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A Practical Assessment of Site Liquefaction Effects and Remediation Needs

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SYNOPSIS: This paper describes a case history where potential earthquake induced liquefaction is of concern at a site where a major housing development is planned. The site comprises inter-layer saturated loose to medium dense sandy silts, silty sands and soft clay layers to a depth of 35 ft. Liquefaction potential at the site was evaluated through the use of cone penetrometer test (CPT) logs and standard penetration test (SPT) data. Results of DESRA-2 effective stress site response analyses were also used to determine pore pressure response at the site for a given design earthquake, and are compared to liquefaction assessments conducted using the empirical SPT approach. Methods for determining post liquefaction settlement and potential surface manifestation of liquefaction are described along with the methods used to assess recommendations for site remediation.

INTRODUCTION

Coastal flood plains comprising interbedded sands, silts and clays, pose major concerns with respect to liquefaction potential when located in regions of high seismicity. Where residential development of such flood plains are proposed, the need for liquefaction assessments and possible site remediation measures to protect the site from the effects of liquefaction are clearly necessary. In this paper, liquefaction investigations conducted at such a site comprising several hundred acres of relatively level land in Southern California, are described.

For level sites, the effects of earthquake induced liquefaction in terms of hazards to constructed facilities, take the form of either excessive settlement or surface manifestation effects such as large ground deformations and/ or surface instability. In both cases, site remedial measures to prevent damage to surface structures is required. If liquefaction occurs at a sufficient depth and over a limited thickness of strata, the effects of settlement may be minimal, and surface manifestation may not occur, in which case no remediation may be required. The nature of the site investigations conducted and the methods used to assess liquefaction hazards and remediation needs are described in the paragraphs below.

SITE STRATIGRAPHY

Numerous borings including Standard Penetration Tests (SPT) tests, together with a number of Cone Penetrometer Test (CPT) soundings were performed at the site. Bore hole data interpreted from both boring logs and CPT soundings for a representative cross section taken across the site are shown in Figure 1. Groundwater levels fluctuated seasonally, but in general were at very shallow depths. Ground surface elevations ranged from zero (mean sea water level) to plus 7 feet. Subsurface soils comprised interspersed layers of sandy, silty, and clayey soils with occasional soft organic soil. As seen in Figure 1, there is no clearly defined horizontal stratigraphy, although there are general interbedding trends where loose to medium dense fine sands or silty sands are contained between strata of soft to medium stiff clays.

CPT soundings are ideally suited for the interpretation of such complex stratigraphy. Figure 2 shows a CPT sounding at the site expressed in terms of cone resistance, friction resistance, and friction ratio as a function of depth. Extensive research conducted by Earth Technology over the past ten years for both the USGS and the NSF (Fugro, Inc., 1980, Douglas and Olsen, 1981, Douglas et.al 1981, The Earth Technology Corp., 1982, 1984, and 1985.) has led to correlations between normalized cone resistance, friction ratio and soil type as shown in classification chart given in Figure 3. The procedure for normalization of cone resistance is similar to that for SPT normalization to an overburden pressure of one ton per square foot. Correlations have also been established between normalized cone resistance, friction ratio, and normalized SPT blow count and are also shown in Figure 3. The direct correlation with modified SPT blowcount is shown by the full lines. The correlation corrected for fines content for liquefaction assessment, is shown by the dashed lines. The use of these correlations effectively allows the continuous evaluation of soil type and modified SPT blow count with depth, allowing relatively thin soil layers to be defined with accuracy, as compared to the SPT procedure where data is generally defined at five foot intervals.

The reliability of CPT correlations have been verified by numerous field studies where both SPT and CPT data have been obtained at adjacent locations. An example of such a verification study is illustrated in Figure 4 where data was obtained at the site under study. SPT blow counts at 5 foot intervals and corrected for

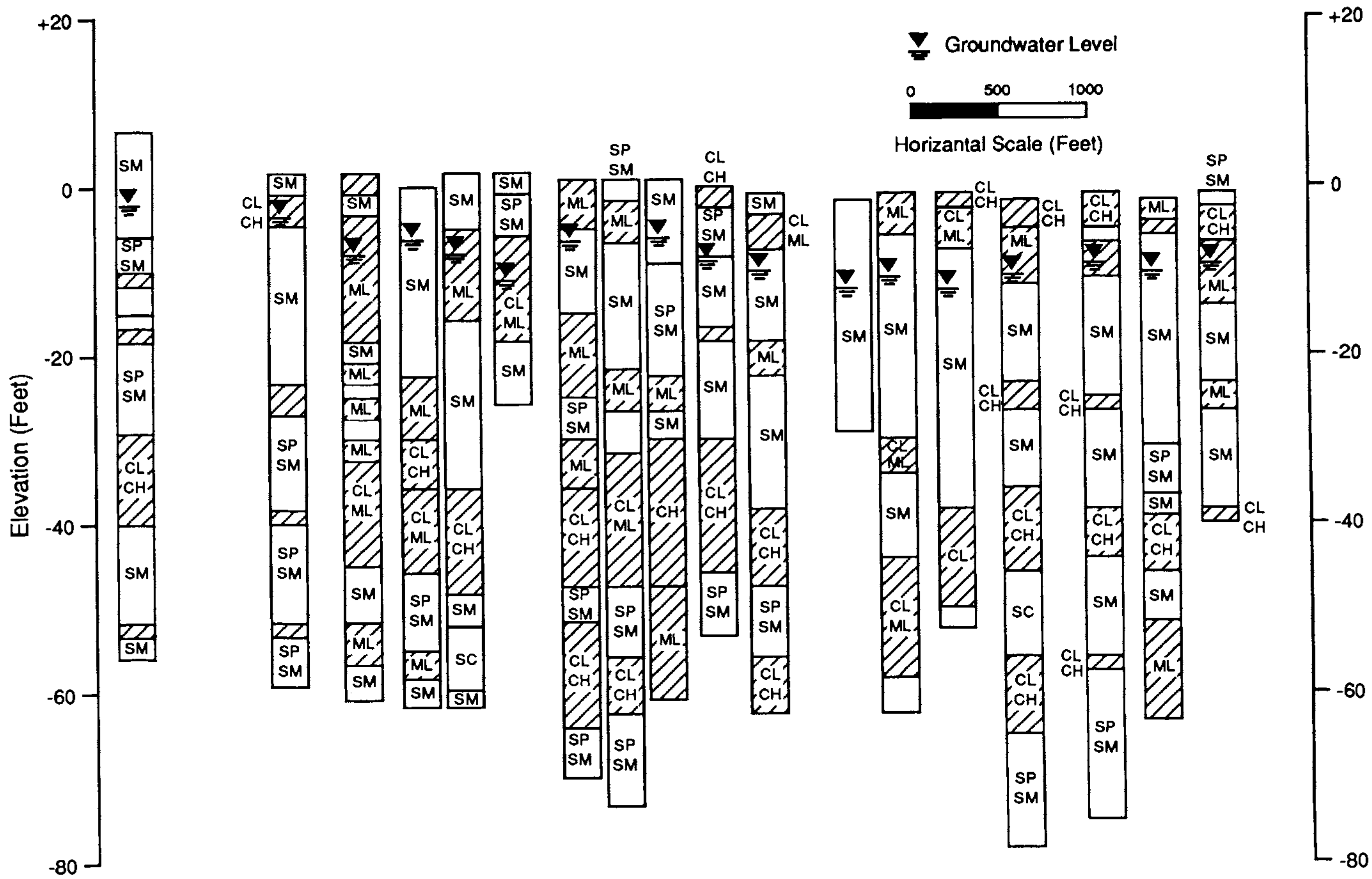

Fig. 1 Borehole Logs Across Site Cross Section

fines content using the procedure described by Seed et.al. (1985), are compared to CPT derived blow count data derived using the correlation chart of Figure 3. In general, the CPT derived SPT data is seen to be in reasonable agreement with measured SPT data. However, note that the five foot SPT approach lacks the ability to pick up the significant variations of SPT values with depth, typical of such complex sedimentary stratigraphy.

LIQUEFACTION POTENTIAL

The design earthquake for the site is based on a Magnitude 7 event producing a peak ground acceleration at the site of 0.25g. The SPT values separating potentially liquefiable and non liquefiable zones at various depths were derived using the simplified procedure described by Seed et.al. (1983) modified to take into account fines content (Seed et.al. 1985). A preliminary evaluation clearly indicated that sandy silt and silty sand strata at shallower depths were potentially liquefiable at many borehole or sounding locations, and that more detailed studies were required to evaluate the significance of the potential liquefaction with respect to settlement and surface manifestation effects. Such an evaluation was complicated by the fact that at many locations on the site, fill was to be placed at heights varying from 0-19 feet.

At the initial stages of the development concept, a marina facility was also planned, and required the installation of retaining structures providing ground support for relatively deep channels. To provide assistance in analysis of such structures, it was also decided to perform effective stress site response analyses using the computer program DESRA-2 (Lee and Finn, 1978, Finn et.al., 1978) to provide information on time histories of pore pressure build up in addition to acceleration time histories. A summary of the approach and results from the above studies is given below.

DESRA ANALYSES

The DESRA-2 computer program applies a one dimensional effective stress modeling technique for the case of horizontally layered deposits subjected to vertically propagating shear waves. Analyses incorporate nonlinear soil stress-strain behavior and the liquefaction strength characteristics of the soils. The program also allows the simultaneous generation and dissipation of excess pore pressure during ground shaking and incorporates the use of a transmitting base boundary to simulate the effects of finite rigidity at the base of the soil deposits where input ground accelerations are applied.

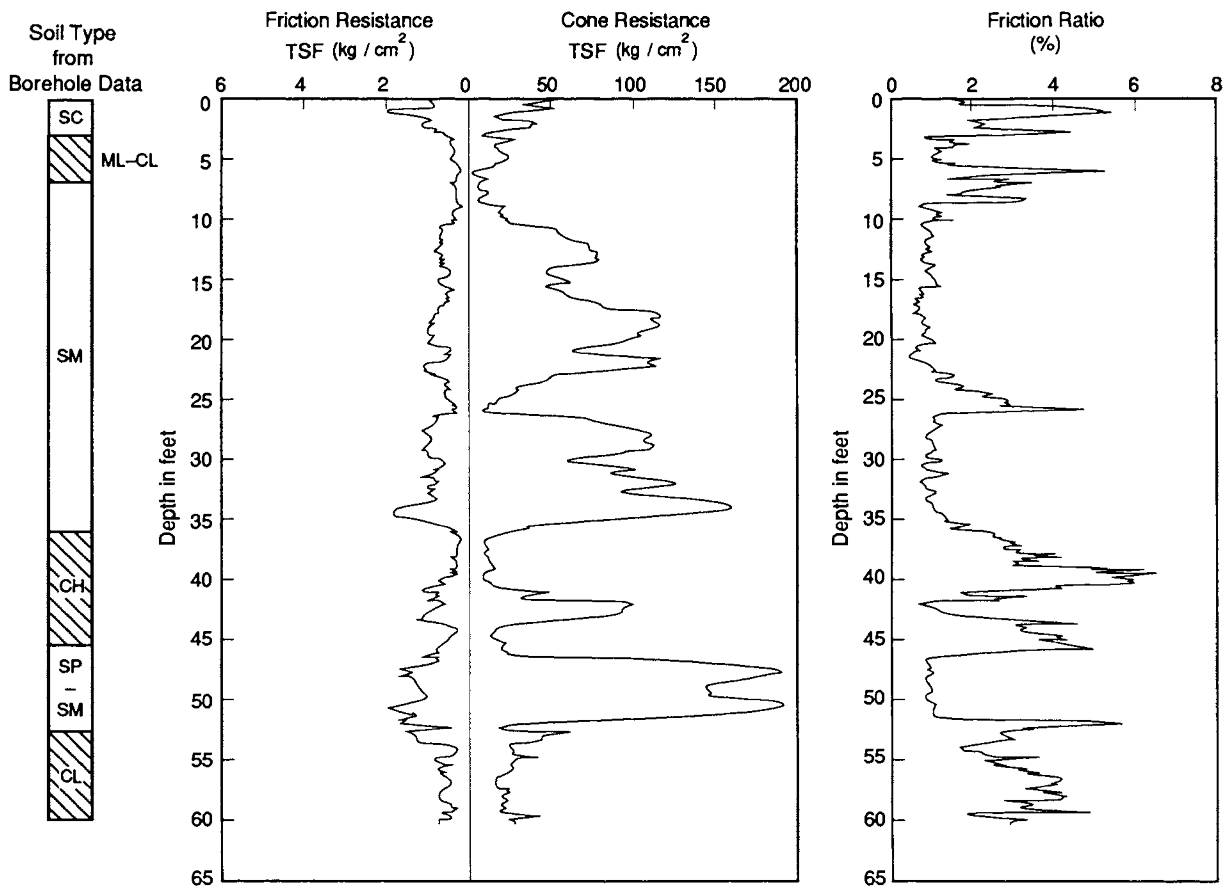

Fig. 2 Representative CPT Sounding

An idealized soil profile representative of typical site soil conditions was developed for analyses. The idealized profile is shown in Figure 5 which indicates the range of modified SPT blow counts measured in the field for the liquefiable sandy layers. Dense soils were encountered at elevations below -48 feet, and hence this elevation was chosen to input firm ground acceleration time histories for site response analyses. Twelve feet of fill was also assumed for the analysis described with a water table elevation at 0 feet.

Liquefaction strength curves for the lower bound SPT values for each sand layer were determined from the empirical SPT versus stress ratio to cause liquefaction relationships described by Seed et.al (1983) for a range of earthquake magnitudes. For example, the liquefaction strength curve corresponding to a modified SPT blow count of 15, was determined by taking the stress ratios to cause liquefaction from the empirical plots (for a blow count of 15) for earthquake magnitudes corresponding to 6, 6-3/4, 7-1/2, and 8-1/2 having corresponding numbers of cycles to cause liquefaction of 6, 10, 15, and 26. Liquefaction strength curves constructed in this matter are shown in Figure 6. The pore pressure generation parameters required by the DESRA program were backfitted to be consistent with the liquefaction strength curves using the procedure described by Martin et.al, (1981). Low strain shear modulus parameters required for the site profile together with the variation in shear modulus with shearing strain were determined from blow count correlations and standard curve shapes documented in the literature. The firm ground input earthquake time history chosen for analyses was that of the Holiday Inn, Orion Boulevard record obtained during the 1971 San Fernando earthquake. The accelerogram is shown in Figure 7, and has a peak acceleration of 0.25g.

A representative pore pressure buildup time history for the layer of sand between elevations of -20 and -25 feet is shown in Figure 8. Initial liquefaction is seen to occur after 11.6 seconds of strong ground shaking. Maximum excess pore pressure buildup during earthquake shaking for each of the sand layers is shown in Figure 9, together with corresponding factors of safety against liquefaction determined using the conventional empirical SPT approach. Results from the DESRA and SPT approaches are seen to be reasonably consistent with two notable exceptions. The uppermost sand layer (SPT F.O.S. = 0.85) does not liquefy in the DESRA analysis. This is attributed to early liquefaction of underlying sand layers and the effects of site response

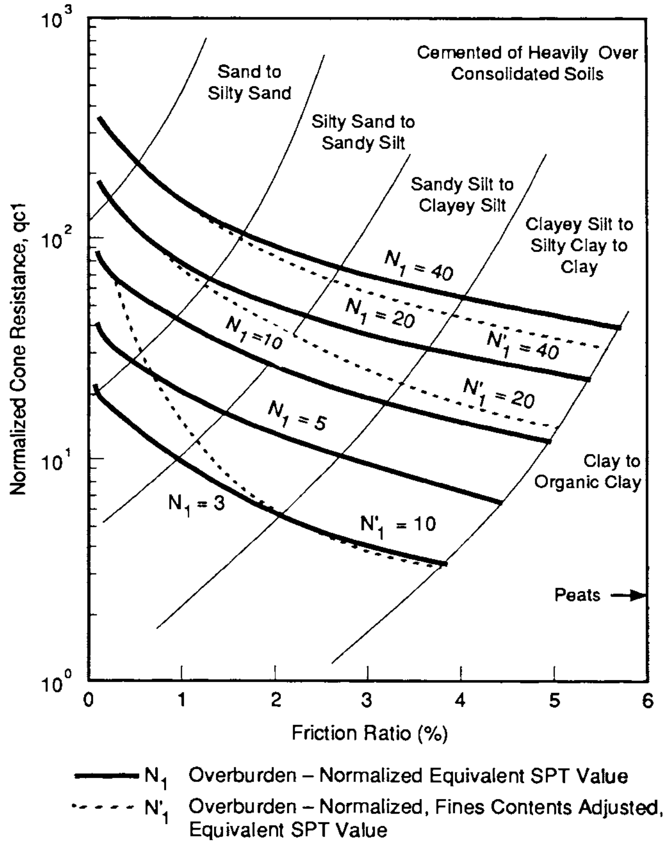

Fig. 3 - CPT - Soil Behavior Classification Chart With Equivalent SPT Blow Count Values

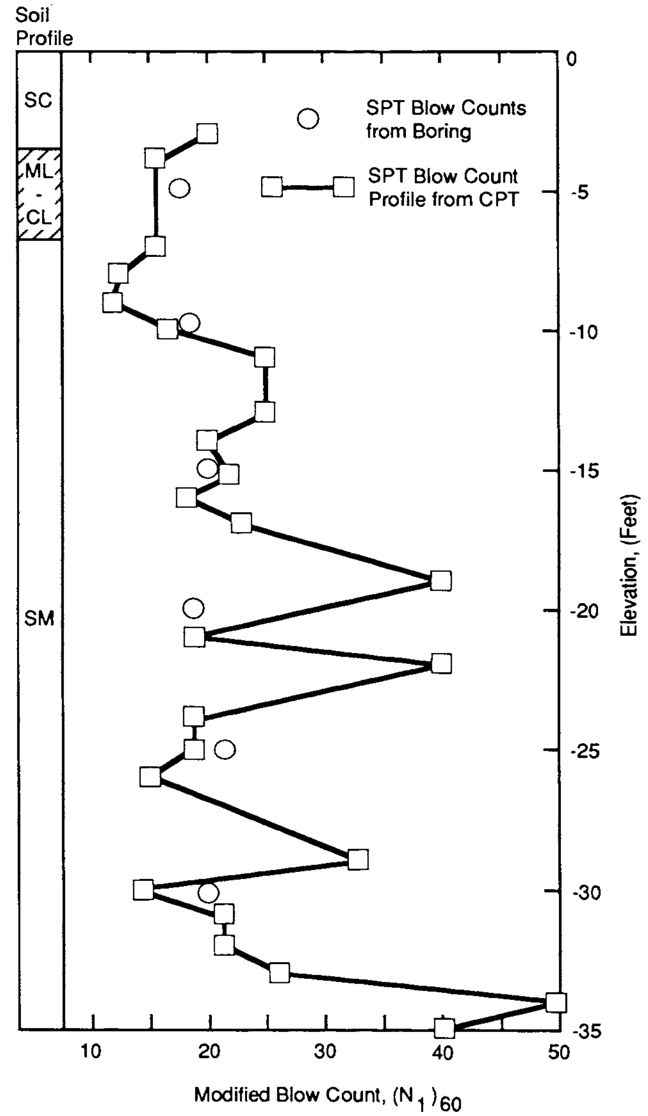

Fig. 4 Comparison of Blow Counts from SPT and Those Derived From CPT Sounding

which reduce ground accelerations in the uppermost layer. The sand layer between elevations of -15 to -20 ft. (SPT F.O.S. = 1.2) liquefied in the DESRA analysis. This is attributed to redistribution of excess pore pressures into this layer from the liquefied sand layers above and below this layer.

The DESRA analysis also indicates that a number of strong motion cycles occur subsequent to liquefaction particularly for the layer at a depth of about 15 feet. This is significant in the sense that the potential for larger post liquefaction settlements and damaging surface manifestation effects become greater when liquefaction occurs, sometime prior to the end of strong ground motion shaking.

SETTLEMENT AND SURFACE MANIFESTATION OF LIQUEFACTION

The subject of settlement of saturated sands resulting from the dissipation of earthquake induced pore water pressures has been reviewed by Tokimatsu and Seed, (1987). Laboratory studies have shown the amount of settlement is significantly influenced by the maximum cyclic shearing strain developed in the soil as well as the relative density, but is insensitive to the effective overburden pressure. Based on available data, Tokimatsu and Seed developed empirical curves showing correlations between cyclic stress ratios during earthquake shaking, normalized SPT blowcounts and volumetric strains occurring as a result of dissipation of excess pore water pressure. Curves showing such correlations for a Magnitude 7 earthquake are shown in Figure 10. For looser sands and high cyclic stress ratios capable of producing high post liquefaction cyclic shearing strains, volumetric strains on reconsolidation are seen to be relatively high.

Case studies for sites where loose sands have liquefied and subsequent settlement has occurred, have indicated that observed settlements were of the order of those predicted by the Tokimatsu and Seed. However, because the correlations were largely developed using results from stress controlled cyclic laboratory tests, the empirical prediction procedure could be somewhat conservative. Post liquefaction cyclic shearing stresses in the field are likely to be somewhat less than those adopted for stress controlled

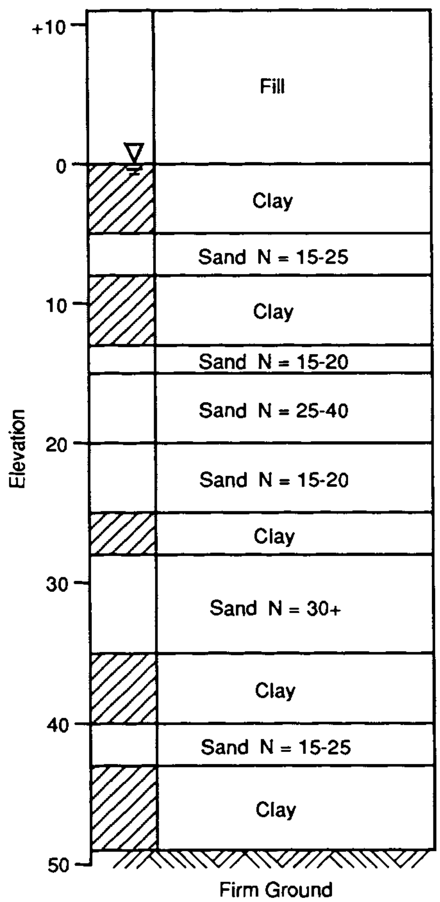

Fig. 5 Idealized Profile for DESRA Analyses

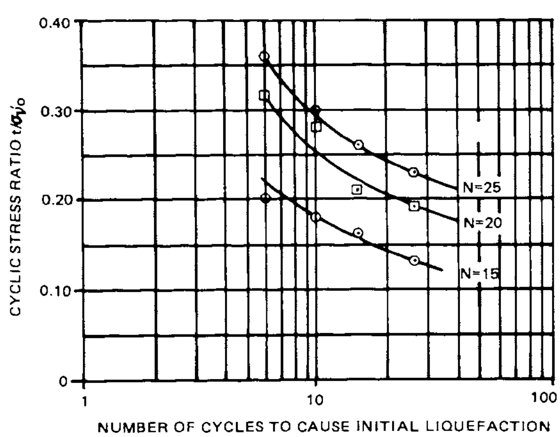

Fig. 6 Liquefaction Strength Curves For DESRA Analyses

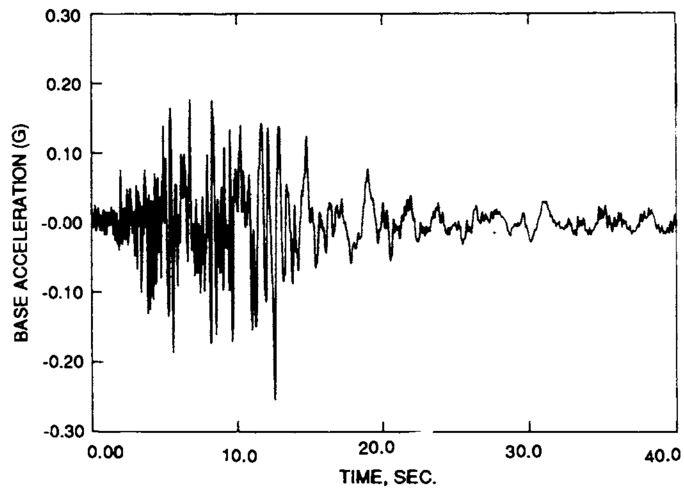

Fig. 7 Accelerogram Used For DESRA Analyses

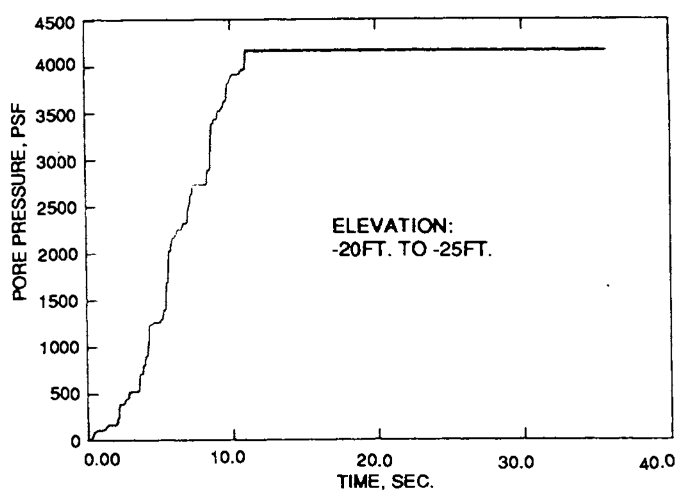

Fig. 8 Pore Pressure Buildup Time History (El. -20 to -25 ft.)

laboratory simulation tests, as the effects of stiffness degradation on incoming earthquake waves could reduce the amplitude of cyclic stresses. Hence in using the correlations to predict field settlements, a factor of safety of 1 with respect to stress ratios causing initial liquefaction was used in calculations.

With respect to surface manifestation of liquefaction effects, studies of case histories in Japan (Isihara, 1985) shows that the occurrence of liquefaction itself in some layer of the soil deposit is not necessarily associated with damage of structures founded on the ground surface. However, when liquefaction is extensive through the depth of a deposit and shallow enough, the effects of liquefaction become hazardous and are associated with sand boils, ground fissures and lateral deformations damaging to surface structures.

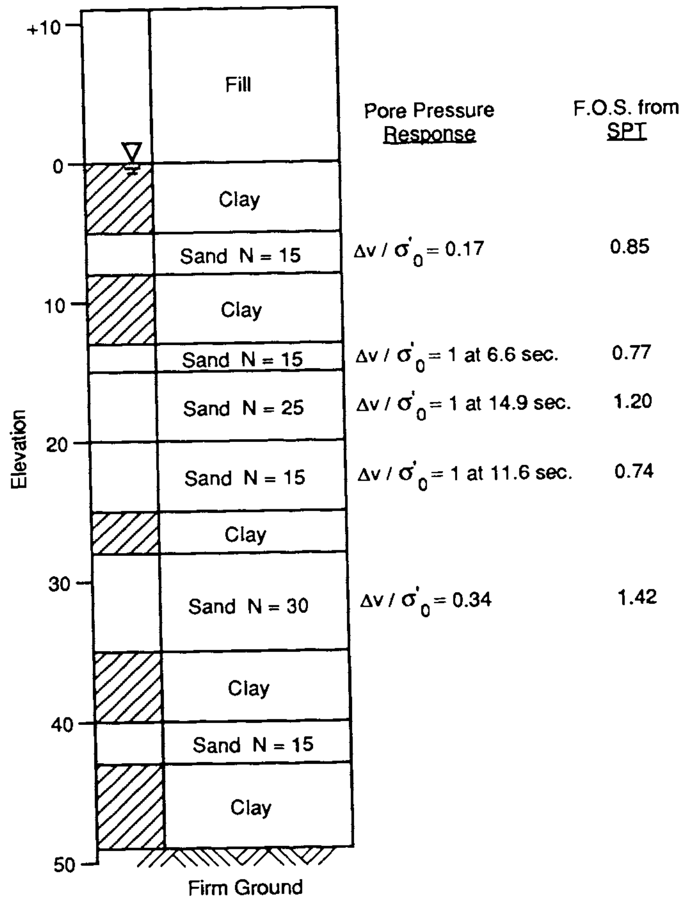

Fig. 9 Maximum Excess Pore Pressure From DESRA Analyses Compared To Factors Of Safety From SPT Method

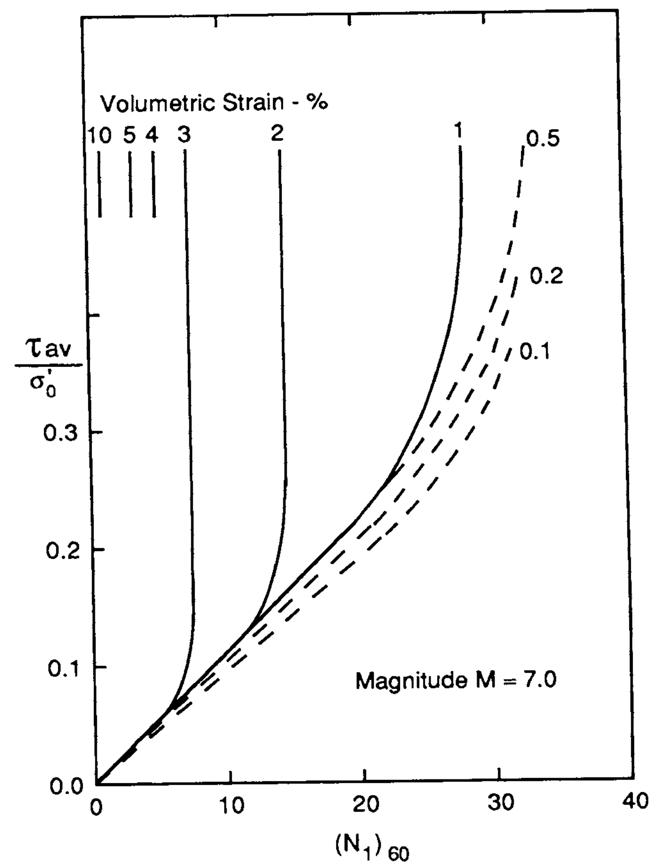

Fig. 10 Relationship Between Cyclic Stress Ratio, Modified Blow Count and Volumetric Strain for M=7.0 (After Tokimatsu and Seed, 1987)

Based on studies of several Japanese sites where liquefaction has occurred in past earthquakes, conditions of subsurface soil stratification which discriminate between occurrence and non-occurrence of damaging ground effects due to liquefaction have been defined. The relationship between the thickness H_1 of a nonliquefiable surface layer and the thickness H_2 of the underlying potentially liquefiable layer for a maximum ground acceleration of 0.25g is shown in Figure 11. H_1 is calculated as the depth to the first potentially liquefiable soil layer. The thickness H_2 was defined as the thickness of potentially liquefiable layers using a factor of safety of 1.25 with respect to the earthquake induced shearing stress ratios. The factor of safety of 1.25 was chosen as the accuracy of the empirical relationship developed by Ishihara is somewhat uncertain. If more than one layer of potentially liquefiable soil was identified from the CPT logs, the expression shown in Fig. 12 was used to calculate the thickness H_2. The application of the above procedures is illustrated by reference to Figure 13 which shows representative modified blowcount data as a function of depth for a typical CPT sounding location at the site. Curves showing modified blowcounts required to resist liquefaction after placement of fill for factors of safety of 1.0 (settlement calculations) and 1.25 (surface manifestation evaluations) are also shown. For the case of settlement calculations, for liquefying zones modified blowcounts on a foot by foot basis were used in conjunction with Figure 10 to compute volumetric strains. The total post liquefaction surface settlement was then computed by integrating the volumetric strains on a foot by foot basis. Evaluation of surface manifestation effects was performed using the procedures described above in conjunction with Figures 11 and 12.

For each CPT or borehole location and for the corresponding height of fill, the calculated post liquefaction settlement along with the potential for surface manifestation was computed. Representative calculations at several locations are shown in Table 1. For preliminary design evaluations, it was recommended that post liquefaction settlements be less than 2 inches. Differential settlements across building slabs associated with such settlements could reasonably be assumed to be less than about 1 inch and the potential consequences to structures alleviated by properly designed reinforced concrete floor slabs. In general where the fill height exceeded 10 to 20 feet, the potential for surface manifestation becomes minimal and post liquefaction

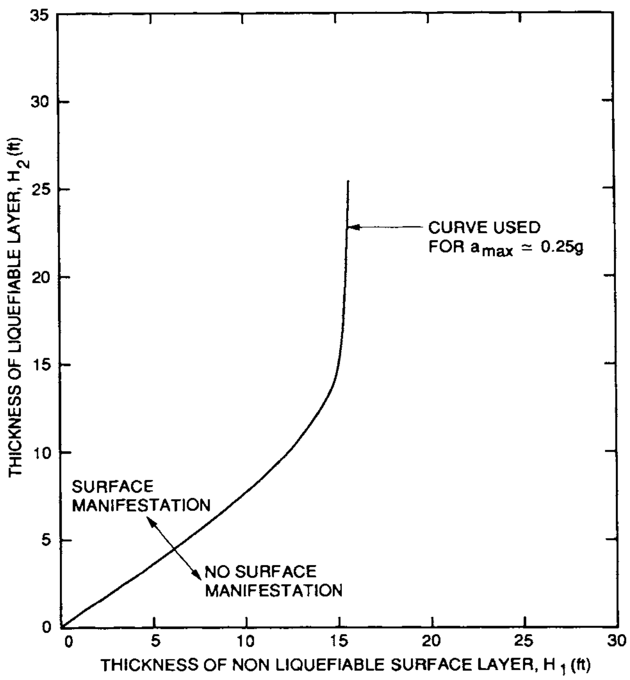

Fig. 11 Chart For Evaluating Surface Manifestation of Liquefaction (After Ishihara, 1985)

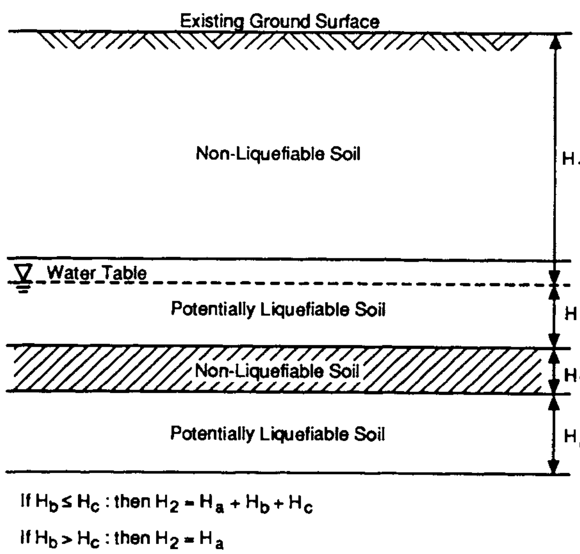

Fig. 12 Procedure For Determination Of The Liquefiable Layer Thickness (After Ishihara 1985)

settlements generally become less than about 2 inches.

SITE REMEDIATION NEEDS

For every borehole or sounding location the depth of ground improvement required to reduce settlement to less than 2 inches or to prevent surface manifestation of liquefaction was computed. Representative data are shown in Table 1. It may be seen that at some locations settlement governed remediation needs while at other

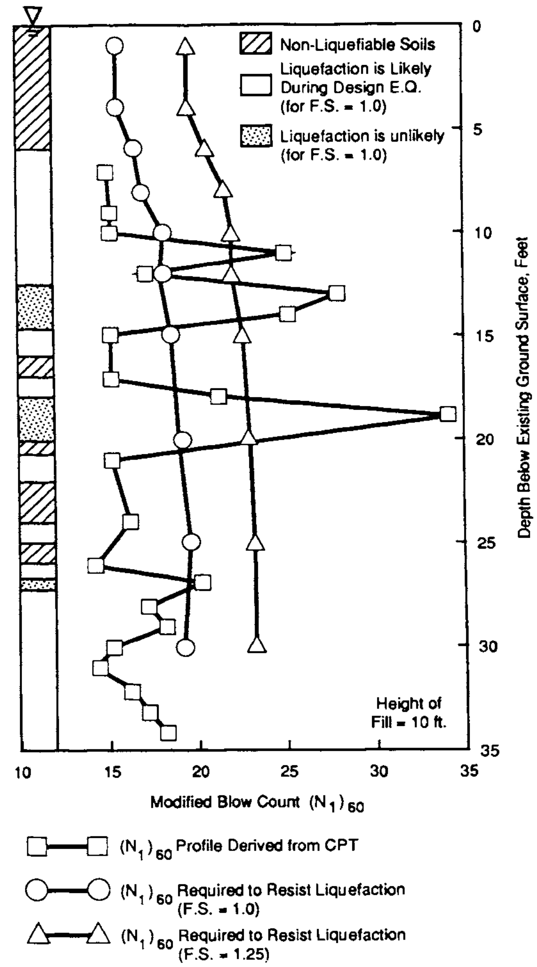

Fig. 13 SPT Blow Counts Required For Liquefaction Layer Thickness (After Ishihara, 1985)

locations surface manifestation was the dominant concern. The depth of ground improvement required was established on the basis of the greater depth requirement considering both settlement and surface manifestation.

Based on the above approach the approximate extent of areas requiring remediation at the site using remediation depth intervals of 5, 10, 15 and 20 feet was established. This data established the basis for preliminary costing of remediation options and the delineation of a more refined CPT site investigation prior to a decision on the final remediation strategy. Both dynamic deep compaction and virbro replacement methods were considered as viable options for remediation, with the latter being used at boundaries near existing housing developments.

CONCLUSIONS

For large level ground sites comprising potentially liquefiable soils, which are being considered for development, the following general conclusions may be drawn from the study:

1.) The use of CPT soundings can provide a rapid, economical and reliable method for defining both stratigraphy and equivalent modified SPT blow-

Table I Surface Manifestation Of Liquefaction and Post Liquefaction Settlement (Representative Site Location)

CPT #	Height of Fill (ft.)	Settle-ment,S (in.)	Surface Manifes-tations (yes/no)	Depth of Improvement Required (ft.)		
				To Reduce S to 2 in.	To Mitigate Surface Manifes-tations	Max. Depth
C-124	6	1.7	No	0	0	0
C-125	5	1.5	Yes	0	10	10
C-127	4	1.7	No	0	0	0
C-130	9	2.2	Yes	8	6	8
C-136	10	3.0	No	15	0	15
C-137	3	3.1	Yes	10	10	10
C-138	10	1.1	No	0	0	0
C-140	4	4.2	Yes	18	11	18

counts for liquefaction assessments. 2.) Whereas the simplified empirical SPT procedure for evaluating liquefaction potential provides conservative assessments for design in most cases, for stratified soil conditions of varying density, DESRA analyses indicates the potential for error in some cases. Research is required to better define the conditions under which the simplified SPT approach is inappropriate. 3.) The prevention of surface manifestation of ground liquefaction is clearly of major concern. Existing design procedures are based largely on past field observations and consequently are empirical in nature. Considering the cost of remediation, more research is required to define conditions leading to surface manifestation. Research where ground shaking is simulated using the centrifuge in combination with a variety of stratified soil models, is recommended as a means of improving design criteria. 4.) Design procedures available for post liquefaction settlement estimates are also empirical in nature and centrifuge studies similar to those recommended above, could be performed to provide verification for improved post liquefaction settlement estimates.

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