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## DIVISION NAME CHANGE

The Technical Activities Committee, at its July 9-10, 1973 meeting, held in Tulsa, Oklahoma, approved the change in name of the Soil Mechanics and Foundations Division to the Geotechnical Engineering Division. However, we are continuing to use the "old" name for the Journals for the balance of 1973. The January 1974 issue will carry the new name.

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## ENGLISH-SI CONVERSION FACTORS

In accordance with the October 1970 action of the ASCE Board of Direction, which stated that all publications of the Society should list all measurements in both customary (English) and SI (International System) units, the list below contains conversion factors to enable readers to compute the SI unit values of measurements. A complete guide to the SI system and its use has been published by the American Society for Testing & Materials. Copies of this publication (ASTM E-380-1972) can be purchased from ASCE at a price of 75¢ each; orders must be prepaid.

All authors of Journal papers are being asked to prepare their papers in this dual-unit format. Until this practice affects the majority of papers published, we will continue to print this table of conversion factors:

| To convert | To | Multiply by |
|---|---|---|
| inches (in.) | millimeters (mm) | 25.40 |
| inches (in.) | centimeters (cm) | 2.540 |
| inches (in.) | meters (m) | 0.0254 |
| feet (ft) | meters (m) | 0.305 |
| miles (miles) | kilometers (km) | 1.61 |
| yards (yd) | meters (m) | 0.91 |
| square inches (sq in.) | square centimeters ($cm^2$) | 6.45 |
| square feet (sq ft) | square meters ($m^2$) | 0.093 |
| square yards (sq yd) | square meters ($m^2$) | 0.836 |
| acres (acre) | square meters ($m^2$) | 4047. |
| square miles (sq miles) | square kilometers ($km^2$) | 2.59 |
| cubic inches (cu in.) | cubic centimeters ($cm^3$) | 16.4 |
| cubic feet (cu ft) | cubic meters ($m^3$) | 0.028 |
| cubic yards (cu yd) | cubic meters ($m^3$) | 0.765 |
| pounds (lb) | kilograms (kg) | 0.453 |
| tons (ton) | kilograms (kg) | 907.2 |
| one pound force (lbf) | newtons (N) | 4.45 |
| one kilogram force (kgf) | newtons (N) | 9.81 |
| pounds per square foot (psf) | newtons per square meter ($N/m^2$) | 47.9 |
| pounds per square inch (psi) | kilonewtons per square meter ($kN/m^2$) | 6.9 |
| gallons (gal) | cubic meters ($m^3$) | 0.0038 |
| gallons (gal) | liter ($dm^3$) | 3.8 |
| acre-feet (acre-ft) | cubic meters ($m^3$) | 1233. |
| gallons per minute (gpm) | cubic meters/minute ($m^3/min$) | 0.0038 |
| newtons per square meter ($N/m^2$) | pascals (Pa) | 1.00 |

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JOURNAL OF THE
SOIL MECHANICS AND
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# Liquefaction Case History[a]

By Schaefer J. Dixon,[1] M. ASCE and Jack W. Burke,[2] A. M. ASCE

## Introduction

The Joseph Jensen Filtration Plant is located in the Granada Hills area of the San Fernando Valley near Sylmar, Calif. The plant is owned and operated by The Metropolitan Water District of Southern California. This $50,000,000 plant treats California Aqueduct water delivered by a pipeline from the state's Castaic Reservoir, terminus of the West Branch of the State Water Project. The first units of the plant were designed to treat 400,000,000 gpd (1,500,000 $m^3/day$).

At the time of the February 9, 1971 San Fernando Earthquake, the first units of the Jensen Plant were under construction and near completion. Extensive ground and structural damage was sustained by the plant as a result of this earthquake. Major landsliding occurred along the eastern portions of the site. The cause of landsliding was liquefaction of a natural deposit of saturated alluvium underlying a thick interval of compacted fill.

This paper summarizes and presents the geologic, seismic and soil data, and analysis leading to the conclusion that liquefaction did occur during the February 9, 1971 earthquake.

## Geology

The plant site, located as shown in Fig. 1, was developed on a small alluvial plain formed primarily of outwash from the Santa Susana Mountains. The

Note.—Discussion open until April 1, 1974. To extend the closing date one month, a written request must be filed with the Editor of Technical Publications, ASCE. This paper is part of the copyrighted Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers, Vol. 99, No. SM11, November, 1973. Manuscript was submitted for review for possible publication on April 13, 1973.

[a]Presented at the April 9-13, 1973, ASCE National Structural Engineering Meeting, held at San Francisco, Calif. (Preprint 1977).

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perimeter of the alluvial plain is defined and the site is underlain by bedrocks mainly of the Saugus Formation of Lower Pleistocene or Pleiocene age. This formation comprises what is termed "soft" bedrock, and it consists of poorly

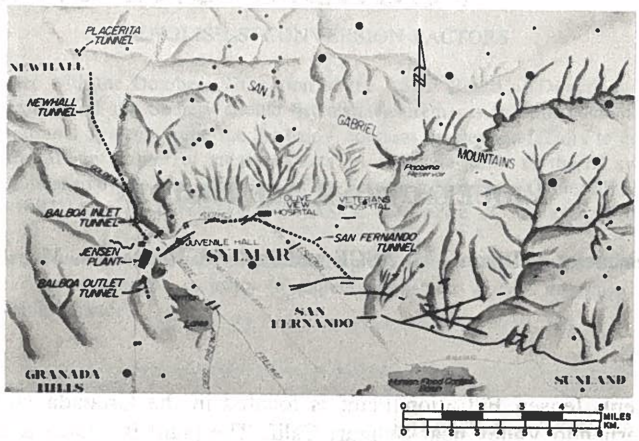


FIG. 1.—Vicinity Map

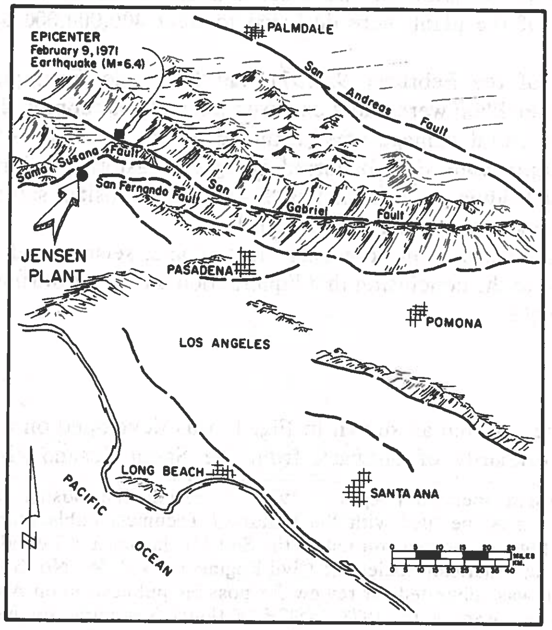


FIG. 2.—Area Fault Map

cemented sandstone, sandy siltstone, and conglomeratic sandstone. The Saugus Formation is underlain by several older rocks with depth to basement granitic



rocks probably in excess of 10,000 ft (3,000 m).

The two major intersecting fault systems (Fig. 2) which dominate the structure of the north San Fernando Valley area are: (1) The northwest-trending San Gabriel fault, which is associated with the San Andreas fault; and (2) the east-trending system of shorter frontal faults which includes the Santa Susana and San Fernando Group.

The Santa Susana fault is a sinuous, north-dipping thrust fault that trends east-west along its exposure on the Santa Susana Mountains north of the San Fernando Valley. The fault has a total known length of approx 16 miles (26 km), and it exhibits evidence of late Quaternary movement (5).

The segments of the San Fernando Fault group that were demonstrably involved in the February 9, 1971 San Fernando Earthquake (Magnitude 6.4) are for the most part east-west trending thrust and left-lateral faults (7). The ground surface ruptures occurred on little-known preexisting faults in a local area of low seismicity and previously unknown ground displacements. Displacements, the maximum of which were approx 3 ft (1 m) vertically, occurred in a zone having a length of about 9 miles (14 km).

## Seismicity

To develop basic data for liquefaction analysis, the statistical seismicity of the site was evaluated from a consideration of past recorded earthquakes. A compilation of earthquakes with a magnitude of 3.8 or greater during the 1934 through 1971 period was made for earthquakes within several different radii from the site. Analysis of these data, by currently available methods (2,6,8,15,19), resulted in the evaluation of site seismicity in terms of the expected number of occurrences of various magnitude earthquakes. By this analysis the site was found to have seismic activity comparable to the average of southern California.

The probability of occurrences of various levels of maximum ground acceleration was evaluated from further statistical analyses and consideration of the proximity of the faults to the site. A summary of the results of the analysis is shown in Table 1, wherein the statistical data are related also to probable fault events. The duration of shaking has been estimated from the probable earthquake magnitude (12).

In an attempt to evaluate the effects of the February 9, 1971 event, strong-motion data (4,11,20,30) were evaluated. In general, ground records for the extended Los Angeles basin showed about 10 sec to 12 sec of higher-frequency shaking, followed by several cycles of longer-period waves. Some of the data were utilized in Fig. 3 to show the effect of distance to the causative fault on accelerations. In Fig. 3, curves for past earthquakes developed by Housner (12) are also presented for comparison. These data indicate that maximum "firm" ground acceleration at the site during the February 9 event was probably 0.30 g to 0.35 g if the fault break was within 5 miles to 10 miles (8 km to 16 km) from the site.

Other studies (14) have shown that some areas of the site had fundamental frequencies approaching that of arriving shear waves; therefore, the response was probably amplified to about 0.4 g or more in such areas.

In summary, information on the San Fernando earthquake collected during the course of the Jensen Plant investigation, related to liquefaction analysis, indicated that: (1) The site was subjected to a maximum horizontal "firm" ground acceleration of between 0.3 g and 0.4 g; and (2) the site was subjected

**TABLE 1.—Seismicity at Joseph Jensen Filtration Plant Site**

| Maximum "firm" ground acceleration level, g (1) | Approximate probability[a] of occurrence per 100 yr, as a percentage (2) | Probable faults[b] and their distances, in miles, to Jensen Site to cause event (3) | Probable earthquake magnitude to generate maximum acceleration (4) | Duration of strong shaking, in seconds (5) |
|---|---|---|---|---|
| 0.40 | 5 | San Andreas—26[c] | 8-1/4 | 40+ |
| 0.30 | 25 | San Andreas—26 | 7-1/4 | |
| | | Aftershock of large event—0 to 10 | 6-1/2 | 20 to 30 |
| | | Local (Santa Susana, San Fernando Group, etc.)—5 to 10 | 6-1/2 | |
| 0.20 | 75 | Local event or aftershocks (Santa Susana, San Fernando Group, etc.)—0 to 10 | 5-1/2 | 5 to 10 |
| 0.10 | 99 | Local event or aftershocks (Santa Susana, San Fernando Group, etc.)—0 to 10 | 4-1/2 | 5 |

[a]Probability analysis excludes the effect of strain rates (1) (2) and past events on San Andreas fault (i.e., 1857).

[b]Smaller and more distant events occurring on the listed faults will produce lower acceleration levels at the site.

[c]1 mile = 1.6 km.

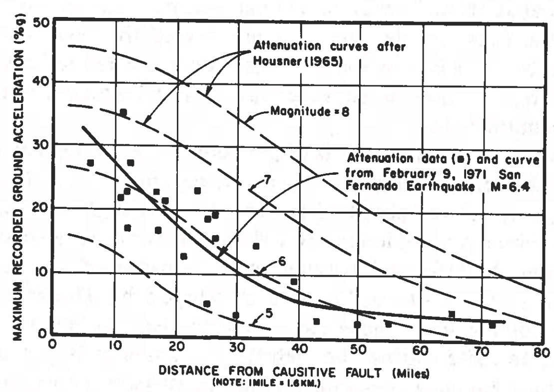


**FIG. 3.—Magnitude, Acceleration, and Distance Relationship**

to a duration of shaking of 10 sec to 12 sec with a predominate frequency of 2 Hz.

In the analysis of liquefaction potential an assessment of probable future



earthquake events was also necessary. Consideration was given to information from the San Fernando earthquake and the data in Table 1. The following summarizes the general conclusion as to the type of future events that can be expected to affect the Jensen site:

1. A Magnitude 8 or greater earthquake on the San Andreas fault [26 miles (42 km) from the site]. Such an earthquake would probably produce a maximum ground acceleration of 0.35 g to 0.45 g and a duration of at least 40 sec.
2. An earthquake of Magnitude 6.5 (duration 10 sec to 15 sec) originating within 5 miles to 10 miles (8 km to 16 km) of the site or an aftershock of the previously mentioned earthquake. Such an event would probably produce ground shaking similar to that of the San Fernando earthquake.
3. Another independent event, such as that of the February 9, 1971 earthquake, within 5 miles to 10 miles (8 km to 16 km) of the site on the same or another fault system.

## Site Development

The initial development phase of the plant area required considerable site grading over a period of several years. Grading commenced in 1965 with the relocation of roads and streets in the site area. The second grading contract began in 1968 with the development of the site grade prior to plant facility construction. In total, grading of the site consisted of placing approx 5,000,000 cu yd (4,000,000 $m^3$) of material. In general, the west section of the site exposes the Saugus Formation at the surface. The remaining areas contain up to 55 ft (18 m) of compacted fill overlying alluvium deposits.

The initial development phase of the treatment plant, which as shown on Fig. 4 was about 90% complete at the time of the earthquake, involved the construction of the first units of the plant structures.

## Field Evidence of Landsliding

The field exploration program for the landslide areas, following the San Fernando earthquake, involved drilling and sampling of over 20 borings. All borings penetrated the compacted fill materials, the alluvium deposits, and at least 30 ft (9 m) of the Saugus Formation bedrock. Slope indicators were installed in 10 of the borings. In addition to borings, a geophysical refraction survey, a detailed mapping program of ground cracking, and other observations were performed within the plant site.

The major landslide occurred on the southeast portion of the site and had a plan dimension of about 2,500 ft (760 m) by 800 ft (240 m) (see Fig. 5). The slide was based, as shown in Fig. 6, in natural solids at 40 ft to 60 ft (12 m to 18 m) below the general ground surface. Based upon observations of ground surface cracking, as shown on Fig. 7, the north portion of the slide apparently pivoted about its southern end with a total easterly movement of 3 ft to 5 ft (0.9 m to 1.5 m). A pressure ridge (see Fig. 8), about 5 ft (1.5 m) wide and 1 ft to 2 ft (0.3 m to 0.6 m) high, developed along a length of 1,000 ft (300 m) at the base of the slope.

Several sand boils (see Fig. 9) were observed at the toe of the slope in the vicinity of the pressure ridge. Water was also observed to be escaping out of cracks on top of the compacted fill. These observations demonstrated the degree of excess pore pressures that were relieved following the earthquake. In addition to surficial evidence, a crack filled with "sand" was observed at

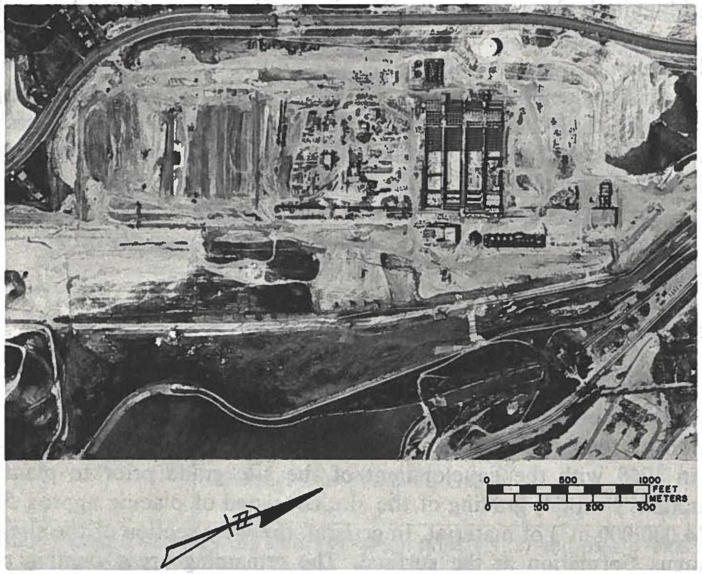


FIG. 4.—Aerial View of Site

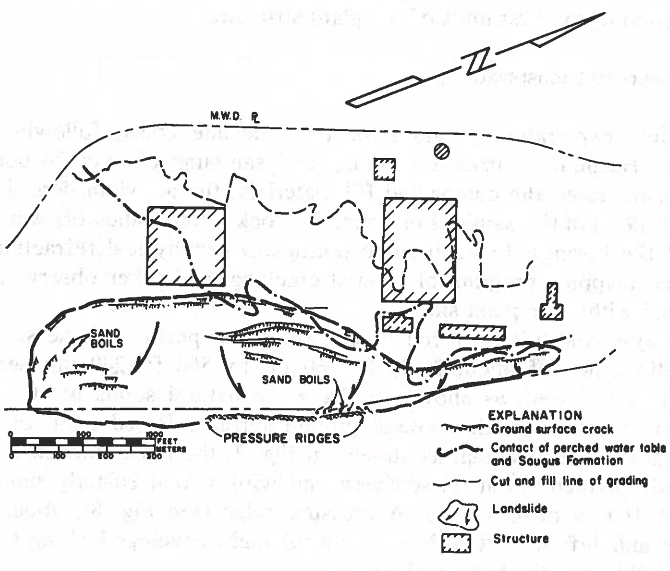


FIG. 5.—Plan of Landslide Area



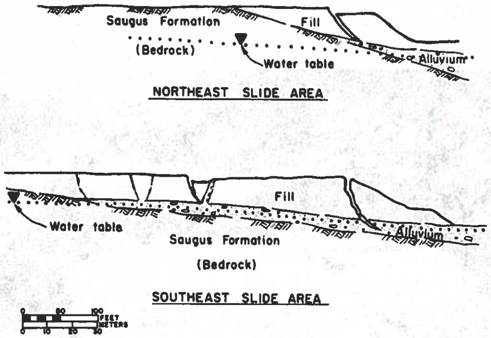


FIG. 6.—Cross Section of Slide Areas

FIG. 7.—Fill Cracks (Looking North from Center of Site)

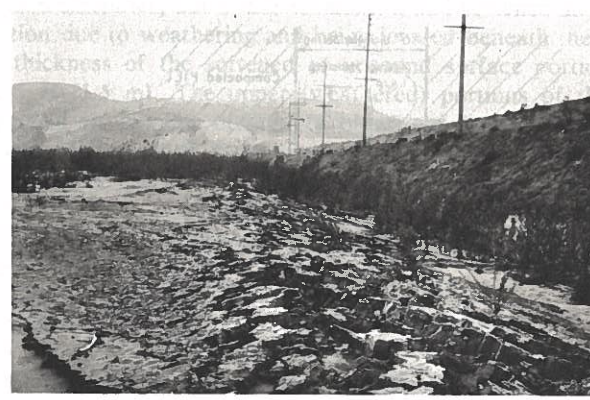

FIG. 8.—Pressure Ridge (Looking South Along Toe of Fill Slope)

the compacted fill-alluvium contact in one of the large-diameter exploration borings (see Fig. 10).

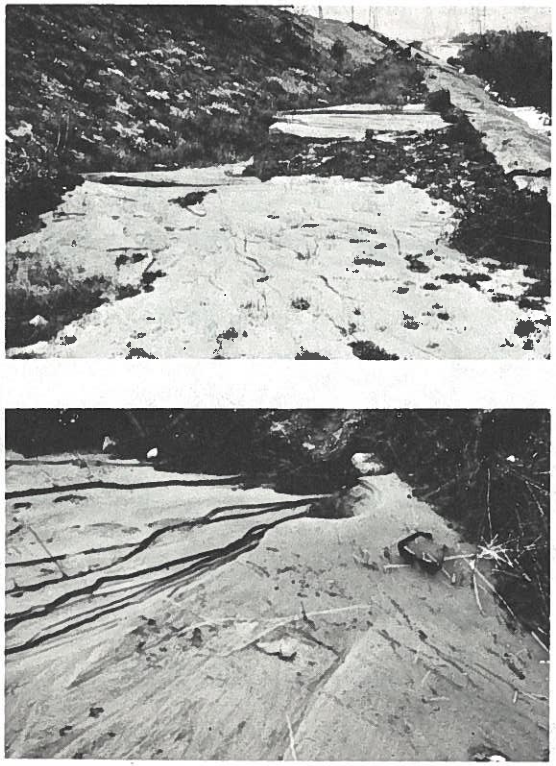

**FIG. 9.—Sand Boils (Top—Looking North Along Toe of Fill Slope)**

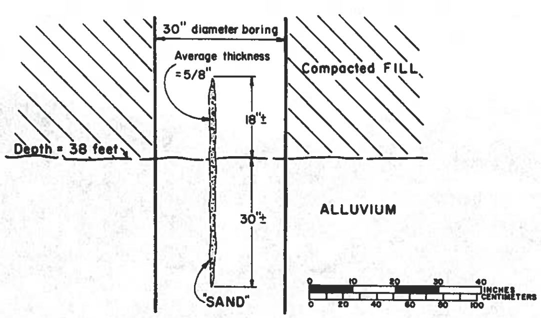


**FIG. 10.—Sketch of Sand Filled Crack**

The fill slope along the northeast perimeter of the site also underwent several feet of movement. This secondary landslide extended along the slope about



1,500 ft (460 m), but in general did not extend more than 100 ft (30 m) back from the top of slope.

The areal extent of the two landslide areas was controlled by the existence of the alluvium and level of the water table within the alluvium. As shown in Fig. 5, ground cracking generally followed the plan trace of the contact of the water table and Saugus Formation. Fig. 6 shows the contact in cross section.

Data collected from slope indicators installed in the landslide areas shortly after the earthquake have shown no significant additional movements.

## Subsurface Conditions

The results of field explorations indicated the following subsurface conditions in the landslide area (see Fig. 6).

From the finished ground surface to the top of the alluvium deposits, all the borings encountered compacted fill materials that were up to 55 ft (18 m) thick. These materials can be described as a mixture of silty sands, sandy silts, and sands with gravel, and occasional zones of silt and clayey silt. The compacted fill materials were generally in a moist and very dense to very stiff in-situ condition with an *N*-value (i.e., results of the Standard Penetration Test) ranging between 30 blows per ft and 80 blows per ft and a total in-situ unit weight of 135 pcf (2,160 $kg/m^3$).

Beneath the compacted fill materials and above the Saugus Formation, all borings penetrated a thickness of alluvium deposits varying generally between 5 ft and 25 ft (1.5 m and 7.5 m). The alluvium deposits were silty sands and sandy silts with occasional zones of clayey silt and silty clay materials. The consistency of these deposits varied from moist to wet and soft to medium dense, with an average *N*-value between 20 blows per ft and 25 blows per ft. These materials were weak and compressible, and had an in-situ relative density averaging 50% to 60% (9,10).

Underlying the alluvium deposits was the Saugus Formation bedrock. This formation normally consisted of soft to moderately hard, slightly cemented sandstones and siltstones, but at this location, it had softened and lost a degree of cementation due to weathering and being located beneath the ground-water level. The thickness of the softened or unsound surface portion varies, but is at least 5 ft (1.5 m). The upper (weathered) portions of these materials occasionally had an *N*-value of only 15 blows per ft to 20 blows per ft, but normally after 10 ft to 20 ft (3 m to 6 m) of penetration, the *N*-values were no less than 40 blows per ft and frequently over 100 blows per ft.

A static ground-water level was encountered in all borings drilled within the slide area. The water level was generally located within the elevation interval of the alluvium deposits.

## Laboratory Studies

The bulk of the laboratory testing program (not presented herein) was composed of consistency (natural water content, natural in-situ density, and grain-size distribution), direct shear strength and compressibility tests on compacted fill, alluvium and unsound Saugus Formation materials. Although the material was

TABLE 2.—Summary—Liquefaction Test Results

| Boring number (1) | Depth, in feet (2) | Natural dry unit weight, in pounds per cubic foot (3) | N-value, in blows per foot (4) | Relative density,[a] $D_R$, as a percentage (5) | Grain-size, $D_{50}$, in millimeters (6) | Cyclic loading factor, $\sigma_{dc}/2\sigma'_a$ (7) | Number of load cycles[b] to liquefaction, $N_l$ (8) | Comments (9) |
|---|---|---|---|---|---|---|---|---|
| (a) Undisturbed Samples | | | | | | | | |
| 8 | 57 | 119 | 26 | 58 | 0.08 | 0.428 | 1 | |
| 14 | 48 | 117 | 31 | 61 | 2.20 | 0.319 | 13 | Gravelly |
| 19 | 43 | 110 | 6 | 25 | 0.16 | 0.271 | 3 | |
| | 47 | 105 | 5 | 23 | 0.10 | 0.317 | 18 | Gravelly |
| | 51 | 107 | 15 | 45 | 0.21 | 0.236 | 3 | |
| | 56 | 124 | 27 | 57 | 0.43 | 0.318 | 2 | |
| 20 | 56 | 112 | 23 | 55 | 0.32 | 0.290 | 12 | Saugus formation |
| 23 | 55 | 119 | 9 | 30 | 0.21 | 0.278 | 3 | |
| | 56 | 120 | 9 | 30 | 0.19 | 0.196 | 8 | |
| 24 | 61 | 105 | 15 | 44 | 0.09 | 0.267 | 3 | |
| 40 | 55 | 111 | 23 | 52 | 0.50 | 0.217 | 14 | |
| 42 | 54 | 108 | 26 | 55 | 0.35 | 0.217 | 4 | |
| | 56 | 99 | 35 | 61 | 0.09 | 0.174 | 20 | Saugus formation |
| | 62 | 111 | 31 | 56 | 0.55 | 0.217 | 26 | Saugus formation |
| | 64 | 116 | 22 | 49 | 0.80 | 0.174 | 46 | Saugus formation |
| 44 | 63 | 103 | 27 | 53 | 0.47 | 0.174 | 26 | |
| | 71 | 103 | 27 | 51 | 0.08 | 0.217 | 72 | |
| | 76 | 111 | 25 | 49 | 0.25 | 0.174 | 162 | Saugus formation |
| 45 | 62 | 121 | 42 | 63 | 0.30 | 0.174 | 56 | Gravelly |
| | 64 | 118 | 39 | 61 | 0.85 | 0.174 | 51 | |
| | 69 | 107 | 14 | 36 | 0.22 | 0.174 | 53 | |
| | 75 | 122 | 26 | 50 | 1.50 | 0.174 | 90 | Gravelly |
| (b) Remolded Samples | | | | | | | | |
| 40 | 55 | 112 | (Assumed equal to value for undisturbed sample) | | 0.50 | 0.217 | 8 | |
| | | 112 | | | 0.50 | 0.174 | 8 | |
| 42 | 54 | 108 | | | 0.35 | 0.217 | 3 | |
| | | 108 | | | 0.35 | 0.217 | 4 | |
| | 62 | 111 | | | 0.55 | 0.217 | 11 | Saugus formation |
| 44 | 63 | 103 | | | 0.47 | 0.174 | 18 | |
| | 71 | 103 | | | 0.08 | 0.174 | 147 | |
| | 76 | 111 | | | 0.25 | 0.174 | 103 | Saugus formation |
| 45 | 69 | 107 | | | 0.22 | 0.174 | 46 | |

[a]Relative density based upon adjacent N-Value test and effective overburden stress.
[b]Number of loading cycles based on when the sample liquefied or the axial strain reached 4%.
(Note: 1 ft = 0.3 m and 1 pcf = 16 kg/m³).

somewhat variable, Fig. 11 shows the predominate range in grain-size distribution for the alluvium deposits.

In addition to the conventional lab tests, cyclic (liquefaction) triaxial shear tests were performed on samples of alluvium deposits and weathered Saugus Formation materials. The cyclic testing equipment consisted of an air-operated cyclic loading device, a triaxial test chamber, a four-channel strip chart recorder, and measuring transducers. The loading device consists of a double-acting piston that is actuated up or down by air pressure. The frequency of loading can be varied from static loading to 5 Hz.

The general cyclic testing procedure (16,17,18,25) for test specimens was to set up and saturate (by back pressuring) in the triaxial chamber. The specimens were then subjected to an effective consolidation pressure equivalent to the average effective overburden pressure in the field. At the end of consolidation, the specimens were subjected to undrained cyclic loading and unloading computed

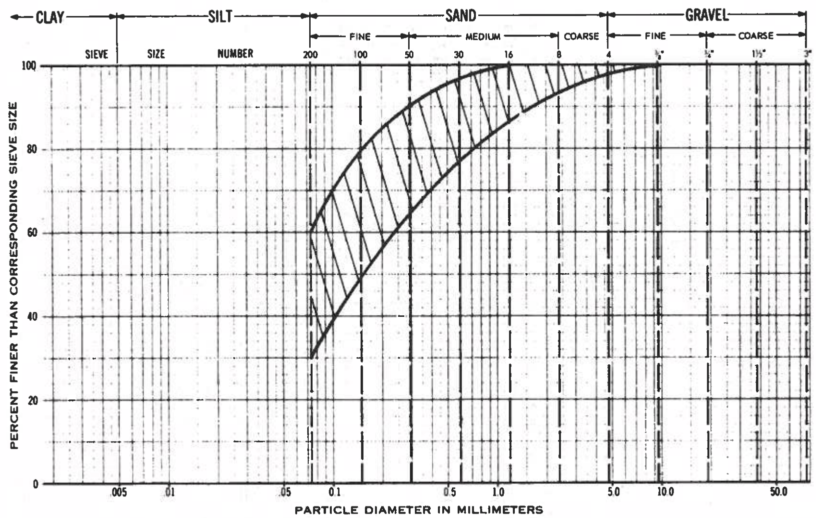


FIG. 11.—Grain Size Distribution—Alluvium

to be equivalent to selected, earthquake induced, stress in the field. The applied loads and the resulting variations in the pore-water pressure and axial deformations were recorded throughout the tests. Tests were stopped when the sample liquefied or the axial strain exceeded 4%.

Several of the undisturbed test specimens, following initial testing, were remolded in the laboratory to their approximate natural dry density and retested in a similar manner for the undisturbed samples.

A total of 31 liquefaction tests were performed on samples of alluvium deposits and Saugus Formation materials. Of the total, 22 tests were on undisturbed samples and nine tests on remolded samples. In addition, five of the 22 undisturbed samples tested were on Saugus Formation materials.

The summary of pertinent data for the liquefaction tests is tabulated in Table 2.



## Liquefaction Analysis

The basic analysis of the laboratory cyclic testing results is shown in Fig. 12. The plot shows cyclic loading factor $[\sigma dc/(2\sigma_a')]$, one-half of the cyclic

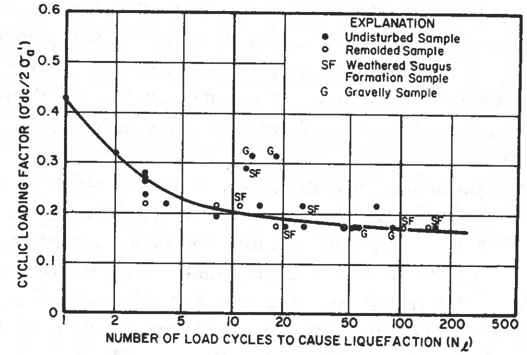


FIG. 12.—Cyclic Loading Factor Versus Load Cycles to Liquefaction

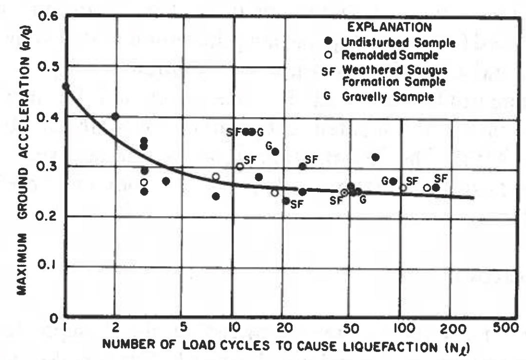


FIG. 13.—Maximum Ground Acceleration Versus Load Cycles to Liquefaction

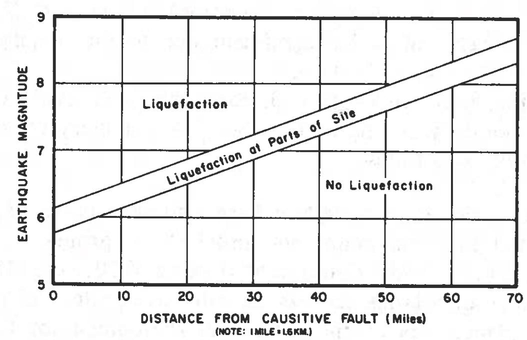


FIG. 14.—Liquefaction, Magnitude, and Distance Relationship

deviator stress divided by the effective consolidation stress] versus the number of load cycles to cause liquefaction. As might be expected, as the cyclic loading factor decreased, the number of cycles to cause liquefaction increased. There was also limited evidence that for a constant cyclic loading factor and relative density, the required number of load cycles to cause liquefaction for the remolded test samples was approx 50% to 75% of the cycles required for the undisturbed test samples. The scatter in test results, shown in Fig. 12, was primarily influenced by the variability of the alluvial materials. Also, several of the tests were on samples of highly weathered Saugus Formation materials and alluvium containing gravel. The $D_{50}$ size of the material tested ranged from less than 0.1 mm to in excess of 1.0 mm.

For engineering purposes, the liquefaction test results were plotted and evaluated for the Jensen Plant, as shown in Fig. 13. This figure is based upon a relationship (27) between the maximum ground acceleration and the cyclic loading factor. As can be seen in Fig. 13, there is a relationship between the maximum ground acceleration and the number of load cycles which cause liquefaction. The data indicate that an acceleration of about 0.25 g will be required to achieve liquefaction for any duration of shaking. Note that the curves shown in Figs. 12 and 13 were the optimum relationships developed by the method of least squares.

Finally, since the values of maximum ground acceleration and duration of shaking can be related (12) to earthquake magnitude and fault distance, liquefaction potential for the existing site alluvium was plotted in Fig. 14 as a function of earthquake magnitude and fault distance. The San Fernando earthquake, with a magnitude of 6.4 and located less than 10 miles (16 km) from the Jensen Plant, plots just within the liquefaction zone. A major event ($M = 8\pm$) on the San Andreas fault at a distance of about 26 miles (42 km) would be well within the liquefaction zone.

## Summary and Conclusions

The phenomenon of liquefaction occurred at the Joseph Jensen Filtration Plant site from the February 9, 1971 San Fernando Earthquake. This liquefaction developed primarily in the zone of alluvium deposits which underlie the final site grade, and resulted in major landslides along the east sections of the site. Although liquefaction cases have been reported in the past (22,23,24,26,28), this occurrence is believed to be significant due to the liquefying soil being located at a depth of up to 55 ft (18 m).

This investigation was concerned with comparing field evidence of an actual landslide with laboratory testing and analysis. A summary of the conclusions of this investigation is as follows:

1. It is estimated that during the San Fernando earthquake, the Jensen Plant site was subjected to a maximum horizontal "firm ground" acceleration of between 0.3 g and 0.4 g, and a duration of shaking of 10 sec to 12 sec.
2. Field evidence of a landslide was an extensive pattern of ground surface cracking and displacements on the surface of the compacted fill and heaving of the toe area.
3. Surface explorations within the landslide area revealed a 5-ft to 25-ft (1.5-m to 7.5-m) thick layer of saturated alluvium sandwiched between bedrock and up to 55 ft (18 m) of site compacted fill. Field evidence of subsurface liquefaction in the alluvium observations of several sand boils at the top and toe of the compacted fill and discovery of a crack filled with "sand" at the compacted fill-alluvium contact.
4. A cyclic triaxial laboratory testing program, on undisturbed samples of the site alluvium, indicated that the deposits did liquefy during the San Fernando event. Analysis of these and other data indicate that substantially more liquefaction and greater landslide movement will occur during a major ($M = 8\pm$) earthquake on the San Andreas fault.



During plant site investigations following the February 9, 1971 earthquake, design data were developed which assisted in the evaluation of damage, and could also be utilized for evaluating liquefaction potential during future earthquakes. Of particular interest are areas immediately adjacent to the more important structures. The importance of certain structures may warrant stabilization of the ground against future earthquakes which could cause strong and long duration ground shaking. Evaluations are in progress (3) in regard to the feasibility and costs of such stabilizations.

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## Appendix.—References

1. Albee, A. L., and Smith, J. L., "Earthquake Characteristics and Fault Activity in Southern California," Special Publication of the Association of Engineering Geologists, Oct., 1966.
2. Allen, C. R., et al., "Relationship Between Seismicity and Geologic Structure in the Southern California Region," *Bulletin of Seismological Society of America*, Vol. 55, No. 4, 1965, pp. 753-797.
3. "Alternative Protection Measures, Main Control Building, Joseph Jensen Filtration Plant, Near Sylmar, California," Converse, Davis and Associates, Pasadena, Calif., April 18, 1972.
4. "Basic Interpretation of Strong-Motion Accelerographs in Buildings," Structural Engineers Association of Southern California, Seismology Subcommittee on Seismic Instrumentation and Testings (Preliminary Report), 1971.
5. Bishop, W. C., "Geology of the Southern Flank of Santa Susana Mountains, County Line to Limekiln Canyon, Los Angeles County, California," thesis presented to the University of California, at Los Angles, Calif., in 1950, in partial fulfillment of the requirements for the degree of Master of Science.
6. Bonilla, M. G. "Surface Faulting and Related Effects," *Earthquake Engineering*, R. L. Wiegel, ed., Prentice-Hall, Inc., Englwood Cliffs, N.J., 1970.
7. "California Geology," Special San Fernando Earthquake Edition, California Division of Mines and Geology, Apr.-May, 1971.
8. Davenport, A. G., and Milne, W. G., "Earthquake Probability," *Proceedings of the Fourth World Conference on Earthquake Engineering*, Chile, 1969.

9. Gibbs, H. J., and Holtz, W. G., "Research on Determining the Density of Sand by Spoon Penetration Tests," *Proceedings of the Fourth International Conference on Soil Mechanics and Foundation Engineering*, Vol. I, 1957, pp. 35-39.
10. Gibbs, H. E., "Standard Penetration Test for Sand Denseners," *Proceedings of the Fourth Panamerican Conference on Soil Mechanics and Foundation Engineering*, Vol. II, 1971, pp. 27-36.
11. Hanks, T. C., Jordan, T. H., and Minster, J. B. "Preice Locations of Aftershocks of the San Fernando Earthquake 2300 (GMT) February 10-1700 February 11, 1971," *Contribution No. 1944*, Seismological Laboratory, California Institute of Technology, Division of Geology and Planetary Sciences, Pasadena Calif., 1971.
12. Housner, G. W., "Intensity of Ground Shaking Near the Causative Fault," *Proceedings of the Third World Conference on Earthquake Engineering*, New Zealand, Vol. 1, 1965.
13. Housner, G. W. "Design Spectrum," *Earthquake Engineering*, R. L. Wiegel, ed., Prentice-Hall, Inc., Englwood Cliffs, N.J., 1970:
14. "Interim Report, Soil and Geologic Investigation, San Fernando Earthquake, Joseph Jensen Filtration Plant, Near Sylmar, California," Vols. I and II, Converse, Davis and Associates, Pasadena, Calif., April 30, 1971.
15. Kallberg, K. T., and Cornell, C. A., "Seismic Risk in Southern California," *Report R69-31 of Department of Civil Engineering*, Massachusetts Institute of Technology, Cambridge, Mass., 1969.
16. Lee, K. L., "Behavior of Saturated Sands Under Cyclic Loading Conditions," thesis presented to the University of California, at Berkeley, Calif., in 1965, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
17. Lee, K. L., and Seed, H. B., "Strength of Anisotropically Consolidated Samples of Saturated Sand Under Cyclic Loading Conditions," Report Soil Mechanics and Bituminous Materials, Laboratory, University of California, Berkeley, Calif., 1966.
18. Lee, K. L., and Seed, H. B., "Cyclic Stress Conditions Causing Liquefaction of Sand," *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 93, No. SM1, Proc. Paper 5058, Jan., 1967, pp. 105-134.
19. Marachi, N. D., and Dixon, S. J., "A Method for Evaluation of Seismicity," *Proceedings of the International Conference on Microzonation*, Vol. I, 1972, pp. 279-394.
20. "Preliminary Approximate Maximum Accelerations," *Seismological Field Survey*, March 13, 1971, National Ocean Survey—National Oceanic and Atmospheric Administration, San Fernando, Calif., Earthquake of February 9, 1971.
21. "Results of Dynamic Soil Tests, Joseph Jensen Filtration Plant, West Sylmar, California," Converse, Davis and Associates, Pasadena, Calif., July 16, 1971.
22. Seed, H. B., "Landslides During Earthquakes Due to Soil Liquefaction," *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 94, No. SM5, Proc. Paper 6110, Sept., 1968, pp. 1053-1122.
23. Seed, H. B., "Soil Problems and Soil Behavior," *Earthquake Engineering*, R. L. Wiegel, ed., Prentice-Hall, Inc., Englewood Cliffs, N.J., 1970.
24. Seed, H. B., "Earth Slope Stability During Earthquakes," *Earthquake Engineering*, R. L. Wiegel, ed., Prentice-Hall, Inc., Englewood Cliffs, N.J., 1970.
25. Seed, H. B., and Lee, K. L., "Liquefaction of Saturated Sands During Cyclic Loading," *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 92, No. SM6, Proc. Paper 4972, Nov., 1966, pp. 103-134.
26. Seed, H. B., and Idriss, I. M., "Analysis of Soil Liquefaction: Niigata Earthquake," *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 93, No. SM3, Proc. Paper 5233, May, 1967, pp. 83-108.
27. Seed, H. B., and Idriss, I. M., "Simplified Procedure for Evaluating Soil Liquefaction Potential," *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 97, No. SM9, Proc. Paper 8371, Sept., 1971, pp. 1249-1273.
28. Seed, H. B., and Wilson, S. D., "The Turnagain Heights Landslide, Anchorage, Alaska," *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 93, No. SM4, Proc. Paper 5320, July, 1967, pp. 325-353.
29. "The Effects of Foundation Soils on Seismic Motion," Structural Engineers Association of Southern California, Annual Report of the Soil Structure Interaction, Subcommittee of the Seismology Committee, 1969.



30. "The San Fernando, California Earthquake of February 9, 1971," U.S. Department of the Interior, U.S. Department of Commerce, U.S. Geological Survey and the National Oceanic and Atmospheric Adminstration. *Geological Survey Professional Paper 733*, 1971.