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Stress-Strain response of Malaysian granitic residual soil grade V, according to Rotational Multiple Yield Surface Framework

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Abstract. In soil mechanics characterizing the soil volume change behavior is based on the effective stress concept. Conventional soil settlement models which have been developed by this principle, are empirical in nature and being verified against experimental or field observations. However, they are not still able to explain and formulate some unusual soil volume change behaviors such as wetting collapse by this concept. The consequence of shear strength in the interaction of effective stress should be integrated into volume change frameworks in such cases in order to puzzle out these weird behaviors. The principle has been incorporated in an anisotropic soil settlement model know as Rotational Multiple Yield Surface Framework (RMYSF). The framework has been developed from the standpoint of the soil stress-strain response within anisotropic stress condition. The anisotropic soil volume change behavior is described from the interaction between applied stress (presented by the Mohr-Coulomb circle) and shear strength (in terms of curved-surface mobilized shear strength envelope). The applicability of the model has been examined for limestone gravel from the United Kingdom and granitic residual soil grade VI from Kuala Kuba Baru, Malaysia before, however still needs to be tested for another kind of soils. In this paper, a series of triaxial tests were conducted on Malaysian granitic residual soil grade V, in saturated and unsaturated condition. The stress-strain curves and volume change behavior of the soil were obtained from laboratory test results. Besides that, the stress-strain response of the soil has been predicted using RMYSF framework. The predicted stress-strain curves were compared with the test result and the accuracy of the framework was examined. The obtained and predicted curves had a fairly good match.

1 Introduction

The stress-strain behavior in a partially saturated soil is highly dependent on the relevant stress variables. Being mostly in unsaturated state, the surface soils are under the influence of evaporation and rainfall. Basically, the engineering properties of unsaturated soil vary from the saturated state. In this respect, various problems related to slope failure and inundation settlement (wetting collapse) can be simply solved using the approaches that take into account of unsaturated condition.

The conventional volume change models [1-4] were piled on Terzaghi effective stress concept [2]. These models are developed in the fact that the increment of effective stress is linked to settlement. When total stress increases or pore water pressure is expelled within a soil mass, the effective stress increases, thereby settlement occurs. However, the settlement would terminate at some point because of rearrangement of soil particles to a denser position and increase of the soil stiffness. This rise in soil stiffness is a sign of the increment of the soil strength. This indicates the importance of shear strength in controlling the settlement behavior. Nevertheless, incorporating the shear strength in a settlement model is not an easy effort and most of such frameworks are the empirical type. In additional, the existence of some unusual soil volume change behaviors such as wetting collapse which are in contrast with effective stress concept makes the situation more complicated.

Some researchers [5-7] reported that wetting collapse happens during the wetting process of soil mass under steady surcharge. Before inundation, soil mass initially is partially saturated and pore water pressure is negative. Soil particles are pushed together due to a surface tension (suction). After infiltration, according to the Terzaghi effective stress concept, pore water pressure changes from being negative to positive, thereby a decrease in effective stress is reached. As a result, wetting collapse happens as a reduction in effective stress. The phenomenon cannot be only be characterized relying on conventional settlement models. Therefore, besides effective stress, a second factor can affect the soil volume change of unsaturated soils. This factor is the reduction of shear strength [8]. The volume change behavior of unsaturated soil can be even more complicated while massive settlement near saturation [9] or extensive wetting collapse at low net stress compared with higher net stress [10] exists.

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The main objective of the current study is to examine the accuracy of a new semi-empirical volume change model know as Rotational Multiple Yield Surface Framework (RMYSF) against the volume change behavior of Malaysian granitic residual soil grade V. The applicability of the model has been examined for limestone gravel from the United Kingdom [11] and granitic residual soil grade VI from Kuala Kuba Baru, Malaysia [12] before, however still needs to be tested for another kind of soils. A series of triaxial tests were conducted on Malaysian granitic residual soil grade V, in saturated and unsaturated condition. The stress-strain curves and volume change behavior of the soil were obtained from laboratory test results. Besides that, the stress-strain response of the soil has been predicted using RMYSF framework. Finally, the experimental result and the predicted result were compared and the accuracy of the framework was examined.

2 Rotational Multiple Yield Surface Framework (RMYSF)

Md. Noor and Anderson [11] proposed an anisotropic soil volume change model known as Rotational Multiple Yield Surface Framework (RMYSF). It has been established on the extended concept of interaction between mobilized shear strength and effective stress. The concept defines settlement as the influence of a reduction in shear strength (wetting collapse) or an increase in effective stress (wetting collapse).

The framework was introduced relying on elastic-plastic soil stress-strain response. The authors claimed that this semi-empirical model is able to predict settlement either for wetting collapse or loading collapse, through a set of laboratory and theoretical concepts. While soil is in the saturated condition, stress state is defined as effective stress, $(\sigma - u_w)$, and in unsaturated condition is taken as net stress, $(\sigma - u_a)$. Stress state is presented by Mohr circles and considered as driving variables. On the other hand, as presented in Figure (1), the curved-surface mobilized shear strength envelope of [13], shows the state of mobilized shear strength and behaves as resisting variable in the soil mass.

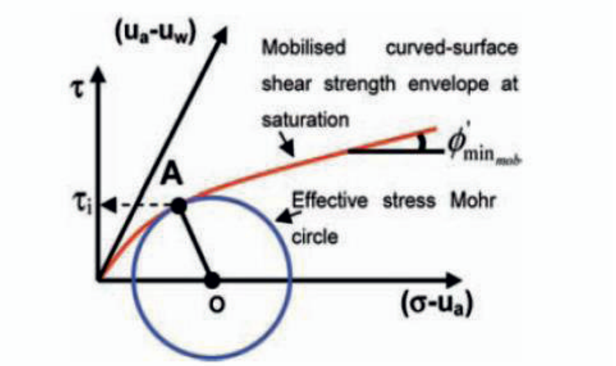

Figure 1. Mobilized shear strength envelope (the Mohr circle representing the state of applied stress and the curved-surface envelope representing the state of shear strength) [12].

Based on the model, the settlement occurs while the state of stress (net or effective) extends beyond the mobilized shear strength envelope. In this situation, the driving variable is greater than resisting variable. While a compression process is in place, soil elements shift to a denser state. At this stage, the mobilized shear strength withstands against this transformation by rotating anticlockwise about the origin towards the mobilized shear strength envelope at failure and providing the frictional resistance. At this point, an addition in shear strength of the soil reaches. The process will move forward till the resisting and driving variables come to an equilibrium state. When this state is reached, the Mohr circle is located under mobilized shear strength. Therefore, the driving variables are smaller than resisting variables and soil is stable. Adversely, if the Mohr circle is located over the mobilized shear strength, it replicates that the soil mass is not stable and it is subjected to the settlement. However, wetting collapse takes a place under constant stress. In such case during inundation, the shear strength of the soil reduces due to a reduction in suction. Decrease in suction causes a non-linear decrease in apparent shear strength (c´) [13] while the size of the Mohr circle remains constant (a variation on suction does not any effect on the net stresses). At this point, if the Mohr circle relocates beyond the mobilized shear strength envelope, settlement occurs. Mobilized shear strength envelope rotates into a position with a bigger mobilized friction angle.

Later on, it was reported that there is a unique relationship between the minimum mobilized friction angle, $Ø'_{min\ mob}$, and axial strain, ε_a [14] . Applying the deviator stress rotates the mobilized shear strength into a new position regardless of the value of effective or net stress in accordance with axial strain either for saturation or unsaturation condition. RMYSF model is based on this unique relationship. The authors claimed that this relationship is able to predict the stress-strain response of a specific soil at every desired net stress or effective stress. Equation 1, was introduced by [14] in order to obtain the best fit curve for the minimum mobilized friction angle, $Ø'_{min\ mob}$ and axial strain, ε_a.

$$\varepsilon_a = \frac{ln\left[\frac{\phi'_{min\,f} - \phi'_{min\,mob}}{\phi'_{min\,f}}\right]}{\Omega} \qquad (1)$$

Ω is a fitting parameter and known as soil coefficient of anisotropic compression. The value of Ω depends on the soil structure.

3 Stress-strain response and Mobilized shear strength envelopes for Malaysian granitic residual soil grade (V)

3.1 Triaxial test results

The soil tested in this study was granitic residual grade V from Seremban, Selangor, Malaysia. The specimen consists of 51.25% sand, 45.23% gravel, 1.18% silt and

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2.25% clay and classified as well graded SAND. Consolidated drained triaxial tests in fully saturated and partially saturation condition were conducted on specimens with 50 mm diameter and 100 mm height. In terms of partially saturated condition a modified double wall triaxial apparatus with suction control was used. The suction of 70 kPa (residual suction obtained from SWCC test) was applied to the specimen using axis translation technique [14]. The triaxial test has been conducted at effective stresses of 50 kPa, 100 kPa, 200 kPa and 300 kPa. From the shearing stage, the stress-strain curves for the saturated and unsaturated condition were plotted as shown in Figures 2 and 3 respectively. Shear strength parameters of the tested soil were obtained following CSESSSM model of [13] and are given in Table 1.

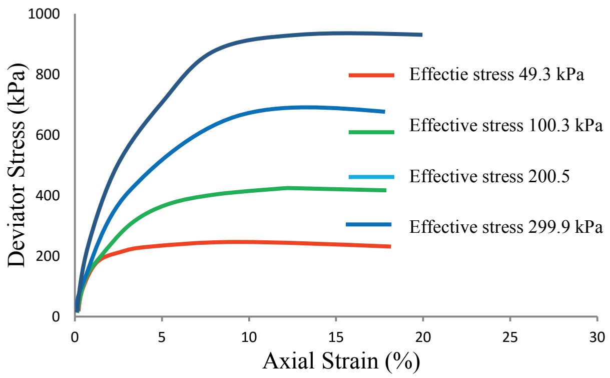

Figure 2. Stress-strain curves in fully saturated condition from the triaxial test.

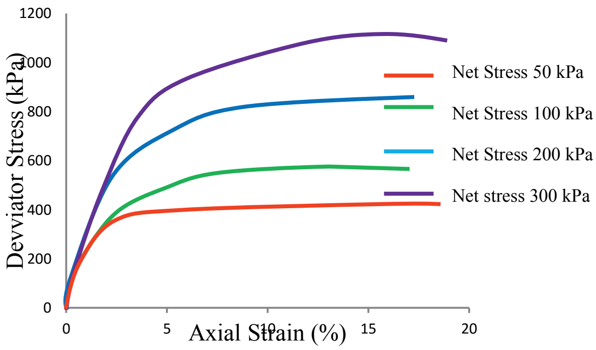

Figure 3. Stress-strain curves in unsaturated saturated condition (70 kPa suction) from the triaxial test.

Table 1. Shear strength parameters using CSESSSM model

Shear strength parameters	Value
$\phi'_{min\ f}$	34˚
$(u_a\text{-}u_w)_r$	70 kPa
$(u_a\text{-}u_w)_u$	250 kPa
$(\sigma\text{-}u_a)_t$	122 kPa
τ_t	105 kPa
C_s^{max}	31 kPa

The value of axial strain in the stress-strain curves (Figures 2 and 3) indicates the specimen axial deformation due to the related deviator stress. For example, for 10% strain at 200 kPa effective stress in the saturation condition, the value of deviator stress is 550 kPa. On the other hand, if the specimen loaded to 550 kPa deviator stress at 200 kPa effective stress in the fully saturation condition, it would settle 10% of its initial height.

Mobilized shear strength envelopes in various axial strains in fully saturated condition are presented in Figures 4-7. Mohr circles were plotted under the effective stress of 49.3, 100.3, 200.5 and 299.9 kPa and their related deviator stress in various axial strains. From the Mohr circles, the mobilized shear strength envelopes and their mobilized friction angles in various axial strains were obtained according to the curved surface envelope of [13].

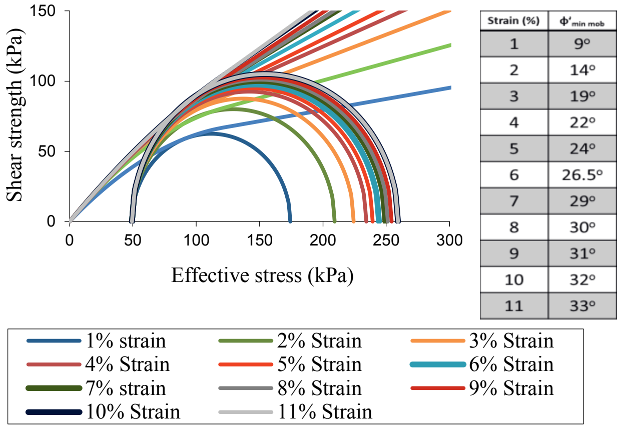

Figure 4. Mobilized shear strength envelopes in various axial strains in fully saturated condition and 49.3 kPa effective stress.

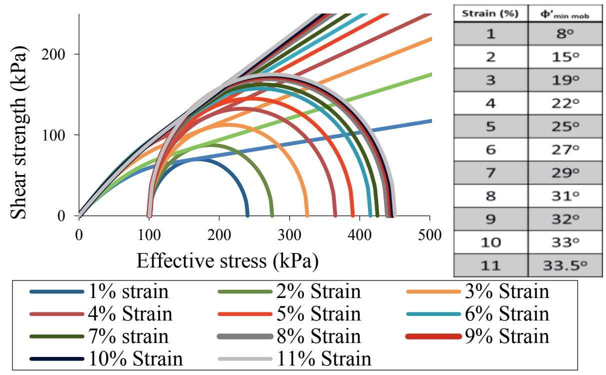

Figure 5. Mobilized shear strength envelopes in various axial strains in fully saturated condition and 100.3 kPa effective stress.

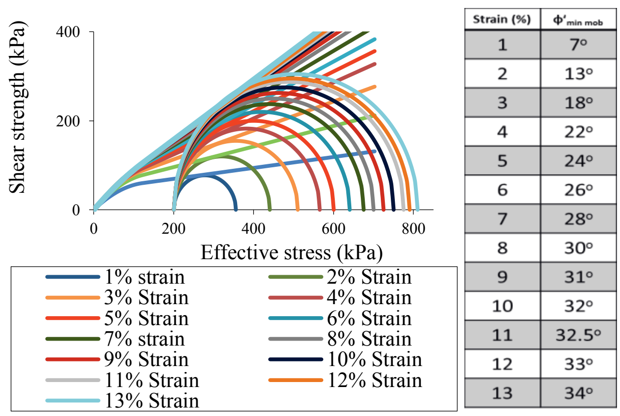

Figure 6. Mobilized shear strength envelopes in various axial strains in fully saturated condition and 200.5 kPa effective stress.

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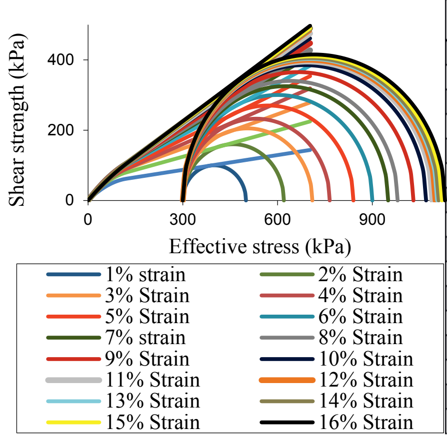

Strain (%)	$\phi'_{min\ mob}$
1	8°
2	14°
3	18°
4	21.5°
5	24°
6	26°
7	28°
8	29°
9	30.5°
10	31.5°
11	32.5°
12	33°
13	33.3°
14	33.5°
15	33.5°
16	34°

Figure 7. Mobilized shear strength envelopes in various axial strains in fully saturated condition and 299.9 kPa effective stress.

As illustrated in Figure 8, it can be observed that there is a relationship between each specific axial strain and $Ø'_{min\ mob}$. In fact, the position of mobilized shear strength presents a specific amount of axial strain irrespective of effective stress. This is the identical unique relationship which has reported by [15]. This unique relationship for Malaysian granitic residual soil, at different effective stresses, is shown in Figure 8. In additional the unique relationship is plotted using the equation 1 with the value of 0.277 for the Ω. It can be observed that there is a good agreement between obtained $Ø'_{min\ mob}$ from the test result and the equation.

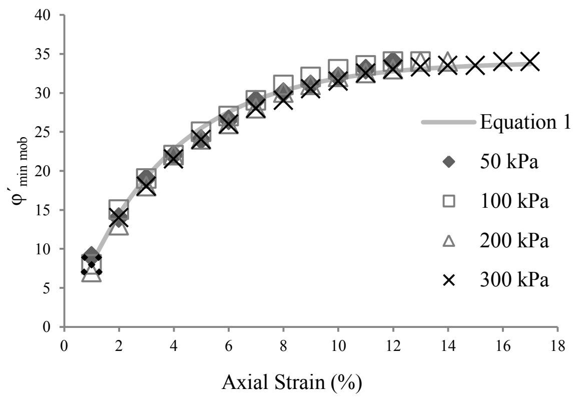

Figure 8. The unique relationship for Malaysian granitic residual soil grade V at different effective stresses using experimental test results and Equation 1.

3.2 Prediction of soil stress-strain response for granitic residual soil in unsaturated condition (70 kPa suction), using RMYSF model

As claimed by RMYSF, the unique relationship presented in Figure 8, is an intrinsic property of the soil. It is valid for the whole range of net stress and effective stress applied during the test. In other words, it is possible to predict the stress-strain curve of the soil at any desired net stress or effective stress up to the peak point of the curve. This prediction is carried out first by drawing Mohr circle, starting at desire σ'3. The Mohr circle has to touch the particular mobilized shear strength envelope and ends up at σ'1. It should be noted that in unsaturated condition, the value of apparent shear strength, c´, related to the desire suction in accordance with CSESSSM model should be applied to the mobilized shear strength envelope. The diameter of the Mohr circle determines the respective deviator stress, q. By knowing the predicted deviator stress and axial strain presented by the mobilized shear strength envelope, the stress-strain can be predicted. The predicted deviator stresses related to various axial strains in the net stress of 50, 100, 200 and 300 kPa for Malaysian granitic residual soil grade V at 70 kPa suction are given at Table2. Figure 9 presents a comparison between predicted deviator stresses which are presented by dotted points and the actual stress-strain curves obtained from experimental results. It indicates that the predicted data is in an acceptable agreement with experimental results.

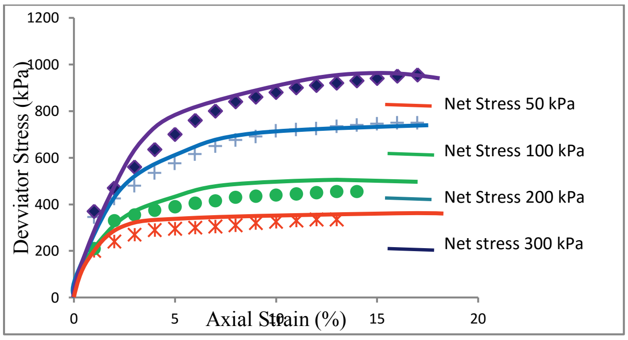

Figure 9. The obtained stress-strain curves from the double wall triaxial test against the predicted ones using RMYSF model.

Table 2. Predicted deviator streses for granitic residual soil grade V in unsaturated condition (70 kPa suction).

Axial Strain (%)	50 kPa	100 kPa	200 kPa	300 kPa
1	200	210	345	370
2	240	330	425	470
3	270	355	480	560
4	290	375	535	635
5	295	390	575	700
6	300	405	615	760
7	305	415	650	800
8	310	430	675	840
9	320	435	690	860
10	325	440	715	880
11	330	445	720	900
12	335	450	725	910
13	335	455	735	920
14		455	740	930
15			745	940
16			750	950
17			750	955

4 Conclusion

The following conclusion can be observed from this study:

- From the experimental test results it can be observed that there is a unique relationship between minimum mobilized friction angle, $Ø'_{min\ mob}$ and axial strain, ε_a, regardless of effective stress for Malaysian granitic residual soil grade V. This relationship approves the concept of RMYSF model.
- The result also shows, using Equation 1 can provide a perfect fit for the unique relationship.
- RMYSF model has the ability to predict the stress-strain response of Malaysian granitic residual soil grade V in unsaturated condition with a good accuracy.

References

[1] N. Janbu, L. Bjerrum, and B. Kjaernsli, "Veiledning ved løsning av fundamenteringsoppgaver," 1956.

[2] K. Terzaghi, *Theoretical soil mechanics* vol. 18: Wiley New York, 1943.

[3] E. de Beer and A. MARTEN, "Method of computation of an upper limit for the influence of hetero-geneity of sand layers on the settlement of bridges'. 4th ICSMFE," ed: London, 1951.

[4] J. H. Schmertmann, P. R. Brown, and J. P. Hartman, "Improved strain influence factor diagrams," *Journal of the Geotechnical Engineering Division,* vol. 104, pp. 1131-1135, 1978.

[5] J. Jennings and J. Burland, "Limitations to the use of effective stresses in partly saturated soils," *Géotechnique,* vol. 12, pp. 125-144, 1962.

[6] R. Tadepalli, H. Rahardjo, and D. G. Fredlund, "Measurements of matric suction and volume changes during inundation of collapsible soil," *Geotechnical Testing Journal,* vol. 15, pp. 115-122, 1992.

[7] R. Blanchfield and W. Anderson, "Wetting collapse in opencast coalmine backfill," *Proceedings of the ICE-Geotechnical Engineering,* vol. 143, pp. 139-149, 2000.

[8] S. Wheeler and V. Sivakumar, "An elasto-plastic critical state framework for unsaturated soil," *Géotechnique,* vol. 45, pp. 35-53, 1995.

[9] E. E. Alonso, A. Gens, and A. Josa, "A constitutive model for partially saturated soils," *Géotechnique,* vol. 40, pp. 405-430, 1990.

[10] M. Md.Noor, R. Jidin, and M. Hafez, "Effective Stress and Complex Soil Settlement Behavior," *EJGE,* vol. 13, 2008.

[11] M. J. Md.Noor and W. F. Anderson, "A Qualitative Framework for Loading and Wetting Collapses in Saturated and Unsaturated Soils," in *16th South East Asian Geotechnical Conference*, Kuala Lumpur, Malaysia, 2007.

[12] M. J. Md.Noor and I. B. Mohamed Jais, "Rotational multiple yield surface framework and the prediction of stress-strain response for saturated and unsaturated soils," in *5th International conference on unsaturated soils* Barcelona, Spain, 2010.

[13] M. J. Md.Noor and W. Anderson, "A comprehensive shear strength model for saturated and unsaturated soils," in *Unsaturated Soils 2006*, 2006, pp. 1992-2003.

[14] P. Saffari, M. J. Md.Noor, B. A. Hadi, and S. Motamedi, "Laboratory Test Methods for Shear Strength Behavior of Unsaturated Soils Under Suction Control, Using Triaxial Apparatus," in *InCIEC 2014*, ed: Springer, 2015, pp. 567-576.

[15] I. B. Mohamed Jais and M. J. Md.Noor, "Establishing Unique Relationship between Minimum Mobilised Friction Angle and Axial Strain for Anisotropic Soil Settlement Model," presented at the Asia Pacific Conference on Unsaturated Soil, Newcastle, Australia, 2009.