Strain Softening Prediction Using Normalized Method

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Abstract. This study assessed the applicability of normalized method in predicting the stress-strain curve at the strain softening phase. The methodology is based on standard test and easily replicable which is conventional triaxial test. The soil sample from Kuala Terengganu, Malaysia was taken for the test. The drained triaxial test was conducted on four samples with various effective stresses (50, 100, 200 and 300kPa). The results showed that the soil is classified as silty clay with high plasticity. Based from the results, the stress-strain curves indicate strain softening clearly. The normalized method is applied in this study. It is based from Rotational Multiple Yield Surface Framework (RMYSF). However, RMYSF is applied to predict the stress-strain curves for unsaturated soil and limited to strain hardening only. Extension work is conducted to the existing method by predicting the strain softening phase for saturated soil. It can be concluded that normalized method is successfully predicted the strain softening phase of the soil. The main advantage of this method is that it can be applied to predict the soil strength parameter for various effective stresses without having to conduct many tests. Therefore, this method will help to cut the time and cost of testing effectively.

1. Introduction
Geotechnical engineering deals with soil deformation problems at low and high stress levels. The deformation problems can be analysed by many methods. However, the main parameter which is the soil shear strength is hard to obtain because the test is really time and cost consuming. Hence, many prediction models were developed in the past decades. These models were based on plasticity theory ([1];[2];[3];[4];[5];[6]) or graphical theory [7]. But the challenges of applying these methods are it is highly depending on assumption and the most important part is that the parameters required sometimes depends on non-standard tests (e.g. MIT-E3 model by [8]). Thus, it can be hard to apply to the industry. The finite element models are also sometimes really confusing because the models developed inside the code is not fully understandable by normal engineers. The problem can be solved by having a simple yet a reliable method to predict the stress-strain curve.

To achieve this, Normalized method was applied to predict the stress-strain curve. Normalized method was initially developed by [9] and [10] to predict the stress-strain behavior of strain hardening soils. It is based from Rotational Multiple Yield Surface Framework (RMYSF) [11]. The concept is simple and does not required many tests. It is reliable because the process is straight forward without having to apply many mathematical equations that sometimes rely on assumptions. The subsequence
topics will explain further the concept with extension work on the strain softening phase prediction on the stress-strain curve.

2. Methodology
The soil samples were collected at Kuala Terengganu, Malaysia. The soil sampling was conducted using thin walled tube sampler with diameter of 50 mm. The undisturbed samples were collected on the dry area of the soil, at 1m below the ground level. The Ground Positioning Station (GPS) using Google Maps shows that the location is at the coordinate of 5°19’ 57.1”N and 103° 4’ 30.5”E. It is a drainage system which act as the catchment area. The soil sample is grey in color and there are traces of granitic residual soils which are not originally from this area. 

Soon after the samples collection, the soil samples together with the tube were sealed in plastic bag and transported to laboratory for soil tests. Figure 1 shows the soil samples collected at Kuala Terengganu, Malaysia. The basic properties tests such as specific gravity, Atterberg limit and particle density were also conducted on the samples. The tests are in accordance to [12].

Figure 1. The soil samples collected at Kuala Terengganu, Malaysia

A triaxial test is essential in order to apply the normalized method for the stress-strain curves prediction. The drained triaxial test is conducted in accordance to [12]. The sample was then removed from the thin walled tube sampler before each triaxial test. The sample was trimmed to 100mm height. Each sample was weighted prior to triaxial test. The drained triaxial test was conducted on the sample due to the nature of the soil. It is classified as silt, so the drained behavior is expected. On top of that, drained triaxial test is selected because there are many undrained tests were conducted by other researches on this type of soil. Instead, this study will look on the drained behavior. The advantage of having this drained triaxial test is the volume change behavior can be observed during the shearing process. On the other hand, undrained test cannot supply the volume change behavior. Volume change behavior is essential in this study because it can be used to detect the dilation of the sample which will result in softening after the yielding point.

3. Results and analysis
The basic properties test results are given in Table 1. The soil is classified as SILT of high plasticity as accordance to [12].
Table 1. The basic properties tests result

| No | Properties                      | Value                  |
|----|---------------------------------|------------------------|
| 1  | Specific gravity (Mg/m³)        | 2.208                  |
| 2  | Liquid limit (%)                | 63                     |
| 3  | Plastic limit (%)               | 51                     |
| 4  | Plasticity Index (%)            | 11                     |
| 5  | Soil classification             | SILT of high plasticity, MH |

The procedure of applying Normalized method is given in Figure 2. For clarification, the results of drained triaxial test for dilatant soil before normalized process as illustrated in Figure 3 is used in the explanation. Typically, the peak strength is reached at different axial strains for stress-strain curves of different confining pressures. The higher the effective stress, the higher the axial strain will be. Hence, normalized method requires the peak strength at a common peak point for each stress-strain curve. To do so, the highest effective stress is selected to be the common peak point (300kPa). So, all the other effective stresses will follow this common peak point. The reason for this configuration of common peak point is to solve the softening part problem. If various peak point is encountered, the softening part will have different shape and hard to do the prediction. Figure 4 shows the stress-strain curve for dilatant soil after normalized at 17% axial strain (common peak point or normalized factor). The normalized process is conducted by dividing all the axial strains with the common peak point axial strain (for this case the axial strain at 17%).

Figure 2: The procedure of predicting the stress-strain curve using Normalized method
Figure 3. Stress-strain curve for dilatant soil before normalized process

Figure 4. Stress-strain curve for dilatant soil after normalized at 17% axial strain

The next step is to draw the Mohr circle. The process of drawing the Mohr circle can be conducted by referring to normalized stress-strain curve. The new stress-strain curve is the same stress-strain curve, but the common peak point is set so that the resulting strain softening phase is following the same shape. Normalized Mohr circles (until peak strength) as illustrated in Figure 5 is based on the
normalized stress-strain curves. The mobilized shear strength curves are plotted for each axial strain. Figure 6 illustrates normalized Mohr circles (after peak strength). This rotational multiple mobilized shear strength envelope act as the ‘signature’ for the soil behavior. If the prediction is required for low stress level (let say 25 kPa), then the effective stress can be mapped inside this envelope and the stress-strain curve prediction can be conducted. To achieve this, firstly, the effective stress is plotted in normalized envelope. Then, the stress-strain curve is generated by neutralize the envelope by applying equation 1.

\[ \varepsilon_a = \varepsilon\% \times \left(1 / \text{normalized factor}\right) \]  

where \(\varepsilon_a\) is the actual axial strain and \(\varepsilon\%\) is the axial strain in normalized envelope. This will yield the stress-strain curve for the effective stress of 25 kPa. In fact, conventional triaxial test cannot give the accurate measurement for this low stress level. Therefore, this can be realized by applying normalized method. The low stress level is very crucial for many geotechnical engineering problems such as slope failure, embankment and foundation designs.

![MOBILISED SHEAR STRENGTH ENVELOPE AT NORMALISED STRAIN FACTOR METHOD (UNTIL PEAK STRENGTH) FOR SATURATED SPECIMENS](image)

**Figure 5.** Normalized Mohr circles (until peak strength)
The prediction of the stress-strain curve is possible with the Normalized method for other stress-strain curves that is not tested in the laboratory. For instance, for a given soil, one just need to test for the highest effective stress (i.e. 220 kPa). The other stress-strain curve can be predicted using normalized method. The stress-strain curve prediction for the effective stress of 150 kPa is illustrated in Figure 7.
4. Conclusions
Normalized method is capable to predict the stress-strain curve because it is based on the inherent property of the soil without having to assume or working blindly under certain theoretical framework. It is solely depending on the behavior of the soil and the prediction is conducted from the ‘signature’ of the stress-strain curves. This prediction method can be used for strain hardening and strain softening as well. The stress-strain curve can be reproduced after normalization effectively.

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References
[1] Roscoe K H Schofield A N and Wroth C P 1958 On the yielding of soils Géotechnique 8, p 22-53.
[2] Jocković S and Vukićević M 2017 Bounding surface model for overconsolidated clays with new state parameter formulation of hardening rule Comput. Geotech. 83, p 16–29.
[3] Dafalias Y F 1986 An anisotropic critical state soil plasticity model Mech. Res. Commun. 12, 6 p. 341-347.
[4] Dafalias Y F 1986 Bounding surface plasticity, I: mathematical foundation and hypoplasticity J. Eng. Mech. 112, 9 p. 966–987.
[5] Lai B T Wong H Fabbri A and Branque D 2016 A new constitutive model of unsaturated soils using bounding surface plasticity (BSP) and a non-associative flow rule. Innov Infrastruct Solut. 1, p. 3.
[6] Casagrande A 1936 Characteristics of cohesionless soils affecting the stability of slopes and earth fills J Bost Soc Civ Eng.
[7] Al-Karni A and Alshenawy A 2006 Modeling of stress- strain curves of drained triaxial test on sand Amerian J Appl Sci. 3,11 p. 2108–2113.
[8] Whittle A J and Kavvadas M J 1994 Formulation of MIT-E3 constitutive model for overconsolidated clays. J Geotech. Eng. 120, 1 p. 173–198.
[9] Rahman A S A Noor M J M Ahmad J and Sidek N 2017 Prediction of soil stress-strain response incorporates mobilised shear strength envelope of granitic residual soil AIP Conf Proc. 1891, 02006.
[10] Md-Noor M J Ibrahim A Abdul-Rahman A S 2018 Normalized rotational multiple yield surface framework (NRMYSF) stress-strain curve prediction method based on small strain triaxial test data on undisturbed Auckland residual clay soils IOP Conf. Ser.: Earth Environ. Sci. 140, 012100.
[11] Md-Noor M J and Hadi B A 2010 The role of curved-surface envelope Mohr-Coulomb model in governing shallow infiltration induced slope failure. Electron. J. Geotech. Eng. 15, p. 1–21.
[12] British Standards Institute. BS1377. Standard Methods of test for soils for civil engineering purposes. 1990