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Characterizing Liquefaction Resistance Of Soil

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Abstract— Liquefaction hazard evaluation involves liquefaction susceptibility analysis, liquefaction potential evaluation, assessment of effect of liquefaction and study of response of various foundations in liquefied soil. These are the major concerns of Geotechnical engineers. In the present study the focus is on liquefaction potential evaluation for determination of the likelihood of liquefaction triggering in a soil in a given earthquake. A review of the various liquefaction potential evaluation methods are presented in this chapter. In the present section, application of various methods for liquefaction susceptibility analysis is discussed in International and natural scenario. In this research, assessment of liquefaction of soils by various approaches have been reviewed and presented in chronological order. The study focused on procedural requirements and assessment for conventional and computational methods. Simplified method given by Seed, Tokimatsu-Yoshimi (T-Y) and Idriss & Boulanger methods of liquefaction assessment have been reviewed which was analyzed in the history. Computational methods are also discussed as capable in liquefaction assessment using database from SPT results. Conventional methods with extended application using concept of correction factors were induced in the analysis. Taking on familiarity from past literatures all methods were critically reviewed, and measures are established..

Index Terms— liquefaction; CRR; CSR; MSF; SPT; empirical methods.

1 Introduction

Liquefaction denotes the condition where the soil will undergo continued deformation at a constant low residual stress or with no residual resistance, due to the buildup and maintenance of high pore water pressures which reduces the effective confining pressure to a very low value; pore-pressure buildup leading to (true) liquefaction of this type may be due to either static or cyclic stress application. There are 9 factors which affects the liquefaction characteristics – grain size distribution, density of deposit (initial relative density), vibration characteristics, location of drainage and dimension of deposit, magnitude and nature of superimposed loads, methods of soil formation (soil structure), period under sustained load, previous strain history, entrapped air. Liquefaction of soil is one of the most disastrous seismic hazards. In the last century seismic hazard accounts around 30% of total casualties and 60% of the total property loss due to different natural hazards. Soil liquefaction phenomena have been noticed in many historical earthquakes after first large scale observations of damage caused by liquefaction in the 1964 Niigata, Japan and 1964 Alaska, USA, earthquakes. Since 1964 a lot of work has been done to explain and evaluate the liquefaction hazard.

Now a day the human life and the environment have frequently been endangered by the natural hazards like earthquake, tsunami, flood, cyclone and landslides. As a consequence of which the human society and the nation's economy get hampered immediately after the occurrence of a natural disaster. In developing countries like India, where the population is very large and is increasing day by day, the social and economic factors force the people to live in vulnerable areas, due to which the effects of these natural disasters are catastrophic. Among all these threats, liquefaction of soil can be pointed out as one of the most disastrous seismic hazards. Hence evaluation of liquefaction susceptibility is an important aspect of geotechnical engineering. The widely used procedures for evaluation of liquefaction potential of soil are the simplified procedure. This procedure was developed from empirical evaluation of field observations and field and laboratory test data. For evaluation of liquefaction potential of soil generally two variables are required, such as: (i) the seismic demand on a soil layer expressed in terms of CSR, (ii) the capacity of the soil to resist liquefaction expressed in terms of CRR. The method for evaluation of CRR is to test undisturbed soil specimens in the laboratory. To avoid the difficulties associated with sampling and laboratory testing, field tests have become the state-of–exercise for routine liquefaction inquiries. The various field tests used for the liquefaction resistance of the soil are (i) Standard Penetration Test(SPT), (ii) Cone Penetration Test (CPT) , (iii) Shear Wave velocity Measurements and (iv) Becker Penetration test(BPT). Simplified methods based on standard penetration test (SPT), cone penetration test (CPT) and shear wave velocity measurement test are most commonly used for the assessment of liquefaction potential of soils, due to difficulty in obtaining high quality undisturbed samples and cost involved therein. Simplified methods pioneered by Seed and Idris [2] mostly depend on a boundary curve which presents a limit sate and separates liquefaction cases from the non-liquefaction cases basing on field observations of soil in earthquakes at the sites where in situ data are available

2 METHODOLOGY :

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Liquefaction hazard evaluation involves liquefaction susceptibility analysis, liquefaction potential evaluation, assessment of effect of liquefaction and study of response of various foundations in liquefied soil. In the present study the focus is on liquefaction potential evaluation for determination of the likelihood of liquefaction triggering in a soil. A review of the various liquefaction potential evaluation methods are presented in the report. Application of various methods for liquefaction susceptibility analysis is discussed in International and natural scenario. In this research, assessment of liquefaction of soils by various approaches have been reviewed and presented in chronological order. The study focused on procedural requirements and assessment for conventional, computational, empirical, simplified methods. Simplified method given by Bolton Seed, Tokimatsu -Yoshimi (T-Y) and Idriss & Boulanger methods of liquefaction assessment have been reviewed. Methods established by seed & idriss are discussed as capable in liquefaction assessment using database from SPT results. Conventional methods with extended application using concept of correction factors were induced in the analysis. Taking on familiarity from past literatures all methods were critically reviewed, and measures are established.

Geotechnical professionals generally investigate subsurface to evaluate the potential for liquefaction. The most common techniques using standard penetration test (SPT) blow count (commonly referred as to the ―N-value‖) follows certain protocols:

1. Estimation of the cyclic stress ratio (CSR) induced at various depths within the soil by the earthquake.
2. Estimation of the cyclic resistance ratio (CRR) of the soil, i.e. the cyclic shear stress ratio which is required to cause initial liquefaction of the soil.
3. Evaluation of factor of safety against liquefaction potential of in situ soils.

Method 1 :- SPT-Based Method for Prediction of Liquefaction Index :- (Seed Et Al.)

After the disastrous earthquake in Alaska and Nigata (Japan) in 1964, Seed and Idriss [1] developed and published the basic, ―simplified procedure‖. The procedure is modified and improved periodically since the time, primarily through landmark papers by the researchers [5-6 & 20-21]. After 3 decades Youd et al. [22] again modified Seed's method in laboratory held by NCEER and NSF. In this study these simplified procedures have been discussed below:

As per Newton's 2nd law of motion, the horizontal earthquake force ‗F' acting on the soil column has a unit width and length i.e.

$$F = ma = \left(W/g\right)a = \left(\gamma z/g\right)a_{max} = \sigma_v\left(a_{max}/g\right) \qquad (1)$$

Where,
F = horizontal earthquake force acting on soil column.
m = total mass of soil column i.e. (⁄).
γ = total unit weight of soil
z = depth from the ground level
a = acceleration which in this case is maximum horizontal ground acceleration caused
α = acceleration which in this case is maximum horizontal ground acceleration caused by the earthquake i.e. a= amax.
σv= total vertical stress at bottom of soil column.
g = acceleration due to gravity.

The force F acting on the rigid soil element is equal to the maximum shear force at the base on the soil element. Since the element is assumed to have a unit base width and length, the maximum shear force F is equal to the maximum shear stress as shown in fig 1.

$$\therefore \tau_{max} = F = \left(a_{max}/g\right)\gamma z \qquad (2)$$

Since the soil column act as a deformable material rather than rigid body during the earthquake Seed and Idriss [4] incorporated a depth (or stress) reduction factor in the right side, then the equation becomes

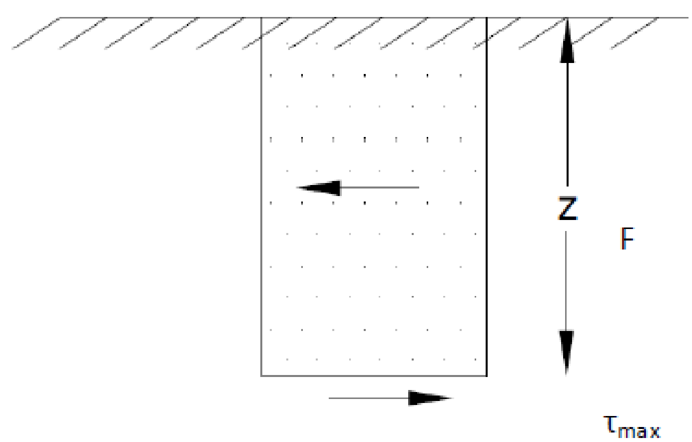

Fig. 1. Conditions assumed for evaluation of the CSR.

$$\tau_{max} = F = ({}^{a_{max}}/_{g})\gamma z r_d \quad (3)$$

Average value of Stress reduction factor r_d is given as:

r_d= 1.0 - 0.00765 z ; for z ≤ 9.15 m (4a)

r_d= 1.174 - 0.0267 z ; for 9.15 m < z ≤ 23 m (4b)

r_d= 0.744 - 0.008 z; for 23 m < z ≤ 30 m (4c)

r_d= 0.50; for z > 30 m (4d)

As depth (z) increases rd also increases. The mean value of rd calculated from above equation is shown in figure below

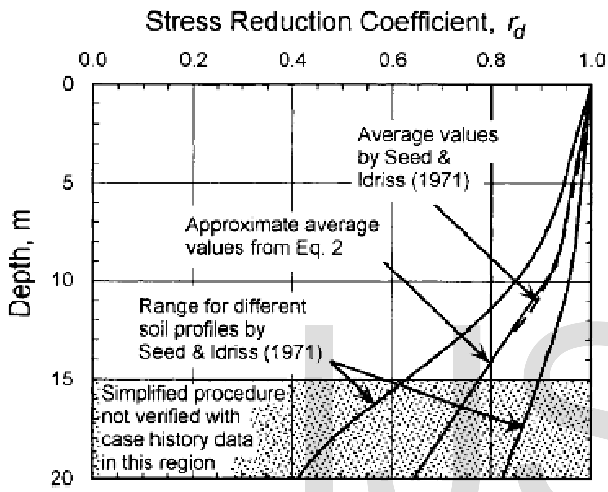

Fig. 2. rd versus depth curves

For ease of computation, the mean value curve plotted in Fig 2 may be approximated by the following equation [22]:

$$r_d = \frac{(1.000 - 0.4113z^{0.5} + 0.04052z + 0.001753z^{1.5})}{(1.000 - 0.4177z^{0.5} + 0.05729z - 0.006205z^{1.5} + 0.001210z^2)} \quad (5)$$

For simplified method Seed et al [23] considered the soil in the field to undergo by average stress τavg, which is 0.65 of τmax. Subsequently the average shear stress is normalized by the vertical effective stress to obtain CSR induced by the earthquake given in Eqn. (6): -

$$CSR = {}^{\tau_{avg}}/_{\sigma'_v} = 0.65\left({}^{a_{max}}/_{g}\right)\left({}^{\sigma_v}/_{\sigma'_v}\right) r_d \quad (6)$$

Where σ_v = total vertical stress
σ'_v = total vertical effective stress (σ_v-u)
u = pore water pressure.

Method 2 :- Cyclic stress ratio (CSR). In the simplified procedure
(Seed and Idriss 1971)

The factor of safety against liquefaction is defined as the ratio of the cyclic resistance ratio, CRRM, that will cause liquefaction of the soil for a given number of cycles, to the cyclic stress ratio, CSR, developed in the soil by the earthquake motion.

$$FS_{liq} = \frac{CRR_M}{CSR} \quad (1)$$

Cyclic stress ratio (CSR). In the simplified procedure (Seed and Idriss 1971), the CSR developed in the soil is calculated by a formula that incorporates ground surface acceleration, total and effective stresses in the soil at different depths (which in turn are related to the location of the ground water table), non rigidity of the soil column, and a number of simplifying assumptions. Seed and Idriss (1971) formulated the following equation for calculation of CSR.

$$CSR = \tau_{av} / \sigma_{v0}' = 0.65(a_{max} / g)(\sigma_{v0} / \sigma_{v0}') r_d \quad (2)$$

where τ_{av} is the average equivalent uniform cyclic shear stress caused by the earthquake and is assumed to be 0.65 of the maximum induced stress, max a is the peak horizontal acceleration at ground surface generated by the earthquake, g is the acceleration of gravity, σv0 and σv0' are total and effective overburden stresses, respectively, and d r is a stress reduction coefficient.

Several methods have been published by individuals for the calculation of d r (Seed and Idriss 1971, Lao and Whitman 1986, Seed et al 2003, Idriss 1999). The expression (Eq. 3) proposed by Idriss (1999) may be used to estimate the average value of r d .

$$r_d = \exp[\alpha(z) + \beta(z) \cdot M] \quad (3a)$$

$$\alpha(z) = -1.012 - 1.126\sin(z/11.73 + 5.133) \quad (3b)$$

$$\beta(z) = 0.106 + 0.118\sin(z/11.28 + 5.142) \quad (3c)$$

in which z is the depth below ground surface in meters, M is the earthquake moment magnitude, and the arguments inside the sine terms are in radians.

Cyclic resistance ratio (CRR). Andrus and Stokoe (2000) developed a Vs-based CRR curve for uncemented, Holoceneage soils with 5% or less fines at an earthquake magnitude 7.5 as shown in Eq. 4.

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$$CRR_{7.5cs} = 0.022\left[\frac{(V_{s1})_{cs}}{100}\right]^2 + 2.8\left[\frac{1}{215-(V_{s1})_{cs}} - \frac{1}{215}\right] \quad (4)$$

where subscript cs is the abbreviation for clean sand (soils with 5% or less fines), and $(V_{s1})_{cs}$ is the overburden stress corrected shear wave velocity as defined in Eq. 5 to account for the influences of the state of stress in soil.

$$(V_{s1})_{cs} = K_{cs}V_{s1} = K_{cs}V_s(p_a/\sigma_{v0}')^{0.25} \quad (5)$$

where Vs1 is the overburden stress-corrected shear wave velocity of sandy soils, pa is the reference stress of 100 kPa or about atmospheric pressure, and Kcs is a fines content (FC) correction factor. Juang et al (2002) suggested the following relationships for estimating Kcs:

$$K_{cs} = 1.0\text{ , for } FC \le 5\% \quad (6a)$$

$$K_{cs} = 1 + (FC-5)T\text{ , for } 5\% < FC < 35\% \quad (6b)$$

$$K_{cs} = 1 + 30T\text{ , for } FC \ge 35\% \quad (6c)$$

Where,

$$T = 0.009 - 0.0109(V_{s1}/100) + 0.0038(V_{s1}/100)^2 \quad (6d)$$

It is preferred that the FC measured from SPT samples be used for above corrections. If measured data is not available, FC estimated from CPT data could also be used (Yi, 2009).

Research indicates that other corrections, such as earthquake magnitude, overburden pressure, and static shear stress, should also be made to the CRR (Seed and Idriss 1982, Seed 1983, Idriss and Boulanger, 2008). For any earthquake moment magnitude M,

$$CRR_M = CRR_{7.5cs}(MSF)K_\sigma K_\alpha \quad (7)$$

where MSF is the magnitude scaling factor, and Kσ and Kα are factors for overburden and initial static stress ratio corrections, respectively. Several expressions have been proposed by individuals for these corrections. The most recently published work by Idriss and Boulanger (2008) can be utilized.

Magnitude scaling factor (MSF). Various relationships between magnitude scaling factor and earthquake moment magnitude have been proposed (Seed and Idriss 1982, Tokimatsu and Yoshimi, 1983, Arabgo 1996, Idriss 1999). By studying the relations between the number of equivalent uniform stress cycles and earthquake magnitude, Idriss (1999) suggested the magnitude scaling factor as:

$$MSF = 6.9\exp(-M/4) - 0.058 \le 1.8 \quad (8)$$

Method 3 :-

Small-strain shear-wave velocity (VS) measurements

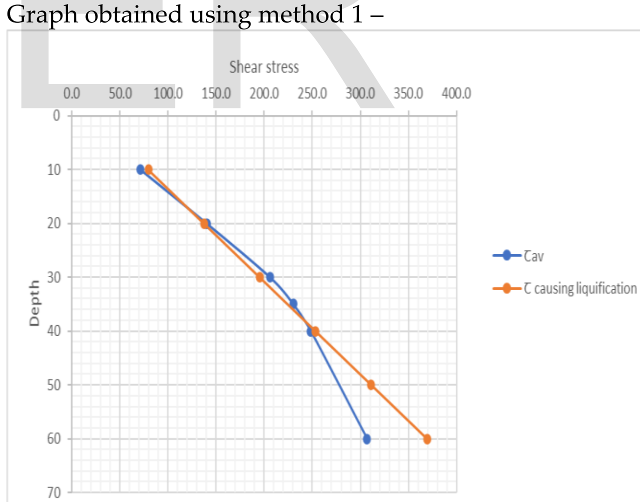
Idris & Boulanger's method

In situ VS measurements provide a promising alternative to the penetration tests, which may be unreliable in some soils, such as gravelly soils, or may not be feasible at some sites, such as capped landfills. In addition, VS is an engineering property, directly related to small-strain shear modulus, and required for dynamic soil response analyses. On the other hand, some factors that affect VS may not equally affect resistance to liquefaction, which is a medium- to large-strain event. Also, VS testing usually does not produce samples for classification or may not be conducted with sufficient detail to detect thin liquefiable strata. Youd et al. [2] and Andrus et al. [3] provide further discussion on the advantages and disadvantages of the VS- and penetration-based liquefaction evaluation methods. The purpose of this paper is to compare the VS liquefaction evaluation method, or curves, proposed by Andrus and Stokoe [4] and updated in Andrus et al. [3, 5] with the SPT and CPT curves summarized in Youd et al. [2] using relationships between penetration resistance and VS. The approach of using penetration-VS relationships to compare curves was applied earlier by Andrus et al. [6] with data from 25 Holocene-age (< 10,000 years) sands with < 10 % fines (particles < 0.075 mm). In this paper, the SPT-VS and CPT-VS databases 20 additional sand data pairs. Regression analyses are performed on the expanded databases and the resulting penetration-VS relationships are used to develop new, more consistent liquefaction evaluation curves.

$$(CSR)_{M=7.5} = {CSR}/{MSF} = 0.65\left({\sigma_v a_{max}}/{\sigma'_v}\right)\frac{r_d}{MSF} \quad (11)$$

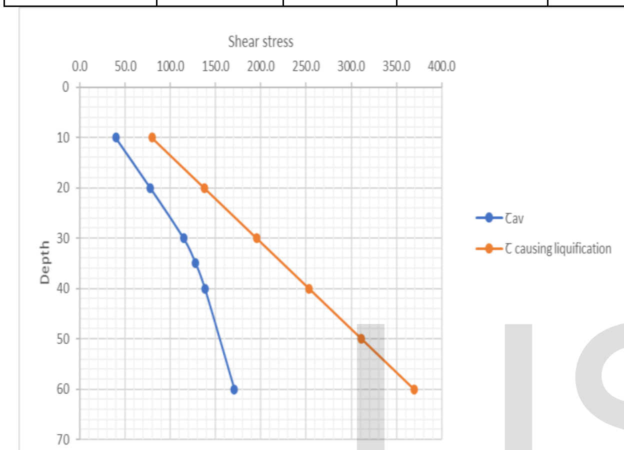
Comparative Study of Above 3 methods :-

Graph obtained using method 1 –

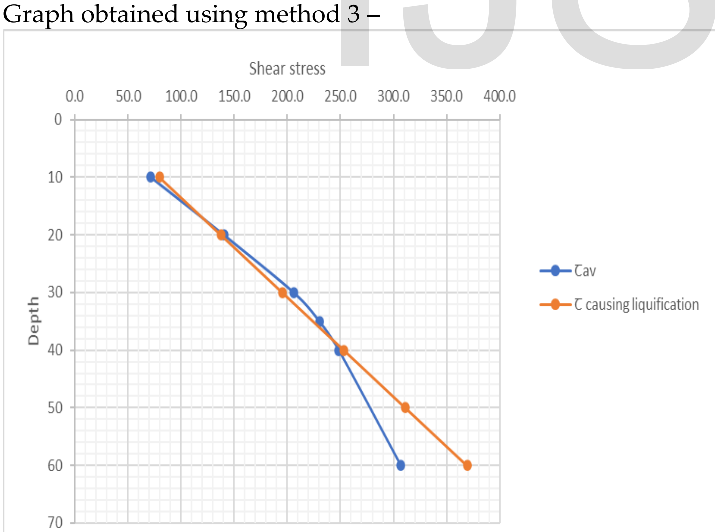


Graph obtained using method 2 –

Magnitude	Seed et al.	Idriss	Boulanger	Result after comparative study
5.5	1.43	2.21	1.68	1.77
6.0	1.32	1.77	1.48	1.52
6.5	1.19	1.44	1.30	1.31
7.0	1.08	1.19	1.14	1.14
7.5	1.00	1.00	1.00	1.00
8.0	0.94	0.85	0.87	0.89
8.25	--	0.78	0.82	0.80
8.5	0.89	0.73	0.76	0.79



Graph obtained using method 3 –



Result & Discussion

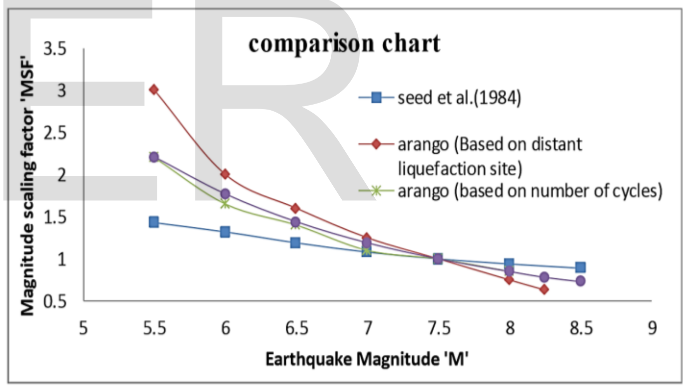
The comprehensive comparative investigation into the interaction analysis of the liquefaction index supported by above 3 methods has been done. The analysis was attempted using more rational approaches and basic realistic assumptions. The system analyzed in the above comparative investigations are considered the 3 major factor which characterized the liquefaction characteristic of soils. The results are compared with the currently used statistical methods in terms of liquefaction index. Close rate of successful prediction for training and testing data shows good generalization capabilities. Various MSFs values calculated by Seed et al. (1985), Arango (1996), Idriss (1999) and Youd et al. (2001) isshown below in table 4 consequently comparative graph between earthquake magnitude scaling factor is depicted.

Calculation of Factor of Safety :-

If the cyclic stress ratio caused by an earthquake is greater than the cyclic resistance ratio of the in situ soil, then liquefaction could occur during the earthquake, and vice versa. The factor of safety (FOS) against liquefaction is defined as:

FSLiquefaction = CRR / CSR

Liquefaction is predicted to occur when FS≤ 1.0, and liquefaction predicted not to occur when FS > 1. The higher the factor of safety, the more resistant against liquefaction, however, soil that has a factor of safety slightly higher than 1.0 may still liquefy during the earthquake.



*purple coloured graph giving optimistic reading on MSF.

The proposed Model :-

The SPT based liquefaction charts are commonly used for determining liquefaction potential. In general, advantages and disadvantages are always associated with discussed methods. Most of the assessment charts take Seed's method as the basis for determination of necessary factors. Factor of safety derived by author is based on the factor affecting liquefaction criteria of soil is to estimate liquefaction potential gradual improvements in these methods made it more precise and viable for almost all kind of soils. Calculation of CSR, CRR and MSF require necessary assumption on early stages, alternatively computational models may save time by omitting lengthy and tedious task of calculation of aforementioned parameters. Based on the formula to work out CRR & CSR have been derived w.r.t. MSF and attempt has been made to ascertain liquefaction potential of soil based on SPT readings post liquefaction standard penetration test (SPT)

Conclusion

In the present study an attempt has been made to work out the most competent method of evaluation of resistance of liquefaction. In the result an attempt has been made to predict the liquefaction potential of soil based on SPT readings post liquefaction standard penetration test (SPT). A comparative analysis is made among the existing methods and the proposed methods for prediction of liquefied and non-liquefied cases in terms of percentage success rate with respect to the field manifestations. To estimate liquefaction potential gradual improvements in these methods made it more precise and viable. for almost all kind of soils. Calculation of CSR, CRR and MSF require necessary assumption on early stages, alternatively computational models may save time by omitting lengthy and tedious task of calculation of aforementioned parameters. Case histories of soil liquefaction are analyzed using empirical methods, further the arithmetic analysis to predict the liquefaction potential of soil. The results are compared with the currently used statistical methods in terms of CRR & CSR. Based on the results, comparison has been done to derive optimistic method to analysis the soil from liquefaction point of view. Comparison chart is illustrative to Magnitude scaling factor by different methods which tends to draw curve giving most safe and valid reading of MSF w.r.t. earthquake magnitude. Close rate of successful prediction for liquefactions shows good generalization capabilities of statistical approach. The developed method is found to be more efficient compared to the empirical methods in identifying the point of liquefaction. However, it needs more study with new data sets of different liquefaction case histories to confirm or disprove the present findings.

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