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Evaluating The Undrained Shear Strength of Kalimati Soil Using Field Vane And Unconfined Compression Test; A Study on Applicability of Bjerrum’s Correction Factor

Sanjaya Pandey[1], Anup Lamichhane[2], Indra Prasad Acharya[1],

[1]Department of Civil Engineering, Pulchowk Campus, IOE, TU

[2]Department of Civil Engineering, Advanced College of Engineering and Management
Email: anup.lamichhane@acem.edu.np

Abstract

Rapid urbanization and geological challenges in Kathmandu have made it crucial to understand the geotechnical properties of the soil in the region. This study here focuses on the undrained shear strength of silty clay in Kalimati, Kathmandu, and investigates the applicability of Vane Shear tests and its parameters over other shear strength tests from other methods. Geotechnical investigations were carried out at three locations within the Kathmandu Engineering College premises and in-situ and laboratory tests were conducted on undisturbed and disturbed samples. Then the study compared the field vane shear strength, undrained strength from unconfined compression tests, and laboratory vane shear strength of the samples. For the field vane shear test the correction factor as suggested by Bjerrum was used and the results indicate that this method overestimates the shear strength in Kalimati soil, indicating no adjustment is necessary. The findings of this study have important implications for the design and construction of structures in the region, and contribute to a better understanding of the geotechnical properties of Kathmandu soil.

Keywords: *Bjerrum Correction Factor, Unconfined Compression test (UCS), Vane Shear test (VST), Plasticity Index, Liquidity Index, Sensitivity*

1. Introduction

The Unconfined Compression Test (UCT) is a commonly practiced laboratory technique for determining the undrained shear strength of fine-grained soils, but its reliability is often questioned due to the sensitivity of the tests to sample disturbance, which is largely influenced by sampling methods (Géotechnique, 2005)._Meanwhile, Tanaka (1994) concluded that undrained shear strength calculated from both Laboratory Vane-Shear Test and Field Vane-Shear Test are similar, indicating that the vane insertion process is not significantly influenced by mechanical disturbance caused by sampling, release of overburden pressure, or increase in the confining pressure. This suggests that Vane Shear Test (VST) may be a more reliable method for measuring undrained shear strength than Unconfined Compression Test (UCT).

Due to the lack of intensive efforts to modify sampling techniques in Nepal, particularly for soft clays, undisturbed sampling is difficult and vane shear tests may be more reliable than Unconfined Compression (UC) tests for measuring undrained shear strength. Currently, there is no established practice for measuring in-situ strengths, and almost all geotechnical investigations rely on Standard Penetration Test (SPT) values followed by laboratory shear strength tests, with some cases using SPT values to determine shear strength through correlations. However, field strength determinations have been largely neglected. *To address this gap, the present study was conducted to evaluate the field strength and establish correlations between Unconfined Compressive Strength (UCS), Field Vane Shear-Strength (FVS), and Laboratory Vane Shear-Strength (LVS).* The resulting large dataset and correlations could be useful for developing transformation models to determine in-situ strengths.

Kathmandu Valley, the capital city of Nepal, has undergone unprecedented urbanization in the last few decades, posing unique challenges for the construction of new structures. The valley's geology comprises fluvo-lacustrine Quaternary deposits that can be extremely compressible and difficult to work with. (Gurung. et al. 2019). In this study the undrained shear strength of clayey silt soil (ranging from high plasticity silt to low plasticity silt) found in Kalimati, Kathmandu is taken. The soil investigated is part of the Kalimati formation, and geotechnical investigations were conducted followed by laboratory tests for analysis. Nepal is situated in a high earthquake-prone zone, and if the soil at the site is sensitive, the disturbance during foundation construction and earthquakes can significantly affect soil strength parameters (Koirala, (2013). During foundation construction, particularly during pile driving, there may be significant soil disturbance and remolding. Therefore, a comprehensive study of sensitivity and thixotropic characteristics of soil is essential on a large scale to understand the reduction of soil strength and changes in settlement patterns due to in-situ soil disturbance. *This research examines the relationship between index parameters and shear parameters with soil sensitivity.*

Undrained shear strength measured by the Vane Shear Test can be influenced by various factors, including the overconsolidation ratio (OCR) (Jamiolkowski et al., 1985), effective confining stress (σ'p) (A. Skempton, 1957; Larsson, 1980), and the plasticity index of the soil. Bjerrum's correction factor, μ, is commonly used to correct field vane shear strength against soil plasticity. This study aims to investigate the suitability of Bjerrum's correction factor in Kalimati soil. The correction factor μ, , was proposed by Bjerrum (1973) based on numerous failure cases for shear strength obtained from the Field VST. However, studies have suggested that the shear strength corrected by μ may be significantly conservative for some types of soil, such as Japanese clay (Tanaka, 1994). *Therefore, this study will address the applicability of Bjerrum's correction factor in Kalimati soil to determine if adjustments need to be made when using this correction factor in the region.*

The aim of this study is to investigate the undrained shear strength of clayey silt soil found in Kalimati, Kathmandu, and to evaluate the applicability of Bjerrum's correction factor in this soil, with the overall goal of improving our understanding of the soil's behavior and providing useful information for geotechnical design and construction in the region.

2. Literature Review

The measurement of vane strength is an important parameter for stability analyses involving embankments on soft ground, bearing capacity, and excavations in soft clays. And this value must be corrected using an empirical correction factor *μv.* The value of μv is related to plasticity index (PI) and/or liquid limit (LL) and/or other parameters based on back calculation from failure case history records of full-scale projects.

$$Su\ (\text{mobilized}) = \mu v\ .Suv \qquad 2.1$$

The mobilized shear strength is given by Equation (2.1), where μv is the empirical correction factor. An extensive review of the factors and relationships affecting vane measurements in clays and silts with PI > 5% led to the recommendation of Equation (2.2) by Chandler (1988).

$$\mu v = 1.05 - b(PI)^{0.5} \qquad 2.2$$

This equation incorporates a rate factor parameter, b, which is dependent on the time-to-failure (tf in minutes) in the actual failure.

$$b = 0.015 + 0.0075 \log t_f \qquad 2.3$$

If both the qu and the Bjerrum's correction method are identical, the ratio of corrected field vane strength and qu/2 must be unity(Tanaka, 1994). When Ip is greater than 40, the ratio of Suv/(qu/2) becomes less than unity but when Ip<40, the corrected vane-UC ratio becomes more than unity. The ratio of field vane strength corrected by Bjerrum's correction factor to qu/2 is plotted against PI for different clays as shown later.

The corrected field vane strength can be compared to the unconfined compression strength (qu) through the ratio of corrected field vane strength and qu/2. Tanaka (1994) found that if both the qu and Bjerrum's correction methods are identical, this ratio should be unity. However, when Ip (plasticity index) is greater than 40, the ratio of Suv/(qu/2) becomes less than unity, while when Ip is less than 40, the corrected vane-UC ratio becomes more than unity. Figure 2 5 shows the ratio of field vane strength corrected by Bjerrum's correction factor to qu/2 plotted against PI for different clays.

In summary, the correction of vane strength measurements in soft clays is essential for stability analyses, bearing capacity, and excavations. Chandler's (1988) empirical correction factor incorporates a rate factor parameter that is dependent on the time-to-failure in the actual failure, providing more accurate results. Additionally, the comparison between corrected field vane strength and qu/2 can provide insight into the behavior of different clays.

There are some empirical relationships provided for estimating geotechnical parameters, reducing the need for extensive laboratory or field testing, and helping to inform geotechnical engineering designs and decisions. These relationships were of other places, so this research is focusing on finding it's own relationship checking with others. Here is a summary of the relationships, literature, transformation models, for various clay types.

1. Su/σ'p - PI (Larsson, 1980) - This relationship provides an estimate of undrained shear strength (Su) in terms of effective vertical stress (σ'p) and plasticity index (PI) for Scandinavian clays. It can be useful in geotechnical design for estimating the shear strength of clayey soils.
2. Su/σ'p - PI (Leroueil and Jamiolkowski, 1999) - This relationship gives an estimate of undrained shear strength (Su) in terms of effective vertical stress (σ'p) and plasticity index (PI) for Eastern Canadian clays. It can be useful in geotechnical design for estimating the shear strength of clayey soils
3. Su (mob) / σ'p - PI (Mesri, 1975, 1989) - This transformation model provides an estimate of undrained shear strength (Su) in terms of effective vertical stress (σ'p) and plasticity index (PI) for soft USSA clays. It can be useful in geotechnical design for estimating the shear strength of clayey soils
4. Su (FVST) / σ'p - PI (Tanaka, 1994) - This transformation model provides an estimate of undrained shear strength (Su) in terms of effective vertical stress (σ'p) and plasticity index (PI) for Japanese clays. It is independent of the plasticity index and can be useful in geotechnical design for estimating the shear strength of clayey soils
5. Su (FVST) / σ'p - PI (Tanaka, 1994) - This transformation model provides an estimate of undrained shear strength (Su) in terms of effective vertical stress (σ'p) and plasticity index (PI) for Bothkennar and Japanese clays. It is independent of the plasticity index and can be useful in geotechnical design for estimating the shear strength of clayey soils.
6. Su - LI (Kayabali et al., 2015) - This relationship provides an estimate of undrained shear strength (Su) in terms of liquidity index (LI) for Turkish clays. It can be useful in geotechnical design for estimating the shear strength of clayey soils.
7. Su (FVST)/Su (UCS) – PI (Tanaka, 1994) - This relationship provides an estimate of the ratio of undrained shear strength (Su) determined by field vane shear test (FVST) to that determined by unconfined compression test (UCS) in terms of plasticity index (PI) for Japanese clays. It can be useful in geotechnical design for estimating the shear strength of clayey soils.
8. µSu (FVST)/ Su (UCS) - PI (Tanaka, 1994) - This relationship provides an estimate of the coefficient of lateral earth pressure (µ) in terms of the ratio of undrained shear strength (Su) determined by field vane shear test (FVST) to that determined by unconfined compression test (UCS) and plasticity index (PI) for Japanese clays. It can be useful in geotechnical design for estimating the lateral earth pressure of clayey soils.

9. PI-St for Norwegian clays is an important empirical relationship that helps estimate the plasticity index (PI) of clays in Norway based on the soil type. The PI is a measure of the plasticity of soil, and it is an important parameter in geotechnical engineering for understanding the behavior of soils under loading conditions. The PI-St relationship can be used to estimate the PI of clay soils in Norway, which can be helpful in designing foundations, retaining walls, and other geotechnical structures.
10. Su-N60 with Su=3.24N60-0.53wn-0.43LL=2.14PI for UC test model is an empirical relationship that relates the undrained shear strength (Su) of fine-grained soils to the SPT N60 value, water content (wn), liquid limit (LL), and plasticity index (PI). This relationship is useful for estimating the undrained shear strength of fine-grained soils in the laboratory, which is an important parameter in geotechnical engineering for understanding the stability and deformation of soil under undrained loading conditions.
11. Su-N60 with Su=4.1*N60 for fine-grained soils according to Hettiarachchi& Brown, 2009 is another empirical relationship that relates the undrained shear strength (Su) of fine-grained soils to the SPT N60 value. This relationship can be used to estimate the undrained shear strength of fine-grained soils in the field, which is an important parameter in geotechnical engineering for understanding the stability and deformation of soil under undrained loading conditions.

3. Materials and Methods

The research methodology involved various stages. Firstly, the site was observed and available literature were reviewed to identify the problem. This was followed by conducting a detailed literature review and desk study on the identified issue. Subsequently, the research objectives and questions were finalized. To achieve the objectives, the study involved collecting field data and conducting in-situ tests, as well as laboratory experiments. The interpretation of the laboratory and field data was followed by a comparative analysis, leading to the results and conclusions.

The site was at Kathmandu Engineering College in Kathmandu valley, where a series of in-situ tests were performed and samples were extracted for further laboratory tests.. The in-situ tests included field vane shear tests (FVS) and standard penetration test (SPT). Three boreholes were drilled to a depth of 12m, from which disturbed and undisturbed soil samples were retrieved. The undisturbed samples were retrieved from different depths of each borehole using the Rotary Drilling Rig, while the disturbed samples were retrieved from each borehole. The SPT readings for penetration of 450 mm were recorded at different depths of each borehole, and FVS strength readings were also recorded as per ASTM D2573-01 standards.

The vane shear strength of the soil was calculated using the equation:

$$S = \frac{T}{\pi(\frac{D^2 H}{2} + \frac{D^3}{6})} \qquad 3.1$$

Where, T is torque in Kgf.cm, D is the overall diameter of the vane in cm, and H is the height of the vane in cm. The torque (T) was obtained from the standard calibration chart provided by the instrument supplier based on the recorded dial gauge reading.

After retrieving undisturbed (UD) samples, the disturbed and undisturbed samples were transported to the laboratory for testing. The laboratory tests were conducted to find index properties such as Atterberg limits, specific gravity, particle size analysis, sensitivity, thixotropy, activity, and unconfined compressive strength tests. The natural moisture content of the soil samples was preserved by sealing the sampling tubes at both ends with wax and plastic wrapping. To determine the unconfined compressive strength of cohesive soil in undisturbed and remolded conditions, UCS test was performed with strain-controlled application of the axial load. For remolded specimens, the undisturbed specimen that failed was wrapped in a thin rubber membrane and worked with fingertip pressure to ensure complete remolding. The material was filled in the mold of circular cross-section, avoiding entrapped air and preserving natural water content.

4. Results and Discussion

Ratio of Su (FVS) / Su (UCS) with respect to PI and Applicability of Bjerrum’s Correction Factor in Kalimati clay

It was revealed that the values of Suv are apparently greater than those of qu/2 in particular when Ip<40 as shown in Figure 4.1 (Tanaka, 1994). In Japanese clay, since Suv/Pc' does not decrease for clays with smaller Ip, it is possible that the increase in Suv/(qu/2) is due to reduced values of qu. This reduction is due to release of negative pore pressures (as permeability of Japanese clay with small Ip is large) and sample disturbances under UC test conditions.

The ratio of Su(v) corrected by μ to qu/2 for Japanese clay is plotted against PI for different clays as shown in Figure 4.2. If both the qu and the Bjerrum’s correction method are identical, the ratio must be unity (Tanaka, 1994). As Ip increases beyond 40, the ratio decreases and as Ip decreases, the ratio increases, which indicates that Bjerrum’s factor μ overestimates when Ip<40 and underestimates when Ip>40 for Japanese clay.

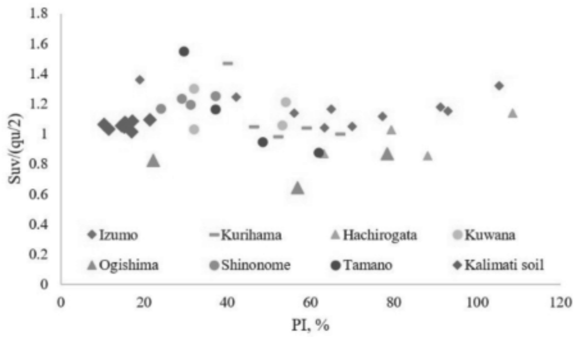


Figure 4.1: Strength ratio of Suv/(qu/2) versus PI (Tanaka, 1994)

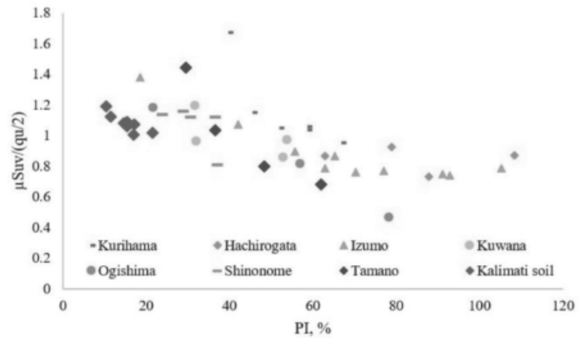


Figure 4.2: Comparison of vane strength corrected by Bjerrum’ factor and qu/2 (Tanaka, 1994)

From our study, it has been seen that the Suv is greater than qu/2 for all Ip values as shown in Figure 4.2. As Suv/Pc’ values is not much dependent on Ip for Kalimati soil, the value of Suv/(qu/2) is greater because of reduction in qu/2. This reduction in our case is majorly due to sample disturbances as content of sand particles are minimum, the effects of release of negative pore pressure is minimum during UC test conditions.

The ratio of Su(v) corrected by μ to qu/2 for Kalimati soil is plotted against PI for all samples as shown in Figure 4.1 and Figure 4.2. In our study all Ip values are less than 25 and all the ratios are greater than unity. This finding is similar to the case of Japanese clay when Ip<40 i.e. Bjerrum’s correction factor overestimates the shear strength in Kalimati soil, particularly when Ip<25.

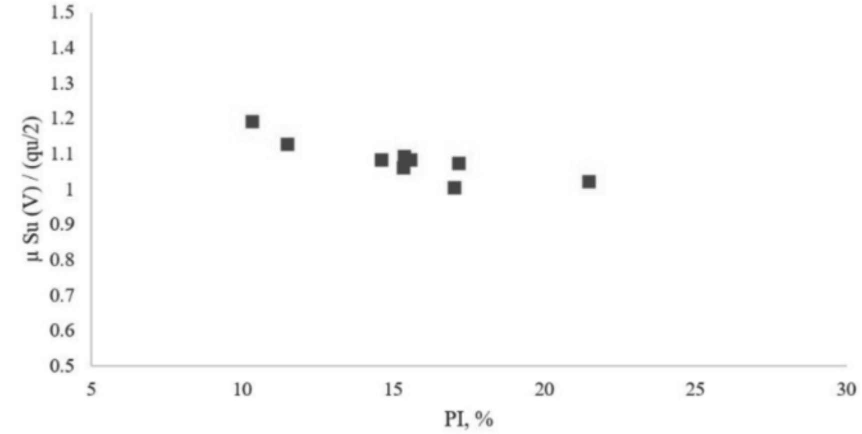
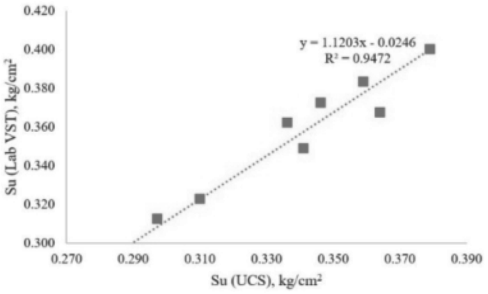


Figure 4.3: Comparison of Vane Strength corrected by Bjerrum's factor and qu/2 in Kalimati Soil

Independent of plasticity index the ratio of field vane shear to q_u /2 is always greater than unity while applying Bjerrum's correction factor. So, Bjerrum's correction factor overestimates the mobilized shear strength in Kalimati soil particularly when PI is less than 25.

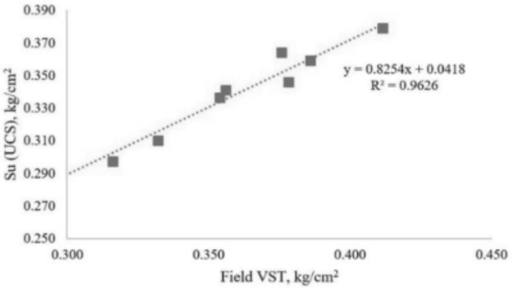
4.1 Comparison between Unconfined Compression and Lab Vane shear test

The comparative results of the unconfined compression test (UCT), lab vane shear test (LVST), and field vane shear test (FVST) on different samples of Kalimati soil shows the valuable information. The results explores that the Lab vane shear test generally gave the higher values of un-drained shear strength compared to the results from the unconfined compression test. For our case, there is an average of 4.6% rise in shear strength result from UCT to LVST. It was observed that Vane shear test generally gave the higher values of un-drained shear strength compared to the results from unconfined compression test. For our case, there is about average 5.9% rise in shear strength result from UC test to Field VS test. A correlation was developed between the shear strengths from LVST and UCS tests with an R^2 value of 0.9472, while the correlation between UCS and FVST yielded an R^2 value of 0.9626. These results suggest that the FVST may be a better indicator of the in-situ shear strength of the Kalimati soil compared to the UCT.



Su (LVST) = 1.1203 x Su (UCS) - 0.0246

Figure 4.4: UCT versus Lab VST



Su (UCS) = 0.8254 x Su (FVST) + 0.0418

Figure 4.5: UCT versus field VST

4.2 Correlation of Su/Pc' with PI

The strength ratio normalized by Pc' was reviewed by Larsson (1980) in Scandinavian clays as shown in Figure 4.6. The Su/Pc' seems to increase with increasing PI. The relationships between Suv/Pc' and Ip was reported for Eastern Canadian clays and confirmed of independency of the ratio of shear strengths normalized by pre-consolidation pressure and found the range of the ratio between

0.25 to 0.35 irrespective of Ip (Jamiolkowski et al., 1985). The two sets of data collected by BJERRUM (1973) and USSA clays was analyzed and concluded that the effect of plasticity on the distribution of soft clays is independent of plasticity and Su (mob)/σ’p is constant and equal to 0.22 as shown in Figure 4.2(Mesri, 1989).

Another evidence of suggesting the independency of Suv/Pc’ with Ip can be seen in Figure 4.7, where Suv/Pc’ ratios for Bothkennar clay in Great Britain and Japanese clay were plotted using data from Nash et al. (1992) together with the ratios obtained from the Japanese clay (Tanaka, 1994). The ratios for Bothkennar clay and Japanese clay are also likely to be independent of Ip.

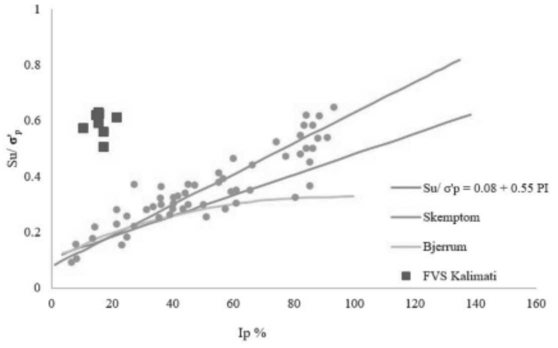


Figure 4.6: Normalized strength versus PI (Larsson, 1980)

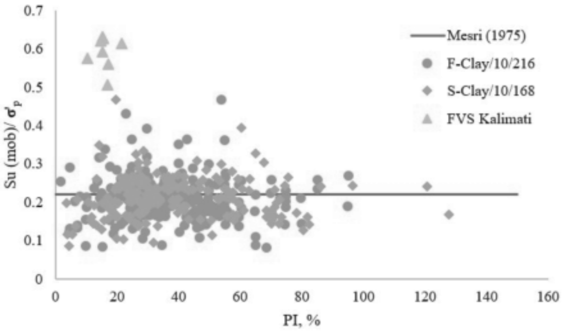
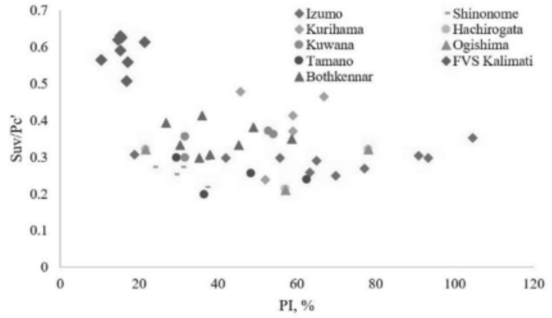


Figure 4.7: Normalized mobilized strength versus PI (Mesri, 1989)

The results from Figure 4.9 illustrates that Su/σ’p seems more likely to be independent of PI in Kalimati soil, thus confirming the suggestion given by Mesri (1989), Tanaka (1994) and Jamiolkowski et al. (1985)but the values of Su/σ’p of Kalimati soil is in the range of 0.5 to 0.63.



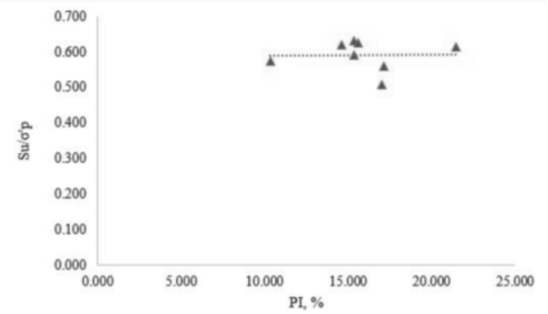


Figure 4.8: Normalized strength versus PI (Tanaka, 1994)

Figure 4.9: Normalized strength versus PI in Kalimati Soil

4.3 Correlation of LI with Su (FVS)

The three step Multiple regression analysis from DATAFIT program were performed on Turkish clays by Kayabali et al. (2015) and revealed that, compared with the result obtained using the Bjerrum’s correction factor, the vane strength from VST correlates better with the liquidity index.

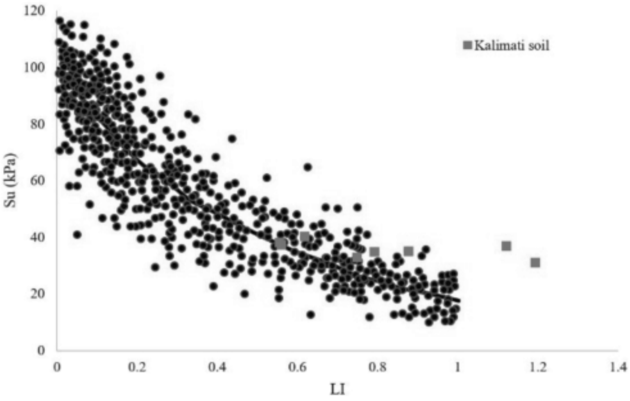


Figure 4.10: LI vs. Shear Strength (Kayabali et. al., 2015)

In a similar manner to (Kayabali et al. (2015), the correlation between undrained shear strength values and liquidity index best captures the influence of soil plasticity on Kalimati soils as per Figure 4.10. It can be clearly seen that shear strengths decreases in Kalimati soil having higher Liquidity Index. Higher LI points of Kalimati soil is slightly scattered when compared with the Norwegian clays.

4.4 Property Interrelationship with Sensitivity

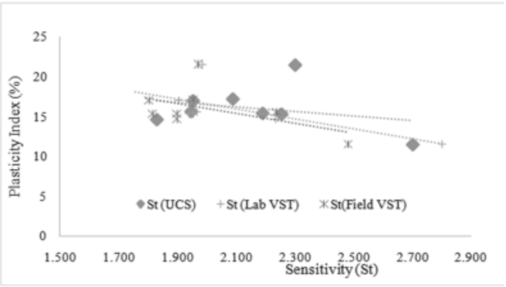


Figure 4.11: Plasticity Index versus sensitivity of Kalimati Soil

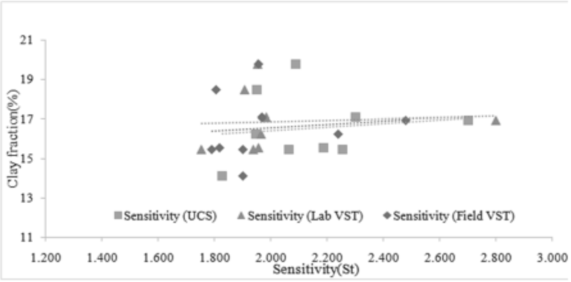


Figure 4.12: Sensitivity versus Percent clay fraction in Kalimati soil

Figure 4.11 shows the relationship between sensitivity and clay fraction of studied soil samples considered in the study. For Kalimati soil, Sensitivity increases with increase in clay fraction. As the percent clay fraction of soil samples is in the range of 14-19%, the incremental slope is not seen much significant with respect to sensitivity of the soil.

From our study, it has been seen that the Plasticity index is inversely proportional to the Sensitivity of clay samples.

The high sensitive soil generally have high value of LI and the sensitivity increases with increase in LI i.e. softness of soil. From our study, it has been seen that the Sensitivity of Kalimati soil samples increases with increment in Liquidity Index as shown in Figure 4.12.

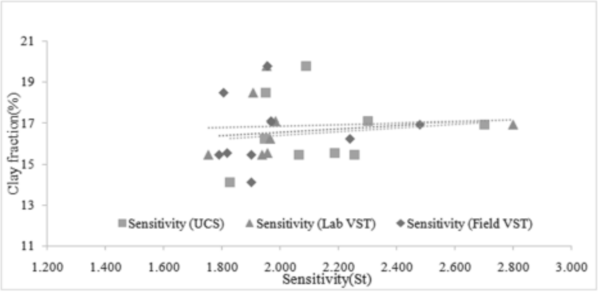


Figure 4.13: Sensitivity versus Percent Clay fraction

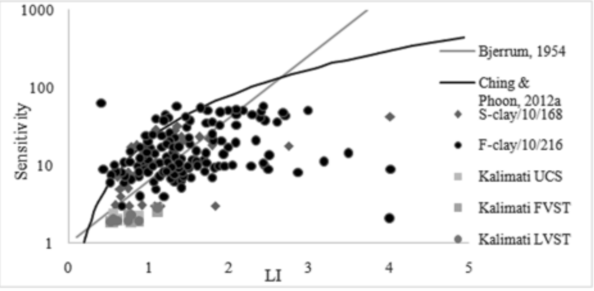


Figure 4.14: LI-St model for Norwegian Clays (Bjerrum, 1954)

4.5 SPT and UCS correlation:

Additionally, a correlation was developed between Standard Penetration Test (SPT) and unconfined compression strength (UCS) with an equation of **Su = 1.2996 x N60 + 23.102** and a regression coefficient of 0.9428. Finally, a regression equation was developed using Python programming language to predict UCS based on the Atterberg limits and N60, with a root mean square error of 1.13 and a regression coefficient of 0.90449. These correlations can be useful in predicting the strength of Kalimati soil based on different types of tests.

Su (UCS) = 1.98 x N60 + 0.55 x Wn – 0.34 x LL + 0.57 x PI

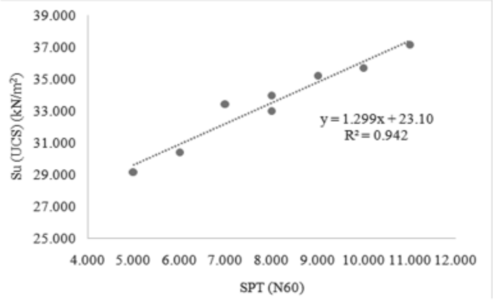


Figure 4.15: Comparison of SPT and UCS value

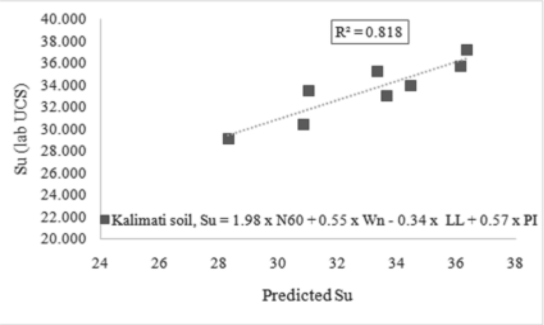


Figure 4.16: Comparison of Predicted Su and Lab Su in Kalimati Soil

5. Conclusion

Based on the Literature review and experimental investigation the following conclusions are drawn.

1. Independent of plasticity index the ratio of field vane shear to q_u /2 is always greater than unity while applying Bjerrum's correction factor. So, Bjerrum's correction factor overestimates the mobilized shear strength in Kalimati soil particularly when PI is less than 25.
2. Sensitivity is found to be increasing with increase in clay fraction with very small increment. Moreover, Sensitivity decrease with increase in Plasticity Index and sensitivity increase with increase in Liquidity Index. The increments or decrements are correspondence with previous results.
3. UC tests and Laboratory vane shear tests are correlated by the equation Su(LVST) = 1.1203 x Su(UCS) - 0.0246 and Unconfined Compressive strength and Field vane strength as Su(UCS)=0.8254 x Su(FVST) + 0.0418
4. SPT and UCS are also correlated and found to be Su(UCS)= 1.2996 x N60+ 23.102. The value of Su(UCS) also is correlated with Wn, N60, LL and PI and the equation obtained through python programming language is found to be Su(UCS)= 1.98 x N60 + 0.55 x Wn – 0.34 x LL + 0.57 x PI

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