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MODELLING CYCLIC SHEAR MODULUS AND FACTOR OF SAFETY AS INDICES FOR PREDICTION OF LIQUEFACTION POTENTIAL FOR NIGER DELTA SOILS

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ABSTRACT

The liquefaction potential of Niger Delta soil was studied through formulated models based on cyclic shear modulus and factor of safety (FS). Data from the experiment were fitted into models to predict the cyclic shear modulus and Factor of Safety. The test analysis shows effective prediction of cyclic shear modulus for a given number of cycles (1 – 40) and cyclic shear strain (0.01 – 5%). Comparison of results shows no significant differences between the measured and predicted cyclic shear modulus, especially from 0.1% shear strain and above. Similarly, the values of factor of safety predicted by the model were very close to those obtained from the experiment; the predicted FS obtained at depths close to 30m across the sites were slightly greater than 1.0, as against the observed results. Despite this slight variation, the FS model still shows high degree of prediction. Therefore, the formulated models can be utilised in the study of liquefaction potential, especially in the Niger Delta region.

1. INTRODUCTION

Soil profiles in seismic active region require assessment of liquefaction potential prior to design of foundations for structural purposes, and evaluation of such soil is important especially when making choice for the selection of suitable soil type, providing design guide against soil liquefaction in the event of earthquake (Noor *et al*., 2019). One engineering tool that is useful for interpretation and prediction of data, is mathematical model, which has been applied over the years for a widely range of studies including the analysis of liquefaction and earthquake. Both numerical and analytical modeling approaches have been useful for liquefaction study. The numerical analysis method has been used by many researchers to study the influence of soil non-linearity, introduced by soil liquefaction on soil-foundation-structure interaction phenomena (Almani *et al*., 2012; Dashti and Bray, 2013; Asgari *et al*., 2014; Marasini and Okamura, 2014; Adamidis and Madabhushi, 2015). However, the complicated procedures in applying the numerical analysis, such as Finite Element Method require users to be equipped with appropriate numerical simulation tools (Adamidis and Madabhushi, 2015). Also, the empirical method is useful and convenient, which is used in practical design (Lu, 2017). For instance, the relationship between settlement and the triggering factors based on data generated from field, numerical analysis, or physical test has been reported (Sancio *et al*., 2004; Shahir and Pak, 2010; Bertalot *et al*., 2013). In Bertalot *et al*. (2013), the relationship between liquefaction and foundation in consideration to the influence of high bearing capacity using empirical model was investigated. Also in earlier study, Sawicki and Mierczynski (2009) developed a simple model based on the concept of force equilibrium to calculate a sinking block in liquefiable soil, and found that the dynamic behavior of soil was influenced by seismic activity. However, studies have shown that modeling based on field data are more reliable and accurate, but they are generally expensive as most analysis involve huge capital to achieve the intended construction and experiment on scale suitable for model application (Dashti *et al*., 2010; Marques *et al*., 2013). Lu (2017) developed a predictive model while studying the occurrence of earthquake and liquefaction of soil as a consequence of groundwater table depth and induced vertical settlement of shallow foundation. This study demonstrated the effectiveness of the model in predicting liquefaction-induced settlement in Taiwan.

Other notable techniques have equally been used for estimation of liquefaction. That is, liquefaction susceptibility of soil can be evaluated by different methods based on energy, cyclic stress and cyclic strain. Thus, the energy-based approach is theoretically based on the principle that the dissipated energy reflects both cyclic stress and strain amplitudes, while the theory of the cyclic strain based method is relied on the existence of threshold volumetric strain below, and that densification will not occur (Noor *et al*., 2019).

In the use of factor of safety (FS) method, both earthquake induced loading and liquefaction resistance of soil are expressed in terms of cyclic shear stress, which are compared against liquefaction or liquefaction potential (Ahmad *et al*., 2015). In general, soil liquefaction is expected to occur at the location, where the stress due to earthquake loading exceeds the resistance of the soil to liquefaction. The equation for determination of FS is basically defined as the ratio of cyclic resistant ratio (CRR) to cyclic stress ratio (CSR), which has been used as basis for estimation of liquefaction potential for over past 30 years (Youd *et al*., 2001).

$$FS = \frac{CRR}{CSR} \tag{1}$$

The use of FS in predicting liquefaction potential of soil at depth measured at specific SPT blow-count employed in determining CRR is said to liquefy when FS ≤ l, or non-liquefiable when FS > l (Noor *et al*., 2019). The soil could be considered more resistant to liquefaction if calculated factor of safety is far greater unity (Ishihara, 1993). However, soil that has a factor of safety slightly greater than 1.0 may still liquefy during an earthquake, as FS against liquefaction depends on the magnitude of peak horizontal acceleration at ground surface generated by the earthquake (Noor *et al*., 2019). Most of Niger Delta areas can be described as coastal zone, which comprises of beach ridges and mangrove swamps, underlain by alternating sequence of sand and clay with high frequency of occurrence of clay within 10m below the ground surface (Nwankwoala and Oborie, 2014). The impact of imposed load on such soil can be worsened by the thickness and consistency of compressible layer, which in addition to other intrinsic factors may contribute to failure of engineering structures (Youdeowei and Nwankwoala, 2013; Amadi *et al*, 2012). For the purpose of generating relevant data inputs for design, construction and averting earthquake disasters, it is essential that factors that affect such disasters be studied and understood. Therefore, the liquefaction potential of Niger Delta soil is studied by mathematical models through the cyclic shear modulus and factor of safety.

2. METHODOLOGY

The models were formulated with the aids of experiments conducted a various locations across the Niger Delta region. The mathematical models were formulated to predict the cyclic shear modulus (G_s) and liquefaction potential of soil, which could be used to study the occurrence of earthquake in the region.

2.1 Cyclic Shear Modulus

In this study, the output response of cyclic shear modulus (G_s), was formulated as a function of shear strain (ε_s) and number of cycles (N_c).This model was formulated based on observed field data, which indicated the variation of G_s as shear strain and the number of cycles were changing in values. Thus, the cyclic shear modulus (G_s) is represented by the mathematical expression given as follows.

$$G_s = \beta \frac{N_c^{\ x}}{\varepsilon^y} \tag{2}$$

The variable β is the constant of model, while *x* and *y* are power indices relating to number of cycles and cyclic shear strain. To enable the determination of the constants β ,*x* and *y*, equation (2) is linearized by taking the natural logarithm of each term. This step leads to equation (3).

$$\log G_s = \log \beta + x \log N_c - y \log \varepsilon \tag{3}$$

Using the method of multiple linear regression, and utilising experimental results, the constant parameters can now be determined. The evaluated parameters are then substituted into the equation (2), which can be used to predict the cyclic shear modulus (G_s) for every shear strain (ε_s) or number of cycles (N_c).

2.2 Liquefaction Potential

The possibility of liquefaction occurrence in Niger Delta soil as experimentally investigated is further studied to establish a mathematical relationship that can be utilised to predict the potential of liquefaction in the region. Thus, in this study the factor of safety (FS), as one of the key parameters used in predicting the possibility of liquefaction occurrence, was expressed as a function of SPT-N (*N*), percentage of fines (*f*), soil depth (*d*) and effective vertical stress (σ). This is mathematically expressed as:

$$FS = \frac{N^a f^b d^c}{\sigma^e} \tag{4}$$

The constant coefficients *a, b, c* and *e* are power indices relating to *N, f, d* and σ respectively. Like in cyclic shear modulus, the constants *a, b, c* and *e* are determined by taking the natural logarithm of each term in equation (4). This step leads to equation (5).

$$\log FS = a \log N + b \log f + c \log d - e \log \sigma \tag{5}$$

After the parameter evaluation, they can be substituted into the equation (4) to predict the FS for every change in SPT-N (*N*), percentage of fines (*f*), soil depth (*d*) or effective vertical stress (σ).

3. RESULTS AND DISCUSSION

Table 1 shows the experimental results for the formulation of factor of safety cyclic shear modulus model, while Table 2 is the experimental results for the formulation of factor of safety model. Tables 3 and 4 are the predicted values of cyclic shear modulus and factor of safety, respectively, as compared with the experimental results.

Table 1: Experimental data for formulation of cyclic shear modulus model

No of cycle	G_s (MPa)				
	0.01% Strain	**0.1% Strain**	**1% Strain**	**2.5% Strain**	**5% Strain**
1	24.40	16.46	8.38	5.61	4.40
5	24.89	17.35	9.25	6.86	5.85
10	24.97	17.58	9.42	7.02	6.06
15	25.06	17.73	9.53	7.08	6.16
20	25.23	17.93	9.59	7.17	6.31
25	25.34	17.98	9.79	7.23	6.37
30	25.51	18.04	9.84	7.32	6.50
35	25.73	18.16	9.97	7.52	6.57
40	25.76	18.20	10.02	7.61	6.66

Table 2: Experimental data for formulation of factor of safety model

d (m)	*N* (blows)	*f* (%)	σ (kPa)	Factor of Safety
0.95	4.00	45.00	0.24	3.97
2.45	7.00	54.00	0.31	3.78
3.95	4.00	59.00	0.31	4.01
4.55	9.00	56.00	0.19	5.01
6.00	10.00	62.00	0.31	5.56
6.70	7.00	60.00	0.21	3.74
8.20	7.00	35.00	0.31	3.78
9.70	14.00	44.00	0.32	7.10
10.05	5.00	40.00	0.16	8.00
11.55	21.00	27.00	0.31	8.91
13.05	27.00	31.00	0.31	11.16
13.35	5.00	25.00	0.15	12.83
14.85	16.00	6.00	0.30	5.67
16.35	20.00	5.00	0.30	6.95
17.60	17.00	3.00	0.27	5.92
19.10	27.00	0.50	0.30	8.99
20.00	17.00	0.30	0.30	0.76
22.10	25.00	0.80	0.30	8.42
23.60	20.00	0.90	0.30	6.95
25.10	20.00	1.10	0.30	6.94
26.55	21.00	0.50	0.30	0.76
28.05	27.00	0.05	0.30	0.76
29.55	30.00	0.02	0.30	0.76
30.00	9.00	0.04	0.16	0.75

Table 3: Comparison of measured and predicted cyclic shear modulus Gs in MPa at varying shear strain

No of cycles	0.01% Strain		0.1% Strain		1% Strain		2.5% Strain		5% Strain	
	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted
1	24.40	23.71	16.46	13.64	8.38	7.85	5.61	6.30	4.40	5.33
5	24.89	25.96	17.35	14.93	9.25	8.59	6.86	6.89	5.85	5.84
10	24.97	27.00	17.58	15.53	9.42	8.93	7.02	7.17	6.06	6.07
15	25.06	27.62	17.73	15.89	9.53	9.14	7.08	7.34	6.16	6.21
20	25.23	28.07	17.93	16.15	9.59	9.29	7.17	7.45	6.31	6.31
25	25.34	28.43	17.98	16.35	9.79	9.41	7.23	7.55	6.37	6.39
30	25.51	28.72	18.04	16.52	9.84	9.51	7.32	7.63	6.50	6.46
35	25.73	28.97	18.16	16.67	9.97	9.59	7.52	7.69	6.57	6.51
40	25.76	29.19	18.20	16.79	10.02	9.66	7.61	7.75	6.66	6.56

Table 4: Measured and predicted factor of safety

Depth	Akwa-Ibom		Bayelsa		Delta		Rivers	
(m)	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted
0.95	3.97	3.55	3.30	4.48	4.31	4.12	3.18	3.79
2.45	3.78	5.47	6.62	6.04	3.93	5.59	4.40	6.01
3.95	4.01	6.30	3.43	6.81	5.28	7.36	8.45	7.14
4.55	5.01	8.50	9.00	7.64	3.93	6.95	7.35	7.83
6.70	5.56	8.53	9.00	9.46	3.93	7.83	5.56	9.74
8.20	3.74	9.47	1.69	9.96	4.38	8.22	3.78	8.09
9.70	3.78	7.51	5.77	8.29	3.93	7.42	5.36	9.79
10.05	7.10	9.55	2.65	8.27	8.48	7.63	11.88	10.04
11.55	8.00	10.11	4.89	9.11	10.42	9.01	4.31	9.15
13.05	8.91	9.11	5.86	9.01	12.53	10.34	3.92	10.19
13.35	11.16	10.38	6.74	9.06	14.07	10.90	7.52	9.86
14.85	12.83	9.82	3.64	9.88	11.36	10.24	8.42	5.99
16.35	5.69	5.77	8.71	10.54	11.63	11.60	5.90	5.95
17.60	6.94	5.79	9.80	10.41	11.82	6.96	7.58	5.21
19.10	5.92	5.05	10.88	11.20	9.97	7.79	3.03	2.85
20.00	8.99	2.85	13.27	6.42	14.04	7.02	5.87	2.48
22.10	0.76	2.28	0.73	7.88	0.74	6.12	0.76	3.60
23.60	8.42	3.52	11.41	8.64	10.91	8.32	10.95	3.82
25.10	6.94	3.65	12.21	5.29	11.07	7.04	13.08	4.24
26.55	6.94	4.01	11.41	5.28	15.02	6.49	14.25	3.46
28.05	0.76	3.13	0.75	7.08	0.74	3.33	0.76	1.49
29.55	0.76	1.47	0.72	6.45	0.74	3.24	0.76	1.24
30.00	0.76	1.49	0.75	4.72	0.74	3.06	0.76	1.59

Figure 1 shows the correlation between the predicted and measured cyclic shear modulus of sandy soil subjected to 400kPa shear stress. The data obtained from one of the selected sites was used for the analysis, representing the other sites. The R^2 was obtained as 0.992, which implies that 99.2% of the measured cyclic shear modulus of the soil has been explained by the model, indicating that the model can be applied to predict the cyclic shear modulus for a given number of cycles and cyclic shear strain.

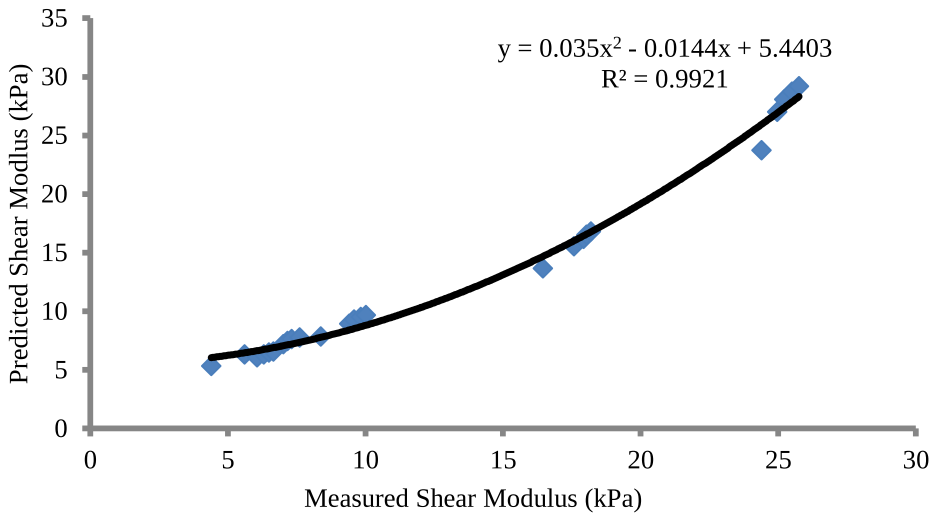

Figure 1: Measured and predicted cyclic shear modulus

Similarly, from the regression analysis, the constant coefficients expressed in model equation (2) were determined as $\beta =$ 7.8457, $x =$ 0.0564 and $y =$ 0.2401. Hence, the predictive model for cyclic shear modulus is expressed as $G_s = 7.8457\frac{N_C^{0.0564}}{\varepsilon_s^{0.2401}}$.Hence, the utilization of the model shows appreciable prediction of cyclic shear modulus at the corresponding measured number of cycles for a given cyclic shear strain. Meanwhile, the predictability of the model showed some weakness at very low percentage strain. Thus, comparison of predicted values with experimental data as presented in Table 3, shows that at 0.01% shear strain, the predicted values were higher than those obtained from the experiment at all cycles, but from 0.1 to 5% strain, the differences between the measured and predicted cyclic shear modulus were not much. From the results (Table 3), the cyclic shear modulus predicted by the model between 1 to 40 cycles, increased from 23.71 to 29.19MPa at 0.01% shear strain as against 24.40 to 25.76MPa obtained from the experiment; 13.64 to 16.79MPa as against 16.46 to 18.2MPa for experiment at 0.1% shear strain;7.85 to 9.66MPa as against 8.38 to 10.024MPa for experiment at 1.0% shear strain;6.30 to

7.75MPa as against 5.61 to 7.61MPa for experiment at 2.5% shear strain; and 5.33 to 6.56MPa as against 4.40 to 6.66MPa for experiment at 5% shear strain.

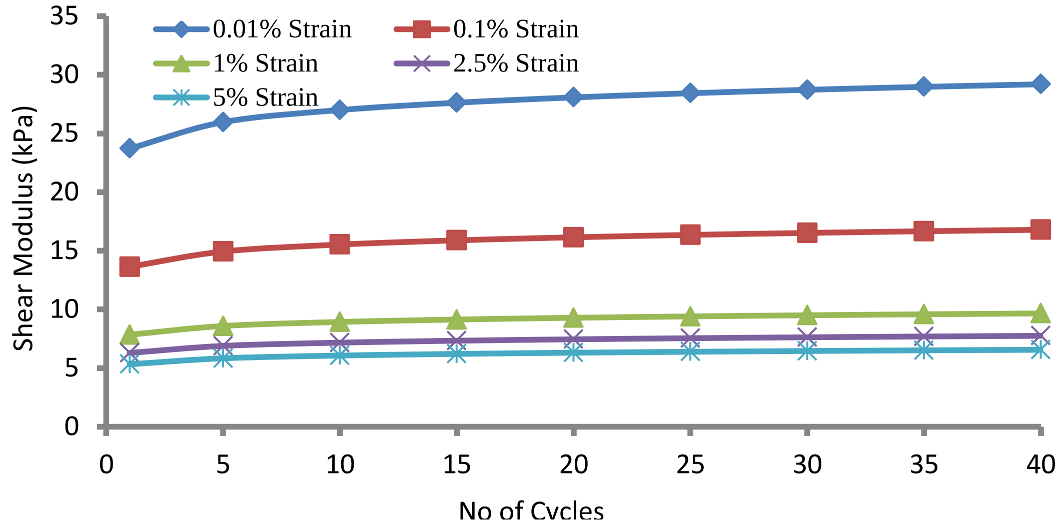

Figure 2: Predicted cyclic shear modulus at various shear strain

Figure 2 demonstrated that the cyclic shear modulus decreased with increasing percentage of shear strain, and at 0.01% strain, the values of cyclic shear modulus were about four (4) times more than those obtained at 5% strain for every corresponding number of cycles.

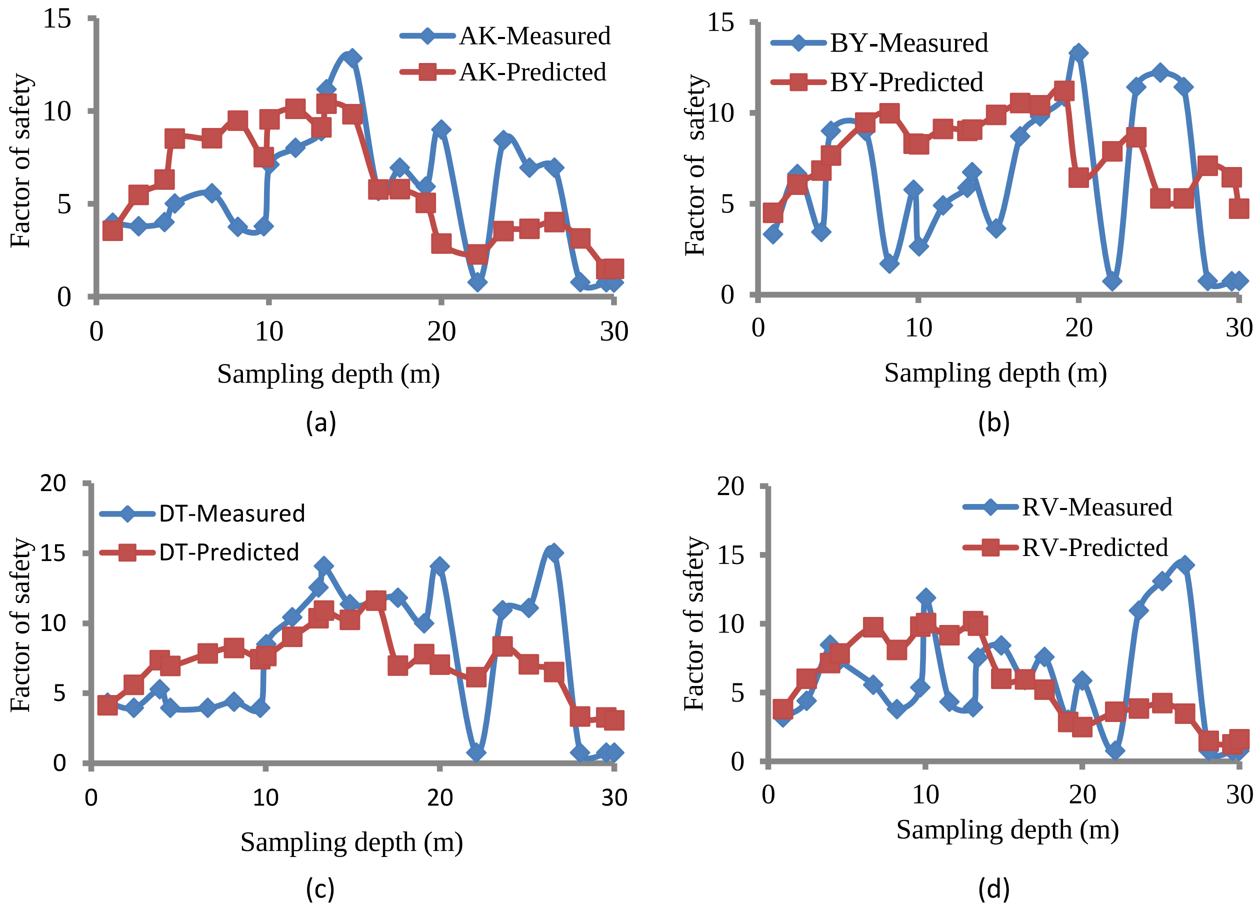

Figure 3: Factors of safety: (a) Akwa Ibom, (b) Bayelsa, (c) Delta and (d) Rivers States

The effective decrease in cyclic shear modulus at reduced percentage strain has also been reported by previous authors, which was attributed to shear deformation characteristics of soil (Arion and Neagu, 2007, 2012), while increase in strain decreased the factor of safety, and hence, the potential for soil liquefaction (Tsai *et al*., 2010; Sadek *et al*., 2014). However, the relationship between cyclic shear modulus of soil, number cycle and shear strain as indicated in this study, has also been outlined in a study by Narepalem and Godavarthi (2019). Other studieshave stated the importance of soil evaluation via mathematical models in the design of engineering structure to reduce the impact of liquefaction (Erzin and Tuskan, 2019; Geyin et al., 2020; Pham, 2021; Subedi and Acharya, 2022).

Figure 3 shows the profiles of the measured factor of safety (FS) for Akwa-Ibom, Bayelsa, Delta and Rivers States. Again, experimental data obtained from one the sites was selected and used to determine the constant coefficients contained in the factor of safety model using the multiple regression analysis. From the data analysis, the power indices relating to the variables in equation (4) were determined as $a = 0.1357$, $b = 0.3516$, $c = -0.3215$ and $d = 0.3899$. However, a correction factor of 0.5 was inserted into the model to reduce over estimation of factor of safety. Therefore, the predictive model for factor of safety with a standard error of 0.0664 is expressed as

$$FS = 0.5\frac{N^{0.1357} f^{0.3516} d^{0.3899}}{\sigma^{0.3215}}. \quad (6)$$

To ascertain the predictability of the model, it was tested with the mean experimental data obtained for each of State, as shown in Figures 3. From the profiles, it be deduced that the factor of safety predicted by model behaves similar to those of the experiments shown in Figure 3, but the high fluctuations associated with the measured values were reduced for the predicted counterparts across the States. From the predicted FS values(Table 4), it can be said that the occurrence of liquefaction that would cause disaster in the Niger Delta is low, as all the FS predicted were higher than 1. However, from the experiment, the FS at some soil depth shows possibility of liquefaction occurrence, as they are below 1.0. According to studies, a factor of safety less than 1 implied that liquefaction may occur (Karim et al., 2010). Also, the use of model to study liquefaction potential has been reported using the factor of safety as a determining parameter (Jawaid, 2010; Khan et al., 2016). In Karim et al. (2010), the factor of safety was modelled as a function of depth, SPT values, cyclic stress and fine content. Diezet al (2019) used numerical technique to estimate the impact of pore pressure on factors of safety against soil liquefaction.

Several authors in recent times have equally used mathematical models in the analysis or prediction of factor of safety against soil liquefaction using various input variables such as earthquake magnitude, peak ground acceleration, standard penetration test, saturated unit weight, fines content, depth of ground water level or soil depth, as functional parameters (Erzin and Tuskan, 2019; Geyin et al., 2020; Pham, 2021; Subasi et al., 2021; Subedi and Acharya, 2022).These studies showed the efficacy of mathematical modeling as a powerful tool for rapid and accurate prediction of factor of safety against liquefaction (Erzin and Tuskan 2019: Pham, 2021; Subasi et al., 2021; Katona and Karsa, 2022; Subedi and Acharya, 2022). Hence, model is imperative in the preliminary stage of design for factor of safety against liquefaction.

4. CONCLUSION

Liquefaction is an important variable in the assessment of soil. The analysis of liquefaction or earthquake is undoubtedly expensive, but through development of appropriate model, it can reduce the rigorous tasks and costs involved in liquefaction analysis. From the experimental results obtained from the sites, models were formulated to predict the cyclic shear modulus and Factor of Safety as a function of the soil characteristic variables. For cyclic shear modulus, the model was formulated as a function of the number of cycles and shear strain, while Factor of Safety was dependent on SPT-N, fines, soil depth and effective vertical stress. From the analysis, it was shown that the models were able to predict the measured cyclic shear modulus and Factor of Safety for the given dependent variables of the respective models. Therefore, based on the level of prediction, the formulated models can be utilised in the study of liquefaction potential, especially in the Niger Delta region.

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