RECOMMENDED PROCEDURES FOR IMPLEMENTAION OF

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GUIDELINES FOR ANALYZING AND MITIGATING LIQUEFACTION IN CALIFORNIA

SECTION 5.0 FIELD INVESTIGATIONS

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Field (or geotechnical) investigations are routinely performed for new projects as part of the normal development and design process. Geologic reconnaissance and subsurface explorations are normally performed as part of the field exploration program even when liquefaction does not need to be investigated.

5.1 Geologic Reconnaissance

Geologic research and reconnaissance are important to provide information to define the extent of unconsolidated deposits that may be prone to liquefaction. Such information should be presented on geologic maps and cross sections and provide a description of the formations present at the site that includes the nature, thickness, and origin of Quaternary deposits with liquefaction potential. There also should be an analysis of groundwater conditions at the site that includes the highest recorded water level and the highest water level likely to occur under the most adverse foreseeable conditions in the future.

During the field investigation, the engineering geologist should map the limits of unconsolidated deposits with liquefaction potential. Liquefaction typically occurs in cohesionless silt, sand, and fine-grained gravel deposits of Holocene to late Pleistocene age in areas where the groundwater is shallower than about 50 feet. Common geologic settings include unlithified sediments in coastal regions, bays, estuaries, river floodplains and basins, areas surrounding lakes and reservoirs, and wind-deposited dunes and loess. In many coastal regions, liquefiable sediments occupy back-filled river channels that were excavated during Pleistocene low stands of sea level, particularly during the most recent glacial stage. Among the most easily liquefiable deposits are beach sand, dune sand, and clean alluvium that were deposited following the rise in sea level at the start of the Holocene age, about 11,000 years ago.

Shallow groundwater may exist for a variety of reasons, some of which are of natural and or man-made origin. Groundwater may be shallow because the ground surface is only slightly above the elevation of the ocean, a nearby lake or reservoir, or the sill of a basin. Another concern is man-made lakes and reservoirs that may create a shallow groundwater table in young sediments that were previously unsaturated.

5.2 Subsurface Explorations

Subsurface explorations are routinely performed using borings, with cone penetration tests (CPTS) becoming more commonplace. The scope of the field exploration program will depend on the type of development or building planned. It might be expected that a high-rise building may require an array of closely spaced exploratory borings (and CPTS, whereas a large housing tract will have an array of exploratory borings or pits (or CPTS) that may be less closely spaced.

There are various methods for evaluation of liquefaction potential. The most popular and common methods relate in situ soil indices, such as the standard penetration test (SPT) or the cone penetration test, to observed liquefaction occurrence or non-occurrence during major earthquakes. These indices can generally be routinely and economically obtained. In the case of silts or sandy silts, liquefaction evaluation may require the cyclic testing of soil samples, which can be obtained by high quality sampling techniques during the field exploration program.

The normal field exploration program may need to be expanded to evaluate the potential for liquefaction. Additional and/or deeper SPT-borings and CPTs may be warranted, or the field exploration program may be augmented with other forms of exploration. The exploration program should be planned to determine the soil stratigraphy, groundwater level, and indices that could be used to evaluate the potential for liquefaction by either in situ testing or by laboratory testing of soil samples. Good engineering judgment will need to be exercised in determining the exploration program needed to obtain adequate and sufficient geotechnical information to evaluate the potential for liquefaction. An inadequate exploration program could lead to either overly conservative or unconservative conclusions and actions.

5.3 Depth of Analysis for Liquefaction Evaluation

Traditionally, a depth of 50 feet (about 15 m) has been used as the depth of analysis for the evaluation of liquefaction. The Seed and ldriss EERI Monograph on "Ground Motions and Soil Liquefaction During Earthquakes" (1982) does not recommend a minimum depth for evaluation, but notes 40 feet (12 m) as a depth to which some of the numerical quantities in the "simplified procedure" can be estimated reasonably. Liquefaction has been known to occur during earthquakes at deeper depths than 50 feet (15 m) given the proper conditions such as low-density granular soils, presence of ground water, and sufficient cycles of earthquake ground motion.

Experience has shown that the 50-foot (15 m) depth may be adequate for the evaluation of liquefaction potential in most cases, however, there may be situations where this depth may note sufficiently deep.

It is recommended that a minimum depth of 50 feet (15 m) below the existing ground surface or lowest proposed finished grade (whichever is lower) be investigated for liquefaction potential. Where a structure may have subterranean construction or deep foundations (e.g., caissons or piles), the depth of investigation should extend to a depth that is a minimum of 20 feet (6 m) below the lowest expected foundation level (e.g., caisson bottom or pile tip) or 50 feet (15 m) below the existing ground surface or lowest proposed finished grade, whichever is deeper.

If, during the investigation, the indices to evaluate liquefaction indicate that the liquefaction potential may extend below that depth, the exploration should be continued until a significant thickness (at least 10 feet or 3 m, to the extent possible) of nonliquefiable soils are encountered.

5.4 Liquefaction Assessment by Use of the Standard Penetration Test (SPT)

One of the most widely used semi-empirical procedures for estimation of liquefaction potential utilizes Standard Penetration Test (SPT) N-values to estimate a soil's liquefaction resistance.

5.4.1 Introduction

Primarily because of their inherent variability, sensitivity to test procedure, and uncertainty, SPT N-values have the potential to provide misleading assessments of liquefaction hazard, if the tests are not performed carefully. The engineer who wants to utilize the results of SPT N-values to estimate liquefaction potential should become familiar with the details of SPT sampling as given in ASTM D 1586 (ASTM, 1998) in order to avoid, or at least reduce, some of the major sources of error.

The semi-empirical procedures that relate SPT N-values to liquefaction resistance use an SPT blow count that is normalized to an effective overburden pressure of 100 KPa (or 1.044 ton per square foot). This normalized SPT blow count is denoted as N_1, which is obtained by multiplying the uncorrected SPT blow count by a depth correction factor, C_N. A correction factor may be needed to correct the blow count for an energy ratio of 60%, which has been adopted as the average SPT energy for North American geotechnical practice. Additional correction factors may need to be applied to obtain the corrected normalized SPT N-value, $(N_1,)_{60}$,- It has been suggested that the corrections should be applied according to the following formula:

$(N_1,)_{60} = N_m\ C_N\ C_E{:}\ C_B\ C_R C_S$

Where N_m = measured standard penetration resistance
C_N = depth correction factor
C_E = hammer energy ratio (ER) correction factor
C_B = borehole diameter correction factor
|C_R = rod length correction factor
C_S = correction factor for samplers with or without liners

A useful reference, which discusses energy delivery and the SPT, is Seed et al. (1985). A summary of the recommended procedure for performing the SPT is given in Table 5.1. The following sections describe some of the general procedures for the SPT and also discuss some of the recommended correction factors.

The SPT tests should be performed to investigate the liquefaction potential of the soils to the minimum depths recommended in the previous section. However, if the SPT tests indicate that there is a potential for liquefaction to extend below the minimum depth, SPT tests should be continued until a significant thickness of nonliquefiable soils are encountered. This thickness is recommended to be at least I 0 feet or meters.

5.4.2 Drilling Method

The borehole should be made by mud rotary techniques using a side or upward discharge bit. Hollow-stem-auger techniques generally are not recommended, because unless extreme care is taken, disturbance and heave in the hole is common. However, if a plug is used during drilling to keep the soils from heaving into the augers and drilling fluid is kept in the hole when below the water table (particularly when extracting the sampler and rods), hollow-stern techniques may be used. If water is used as the fluid in a hollow-stem hole, and it becomes difficult to keep the fluid the hole or to keep the hole stable, it may be necessary to use a drilling fluid (consisting -of mud or polymers).

With either technique, there is a need for care when cleaning out the bottom of the borehole to avoid disturbance. Prior to extracting the drill string or auger plug for each SPT test, the driller should note the depth of the drill hole and upon lowering of the sampler to the bottom of the hole, the depth should be carefully checked to confirm that no caving of the walls or heaving of the bottom of the hole has occurred.

5.4.3 Hole Diameter

Preferably, the borehole should not exceed 115 mm (4.5 inches) in diameter, because the associated stress relief can reduce the measured N-value in some sands. However, if larger diameter holes are used, the factors listed in Table 5.2 can be used to adjust the N-values for them. When drilling with hollow-stem augers, the inside diameter of the augers is used for the borehole diameter in order to determine the correction factors provided in Table 5.2.

5.4.4 Drive-Rod Length

The energy delivered to the SPT can be very low for an SPT performed above a depth of about 10 m (30 ft) due to rapid reflection of the compression wave in the rod. The energy reaching the sampler can also become reduced for an SPT below a depth of about 30 m (100 ft) due to energy, losses and the large mass of the drill rods. Correction factors for those conditions are listed in Table 5.2.

5.4.5 Sampler Type

If the SPT sampler has been designed to hold a liner, it is important to ensure that a liner is installed, because a correction of up to about 20% may apply if a liner is not used.

In some cases, it may be necessary to alternate samplers in a boring between the SPT sampler and a larger-diameter ring/liner sampler (such as the California sampler). The ring/liner samples are normally obtained to provide materials for normal geotechnical testing (e.g., shear, consolidation, etc.) If so, the N-values for samples collected using the California sampler can be roughly correlated to SPT N-values using a conversion factor that may vary from about 0.5 to 0.7. In a recent study at the Port of Los Angeles, Pier 400 Landfill, Zueger and McNeilan (1998) estimated an average conversion factor of about 0.63 (1 ¸ 1.6). Because significant uncertainty is associated with such conversions, equivalent SPT N-values obtained in that manner should be used primarily for comparison with the intervening SPT results, and not as the primary source of blow-count data for a liquefaction assessment.

Although the use of a plastic sample catcher may have a slight influence on the SPT N-values, that influence is thought to be insignificant and is commonly neglected.

5.4.6 Energy Delivery

One of the single most important factors affecting SPT results is the energy delivered to the SPT sampler (Table 5.3). This is normally expressed in terms of the rod energy ratio (ER). An energy ratio of 60% has generally been accepted as the reference value. The value of ER (%) delivered by a particular SPT setup depends primarily on the type of hammer/anvil system and, the method of hammer release. Values of the correction factor used to modify the SPT results to 60% energy (ER/60) can vary from O.3 to 1.6, corresponding to field values of ER of 20% to 100%. Table 5.2 provides some guidance for the selection of energy correction factors; Seed et al. (1985) provide specific recommendations for energy correction factors.

Down-hole hammers, raised and lowered using a cable wire-line, should not be used unless adequately designed and documented correlation studies have -been performed with the specific equipment being used. Even then, the use of such equipment typically results in highly variable results, thereby making their results questionable.

5.4.7 Spatial Frequency of Tests

SPT tests should be performed at intervals that are consistent with the geotechnical needs of the project. At a minimum, for liquefaction analyses, SPT tests should be performed at vertical intervals of no more than 5 feet or at significant stratigraphic changes, whichever results in more tests. The horizontal spacing between borings will depend on the project needs.

5.4.8 SPT Testing in Gravel Deposits

SPT tests are difficult, at best, to perform in gravel deposits. Because of the coarse size of the particles, as compared to the size of the sampler, those deposits have the potential to provide misleadingly high N-values. However, if a site has only a few gravel layers or if the gravel is not particularly abundant or large, it may be possible to perform SPT tests if "incremental" blow-counts are measured.

To perform "incremental" blow-count measurements, the number of blow-counts is noted for each one-inch of penetration instead of recording the number of blows for a whole 6-inchinterval. In that manner, it may be possible to distinguish between N-values obtained in the matrix material and those affected by large gravel particles. If so, the N-value can be estimated by summing and extrapolating the number of blows for the representative one-inch penetrations that appear to be uninfluenced by coarse gravel particles. The gravel testing procedure is described in Vallee and Skryness (1980).

Andrus and Youd (1987) describe an alternative procedure to determine N-values in gravel deposits. They suggest that the penetration per blow be determined and the cumulative penetration versus blow count be plotted. With this procedure, changes in slope can be identified when gravel particles interfere with the penetration. From the slope of the cumulative penetration, estimates of the penetration resistance can be made where the gravel particles did or did not influence the N-value penetration resistances.

An alternative in gravel deposits is to obtain Becker Hammer blow counts, which have been correlated to the standard penetration test blow count. Another alternative would be to measure the shear wave velocities of the gravel deposits to determine the liquefaction potential.

Table 5. 1. Recommended SPT Procedure

Borehole size	66 mm < Diameter < 1 15 mm
Borehole support	Casing for full length and/or drilling mud
Drilling	Wash boring; side discharge bit Rotary boring; side or upward discharge bit Clean bottom of borehole*
Drill rods	A or AW for depths of less than 15 m N or NW for greater depths
Sampler	Standard 51 mm O.D. +/- 1 mm 35 mm I.D. +/- 1 mm >457 mm length
Penetration Resistance	Record number of blows for each 150 mm; N = number of blows from 150 to 450 mm penetration
Blow count Rate	30 to 40 blows per minute*

*Maximum soil heave within casing <70 mm

Table 5.2. Corrections to Field SPT N-Values (modified from, Youd and ldriss, 1997)

Factor	Equipment Variable	Term	Correction
Overburden Pressure		C_N	$(P_a/s\ '_{vo})^{05\ ;}$ $0.4£\ C_N\ £\ 2$ *
Energy Ratio	Safety Hammer Donut Hammer Automatic Trip Hammer	C_E	0.60 to 1. 1 7 0.45 to 1.00 0.9 to 1.6
Borehole Diameter	65 mm to 115mm 150 mm 200 mm	C_B	1.0 1.05 1.15
Rod Length**	3 m to 4 m 4 m to 6m 6 m to 10 m 10 m to 30 m >30 m	C_R	0.75 0.85 0.95 10 <1.0
Sampling Method	Standard Sampler Sampler without liners	C_S	1.0 1.2

*The Implementation Committee recommends using a minimum of 0.4.
** Actual total rod length, not depth below ground surface

Table 5.3. Factors affecting the SPT (After Kulhawy and Mayne, 1990)

Cause	Effects	Influence on SPT N-value
Inadequate cleaning of hole	SPT is not made in original in- situ soil. Therefore, spoils may become trapped in sampler and be compressed as sampler is driven, reducing recovery	Increases
Failure to maintain adequate head of water in borehole	Bottom of borehole may become "quick" and soil may sluice into the hole	Decreases
Careless measure of hammer drop	Hammer energy varies (generally variations cluster on low side)	Increases
Hammer weight inaccurate	Hammer energy varies (driller supplies weight; variations of about 5 to 7 percent are common)	Increases or Decreases
Hammer strikes drill rod collar eccentrically	Hammer energy reduced	Increases
Lack of hammer free fall because of ungreased sheaves, new stiff rope on weight, more than two turns on cathead, incomplete release of rope each drop	Hammer energy reduced	Increases
Sampler driven above bottom of casing	Sampler driven in disturbed, artificially densified soil	Increases greatly
Careless blow count	Inaccurate results	Increases or decreases
Use of non-standard sampler	Corrections with standard sampler not valid	Increases or decreases
Coarse gravel or cobbles in soil	Sampler becomes clogged or impeded	Increases
Use of bent	Inhibited transfer of energy of sampler	Increases

5.5 Liquefaction Assessment by Use of the Cone Penetration Test (CPT)

This section presents suggested minimum requirements for Cone Penetration Test or CPT-based liquefaction evaluation.

The primary advantages of the CPT method are:

1. The method provides an almost continuous penetration resistance profile that can be used for stratigraphic interpretation.

2. The repeatability of the test is very good.

3. The test is fast and economical compared to drilling and laboratory testing of soil samples.

The limitations of the method are:

1. The method does not routinely provide soil samples for laboratory tests.

2. The method provides approximate interpreted soil behavior types and not the actual soil types according to ASTM Test Methods D 2488 (Visual Classification) or D 2487 (USCS Classification) [ASTM 1998].

3. The test cannot be performed in gravelly soils and sometimes the presence of hard/dense crusts or layers at shallow depths makes penetration to desired depths difficult.

The CPT method should be performed in general accordance with ASTM D 3441 (ASTM, 1998).

The recent proceedings from the January 1996 NCEER workshop (Youd and ldriss, 1997) on the evaluation of liquefaction resistance of soils represent the most up-to-date consensus among some of the foremost experts in the liquefaction field. That document will likely set the standard of practice for liquefaction potential evaluation for the next several years.

Historically, CPT-based liquefaction evaluations typically use a CPT-SPT correlation to estimate the SPT blow count values from CPT data. This method of liquefaction evaluation is, also considered acceptable according to the NCEER report (Youd and ldriss, 1997). However, direct use of CPT may have supplanted these procedures.

The NCEER report identifies the CPT as a prime candidate for reconnaissance exploration and indicates that the CPT can be used to develop preliminary soil and liquefaction resistance profiles for site investigations. These preliminary profiles should always be checked by the use of selected boring samples retrieved during site investigations. The CPT-based liquefaction potential evaluation method outlined in the NCEER document calls for sampling and testing of soils that are characterized as clayey soils (the Soil Behavior Type Index $I_c > 2.4$) and/or sensitive soils (the Soil Behavior Type Index $I_c > 2.6$ and normalized friction ratio < 1%). However, at the present time, there is no strong consensus regarding the exact values of the parameter I_c, to discriminate between liquefiable and nonliquefiable materials. The parameter I_c has great promise, but will need further study and verification to gain wider acceptance.

In practice, site investigations are seldom performed solely for the purpose of evaluating liquefaction potential. Soil samples (and therefore, soil borings), both disturbed and "relatively undisturbed," are usually needed to perform laboratory tests for typical geotechnical studies. Therefore, typically CPT alone will not be sufficient to provide the geotechnical consultant with all the information needed to prepare a complete geotechnical report.

The following suggestions on the use of CPT soundings for liquefaction study are made:

- CPT soundings should be extended to the minimum depth needed for proper evaluation of liquefaction potential. (i.e., the same minimum depth recommendations used for the SPT evaluation should be met)
- The minimum recommended depth of investigation is 50 feet (15 m). When a structure may have subterranean construction or deep foundations, the depth should extend to a minimum of 20 feet (6 m) below the lowest expected foundation level (bottom of caisson or pile) or 50 feet (15 m) below the ground surface, whichever is deeper. If there is a potential for liquefaction to extend below the minimum depth, CPTs should be continued until a significant thickness (at least 10 feet or 3m) of nonliquefiable soils are encountered. The CPT tip resistance in that zone should exceed a corrected value of 160 tsf (16 MPa) in coarse-grained soils or the soils should be demonstrated to be nonliquefiable.
- As a minimum, one boring used for sampling and testing (for providing other geotechnical recommendations) should be performed next to one of the CPT soundings to check that the CPT-soil behavior type interpretations are reasonable for the project site. The boring and CPT sounding should not be spaced so closely that stress relief would significantly affect the result,%; therefore, consideration should be given to the sequence of the explorations. This boring should be extended to at least the same depth as the CPT sounding. Soil samples should be taken at least every 2 1/2 or 3 feet using SPT, Modified California Drive, or other appropriate samplers, or at changes in soil stratigraphy. Blow-counts from the Modified California or other samplers should not be relied upon. Any differences between the SPT and CPT should be reconciled before proceeding with liquefaction analyses.
- Additional confirmation borings may be necessary if the site is large or the subsurface conditions vary significantly within the site. If an additional boring(s) is performed for other geotechnical design purposes, it may serve as confirmation boring(s). The need for and the number of additional borings shall be determined by the project keotechnical consultant, subject to the review of the appropriate regulatory agencies.
- Additional exploratory borings in the vicinity and soil samples shall be needed to test the soils that are interpreted as clayey or sensitive soils by the CPT method. Extra caution should be exercised in interpreting the data whenever the CPT tip resistance falls below 30 tsf (3 MPa) because at low tip resistance values, the soil behavior type interpretations can be questionable.
- For clayey soils ($I_c > 2.4$), the results based on the so-called modified Chinese criteria (Seed et al.., 1985) supersede the CPT-based results.

5.6 Liquefaction Assessment Using Other In Situ Indices

As data and correlations are being developed and verified with other in situ indices, alternative methods of assessment may become available. A limited amount of data have been collected and correlated to relate the liquefaction potential to shear wave velocities (Youd and Idriss, 1997). In particular, the shear wave velocity approach may be an alternative method to the Becker Hammer method (Youd and Idriss, 1997) for evaluating the liquefaction potential of gravelly deposits.

5.7 Overburden Corrections For Differing Water Table Conditions

To perform analyses of liquefaction triggering, liquefaction settlement, seismically induced settlement, and lateral spreading, it is necessary to develop a profile of SPT blow-counts or CPT q_c-values that have been normalized using the effective overburden pressure. That normalization should be performed using the effective stress profile that existed at the time the SPT or CPT testing was performed. Then, those normalized values are held constant throughout the remainder of the analyses, regardless of whether or not the analyses are performed using higher or lower water-table conditions. Although the possibility exists that softening effects due to soil moistening can influence SPT or CPT results if the water table fluctuates, it is commonly assumed that the only effect that changes in the water table have on the results are due to changes in the effective overburden stress.

Raw, field N-values (or q_c-values) obtained under one set of groundwater conditions should not be input into an analysis where they are then normalized using C_N correction factors based on anew (different) water table depth.