Effective Stress Method on Threshold Stress of Clay under High Rate Cyclic Loading

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ABSTRACT: This paper discussed the undrained triaxial testing of soft clay which may be encountered as subgrade soil in the alignment of railway track or road pavement. Several series of both static and cyclic undrained triaxial test were conducted. The static undrained triaxial test provides a prior indication on the maximum stress level from which the cyclic stress level can be apportioned. The cyclic undrained triaxial test simulates the behaviour of clay subgrade under the passing train axle's loading. The analysis of test results showed the feasible use of "effective stress" analysis in establishing threshold stress for clay under high cyclic loading rate. The study reaffirmed the influence of stress history on the level of threshold stress. In particular, cyclic stress ratio (CSR) of threshold stress was found reducing with higher over-consolidation ratio. The threshold stress so obtained represents the lower-bound bearing strength for unsaturated clay subgrade of railway track.

KEYWORDS: Cyclic Loading; Triaxial; Clay; Threshold Stress; subgrade

1 INTRODUCTION

In planning the railway line, crossing area of soft formation soil for straight line alignment may become necessary either for cost efficiency or shorter travelling time. A better understanding of clay subgrade response under cyclic loading caused by the passing wheels will enable engineers to design for stable track foundation with less frequent track repairs and re-alignment. Traditional railway foundation or substructure consists of a layer of ballast and sub-ballast overlaying a subgrade or natural formation. With the passing of train axles/wheels, subgrade soil beneath railway tracks experiences stress of cyclic nature that can result in progressive shear failure at a stress level lower than its monotonic strength. British researcher (Heath et al. 1972; Waters 1968) has long established the existence of "threshold stress" in clay subgrade. When the track subgrade will to be stressed below the threshold stress level, stabilization of the track vertical alignment can be achieved.

Under undrained cyclic compression, clay specimen with cyclic deviator stress less than its monotonic deviator strength can build up its full excess pore water pressure within hours and led to ultimate failure with large strain. In the real case, clay subgrade though normally exists in unsaturated state can become highly saturated in wet season. The dissipation of the excess pore water pressure built up in the subgrade will likely to be a slow process due to its thickness with longer drainage path. Therefore, an assumption of using an "undrained" testing can be justified. The employment of the undrained triaxial tests on a saturated soil specimen in test simulation and the determination of threshold stress will produce a "lower-bound" solution for subgrade bearing strength in the design of railway track foundation with an unsaturated subgrade.

Previous research and studies have produced various methods of establishing the threshold stress for clay (Frost 2004; Heath et al. 1972; Procter 1984; Sangrey 1969; Sangrey 1978; Shahu 2008; Waters 1968; Yudhbir and Shahu 1995). They are generally being seen as either "total stress" (Heath et al. 1972; Lefebvre 1986; Procter 1984; Shahu 2008; Waters 1968) or "effective stress" (Sangrey 1969; Shahu 2008) method. Use of "effective stress" analysis can provide a more fundamental understanding of the soil behaviour under cyclic loading. But for high rate cyclic loading on clay, "effective stress" analysis was uncommon largely due to concern over the slow process required for equalization of excess pore water pressure within the clay specimen (Sangrey et al. 1978). Notwithstanding this, "effective stress" analysis will be appropriate if the equilibrium state of stress, rather than the transient state of presiding loading cycles, is of prime interest. In this paper, the feasibility of "effective stress" analysis in determining the “threshold stress” using critical state soil mechanics framework will be demonstrated, with particular highlight into the effect of the stress history on the “threshold stress”.

2 TESTING PROGRAM

2.1 *Soil Used*

The soil used in the investigation was fully saturated soft kaolinite clay. It was reconstituted by one-dimensional consolidation of the slurry prepared by mixing dried commercial grade kaolinite power with distilled water. Tube samples of 35 mm diameter were extracted from the consolidated clay. The final prepared specimen size was 35 mm in diameter and 70 mm in height. The index properties of the clay are given as follows: Specific gravity of soil, G_s = 2.65; Plastic limit of soil, w_P = 26 %; Liquid limit of soil, w_L = 53 %; Coefficient of Consolidation, C_v = 2.41mm^2/min (at $\sigma_3^{'}$ = 300 kPa)

2.2 *Apparatus*

The cyclic triaxial testing System consists of a triaxial cell, a load frame with computer-control platen, two computer-control flow pumps to control chamber pressure and back pressure, a high performance linear servo control electro actuator for cyclic loading with update rates of 500 times per second, a microprocessor for controlling cyclic loading, a PC with a Pentium processor to control the test, and to log test data. The cyclic axial load is applied at the top of specimen by the loading piston. Various transducers are mounted in the system for measuring the axial load, confining pressure, pore water pressure and axial strain.

2.3 *Testing Procedure*

Four series of test were conducted that represent a wide range of stress history. There are isotopic normally consolidated (NC) series and isotropic over-consolidated (OC) series which have the over-consolidation ratio of 1.5, 4 and 20.

All specimens were consolidated using a back pressure of 200 kPa. The back pressure at this level is sufficiently high to achieve full degree of saturation. Over-consolidated specimens were prepared by prior consolidation of specimen, and subsequently allow it to swell under a lower isotropic consolidation pressure. In each consolidation (or swelling) stage, the all-round pressure was maintained for a period equal three times the duration required for 100% primary consolidation, t_{100}.

Static axial compression tests were conducted at a control rate of deformation between 0.0035 – 0.015 %/min. The range of axial strain rate was deemed slow enough to ensure adequate equalization of excess pore water pressure within the specimen before reaches its peak strength (Head 1986).

In each cyclic undrained compression test, a specimen was subjected to cyclical undrained compression by the continuous application of cyclic deviator stress σ_d of sinusoidal shape. The cyclic loading was continued until the specimen either failed with large deformation, or a state of stress equilibrium was achieved in which the stress path followed closed hysteresis loops and axial deformation stabilized. In each series, cyclic tests of varying cyclic stress ratio (CSR) were carried out in order to establish a trend line which represents state of stress equilibrium in the *p'*- *q* plot. The tests were conducted at a cyclic loading frequency of 1Hz simulating the passing axles of a train travelling at a speed of 50 km/hour, with pore water pressures measured at the top and bottom of the specimen. With cyclic loading frequency at this rate, though equalization of pore water pressure within specimen will not take place in each loading cycle, the pore water pressure would have become equalized after the arrival of the state of stress equilibrium.

3 DEFINITION, TEST RESULTS AND ANALYSIS

The triaxial testing provides an axis-symmetric stress condition applied on a cylindrical specimen ($\sigma_2^{'} = \sigma_3^{'}$), with σ_{dev}= deviator stress and axial stress $\sigma_1^{'} = \sigma_3^{'} + \sigma_{dev}$, the general stress invariants and the terminology used are:

Mean effective stress, $p^{'} = \frac{1}{3}\left(\sigma_1^{'} + 2\sigma_3^{'}\right)$ (1)

Axial deviator stress, $q = \sigma_{dev} = \sigma_1^{'} - \sigma_3^{'}$ (2)

Cyclic stress ratio, CSR = $\dfrac{\left(\sigma_{dev}\right)_{cyclic}}{\left(\sigma_{dev}\right)_{static-\max.}}$ (3)

3.1 *Isotropic Normally Consolidated (NC) Series*

In this series, all test specimens were given an isotropic consolidation of 300 kPa. Static undrained compression test was first performed to determine the maximum stress level. Figure 1 shows the peak deviator stress of 140 kPa was attained at 15% axial strain.

The cyclic undrained compression tests were subjected to a cyclic deviator stress, which was the various proportion of 140 kPa obtained from the static undrained compression test. The result of the test with a cyclic deviator stress of 50 kPa (CSR = 0.36) is shown in Figure 2. Figure 2(a) shows the maximum excess pore water pressure corresponding to the peak deviator stress of each loading cycle. The excess pore water pressure was building up at a reducing rate until it reaches a plateau at about 100,000 cycles. The total axial strain (which include both the plastic and the elastic axial strain) was also increasing with the loading cycles as shown in Figure 2(b), but began to show sign of stabilization after 60,000 cycles.

Presented in *p'-q* plane, Figure 2(c) shows the stress path of the 1st, 1000th, 10,000th, 100,000th and 150,000th cycle. Due to the increasing pore water pressure, the stress path of each cycle gradually migrated to the left and began to form hysteresis loop at about 100,000th cycle. By this time, the total axial strain of the specimen had also achieved strain stabilization as shown in Figure 2(b). A state of resiliency has arrived in which both the state of stress equilibrium and the strain stabilization exist. The term "Peak stress path" is introduced here which represents the state of stress in each cycle when the deviator stress is at the maximum. In this test, the peak stress path of the cyclic undrained compression has arrived at a state of stress equilibrium.

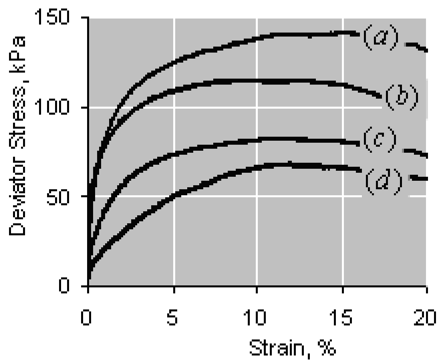

Figure 1 Results of static undrained test: (a) consolidation = 300kPa, OCR =1; (b) consolidation = 200 kPa, OCR = 1.5; (c) consolidation = 75 kPa, OCR = 4; and (d) consolidation = 30 kPa, OCR = 20 (kaolinite clay).

The results of tests in the NC series, for which the cyclic deviator stress of various CSR were applied, are presented here. Figure 3 shows the generation of excess pore water pressure, and Figure 4 presents the progressive built-up of the total axial strain with each cycle of loading application. In Figure 5 an overall view of all the peak stress paths of the various cyclic tests were shown. The stagnation of peak stress path occurred between 100,000 and 150,000 cycles indicated that all of the tests reached the state of stress equilibrium, except that the peak stress path for test (with CSR = 0.71), moved towards and reached the critical state line CSL, causing ultimate compression failure as specimen failed with high axial strain.

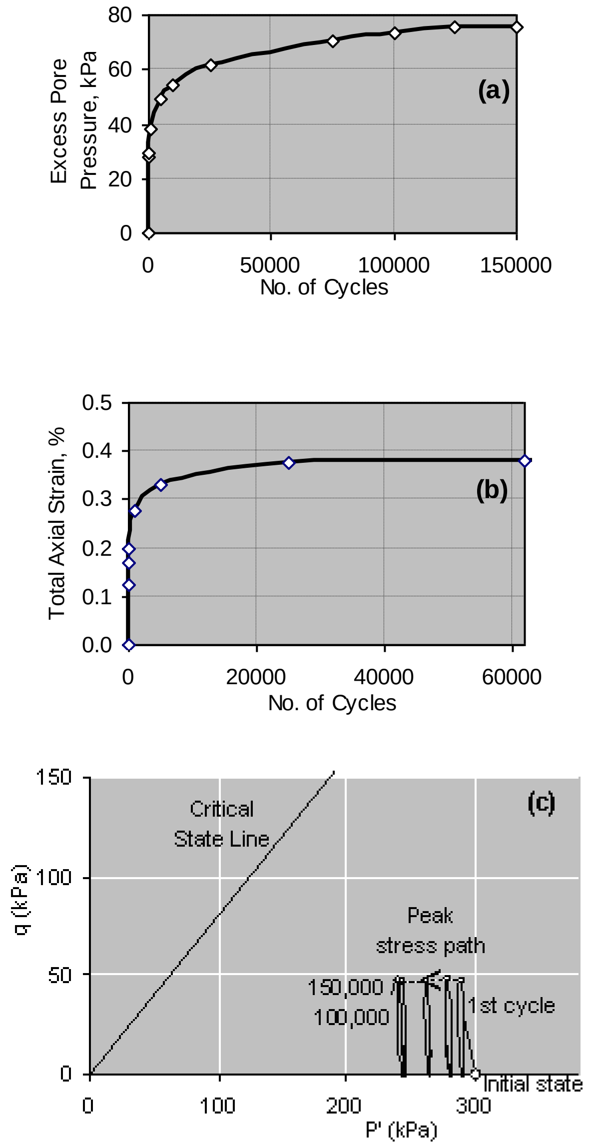

Figure 2 Results of cyclic undrained compression test on kaolinite clay that led to a resilient state (normally consolidated at 300 kPa, with cyclic deviator stress = 50 kPa, CSR=0.36)

Of interest in this study is the identification of the maximum deviator stress ("threshold stress") amongst all possible state of stress equilibrium that can be achieved. By examined the locus at the end of the peak stress path which represents a state of stress equilibrium, these locus can be connected together to form a line. (Refer here as the line of cyclic stress equilibrium state, LCSES). The LCSES can be extrapolated to intercept the critical state line (CSL) at a point "Ts "(see Figure 5) at which the deviator stress is the threshold stress of the kaolinite clay that had been normally consolidated to 300 kPa.

The kaolinite clay tested in this series revealed that under an isotropic normally-consolidation pressure of 300kPa, the achievable maximum cyclic deviator stress (threshold stress) was 89 kPa. With the static deviator strength of 140 kPa, the cyclicl stress ratio (CSR) of the "threshold stress" is 0.64.

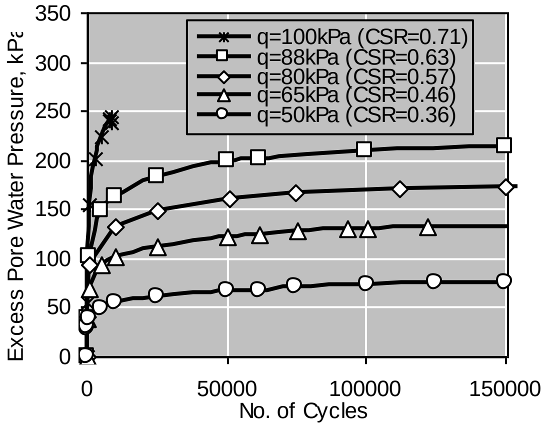

Figure 3 Generation of excess pore water pressure correspond to the peak stress of each cycle.

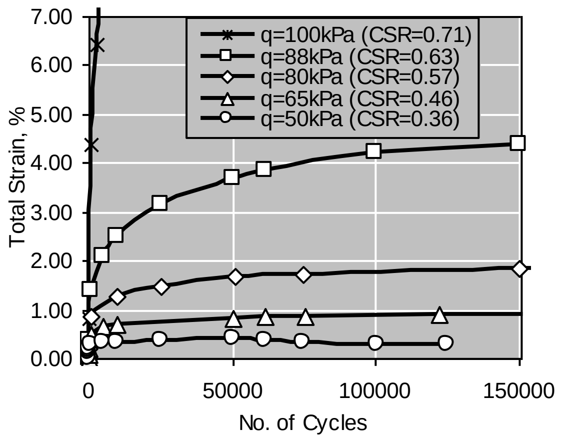

Figure 4 Progressive built-up of total axial strain for the normally consolidated series.

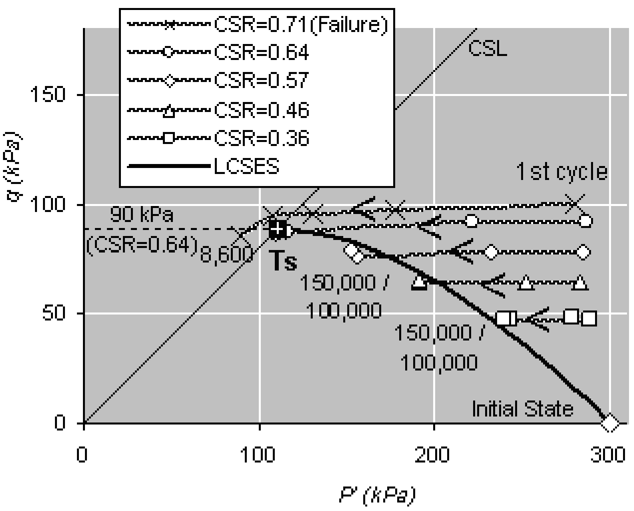

Figure 5 The locus of stationary ends of peak stress paths connected to form line of cyclic stress equilibrium state. (Normal-consolidated NC series)

3.2 *Isotropic Over-consolidated Series*

Similar tests were conducted for the three over-consolidated series. Results of the static compression tests showing deviator stress (*q*) verses axial strain were shown in Figure 1.

In OC1.5 series, generally, a state of stress equilibrium was reached for all cyclic deviator stress smaller than its "threshold stress". At the same time, an increase of the axial strain at a decreasing rate with each application of cyclic loading was observed. For the OC4 and OC20 series, however, an inherent state of stress equilibrium exists from the 1st cycle of the loading test as stress path hysteresis loop appeared (as shown in a typical test in Figure 6), while the axial strain of the specimen was developing until it reaches a plateau at a relatively early stage of cyclic loading. This occurred for all tests with its cyclic deviator stress smaller than its threshold stress in these two series and also in the OC1.5 series with a low cyclic stress (CSR = 0.35).

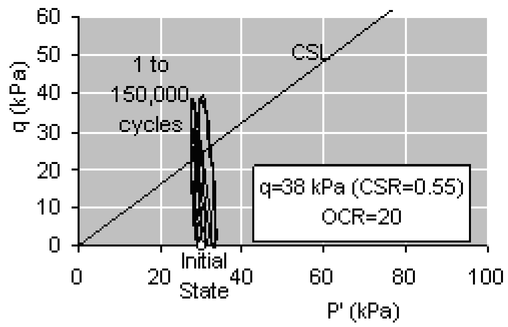

Figure 6 Cyclic stress path formed hysteresis loop

The *p'*- *q* plot showing the line of cyclic stress equilibrium state (LCSES) for each series is shown in Figure 7. Similar to the normal-consolidated soil, it was clear that the LCSES of OC1.5series intercepted the CSL at which the deviators stress (*q*) equal threshold stress. It was not quite the case for OC4 series and for the heavily consolidated OC20 series in particular, when the LCSES went beyond CSL. In these two over-consolidated series, cyclic stress higher than its threshold stress showed no sign of pore water pressure build-up, but failed ultimately with large strain. Consequently, the threshold stress for these two series can only be established using strain stabilization criteria, to identify the maximum cyclic deviator stress that will lead to a stabilized strain. This will involve conducting additional tests at levels between the previously highest cyclic deviator stress which achieved strain stabilization and the lowest cyclic deviator stress which had failed with high deformation.

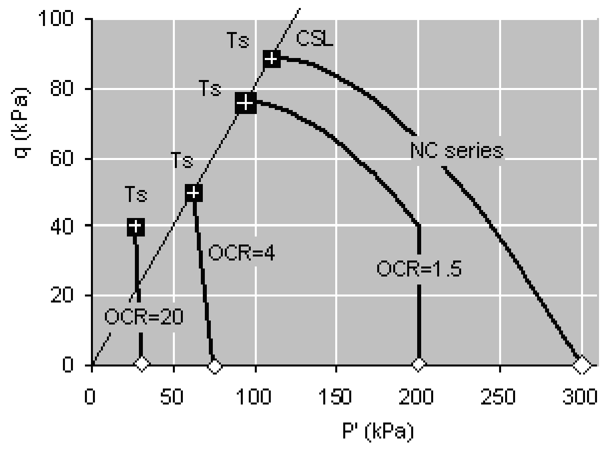

Figure 7 The line of cyclic stress equilibrium state (LCSES) for various consolidation state (kaolinite clay)

From the test results described above, it is apparent that the level of "threshold stress" is dependant of current state of stress and the stress history, i.e. its over-consolidation ratio. In terms of the ratio of threshold stress to its maximum static deviator strength, the CSR of the "threshold stress" for OC1.5, OC4 and OC20 series were worked out to be 0.65, 0.61 and 0.58 respectively. The heavily consolidated soil appeared to have a lower CSR for its threshold stress.

4 CONCLUSION

The undrained triaxial compression of soft clay described in this paper showed that the use of "effective stress" method in the analysis of cyclic compression test with fast loading rate is appropriate if the interest is on analyzing the stress-strain behavior of clay at the state of stress equilibrium, rather than the transient state of stress prior to stress equilibrium.

A focus on the cyclic peak stress path on a *p'*- *q* plot to detect the state of stress equilibrium was described in the above analysis as it represents the most vulnerable and critical stress state in the cyclic stress path of undrained cyclic compression. For normal-consolidated clay, the arrival of stress equilibrium state implies a state of resiliency in stress / strain behaviour. The level of deviator stress at the intercept of the line of cyclic stress equilibrium state (LCSES) and the critical stress line (CSL) indicates the threshold stress. In the case of over-consolidated clay, a state of cyclic stress equilibrium does not imply the arrival of a state of resiliency, except when strain becomes stabilized. For this reason, the detection of threshold stress for heavily over-consolidated soil will be, for practical purpose, directly detectable using strain stabilization criteria (total stress analysis).

The level of threshold stress is influenced by current state of stress and stress history of clay. It was observed that the threshold stress of heavily over-consolidated clay has a lower cyclic stress ratio compared with the lightly over-consolidated and the normally consolidated clay.

The determination of "threshold stress" described in this paper represents a "lower bound" threshold stress for the design of unsaturated clay subgrade foundation for railway tracks.

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