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Liquefaction of the mixture of sand and fines are the prime problem in geotechnical era of civil engineering

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Abstract: Liquefaction is one of the devastating effects of earthquake. It has occurred even before the recorded cases in the history. Liquefaction causes not only failure of super-structure but also produces instability of sub-structure, which results into catastrophic damages. Liquefaction is the term commonly used to describe the sudden, dramatic strength loss which mostly occurs in sands during seismic loading. It is a consequence of increased pore pressure and reduced effective stresses resulted into the transformation from a solid state to a liquefied state of soil. While most frequently associated with cohesion-less soils and dynamic loadings, it has been reported in all types of soils ranging from fine-grained to gravelly type soil under both dynamic and static loadings depending upon extent of the seismic and environmental factors. It is the globally recognized prediction standard for identification of liquefaction of mixture of sand with fines.

To achieve the objective, the present research work commenced with the literature review for the identification of existing prominent liquefaction susceptibility criteria. It was beneficial to extract the significant soil parameters from the prominent eight criteria. The comparison among these criteria revealed the discrepancies regarding the selection of liquefaction parameters and their ranges. The root-cause for the discrepancies in the pre-existing criteria is their site-dependency. It was observed that the database comprised mostly the same parameters of database of sandy soil. Hence it was converted in terms of parameters considered for prominent criteria by using the basic geo-technical relations and the conversion charts by carrying out more than 1000 computations. The total database for fine grained soil comprises 291 data-cases, with 194 liquefied cases and 97 non-liquefied cases. The final output of this method was the regression equation giving the relation between most significant parameters and the prediction response of liquefaction. The proposed probable liquefaction criterion was verified successfully by DOE technic. The proposed criterion comprised the index properties of fine grained soil as the most significant parameters for prediction of liquefaction. The determination of these properties in the laboratory can be carried out by very simple laboratory procedures. Hence the proposed criterion

may be considered as the effective and accurate yet simplest method for assessing the liquefaction of sand with fines.

Key Words: Liquefaction, earthquake and geo-technical relations.

Introduction: Derived from the Latin verb “liquefacere”, meaning to melt, to dissolve, or to weaken, Liquefaction is the term commonly used to describe the sudden, dramatic strength loss which sometimes occurs in sands during seismic loading. While most frequently associated with cohesion-less soils and dynamic loadings, it has been reported in many types of soils under both dynamic and static loadings. Liquefaction is one of the devastating and complex phenomenons in geotechnical earthquake engineering. Liquefaction induced failure has been and continues to be the major cause of destruction during earthquakes is the occurrence of liquefaction.

Recently, the newest definition has presented with Idriss and Boulanger (2008) as ‘Loose cohesion-less soils tend to contract during cyclic loading, which can transfer normal stress from the soil skeleton to pore water, if the soil is saturated and largely unable to drain during shaking.

The liquefaction of loose, saturated sands has been studied extensively and currently is relatively well understood. Under cyclic loading, such as an earthquake, the soil particles have a tendency to rearrange and densify. With the densification of the particles, the mineral solids transfer the shear stress developed by the earthquake for cesto the incompressible pore water in-between in the pore-voids. Due to incompressibility of pore water and transfer of earthquake stress, there is tendency to increase in pressure of the pore water. With increase in pore water pressure, effective confining pressure decreases, leading to a significant loss of shear strength. It is resulted in loosing contact between the soil particles. This phenomenon causes significant damage to the structures above that rely on soil for support.

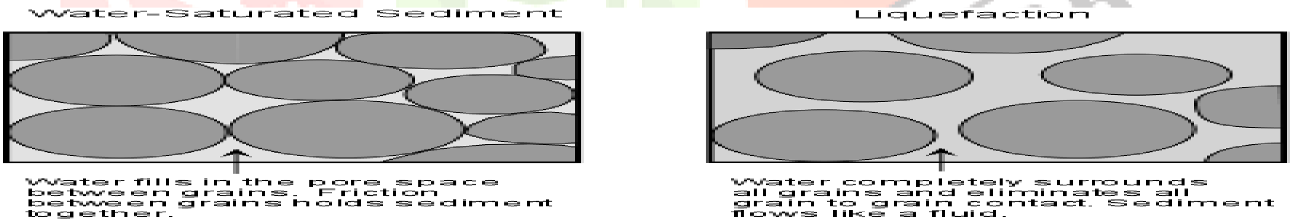

Figure 1 shows inter-granular contact before and after liquefaction. These phenomena can be divided into two main categories: flow liquefaction and cyclic mobility.

Figure 1.2: Flow liquefaction damage during Alaska earthquake, 1964

Figure 1.3: Cyclic mobility during Guatemala earthquake 1976

When the liquefaction occurred due to the shear stresses developed by cyclic loading, it is called as cyclic mobility. In this case also, static shear stresses lower than the soil strength. Deformations due to cyclic mobility develop incrementally because of static and dynamic stresses that exist during an earthquake. Lateral spreading, a common result of cyclic mobility, can occur on gently sloping and on flat ground close to rivers and lakes.

Extensive effort has been devoted to the study of liquefaction of sands in the last 50 years and research has progressed to the stage that liquefaction behavior of saturated cohesion-less soils can be predicted from laboratory testing by direct shear test and tri-axial shear test or from simple field test data such as standard penetration values [N1 or (N1)60] or Cone Penetration Test (CPT) data.

Need for Change in the Approach

Very rarely a sandy soil is clean in nature but it is mixed fine grained soils. The fine-grained soil is again sub-classified into non-plastic silts and plastic clay. Firstly, it was reported by Kishida (1969) about the liquefaction of soils with part of fines up to 70% and clay fraction upto10% during Mino- Owar, Tohankai and Fukui earthquakes. It was assumed before 1975 Haicheng and 1976 Tangshan earthquakes that only “clean sandy soils” with few amount of fines do liquefy. The cohesional component of shear strength of the fine grained soil overcomes the shear stresses due to seismic forces. This tendency reduces the possibility of liquefaction of such soil. However, those earthquakes gave evidences that even cohesive soils could liquefy.

Motivation and Problem Definition:

Generally soil in nature is the combination of sand with fines with different proportions. Such type of soil is observed beneath critical infrastructures. At such site, many earthquake-induced ground failures had occurred resulted in the major damages to the infrastructures. Hence, there is need of method to predict the liquefaction of the mixture of sand with fines. Based on the study of the major earthquake in China, Dr.Wang Henshao introduced ‘Chinese criteria’ to assess the liquefaction potential of such type of soil. It is purely based on the plasticity characteristics of soil. After application of the pre-existing significant criteria on the compiled database and studying the % success rate it could be determined to modify the existing criterion or to develop a new criterion. To check the reliability of abovementioned work, it is assessed by the analytical method as well as laboratory tests.

Aim

The damages due to liquefaction of the mixture of sand and fines are the prime problem in geotechnical era of civil engineering. To provide the proper mitigation work after damaged by seismic liquefaction, the prior information about the probable triggering of liquefaction and its intensity is necessary. The aim of this study is to modify the pre-existing prominent liquefaction criteria or develop a new liquefaction criterion for triggering a seismic liquefaction which is globally applicable. The aim of this study frame anew criterion for the assessment of liquefaction triggering potential of fine grained soils based on the most liquefaction parameters with various ranges.

Objectives

- By detailed literature survey work, acquire in-depth state of art.
- Collection of database from past earthquakes for already performed in-situ & laboratory tests.
- Develop new correlation between significant soil parameters to form new criterion.
- Validation of correlation with test results of past earthquakes as well as the laboratory tests.

Literature review

Liquefaction of soils is caused by the significant loss in shear strength and stiffness due to increase in pore pressure. This is one of the major reasons for damage and life loss during the earthquakes. Numerous researches have been carried out to understand this phenomenon in depth after observing severe liquefaction- induced damages observed during and after 1964 Niigata and1964 Great Alaska earthquakes. After the pioneer studies, the numbers of both case histories and high-quality test data have increased in almost five decades, enhancing the reliability and accuracy regarding the prediction of liquefaction of sandy soil.

In this method proposed by Seed and Peacock (1971), the average shear stress denoted by τav is calculated in the manner same as in Seed and Idriss method. The permissible shear offered by soil denoted τv at the chosen depth of the soil strata is obtained by using the curves recommended for calculation of CRR from corrected SPT data (Youd & Idriss, 1997; Youd et al., 2001). If τav>τvthen soil willliquefy, otherwise there is no possibility of liquefaction. Here, τavand τvare shear stress induced by earthquake and permissible limit of shear stress of soil respectively.

A simple geotechnical method which was included in the Japanese Bridge Code was proposed by Iwasaki et al. (1982). In this method, soil liquefaction capability factor R, is calculated along with a dynamic load L induced in a soil particle by the seismic motion. The ratio of both is defined as liquefaction resistance. The soil liquefaction capacity is designed by the three factors namely overburden pressure, Grain size and fine content.

Effect of plastic fines on soil liquefaction:

- **Adhesion** Researchers using different approaches have reached an agreement that plasticity index (PI) may serve as a better indicator in distinguishing liquefaction susceptibility. The advantages of plasticity index, to be used as susceptibility criteria, are procedural simplicity, easy to measure and highlyvalidable.
- **Clay fraction** NLiquefaction resistance firstly decreases with addition of plastic fines, then increases when exceeding certain percentages of fines by weight. The transition zone for clayey sands is between 15% to 35% plastic fines..
- **Water trap ability** The specimens having plastic fines up-to 20% will have higher water trap ability compared to clean sands. The pore pressure generation below 20% clay is higher because clay content decreases the permeability and conductivity within the sandy soils. However, the pore pressure generation drops when specimens are having more than 30% of plastic fines.

Mamtani and Green, 2006, Bindu, R. S. and Ahuja, B.B. (2010) and Rajhans, R.R. and Ahuja, B.B. (2012). Nowadays MCDM procedures such as Analytic Hierarchy Process (AHP), the Entropy method and Relative Reliability Risk Index [R^3I] are being widely used in the fields of industrial engineering and operational research areas (Mamtani and Green, 2006, Bindu and Ahuja, 2010, Rajhans and Ahuja, 2012). The main objective to carry out these MCDM methods is to determine the weight of each parameter affecting the ultimate goal. When a large set of parameters affect the goal, it becomes necessary to identify the significant parameters so as to perform reliable and accurate prediction.

Research methodology

It explains the research approach used in this work namely the extraction of significant liquefaction parameters from the pre-existing prominent liquefaction criteria of the mixture of sand with plastic fines, the data collection, the confirmation of liquefaction parameters by specialized statistical tools and development of new criterion for assessment of lique faction of the mixture of sand and fines. The validation of the proposed liquefaction criterion by analytical method namely 'Design of experiment' and laboratory evaluation by 'Static tri-axial shear test' is also described.

Following the 1964 Good Friday Earthquake in Alaska, the issue of liquefaction of fine grained soil received initial scrutiny immediately but it had not been a research emphasis since that time. The recent geotechnical investigations have started to focus revealing the evidences of recent field observations involving ground failures and poor foundation performance at sites underlain by fine grained soil. The evaluation of cyclic soil behavior of such soil is often based on the models that are either established for sands. A specific example is provided by the Simplified Procedure for liquefaction of sandy soils that is the standard of practice in geotechnical engineering (Youd et al. 2001).In this procedure the modification is done for liquefaction resistance of sandy soil for the presence of fines, up to a maximum fines-content of 35%. However this procedure for fine grained soil is not fairly suited for the application. A review of the literature reveals the conflicting evidence as to the effect which fines have on the liquefaction resistance of sand.

Results

The first interim output obtained after feeding the above-mentioned data to the DOE software is the possible combinations i.e. 324. This out-put can be verified by considering the theory related to statistics. According to theory, number of combinations can be computed as follows:

Total Number of combination

=NumberofReplication×(Numberofcombinationforfactorswithlevels2)×(Number of combination forfactorswithlevels3) (Equa.3.9)

Here No. of factors with levels 3=Number of level Number of factor =34 =81

No. of factors with levels 2=1

Number of combination of factor with level 2 =Number of level Number of factor=21=2

So, Total number of combination=2×81×2=324

So, the interim out-put i.e. No. of combination is in agreement with the theoretical value. (Source: Jain, R.K. and Purandare, A.S.2018)

To determine the computer-based regression equation to predict the triggering of liquefaction, it is necessary to the feed the input of the response of all above-mentioned combinations of the liquefaction parameters to the DOE software.

The response for the combination of factors with various levels is determined by using the proposed criteria for assessment of liquefaction with following procedure. The sum of numerical value of weights for all significant factors (parameters) is computed according to the proposed liquefaction criteria C-8 as presented in Table 3.26.According to this criteria, threshold value of sum, for assessment of "Yes" liquefaction should be equal or more than '2.0' otherwise "NO" liquefaction. The response for DOE method, in digital value terms is "1" is for "Yes" liquefaction otherwise “0” for “No” liquefaction. This procedure is adopted to find response for each andevery combination. The result after running the DOE software in terms of co-efficient for the factors with various levels and their p-value is presented in Table3.29.The relation between the numerical value of response and the coefficient of each parameter corresponding to the range is given in the form of regression equation presented as:

Regression Equation for Response in numerical value = (0.5)
+[(0.2407) for PI in 1st range+ (0.0)for PI in 2nd range+(-0.2407)for PI in 3rd range] + [(0.2407) for σ’vo in 1st range+(0.0) for σ’vo in 2nd range+(-0.2407) for σ’vo in 3rd range]
+ [(0.2407) for Wc /LL in 1st range+(0.0) for Wc /LL in 2nd range +(0.2407)for Wc /LL in 3rd range] + [(0.2407) for D50 in 1st range+(0.0) for D50 in 2nd range+(-0.2407) for D50 in 3rd range] + [(0.1173) for %CC in 1st range-(0.1173) for %CC in 2ndrange]

To develop new criteria suitable for this issue, as a basic starting step of ladder of this research work, the prominent liquefaction criterion from the cluster of criterion are selected and studied in detail as follows:

Table 1:- Co-efficient for various ranges of factors

S. N.	Term	Range of factor	Primary Co-efficient	Secondary Co-efficient	Tertiary Co-efficient	p-value
1	Constant		0.5000	0.0611	31.00	0.0000
2	PI	0-15	0.2407	0.0228	10.55	0.000
		16-25	0.0000	0.0228	0.000	1.000
		>25	-0.2407	-0.0228	-10.55	-0.000
3	σ'_{vo}	<150	0.2407	0.0228	10.55	0.000
		150-250	-0.000	0.0228	-0.00	1.000
		>250	-0.2407	-0.0228	-10.55	-0.000
4	W_c/LL	>0.9	0.2407	0.0228	10.55	0.000
		0.75.-09	-0.000	0.0228	-0.000	1.000
		0.75	-0.2407	-0.0228	-10.55	-0.000
5	D_{50}	>0.02	0.2407	0.0228	10.55	0.000
		0.002-0.02	-0.0000	0.0228	-0.000	1.000
		<0.002	-0.2407	-0.0228	-10.55	-0.000
6	%CC	0-15	0.1173	0.01617	0.000	1.000
		>15	-0.1173	-0.01617	-0.000	-1.000

The following inferences may be drawn from the regression equation (Table No.1)

- The primary co-efficient of the significant factors Plasticity Index (PI), Effective vertical overburden pressure (σ’vo), Ratio of water content to Liquid Limit(Wc/LL) and mean particle size (D50) are equal i.e. 0.2407, from it may be inferred that the impact of these significant factors on assessment of liquefaction of fine grained soil is thesame.

- The primary co-efficient of the significant factor %CC is 0.1173 which is quite less as compared to other significant factors. This reflects that it has less impact on liquefaction as compared to remaining significant factors (PI, σ'vo, Wc/LL, andD50)
- Eqn. 3.10 gives the response in the numerical value. From it's numerical value, the possibility of liquefaction at a site with the prescribed set of values of significant factors may bepredicted. From this regression equation 3.10, the triggering the liquefaction can be assessed by adopting following procedure:
- The level (the range) of the factor (liquefaction parameter) is determined from the given database.
- The co-efficient of the level is obtained by referring the regression equation orTable3.29 for each and every factor.
- The summation of all five co-efficient along-with the constant i.e. 0.5000 gives the numerical response of DOE method.
- The nature of response is assigned according to the numerical value as follows:
- For '+ ve' response i.e. 'Yes' liquefaction, it's in numerical value ≥1other- wise '– ve' response i.e. 'No' liquefaction.
- Hence it may be inferred that Design of Experiments is a powerful unique statistical technique to identify the most significant factors and their comparative impact on the response. The results of this technique are in good agreement with AHP with Entropy method and the proposed liquefaction criterion for fine grained soil. (Jain, R.K. and Purandare, A.S.2018)

The foot-steps were set from step by step information gathered by reviewing the literature related to the liquefaction of mixture of sand with fines in the preceding chapter. The journey of this research work is progressed along these foot-steps. The work commenced from the identification of prominent liquefaction criteria for the soil type abovementioned. The benefits of this step are the extraction of the significant parameters with their range governing this phenomenon and the decision to develop a altogether new criterion instead of moderate modifications. The global database is compiled to enhance the accuracy of to be developed liquefaction criterion. The extraction of the significant parameters is confirmed by number of statistical tools namely the application of the basic criterion on the compiled database, the AHP with Entropy and DOE methods. Based on it, a series of liquefaction criterion was framed by addition of new parameters and/or the modification in the parameters. The criterion C-8 which comprised all most significant liquefaction parameters with the maximum % success rate numerically 83% is considered the proposed liquefaction criterion. The proposed criterion is validated by the DOE method successfully.

Experimental work

For determination of four parameters out of five, constituting the proposed criterion the experimental work is performed in the laboratory. In addition, experimental work is done to obtain the pre-requisite fundamental properties of soil samples to perform 'Tri- axial shear test'. Based on the preliminary knowledge of the tri-axial testing and the fundamental properties of sand, kaolin clay and their various combinations, the consolidated un-drained static shearing tests for each effective confining pressure mentioned in the above test schedule were performed. Up-to the significant reduction in the load carrying capacity of sample, each test was continued. The analysis of the data collected from the tests was carried out to compute the values of deviator stress, % axial strain, major and minor principal stresses, effective major and minor principal stresses. The investigation is carried out by comparing the results of tri-axial test and by applying the proposed liquefaction criterion on the laboratory derived database in the succeeding chapter to validate the proposed liquefaction criterion.

Conclusions

- The comparison among them reveals the discrepancies regarding the selection of liquefaction parameters and their ranges. Hence, it was inferred that there is a need to modify the range of parameters of pre-existing criteria or to develop a new one.
- The extent of data collected for these types of soils is less as compared to sandy soil. At the same time, these databases contain mostly the same parameters of database of sandy soil (such as SPT, CPT, and Relative density). Some non-available data for % CC and D50 parameters in the above-mentioned database are extracted from soil profiles obtained by SPT and /or CPT investigation at the respective sites. Some D50 data points are computed by using co-relations between normalized Standard Penetration Test value i.e. (N1)60, Cone Penetration Test value i.e. qc , and mean grain size D50, as suggested by Robertson et al.(1983).
- The outcome of this work gave the importance of each parameter and necessary clubbing of parameters to develop a new criterion. A unique statistical method, namely 'Multi criterion decision making' with 'Entropy method' was applied on the set of parameters for identification and gauging the importance of liquefaction parameters. The identified parameters formed the set of 'significant liquefaction parameters'.
- The appropriate weight (mark) was assigned for satisfying the range of the parameter. A trial criterion (C-1) was formed with above procedure and it was applied on the compiled database resulting with success rate greater than the maximum success rate of pre-existing criteria. This inferred that the research work is on right path.

It is revealed from the conclusion that the triggering of liquefaction may be predicted by applying the proposed liquefaction criterion for sand with clay with fair accuracy. It is constituted by five most significant liquefaction parameters along with the effect of range of parameter which is actually the governing factor for this phenomenon. The numerical value of all these parameters can be determined in the laboratory in short duration by performing very simple standard procedures. The obtained weights of every parameter of this proposed criterion according to the prescribed range are clubbed together which gives the overall effect of all parameters. It is the essence of this criterion hence it may be used to predict the onset of liquefaction of the mixture of sand with various proportion of clay.

Major contributions from the research work:

- The pre-existing prominent criteria were site specific; hence it is necessary to compile the updated world-wise database. This work will add a dependable data set for liquefied and non-liquefied-cases for the mixture of sand and fines which would satisfy the pre-requisite to enhance the accuracy and dependability of lique faction criteria.
- An application of the novel method of 'multi criteria decision making' integrating AHP and Entropy generate 'comparative matrix' and 'decision matrix' to determine the identification of significant parameters with their weights. This method is carried out for the mixture of sand with fines first time.
- Design of Experiments is a powerful unique statistical technique to identify the most significant factors and their comparative impact on the response. It also provides the relationship between the significant factors and the response in terms of 'Regression Equation'. This technique is used first time in this domain of 'Liquefaction of fine grained soil' and it confirms the selection of the set of significance parameters with their importance. The onset of liquefaction of sand with clay may be predicted by computing the numerical and digital value of the response. The results of this technique are in good agreement with AHP with Entropy method and the proposed liquefaction criterion for fine grained soil.

- The triggering of this phenomenon depends upon the significant parameters and their ranges. All these factors were considered in developing new proposed criterion by assigning appropriate weights. The addition of obtained weights after satisfying the range of each parameter gave the combined effect of all selected significant parameters along-with their range. The proposed criterion with this concept is the major contribution from this research work.

Future Scopes

- As the years passed with the new eruption of the earthquakes, the nature will continue to provide new lessons and data; the data-base can be updated and expanded. With the expanded database, the accuracy and reliability of the criterion may be enhanced by doing the modifications if required.
- The laboratory testing is done on the soil specimens prepared from sand and up-to 20% kaolin clay. In future work, the plasticity can be increased by increasing proportion of clay and /or by adding more plastic clay such iolite and betonies. Also silt can be added in this mixture.
- In this study, the focus was given on the soil properties only, though the seismic properties namely maximum acceleration, earthquake magnitude, hypo-central distance, time duration etc. have tremendous influence on the shear stresses developed during eruption of earthquake. The intensity of the shear stress produced by earthquake is the major governing factor. This strength of an earthquake affects liquefaction susceptibility. The destructive capacity of the liquefaction highly depends upon the above-mentioned seismic parameters also. They were not considered in this study due to pre-decided scope of the work, it may be considered in the future research work.

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