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Plasticity based Liquefaction Susceptibility using Multi-Linear Regression Model

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Abstract. Bihar falls in high seismic zone of India as most of the area lies in zone IV and V which is also densely populated. These areas have alluvial soil deposits due to existence of numerous flood plain. Therefore, evaluation of liquefaction susceptibility is necessary to provide a guidance for engineers and designers towards safer and economical design of civil engineering structures. The alluvial soil deposits consists of material like silt or clay which tends to make an important and consistent difference in the cyclic strength of the soil. Generally, the presence of plastic fines tend to increase the liquefaction resistance of a soil due to dilatative nature but, there is a contradictive statement for non-plastic fine behaviour towards liquefaction resistance. The present paper summarizes the effect of plasticity of the soil on liquefaction of alluvial soil deposits in areas close to river Ganges and falls under seismic Zone-V. Since these areas are highly significant in terms of economy and population and have a past experience of large scale liquefaction, therefore, liquefaction potential analysis using multi-linear regression tool have been carried out to predict the liquefaction susceptibility considering plasticity of soil deposits as the key criteria. A comparative study has also been presented between the regression model and the conventional methods and results confirm that the developed regression model is an effective and prominent approach for the prediction of the liquefaction potential of soil as compared to the conventional approaches.

Keywords: Liquefaction susceptibility, plasticity, multi-linear regression analysis

1 Introduction

Liquefaction has been studied extensively by researchers all around the world right after the 1964 Niigata (Japan) and 1964 Great Alaskan Earthquake in which large scale soil liquefaction occurred, causing wide spread damages to building structures and underground facilities. Since then liquefaction became a very common and burning problem for many countries. The evaluation of liquefaction potential of a soil deposit have become one of the significant aspects of geotechnical engineering. Ground failures associated with earthquakes not only initiates the failure of superstructure as well as it triggers the instability of substructures. Such failures can cause catastrophic impact and severe casualties especially in urban cities with alarmingly high population. Therefore, evaluation of liquefaction potential of soil deposits has been a subject of rigorous research in the field of Geo-technical engineering over the last few decades. At initial stages of the research, it was considered that liquefaction is a phenomenon that is only applicable for loose, cohesionless and saturated soil deposit only but observations made during several earthquakes showed evidence of liquefaction in soil with fine content having medium to low plasticity. These type of soil dilate extensively throughout shearing. Material like silt or clay are non-plastic or plastic in nature tends to make an important and consistent difference in the cyclic strength of such soil deposits. Wang (1979) noted liquefaction in silty sand to slightly sandy silt soils during Haicheng, 1975 and Tangshan, 1976 earthquakes. A criteria for clayey soil was proposed which stated that soil containing less than 15–20% particles by weight smaller than 0.005 mm and having a water content (w_c) to liquid limit (*LL*) ratio greater than 0.9 is vulnerable to liquefaction. Clayey soils could be susceptible to liquefaction only if all three of the following conditions are met, first percent of particles less than 0.005 mm<15%, second *LL*<35% and *wc/LL*>0.9 (Wang, 1979; Seed and Idriss, 1982). This standard came to be known as the Chinese criteria due to its origin. Martin and Lew (1999) stated that clayey soils are those that have a clay content greater than 15% and such soil deposits should be considered as non-liquefiable. However, number of cases were observed where ground failure caused considerable damage to buildings in silty and clayey soils containing more than 15% clay-size particles during Northridge (1994), Kocaeli (1999) and Chi-Chi (1999) earthquakes. Based on experimental and analytical analysis, it was suggested that soils observed to be liquefied during Kocaeli (1999) earthquake and did not meet the Chinese criteria. Andrews and Martin (2000) reviewed empirical approach and suggested a new assessment index which transformed the conventional Chinese Criteria in accordance with US standards and renamed as Modified Chinese Criteria. Studies undertaken in early 1980's by various researchers at University of Missouri–Rolla (UMR) (now Missouri University of Science & Technology) acknowledges the effect of plasticity of soil on the liquefaction of silts based on laboratory data. Seed et al. (2001) recommended that liquid limit as well as plasticity index differentiates the susceptible soil to those falling in "uncertain range". Soil samples that lies in uncertain zones of the plasticity chart should be additionally investigated through laboratory investigation. Conclusion drawn from the work of various researchers suggests that interdependency exists in between plasticity and cyclic strength of soil which gives rise to use of fine content, liquid limit (*LL*), plasticity index (*PI*) as a key criteria's for the evaluation of liquefaction susceptibility of soil deposits [Ishihara and Koseki (1989), Sandoval (1989), Prakash and Sandoval (1992) Polito(2001), Seed et al. (2003), Bray et al. (2004), Bray and Sancio (2006), Gratchev et al. (2006), Idriss and Boulanger (2006), Marto et.al (2015), Paydar and Ahmadi (2016)]. Evaluation of liquefaction potential of soil with the presence of fine content can be profoundly dependent on numerous factors such as liquid limit (*LL*), Plasticity index (*PI*), moisture content (w_C) as observed in the literature, but there are many possible reasons that may cause uncertainty in the prediction of liquefaction problems and thus a reliable approach is needed. The present study makes an attempt to develop a multi-linear regression model (MLR_{model}) for quick evaluation of liquefaction susceptibility of silty clay soil deposits considering few basic soil parameters. Multi-linear Regression analysis is a statistical technique which can be used to examine the relationship between a dependent variable (input parameters) and a set of independent variables i.e. output parameter. For a multiple linear regression analysis, it is assumed that the relationship between the input variables and output variables is linear and has the following form:

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ...\beta_p X_p \tag{1}$$

where y is the predicted or expected value of the dependent variable, X_1 through X_P are p distinct independent or predictor variables, β_0 is the value of y when all of the independent variables (X_1 through X_P) are equal to zero, and through β_1 are β_p the estimated regression coefficients.

Bartlett and Youd (1992 and 1995) used multilinear regression (MLR) to develop an empirical equations for the prediction of lateral spread displacement which gained wide use in engineering practice. Youd et al. (2002) revised this work to predict a new MLR equation which prevents unrealistic over prediction of displacements. Babu and Singh (2010) used regression models to study the influence of variability of in-situ soil properties on the stability of soil nail walls. Chatterjee and Choudhury (2013) used regression analysis to establish a correlation between shear wave velocity (*V*s) and SPT (*N*) value for various soil profiles of Kolkata city. Latha et. al. (2013) used multiple regression equation to predict the bearing capacity of geosynthetic reinforced sand beds. Youd (2018) applied a multiple-linear regression (MLR) procedure to prediction the liquefaction-induced lateral spread displacement. Anwar et al. (2016) preformed an assessment of liquefaction potential of soil using multi-linear regression modelling for a particular location at a site in Lucknow city. Many researcher have promoted the use of MLR in geotechnical engineering [Liao (1988); Joyner and Boore (1993); Bartlett and Youd (1992, 1995); Youd et. al (2002)]. Hence, a robust regression model for evaluating the liquefaction susceptibility which is based on field test data such as plasticity index, liquid limit, SPT value and water content for preliminary prediction would be of great help in the field of geotechnical engineering.

Bihar has a past history of major earthquakes; the worst was the 1934 earthquake with a magnitude of 8.0 in which more than 10,000 people lost their lives, followed by 1988 earthquake and recent earthquake was the Sikkim earthquake in September 2011. The new and growing urban centers in the state where building codes and control mechanisms are not enforced, earthquake remains a major threat to cities. With most of the districts falling in high seismic zones and infrastructures such as schools and hospitals that are not built to be earthquake resistant and could lead to serve damage and loss of lives as well. Various authors have showed the need for location based study for seismic soil properties and analysis for liquefaction potential of soil deposits. The present paper develops a liquefaction prediction model using multi-linear regression analysis for a site in Madhubani district of Bihar which falls under seismic zone V based on the vulnerability atlas of India, BMTPC (Building Materials and Technology Promotion Council).

2 Predicting Liquefaction Potential as Per Conventional Method

Liquefaction evaluation for the soil with fine content and plasticity was originally proposed by Wang (1979) which came to be known as Chinese Criteria, but after series of studies and observation made from the past literature various researcher proposed several methods or ranges of soil properties to classify a proposed soil deposit as liquefiable or non-liquefiable.
In this study, a comparative study of conventional methods has been carried out using three different criteria's to evaluate liquefaction susceptibility of fine-grained soil.

2.1 Chinese criteria (1979)

First liquefaction susceptibility criteria was given by Wang (1979) and it was modified by Seed & Idriss (1982). The Chinese criteria stated that stated that a fine-grained soil is considered to be susceptible to liquefaction, when Liquid Limit < 35%, Liquidity Index > 0.75, Natural Water Content > 0.9 x Liquid Limit, Percent Passing 0.005 mm Sieve Size < 15%

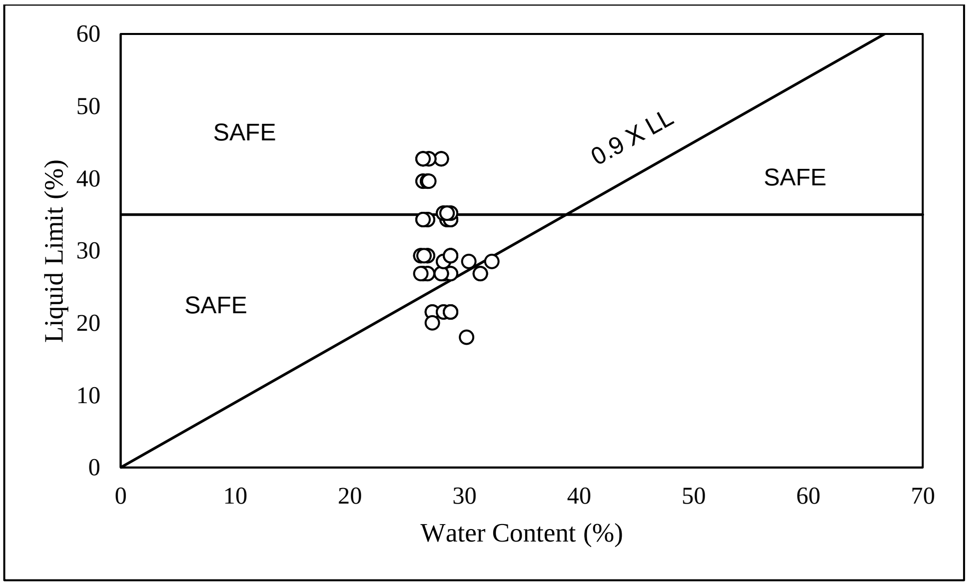

Fig. 1. Liquefaction Susceptibility as per Chinese criteria (1979)

2.2 Seed et al (2003)

Seed et al proposed the criteria based on plasticity index and liquid limit of the soil. According to Seed et al (2003) soil in Zone A defines potentially liquefiable soil and Zone B defines more test require to justify liquefiability of soil. Soil outside of these zones are not vulnerable in terms of liquefaction.

Zone A: Potentially Liquefiable if (FC≥35%, PI<12%, Wc≥0.85LL)

Zone B: Test if (FC≥ 20%, PI>12% and Wc≥0.85LL)

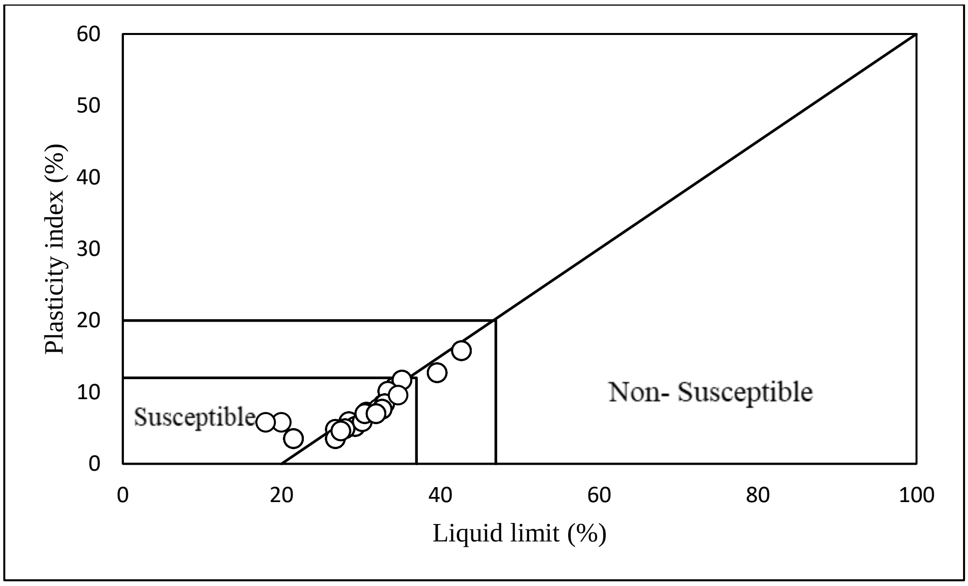

Fig.2. Liquefaction Susceptibility as per Seed et al. (2003) criteria

2.3 Bray et al. (2004 & 2006)

Bray & Sancio (2004) criteria states that soils with PI≤12 and Wc/LL≥ 0.85 are highly susceptible to liquefaction and 12<PI≤20 and Wc/LL≥0.80 are moderately susceptible to liquefaction whereas the Bray & Sancio (2006) criteria suggests that soils with PI<12 and Wc/LL≥0.85 are highly susceptible to liquefaction and 12<PI<18 and Wc/LL>0.80 are moderately susceptible to liquefaction and *PI* >18, are resistant to liquefaction.

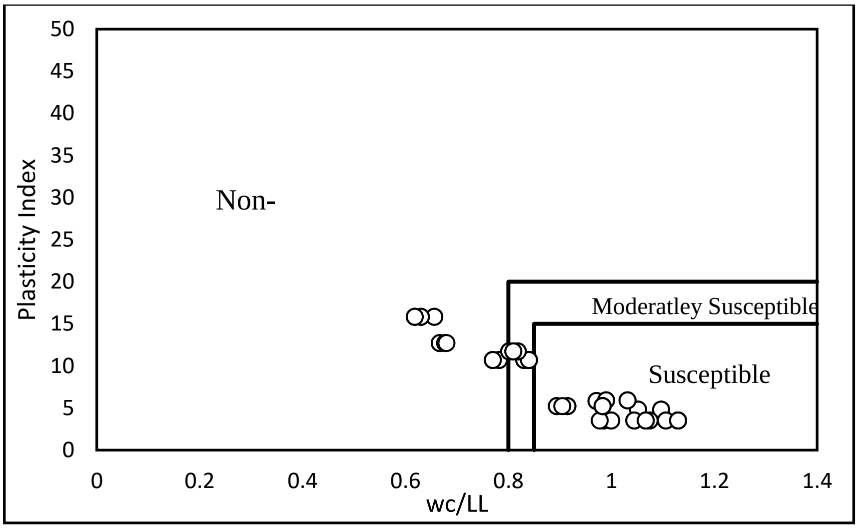

Fig.3. Liquefaction Susceptibility as per Bray & Sancio (2006) criteria

Fig: 1, 2 and 3 presents the liquefaction susceptibility of the selected site as per Chinese criteria (1979), Seed et al. (2003) and Bray & Sancio (2006) criteria. As observed from the figures, only two or three input parameters were used to evaluate liquefaction potential, so for better understanding and more appropriate approach this study uses five input parameters to predict liquefaction of a soil deposit. Table: 1 shows the soil parameters used in Chinese criteria (1979), Seed et al (2003) criteria and Bray and Sancio (2006) criteria and parameters used in this study.

Table 1. Parameters used by various researchers v/s parameters used in present study

Soil Parameters	Chinese Criteria(1979)	Seed et. al (2003) criteria	Bray and Sancio (2006) criteria	Present study
LL	✓	✓	✓	✓
PI		✓	✓	✓
*w*c	✓		✓	✓
SPT				✓
wc/LL				✓

3 Predicting Liquefaction Potential as Per Multiple Regression Analysis

Multiple linear regression analysis of the results obtained from the conventional methods were carried out considering all the significant parameters as observed from the literature and an equation is proposed to evaluate the liquefaction susceptibility. The performance of the regression model is generally investigated by statical performance parameters enlisted below and the formulas used to compute the mentioned parameters R^2, and MSE are presented in equation 3 and 4 respectively.

1. Coefficient of Determination or Model Fit Value (R^2),
2. Mean square error (*MSE*)

$$R^2 = \left[\frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{I=1}^{N}(x_i - \bar{x})^2 \sum_{I=1}^{N}(y_i - \bar{y})^2}}\right]^2 \qquad (2)$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_a - y_p)^2 \qquad (3)$$

R^2 ranges from 0 to 1. The closer it is to 1, the better the fit. If R^2 equal to 1 it means perfect linear relationship exists between the dependent variable and independent variables, while R^2 equal to 0 indicates independent variables have no impact on the dependent variable. *MSE* is the estimate of standard error, smaller the values the better the fit. These measurement provides an excellent indication of the quality of the fit when the prediction is important for the model. The values of R, R^2 and *MSE* determines the goodness of the model.

4 Result and Discussion

The proposed site belong to seismic zone V and is vulnerable to high intensity earthquakes that may lead to large scale ground deformation and liquefaction. Liquefaction potential of the proposed site has been obtained from the above enlisted criterias shown in Fig: 1 to Fig: 3. It was observed that major segment of the site falls under susceptible and moderately-susceptible zones, few soil layer were lying in non-susceptible zones. The three mentioned criteria uses different input parameters and suggest different limits and boundaries for those parameters to classify liquefiable and non-liquefiable soil deposit, these dissimilarity and variation develops the risk of uncertainty and error while predicting and designing structures to with stand liquefaction. Due to such uncertainty and confusion observed in the conventional methods, a multi-linear regression analysis was performed and an equation have been proposed that can facilitate the predication of liquefaction susceptibility. The following section provides an insightful data obtained from the regression model.

Table 2. Regression Co-efficient

Regression Co-efficient	Values
Intercept	3.54
PI	0.21
LL	-0.15
SPT	0.01
wc	0.09
wc/LL	-2.78

Based on the regression co-efficient in Table: 2, an equation has been formed to determine the liquefaction susceptibility of districts falling in seismic zone V of Bihar.

$$LS = 3.54 + 0.21 * PI - 0.15 * LL + 0.01 * SPT + 0.09 * wc - 2.78 * wc / LL \quad (4)$$

The significance level is set to 0.05 in this study.
Where, *LS* is liquefaction susceptibility of the soil,
PI is plasticity index,
LL is liquid limit,
N is SPT blow count value,
w_c is water content,
w_c/LL is the ratio of water content to liquid limit.
Result obtained from equation (4) will determine whether the soil deposit is liquefiable or non-liquefiable. Regression statistics of the above model are shown in Table 3. The R^2 value of the developed regression model which indicates the model fit value is closest to Chinese Criteria's (1979) prediction. The average value of $R^2 = 0.74$, which signifies that the strength of relationship of the developed model is 74%, also indicating that the accuracy of the model is good and can be used as a preliminary tool to determine liquefaction susceptibility of cohesive soil deposits based on basic soil properties. The average value of $R = 0.86$ signifies that 86% changes are due to the factors considered in regression modelling.

Table 3. Statical performance parameter obtained from Regression Model

Name of the criteria	R^2	R	MSE
Chinese Criteria (1979)	0.88	0.94	0.372
Seed et. al (2003)	0.61	0.78	0.119
Bray & Sancio (2006)	0.72	0.84	0.079

Table 4 shows and compares the success rate between all the comparative studies and developed regression model. It is observed that the developed model has the most optimum success rate amongst all the other criterias. The results of success rate have been plotted in Fig: 4.

Table 4. Success rate of all the comparative studies and developed regression model

Name of the Criteria	Success Rate (%)	
	Liquefaction	No-Liquefaction
Chinese Criteria (1979)	52.3%	47.7%
Seed et. al Criteria (2003)	81.3%	18.5%
Bray & Sancio (2006)	73.8%	26.2%
Regression Model	**49.2%**	**50.8%**

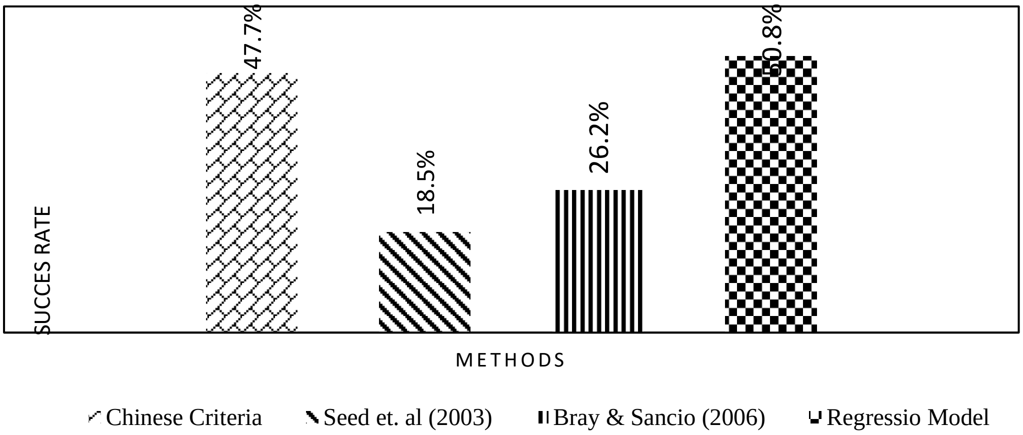

Fig. 4. Relative success rate (%) of methods adopted and developed regression model

Fig: 5 and Fig: 6 shows the trend of liquefaction prediction as per regression model for plasticity index and liquid limit respectively. It shows that with an increase in liquid limit and plasticity index liquefaction susceptibility decreases. '0' indicates liquefiable soil deposits whereas '1' indicates non-liquefiable deposit. The green colour indicates safe soil layer with higher plasticity index and liquid limit and red colour indicates soil layers that may experience liquefaction and has low plasticity index and liquid limit. From the observed results it can be concluded that the developed regression model has good prediction capability with least error and the key input parameters plasticity index

(*PI*) and liquid limit (*LL*) shows the same significant effect on the output as observed in the literature.

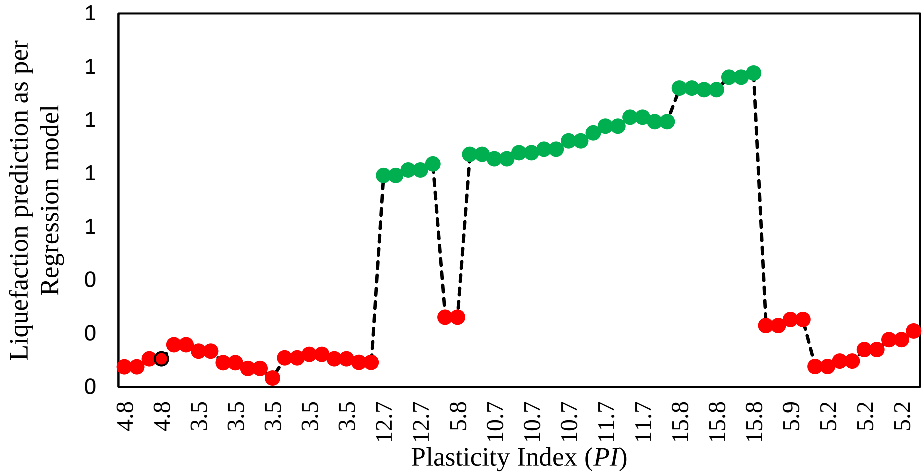

Fig.5. Regression model liquefaction prediction trend as per plasticity index

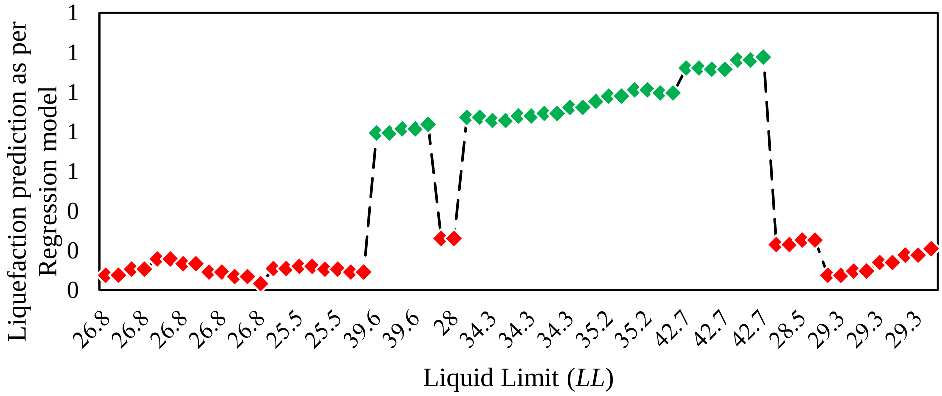

Fig. 6. Regression model liquefaction prediction trend as per liquid limit

5 Conclusions

Application of Regression Analysis in geotechnical engineering are very limited. The aim of the study was to develop a linear equation based on multi-linear regression analysis of the data obtained from laboratory tests to estimate the liquefaction susceptibility of silty clay soil deposit present in high seismic zone of Bihar. It should be noted that the developed regression model was found to be predicting the liquefaction susceptibility reasonably well and overcomes the shortcomings and limitations of the conventional methods. The paper also emphasises on the use of plasticity in predicting liquefaction of clayey soil deposit as it has the potential to reduce the uncertainty and error present in the empirical methods and can become a robust method for liquefaction prediction. The regression model developed in the present study could be used for the preliminary design calculations of the civil engineering structures constructed on silty clay deposits of high seismic zones.

References

1. Andrews, D. C. A., and Martin, G. R. (2000) Criteria for liquefaction of silty soils Proc., 12th World Conf. on Earthquake Engineering, Auckland, New Zealand.
2. Anwar, A. Jamal, Y. Ahmad, S, Khan, M.Z, ‘Assessment of liquefaction potential of soil using multi-linear regression modeling’ International Journal of Civil Engineering and Technology (IJCIET), volume 7, Issue 1, pp. 373-415, (2016)
3. Bartlett, S. F., and Youd, T. L. (1992) ‘‘Empirical analysis of horizontal ground displacement generated by liquefaction-induced lateral spread.’’ *Tech. Rep. No. NCEER-92-0021*, National Centre for Earthquake Engineering Research, Buffalo, N.Y., 114.
4. Bartlett, S. F., and Youd, T. L. (1995). “Empirical prediction of liquefaction-induced lateral spread.” J. Geotech. Eng., 10.1061/ (ASCE) 0733-9410(1995)121:4(316), 316–329.
5. Bray J. D. and Sancio R. B. (2006) Assessment of the Liquefaction Susceptibility of Fine Grained Soil Journal of Geotechnical Engineering, 132 (9), 1165–1177.
6. Bray, J.D., Sancio, R.B., Reimer, M.F. and Durgunoglu,,T. (2004), “Liquefaction Susceptibility of Fine-grained Soils”, Proc. 11th Int. Conf. on Soil Dynamics and Earthquake Engineering and 3rd Inter. Conf. on Earthquake Geotech. Engrg., Berkeley, CA, Jan. 7-9, Vol. 1, pp. 655-662.
7. G L Sivakumar Babu and Vikas Pratap Singh (2010) Reliability analyses of a prototype soil nail wall using regression models, Geomechanics and Engineering, An International Journal, Techno Press Publication
8. Gratchev, I., Sassa K. and Fukuoka H. (2006) How reliable is the plasticity index for estimating the liquefaction potential of clayey sands? Journal of Geotechnical and Geo-environmental Engineering 132 (1), 124 127.
9. Idriss, I. M and Boulanger, R.(2006)Semi-empirical procedures for evaluating liquefaction potential during earthquakes, Journal of Soil Dynamics and Earthquake Engineering 26(2):115-130
10. Ishihara, K., and Koseki, J. (1989) Cyclic shear strength of fines-containing sands, Earthquake and Geotech. Engg. Japanese Society of Soil Mechanics and Foundation Engineering, Tokyo, 101–106.
11. Joyner, W. B., and Boore, D. M. (1993). “Methods for regression analysis of strong-motion data.” Bull. Seism. Soc. Am., 83, 469–487.

12. Kaustav Chatterjee and Deepankar Choudhury (2013); "Variations in shear wave velocity and soil site class in Kolkata city using regression and sensitivity analysis", Natural Hazards, (ISSN: 0921-030X, Impact Factor: 1.639/2012) Springer, Netherlands, Vol. 69, No. 3, pp. 2057-2082, doi: 10.1007/s11069-013-0795-7
13. Latha, G.M., Somwanshi, A. & Reddy, K.H. A Multiple Regression Equation for Prediction of Bearing Capacity of Geosynthetic Reinforced Sand Beds. Indian Geotech J 43, 331–343 (2013). https://doi.org/10.1007/s40098-013-0053-7
14. Liao, S. S. C., Veneziano, D., and Whitman, R. V. (1988) "Regression models for evaluating liquefaction probability." J. Geotech. Engrg, 114(4), 389–411.
15. Liao, S. S. C., Veneziano, D., and Whitman, R. V. (1988) "Regression models for evaluating liquefaction probability." J. Geotech. Engg, 114(4), 389–411.
16. Martin, G.R. and Lew, M. Recommended procedures for implementation of DMG Special Publication 117 – Guidelines for analyzing and mitigating liquefaction hazards in California, Southern California Earthquake Centre. (1999)
17. Marto, A;Tan, C S; M Akhtar, A M; Ung S W and Lim, M Y (2015) Effect of Plasticity on Liquefaction Susceptibility of Sand-Fines Mixtures, Applied Mechanics and Materials, Vols. 773-774, pp. 1407-1411.
18. Paydar, N.,A., and Ahmadi, M.,M.,(2016) Effect of Fines Type and Content of Sand on Correlation Between Shear Wave Velocity and Liquefaction Resistance, Geotechnical and Geological Engineering, Volume 34, Issue 6, pp 1857–1876
19. Polito C., (2001) Plasticity based liquefaction criteria, Proc. of the 4th intl. Conf. on recent advances in geotechnical earthquake engineering and soil dynamics.
20. Prakash, S., and Sandoval, J. A. (1992). Liquefaction of low plasticity silts, J. Soil Dynamics and Earthquake Engg, 71(7), 373–397.
21. Sandoval, J. (1989). Liquefaction and settlement characteristics of silt soils, PhD Dissertation, University of Missouri–Rolla, Mo.
22. Seed, H. B., and Idriss, I. M "Ground motions and soil liquefaction during earthquakes" Earthquake Engineering Research Institute, Berkeley, Calif. (1982)
23. Seed, R.B, K.O. Cetin, and R.E.S. Moss (2001), Recent Advances in Soil Liquefaction Hazard Assessment, 15th ICSMGEG, TC4 satellite conference on Lessons Learned from Recent Strong Earthquakes, Istanbul, Turkey.
24. Seed, R.B., Cetin, K.O., Moss, R.E.S., Kammerer, A.M., Wu J., Pestana J.M., Riemer M.F., Sancio R.B., Bray J.D., Kayen R.E., Faris A. (2003) Recent advances in soil liquefaction engineering: A unified and consistent framework, EERC-2003–06, Earthquake Engineering Research Institute, Berkeley, California.
25. W. Wang, (1979) Some Findings in Soil Liquefaction. Report Water Conservancy and Hydro-electric Power Scientific Research Institute, Beijing, China, 1-17.
26. Youd, T. L., Hansen, C. M., and Bartlett, S. F. (2002). "Revised multilinear regression equations for prediction of lateral spread displacement." J. Geotech. Geoenviron. Eng., 10.1061/ (ASCE)1090-0241(2002) 128:12(1007), 1007–1017.
27. Youd, T.L, 'Application of MLR Procedure for Prediction of Liquefaction-Induced Lateral Spread Displacement' J. Geotech. Geoenviron. Eng., 144(6), (2018)