Failure States For Normally and Overconsolidated Soft Bangkok Clay

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Abstract: Extensive triaxial test data on soft Bangkok clay indicate that a unified normalized failure envelope in compression can be obtained for all states and this envelope is only dependent on the frictional component. The failure envelope on the extension side is a mirror image of the compression envelope on the mean normal stress axis. Triaxial compression and extension tests performed with a wide variety of stress paths as well as stress probing experiments inside the state boundary surface seem to confirm this single set of normalized failure envelopes. Such normalizable failure surfaces merge with the undrained stress paths of the normally consolidated states to form the state boundary surface. This would imply that for natural un-cemented deposits of soft clays, effective stress analysis could be performed successfully only with frictional mechanism in the limit state and the friction angle will vary dependent on the overconsolidation ratio. Many of the case histories in the Muar clay series of test embankments seem to give successful predictions when analysed using the CRISP Program and the limit state friction strength envelope. Similar experience is also noted in the performance of the test embankments with the Bangkok clay.

1 INTRODUCTION

Traditionally total stress analysis is carried out with $\phi_u = 0$, condition in saturated soft clays and the shear strength assumed as only the cohesive component, c_u as determined from the vane shear tests. However in a situation where there is possible piezometric drawdown and its effect on the soil profiles, effective stress analysis seems more appropriate. Especially when finite element analysis is performed to determine the lateral movement profiles below a loaded area, effective stress analysis with Modified Cam clay theory and the use of a constant q yield loci seems more realistic in predicting the settlement and lateral movements. Alternatively, a Roscoe & Poorooshasb (1963) type model can be used as the necessary data for a FEM analysis can be obtained from simple triaxial tests.

In this paper, continuous strength envelopes both on the compression and extension side and bounded by the undrained stress paths in the normally consolidated states is obtained from triaxial tests with a wide variety of stress paths. Such a limit surface indicate when the soft clay is subjected to stress increments, non failure states can occur when the stress states are inside the state boundary surface as bounded by the undrained stress paths in the normally consolidated states and the failure surfaces in the overconsolidated states.

2 EXPERIMENTAL OBSERVATIONS

The stress strain behaviour and strength characteristics of Soft Bangkok clay in the normally and overconsolidated states were studied both under itotropic and K_0 pre-shear consolidation conditions in compression and in extension. The experimental program included:

1. Isotropic and K_0 consolidation and swelling tests
2. Four series of undrained triaxial tests, three of them in compression and one in extension
3. Ten series of drained tests
4. One series of constant p isotropic compression tests
5. One series of constant p extension tests
6. Four series of stress probing type of tests conducted from different initial stress states within the SBS, but each series had applied stress paths in directions covering the full 360 degrees in the (p, q) stress space.

3 TEST RESULTS

Fig. 1 shows the failure points of samples sheared from K_0 pre-shear stress conditions together with their applied stress paths both in compression and in extension. The curve E_0C is the undrained stress path of the normally consolidated sample having the same initial water content as the K_0 consolidated samples. The curve OCN indicates the Hvorslev failure envelope and the critical state line on the compression side. The mirror image of these two curves about the p-axis is shown as E_0C' and OC'N'. The undrained stress paths of K_0 normally consolidated samples both in compression (CK0U1) and in extension (CK_0UE1) conditions are also shown as ADE and A'D'E' respectively. It is interesting to note from this figure that all the samples in extension conditions attain their failure at the curve OC'N' with little deviations. This indicates that the state boundary surface (SBS) is symmetric in nature about the p-axis for isotropically consolidated samples. All failure points from undrained tests are added to those from the drained tests and are plotted together in Fig. 2. The strength envelope OC"N" on the extension side in this figure is now drawn from the test data. Fig. 3 illustrates the projection of the failure envelope in a $(\Delta e_f, \ln(p_f / p_e))$ plot, which is very similar to the Henkel water content strength envelope.

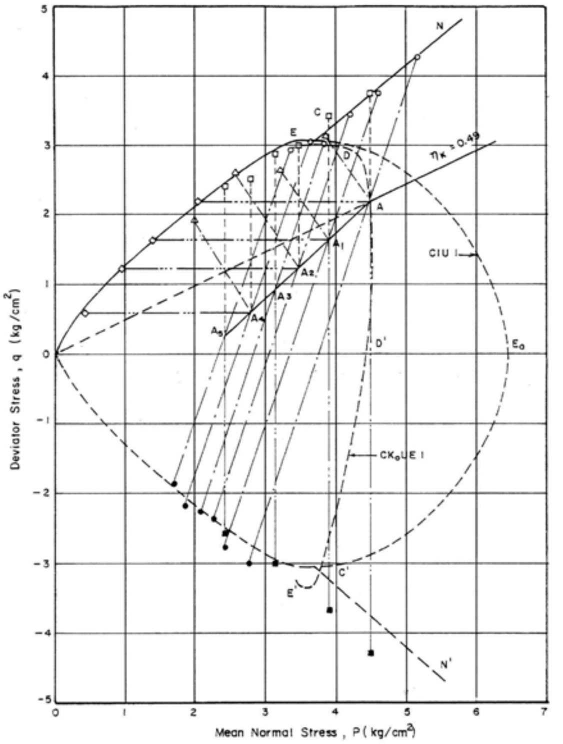

Fig. 1. Strength envelope and stress paths in the (*q*, *p*) plot.

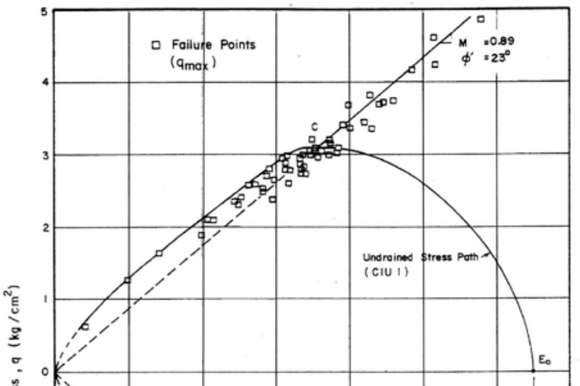

Fig. 2 State boundary surface and failure points from drained and undrained tests in the (*q*, *p*) plot.

Volumetric yield points are normally determined from the (ε_v, p) relationship with a bi-linear construction. Such a construction is only an approximate technique and is somewhat similar to the Casagrande method for the determination of the maximum past pressure. Such volumetric yield points, therefore, correspond to the volumetric yield locus which lie on the simplified Roscoe surface on the wet side of the critical state line and a similar limit state dilatational yield locus on the dry side seeking the Hvorslev failure envelope. The yield points were determined from all the drained tests on K_0 and anisotropically consolidated samples and when plotted together lie in a zone as shown in Fig. 4 in the $(q/p_e,\ p/p_e)$ plot. In Fig.4, the simplified elastic zone for the K_0 consolidated samples is also shown. This elastic zone has a distorted elliptic shape with the major axis along the idealized K_0 line. Fig. 5 shows the shear strain contours from the K_0 consolidated drained compression tests. These contours are somewhat sub-parallel to the idealized K_0 consolidation line. The samples in the drained tests experience more shear strain than those in the undrained conditions.

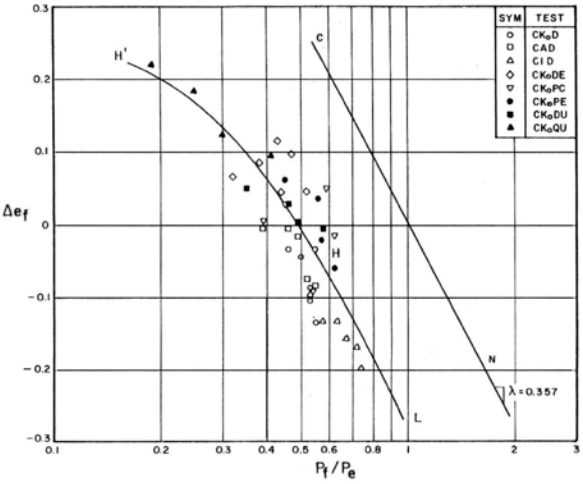

Fig. 3. $(\Delta e_f, \ln(p_f / p_e))$ plot from drained test.

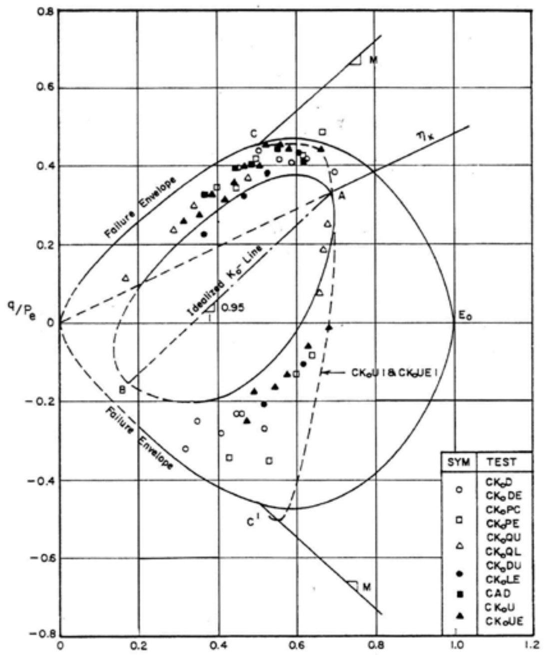

Fig. 4. State boundary surface and elastic zone for K_0 consolidated samples in the $(q/p_e,\ p/p_e)$ plot.

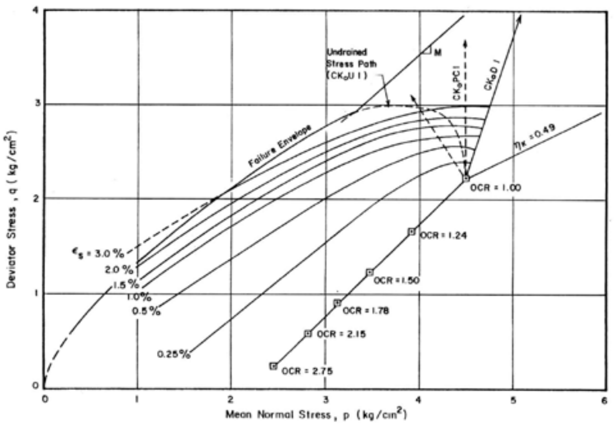

Fig. 5. Shear strain contours from drained tests for K_0 consolidated samples in the (*q*, *p*) plot.

3.1 Stress Probing Experimental Results

Stress probing experiments were formed from four stress states inside the state boundary surface. These stress points and the stress paths followed are shown in Figs. 6a to 6d. The failure surface as determined from these stress probing experiments are presented in Figs. 7a to 7d. The failure surfaces though show some differences are similar in shape to those obtained by Kim (1991). They all indicate that, a common surface can be formulated to include the state surface of the normally consolidated clays during volumetric yielding with the failure surfaces resulting from normally consolidated and overconsolidated clays. This would imply that in finite element analysis and also in effective stress analysis, the limit surface as shown in Fig. 8 can be used to define the failure states with varying critical state parameter M dependent on the mean normal stress in the overconsolidated states. The finite element analysis performed on many of the test embankments at the Muar flat site in Malaysia, and also in Bangkok, seems to indicate that, better predictions are made when the actual failure surfaces are used with variable M values dependent on the mean normal stress at failure.

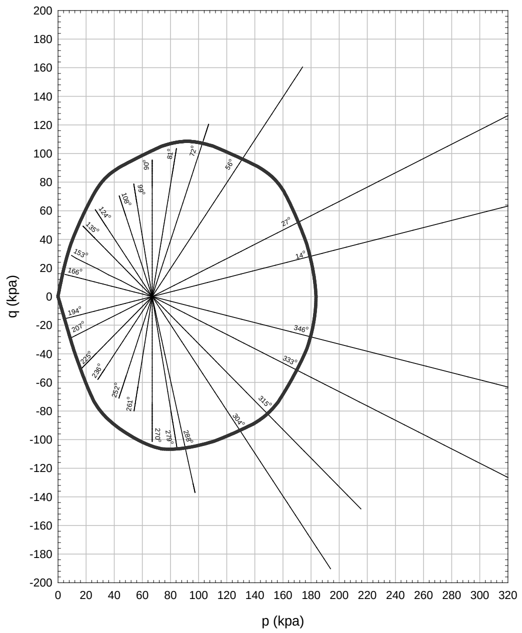

Fig. 6a. Summary of radial stress path tests (Anuchit, 1998; and Navaneehtan, 1999).

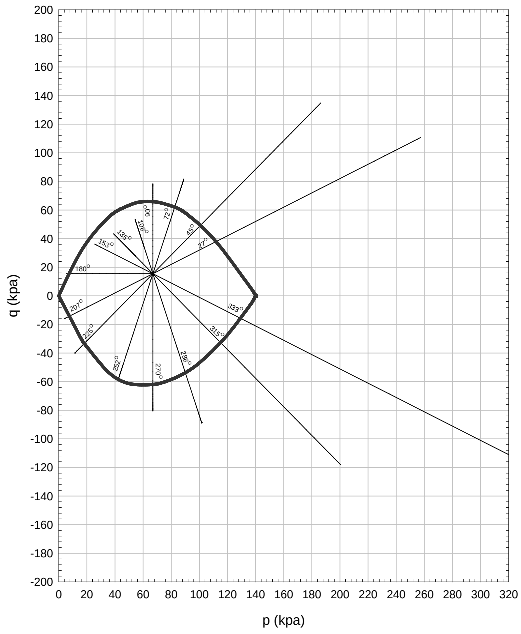

Fig. 6b. Summary of radial stress path tests (Khan, 1999).

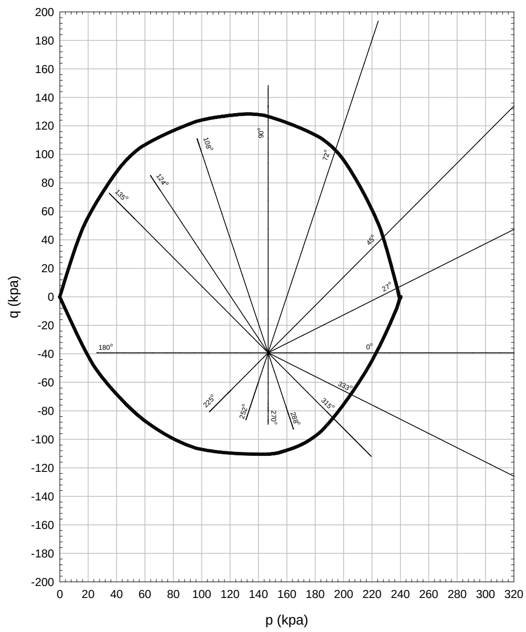

Fig. 6c. Summary of radial stress path tests (Lena, 2000)

3.2 Effective Stress Strength Parameters

The effective stress strength parameters were established for Bangkok clays especially in the upper clay layer to a depth of about 16m. These values from CIU tests at depths of 1, 1.5, 2.5, 3.9, 5.3, 5.4, 7.5, 9.3 and 11.5 m indicated zero cohesion in the normally consolidated state and φ' values of 20.2, 24.8, 21.9, 20.2, 21.4, 22.6, 21.4, 23 and 22.5 degrees. The corresponding values from CK_0U tests at depths of 3.8, 4.6, 5.3 and 8.1 m gave φ' values of 29.9, 27.8, 30.9 and 28.7 degrees. Also, the corresponding values of φ' from CID tests at depths of 3.2, 8.9, 15.2 and 16.4 m depths are 24.9, 22.4, 19.2 and 19.3 degrees respectively. In the overconsolidated range, the strength parameters are given in Table 1

Stability analysis performed on a sand embankment built to failure at 3.4 m height gave an effective stress analysis factor of safety in the range of 1.2 to 1.4 by the Bishop simplified method. The corresponding value with the effective stress analysis and using the Swedish simplified method ranged from 1.05 to 1.2.

4 SHEAR STRENGTH FROM VANE TESTS

Undrained shear strengths as obtained from field vane tests at the same site are also shown in Fig. 9. From these results it appeared that the undrained shear strength need to be modelled in five zones with depths ranging from 0.3 to 2m. 2 to 7 m, 7 to 11m, 11 to 13m and 13 to 15 m. A total stress analysis carried out on the 3.4m height sand embankment at failure using the vane strength gave a factor of safety of 1.4.

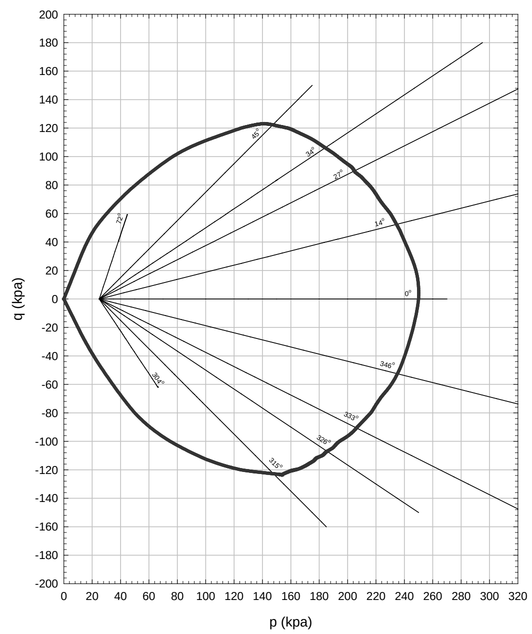

Fig. 6d. Summary of radial stress path tests (Amorndech, 2001)

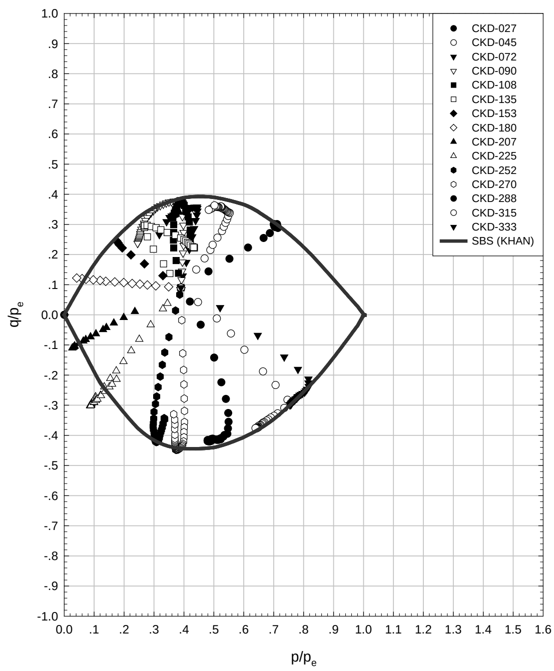

Fig. 7b. Normalized stress paths (Data from Khan, 1999).

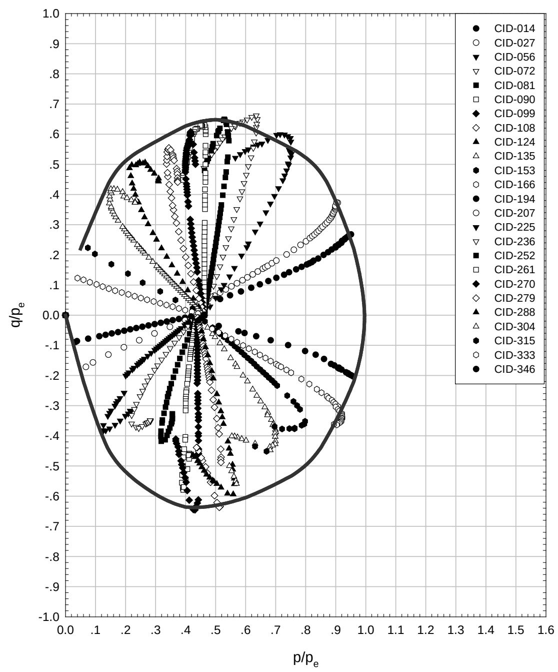

Fig. 7a. Normalized stress path of (Data from Anuchit, 1998 and Navaneethan, 1999).

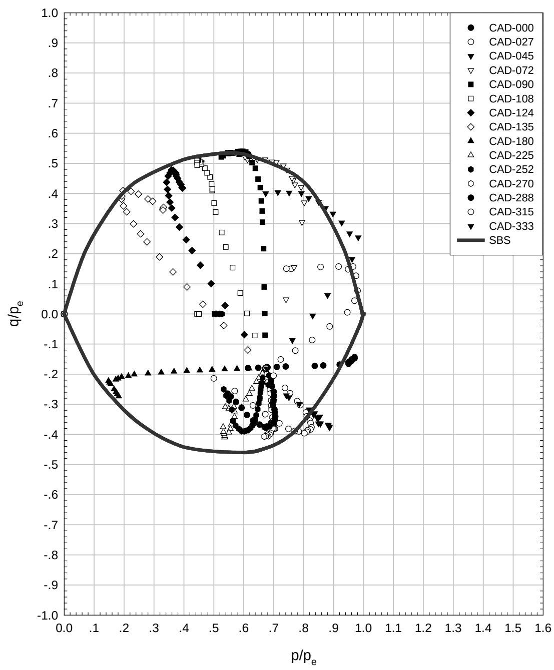

Fig. 7c. Normalized stress paths (Data from Lena, 2000).

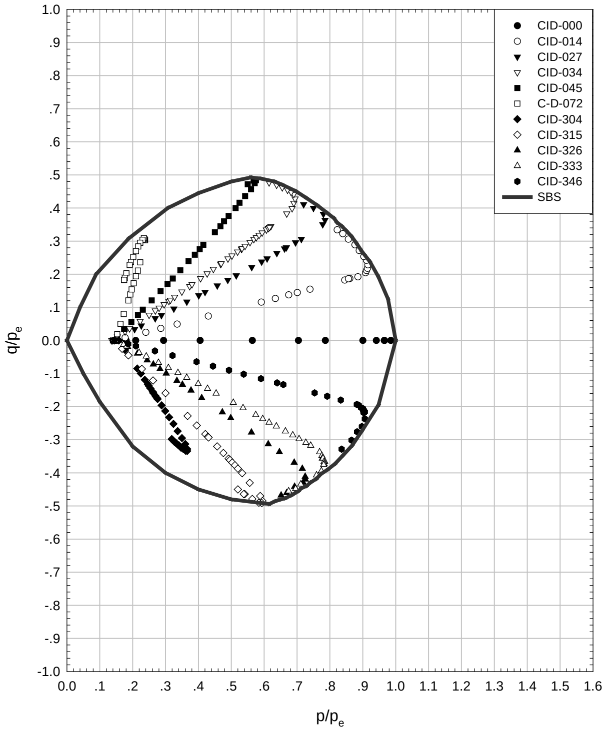

Fig. 7d. Normalized stress paths (Data from Amorndech, 2001).

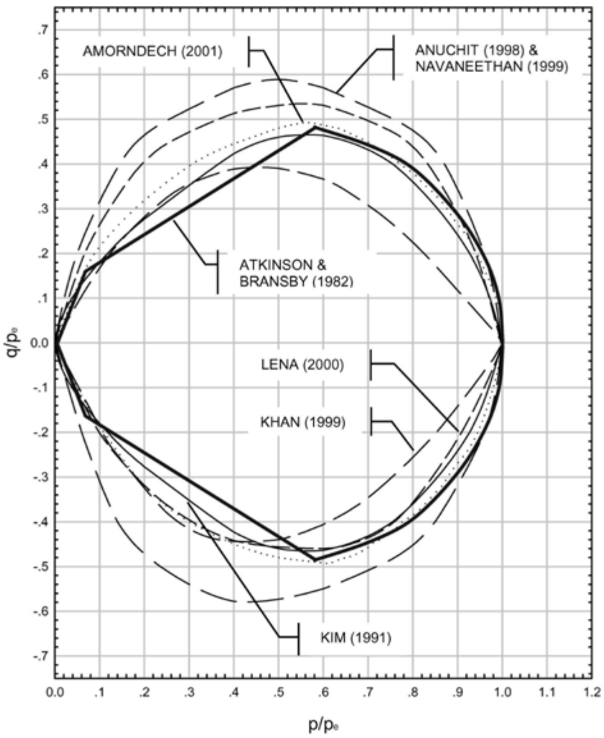

Fig. 8. Comparison of the SBS

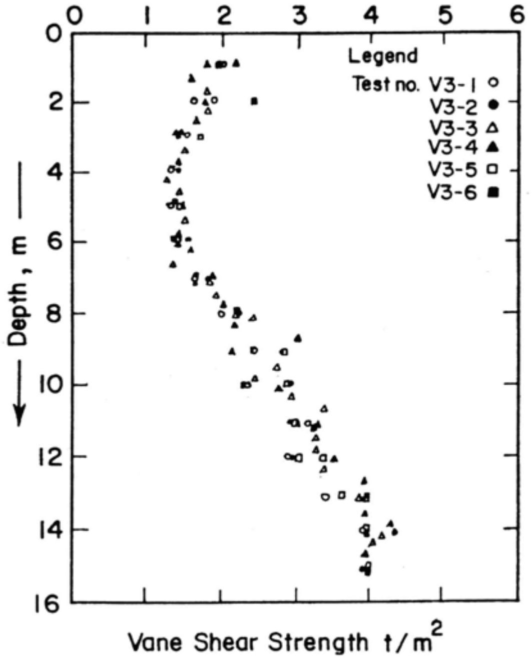

Fig. 9. Vane strength profile.

Table 1 Effective stress strength parameters in the overconsolidated region

Depth	Shear strength c' (kN/m^2)	φ' (deg)	Test conditions	Stress conditions
1.1-1.3	11.7	19.0	Strain controlled	CAU
	11.5	16.7	Stress controlled	Compression
	10.1	13.1	Strain controlled	CIU
	11.4	15.5	Stress controlled	Compression
	11.7	20.1	Strain controlled	CAU
	13.1	16.8	Stress controlled	Compression
	11.7	19.0	Strain controlled	CIU
	13.1	17.1	Stress controlled	Compression
2.5-3.0	8.8	15.3	Stress controlled	CAU Compression σ_3 decreasing
4.0-4.5	3.9	16.1	Strain controlled	CIU Compression
5.5-6.0	16.8	18.6	Strain controlled	CAU
	8.9	21.3	Stress controlled	Compression
	9.2	13.8	Stress controlled	CIU
	9.9	10.1	Stress controlled	Compression
7.0-7.5	13.3	16.6	Strain controlled	CAU Compression

5 CONCLUSIONS

Uncertainty still persists with the use of the traditional total stress analysis using vane strength and the effective stress analysis with cohesion and friction in stability analysis of embankments and excavations. In this paper a unified normalized strength envelope with friction component only is proposed as the failure characteristics of soft Bangkok clay. Initial finite element analysis carried out using such concept with the CRISP Program could predict the deformation characteristics of embankments built in Bangkok clay and in the Muar clay site in Malaysia. Further comprehensive analysis is proposed to use such an effective stress analysis with a unified and normalizable failure envelope.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

Amorndech , N. 2001. *Triaxial Tests With Selected Stress Paths On Soft Bangkok Clay From The Heavily Overconsolidated State*. MEng. Thesis, Asian Institute of Technology, Bangkok.

Anuchit, U. 1998. *Triaxial Tests on Soft Bangkok Clay with Different Applied stress Paths*. MEng. Thesis, Asian Institute of Technology, Bangkok.

Atkinson, J. H. & Bransby, P. L. 1982. T*he Mechanics of Soil – An Introduction to Critical State Soil Mechanics*, London, McGraw-Hill.

Khan, M. R. A. 1999. *Stress-Strain Behaviour of Soft Bangkok Clay below the Dtate Boundary Surface under Anisotropic Conditions*. MEng. Thesis, Asian Institute of Technology, Bangkok.

Kim, S. R. 1991. *Stress Strain Behaviour and Strength Characteristics of Lightly Overconsolidated Clays*. PhD Thesis, Asian Institute of Technology, Bangkok.

Lena, T., 2000. *Behavior of Soft Clay below the State Boundary Surface with Stress Paths from Extension to Compression*. MEng. Thesis, Asian Institute of Technology, Bangkok.

Navaneethan, T. 1999, *Extension Behavior of Soft Bangkok Clay with Selected Applied Stress Paths*. MEng. Thesis, Asian Institute of Technology, Bangkok.