

# Undrained Behavior of Lime Treated Soft Clays

*E. Y. N Oh, M. W. Bolton, A. S. Balasubramaniam*  
Griffith School of Engineering, Griffith University,  
Queensland 4222, Australia

*B. Buessucesco*  
Department of Civil Engineering, University of the Philippines,  
Diliman, 1101 Quezon City, Philippines

## ABSTRACT

Unconfined compression tests are normally carried out on lime treated soft clays with variation of the additive content and curing time. These studies were valuable in having a good understanding on the strength of the treated clays. In this paper, some works carried out under triaxial undrained consolidation conditions are presented and discussed within the frame work of state boundary surface and associated stress-strain behavior. The results clearly illustrate the effect of additive content and the curing time in the development of pore pressure and shear strain under undrained condition.

**KEY WORDS:** Soft clay, triaxial tests, lime, state boundary surface.

## INTRODUCTION

Chemical stabilization method has been used successfully for more than three decades to reduce settlements and to increase the stability of embankments and excavations (Broms and Boman, 1976; Holm and Ruin, 1999; Bergado *et al* 1999). Most of the fundamental studies related to the behavior of these columns were based on unconfined compression tests of additives treated soft clays.

The critical state concept (Roscoe *et al.*, 1963; Roscoe and Poorooshasb, 1963; Roscoe and Burland, 1968), originally proposed by the Cambridge group assumes that the behavior of normally consolidated clay is frictional in nature. With the use of lime additives, cementation bonds are developed depending on the additive content and the curing time. These bonds give a porous structure to the soft clay whereby, the voids ratio of the treated samples is found to be much looser than the states corresponding to the virgin condition of the untreated samples. In the earlier studies conducted, little attention was paid to the compressibility characteristics of the treated clays as studied in the Oedometer and triaxial conditions. wherein the  $(e, \log p)$  relations can be studied with a view to explain the treated behavior in terms of the apparent pre-consolidation pressure of the untreated samples and the quasi-pre-consolidation pressure as developed with lime and cement treatment. In this paper and in others the authors were trying to interpret the behavior of lime and cement treated soft clays somewhat similar to those of the heavily over-consolidated clays with very high quasi-pre-consolidation pressure thought to have developed

as a result of the cementation bonds formed by the treatment. It is therefore easy to present this idea by appealing to the  $(e, \log p)$  relationship.

The data presented in terms of the stress strain behavior (under undrained condition) is to illustrate the effect of the cementation bonds in demonstrating the progressive growth of the yield loci with increasing contents of the additive and thereby developing a rigid structure of the treated soil which is highly incompressible and shear resistant.

The second aspect emphasized in this paper is the dilatancy characteristic as represented by the quantity  $d\varepsilon_v/d\varepsilon_s$  as obtained from isotropic and anisotropic consolidation paths, which are radial in nature in the  $(q, p)$  plot. No attempt is made to estimate the plastic version of the dilatancy as defined by  $d\varepsilon_v^p/d\varepsilon_s^p$ , since this later quantity is of the same order as the dilatancy defined with respect to total strains, since the elastic volumetric strains are small and the elastic shear strains are neglected. For the purpose of the intended communication here, it was thought that such an approach is adequate. Also, the third aim of the paper is to study the pattern of strength increase with additive content and curing period as well as the strength degradation of the treated soil with shear strains larger than those corresponding to the peak deviator stress. This latter aspect is an important issue to be aware of in the design of lime piles as well as in jet grouting that there is substantial strength reduction with progressive shear strains beyond the peak value and the treated strength values can reduce to as low as the original untreated value corresponding to the critical state condition.

## TRIAXIAL CONSOLIDATION BEHAVIOUR

Soft clay when tested under triaxial consolidation at increasing stress ratio from 0 to 0.8 (close to the critical state), illustrate a zone with voids ratio-log mean normal stress as shown in Fig. 1. At any value of mean normal stress the incremental voids ratio between the isotropic consolidation and the critical state is about 0.6. With lime and cement treatment all these voids ratio-mean normal stress relations cluster together as a band and are curved, so that the lime treated samples undergo very little voids ratio change as they are sheared from the isotropic state to failure. Also, the  $\eta_{max}$  value at peak condition is much higher than the critical state, M value.

Another important point to note is how the  $(e, \log p)$  relations are very

similar to heavily over-consolidated clay and the slope changes from a value very small and similar to the swell index ( $C_s$ ) to the maximum compression index ( $C_c$ ) in the normally consolidated stress state. As such the lime treated clays show very little pore pressure development under undrained shear. The yield loci determined from the voids ratio pressure relations with additive contents are as shown in Fig. 2 and are convex in shape, similar to the volumetric yield loci for soils with an associated flow rule obeying the normality condition.

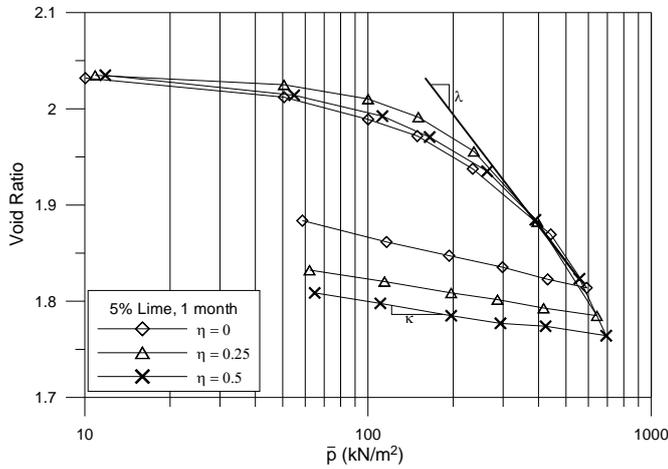


Fig. 1(a) ( $e$ - $\log p$ ) relationship during anisotropic consolidation tests (5% lime content, 1 month curing)

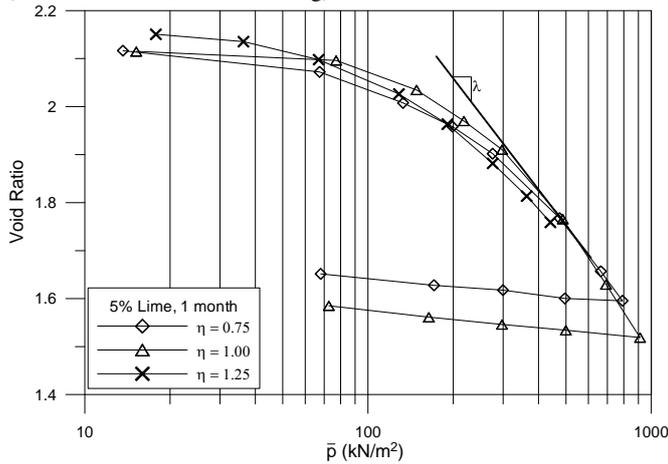


Fig. 1(b) ( $e$ - $\log p$ ) relationship during anisotropic consolidation tests (5% lime content, 1 month curing)

## EXPERIMENTAL PROGRAM

Table 1 summarizes the engineering properties of the untreated base clay. The strength and deformation characteristics of the base clay were investigated under triaxial compression conditions. The full experimental program included extensive tests on the index properties, unconfined compression tests, Oedometer tests and triaxial tests. In this paper, only results from the undrained triaxial tests will be presented. Fifteen series of undrained triaxial tests were performed, with test variables included the lime content, the curing time, and the pre-shear consolidation pressure. These tests are sub-divided into two groups. In Group 1, three series of anisotropic consolidation tests were conducted on the lime treated samples, in which the stress ratios were 0.0, 0.25,

0.5, 0.75, 1.0 and 1.25. Two lime contents of 5 and 10 % were employed for samples cured for one month; an additional series of tests was also carried out on samples with 5 % lime content but with two months curing. A total of eighteen consolidation tests were carried out. In Group 2, the undrained behaviour was investigated by carrying out six series of conventional triaxial compression tests on isotropically consolidated samples of lime treated clay, at one-month curing period. Initially, six lime contents were used ranging from 2.5 to 15 percent. The pre-shear consolidation pressures were 50, 100, 150, 200, 400 and 600 kN/m<sup>2</sup>. Based on initial observations, the range of lime contents was trimmed down to three (5, 7.5, and 10 %) for all further tests. One series of CIU tests was also carried out on undisturbed untreated clay specimens. A summary of the triaxial testing programme is presented in Table 2. A total of at least 108 lime treated samples was prepared for triaxial testing.

Table 1: Physical properties of base clay

Property	Values
Liquid limit (%)	103
Plastic limit (%)	43
Plasticity Index (%)	60
Water content (%)	76-84
Liquidity Index	0.62
Total Unit Weight (kN/m <sup>3</sup> )	14.3
Dry Unit Weight (kN/m <sup>3</sup> )	7.73
Initial Voids Ratio	2.2
Colour	Dark Grey
Activity	0.87
Sensitivity	7.3
Grain Size Distribution	
Clay (%)	69
Silt (%)	28
Sand (%)	3

Table 2 Summary of triaxial testing program on lime treated samples

Type of test	Curing time (months)	Lime content (%)	Number of tests	Pre-shear consolidation pressure (kN/m <sup>2</sup> )		
Isotropically Consolidated Undrained Compression (CIU) Test	1	2.5	6	50, 75, 100, 200, 400, 600		
		5	6			
		7.5	6			
		10	6			
		12.5	6			
	2	5	6			
		7.5	6			
		10	6			
	-	-	Untreated		3	100, 200, 400

## UNDRAINED TRIAXIAL SHEAR

The lime and cement treatment induces cementation bonds in the soft clay and makes the structure more rigid than untreated soft clay. These cementation bonds can be broken both by consolidation as well as by shear. These aspects can be visualized in the ( $q$ ,  $\epsilon_s$ ) and ( $u$ ,  $\epsilon_s$ ) relations during undrained shear and the stress paths with strength envelopes in the ( $q$ ,  $p$ ) plot. The increasing lime and cement contents make more and more bonds to develop and strengthen the effects of the bonds causing

less resistance to consolidation and shear. Increasing the additive content and increasing the curing time have the same effect of increasing the strength of the cementation bonds.

In Fig. 3, the  $(q, \epsilon_s)$  relationship is shown under undrained condition at the lowest pre-shear consolidation pressure of  $50 \text{ kN/m}^2$  with 5, 7.5, and 10 percent lime content and curing period prior to shear of 2 months. The lowest lime content gives mild peak and at the highest lime content the peak is well defined in the  $(q, \epsilon_s)$  plot. At large strains, strain softening behavior is noted and de-structurization of the bonds with shear takes place and the deviator stress at large strains seek the lower critical state values than the peak stress ratio reached before.. The  $(u, \epsilon_s)$  relationship for the undrained test is shown in Fig. 4. In Fig. 4, at high lime content, the sample tends to dilate at higher shear strains similar to heavily over-consolidated samples.

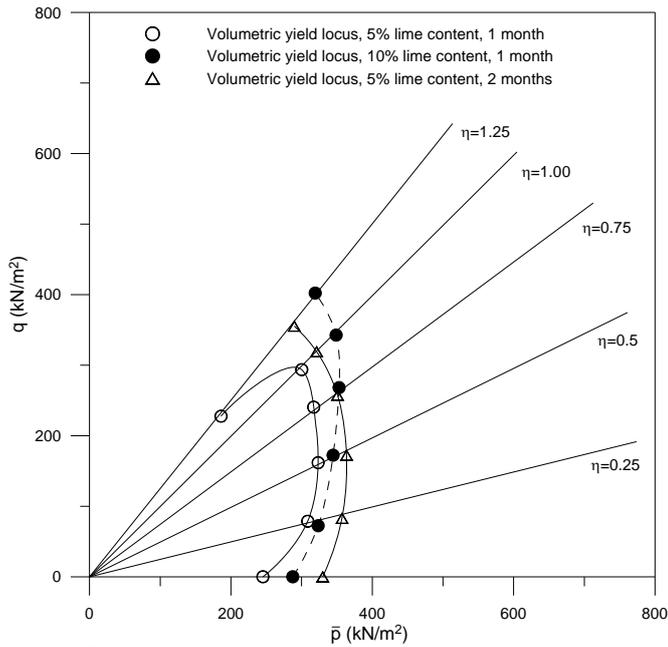


Fig. 2 Influence of lime content and curing time on yield locus

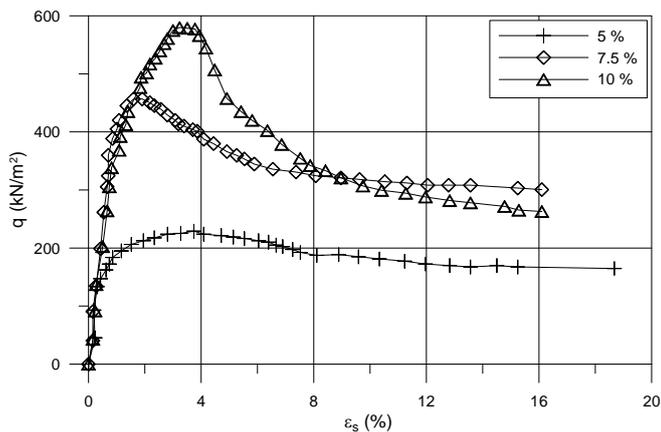


Fig.3  $(q-\epsilon_s)$  plot with various lime content from CIU tests ( $p_0 = 50 \text{ kN/m}^2$ , 2 months curing time)

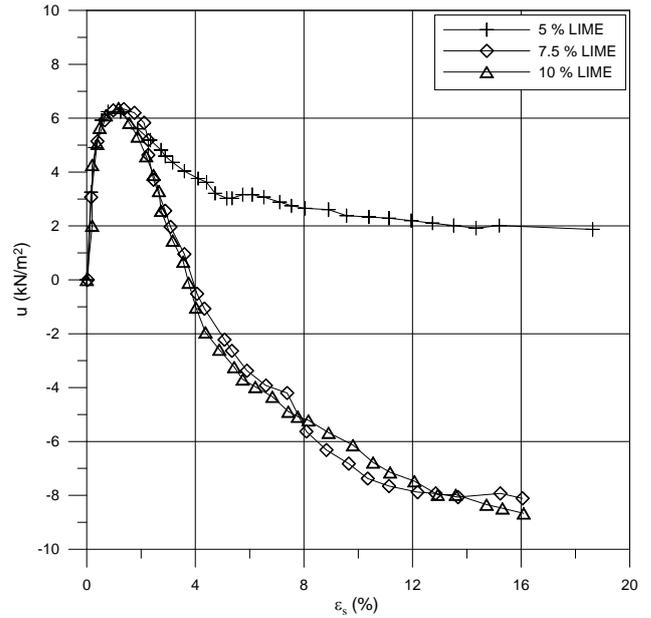


Fig. 4  $(u-\epsilon_s)$  plot with various lime content from CIU tests ( $p_0 = 50 \text{ kN/m}^2$ , 2 months curing time)

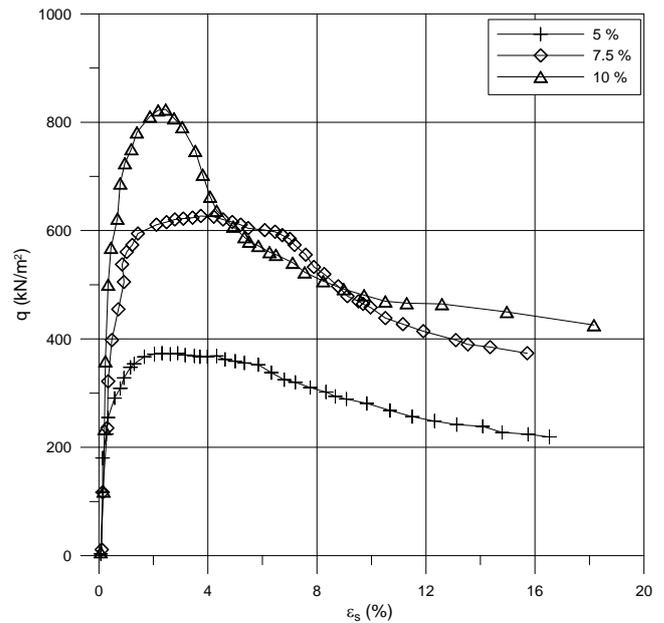


Fig. 5  $(q-\epsilon_s)$  plot with various lime content from CIU tests ( $p_0 = 400 \text{ kN/m}^2$ , 2 months curing time)

At high pre-shear consolidation pressure of  $400 \text{ kN/m}^2$ , the undrained behavior in  $(q, \epsilon_s)$  and  $(u, \epsilon_s)$  plots are shown in Figs. 4 and 5. Now the behavior in Figs. 6 and 7 illustrate the effect of the cementation bonds being reduced by consolidation to higher pre-shear consolidation pressure and the behavior is similar to lightly over-consolidated clays. The  $(\eta, \epsilon_s)$  relationships are shown in Fig. 7 for the undrained cases. It is seen that substantial strength reduction takes place with additional shear during the post peak conditions. It is important that this strength reduction be carefully modeled to understand better the jet grouted slab and lime and cement treated ground under large strain beyond the peak

conditions. The stress paths and the strength envelopes showing the seeking of critical state in the de-structured phase during large shear is shown in Figs. 8 to 10. A mechanistic picture for modeling purposes of the behavior is also shown in Figs. 11 and 12.

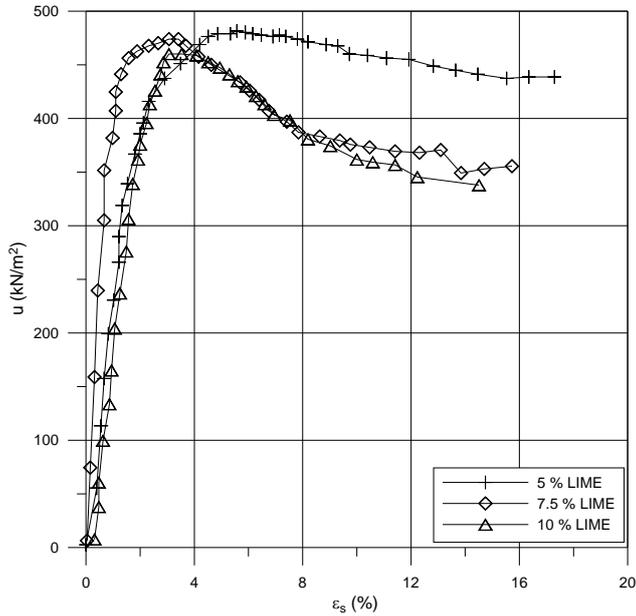


Fig. 6 ( $u - \epsilon_s$ ) plot with various lime content from CIU tests ( $\bar{p}_0 = 400 \text{ kN/m}^2$ , 2 months curing time)

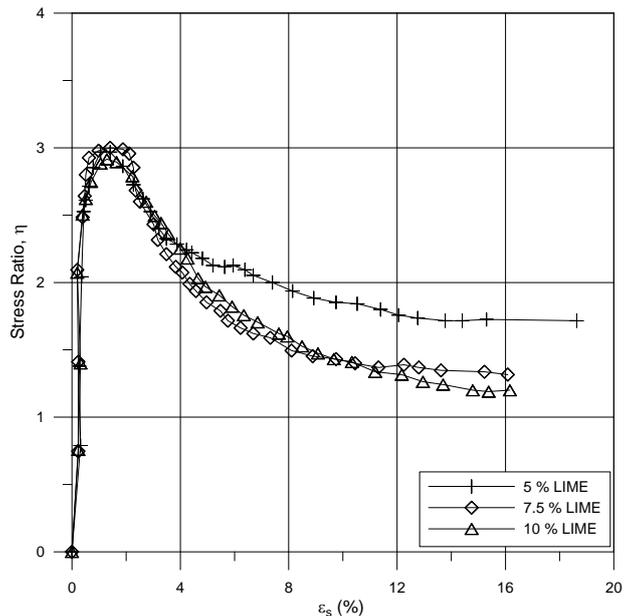


Fig. 7(a) ( $\eta - \epsilon_s$ ) plot with various lime content from CIU tests ( $\bar{p}_0 = 50 \text{ kN/m}^2$ , 2 months curing time)

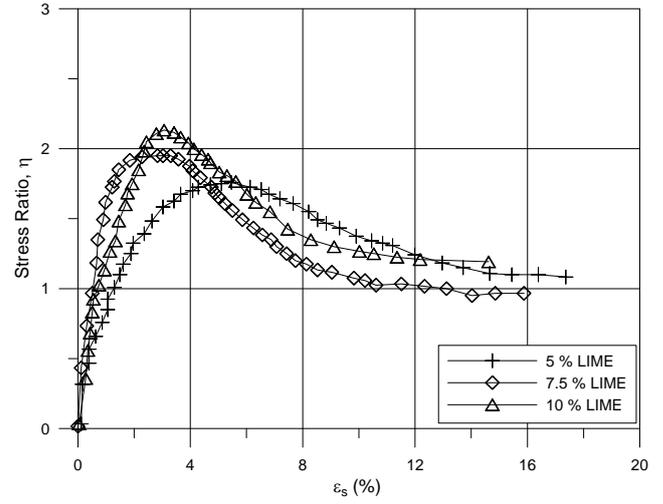


Fig. 7(b) ( $\eta - \epsilon_s$ ) plot with various lime content from CIU tests ( $\bar{p}_0 = 400 \text{ kN/m}^2$ , 2 months curing time)

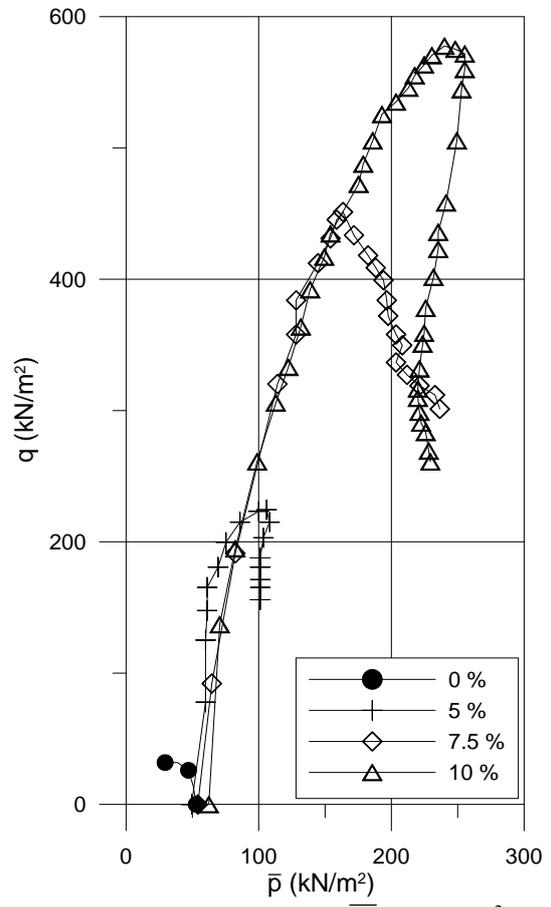


Fig. 8(a) Undrained stress paths ( $\bar{p}_0 = 50 \text{ kN/m}^2$ , 2 months curing time with different lime content)

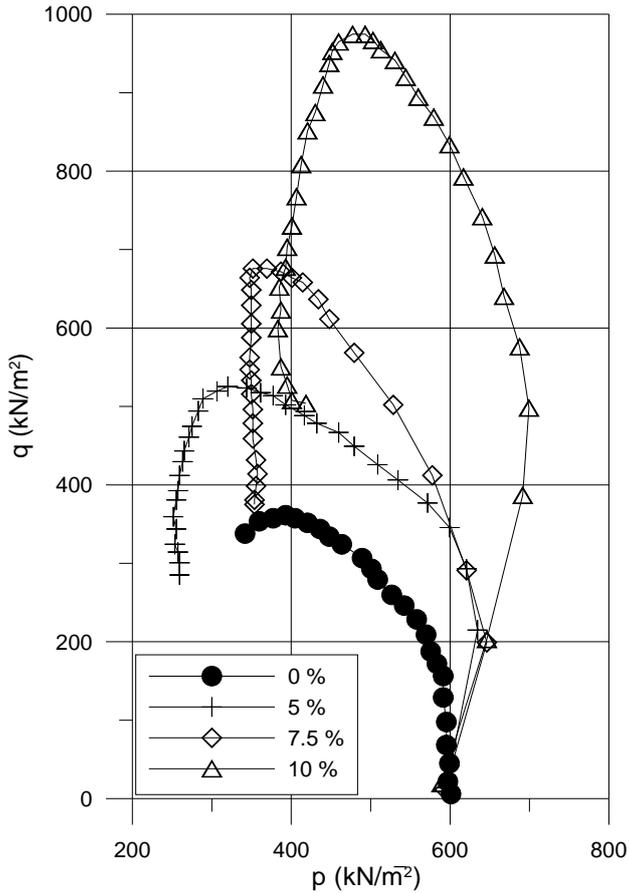


Fig. 8(b) Undrained stress paths ( $\bar{p}_0 = 600 \text{ kN/m}^2$ , 2 months curing time with different lime content)

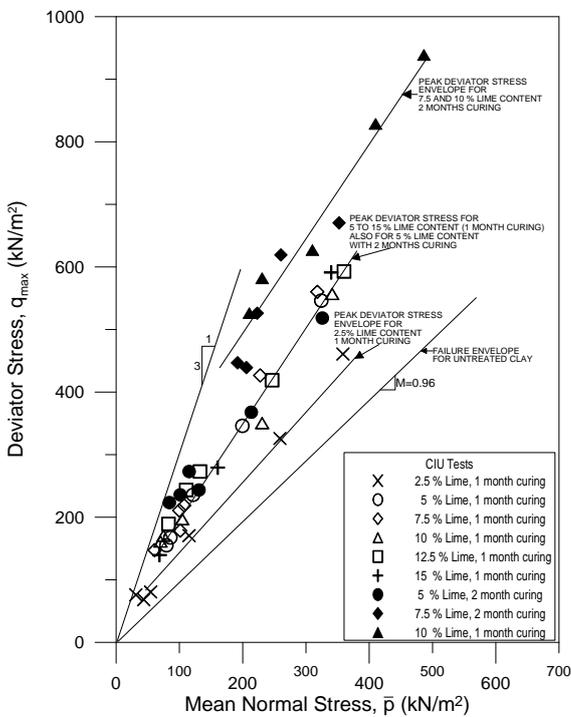


Fig. 9 Peak deviator stress envelope from CIU tests

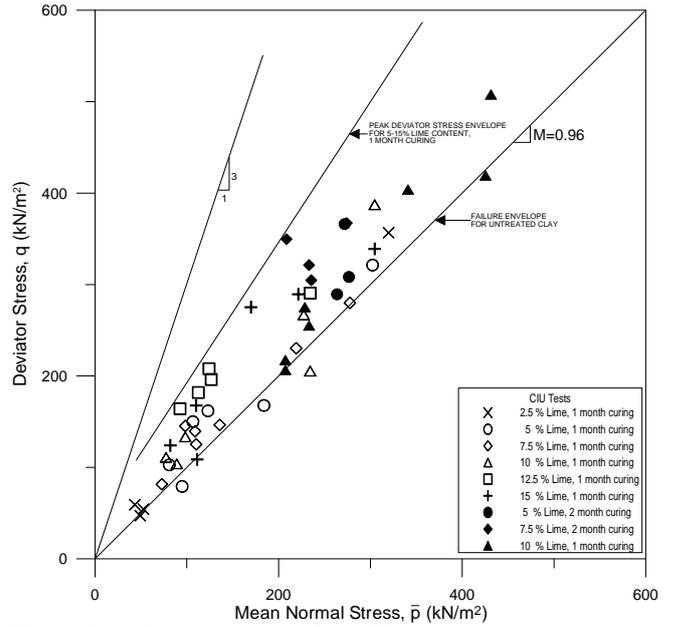


Fig. 10 End of test stress points from CIU tests

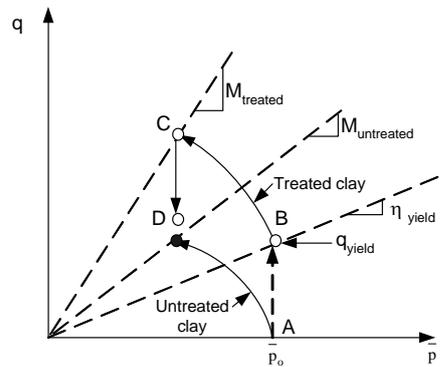


Fig. 11 Schematic diagram of undrained stress path for lime treated clay showing yield point

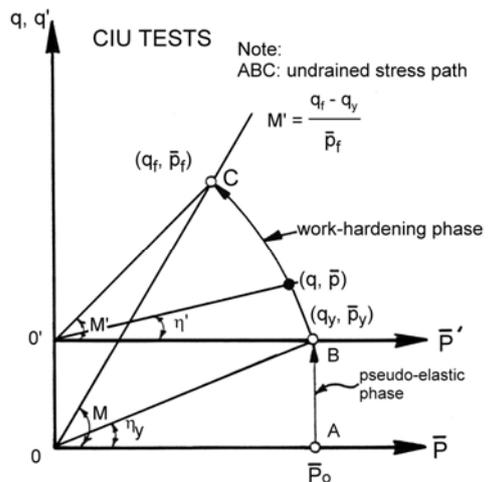


Fig. 12 Modification of axes for the application of the revised theory (CIU tests)

## CONCLUSIONS

The paper summarizes pioneering works carried out on lime treated clays in the triaxial apparatus under undrained consolidation conditions. All data are presented in the (p, q, e) plot, as traditionally used in the interpretation of triaxial data. The growth of the yield points during the undrained phase in the (q,  $\varepsilon_v$ ) and (u,  $\varepsilon_v$ ) plots with increasing additive content and curing time is clearly evident. The growth of yield points in the (q, p) plot is also presented. The development of strength with additive content and increasing curing time beyond the Critical State and as bounded by the tensile strength envelope as the upper limit and the Critical State as the lower limit is also evident. The breaking of cementation bonds with increase in mean normal stress and the deviator stress is also noted. The strength degradation from peak conditions to the Critical State with increasing shear strain is also demonstrated.

## ACKNOWLEDGEMENTS

The authors wish to thank their colleagues Prof. Dennes Bergado and Dr. Noppadol Phien-wej for many valuable discussions and assistance with the interpretation of the data as presented in this paper.

## REFERENCES

- Bergado, DT., Ruenkrirergsa, T., Taesiri, Y. and Balasubramaniam, AS. (1999). "Deep Soil Mixing Used to Reduce Embankment Settlement", *Ground Improvement*, Vol. 3, pp 145-162.
- Broms BB. and Boman P. (1977). *Stabilization of Soil with Lime Columns*. Royal Institute of Technology, Stockholm.
- Holm G. and Ruin, M. (1999). "Column penetration tests and extraction of lime/cement columns", *Proceedings of DMM for Deep Soil Stabilization*, Balkema, Rotterdam, pp 311-314.
- Roscoe, KH. and Burland, JB. (1968). "On the generalized stress-strain behavior of wet clay", *Engineering Plasticity*, Cambridge, pp 535-609.
- Roscoe, KH. and Poorooshasb, HB. (1963). "A theoretical and experimental study of strains in triaxial tests on normally consolidated clays", *Geotechnique*, Vol. 13(1), pp 12-38.
- Roscoe, KH, Schofield, AN. and Thurairajah, A. (1963). "Yielding of clays in state wetter than critical", *Geotechnique*, Vol 13(3), pp 211-240.