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A developed procedure for predicting the risk of liquefaction: A case study of Rasht City

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ABSTRACT: Soil liquefaction is one of the most important and complex seismic geotechnical and engineering topics. Most experimental methods in the study of liquefaction have been based on deterministic analysis, and parameters, such as soil resistance and earthquake loads, have been considered without dispersion and fault. Statistical analysis, particularly reliability analysis, is a new and comprehensive approach used to solve and evaluate problems, as well as entering of uncertainties in calculations. In this study, information on 50 boreholes were obtained using a database of Standard Penetration Test (STP), and diverse experimental procedures, such as NCEER2001, Idriss and Boulanger, Highway bridge of Japan, OCDI and reliability approach, were used in the evaluation of soil liquefaction in Rasht and finally, the results were compared with each other. By comparing the different methods, it was observed that these methods do not correspond with clay soils and their results were different from each other. Also, safety factor of greater or lesser than one is the mean of safety and occurrence of liquefaction, therefore, reliability analysis was used to ensure the probability of liquefaction. Finally, two empirical relationships based on the probability of liquefaction (PL) and safety factor (FS) were proposed from which the liquefaction potential can be calculated directly. Soil liquefaction risk can be assessed by the proposed relationship between (PL) and (FS) based on deterministic approaches.

Keywords: Probability of liquefaction, SPT, Safety factor, Empirical equation.

1. INTRODUCTION

Iran is among the countries located in the earthquake belt, and the nature of the soil in many areas indicates high liquefaction potential under dynamic wind effects of earthquake. Since all the soils do not have the potential to be liquefied, the first step in liquefaction risk assessment is usually to evaluate the liquefaction potential[1]. Most experimental approaches, such as the Idriss approach, NCEER2001 procedure, Highway bridge of Japan and the Overseas Coastal Area Development Institute of Japan (OCDI), are based on a definitive analysis in evaluating liquefaction, and parameters including soil resistance and earthquake loads are considered precisely, without dispersion and faults[2]. In addition, there is no exact correlation between the probability of liquefaction and safety factor in the use of these methods. Statistical analysis, particularly reliability analysis is a new and comprehensive approach to studying and solving problems, as well as entering of uncertainties in calculations [3]. Different methods of reliability analysis, such as the second moment of the first order (FORM), Estimation of point (PEM), Monte Carlo simulation (MCS) and new method combined FROM-PEM, can be used in the evaluation of soil liquefaction. In this study, information on 50 boreholes were obtained from the database of standard penetration test (SPT) as shown in Figure 1. Different experimental procedures such as NCEER2001, Idriss and Boulanger, Highway bridge of Japan, OCDI method and reliability procedure were used in the study of soil liquefaction in Rasht, and the results were compared with each other[4]. It is very important to assess the liquefaction potential of Rasht city because of the sandy soils present in some areas and earthquake prone area as well as high levels of ground water that can lead to saturated soil. Thus, one of the main objectives of this study is to identify the liquefaction potential segments and determine the most appropriate method of evaluating liquefaction potential[5].

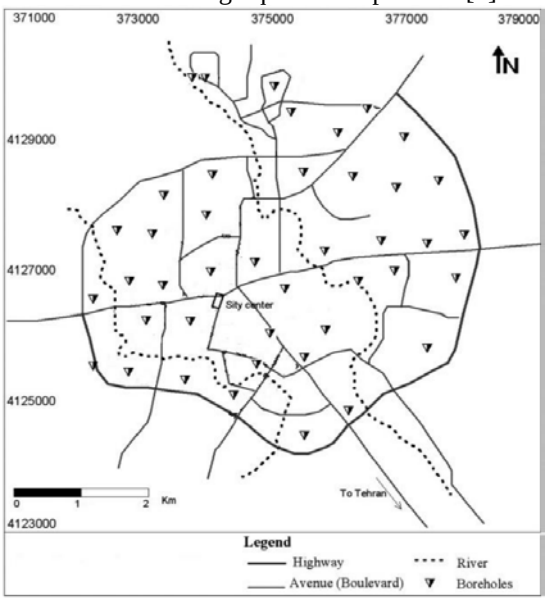


Fig.1 Location of boreholes in Rasht City

2. GENERAL GEOLOGY

Gilan plain includes an alluvial area located on the northern slopes of the Alborz Mountains and the southern coast of the Caspian Sea. This plain is divided into three narrow plains: eastern, north-western and central plain. Rasht city is located in the central part of Gilan plain at a distance of approximately 30 km from the Caspian Sea.

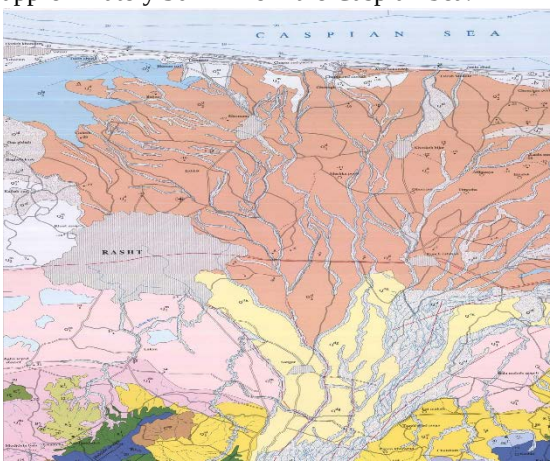


Fig.2 Location of Rasht City in Gilan plain

Rasht city is located at 37° and 1 min to 37° and 27 min of the north latitude from the equator and 48° and 35 min to 49° and 3 min of longitude from the meridian of the Caspian Sea and its area is about 136 km. The existing sediments in Rasht city is related to the fourth age of geology. Rasht city is located on the confluence of 5 types of sediment including coastal sediments, new marine sediments, wetland sediments, the new alluvium delta and marine sediments in terms of geology[6].

The density of existing clay soils in Rasht city is high (SPT average number equal to 15) and the soils are relatively pre-consolidated (with OCR Average equal 2.75). The natural moisture content of the clay varies due to changes in groundwater level, and its average is 24.4%. The plasticity limit, plasticity index and shrinkage limit of clay in Rasht city are 54, 29 and 13.4%, respectively. Also, the existing grain soil varies in terms of density. The cohesion of these soils is in the range of 0 to 2.0 kg/cm2 (mean 1.0), the angle of internal friction is in the range of 17 to 44° (mean 26) and the standard penetration number is in the range of 8 to 50 (mean 18)[7]. In a research conducted by the Geotechnical Group International Institute of Earthquake Engineering, the liquefaction zoning maps of Iran were plotted, where Rasht city was shown to have high liquefaction capacity.

3. THE METHODS USED TO ASSESS LIQUEFACTION BASED ON NSPT

The safety of factor was calculated at different depths and the soil of Rasht was analyzed to identify the liquefiable and non-liquefiable areas[11]. All records were then analyzed to identify areas of liquefaction and non-liquefaction by the Overseas Coastal Area Development Institute of Japan (OCDI) procedure. Unlike previous approaches, the main criterion of this method is the possibility of liquefaction and a definitive amount cannot be calculated. Through this method. $(N_1)_{60}$ should be calculated using the proposed equation to predict liquefaction for records in Rasht.

$$N_{65} = \frac{N - 0.019\left(\sigma_v^{'} - 65\right)}{0.0041\left(\sigma_v^{'} - 65\right) + 1.0} \quad (1)$$

In this equation, (N_{65}) is the equivalent N-value, (N) is the N-value of the subsoil, and $(\sigma_v^{'})$ is the effective overburden pressure of the subsoil calculated in the approach at different depths in Rasht. In the following step, the equivalent acceleration was calculated using Eq. (4)[12].

$$A_{eq} = 0.7 \frac{\tau_{\max}}{\sigma_v^{'}} g \quad (2)$$

This Eq. is used in the OCDI method where $(\tau_{\max})$ is the maximum shear stress (KN/m^2) and g is the gravitational acceleration. Liquefaction can be predicted utilizing the equivalent N-value and equivalent acceleration. The soil layer was categorized according to a diagram that was divided into four segments. A total of 50 diagrams were drawn for each bore log and the liquefaction potential was evaluated based on (A_{eq}) and (N_{65}) for different records in Rasht[13].

Performance function is recognized as one of the major elements in reliability analysis. Some of the uncertainty in determining the (CRR) and (CSR) are also considered in the order provided by the (R) and (S) and can act as random variables which are normally distributed. Performance function can be defined as (Z=R-S)[14]:

If $(Z < 0)$ the performance functions is designated as 'failed'. If $(Z > 0)$ the performance functions is designated as the safe zone and liquefaction does not occur in that area, and if (Z=0) the performance state is designated as a 'limit state'. After obtaining some of the uncertainties inherent in the estimation of (CSR) and (CRR), the (R) and (S) can be accepted as random variables. The liquefaction probability is defined as the probability that $(Z \langle 0)$[15].

However, an exact evaluation of this probability is not an easy task. Indeed, it is so tough to accurately determine the (PDFs) of random variables, such as (R) and (S). A simplified calculation approach, the first order and second-moment method, has been improved to meet this need. The method utilizes the statistics of the basic independent random variables, such as (R) and (S). If the probability density functions (PDF) and the cumulative probability function (CPF) of (Z) are defined as (f_z (Z)) and (F_z (z)), respectively, the

liquefaction probability (P_L) then equal the probability of ($Z\langle 0$). If the mean values and standard deviations of (R) and (S) are (μ_R) , (μ_S), (σ_R), (σ_S) according to the first order and second moment method, the mean, standard deviation and coefficient of variance of the (Z), by using the following Eq[16]:

$$\delta_Z = \frac{\mu_Z}{\sigma_Z} = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}} \quad (3)$$

The reliability index (β) is defined as the inverse of the coefficient of variation (δ_z), and is used in calculating the reliability of the results of liquefaction assessment. It is assumed that (R) and (S) are independent variables with a normal distribution to display the process of the reliability analysis. According to this assumption, the performance function (Z) can be in a normal distribution of ($Z \sim \left(\mu_z, \delta_z^2\right)$). By placing the (PDF) of (Z), for (P_L):

$$P_L = \Phi(-\beta) = 1 - \Phi(\beta) \quad (4)$$

In the aforementioned Eq., (P_L) represents failure probability, (σ_z) represents the standard deviation, (μ_z) represents the mean value, (β) represents the reliability index and ($\Phi(\beta)$) represents the cumulative probability. A computer program was written in the MATLAB environment to assess the liquefaction potential based on reliability for approximately 500 records in the study area. The seismic information, mean, and coefficient of variation associated with effective parameters were introduced to the program as fixed input parameters to assess liquefaction and the parameters relevant to the genetic algorithm. The geotechnical information required for assessment of liquefaction involves groundwater level, soil bulk density, depth of soil layers, soil type, (SPT) number, the percentage of fines (sieve 200) as variable input parameters.

The application reliability index values were calculated from boreholes to different depths based on the flowchart designed and the probability of liquefaction was then evaluated in these depths.

4. RESULTS AND DISCUSSION

Due to the variety and heterogeneity of existing deposits in Rasht city on the surface and at different depths, the best way to evaluate the characteristics of liquefaction in the city is by data collection. For this purpose, conducted reports and geotechnical studies in Rasht city on construction projects, such as private buildings, administrative and bridges, were collected and the required data were extracted. The present information resources were developed using a database of the Standard Penetration Test (SPT) related to 500 data with 50 boreholes, which were conducted by the Consultant Engineers Company of Iran soil, Moshaver Asas Gostar Khak and Pay, and Advisor of Gill Design and Control in different areas of Rasht City. In this study, plan acceleration was selected (3.0 g) based on Iran 2800 Regulation (Third Edition), and the Richter magnitude of the earthquake was determined as 7. After analyzing the geotechnical data of Rasht city, 2 boreholes were selected for discussion from the different segments of Rasht city based on engineering judgment. To compare the results of the liquefaction potential assessment with different approaches, the maximum liquefaction depth obtained from the different methods were compared with each other. Based on the above description and considering the safety factor of less than or equal to 1 for NCEER2001, High bridge of Japan, and Idriss and Boulanger approaches as a measure of liquefaction, the results of the field operations, the charts and the comparison of the results of the liquefaction potential assessment in the selected boreholes are shown in Figures 3 to 6.

Table 1 Summary of data and calculation of liquefaction in the studied area (boreholes 1)

P_l	β	Aeq	N65	FS 3	FS 2	FS 1	CR R3	CR R2	CR R1	CSR 3	CSR 2	CS R1	FC	N	Soil	De pth	R o w
28	0.23	437	39.3	0.8 1	0.9 5	0.9 5	0.32	0.2	0.21	0.39	0.38	0.4	3	15	SP	2	1
12	1.17	431	42.1	0.8 3	1.3 5	0.1 9	0.32	0.26	0.26	0.38	0.34	0.4	3	18	SP	4	2
45	- 0.07	425	31.8	0.7 7	1.1 4	1.1 2	0.28	0.19	0.24	0.37	0.3	0.3 9	9	15	SP	6	3
3	1.42	401	33.6	1.1	2.4 0	2	0.38	0.3	0.42	0.34	0.22	0.3 7	37	19	SM	10	4
65	0.11	352	33.3	1.6	1.1 3	0.6 1	0.52	0.29	0.11	0.32	0.16	0.3 2	80	18	CH	14	5
48	0.14	323	35.4	1.4 9	4.0 3	0.7 9	0.46	0.32	0.13	0.31	0.13	0.2 9	65	22	ML	16	6
88	- 0.56	295	20.2	1.4 6	2.6 9	2.2 4	0.43	0.18	0.34	0.3	0.11	0.2 7	85	16	CH	18	7

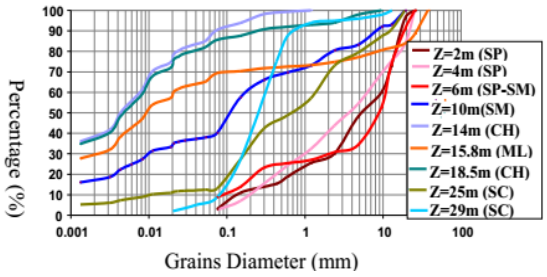
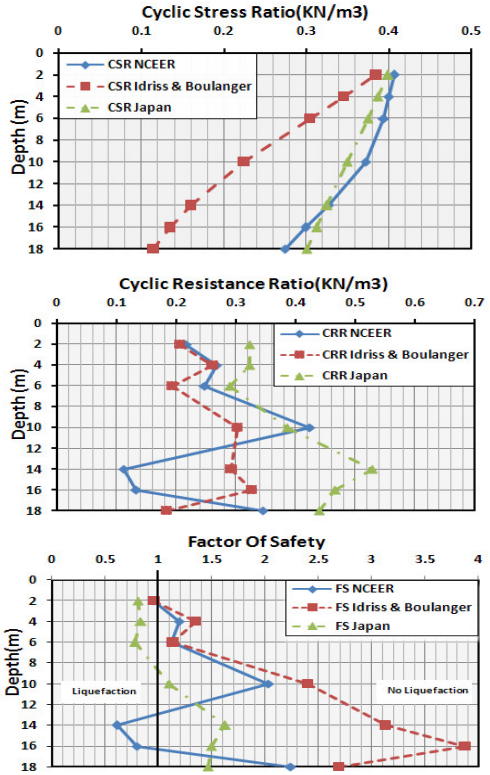


Fig.3 Specifications of second boreholes (Rasht – Golbagh Namaz – next to the Administration Laboratory)



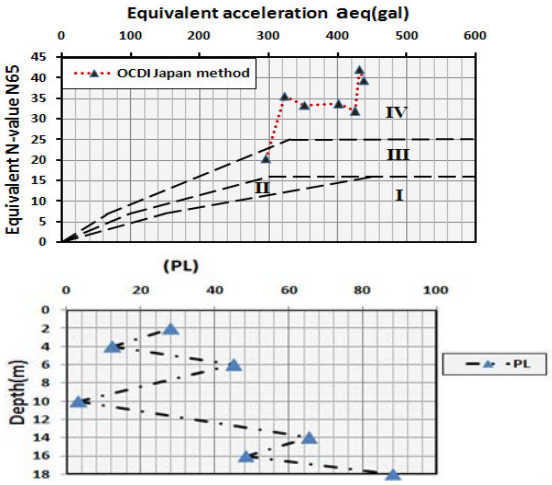


Fig.4 Results of the comparison of different ratios of cyclic resistance based on different methods used to assess the liquefaction potential in the second boreholes

At a depth of 2 m, in the first boreholes having sand with bad granularity, a safety factor of NCEER2001, Idriss and Boulanger, and Highway Bridge of Japan methods were identified as close to 1, and this indicates that liquefaction will occur. However, according to reliability procedure, it has no liquefaction potential but based on the OCDI method, liquefaction is possible.

At 10 m depth of silty sand, the results of analyzing different methods are similar and the soil is considered as non-liquefiable. At depths of 14, 16 and 18-m in which the layers of soil are made of clay and silt, the results were completely different from each other and as such, an accurate and definitive idea could not be determined.

Table 2 Summary of information and calculations of liquefaction in the studied area (boreholes 2)

P_l	β	Aeq	N65	FS3	FS2	FS1	CR R3	CR R2	CR R1	CSR 3	CSR 2	CSR 1	FC	N	Soil	Depth	Row
58	0.01	435	28.6	0.68	0.73	0.69	0.26	0.15	0.15	0.40	0.37	0.40	3	11	SP	2.5	1
19	0.84	426	36.6	1.03	1.59	1.85	0.38	0.28	0.41	0.39	0.31	0.39	42	15	SP	5.5	2
35	0.43	415	36.6	0.89	1.62	1.14	0.32	0.32	0.24	0.38	0.26	0.38	3	19	SP	8	3
27	0.46	401	44.5	1.49	2.99	1.27	0.52	0.62	0.22	0.37	0.25	0.37	63	25	CH	10	4
39	0.32	352	26.4	0.82	1.78	0.93	0.26	0.16	0.16	0.32	0.16	0.32	3	18	SP	14	5
19	0.84	396	21.9	0.90	2.69	1.39	0.27	0.18	0.21	0.27	0.11	0.27	22	14	SP	18	6

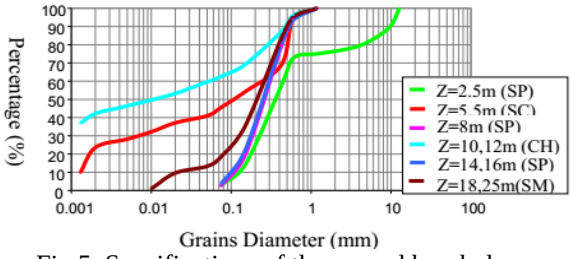


Fig.5 Specifications of the second boreholes (Rasht – Seyghalan Square).

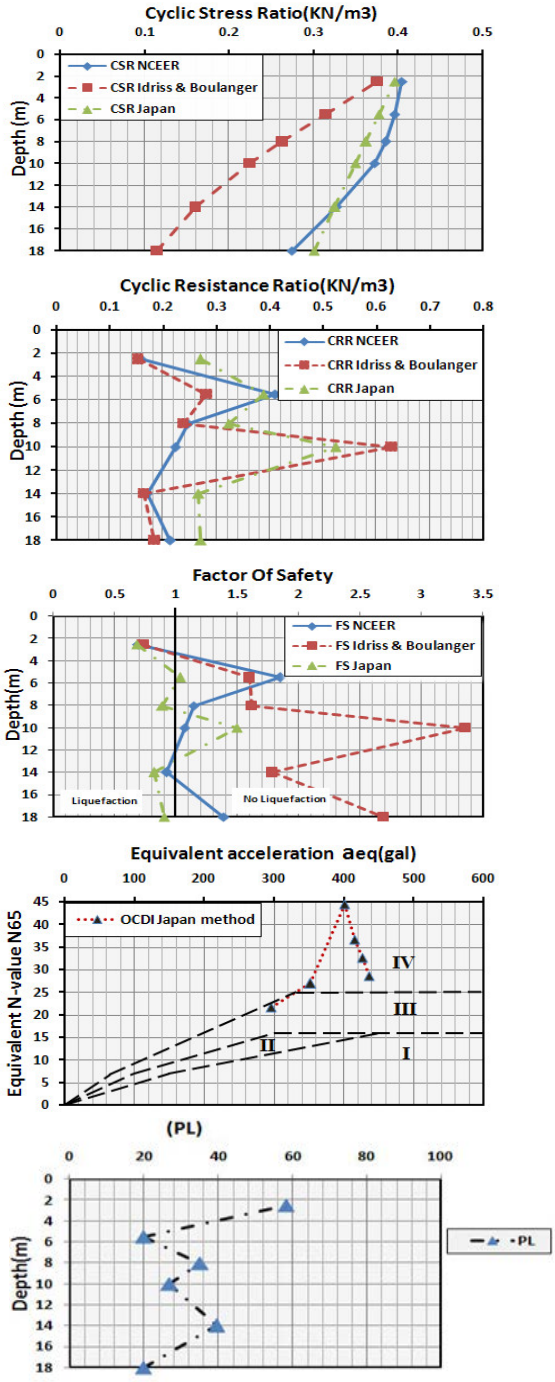


Fig.6 The results of comparison of different ratios of cyclic resistance based on liquefaction potential evaluation with different methods in the fourth boreholes

In boreholes with depths of 2.5 and 5.5 m, having sand with good granularity and silty sand, respectively, the results were similar and the soils were recognized as non-liquefaction and liquefaction, respectively. For boreholes with a depth of 8 m, having sand with bad granularity, the probability of liquefaction indicated that liquefaction incidence and liquefaction non-occurrence are equally probable, thus NCEER2001, Idriss and Boulanger, and the OCDI methods indicated that liquefaction will occur, whereas a comparison of the calculated highway bridge of Japan procedure suggested that there will be no occurrence of liquefaction. At a depth of 10 m, the results could not be trusted due to the presence of clay soil with high plastic properties. For boreholes with a depth of 14 m having sand with bad granularity, a comparison of the calculated OCDI approach showed that the soil is in the 3 area and the possibility of liquefaction is low. On the other hand, the Idriss and Boulanger method suggested that liquefaction will not occur. However, the results obtained from the reliability approach showed that the possibility of liquefaction and non-liquefaction is equal.

5. EXTRACTED EQUATION FROM PROPOSED MODEL

The final step was performed with the help of the GP.NET software (Genetic programming). Program Settings were carried out in the setting menu and it was possible to adjust the number of equation constants. The type of relations considered was adjusted in the Function menu. The program became set to begin the analysis by entering the Run menu program. Finally, the output equation became available after completion of the analysis time in the Model menu. The output equation derived from liquefaction assessment based on the result of the Highway bridge of Japan and the GP.NET Software is shown in Relation (9) and Figure (7). The relation between (P_L), (FS) with correlation coefficient ($R^2 = 0.85$) shows that this equation has 85% similarity to reality, hence the result is acceptable.

$$PL = 1.97 + \sin A - FS \quad (5)$$
$$A = 2.14\cos(4.95 + 1.98\cos B)$$
$$B = [\tan(\tan(FS))\tan(1.07FS^2) + \sin(6.41e4FS)]$$

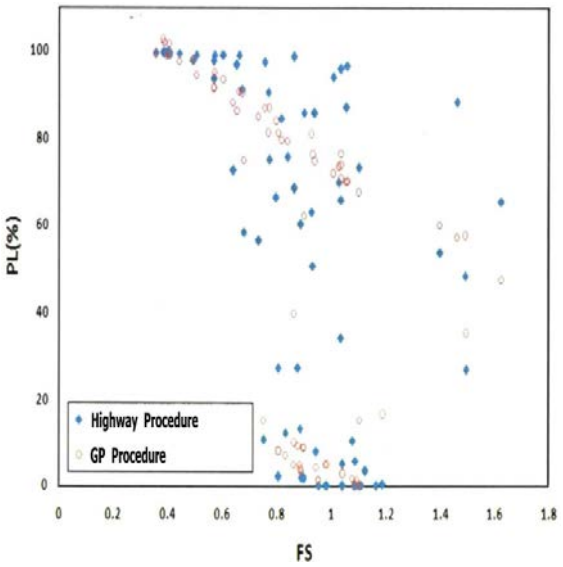


Fig.7 Graph of safety factor showing changes in the behavior of Highway Bridge of Japan method with probability using GP software

Also, the obtained results of the liquefaction potential assessment by Idriss and Boulanger and the obtained results of GP with correlation coefficient $(R^2 = 0.82)$ is as shown by relation (10) and Figure (8).

$$PL = 2.06 + A + B \quad (6)$$
$$A = (-0.18\tan(-1.55e3FS^3)$$
$$/(2.06 + \sin(FS + 4.88FS^4))$$
$$B = \sin(FS + 4.88FS^4) - 0.429FS$$

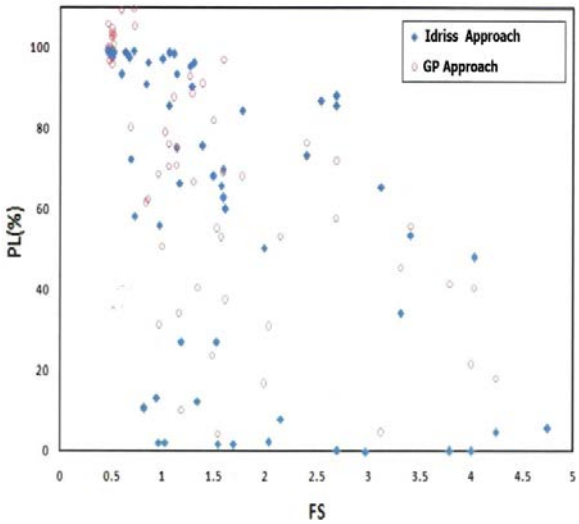


Fig.8 Graph of safety factor showing changes in the behavior of Idriss and Boulanger's method with probability using the GP software

In this study, the potential of liquefaction in Rasht city was evaluated using NCEER2001, Idriss and Boulanger, the Highway bridge of Japan, OCDI and reliability procedures.

According to seismic zone, due to the diversity of alluvial sediments, high level of groundwater, and saturated soil, this area has a high potential for liquefaction. Therefore, the liquefaction potential assessment of this area is important to avoid probable dangers and hazards, especially in times of severe earthquake.

6. CONCLUSION

By collecting and testing 500 reports of geotechnical boreholes in different depths of Rasht city, about the public profile of Rasht city soil and the existing geotechnical properties, the liquefaction potential of different layers can be explained as follows: the values were first obtained from different areas in Rasht with no absolute ideal distribution; and secondly, the values were obtained by relying on the results of other studies.

1. By comparing the liquefaction potential assessments based on the different methods, it was observed that the climatic conditions of Iran have some similarities with the United States. Moreover, the main criteria of Idriss and Boulanger's method is based on $(N1)_{60}$ and the obtained results have high accuracy. Therefore, it can be concluded that Idriss and Boulanger's method is a better option for liquefaction potential assessment in Iran.

2. In the Highway bridge of Japan approach and OCDI method due to the climatic conditions of Japan and the soil type of this area, the soil liquefaction ability is assumed to be highly conservative. This is not affordable in terms of economic issues. In the OCDI procedure, which is based on the classification of areas to assess liquefaction possibility, the importance of structure can play a significant role in liquefaction diagnosis in areas II and III.

3. Analysis of the reliability approach is recognized as the best means of providing a logical framework for considering the uncertainty in assessing liquefaction potential. The main result of the liquefaction calculation, based on the reliability method, is that the calculation of probability of liquefaction incidence is possible qualitatively using a confidence coefficient.

4. Therefore, based on the results obtained in the present study, an appropriate method should be used based on the geotechnical area and climatic conditions. Thus, the utilization of both probabilistic and deterministic procedures in

assessing liquefaction potential seems to be more reasonable and conservative in achieving more definite liquefaction potential.

5. In this research, it was determined that a confidence coefficient greater or lesser than 1 does not mean safety and/ or liquefaction in cadence for liquefaction, hence, in order to ensure liquefaction probability, reliability-based method analysis should be used.

6. Regarding the proposed relationship between (P_L) and (FS), the liquefaction probability of soil layers can be obtained using the deterministic methods. This is a big advantage for geotechnical engineers who make use of common methods based on confidence coefficient for liquefaction potential assessment.

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