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LIQUEFACTION POTENTIAL OF UNCONSOLIDATED SEDIMENTS IN THE SOUTHERN SAN FRANCISCO BAY REGION, CALIFORNIA

By

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Liquefaction potential of unconsolidated sediments in the southern San Francisco Bay region, California

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Abstract

A preliminary map of liquefaction potential of unconsolidated sediments has been made for the southern part of the San Francisco Bay region. Map zones are established on the basis of recent detailed geologic mapping. Liquefaction potential for each zone is estimated from an analysis of lithologic, water-table and standard penetration test data. Due to empirical aspects of the evaluation method, approximations in establishing parameters and the generalizations of limited test data to entire map zones, the liquefaction potential map must be considered as preliminary and approximate. Nevertheless, the map should serve the intended purpose of generally delineating areas where the probability for liquefaction during a major earthquake is greatest and, hence, areas where special attention should be given to the possibility of liquefaction.

Sediments with the highest potential for liquefaction are clean granular layers within the younger bay sediments. These layers are not

everywhere present but commonly occur locally near present and former stream channels. Clean granular beds and layers immediately beneath the younger bay sediments generally have a lesser but significant potential for liquefaction. Younger (Holocene) alluvial deposits have an even lower potential, however, the potential can be locally high in recent channel and overbank deposits. Part of the Holocene unit is normally above water-table and thus would have only a seasonal potential for liquefaction. Older (Pleistocene) alluvial fan deposits have a generally low liquefaction potential. Lateral spreading landslides are commonly associated with liquefaction beneath gentle slopes. Thus, during a major earthquake, slides of this type would probably be the most pervasive damaging effect of liquefaction on the broad alluvial plain surrounding San Francisco Bay.

Introduction

Liquefaction has produced abundant and sometimes catastrophic ground failures during earthquakes and, hence, must be considered in assessing seismic risk or hazard. Conditions requisite for seismically induced liquefaction—saturated unconsolidated deposits and high seismicity,— are both present and widespread in the San Francisco Bay region. Evaluation of the liquefaction potential of these deposits thus forms an important element in seismic hazard mapping of the area.

This report describes how a preliminary liquefaction potential map of part of the San Francisco Bay region was made and describes types of ground failure commonly associated with liquefaction. Map zones are based on detailed geologic studies of the unconsolidated sediments (Helley and Brabb, 1971; Helley and others, 1972; written communication, K. R. Lajoie).

←—— Liquefaction potential is based on an analysis of maximum horizontal surface accelerations, duration of ground motion, depth of water-table, and depth and relative density (standard penetration resistance) of clean granular sediments. The results were then statistically averaged to estimate the liquefaction potential of each zone.

Liquefaction is defined here as the transformation of a granular material from a solid state into a liquified state as a consequence of increased pore-water pressures (Youd, 1973). This definition distinguishes liquefaction as a transformation process rather than liquified flow or a type of ground failure. Hence, a potential for liquefaction does not necessarily indicate a similar potential for ground failure.

Geology and seismicity of study area

The mapped area, bounded approximately by the Hayward and San Andreas faults on the east and west, respectively, and by the cities of Oakland on the northeast, San Francisco on the northwest, and San Jose on the south, contains the broad alluvial plain surrounding the southern part of San Francisco Bay. This plain is underlain by late Cenozoic sediments, which vary greatly in density and degree of consolidation. The sediments are subdivided into units with generally similar geotechnical properties, in this case, for liquefaction potential mapping. Those sediments whose grain-size distribution (clay-free sands and silts) and degree of lithification (completely uncemented) make them potentially liquefiable, occur within two units, one of which, the older, was deposited during Pleistocene time and the other, the younger, during

Holocene time. These sediments include alluvial, marine, estuarine, eolian, and lacustrine deposits. Environments of deposition during both the Pleistocene and Holocene were similar to those of today except that marine and estuarine conditions were absent during parts of the Pleistocene.

The older deposits are denser and more consolidated and tend to be coarser grained. Because they have been long exposed to weathering processes and changing climatic regimes they commonly contain well-developed soil profiles. Where exposed, the older deposits are expressed geomorphically as slightly dissected alluvial fans and aprons generally lying at higher altitudes near the margins of the plains, where they gradually merge into the surrounding foothills. Because these fans are in the highest part of the plain, ground-water levels are generally deep but may be temporarily high during wet seasons.

The younger alluvial deposits, which are much looser, wetter, and less consolidated than the older fan deposits on which they rest, grade into the modern sediments of San Francisco Bay. The interfingering of alluvial and estuarine (bay) sediments in these younger deposits reflects the post-Wisconsin marine transgression into the San Francisco Bay basin.

The San Francisco Bay region is very active seismically, having been subjected to large historic earthquakes originating nearby on both the San Andreas and Hayward faults. For example, the 1906 earthquake ($\bar{M} \approx 8.2$) was accompanied by a continuous 200-mile (320-km) surface rupture on the San Andreas fault. The 1868 (and possibly the 1836) earthquake on the Hayward fault also produced significant surface ruptures.

Design earthquakes

Sediments are classified by liquefaction potential as follows: (1) Sediments likely to liquefy in the event of a moderate earthquake (M = 6.5) originating nearby on the San Andreas, Hayward, or other local fault are considered to have a high liquefaction potential. (2) Sediments unlikely to liquefy even in the event of a major earthquake (M = 8.0) nearby on the San Andreas fault are considered to have a low liquefaction potential. (3) Sediments in between these two extremes are considered to have a marginal liquefaction potential dependent on earthquake size and duration and sediment properties such as grain-size and degree of sorting. A moderate-sized event would be characterized by approximately 10 significant strong motion cycles (Seed and Idriss, 1971) with maximum horizontal surface accelerations of 0.2 g or greater (Page and others, 1972) over much of the area, and a large event by as many as 30 significant strong motion cycles (Seed and Idriss, 1971) with maximum horizontal surface accelerations of 0.5 g or greater (Page and others, 1972). These parameters are used in the following analyses.

Method of evaluating liquefaction potential

The method used to estimate liquefaction potential is based on the "simplified procedure for evaluating liquefaction potential" which was developed for materials that underlie relatively level surfaces (Seed and Idriss, 1971, p. 1249) and have relative densities less than about 80 percent (ibid., p. 1256). Slopes on the alluvial plain surrounding San Francisco Bay are gentle, so the method can be applied over most of the area. However, because the large design earthquake could produce liquefaction in sediments with relative densities greater than 80 percent, the Seed and Idriss procedure was extended to permit evaluation of liquefaction potential for these extreme conditions.

The simplified procedure is based on two basic relationships. First, the average cyclic shear stress (τ_{av}), developed during a given earthquake at a depth (h), beneath a level surface is estimated from the equation

$$\tau_{av.} = 0.65\ r_d \gamma h (a_{max}/g) \qquad (1)$$

where r_d is an empirically determined stress reduction coefficient, γ is the unit weight of the soil, a_{max} is the maximum horizontal surface acceleration, and g is the acceleration of gravity. (Equation 1 is equation 4 of Seed and Idriss, p. 1256.) Second, the ratio of *in situ* cyclic shear stress (τ) required to produce liquefaction in a given number of cycles (ℓ) on laboratory samples molded at the *in situ* relative density (D_r)[1/] to the effective overburden pressure (σ_o') is related to laboratory cyclical triaxial compression test results as follows:

$$(\tau/\sigma_o')_{\ell D_r} = C_r(\sigma_{dc}/2\sigma_a)_{\ell 50}\ (D_r/50) \qquad D_r < 80 \text{ percent} \qquad (2)$$

where C_r is a correction coefficient applied to triaxial compression

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[1/] Relative density (D_r), in percent, is defined as follows:

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} (100)$$

where e_{max} and e_{min} are void ratios of a given granular material in its loosest and densest states, respectively, and e is the void ratio of the material at the density in question.

test results, σ_{dc} is the cyclic deviator stress producing liquefaction in ℓ cycles on a remolded sample of the *in situ* or similar material at a relative density of 50 percent, and σ_a is the initial effective confining pressure. (Equation 2 is equation 6 of Seed and Idriss, p. 1258.) Empirical curves have been constructed by Seed and Idriss for estimating C_r and $(\sigma_{dc}/2\sigma_a)_{\ell 50}$ from density state and gradational properties of the soil and the number of significant strong motion cycles. Thus, by comparing the average cyclic shear stress (τ_{av}) developed at any given depth (equation 1) with the cyclic shear stress (τ) required to produce liquefaction on the materials at that depth (equation 2), a criterion is established for assessing liquefaction potential.

For the moderate-sized design earthquake the following parameters were used in equations 1 and 2 to estimate limiting relative density values at which liquefaction would likely occur:

$a_{max} = 0.2$ g,

$\ell = 10$ cycles,

$0.8 < r_d < 1.0$,

$0.6 < C_r < 0.7$,

$90 \text{ lb/ft}^3 < \gamma < 110 \text{ lb/ft}^3$,

$0.2 < (\sigma_{dc}/2\sigma_a)_{\ell 50} < 0.3$, and

$0 \text{ ft} < h_w < 10 \text{ ft}$

where h_w is depth to the water-table. Substitution of reasonable combinations of these parameters into the equations shows that most granular soils with relative densities less than 65 percent that are located beneath the free water surface would have a high potential for liquefaction during the estimated moderate earthquake conditions.

To evaluate liquefaction potential for the large design earthquake it was necessary to extend the simplified procedure to relative densities greater than 80 percent. To do this, data presented by Peacock and Seed (1968) were used to evaluate stress conditions causing liquefaction at these higher densities. Average shear stress ratios (τ/σ_o') producing liquefaction in 30 loading cycles (simple shear) on samples with relative densities ranging from 50 to 90 percent (Peacock and Seed, 1968, p. 701) are as follows:

$\tau/\sigma_o' = 0.060$ for $D_r = 50$ percent

$\tau/\sigma_o' = 0.093$ for $D_r = 80$ percent

$\tau/\sigma_o' = 0.152$ for $D_r = 90$ percent

According to Seed and Peacock (1971, p. 1102) these stress ratio values should be increased 35 percent because of subsequent "improvements in sample preparation and cap seating techniques." They also state that the results should be increased by a compounded 15 percent (p. 1102) to agree with results using rough plattens. Even after applying these corrections, Seed and Peacock (1971, p. 1111) further increased the values by an additional factor (which varies with density) to bring the results into agreement with estimated field behavior. These factors (interpolated from data given on p. 1112) are:

22 percent for $D_r = 50$ percent

46 percent for $D_r = 80$ percent

55 percent for $D_r = 90$ percent

Thus, estimated stress ratios required to produce liquefaction in the field during 30 cycles of ground motion are as follows:

$\tau/\sigma_o' = 0.114$ for $D_r = 50$ percent

$\tau/\sigma_o' = 0.211$ for $D_r = 80$ percent

$\tau/\sigma_o' = 0.366$ for $D_r = 90$ percent

These data are plotted on figure 1 and a curve (reconstructed curve) drawn through them. A plot of equation 2 is also drawn on the figure for comparison. Parametric values used in constructing the latter curve include 30 cycles of ground motion, $(\sigma_{dc}/2\sigma_a) = 0.18$, a minimal (worst condition) value, (see Seed and Idriss, 1971, p. 1257), and C_r values taken directly from curves given by Seed and Idriss (1971, p. 1258).

To facilitate the use of the reconstructed curve for evaluating the liquefaction potential of sands at relative densities greater than 80 percent, equation 2 was modified to the following form:

$$(\tau/\sigma_o')_{\ell D_r} \simeq M \qquad D_r > 80 \text{ percent} \qquad (3)$$

where the value of M is taken directly from the reconstructed curve. Next, τ in equation 3 was equated with τ_{av} in equation 1 to solve for limiting M-values at which liquefaction could occur:

$$M \simeq 0.65\, r_d(\gamma h/\sigma_o')(a_{max}/g) \qquad (4)$$

For the large design earthquake the following parametric values were used: $a_{max} = 0.5$ g, $\ell = 30$ cycles and other values as given for the moderate-sized design earthquake. Substitution of reasonable combinations of these parameters into equation 4 yields limiting M-values between 0.3 and 1.0. This corresponds to relative densities ranging from 87 to 92 percent. (The range is narrow because of the steep slope of the reconstructed curve, figure 1.) Thus, a limiting density of 90 percent was selected as the maximum at which liquefaction might be expected to occur during a large earthquake in the San Francisco Bay region.

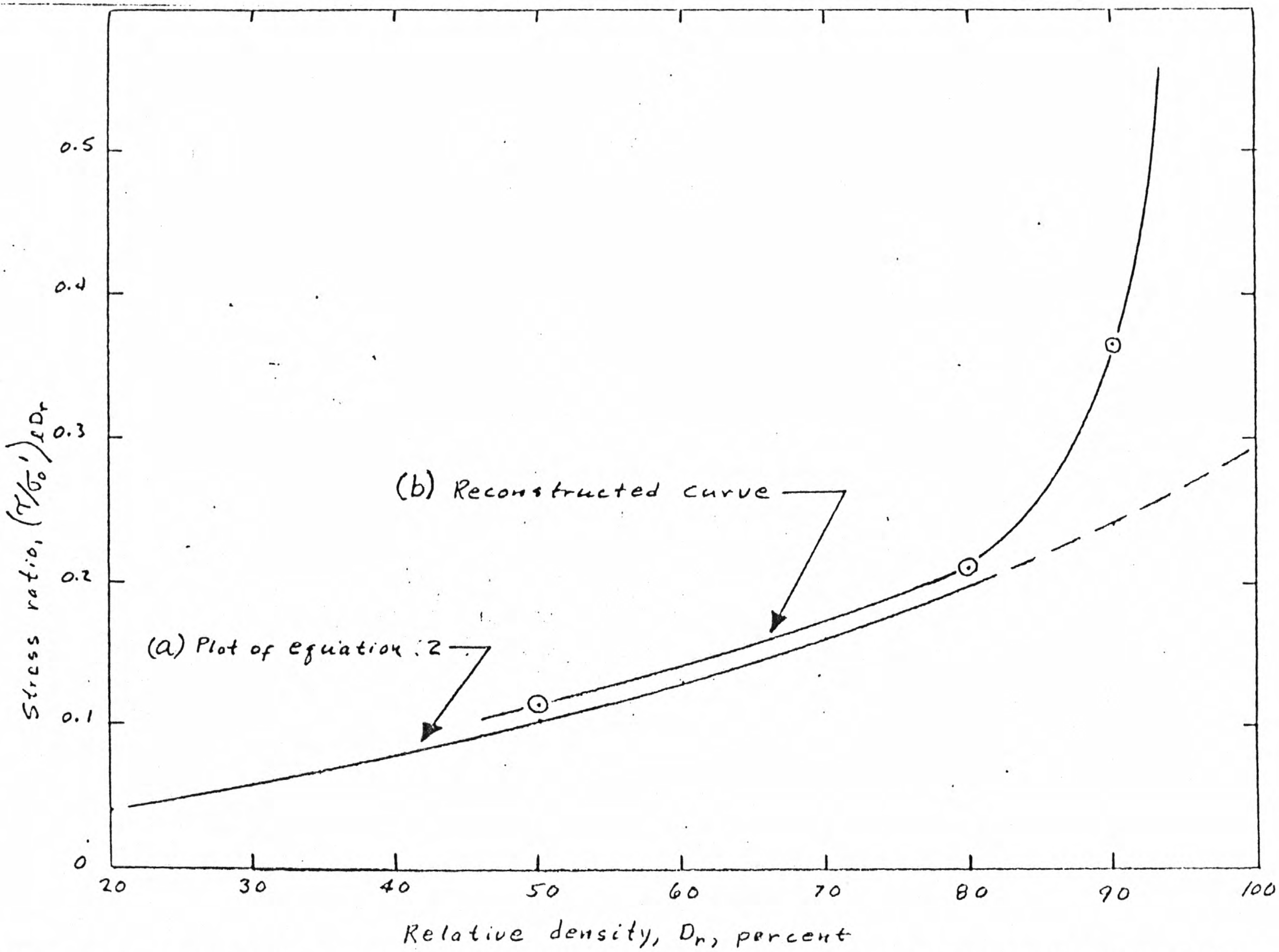


Figure 1. -- Stress ratio estimated to produce liquefaction in 30 cycles of seismic loading under field conditions. (a) Plot of equation 2 (equation 6 of Seed and Idriss, 1971). (b) Reconstructed curve plotted from data given in Seed and Peacock (1971).

The liquefaction potential criteria can now be summarized as follows: Saturated, clay-free granular sediments with relative densities less than 65 percent are considered to have high liquefaction potential, even in a moderate earthquake. Clay-free granular sediments with relative densities greater than 90 percent are considered to have low liquefaction potential, even in a major earthquake. Saturated, clay-free granular sediments with relative densities between 65 and 90 percent have marginal liquefaction potential that depends on intensity and duration of ground shaking and textural properties of the sediments.

To facilitate application of the liquefaction criteria to field observations, relative densities were estimated from standard penetration test blow count data using relationships developed by Gibbs and Holtz (1957). This procedure was also used by Seed and Idriss (1971). Standard penetration versus depth curves taken from the Gibbs and Holtz relationships are plotted on figure 2 for relative densities of 65 and 90 percent. Assumed parameters used in constructing these curves include a water-table depth of 10 ft (3.3 m) at the time of drilling and a dry unit weight of 100 lb/ft^3 (dry density = 1.6 g/cm^3).

Mapping of liquefaction potential

Boring logs from throughout the study area were collected from numerous private consultants and governmental agencies. Standard penetration data from clay-free granular deposits within 50 feet of the surface were compiled and statistically analyzed in each of the following generalized map zones shown on figure 3. These zones were derived from the geologic map of unconsolidated sediments (Helley and Brabb, 1971; Helley and others, 1972; written [redacted] commun., Lajoie). Zone 1 is underlain

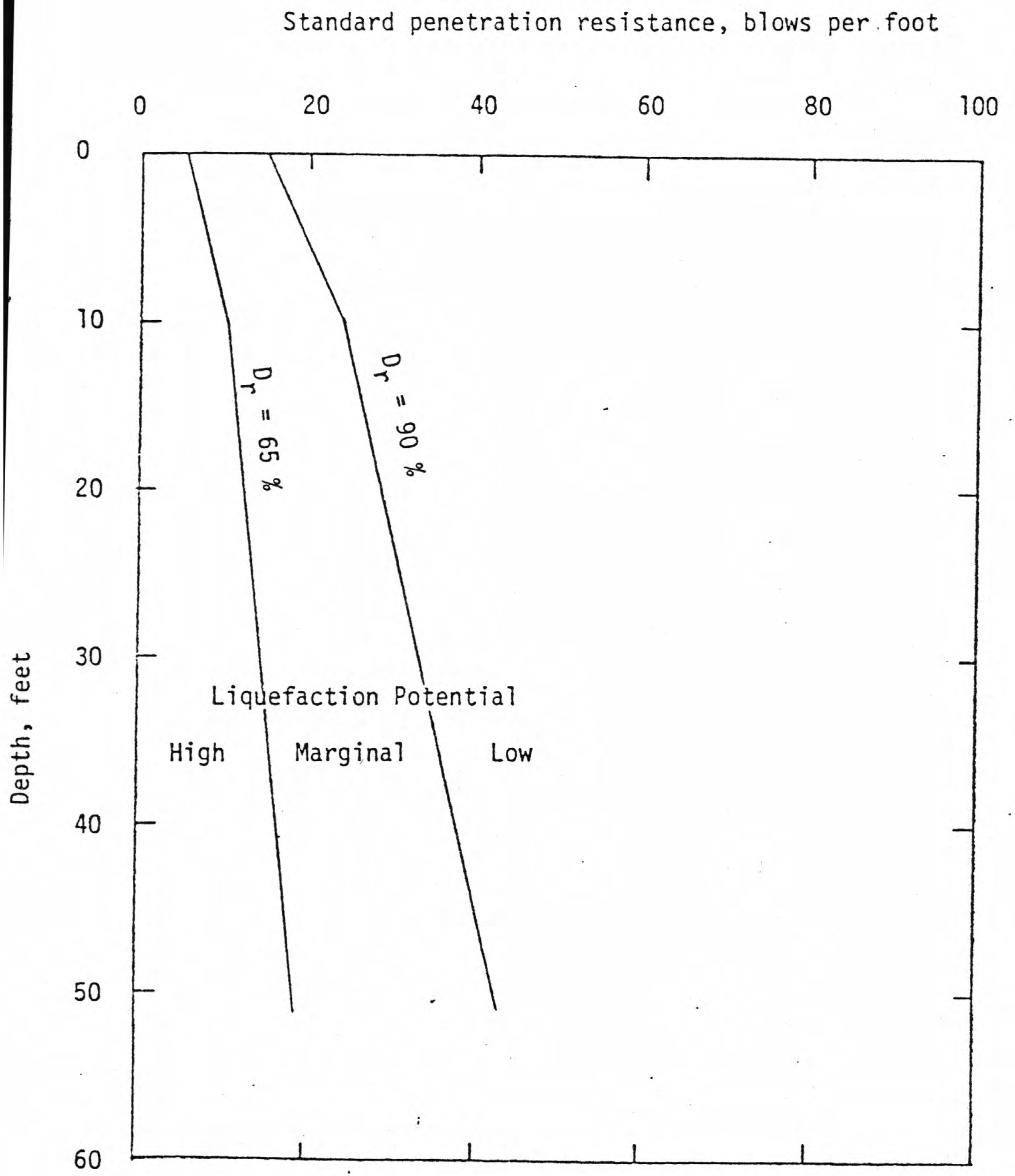
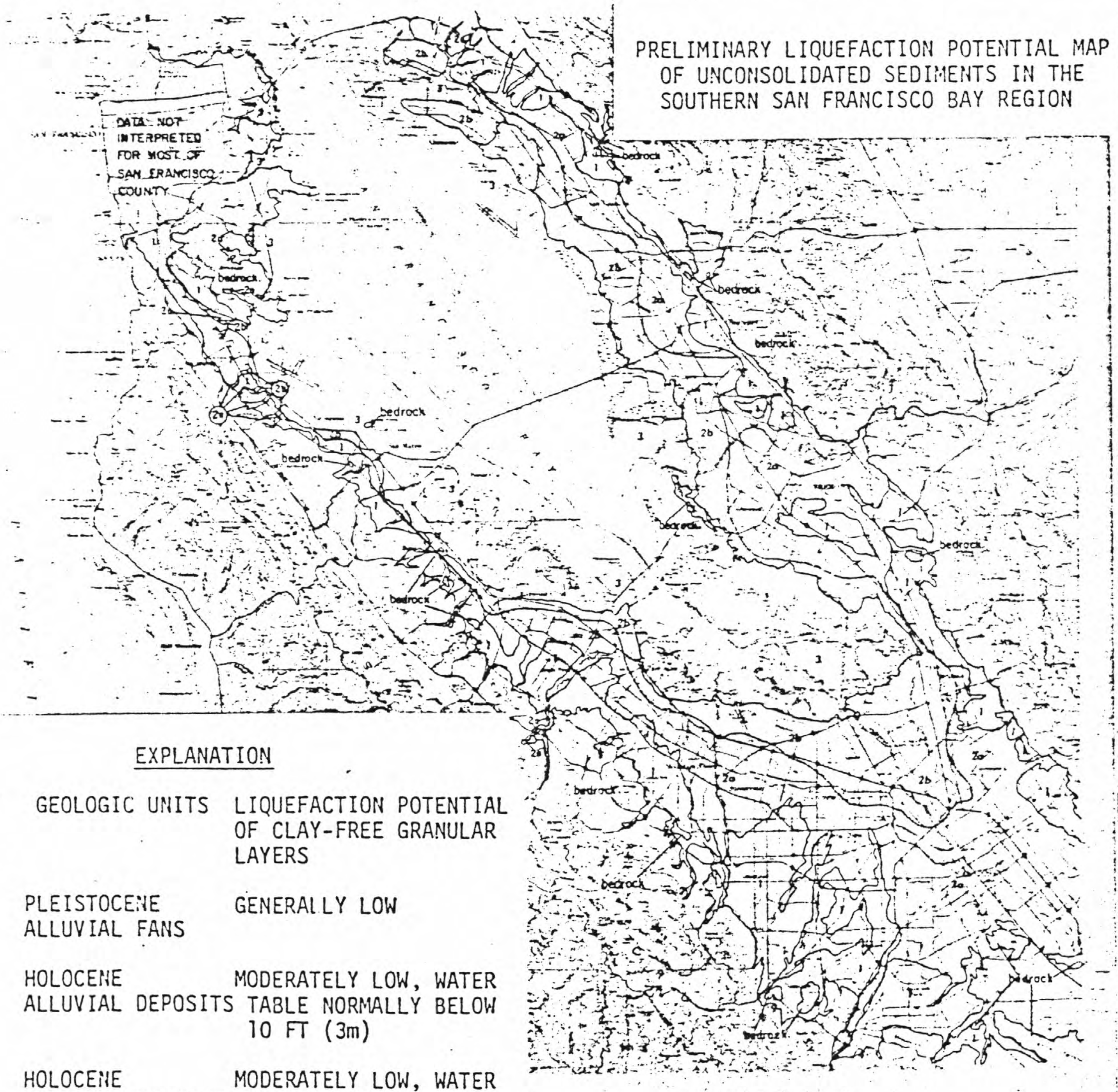


Figure 2. -- Criteria used for estimating liquefaction potential in the field based on a correlation between standard penetration resistance and relative density developed by Gibbs and Holtz (1957). Curves assume a 10 ft (3 m) water-table depth at time exploratory borings were made from which penetration data were extracted.

PRELIMINARY LIQUEFACTION POTENTIAL MAP OF UNCONSOLIDATED SEDIMENTS IN THE SOUTHERN SAN FRANCISCO BAY REGION



EXPLANATION

GEOLOGIC UNITS	LIQUEFACTION POTENTIAL OF CLAY-FREE GRANULAR LAYERS
PLEISTOCENE ALLUVIAL FANS	GENERALLY LOW
HOLOCENE ALLUVIAL DEPOSITS	MODERATELY LOW, WATER TABLE NORMALLY BELOW 10 FT (3m)
HOLOCENE ALLUVIAL DEPOSITS	MODERATELY LOW, WATER TABLE NORMALLY ABOVE 10 FT (3m)
SAN FRANCISCO BAY SEDIMENTS	GENERALLY MODERATE, LOCALLY HIGH WHERE CLEAN GRANULAR LAYERS LIE WITHIN YOUNG BAY SEDIMENTS

to a considerable depth by overconsolidated older alluvial fan deposits of late Pleistocene age (10-120 thousand years old). The subsurface deposits in zone 2 are Holocene alluvium (less than 10 thousand years old) underlain by Pleistocene alluvium. This zone is subdivided on the basis of water-table depth. Areas in which the water table is normally 10 ft (3 m) deep or greater are labeled 2a. Areas with a shallower water-table are labeled 2b. The Holocene alluvium is generally less than 10 ft (3 m) thick in subzone 2a, and thus is normally above the water-table. Therefore the Holocene sediments in this zone are at most only seasonally susceptible to liquefaction. In subzone 2b, the Holocene alluvium is generally more than 10 ft (3 m) thick and thus extends below the normal water-table. It, therefore, has a continual potential for liquefaction. Zone 3 is underlain by young bay sediments (7,000 years and younger) overlying Holocene and Pleistocene alluvium. Clean granular layers are not generally found in the young bay sediments except along present and former stream channels, where such layers locally interfinger with fine-grained estuarine sediments. Throughout zone 3 clean granular layers are rather common beneath the younger bay sediments.

Table I summarizes the percentage of standard penetration test data points for each zone plotting in each liquefaction potential segment of figure 2. The data show that granular layers within the younger bay sediments have a generally high potential for liquefaction. Seventy-three percent of the penetration data from these layers indicate high potential for liquefaction, and an additional 21 percent indicate marginal potential. Only 6 percent of the penetration data indicate low potential.

Table I

Summary of liquefaction potential analysis using standard penetration data and criteria developed on Fig. 2. Two probable local earthquakes are considered; (a) a moderate event ($M \simeq 6.5$) and (b) a large event ($M \simeq 8.0$). Sediments likely to liquefy during a moderate event are classified as having high liquefaction potential; those unlikely to liquefy during a large event are classified as having low liquefaction potential; and those intermediate between these two categories are classified as having marginal liquefaction potential.

		Standard Penetration Test Data			
		Percent Indicating			Number of Tests
Zone	Sedimentary Unit	$D_r < 65\%$ (high liquefaction potential)	$65\% < D_r < 90\%$ (marginal liquefaction potential)	$D_r > 90\%$ (low liquefaction potential)	
1	Older (Pleistocene) alluvial deposits	11	29	60	357
2	Younger (Holocene) alluvial deposits	22	33	45	708
3	Deposits underlying young bay sediments	33	28	39	155
3	Deposits within young bay sediments	73	21	6	53

The granular layers beneath the younger bay sediments show a much lesser but significant potential for liquefaction. Thirty-three percent of the data from these layers indicate high potential for liquefaction, and an additional 28 percent suggest marginal potential. Virtually all the younger bay sediments and underlying deposits lie below the ground water table and thus there is a continuing threat of liquefaction in susceptible segments of these sediments.

Granular sediments within the Holocene alluvium in Zone 2 show on the average less potential for liquefaction than those within or beneath the younger bay sediments, both because of their greater density and the greater depth of the water-table. For example, 22 percent of the penetration values for these sediments indicate high potential for liquefaction, and an additional 33 percent indicate marginal liquefaction potential. Also the Holocene sediments of subzone 2a would be, at most, seasonally or intermittently liquefiable because they are normally above the water-table. It was also noted, though not specifically shown in figure 3 or table I, that the relatively recent channel and overbank deposits along present drainageways are generally characterized by lower penetration resistance and thus have a higher potential for liquefaction than deposits in the adjacent alluvial plains.

Liquefaction potential in the older (Pleistocene) alluvial fan deposits (zone 1) is generally low. Only 11 percent of the penetration values from clay-free layers in these deposits indicate a high potential for liqueaction, whereas 60 percent indicate a very low potential. Liquefaction potential in this zone is further diminished by a generally deep water-table owing to its relatively high topographic position.

Ground failures associated with liquefaction

Three types of ground failure are commonly associated with liquefaction (Seed, 1968; Youd, 1973): (1) Flow landslides. -- These failures generally occur on moderate to steeply sloping terrain underlain by loose granular deposits. In this case, once liquefaction has occurred, flow deformation commences and continues unabated until the driving shear forces are reduced (as by slope reduction) to a value less than the viscous shear resistance of the liquefied soil. When that state is reached, the material stops flowing and solidifies, usually far from the point of origin. Loose granular deposits on moderate to steeply sloping hillsides in the San Francisco Bay region could be susceptible to this type of failure provided they are or become saturated. Such failures occurred on San Bruno Mountain near Colma and near Half Moon Bay during the 1906 San Francisco earthquake (Crandall, *in* Lawson, 1908, p. 249: Anderson, *in* Lawson, 1908, p. 395). Because of the generally minute slopes, it is unlikely that this type of failure would occur on the broad alluvial plain sourrounding San Francisco Bay.

(2) Lateral-spreading landslides. -- These failures occur most commonly on gentle to nearly horizontal slopes underlain by loose to moderately dense granular deposits or layers. In this type of failure, liquefaction occurs and flow commences; however, after a finite displacement, flow is arrested by a pore-water pressure drop resulting from the tendency for all but very loose granular sediments to dilate during shear. Continued shaking may cause reliquefaction (providing the shaking causes shear stress reversals (Seed and Lee, 1969; Youd, 1973)), and a second episode of flow displacement may occur followed by

by restabilization. This sequence may continue as long as strong seismic shaking continues. Displacements ranging from essentially zero to several tens of feet have been produced by these kinds of failures, which are generally of the lateral-spreading landslide type (Varnes, 1958; Youd, 1973). Factors which contribute to greater displacement include greater duration of shaking, loose sediments, and optimal slope conditions. (Slopes too flat inhibit movement and slopes too steep inhibit shear stress reversals necessary for the generation of repeated episodes of liquefaction (Youd, 1973).) Cracks, fissures and differential settlement are common on, and especially at the margins of lateral-spreading failures. Although these features and accompanying slide movements may appear rather inconsequential in open terrain, they have proven to be very damaging and disruptive to structures and utilities constructed across, on, or within the slide mass.

Lateral-spreading landslides would likely be the most pervasive type of ground failure associated with liquefaction on the broad alluvial plain surrounding San Francisco Bay. Bay sediments containing granular layers, expecially the younger bay sediments, and recent channel and overbank deposits in the Holocene alluvium would likely be the material most susceptible to this type of failure because of their greater potential for liquefaction and generally loose state. The latter would permit greater slide movement following liquefaction. Least susceptible to this type of failure would be the older (Pleistocene) sediments (zone 1) becuase of their low potential for liquefaction and generally dense state, which in turn would prevent significant displacements from occurring even if liquefaction should develop.

Evidence of lateral-spreading landslides was reported at several locations within the study area during the 1906 San Francisco earthquake. These locations are consistent with the units defined above. For example, lateral ground movements, some as large as 6 ft (2 m), occurred over several arms of bay sediments (zone 3) extending beneath the city of San Francisco (Wood, *in* Lawson, 1908, p. 220-245). In addition, specific mention was also made of the lateral displacement of flood-plain deposits toward the depressions of Alameda and Coyote Creeks (Lawson, 1908, p. 400). Many more lateral-spreading landslides may have been generated in 1906 but not reported because of their generally unspectacular character (unless they disrupted constructed works) and gaps in the investigation of earthquake effects in many undeveloped areas, particularly those near the bay.

(3) Quick-condition failures. -- Historically, these failures have occurred most commonly in flat areas with high water tables and loose to moderately dense granular sediments extending from the surface to substantial depths. In this case liquefaction leads to a quick condition and often to the loss of bearing capacity with the result that structures, embankments, or other loads founded on the surface may sink and rotate into the liquefied sediments. In other instances buried tanks or other structures may buoyantly rise. Other than subsidence of several roadway fills in San Francisco, which may or may not have been due to liquefaction, the authors have found no reports that this type of failure occurred in the study area during the 1906 San Francisco earthquake.

Summary

A preliminary map of liquefaction potential of unconsolidated sediments has been made for the southern part of the San Francisco Bay region. Map zones are established on the basis of recent detailed geologic mapping of the unconsolidated deposits. Liquefaction potential estimates for each zone are based on an analysis of estimated intensity and duration of earthquake ground motions and lithologic, water-table, and standard penetration test data extracted from boring logs.

Areas underlain by young bay sediments containing clean granular layers have high potential for liquefaction. Clean granular layers underlying the young bay sediments have significant but lesser potential. Clean granular sediments within the Holocene alluvium have even lower potential; furthermore, a major part of this unit is normally above water-table and thus, at most, only seasonally or intermittently susceptible to liquefaction. Channel and recent overbank deposits in the Holocene alluvium are generally characterized by a greater liquefaction potential than adjacent deposits in the alluvial plain. Because of their relatively high density and generally deep water-table, clean granular layers in the older (Pleistocene) alluvial fan deposits have low potential for liquefaction.

Zones delineated in this study as having significant liquefaction potential only indicate areas in which the liquefaction process may occur in clean granular layers and give no indication of type or amount of ground failure movement, if any, that might follow liquefaction. However, lateral-spreading landslides are a common consequence of liquefaction beneath gentle slopes. Hence, in the event of a major earthquake this type of failure is likely to be the most common consequence of liquefaction beneath the alluvial plain surrounding San Francisco Bay.

The criteria used for evaluating liquefaction potential are based on empirical procedures formulated by Seed and Idriss (1971) and approximate estimates of ground-motion parameters and geotechnical properties. In addition, the estimated potential of each zone is based on somewhat limited data generalized to cover the entire map unit. Thus, the liquefaction potential map must be considered preliminary and approximate and not valid for direct determination of liquefaction potential at any specific site. However, despite its limitations, the map should serve the intended purpose of generally delineating areas where the probability for liquefaction during a major earthquake is greatest, and hence, areas where special attention should be given to the possibility of liquefaction.

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