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Trials to Determine the Usefulness of Vibro Stone Columns in the Prevention of Liquefaction of Silty Sands

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Summary A proposed Liquefied Natural Gas (LNG) plant in the south of Trinidad involved the foundation design of two 74.4 m diameter, 30 m high, concrete outer wall, LNG tanks. The site is located 1 km from an active fault. The proposed foundation system was steel tubular driven piles. Vibro stone columns were proposed to densify the silty sand layers above the founding stratum in order to minimise the number and size of piles required. This paper presents the results of trials carried out on the top feed vibro replacement wet method of stone column installation, including CPTs before and after installation. These trials showed the method to be unsuccessful in densifying all the silty sand layers. Hence these silty sands fall into an intermediate category of a material which can liquefy under earthquake conditions, but cannot be densified using this method of stone column installation.

1 INTRODUCTION

A liquefied natural gas (LNG) plant is being constructed by Bechtel for ALNG in the south of Trinidad. The plant has two 74.4 m diameter, 30 m high LNG tanks, Tank A and Tank B, which are being constructed by Whessoe Projects Limited. The site was located 1 km from an active fault. The stratigraphy comprised approximately 10 m of Fill and Marine Deposits overlying a hard clay or silt. The Fill and Marine Deposits contained silty sands. In order to prevent liquefaction of these sands during an earthquake, it was proposed to install stone columns, using the top feed vibro replacement wet method, through the Fill and Marine Deposits to the top of the hard clay/silt below. The purpose of this was to minimise the number and size of piles required for foundation design. Three vibro stone column tests to establish the effectiveness of the treatment in the silty sands were carried out.

2 GROUND CONDITIONS

2.1 Site Investigation

A site investigation was carried out to establish the bearing capacity of the hard clay/silt for pile design and to assess the composition of the Fill and Marine Deposits. The site investigation was supervised by Ove Arup & Partners UK and comprised fifteen boreholes approximately 30 m deep, with two to 70 m. Fifty-six Cone Penetration Tests (CPTs) were carried out to confirm the composition of the Fill and Marine Deposits at the tank locations.

2.2 Stratigraphy

At the location of Tank A, essentially three strata were encountered. The first stratum was recently-dumped Hydraulic Fill which comprised a mixture of soft to firm clays and loose to medium dense silts and sands. This overlay Marine Deposits which generally comprised loose to medium dense silty sands to sandy silts. This stratum overlay a stiff to hard Grey Clay. Figure 1 shows a section through Tank A.

At the location of Tank B, five strata were encountered. The first and second were the Fill which overlay the Marine Deposits as found in Tank A. Over parts of Tank B this overlay a firm to hard Brown and Grey Clay which overlay the Grey Clay as found in Tank A. For the remainder of Tank B, the Marine Deposits were underlain by a hard or very dense Oily Silt. Figure 2 shows a section through Tank B.

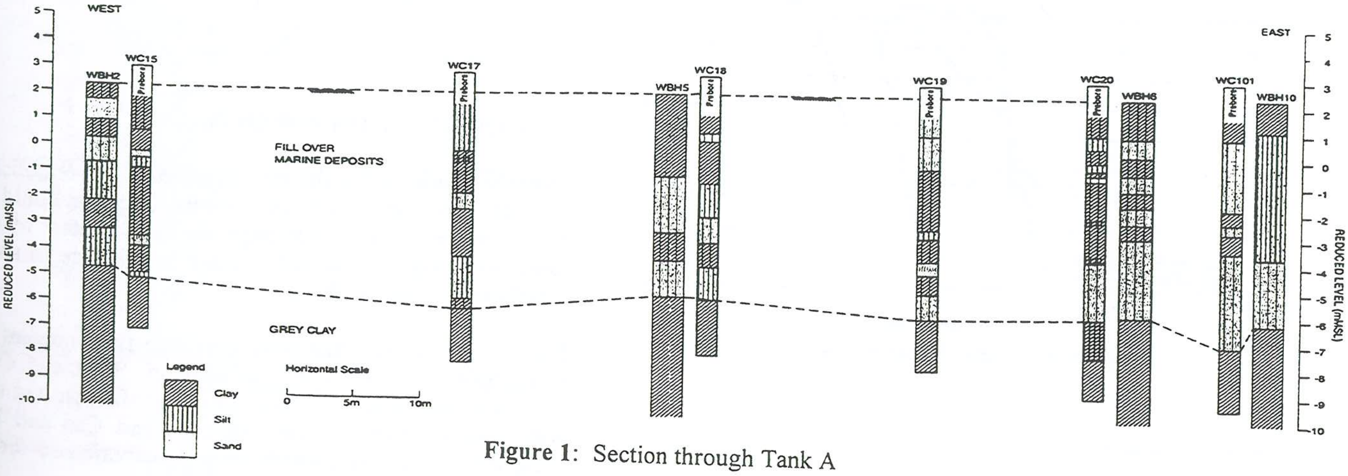

Figure 1: Section through Tank A

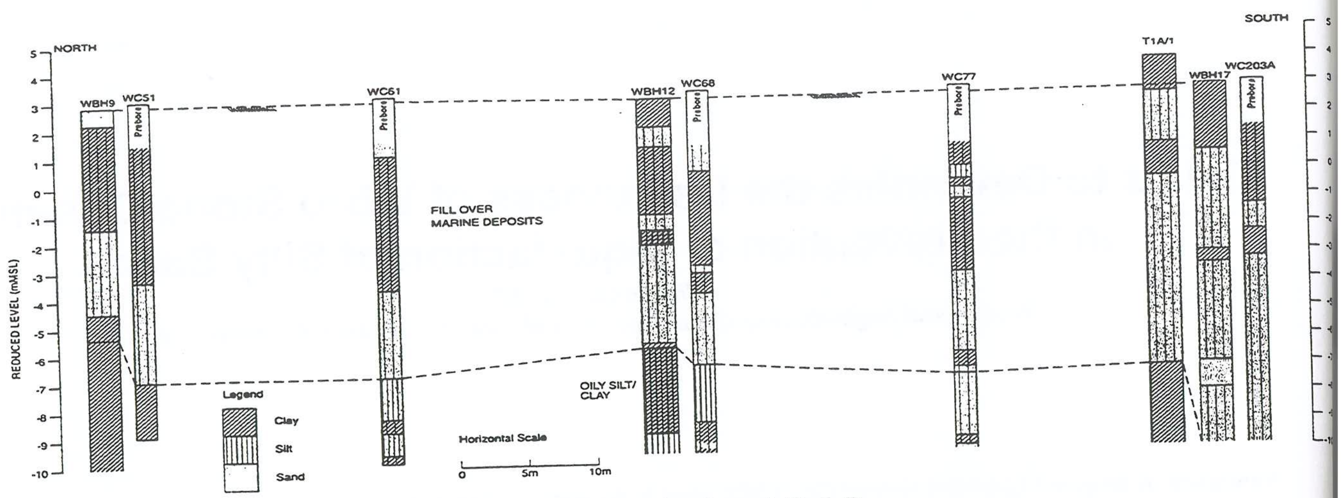

Figure 2: Section through Tank B

2.3 Properties of the Silty Sands

Particle size distribution tests were carried out according to ASTM-D422 for the sand materials in the Fill and Marine Deposits. The distributions are plotted in Figures 3, 4, 5 and 6 and are compared with the boundaries proposed by Tsuchida (1) for most liquefiable and potentially liquefiable soils. The grading curves show the sands to have high fines content generally close to the boundary between most and potentially liquefiable soils*.

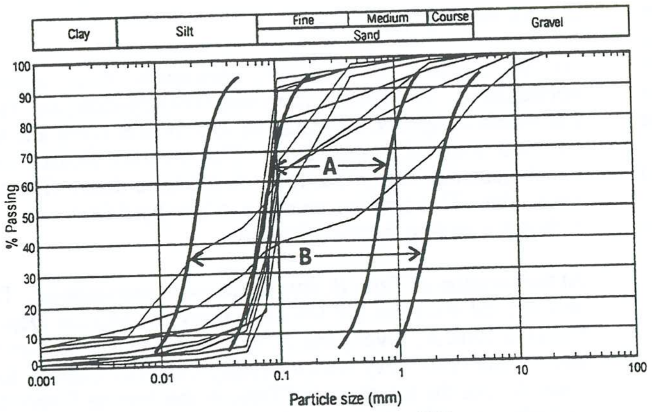

Figure 3*: Tank A Fill

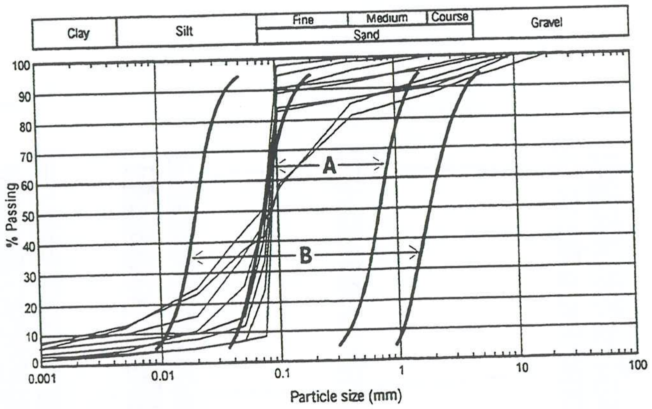

Figure 4*: Tank A Marine Deposits

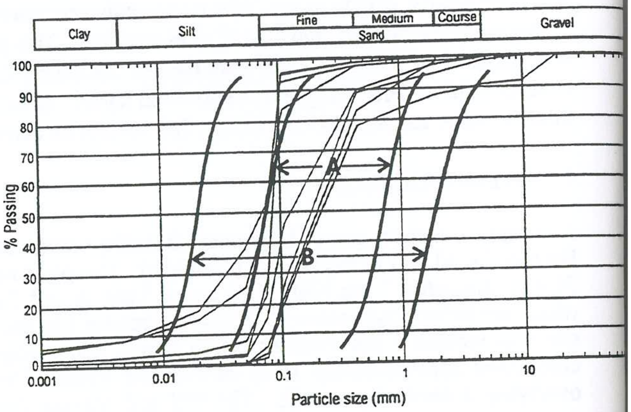

Figure 5*: Tank B Fill

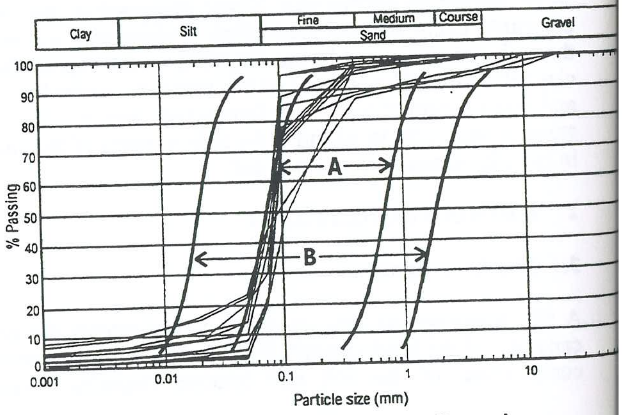

Figure 6*: Tank B Marine Deposits

3 LIQUEFACTION POTENTIAL

From the results of the site investigation, it was established the silty sands in the Fill and Marine Deposits could liq during an earthquake. Although the fines content of the sands were high (up to 40%), there is evidence to show liquefaction could occur.

Figures 3 to 6 show that soils with high fines content ma susceptible to liquefaction. In addition, Stark and Olse compiled case histories which show liquefaction had occu with fines content in excess of 50% and Cao and Law compiled case histories which show liquefaction occurring clay contents of up to 12%.

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* For Figures 3, 4, 5 and 6
A = Most liquefiable soils, B = Potentially liquefiable soils

4 STONE COLUMN TRIALS

Initially two trials had been planned but this was extended in scope following the first two trials. The stone columns were installed using the top feed vibro replacement method which involves vibrating the vibro-flot, which has a water jet, into the ground to the required depth. The vibro-flot is then partially withdrawn and stone fed from the top and the vibro-flot reintroduced into the ground. This continues until a column of the required size has been formed. The three trials carried out were as follows:

Trial 1: Tank A - 600 mm Columns
Trial 2: Tank B - 600 mm Columns
Trial 3: Tank B - 1200 mm Columns

The trials comprised at least sixteen columns at 2 m square grid spacing. The trials were located close to boreholes considered to be representative of the ground conditions at the tank locations.

5 ACCEPTANCE CRITERIA

The CPTs carried out as part of the site investigation were correlated with the boreholes in order to be able to accurately identify the presence and consistency of sands and silty sands. Therefore CPTs were carried out between the stone columns before and after the vibro trials to identify the strata and assess the effectiveness of the treatment. The acceptance criteria against liquefaction were calculated based on a method devised by Seed et al (4) which determines the liquefaction potential based on the N-value from a standard penetration test. The relationship is between stress ratio $\frac{(\tau_{av})}{(\sigma_{v'})}$, N value and percentage of Fines. Figure 7 is an extract from the Seed et al (4) paper.

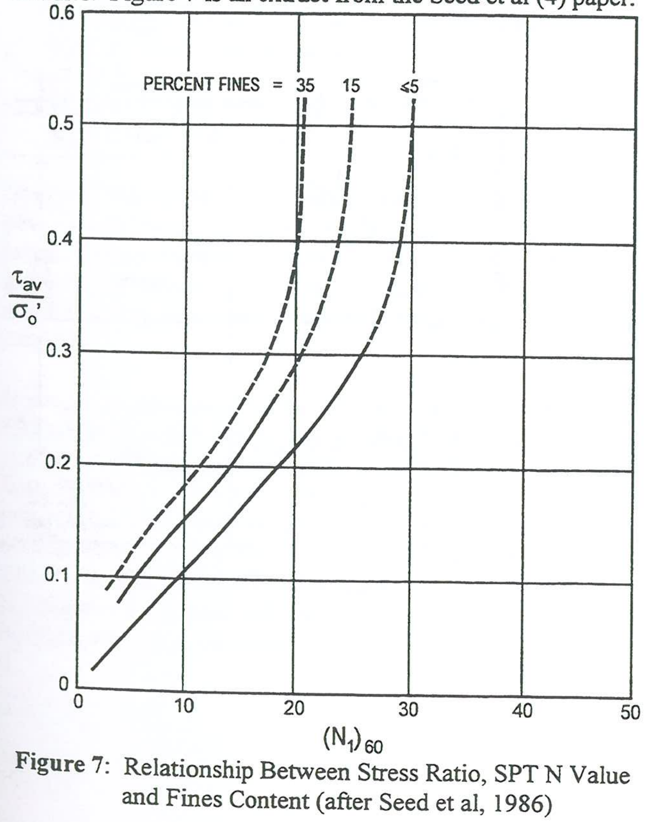

Figure 7: Relationship Between Stress Ratio, SPT N Value and Fines Content (after Seed et al, 1986)

The equation for $\frac{(\tau_{av})}{(\sigma_{v'})}$ is:

$$\frac{\tau_{av}}{\sigma_{v'}} = 0.65 \cdot \frac{a_{max}}{g} \cdot \frac{\sigma_v}{\sigma_{v'}} \cdot r_d \cdot M_F$$

where a_{max} = peak horizontal ground acceleration

r_d = stress reduction factor - varies from 1 to 0.9 from surface depth to 10 m depth

M_F = Modification Factor due to earthquake magnitude (assumed = 1.0 for magnitude of 7.5).

The CPT cone resistance, q_c, values are converted to SPT N-values using a relationship proposed by Stark and Olsen (2). Figure 8 is an extract from the Stark and Olsen paper (2) showing conversion factors for different fines contents.

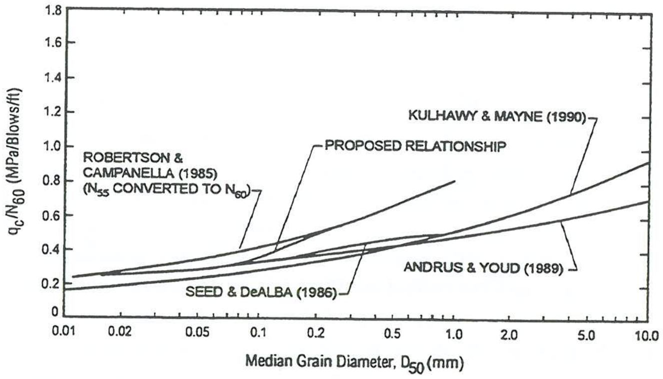

Figure 8: Conversion of CPT q_c Values to SPT N Values Using Median Grain Diameter (after Stark and Olsen, 1995)

There are two design earthquake cases, the Operating Base Earthquake (OBE) where the plant should be operational following an Earthquake, and Safe Shutdown Earthquake (SSE) where the structure must remain intact to allow safe disposal of the contained LNG. The design earthquake magnitude is 7.5. The horizontal ground acceleration for the OBE is 0.3g and for the SSE is 0.55g.

Figure 9 shows the calculated CPT acceptance criteria plotted against liquefaction for 25 % fines content.

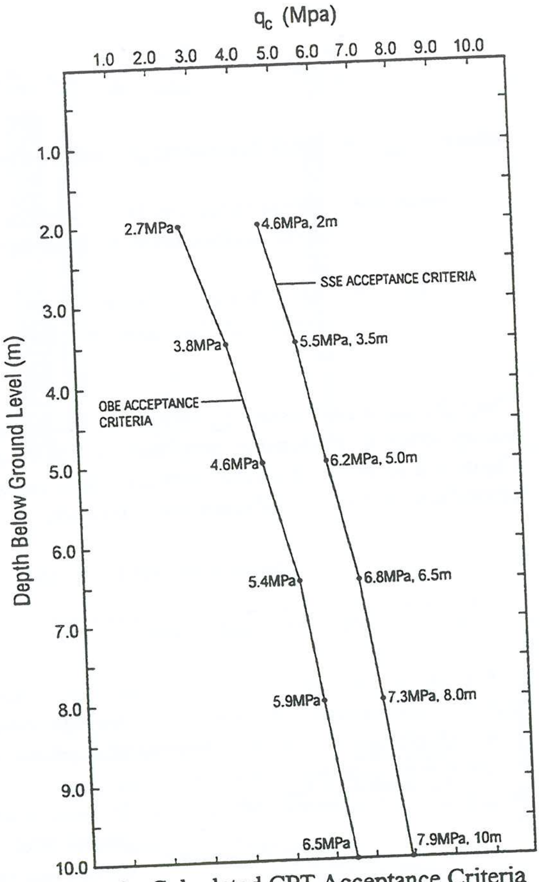

Figure 9: Calculated CPT Acceptance Criteria

6 RESULTS

Before and after results of trials 1, 2 and 3 are presented in Figures 10, 11 and 12 respectively and are described below.

Trial 1:	Tank A 600mm columns There was an improvement in the sand layers above 5 m depth in five of the nine post-vibro CPTs. However, in the silty sand layer between 7 m and 10 m, there was little or no improvement. Figure 10 shows the improvement in one of the CPTs.
Trial 2:	Tank B 600mm columns There was an improvement in the upper part of the sand layer between 6 m and 10 m. However, little or no improvement occurred below this. Figure 11 shows the improvement in one of the CPTs.
Trial 3:	Tank B 1200mm columns As per trial 2, there was an improvement of part of the sand layer below 6 m but not over the entire layer. Figure 12 shows the improvement in one of the CPTs.

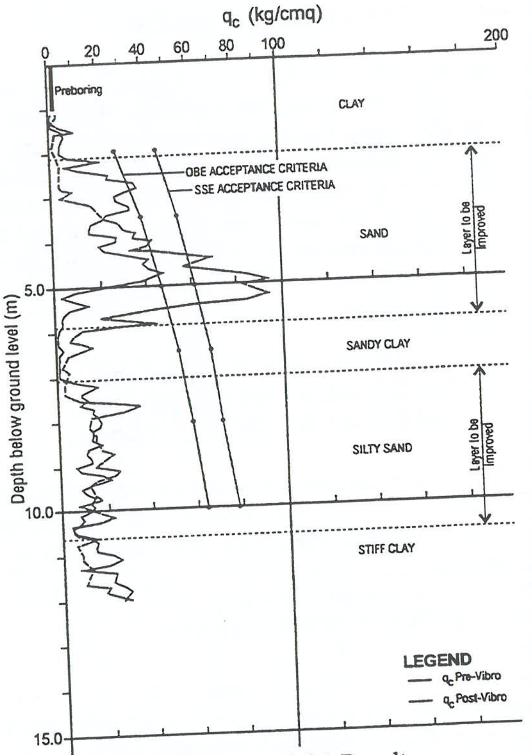

Figure 10: Trial 1 Results

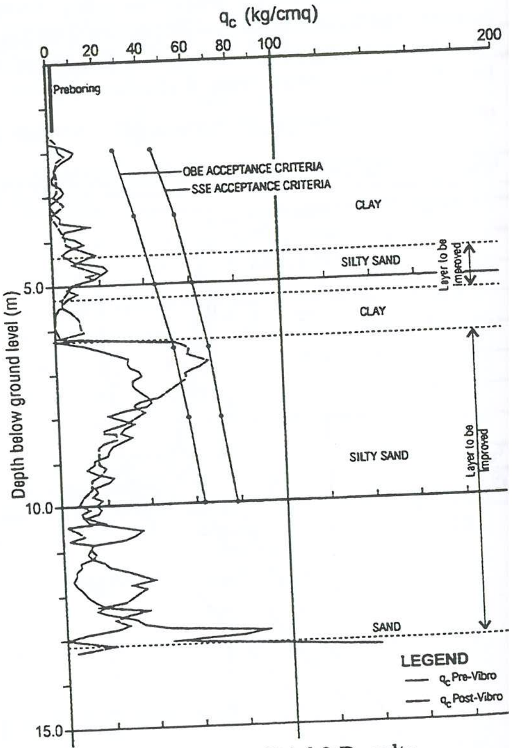

Figure 11: Trial 2 Results

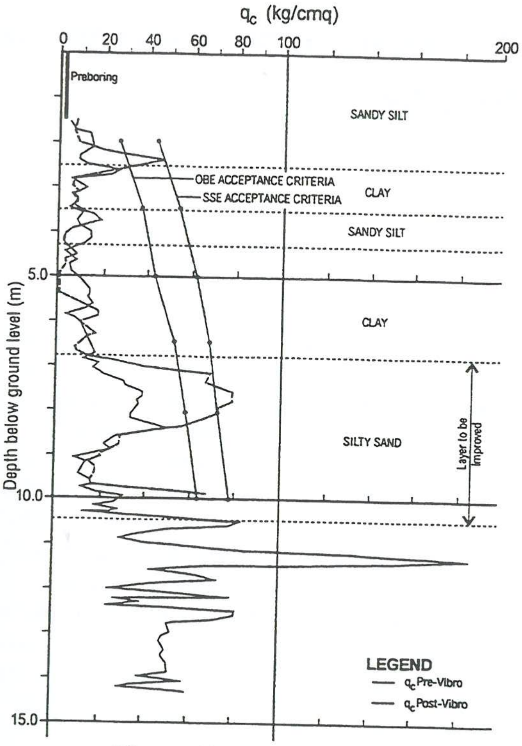

Figure 12: Trial 3 Results

7 DISCUSSION

From the results of the trials, a number of observations can be made.

- The wet method was successful in densifying the sand layers at shallow depths. The improvement in trial 3 was more marked than in trial 2, probably due to the larger diameter stone columns used in trial 3.
- There was little improvement of the silty sand layers at depth in any of the trials.

Therefore, the top feed vibro replacement wet method of stone column installation was not successful at improving all the sand layers, in particular the silty sand layers below about 7 m. There is a potential reason for this: due to the high fines content, the vibrations may have been dampened, preventing densification occurring.

However, as discussed above, although the gradings and the CPTs indicate a high percentage of fines, there is a good deal of published information showing liquefaction can occur with large fines content. Therefore although this high fines content prevents the vibro treatment from improving the silty sand, this does not mean it would not liquefy under earthquake conditions. Therefore, as it had been shown that the vibro stone columns did not improve the ground sufficiently, the piles were designed to resist forces due to liquefaction.

8 REFERENCES

1 Tsuchida H., “Prediction and Countermeasures against liquefaction in sand deposits”, Abstract of the seminar in the Port and Harbour Research Institute pp 3.1-3.33 (in Japanese).

2 Stark T.D. and Olsen S.M., “Liquefaction resistance using CPT and field case histories”, Journal of Geotechnical Engineering, December 1995.

3 Cao Y.L and Law K.T., “Energy approach for liquefaction of sandy and clayey silts”, Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Missouri March 1991.

4 Seed H.B, Tokimatsu K, Harder L.F and Chung R.M., “Influence of SPT procedures in soil liquefaction evaluations”, ASCE Journal of Geotechnical Engineering Vol III No 12 1985, pp 1425-1445.

8 ACKNOWLEDGEMENTS

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