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A Comparative Study on Methods of Estimating Liquefaction for Diyala Soil

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ABSTRACT

The phenomenon of liquefaction is one of the most important problems in engineering projects. It occurs in saturated sandy soils during the occurrence of earthquakes. Methods based on the standard penetration test (SPT) were developed to calculate the liquefaction potential according to the seismic loads. These methods have been developed and updated over time by some researchers. This paper analyses the comparison between methods of calculating liquefaction potential. The case study that was selected for the analysis of the comparison methods is Diyala Governorate soil. The methods that have been chosen for making a comparative analysis are the Japanese method, National Centre for Earthquake Engineering Research 1997 (NCEER) workshop, Task Force Report 2007 (Vancouver) and Boulanger and Idriss 2014. The analysis of results stated that the Boulanger and Idriss method is considered more suitable than others for calculating the potential for liquefaction in Diyala Governorate soil. It is found that the Boulanger and Idriss method has higher safety factor than the two methods (80.7% from Vancouver and 38.8% from the NCEER workshop) and less than the Japanese method.

1. Introduction

Soil liquefaction is one of the hazardous phenomena of earthquakes. This phenomenon occurs due to seismic tremors, which causes the pressure of the pore water to increase, causing the soil to lose its shear strength significantly. Consequently, it leads to a failure in the surface of the earth, causing damage to buildings and loss of life. Therefore, this phenomenon is a topic of great importance to civil engineers, in particular geotechnical engineers. Where the potential for liquefaction of soil can be calculated using two methods:(1) a laboratory examination method for non-disturbed soil models, (2) method of using empirical relationships based on field tests. The used field tests in calculating the potential for soil liquefaction are (1) Standard penetration test SPT, (2) cone penetration test CPT, (3) Becker penetration test BPT and (4) Shear wave velocity Vs [1]. In general, the use of field tests is due to the fact that laboratory tests are complicated and expensive to implement, in comparison with field tests that are more common to use and easy to perform. It is older and is still used in calculating liquefaction potential. In this study, the SPT field test has been selected to calculate the liquefaction potential of Diyala Governorate soil.

Several methods based on SPT values have been used in the calculation of liquefaction potential. The SPT-based method for calculating the liquefaction potential that has been used over the last four decades was originally proposed by [2], in fact this method has been developed, modified and updated over time by some researchers. A calculation method based

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on SPT was proposed and developed by (12) and was called it (simple geotechnical analysis). This method was the approach that used the factor of safety in the liquefaction capacity of the soil. It is called Japanese Bridge Code.

The NCEER method, in 1996 was sponsored by the (National Center for Earthquak Engineering Research) workshop, Professor Youd and IIdriss met 20 experts to redevelop the calculation method proposed in (1985). Its purpose was to obtain consensus on updates and enhancements on the simplified procedure. Where the following topics were reviewed and recommendations were made (1) SPT examination standards, (2) CPT examination standards, (3) Vs examination standards, (4) use of BPT in gravel soils, (5) calculations for the magnitude scaling factor (MSF), (6) correction coefficients (overburden pressures, ground inclination), (7) enter values for earthquake and maximum acceleration.

Either in the third method, the Task Force Report (Vancouver), this method created working group consensus on best practices for geotechnical design for buildings on a liquefaction site in Greater Vancouver. These recommendations and opinions that came in the report are specific to the members of the working group and not to their organizations [3]. It started in 1991 and consisted of a group of local structural and geotechnical engineers who produced a report entitled Seismic Design in the Fraser Delta (Task Force Report 1991). It was also updated over time to the year 2005.

As for [4], it is a method that has been updated and developed more than once. In its infancy, it mainly used cases that were summarized by [5] and [6, 7]. The databases were then updated by [8]. The updated database included more case histories. These databases continue to support previously derived relationships to derive correlations. The total number of case histories in the updated database became 230, of which 115 cases indicated the presence of liquefaction, 112 cases were indicative of the presence of liquefaction, and 3 cases were between liquefaction and not [9].

Calculation of the liquefaction potential can be addressed by means of a deterministic and probabilistic approach. In deterministic approach soil liquefaction response is defined by the safety factor (FS). The safety factor is defined as the ratio of cyclic resistance ratio (CRR) devided by cyclic stress ratio (CSR). If the values of the safety factor are less than or equal 1, it indicates the possibility of liquefaction, If the safety factor is greater than 1, then liquefaction does not occur [10]. Also, many of studieds deals with evaluation of liquiefaction are introduced by [26, 27, 28, 29 and 30]. The purpose of this study is a comparative analysis of the potential for liquefaction of four methods, namely, the Japanese method, the NCEER 1997 workshop method, the Task Force Report 2007 method and the Boulanger and Idriss 2014 method.

2. Case study area

The case studied is Diyala Governorate soil. It is one of the governorates of Iraq. Diyala is situated at a Latitude 33º N and a Longitude 45º E, East of the capital Baghdad and on the western borders of Iran, an area of about 17685 km2, the population of more than 1.6 million. With a population density of 89.6 persons per km2, Diyala region is located Northeast of Arabian Plate and near the Turkish and Iranian plates, at 35- 600 m above mean sea level (MSL) [11].

3. Liquefaction calculation methods

All four methods work are used to extract the safety factor, but each method calculates the parameters in a slightly different way from the other and as shown in the following:

3.1 Japanese bridge code

The method for the specifications of Highway bridges (TC4-ISSMGE, 1999) is based on the procedure developed by [12] termed “simple geotechnical analysis”.

The result of soil liquefaction is calculated by adding three factors by taking overburden pressure, fine content and grains size in the calculations [13].

To evaluate factor of safety FS in equation bellow:

$$FS = \frac{R}{L} \quad (1)$$

where: R is the cyclic resistance ratio, and L is the cyclic stress ratio.

$$R = R_1 + R_2 + R_3 \quad (2)$$

$$R_1 = 0.0882\sqrt{\frac{N}{\sigma'_v + 0.7}} \quad (3)$$

where: σ'_v is the effective overburden pressure, N is the value measured with the SPT-equipment most commonly used in Japan which is calculated according to equation as follows [13]:

$$N = 0.833(N1)_{60} \quad (4)$$

$$R_2 = \begin{cases} 0.19 & , 0.02mm \le D_{50} < 0.05mm \\ 0.225\log\left(\frac{0.35}{D_{50}}\right) & , 0.05\text{mm} \le D_{50} < 0.6mm \\ -0.05 & , 0.6mm \le D_{50} < 2.0mm \end{cases} \quad (5)$$

$$R_3 = \begin{cases} 0 & , \ 0 \le D_{50} \le 40\% \\ 0.04FC - 0.16 & , \ 40\% < D_{50} \le 100\% \end{cases} \quad (6)$$

where: D_{50} is the mean grain size and FC is the fine content.

The cyclic stress ratio induced in soil is calculated as follows:

$$L = \left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_v}{\sigma'_v}\right) r_d \quad (7)$$

where: σ_v is the total overburden pressure, a_{max} is the peak surface acceleration, g is the acceleration of gravity (980 cm/s2) and r_d is stiffness reduction coefficient factor.

$$\mathrm{r_d} = 1 - 0.015 * \mathrm{Z} \quad (8)$$

where: Z is the depth in meter below the ground surface.

3.2 National Centre for Earthquake Engineering Research (NCEER) workshop 1997

To evaluate the factor of safety FS by this method as follows [14]

$$FS = \frac{CRR_{7.5}}{CSR} * MSF * K_\sigma * K_\alpha \quad (9)$$

where: CRR7.5 is the cyclic resistance ratio for magnitude 7.5 earthquakes CSR is the cyclic stress ratio MSF is the magnitude scaling factor K_σ is a correction factor for effective overburden stresses; and K_α =1 is a correction factor for ground slope Seed and Idriss (1971) [2] create the following equation to calculate of the cyclic stress ratio:

$$CSR = \frac{\tau_{av}}{\sigma'_v} = 0.65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_v}{\sigma'_v}\right) r_d \quad (10)$$

The following equations used to estimate values of r_d (Liao and Whitman (1986b)) [15]

$$r_d = 1.0 - 0.00765 * Z \ \ , Z \le 9.15m \quad (11a)$$
$$r_d = 1.174 - 0.0267 * Z, 9.15 < Z \le 23m \ (11b)$$

Some investigators have suggested additional equations for estimating r_d at greater depths (Robertson and Wride 1998) [25]

$$r_d = 0.744 - 0.008 * Z \quad , 23 < Z \le 30m \ \ (11c)$$

William F. Marcuson [16]

$$r_d = 0.5 \qquad , Z > 30 \qquad (11d)$$

Thomas F. Blake creates the following equation and it is valid for $(N1)_{60}$ less than 30 [16]:

$$CRR_{7.5} = \frac{a + cx + ex^2 + gx^3}{1 + bx + dx^2 + fx^3 + hx^4} \quad (12)$$

where: x=$(N1)_{60}$, a=0.048, b=-0.1248, c=-0.004721, d=0.009578, e=0.0006136, f=-0.0003285, g=-0.00001673, h=0.000003714

$$(N1)_{60} = NC_N C_E C_B C_R C_S \quad (13)$$

where: N is the SPT blow count, CN is a correction factor of overburden pressure, CE is hammer energy correction factor, CR is a correction factor of rod length, CB is a nonstandard borehole diameters correction factor, and CS is a using split spoons correction factor.

$$C_N = \left(\frac{P_a}{\sigma'_v}\right)^{0.5} \quad (14)$$

A magnitude scaling factor (MSF) works to correct the safety factor (FS) when the magnitude of earthquake is not equal 7.5:

$$MSF = \frac{10^{2.24}}{M^{2.56}} \quad (15)$$

I.M. Idriss developed the following equations with help from R.B. Seed are recommended to correcting the resistance of standard penetration determined for silty sands to an equivalent the resistance of clean sand penetration:

$$(N1)_{60cs} = \alpha + \beta(N1)_{60} \quad (16)$$

$$\alpha = \begin{cases} 0 & , \quad (FC \leq 5) \\ exp\left(1.76 - \left(\frac{190}{FC^2}\right)\right) & , \quad (5 < FC \leq 35) \\ 5 & , \quad (35 \leq FC) \end{cases} \quad (17)$$

$$\beta = \begin{cases} 1 & , \quad (FC \leq 5) \\ \left(0.99 + \left(\frac{FC^2}{1000}\right)\right) & , \quad (5 < FC \leq 35) \\ 1.2 & , \quad (35 \leq FC) \end{cases} \quad (18)$$

Equations (15, 16, 17) yield values that are essentially identical in equation (11).

To evaluate correction factors K_σ from figure (1) below:

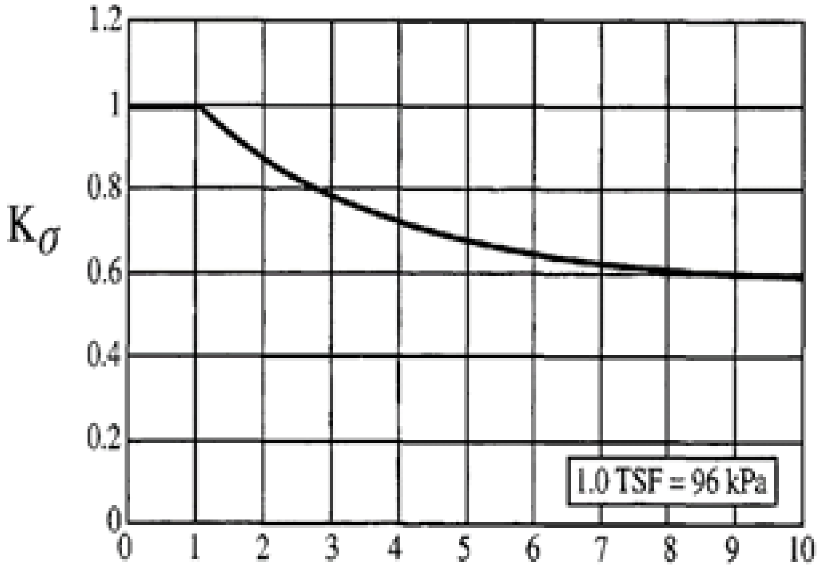


Figure 1. Minimum values for K_σ, recommended for clean and silty sands and gravels [17]

3.3 Task force report 2007(Vancouver)

$$FS = \frac{CRR}{CSR} \quad (19)$$

$$CSR = 0.65 * \frac{\sigma_v}{\sigma'_v} * a_{max} * r_d \quad (20)$$

The values of r_d can be obtained from Equation (20). It is derived from the r_d values given by [14]

$$r_d = 1 \qquad for\ Z \leq 4m \quad (21a)$$
$$r_d = 1 - 0.015 * (Z - 4) \geq 0.6 for\ Z > 4m (21b)$$

$$CRR = CRR_1 * K_m * K_\sigma * K_\alpha \quad (22)$$

where: K_m is a correction factor for earthquake magnitudes other than 7.5;

$$K_\alpha = 1 \quad (23)$$

$$K_\sigma = \left(\frac{\sigma'_v}{P_a}\right)^{f-1} \quad (24)$$

where Pa is atmospheric pressure in the chosen units, f depends on relative density, Dr, and given by:

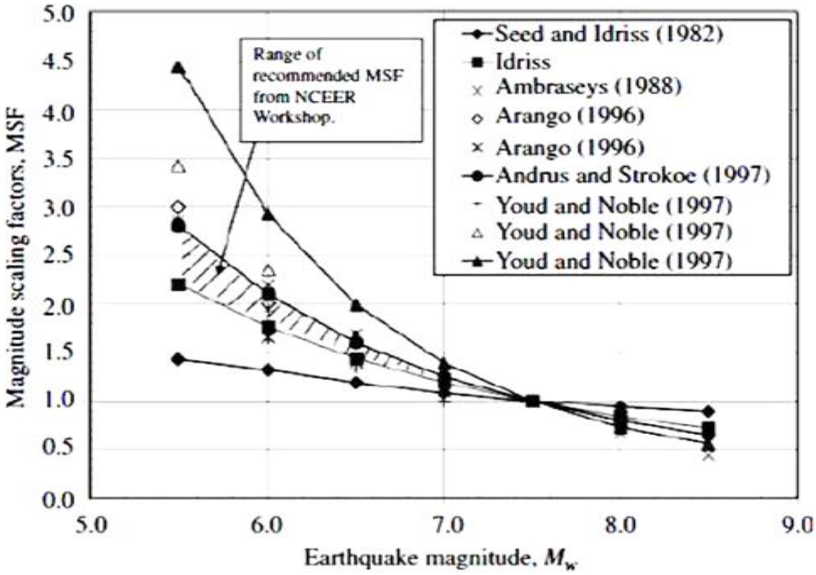


Figure 2. Magnitude scaling factors derived by various investigators [18, 19]

$f = 1 - 0.005 * D_r \quad for\ 40\% < D_r < 80\%$ (25)

Dr ≤ 80% can be estimated using:

$$D_r = \left[\frac{(N1)_{60}}{46}\right]^{0.5} * 100 \tag{26}$$

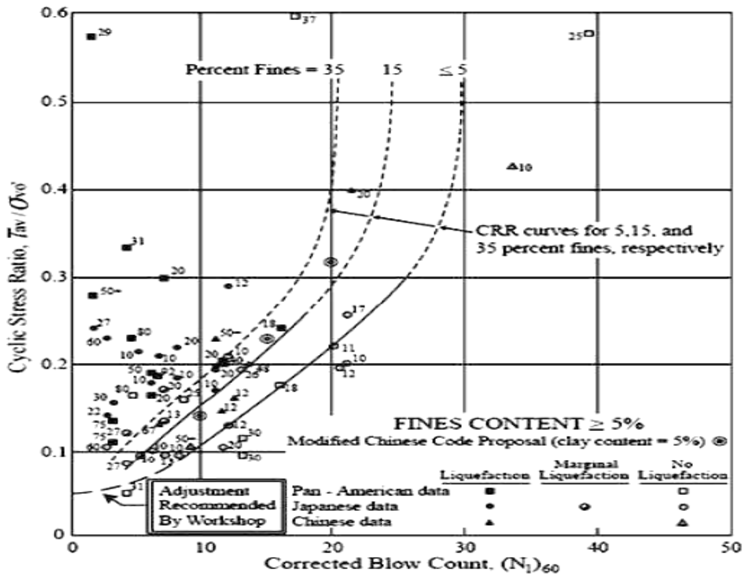


Figure 3. Base curve recommended to calculation of CRR_1 from SPT data (modified from the Seed et al., 1985) [20]

3.4 Boulanger and Idriss 2014

$$FS = \frac{CRR_{M,\sigma'_v}}{CSR_{M,\sigma'_v}} \tag{27}$$

$$CSR_{M,\sigma'_v} = 0.65\frac{\tau_{max}}{\sigma'_v} = 0.65\frac{a_{max}}{g}\frac{\sigma_v}{\sigma'_v}r_d \tag{28}$$

The parameter rd could be expressed as, (Idriss 1999) [21]

$$r_d = exp[\alpha(z) + \beta(z).M] \tag{29}$$

$$\alpha(z) = -1.012 - 1.126sin\left(\frac{z}{11.73} + 5.133\right) \tag{30}$$

$$\beta(z) = 0.106 + 0.118sin\left(\frac{z}{11.28} + 5.142\right) \tag{31}$$

$$MSF = 6.9exp\left(\frac{-M}{4}\right) - 0.058 \quad \leq 1.8 \tag{32}$$

Idriss and Boulanger (2008) [19] recommended the resulting $\boldsymbol{K_\sigma}$ be expressed in term of (N1)60cs values as follows:

$$K_\sigma = 1 - C_\sigma ln\left(\frac{\sigma'_v}{P_a}\right) \leq 1.1 \quad (33)$$

$$C_\sigma = \frac{1}{18.9 - 2.55\sqrt{(N1)_{60cs}}} \leq 0.3 \quad (34)$$

$$(N1)_{60} = NC_N C_E C_R C_B C_S \quad (35)$$

Idriss and Boulanger (2003, 2008) [22, 23] subsequently suggested shear stress reduction factor, rd, relationship recommended that the Dr-dependence of the C_N relationship could be expressed in terms of $(N1)_{60cs}$ as follows:

$$C_N = \left(\frac{P_a}{\sigma'_v}\right)^{0.784-0.0768\sqrt{(N1)_{60cs}}} \leq 1.7 \quad (36)$$

$$(N1)_{60cs} = (N1)_{60} + \Delta(N1)_{60} \quad (37)$$

$$\Delta(N1)_{60} = exp\left[1.63 + \frac{9.7}{FC + 0.01} - \left(\frac{15.7}{FC + 0.01}\right)^2\right] \quad (38)$$

$$CRR_{M,\sigma'_v} = CRR_{M=7.5,\sigma'_v=1atm} * MSF * K_\sigma \quad (39)$$

4. Analysis of data

SPT data were collected for 265 boreholes distributed over 81 sites spread over Diyala governorate area. Then 15 boreholes were selected to determine factor of safety using the aforementioned four methods, and to make a comparison among them. The regions in the middle and east of Iraq have seismic acceleration more than 0.2g with earquake magnitude more than 4, (26).

5. Choose the suitable method

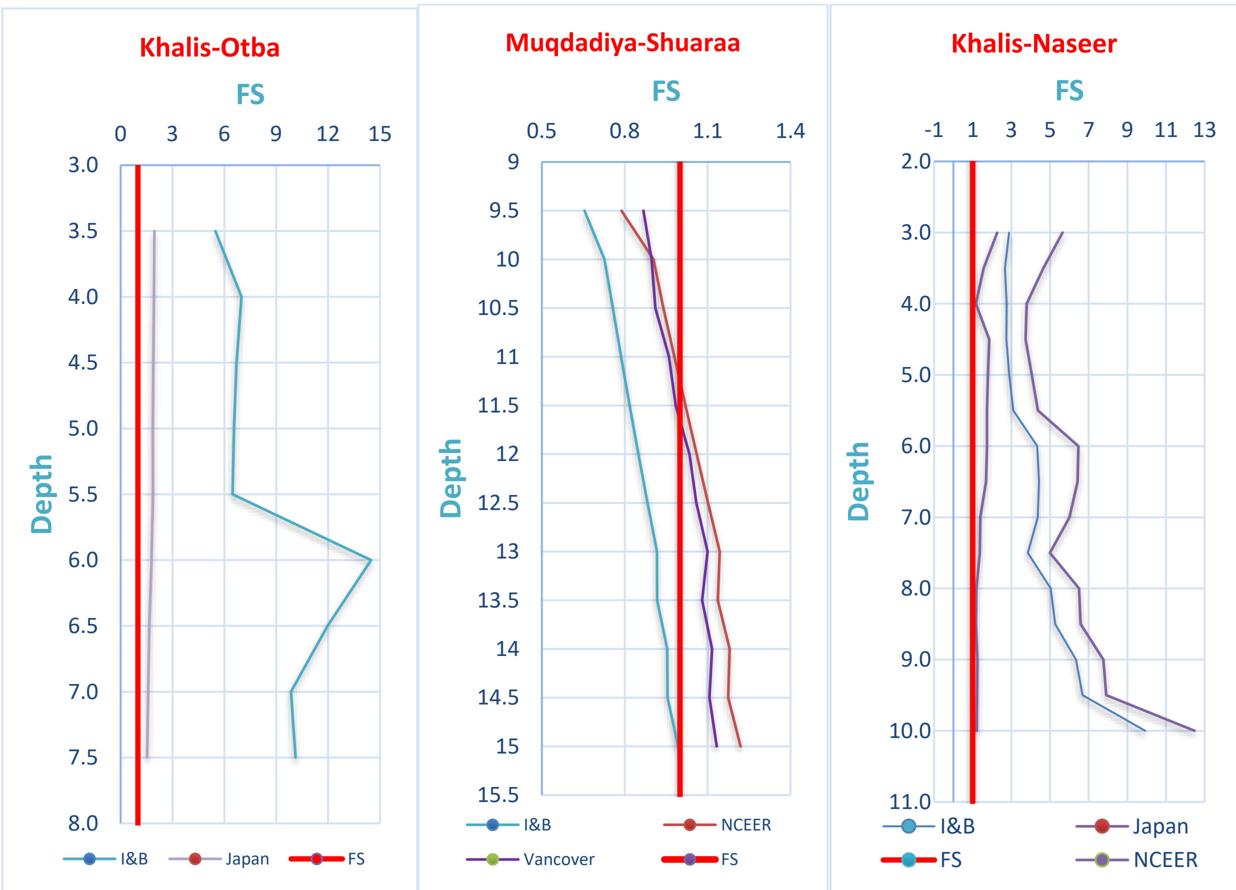
After determining the values of factor with depth for selected 15 boreholes, we find the Boulanger and Idris method is suitable for determining variation of factor of safety with depth in Diyala Governorate soil and this is for the following reasons:

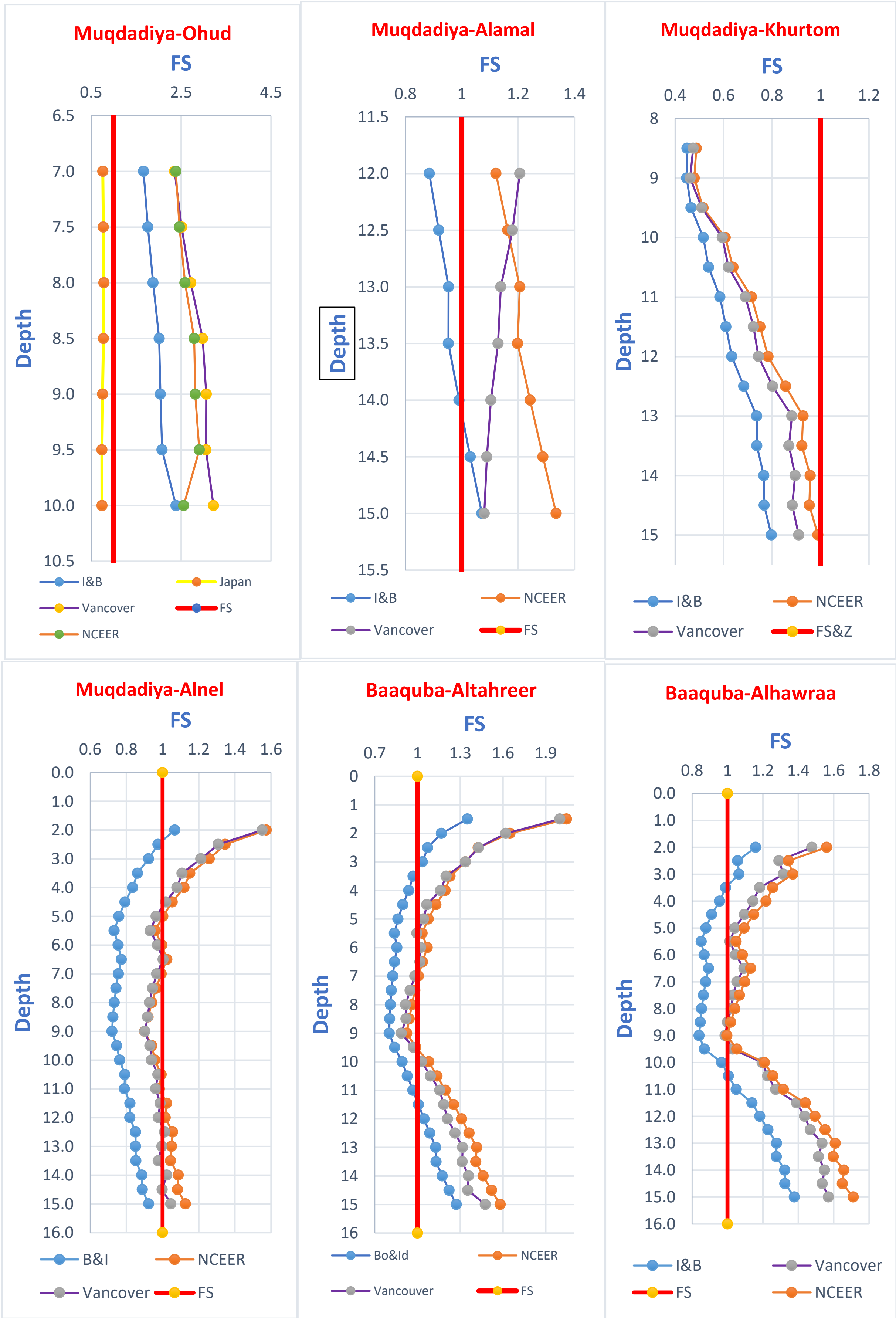
1. It is the newest method, which has been updated continuously
2. It is based on a trial-and-error process so its results are closer to reality.
3. It is the only method by which all types of Diyala governorate's soil can be calculated. Because it did not put limits to its equation.
4. It is close to the NCEER workshop and Vancouver methods, but safer than both.
5. Many scholars and organizations have chosen this, for example: (1) there was a study of [24] that performed a reliability study of a liquefaction analysis based on SPT. It mentioned that the Idriss and Boulanger [8] method is the most appropriate method with the lowest error rate for the weighted factor, (2) The Dutch National Annex to the Euro code for the seismic actions, recommends the use of the Idriss and Boulanger (2008) variant of the simplified liquefaction evaluation procedure, but allows other variants to be used if they are in line with the safety philosophy of the NPR 9998-2017. As a result, the Idriss and Boulanger (2008) variant and the updated variant (Boulanger and Idriss 2014) have been used in several liquefaction studies in Gronginen [8]. (3) Moreover, a method from Idriss and Boulanger, [6], in which stated as the most suitable method for a certain case in Indonesia [20].

6. Results and discussion

In general, the methods for calculating liquefaction potential are basically similar, but the difference is in calculating some of the parameters and the equations that calculate these parameters. Thus, these methods were calculated the change of safety factor FS with depth of borehole. Therefore, a comparison among the four methods will be made through the safety factor FS, and the differences between these methods will be known. The four methods were calculated the safety factor FS, each one according to its own equations, this results in values for the safety factor that vary with the depth and as shown in the figure (4), after calculating 15 boreholes, the difference in the safety factor FS section is between the four methods almost the same in all, as described in the figure (4), which shows in the following points.

1. In general, the safety factor in the Japanese method is high and very conservative. If the values of the safety factor are small as in figure (4) (27.7% from Boulanger and Idriss), the equation cannot be always applied because most of the Diyala Governorate soil is not within the equation limits. So that the drawing of this method did not appear in some of these figures.
2. Generally, the safety factor in the Task Force Report 2007 (Vancouver) method is the less than the Japanese method and it is close to the NCEER method, and also cannot determine some of Diyala Governorate soil because some of them is not enter into the limits of equation. As described in the Figure (4), the drawing of this method does not appear in this figure.
3. The safety factor in the NCEER method is close to the Vancouver method and the equation cannot be applied to some Diyala Governorate soil so that they do not enter within the equation limits. As described in figure (4).
4. The safety factor in the Boulanger and Idriss 2014 method is higher than the NCEER and Vancouver slightly, that means the FS values are smaller than them (38.8% from NCEER and 80.7% from Vancouver) which is safer than the equivalent and the equation can be applied to all of the types of Diyala Governorate soil as described in figure (4).

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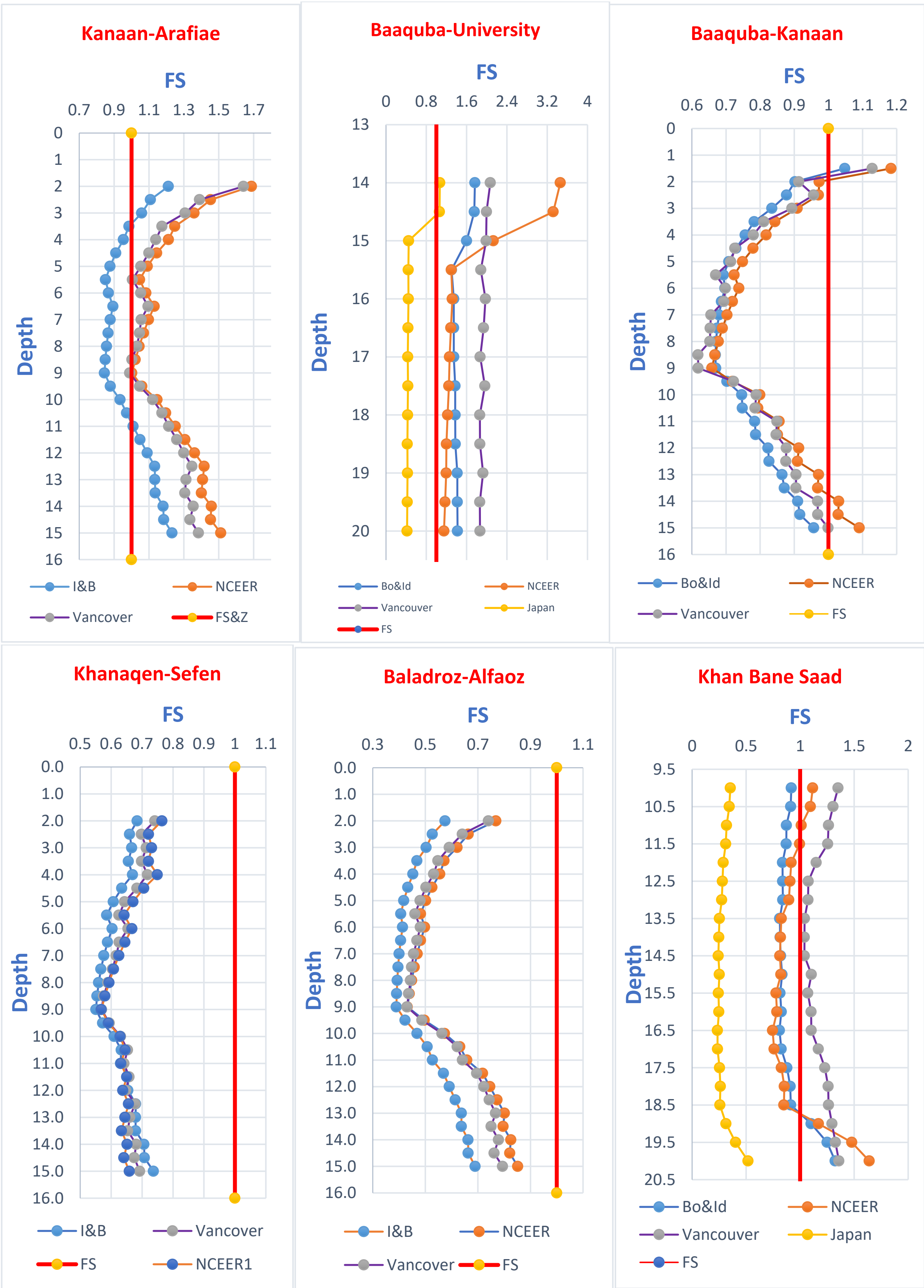

Figure 4. The change of the safety factor FS with the depth

5. Generally, the safety factor in the Task Force Report 2007 (Vancouver) method is the less than the Japanese method and it is close to the NCEER method, and also cannot determine some of Diyala Governorate soil because some of them is not enter into the limits of equation. As described in the Figure (4), the drawing of this method does not appear in this figure.
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7. Conclusions

In summary, Liquefaction is one of the critical topics in geotechnical engineering. SPT-based methods were developed by researchers to evaluate liquefaction potential. This paper studied a comparison analysis of the liquefaction potential by finding the factor of safety (FS) according to four methods proposed by Japanese, Task Force Report 2007 (Vancouver), NCEER workshop, and Boulanger and Idriss. It was found that the safety factor computed by the Japanese method was higher than the other three methods by 27.7% compared to Boulanger and Idriss. The lowest safety factor is calculated using NCEER method. The Vancouver method has low safety factor values as compared to the NCEER workshop method. As for the Boulanger and Idris method, a higher safety factor was founded than the other methods (80.7% from Vancouver and 38.8% from the NCEER workshop) and less than the Japanese method. The Boulanger and Idris method are the most suitable method for calculating the factor of safety of Diyala Governorate soil.

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