A PROCEDURE IN ENGINEERING ANALYSIS TO EVALUATE THE LIQUEFACTION POTENTIAL OF THE SOIL

AWAD ALI AL-KARNI
King Saud University, Saudi Arabia

ABSTRACT

Malaysia is now becoming concerned about the affects of earthquakes centred in the neighbouring Indonesia. This paper is an example how researchers in another country study the liquefaction effects due to ground movements. The standard penetration test (SPT) procedures are used to evaluate the liquefaction potential of the sandy soil with fines less than 35%. In this paper, the procedures were simplified by transferring the data needed from the analysis charts to best fit formulas. These procedures were used to evaluate the liquefaction potential of the soil at the location of the University of Jazan in Jazan City which lies on the east side of the Red Sea, in the south-west of the Kingdom of Saudi Arabia. Jazan City is located in an active zone of earthquakes classified as zone 2B with maximum applied horizontal acceleration of 0.2g. Many boreholes soil samples were taken at different locations around location of the University and the soil type was found to have a wide variety from sand to silt-clay mixture. Since the water depth was located at shallow depth of less than 2 m from the ground surface, the soil could be subjected to liquefaction due to the tremor of the future earthquakes. The liquefaction potential of the saturated soil up to depth of 25 m below the ground surface was assessed. By using the SPT procedures, the variation of the safety factor against the liquefaction potential with the depth of the soil was drawn at the locations of the boreholes. The results show that the top 10 m of soil at University of Jazan has high susceptibility of liquefaction.

Keywords: *Soil, Liquefaction, Earthquake, Jazan, Saudi Arabia*

1. INTRODUCTION

One of the major problems in geotechnical earthquake engineering is the phenomenon of liquefaction of loose to medium-dense sands below the water table. Liquefaction is defined as the reduction of the soil shear strength when subjected to undrained (constant volume) loading, whether that loading is monotonic, cyclic, or dynamic. In case of earthquakes, during tremor, the sand tends to compact. The water in the pores cannot escape quickly enough, at least in the finer sands, to accommodate instantaneously the compaction. Therefore stresses are thrown on the water which increase the pore water pressure and reduce the effective or intergranular stresses between the sand particles. Sand depends on the effective stresses between the grains to mobilize shear strength and resist the displacement. Therefore the increasing pore water pressure leads to strength loss. When pore water pressure equals to the total stresses, the sand loses its shear strength completely and behaves like viscous fluid. Since it only occurs in saturated soils, liquefaction is most commonly observed near rivers, bays, offshore, and other bodies of water.

Jazan City lies on the east side of the Red Sea, in the south-west of the Kingdom of Saudi Arabia (see Figure 1). It is located in an active zone of earthquakes that is classified as 2B earthquake zone with maximum applied horizontal acceleration of 0.2g Al-Haddad, et al. (1994). The geotechnical aspects of Jazan soil were studied by many authors as (Dhowian et al., 1987; Erol, 1989; Dhowian, 1990; Al-Shamrani and Dhovian, 1997). The city of Jazan is situated on an elevated terrain underlain by a salt dome measuring 4 km^2 in area and reaching about 50 m above sea level. The salt dome is surrounded by vast areas of sabkha flats and wind-blown sand stretching north and south for approximately 190 km. The sabkha sediments possess highly variable profile characteristics with regard to the soil composition. The subsoil profiles in the

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coastal zones (close to shoreline) consist of loose fine sand, whereas the subsoil profile of inland zones are characterized by very soft clay and silt with appreciable organic material (Al-Shamrani, 1997). The three zones characterization of this soil profile include: (1) sabkha crust; (2) compressible sabkha complex; (3) sabkha base. The sabkha crust is relatively thin dry silt sand soil of an average thickness of about 2.0 m existing above the water table which is 1-2 m of the ground surface. This layer appears to be of hard nature but highly susceptible to loose its strength instantaneously upon saturation. The compressible sabkha complex is soft, loose material composed of soils varying from non-plastic silty, clayey fine sand to highly plastic organic clays and silts with thickness up to 8 m. The sabkha is a firm stratum consisting mainly of medium dense to dense sand with relatively high bearing capacity and low compressibility characteristics.

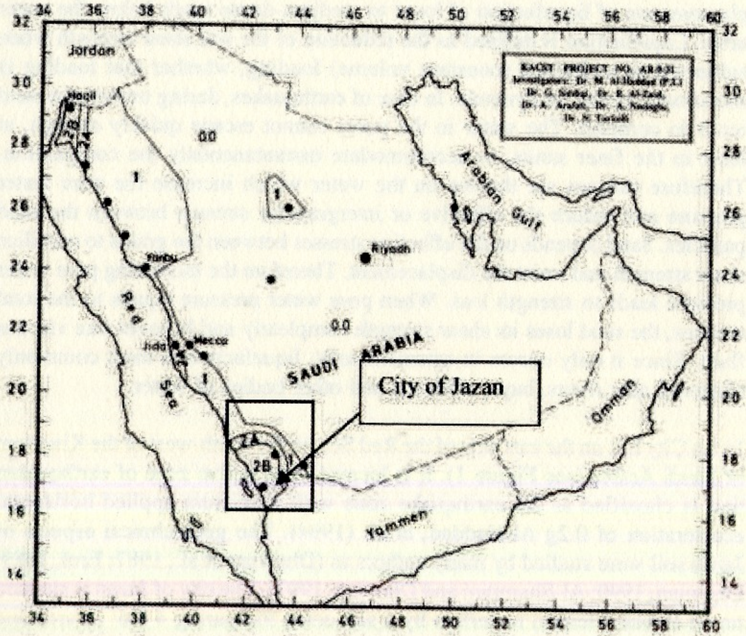

Figure 1. Seismic zonation map of Saudi Arabia (Al-Haddad, 1994).

Jazan City is part of the south and the southwest of Arabian plate and is an active spread of the sea floor along the axial troughs in the Gulf of Aden and the Red Sea. The historical event of 1121 AD with the magnitude of 6.8 offers a significant indication of the future potential for seismic hazard in the region Ambraseys (1998). Due to an expected strong event in the future and shallow water table and fine sand, the evaluation of the liquefaction potential of the soil is needed.

The liquefaction potential of the subsurface saturated sandy soil is assessed by the use of cyclic stress approach in conjunction of the standard penetration test (SPT) procedures. The cyclic stress ratio (CSR) of the saturated sandy soil with fines less than 35% was assessed by the use of the standard penetration test (SPT) according to the established method of Seed et al. (1983) and Seed et al. (1985). These procedures are based on the data from the analysis charts which are difficult to program. Youd and Idriss (1997) transferred the data of these charts into formulas with long expressions and many parameters. In this paper, new formulas were developed to transfer the data from the analysis charts into mathematical expressions with fewer parameters using the best fit techniques. The new formulas will be used in evaluating the liquefaction potential of the soil at the location of the University of Jazan in Jazan City. For plastic soil at the location with fines more than 35%, the CSR is evaluated using the proposed nonlinear relationship by Parakash and Tianqiang (1998).

2. THE PROCEDURES OF THE SPT

The SPT method of field testing has been used in this study to evaluate the liquefaction potentials. The irregular time history of the design earthquake needs to be replaced by an equivalent number of uniform cyclic shear stresses to apply in the empirical procedures. Seed et al. (1983) suggested the following relationship,

$$\lambda_c = 0.65\sigma_v \frac{a_{\max}}{g} r_d \qquad (1)$$

Seed et al. (1983) also suggested that this uniform cyclic shear stress to be normalized by dividing it by the effective overburden stress as,

$$CSR = \frac{\tau_c}{\sigma'_{vo}} = 0.65\frac{\sigma_v}{\sigma'_{vo}}\frac{a_{max}}{g}r_d \qquad (2)$$

Where

CSR	= cyclic shear stress ratio.
l_c	=equivalent average shear stress.
s_v	= total overburden stress.
s'_{vo}	=effective overburden stress.
a_{max}	=maximum surface acceleration in units of g
g	= acceleration due to gravity.
r_d	=a reduction factor to account for soil flexibility and depth.

Figure 2 shows the variation of the factor r_d with depth in accordance to Seed et al. (1971) and can be calculated using the following polynomial function as

$$r_d = 0.98 + 0.004 * \left(\frac{Z}{0.3048}\right) - 2.55E\text{-}4 \cdot \left(\frac{Z}{0.3048}\right)^2 + 1.6E\text{-}6 \cdot \left(\frac{Z}{0.3048}\right)^3 \qquad (3)$$

Where Z = depth in meters.

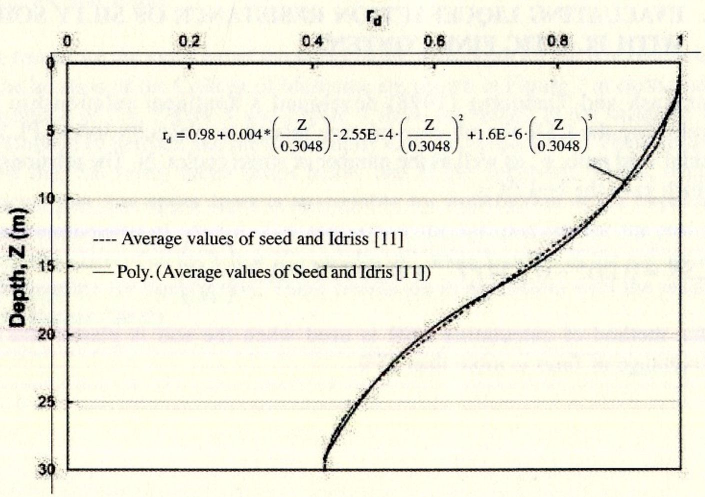

Figure 2: Variation of average value of reduction factor with depth.

A correlation between the SPT N-value (i.e. $(N_1)_{60}$) and the cyclic shear stress ratio to cause liquefaction (CSR_{crit}) during earthquake of magnitude M=7.5 is shown in Figure 3. Lower bound curves separating liquefied from non-liquefied sites are shown corresponding to various fines contents. These curves can be represented by the following relationship

$$CSR_{M=7.5} = a \cdot \exp^{b \cdot (N_1)_{60}} \qquad (4)$$

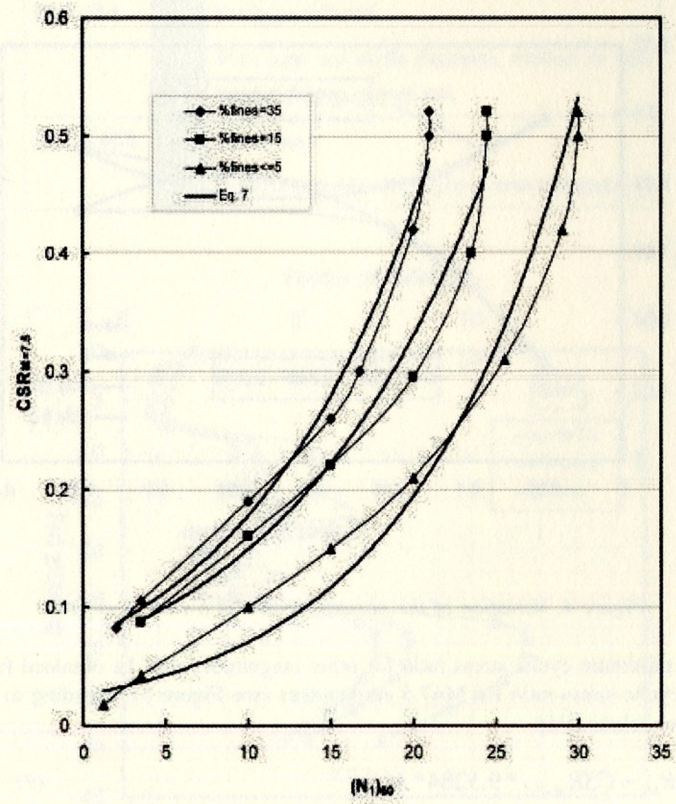

Figure 3. Relationship between cyclic stress ratios causing liquefaction and (N_1) values for silty sands in M=7.5 earthquakes (Seed et al., 1983).

Where a and b are parameters and their variation with the percentage of fines (F) are shown in Figure 4 and can be expressed as function of F as:

$$a = -1.24F^2 + 0.645F - 0.0016 \quad (5)$$

and

$$b = 0.82F^2 - 0.357F + 0.1146 \quad (6)$$

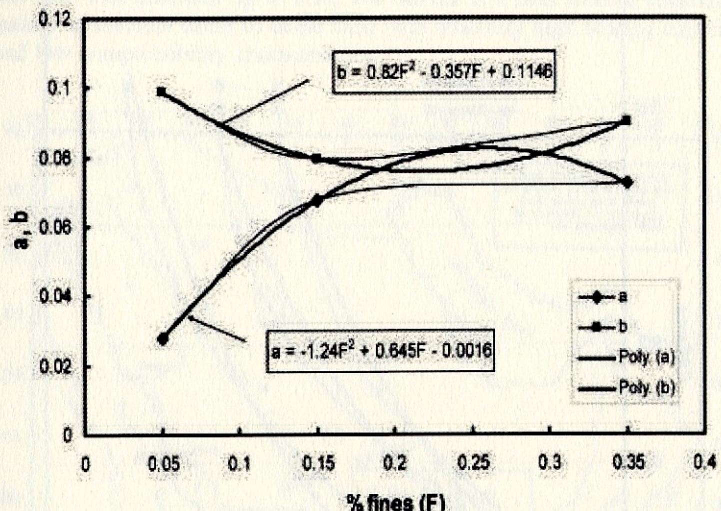

Figure 4. Variation of the parameters a and b with % of fines.

The minimum cyclic stress ratio for other magnitudes may be obtained from the cyclic stress ratio for M=7.5 earthquakes (see Figure 5) according to the power relationship

$$CSR_M = CSR_{M=7.5} * 9.5284 * M^{-1.1123} \quad (7)$$

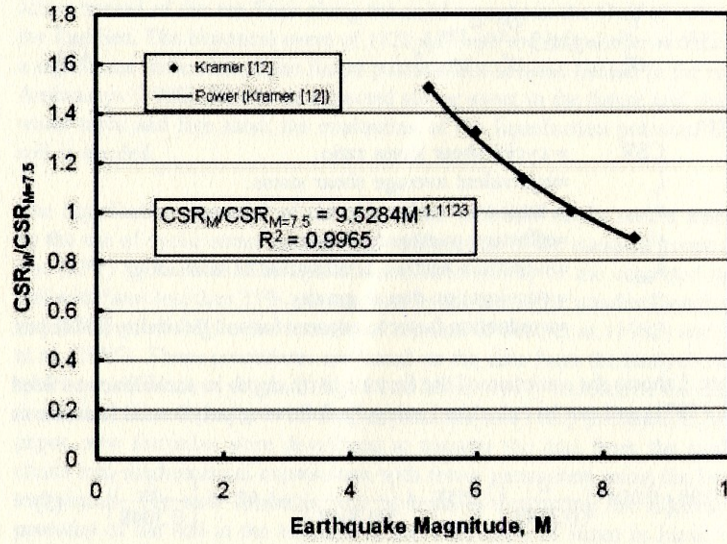

Figure 5. Variation of $CSR_M/CSR_{M=7.5}$ with earthquake magnitude.

3. EVALUATING LIQUEFACTION RESISTANCE OF SILTY SOILS WITH PLASTIC FINE CONTENT

Parakash and Tianqiang (1998) developed a nonlinear relationship for evaluating the CSR for silt-clay mixture related to plasticity index, PI, and initial void ratio, e_o, as well as the number of stress cycles, N. The relationship which gave the best fit is:

$$CSR = 0.065 - 0.234PI^{0.5} + 0.057PI + 0.34\left(\frac{e_o}{N}\right)^{-0.028} \quad (8)$$

This method of calculating CSR is used when the soil is plastic and the percentage of fines is more than 35%.

4. LIQUEFACTION POTENTIAL IN THE STUDY AREA

The study area is limited to the data collected from 41 boreholes at the location of the University of Jazan. The required data for evaluating the liquefaction potential were collected by conducting SPT tests and some laboratory tests. The SPT tests were conducted in the boreholes for every 2 m of depth up to 25 m. The depth of water table was determined for each borehole. The variation of the soil classification along the borehole depth was determined by analyzing the soil samples. The soil density and the water content were determined along the borehole. For plastic soil, Atterberg limits, and initial void ratio were determined. The soil liquefaction susceptibility was evaluated at each point of SPT test along the depth of the borehole.
A summary of the soil classifications along the boreholes at the location of the College of Medicine are shown in Table 1. Using the corrected N values for magnitudes of earthquake intensity of M=7.5, the variation of the factor of safety against the liquefaction potentials with depth of the soils at borehole #1 is shown in Figure 6. At the expected maximum magnitude of 6.8, the soil within the depth of 2.5 m to 7.5 m is susceptible for liquefaction. A comparison of the variation of the safety factor with depth at earthquake magnitudes of 5, 6.8, and 7.5 is shown in Figure 6. At this borehole site, the soil will not reach the liquefaction stage until the earthquake magnitude exceeds 5 where the safety factor against liquefaction at this magnitude becomes greater than one along the soil depth.

The results for the variation of the safety factor with depth for the five boreholes at the location of the College of Medicine are shown in Figure 7 at earthquake magnitude of 6.8. Figure 8 and Figure 9 show the results at the locations of the College of Science and the Community College, respectively. These results show that the safety factor drops below one in the upper ten meters, which indicate that this upper layer is susceptible for liquefaction at the expected future earthquake of M=6.8. The analysis of the soil profiles for the rest of boreholes shows that the upper 10 m of the soil in the location of the university is susceptible for liquefaction. These results are in agreement with the results of Al-Refeai (2002).

Table 1. General Classification of the Soil along the Boreholes.

Depth (m)	Soil Classification
0.0 to 1.5	Fill
1.50 to 9.0	Silty sand Loose to very loose, brown to dark gray, wet
9.0 to 25.5	Poorly graded sand With coral and shells fragments, medium to very dense, light gray to gray, wet.
25.5 to 40.0	Clayey sand Dense to very dense, light gray to brownish gray, wet

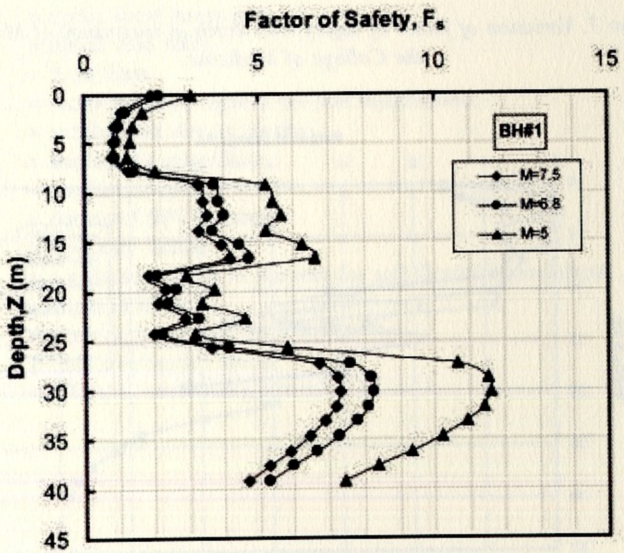

Figure 6. Variation of factor of safety with depth for borehole #1 at different magnitude.

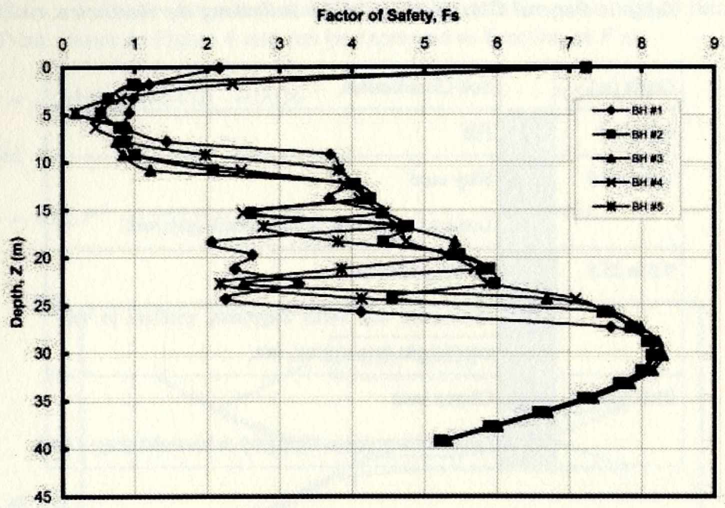

Figure 7. Variation of factor of safety with depth at magnitude of M=6.8 at the College of Medicine.

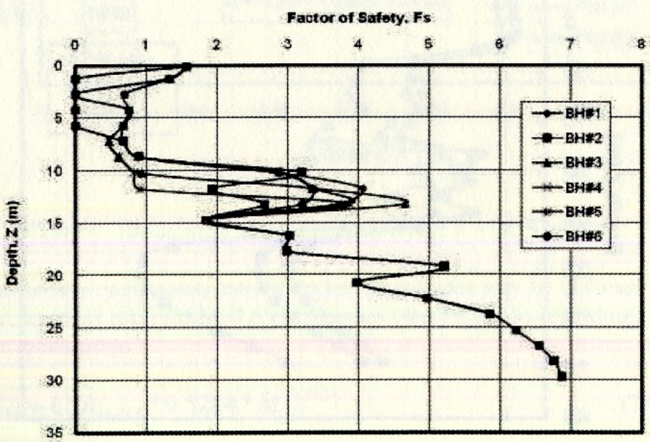

Figure 8. Variation of factor of safety with depth at magnitude of M=6.8 at the College of Science.

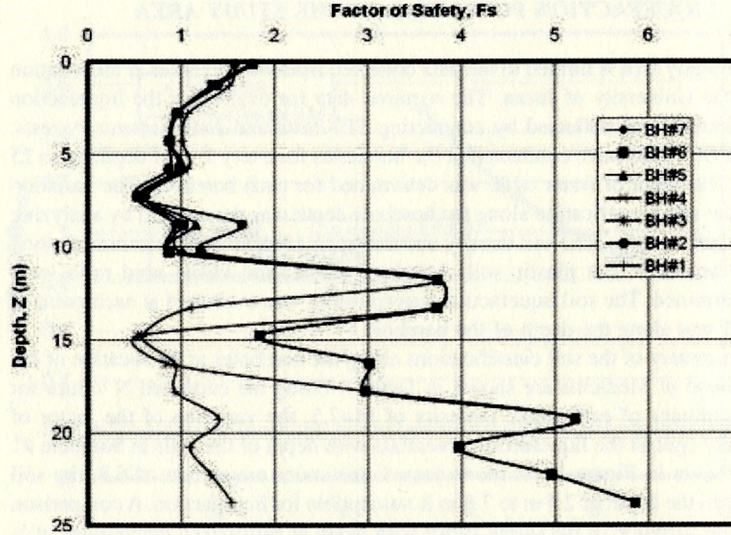

Figure 9. Variation of factor of safety with depth at magnitude of M=6.8 at the Community College.

5. CONCLUSIONS

The procedures of the SPT for evaluating the liquefaction potential of the soil were simplified by transferring the data from the analysis charts into formulas with short expressions and few parameters. Then, the liquefaction potential of the subsurface saturated soil at the location of the University of Jazan in the city of Jazan in the southwest of Saudi Arabia was assessed by the use of these procedures using the new expressions. The results of the analysis of liquefaction of the 41 boreholes show that the soil at the top 10 m in the area of the university has high susceptibility of liquefaction at earthquake magnitude of more than 5. These results should be considered in designing the foundation systems for the buildings of the University of Jazan to reduce the risk of any future earthquakes in the region.

6. ACKNOWLEDGEMENT

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NOMENCLATURE

a_{max} = maximum surface acceleration in units of g.
CSR = cyclic shear stress ratio.
e_o = initial void ratio.
Fc = % of fines.
Fs = factor of safety against the soil liquefaction.
g = acceleration due to gravity.
M = earthquake magnitude.
N = number of cycles.
$(N_1)_{60}$ = corrected SPT number.
PI = plasticity Index.
r_d = a reduction factor to account for soil flexibility and depth.
Z = depth in meter.
l_c = equivalent average shear stress.
s_v = total overburden stress.
s'_{vo} = effective overburden stress.