thus, the ratio of vertical to horizontal displacement nearest the site was about 2:1.

1971 Santa Susana Fault Displacements

The Santa Susana fault is about 1 mile northwest of the site. Relative displacement of about 1 foot left-lateral strike-slip occurred near the south end of the rupture. An extension of this zone of ruptures, just northeast of the Golden State freeway, showed net left-oblique displacement of about 0.25 feet (Refs. 5 and 6). Southwest of the freeway, a road was displaced left-laterally about 1 foot (Ref. 7). Therefore, the ratio of vertical to horizontal displacement on this segment of the Santa Susana fault is about 1:4.

SITE AREA GEOMORPHOLOGY

The site is situated near the south flank of the Santa Susana Mountains. Grapevine and Weldon Canyons drain toward the site and have been deeply incised into the mountain's sedimentary bedrock. These incisions are due to rapid, pulsating uplift along the Santa Susana fault at the base of the mountains. Coalescing alluvial fan deposits have formed at the mouths of Grapevine and Weldon Canyons from torrential streamflows, interspersed with occasional mudflows. A strong northeast-trending topographic lineament (inferred fault), with the south side standing tens of feet above the adjoining north surface, occurs just north of the site. Alluvial fans were deposited north of this lineament during the late Pleistocene epoch, and possibly as recent as the early Holocene epoch. The area north of the lineament continued to receive sediments from the alluvial fans and is a relatively young geomorphic surface. The alluvial deposits south of the lineament were cut off by the topographic high. The area south of the lineament has not received sediments for thousands of years and is a relatively old geomorphic surface.

DATING SOIL PROFILES

The most appropriate technique for dating the minimum age of onsite faults was to determine the age of overlying, undisplaced relict paleosols (Qr) and colluvium (Qc) logged in 1,800 feet of exploratory trench excavations. Soil stratigraphy dating was performed by Dr. Roy J. Shlemon, and geologic logging of trenches and faults by John R. Stellar.

Age Dating Techniques

To determine a relative data for the last movement of a fault, it is necessary to ascertain the age of geomorphic surfaces and their underlying sediments. In this regard, the ages of late Quaternary alluvial fan sequences bordering the south flank of the Santa Susana Mountains were most important, especially those fan materials deposited onsite (old geomorphic surface) and mapped in the exploratory trenches.

The approximate age of these deposits was ascertained by the relative development of pedologic (soil) profiles which, in turn, served as a means to reconstruct the late Quaternary tectonic history of the study area.

Relative Soil Profile Development

Relative development of a soil refers to progressive morphological changes with the passage of time. In brief, soils pass through transitional stages deemed "undeveloped", "slightly", "moderately" and "strongly developed" where they form on well-drained and geomorphologically stable landscapes. The rate of soil formation is not constant but varies with time and, to a great degree, is influenced by late Quaternary climatic change. However, where calibrated by radiometric dating, modern soils and paleosols (relict, buried and exhumed) are excellent stratigraphic markers for differentiating and correlating Quaternary deposits and landforms (Ref. 8).

Inspection of Trench 1 indicated the presence throughout much of its length of a distinctive surface soil (pedogenic profile) useful to date (minimum age) the underlying sediments. Accordingly, a detailed soil profile and measurement of a 4-foot section at Station 3+25 (east wall) of Trench 1 was made to document this stratigraphic marker. Several of the soil horizons identified could be traced directly to the fault zone, particularly where exposed at Station 4+00 in Trench 2. The small faults clearly do not displace the ground surface, the measured and described soil, or even sediments below the soil (parent material) to at least a depth of about 6 feet below the ground surface.

As shown on the detailed soil profile, the surface pedon is moderately developed; that is, it is typified by an almost 2-foot thick B horizon (argillic) with strong angular blocky structure, reddish brown color (5YR 4/4 - Munsell notation), and thin, continuous clay films on ped faces and in interstitial pores. Further, the soil bears a distinctive CCA horizon (calcic) that is widely traceable in the trench.

Although the original surface has been somewhat disturbed by grading and plowing, sufficient soil horizons remain to indicate that the profile formed on a relatively stable, old geomorphic surface over a long period of time. These surface soils where measured in Trench 1 required at least 35,000 to 40,000 years to form (isotope stage 3), based on comparison with radiometrically dated soils which were formed under similar climates and lithologic controls elsewhere in mediterranean California. It is quite possible, however, that the soil began to form on the order of about 80,000 years ago (substage 5a). In any event, the underlying sediments are older. Accordingly, from a conservative age standpoint, it is judged that the last displacement of the fault identified in site Trenches 1 and 2 took place at least 35,000 to 40,000 years ago.

The following summarizes conclusions regarding the age of faults exposed in Trenches 4, 5 and 6.

Trench 4 exposes Fault F-3 displacing early Quaternary Saugus Formation and overlying older alluvium (Qalo3). Displacement increases with depth, indicating multiple movements in this zone. Timing of the last offset is not discernible in this trench owing to previous removal by grading equipment of 15 to 16 feet of younger Quaternary sediments. Of particular significance is the presence of the fault directly in the middle of the older alluvial channel fill, rather than confined along the sidewall contact with the Saugus

Formation. This fault-stratigraphic relationship indicates that displacement was truly tectonically generated at the site, rather than a result of dewatering of the channel fill caused by regional seismic shaking.

Trench 5 also exposes Fault F-3, discerned in older alluvium by offset bedding and carbonate-filled fractures. The fault terminates within the older alluvium (Qalo2), well below the base of a relict paleosol estimated to be at least 35,000 to 40,000 years old. Last movement of this fault therefore occurred before about 35,000 years ago. Fault F-3 is traced into the base of the paleosol where it displaces the B_3 horizon about 0.7 feet (vertical). Fault F-3 likely continues higher into the paleosol approaching the present surface, but the slip-plane is not preserved owing to seasonal movement (expandable clays) within the soil argillic horizon. Colluvium, with no distinct stoneline, overlies the paleosol. Accordingly, from the available stratigraphy in Trench 5, the last displacement took place after about 35,000 to 40,000 years ago. If assumed to have occurred during one event, maximum vertical offset was approximately 0.7 feet.

Trench T-6 likewise exposes Fault F-3 that terminates well below the 35,000- to 40,000-year old paleosol. However, a splay of Fault F-3 extends up into and vertically displaces the B_{31} and B_{32} horizons some 6 inches. Measured displacement along the rake of the fault is 7 inches (reverse sense, north side up. The paleosol has been truncated and is now covered by about 2 feet of locally-derived colluvium. The contact is marked by abrupt changes in grain-size, structure, density, color, and the presence of a distinct stoneline containing clasts to 6 inches in diameter. The colluvium bears only a weakly developed soil profile (A-C) lacking in structural development (granular to massive), and showing the absence of clay films in pores and root tubules. The colluvium is hence judged to be not more than 5,000 to 10,000 years old. Accordingly, last displacement along Fault F-3 occurred after about 35,000 to 40,000 years ago but possibly as recent as 5,000 to 10,000 years ago.

ONSITE FAULTS

Four onsite faults, F-2, F-3, F-4 and F-5 were mapped in the exploratory trenches. A description of each fault is as follows:

Fault F-2

Fault F-2 is a 45° south-dipping normal fault striking east-west. It displaces old alluvium ($Qalo_{(u)}$) 0.3 feet down on the south but does not offset the overlying relict paleosol (Qr) which has a minimum age of about 35,000 to 40,000 ybp. No evidence of multiple fault-slip events was observed.

Fault F-3

Fault F-3 is an east-trending reverse fault, dipping north 49° to 78°. It offsets well stratified sand and gravel of Old Alluvial units $Qalo_3$, $Qalo_2$ and $Qalo_{2(U)}$ and displaces 35,000- to 40,000-year old relict paleosol (Qr) but not the 5,000- to 10,000-year old Colluvium (Qc). Multiple movements occurred on Fault F-3, the last single-slip event was 0.7 feet vertically about 5,000 to 10,000 years ago.

Fault F-4

Fault F-4 is an east-trending reverse fault (north side up) dipping 36° north. It does not offset the 35,000 to 40,000 ybp pedologic profile.

Fault F-5

Fault F-5 is an east-trending, low-angle reverse-slip (thrust) fault dipping 46° south. Encountered solely within bedrock of the Saugus Formation (no alluvium involved), it displaces the Saugus Formation about 0.7 feet (south side up) and terminates in the Saugus Formation 4 feet below the ground surface; therefore, the last displacement was at least 80,000 ago and probably was hundreds of thousands of years ago, considering the Saugus Formation is lower Pleistocene age.

Summary of Faults F-2 Through F-5

From a conservative age standpoint, the last displacement on Faults F-2 and F-4 took place more than 35,000 years ago, and on Fault F-5 80,000 years ago. Faults F-2, F-4 and F-5 are, therefore, judged not active faults, but Fault F-3 is considered active.

PROBABILITY OF FUTURE SURFACE DISPLACEMENT

The probability of future surface displacement on Faults F-2, F-4 and F-5 is very low. Fault F-3 is judged to be an active fault with an estimated average recurrence interval of 5,000 years. Assuming an average single slip recurrence interval of 5,000 years on Fault F-3, the probability of equaling the observed 0.7-foot surface fault displacement was about 2 percent in 100 years or 1 percent in 50 years. This is a conservative estimate based on available geologic evidence; therefore, the probability of future fault displacement on Fault F-3 is low.

RISK EVALUATION

There are three separate steps to determine the acceptability of risk to a facility due to fault rupture:

Step 1: assessment of the probability for future surface displacement (which has already been described);

Step 2: assessment of risks to the structures from surface faulting under various alternatives;

Step 3: selection of one of the various alternatives and the judgement of the acceptability of the risks associated with that alternative.

The various alternatives in Step 2 are:

a. no action, continue design as planned;

b. relocation of facilities, partial or complete;

c. modification of structures, to localize damage or to resist damage; and

d. modification of plant processes, including changes in hydraulic systems or bifurcation of affected structures.

The assessment in Step 2 includes:

a. benefits of the alternatives in terms of mitigating the effect of surface displacement along the fault;

b. the costs of the alternatives, in terms of project delays due to redesign, additional cost of engineering, additional cost of construction; and

c. effects on overall plant operation.

While these assessments are engineering tasks, the judgement of the acceptability of the risk for any given alternative falls squarely on the shoulders of the owner. This is a value judgement that the owner must make relative to public policy and health issues, economic aspects, and a wide variety of related, but intangible, considerations.

It was determined that none of the alternatives would completely eliminate the risk due to surface displacement along the fault. As a result, it was possible to determine, early in the process, that Step 2 alternatives b, c and d were either too costly or were not sufficient in mitigation effects to adequately protect the facility. Therefore, the engineer (Brown & Caldwell-Camp Dresser & McKee) recommended, and the owner (Los Angeles Department of Water and Power) agreed, that the "no action" alternative was an acceptable risk.

This decision allowed the design of the water filtration plant to continue on schedule, with a minimal cost for engineering assessment and evaluation.

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