LIQUEFACTION ANALYSIS FOR FOUNDATIONS OF MOTORWAY BRIDGES IN HAWKE'S BAY

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SUMMARY

The results of in-situ Standard Penetration Testing and Cone Penetration Testing were used to assess the soil liquefaction potential at the bridge sites for the proposed extension of the Napier - Hastings motorway. Published correlations between the in-situ tests and field performance of sites subjected to earthquake shaking were used to identify liquefiable soil layers and to estimate the intensity of ground shaking that is likely to cause liquefaction.

A seismic hazard study was compared with the results of the liquefaction analysis to produce a quantitative estimate of the risk of soil liquefaction. This data can be used in an economic assessment of the various options to mitigate the effects of soil liquefaction on the performance of bridge structures in earthquakes.

INTRODUCTION

The first section of a two lane arterial motorway linking Napier and Hastings was opened in 1970, followed by extensions in 1973 and 1975. Investigation and design work is currently underway for additional extensions to the motorway that will require construction of up to five major bridge structures.

The motorway is located within the Heretaunga Plains in Hawke's Bay; a sediment filled depression formed by tectonic subsidence. The Hawke's Bay area is seismically active, and evidence of soil liquefaction, such as sand boils and lateral spreading, has been reported during past earthquakes.

Current design criteria do not explicitly state recommended methods of assessing the potential for soil liquefaction or the possible effects of liquefaction on bridge structures.

CAUSES OF LIQUEFACTION

The upward propagation of shear waves through the ground in an earthquake induces repeated cycles of loading and unloading within the subsoils. These repeated cycles of stress often result in progressively increasing magnitudes of excess porewater pressure within sandy soils. If the porewater pressures build to a magnitude equal to the confining stress, the effective stress is reduced to zero, at which point the granular soil loses its strength and essentially flows like a liquid, hence the term liquefaction.

Even if the induced cyclic porewater pressure does not reach the confining stress, the reduction of effective stress within granular soils and consequent reduction of shear stress can result in significant strains, even in dense dilative sands. This phenomenon is known as cyclic mobility. Although the soil does not suffer a complete loss of strength, the deformations caused by the earthquake may be greater than the structure can tolerate.

In this paper the term liquefaction is used in its generic sense to include cases of complete loss of shear strength and instances of excessive deformation resulting from cyclic mobility.

Some potential effects of liquefaction are sand boils, decreased lateral soil stiffness, landslides, lateral spreading of embankments, settlement or tipping of shallow foundations, ground cracks and buoyancy of buried structures.

The main factors affecting the liquefaction potential of a soil deposit are:

- Intensity of ground shaking;
- Duration of ground shaking;
- Soil type;
- Initial confining pressure;

- Relative density or void ratio.

Soils must also be at or near saturation to experience the porewater pressure increase that leads to liquefaction.

Soils most susceptible to liquefaction are loose, uniform, fine grained sands. Liquefaction potential decreases as the density or the fines content increases. Soils with high plasticity are not likely to liquefy.

SEISMIC HAZARD ANALYSIS

A probalistic seismic hazard evaluation was carried out by the Institute of Geological and Nuclear Sciences (IGNS) [2] for the motorway project area. Some points noted by IGNS in their report are:

- Hawkes Bay lies in one of the most seismically active regions of New Zealand
- At least 11 seismically active faults/folds are within 50 km of the bridge sites
- A magnitude 7.8 earthquake occurred in 1931 along the Napier-Hawke Bay fault. This is considered the Maximum Credible Event and has a return period of 5000 years.

Intensity of ground shaking is related to the level of cyclic shear stress induced by an earthquake. Induced shear stress in the ground is commonly estimated as a function of the peak horizontal ground acceleration (PGA). The return period versus peak ground acceleration relationship determined by IGNS for the project area is presented in Figure 1.

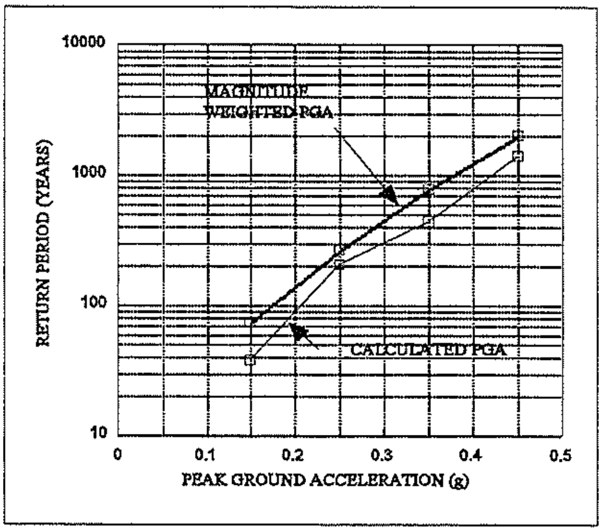

Figure 1: Seismic Hazard Analysis [2]

Other earthquake parameters, such as duration of shaking and frequency content, have significant influence on the potential for soil liquefaction. Generally, earthquakes of higher magnitude are more damaging for a given peak ground acceleration. Magnitude-weighting factors were applied to the peak ground accelerations to account for the difference in various magnitude earthquakes. The magnitude-weighting factor normalizes the PGA with respect to a magnitude of 7½. This magnitude was chosen because most of the field data regarding liquefaction of sands and silty sands is for magnitudes of approximately 7½. Figure 1 also shows the relationship between magnitude-weighted PGA and return period.

ANALYSIS OF LIQUEFACTION POTENTIAL

Grain Size Criteria

Many soils at the bridge sites are described as clay, clayey silt or clayey sand. Both laboratory tests and field performance data have shown that most clayey soils will not liquefy during earthquakes. According to criteria reported by Seed *et al.* [4], soils may be considered non-liquefiable if they meet any of the following conditions:

- Percent finer than 0.005 mm > 15%
- Liquid limit > 35%
- Water content < 0.9 x liquid limit

The limits in the particle size distribution curves proposed by Iai *et al.* [1] may be used as alternate criteria to decide if a soil has a gradation that is susceptible to liquefaction.

In-Situ Tests

The adopted method of evaluating the liquefaction potential at the motorway sites is to compare the critical intensity of ground shaking which is likely to cause liquefaction to the expected intensity of ground shaking for various levels of risk. The critical intensity of ground shaking in the local soils is determined by comparing results of in-situ tests, such as the Cone Penetration Test (CPT) and Standard Penetration Test (SPT), with field observations of the performance of sites subjected to earthquakes in the past where similar tests were carried out.

Seed and De Alba [3] compared the SPT 'N' values at several sites that suffered liquefaction with those that did not liquefy during strong earthquakes. They used these data to derive relationships between the stress ratio (a function of the PGA) causing liquefaction and corrected 'N' values for sands and silty sands shown on Figure 2.

Compared with the SPT, the CPT produces a more continuous profile of subsurface conditions, is less susceptible to variations in test procedures and is quicker. The disadvantages are that no sample is retrieved and fewer data are available to compare the liquefaction resistance of soils to CPT results.

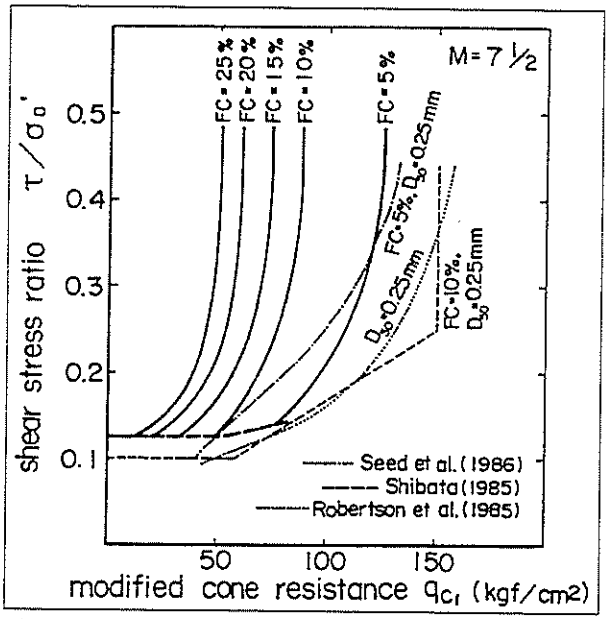

Figure 3: Proposed Correlation Between Liquefaction Resistance of Sands and Cone Resistance [5]

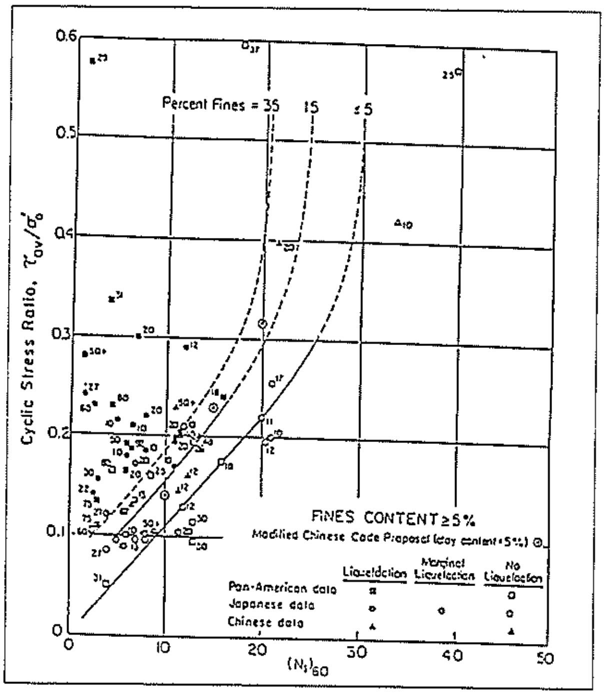

Figure 2: Relationships Between Stress Ratio Causing Liquefaction and N_1 -Values for Silty Sands for M = 7½ Earthquakes [3]

Seed and De Alba [3] used published correlations between SPT and CPT results to convert the SPT-Liquefaction correlation to a CPT-Liquefaction correlation. Sugawara [5] proposed a correlation between liquefaction resistance of sands and CPT cone resistance based on CPT field performance data of previous earthquake sites, and cyclic triaxial testing. Sugawara's correlation, shown on Figure 3, is in good agreement with that suggested by Seed and De Alba and was adopted for assessing the liquefaction potential for the motorway bridge sites.

The adopted procedure for assessing liquefaction resistance at the motorway sites is as follows:

- Eliminate tests in clayey soils and those above the water table

- Calculate the effective overburden pressure at test depth. Correct the measured SPT result (N), or CPT point bearing resistance (q_c), to equivalent values at effective stress of one ton/sq. ft. (95.8kPa) by multiplying by a factor, C_N,

$$C_N = \frac{(\sigma_v' + 0.07)}{0.17} \quad (\sigma_v' \; in\, MPa) \tag{1}$$

- Determine the critical cyclic shear stress ratio to cause soil liquefaction, *CSR*, from Figure 2 for SPT values and Figure 3 for CPT values. Use the curve appropriate for the fines content of the soil being tested.

- Calculate the critical PGA causing liquefaction from the following equation:

$$PGA_{crit} = CSR \times \frac{\sigma_o'}{\sigma_v} \times \frac{1}{0.65} \times \frac{1}{r_d} \tag{2}$$

where:

$$r_d = 1 - \frac{depth^2}{1486} \quad depth\ in\ metres,\ valid\ above\ 30\ m \tag{3}$$

- Compare the calculated critical PGA with the magnitude-weighted PGA on Figure 1 to find the risk of liquefaction for the soil represented by the SPT or CPT test.

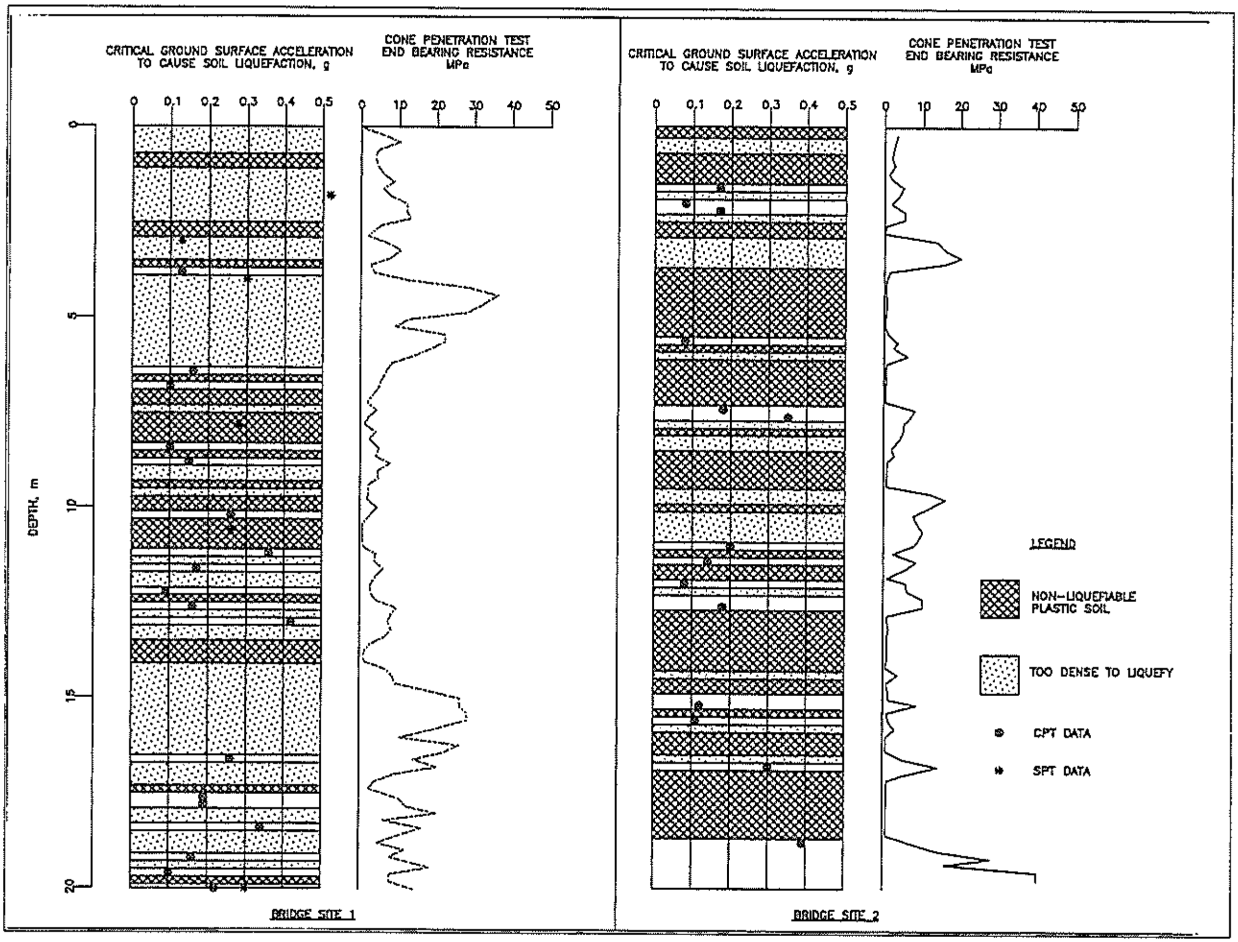

Figure 4: Risk of Soil Liquefaction at the Sites of Two of the Proposed Bridges at the Napier Hastings Motorway

Figure 4 presents the results of the liquefaction assessment for typical data at the motorway bridge sites. Both examples show several layers of soil that are potentially liquefiable at peak horizontal ground accelerations of between 0.08g and 0.42g. This corresponds to a return period for liquefaction of between 120 years and 1500 years.

The measured CPT resistance in thin layers of sandy soil may be influenced by adjacent layers of soft cohesive soils. Vreugdenhil, Davis and Berrill [6] used elastic theory and experimental data from CPT calibration chamber experiments to investigate this effect. They showed that a thin layer could be incorrectly classified as susceptible to liquefaction. Many thin zones of cohesionless material at the motorway sites (some are only 200 mm thick or one CPT measurement) are likely to have higher critical peak accelerations than calculated using the above method. The results of the liquefaction analysis should be interpreted accordingly.

IMPLICATIONS FOR MOTORWAY STRUCTURES

The liquefaction assessment described above is a screening process, based on empirical data, to identify potential liquefaction problems under design earthquake conditions. It does not explicitly determine earthquake soil parameters, such as strength, stiffness or settlement, nor does it predict the consequences of soil liquefaction. Potential effects of soil liquefaction on the motorway bridge structures are described below.

Negative Skin Friction on Piles

Liquefaction of soils at the bridge site would tend to densify the affected soils, causing some surface settlement. The downward movement of the soil induces downdrag on the pile that tends to reduce the usable pile capacity. This condition would be temporary and apply only until the excess porewater pressures within the soil have dissipated after the earthquake.

Reduced Pile Capacity

The rise in pore water pressures decreases the effective confining stress within the soil, which in turn decreases the available shear strength. Analysis methods to estimate the residual strength of liquefied soils are not well developed. A conservative approach is to assume zero shear strength and the lateral stiffness in soil layers identified as liquefiable under design earthquake conditions.

Approach Embankment Failure

Earthquake-induced deformations or excessive settlements in the approach embankments could take bridge structures out of service temporarily until they could be reestablished following the earthquake. In addition, slumping of approach embankments could impose unacceptably large loads on the bridge structure itself.

Liquefaction is not anticipated in the embankment fills since they are above the water table and the embankment fill can be compacted to high densities. Earthquake-induced failures will more likely take the form of lateral spreading or slumping because of liquefaction in the foundation soils.

Lateral Loads

Lateral loads on abutment retaining walls would be increased during earthquake shaking because of inertial loads of the retained soil. Liquefaction of the retaining wall's foundation would lower the resistance to sliding and may result in a bearing capacity type failure.

GROUND IMPROVEMENT

Several methods can be considered to modify the properties of the in-situ soils to reduce the potential for liquefaction and/or reduce its damaging effects. The goal of the ground improvement programme is to increase the liquefaction resistance of the ground by either densifying the susceptible soils or providing additional shear strength that is not reduced by earthquake shaking.

Preloading

Ground treatment by preloading involves placing a precompression load, usually earth fill, on top of the ground to be treated before the construction of the proposed structure. Preloading treatment may be recommended to reduce the post construction settlement of the approach embankments, and for densifying the foundation soils to improve their liquefaction resistance.

The effect of preloading is felt mainly in the near surface soils where the applied pressures are the highest. This method therefore has limited effect on performance of pile foundations.

Heavy Tamping

This technique consists of dropping a heavy steel or concrete weight repeatedly on the surface of the ground to be treated. The strain waves generated by these impacts rearrange the soils into a denser state, which may be expected to have a greater resistance to liquefaction. Using conventional lifting equipment, silty sands and sands may be treated to depths of 10 to 12 metres.

Vibro Processes

Several types of vibrators are available which are inserted in the ground to densify the in-situ soils. Vibrating probes, combined with water jetting can reach significant depths of penetration. Variations of this technique (known as vibro-replacement or stone column methods) include techniques in which soil washed out during the jetting are replaced with coarse materials that are then compacted as the probe is withdrawn.

Blasting

Deep compaction of saturated sands has been achieved by detonating buried explosives. No generally accepted theoretical design procedures are available for densification by blasting, and field trials are usually carried out before production blasting.

Injection and Grouting

This class of ground improvement includes techniques such as cement injection or deep lime mixing and compaction grouting. These techniques create chemical bonds to provide additional shear strength in the soil, or, act as a radial hydraulic jack to compress the surrounding soil.

Embankment Reinforcement

The risk of lateral spreading of the embankment fills could be reduced by installing structural elements within the fill, such as plastic geogrids, which impart some tensile strength to the fill. Additional benefits from use of embankment reinforcement may also be realized, such as reduced batter angles. In abutment areas, where embankment failure could affect structural components of a bridge designing the reinforcement to encourage failure in a direction that will not affect the structural components may be possible.

CONCLUSION

Empirical methods of comparing the results of in-situ CPT and SPT results to field performance of sites that have undergone liquefaction have been used to assess the risk of soil liquefaction at the sites of several bridge structures at the proposed extension to the Napier to Hastings motorway. Soil layers that have the potential to liquefy in an earthquake have been identified.

Correlations between the results of in-situ tests and the field performance of sites subjected to earthquakes are often used to determine a profile of critical SPT or CPT results for given design earthquake parameters. This is plotted against measured SPT or CPT values to assess the potential of the soil to liquefy under those earthquake conditions.

For the present study, these correlations were used to find critical peak ground acceleration required to cause liquefaction at each bridge site. A quantitative estimate of the risk of liquefaction at each site can be made by comparing the critical peak ground acceleration to the magnitude-weighted peak ground accelerations calculated in seismic hazard assessment. This can then be used in a risk based economic assessment of the available options to mitigate against soil liquefaction.

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