International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:6, No:8, 2012

Threshold Stress of the Soil Subgrade Evaluation for Highway Formations

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***Abstract*—**The objective of this study is to evaluate the threshold stress of the clay with sand subgrade soil. Threshold stress can be defined as the stress level above which cyclic loading leads to excessive deformation and eventual failure. The thickness determination of highways formations using the threshold stress approach is a more realistic assessment of the soil behaviour because it is subjected to repeated loadings from moving vehicles. Threshold stress can be evaluated by plastic strain criterion, which is based on the accumulated *plastic strain* behaviour during cyclic loadings [1]. Several conditions of the all-round pressure the subgrade soil namely, zero confinement, low all-round pressure and high all-round pressure are investigated. The threshold stresses of various soil conditions are determined. Threshold stress of the soil are 60%, 31% and 38.6% for unconfined partially saturated sample, low effective stress saturated sample, high effective stress saturated sample respectively.

***Keywords*—**threshold stress, cyclic loading, pore water pressure.

I. Introduction

DESIGNING a more stable highway formation is needed to facilitate increased efficiency in ensuring a longer life with low maintenance costs, and smooth running for heavier and faster vehicles.

Design of highway formations thickness can be determined by several methods that are available [2]. The commonly used design methods are AASHTO (American Association of State Highway and Transportations Officials) method and Asphalt Institute method in the United States, and *Arahan Teknik-Jabatan Kerja Raya (JKR)* manual for pavement design in Malaysia. Highway construction is divided into two types, namely, flexible pavement and rigid pavement. A flexible pavement construction consists of several layers, that is, the surface, base, sub-base and subgrade as the natural soil, formed from top to bottom, respectively. Rigid Pavement consists of surface and sub-base on top of the subgrade. Subgrade soil, the lowest layer, provide a foundation for supporting all the overlying pavement layers which is considered as one of the most critical design factor in achieving excellent performance in any pavement construction. The need to develop a better highway design and construction methods for the asphalt pavement layer is needed beside the current available method of pavement design. Threshold stress approach can be used as an alternative design method for the highway formation design.

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II. Literature Review

A. Threshold Stress Definition

Larew and Leonard studied the threshold stress of soil based on the total stress cyclic tests [3]. Threshold stress can be defined as the stress level above which the cyclic loading caused rapid permanent deformation [4] and the increasing pore water pressure build up leading to failure below the static failure value [1].

Threshold stress of the soil can be defined as a deviator stress equivalent to 50% of the soils' measured for design purposes [5]. The threshold stress definition based on the concept by ORE [6] investigation and carried out the threshold stress studies based on this concept. Threshold stress of the subgrade soil is maximum deviator stress that can be applied to the sample that does not cause cumulative strain greater than 10 percent in 1000 cycles. Moreover, for alternative approach, threshold stress can also be recognized as a deviator stress value at 1% permanent strain in the sample [7].

B. Cyclic Stress Ratio

The cyclic stress ratio (R_f) is defined for purposes of analyzing threshold stress of the soil results. The cyclic stress ratio is the cyclic stress level over the ultimate failure stress level. Cyclic stress level is the stress level imposed during cyclic loadings, while failure stress is the stress level at which the sample failed.

The cyclic stresses caused by stress pulses transmitted by moving vehicles, creates vertical stress which can be approximated by haversine or triangular functions [8].

Threshold stress was introduced in cyclic characterisation of sand by Dobry *et al.*[9], is later termed as volumetric threshold cyclic shear strain, γ_{tv} [10]. In addition, cyclic strength defined as the number of cycles at a given cyclic stress ratio, to generate a double-strain amplitude, ε_{DA} of 5% [3].

The Unconfined Compressive strength test is defined the cyclic stress ratio, R_f [10], as a percentage as:

$$R_f = \left(\frac{q_r}{q_u}\right) x\ 100\% \qquad (1)$$

Where, q_r = the cyclic deviator stress
q_u = the unconfined compressive strength.

Knowing q_u from the Unconfined Compression test on a similar sample, q_r may be obtained for the required R_f value using Equation (1).

The threshold stress is defined as the deviatoric stress level at which the rate of accumulation of deformation increased exponentially [12]. The properties of the material which affect the level of the threshold stress are its stress history, water content, and therefore, shear strength.

Furthermore, the cyclic stress ratio is also studied by using of cyclic stress ratio developed [13, 14, 15]. They defined cyclic stress ratio as the ratio between cyclic deviator stresses, q_{cyclic}, to the static deviator stress at failure, $q_{failure}$, depicted as follows:

$$\text{Cyclic stress ratio} = q_{cyclic} / q_{failure} \quad (2)$$

Where, q_{cyclic} = cyclic deviator stress
$q_{failure}$ = static deviator stress at failure

C. Threshold stress evaluation

Plastic strain or permanent strain may have much greater role in the life and performance of flexible pavements than designer currently recognizes [16]. It can also be used to model the response of the soil. When the soil is being loaded by vehicles traversing along the road in a cyclic loading, there will be a certain deformation occurred on the sample formations.

Based on the accumulated *plastic strain* behaviour during cyclic loadings in the triaxial test of subgrade *soils*, the equation for railway track can be developed [6]. ORE developed the equation for undisturbed samples of London Clays for the drained cyclic loading test, as seen in Equation (3).

$$\text{Log}(\varepsilon_p) = 1.39\,\varepsilon_e - 1.74 + 0.622 \log N \quad (3)$$

Where, ε_e = average elastic strain (%)
N = number of cyclic loadings

Thus, the real condition governing the performance of the railway track is the cumulative deformation which is indicated in terms of plastic strain [6, 17, 18]. ORE [6] recommended the $\varepsilon_p < 10\%$ in 1000 cycles, while Shahu [10] recommended the $\varepsilon_p < 10\%$ in 100 cycles as a failure criterion in the laboratory tests.

Shahu *et al.* [1] determined the cyclic stress ratio, R_f, which is defined as the ratio at which a sudden increase in incremental plastic strain occurred due to cyclic loadings after some cycles. The data is plotted in terms of incremental values of the plastic strain in relation to R_f for the different confining stress values. Thus, based on studies related to the development of plastic strain, the relationship between cumulative plastic strain and cyclic stress ratio is evaluated. Changes in plastic strain generation on cyclic loadings and stiffness of the soil are relevant to highway and runway pavement formations [11].

Threshold stress is a point beyond which plastic strain occurs if the application of cyclic loads on the soil is continued. The cyclic triaxial and simple shear tests are used to obtain the values of the cyclic yield stress and threshold stresses [19].

III. METHODOLOGY

A. Material and Properties

Soils are local soil as subgrade soil used to determine its threshold stress which can subsequently be used for thickness design formation.

The highway formation is laid either in filling or cutting area. When the formation is laid in filling, it is compacted and the pavement layers are constructed over it, but when the formation is laid in cutting, the compaction of the formation may not be needed. To develop the methodology of testing, both proper control and sample reproducibility are needed. Due to the difficulties to obtain reproducible samples, tests are performed on compacted samples. The compaction control has been specified in term of maximum dry density achieved using Modified Proctor Compaction.

B. Test Performed

Triaxial tests were carried out using Geotechnical Digital System (GDS) Triaxial Instruments, GDSLab V2, 2005 manual is for both static and cyclic triaxial tests. The maximum frequency of cyclic loading is 1 cycle per minute. All tests are performed in such a way that maximum pressure capacity of GDS system (1700 kPa) should not be exceeded.

Sample is tested for 100 cycles in the cyclic test. The sample can be cyclic from 4 up to 10,000 cycles for pore pressure measurement [4, 18], where the first-cycle of deformation dominates the magnitude of plastic strain [20].

Threshold stress of subgrade soil can be determine based on soil condition, namely, at zero confinement, low confining pressure and high confining pressure. The tests conducted are as follows,

C. Unconfined Compression Test

Unconfined Compression test (UCT) in this study consists of two steps during loading. Firstly the soil subgrade is loaded in cyclic condition for 100 times at a low frequency of 1 cycle per minute. Then secondly the sample is sheared in static loading at a rate of strain of 0.5mm/minute until it fails. The tests are carried out at axial stress amplitude from the lower stress to the higher stress in which the sample may fail before reaching the 100 cycles.

Sample is subjected to cyclic loading with cyclic stress ratio, R_f, used the Equation (1). The cyclic deviator stress level has been varied, while the frequency is kept constant for all tests.

D. Unconsolidated Undrained Static and Cyclic Test

Unconsolidated Undrained (UU) triaxial test gives shear strength of soil at different confining stresses. In these tests the cell tube is filled with water in order to give a certain pressure to the soil.

In this test, the cell pressure is applied to a desired value then the sample is allowed to settle down for at least 6 hours to have evenly all around pressure. When the sample is loaded either in static or cyclic mode, the pore pressure of the sample is recorded, before it gets sheared and after failure. The response of the partially saturated soils for high confining pressure can be investigated by raising the cell pressure up to a value where the air in the voids is totally dissolved, and the soils may behave like a saturated material. The threshold stress ratio can then be determined.

E. Consolidated Undrained Static and Cyclic Test

In this test, the cell pressure and back pressure are applied at the incremental value, in order to produce the fully saturation sample as nearly as possible by the saturation stage that is expressed in terms of the Skempton's pore pressure coefficient, B. Since the B-value is defined as the ratio of the induced pore water pressure to the applied all-round pressure, it can be simply obtained in the triaxial test in laboratory [21, 22]. The Skempton's B-value method has been widely used to determine the state of saturation of laboratory soil specimens at the end of this stage the Skempton's value (B) was checked whether it has achieved the value more than 95% when it can be concluded that the sample was fully saturated. The minimum acceptable value of B in laboratory test is 0.95 to 0.97. When the saturation is not satisfactory then the back pressure is raised to a higher value so that the air present is expelled and the remaining size of air bubbles is decreased [23]. After the sample is fully saturated the consolidation stage is then applied and the effective stress that equal to difference between cell pressure and pore pressure is recorded. Furthermore, when the consolidation process has been completed the sample is sheared in cyclic loading then in static loading.

F. Evaluation Methods

Threshold stress of the subgrade soils is defined as the maximum cyclic stress level at which the cyclic loading initiates rapid permanent deformation and cumulative increase of pore water pressure leading to failure below the static failure value. The threshold stress ratio, R_{TS} is the ratio of threshold stress to the ultimate static failure stress. Cyclic stress ratio, R_f is the ratios of the cyclic stress to the ultimate static failure stress obtained from cyclic triaxial test.

Threshold stress determination is using the curve of cumulative plastic strain, $\square_P$ as developed by Shahu investigation [18]. He has used the cyclic stress ratio, R_f parameter and threshold stress ratio, R_{TS}. Then proposed the threshold stress ratio as a measurement of the value of R_f at which sudden increase in incremental plastic strain occurs. Moreover, has concluded that the threshold stress is a critical level of repeated loading at which soil failure will never occur or no more increase in plastic strain deformation occurs [24].

IV. Result And Discussion

Subgrade soils assumed to be laid in fill area that is needed to be compacted. Samples are prepared by modified Proctor Compaction to derive its optimum moisture content. Total sample tested for threshold stress determination consist of 8 samples for Unconfined Cyclic Compression test, 4 samples for Unconsolidated Undrained Triaxial test, and 5 samples for Consolidated Undrained Triaxial tests. All samples were cyclic for 100 cycles at various cyclic stress levels then sheared in static loading until the sample fail.

A. Plastic strain development for zero confining pressures

Cyclic loadings lead to the accumulation of deformation that resulted in permanent deformation. The deformation of the sample after 100 cycles of loading is presented in Fig. 1, where it illustrates the effects of the various cyclic stress ratios on the deformation generated by the Unconfined Compression cyclic triaxial test.

Fig. 1 presents the deformation of the sample due to cyclic loading. The deformation is developed quickly as the cyclic stress ratio is increased. It can also be noted from this figure that at low cyclic stress ratios (R_f < 50%), the deformation of the sample, or axial strain, is still below 5% where it can still sustain the cyclic-loading utilization up to 100 cycles. As the cyclic stress ratio is increased (R_f > 50%), the deformation of the sample increased sharply. Eventually, it led to the failure of the sample. In this study of cyclic stress ratios above 60%, the sample failed before 100 cycles of loading.

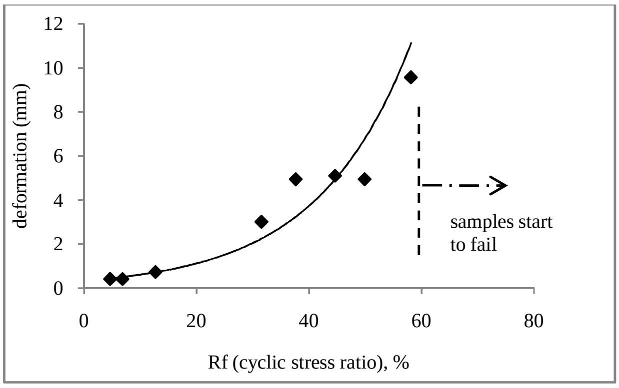

Fig. 1 Deformation of the sample due to cyclic shear loading

To determine the threshold stress value of the soil subgrade in an unconfined condition, Fig. 2 is drawn based on the results of the unconfined cyclic triaxial test. Three parameters were studied, namely, axial strain before cyclic loading, axial strain after 100 cycles, and finally, axial strain at failure, where it is determined by monotonic shearing after performing cyclic loading [18]. It was found that the cyclic loading at stress level R_f, around 60%, led to failure.

Fig. 2 depicts data in terms of incremental values of plastic strain, ε_p, in relation to the cyclic stress ratio, R_f. For higher R_f, the samples suffered high incremental deformation. The value of the threshold stress ratio, R_{TS}, is indicated as a sudden increase in incremental plastic strain [6, 17].

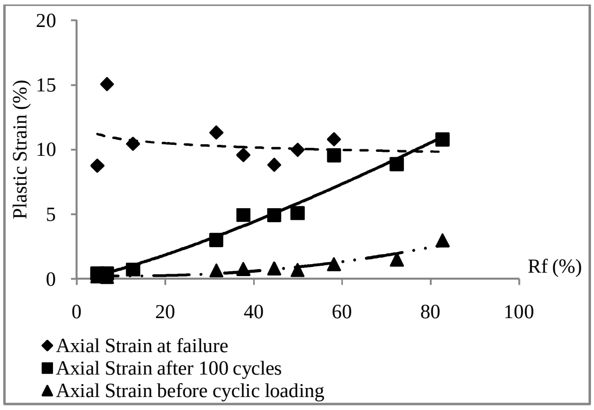

Fig. 2 Plastic strain versus R_f for unconfined cyclic tests

It can also be observed from Fig. 2 that the axial strain before cyclic loading was high for R_f above 60%, and for R_f more than 60% (indicated with arrows), the sample failed with excessive strains in lower cycles, while the axial strain at 100 load cycles becomes very high, leading to failure of the sample. The corresponding value of the plastic strain, ε_p, after 100 cycles, is of the order of 7% in the case of unconfined tests on soil samples compacted at the optimum moisture content. In addition, this value is below the failure strength.

B. Plastic strain development for low confining pressure

The development of the cumulative plastic strain, ε_p, with the number of load cycles during undrained shear for the CU cyclic triaxial test with saturated back pressure is presented in Fig. 3 for effective stress, σ_c' lower than 40 kPa.

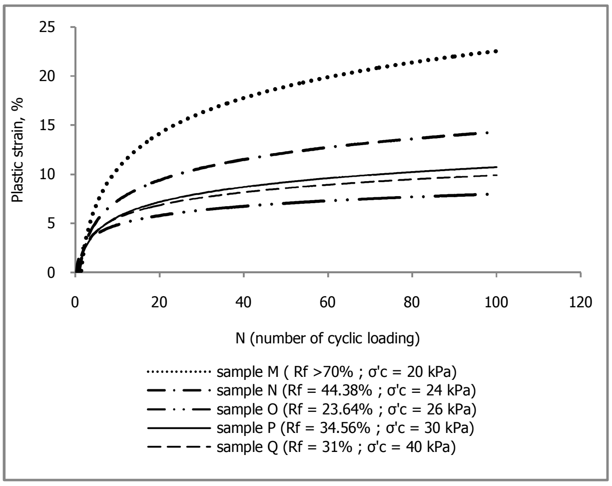

Fig. 3 Increase in plastic strain with cyclic loading ($\sigma_c' \leq 40$ kPa)

As can be observed from Fig. 3, the plastic strain value, ε_p, increased with the increasing R_f. The plastic strain value, ε_p, at the same number of cycles for sample M and N showed a sudden increase in magnitude. It can be said that their cyclic stress level is above the threshold stress ratio ($R_f > R_{TS}$). The plastic strain of the sample M with $\sigma_c' = 20$ kPa appeared to exceed the threshold stress level as well as the sample N with plastic strain above 10% [6, 18]. In addition, during the application of cyclic loadings for these two samples, both samples failed before they could achieve 100 loading cycles.

C. Plastic Strain for High Confining Pressure

The development of plastic strain under high confining pressure is presented in Fig. 4. Fig. 4 presents that the rate of accumulation of plastic strain increased as the cyclic stress ratio is increased. On the contrary, as the cyclic stress level decreased, the plastic strain is also decreased. From the two Figures of Fig. 3 and Fig. 4, it can be observed that the application of cyclic loading assumes the power law correlation between plastic strain developments and the number of cycles (ε_p vs N). Similarly with the Shahu's investigation where studied the compacted campus silt [18].

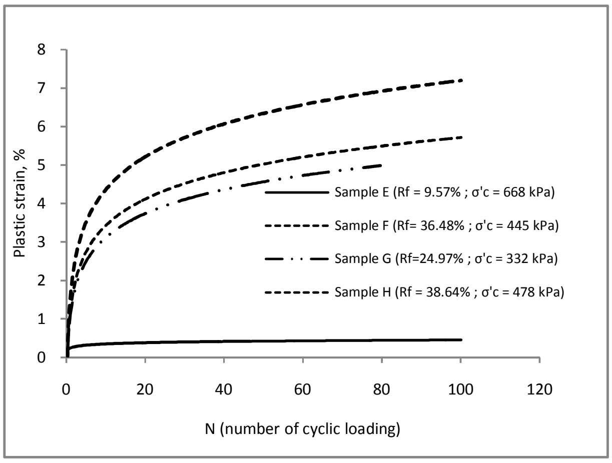

Fig. 4 Increase in plastic strain with cyclic loading (high confining pressure)

Assuming that the expected ratio of the threshold stress ratio from Yudhbir *et al.* [24] investigation as,

$$R_{TS} = 0.045 + 1.29\ PI \quad (4)$$

and

$$R_f = R_{TS} \pm 0.1 \quad (5)$$

Where,

R_{TS} = threshold stress ratio
R_f = cyclic stress ratio
PI = Plasticity Index

Thus, the relationship of ε_p versus N can be evaluated in order to determine the plastic strain at 100 cyclic loads. As Plasticity Index (PI) equal to 28% in this type of subgrade soil, thus the equation can be developed for two categories, i.e., below R_f and above R_f.

The equations for low confining pressure of the sample are presented as follows,

a. Below cyclic stress ratio, R_{TS}
   - σ'_c = 26 kPa (R_f = 23.64%) Sample O

$$\varepsilon_p = 1.3678\ln(N) + 1.7043 = 8.0\ \% \quad (6)$$

- σ'_c = 40 kPa (R_f = 31%) Sample Q

ε_p = 1.892ln(N) + 1.1967 = 9.91% (7)

b. At threshold stress

- σ'_c = 30 kPa (R_f = 34.56%) Sample P

ε_p = 2.1979ln(N) + 0.5956 = 10.7% (8)

c. Above cyclic stress ratio, R_{TS}

- σ'_c = 24 kPa (R_f = 44.38%) Sample N

ε_p = 3.0381ln(N) + 0.3145 = 14.3% (9)

- σ'_c = 20 kPa ($R_f >> R_{TS}$) Sample M

ε_p = 5.2149ln(N) − 1.4737 = 22.5% (10)

While for high confining pressure, the equations developed based on the Fig. 4 are as follows.

- σ'_c = 444.92 kPa (R_f = 36.482%) Sample F

ε_p = 0.995ln(N) + 1.138 =5.7% (11)

- σ'_c = 332 kPa (R_f = 24.974%) Sample G

ε_p = 0.9018ln(N) + 1.041 =5.2% (12)

- σ'_c = 478 kPa (R_f = 38.638%) Sample H

ε_p = 1.233ln(N) + 1.523 = 7.2% (13)

By means of these equations, the deformation of the samples during N cycles at a given cyclic stress level can be determined. In addition, the plastic strain 10% after 100 cyclic loading can be shown.

This compares well with the failure criterion recommended by ORE [6], who has defined the threshold stress as a maximum deviator stress that can be applied to the sample that does not cause cumulative strain greater than 10 percent in 1000 cycles. The 100 cycles seems can be accepted as suggested by Wood [4] investigation that to observe the soil parameter only the first few cycles is important. It also strengthens by Shahu [18] investigation that he was also able to determine the threshold stress of the soil for railway formations for 100 cyclic loads.

Shahu proposed that the value of R_f, at which sudden increase in incremental plastic strain occurs, is taken as a measure of the threshold stress ratio (R_{TS}) [26], and the threshold stress is represented as a critical level of repeated loadings in which soil failure will never occur [23],. It can be seen from Fig. 4 that at low cyclic stress level ($R_f < R_{TS}$) for $\sigma_c' \leq$ 26 kPa, the maximum plastic strain value is attained at approximately 60 to 70 cycles with no further increase in plastic strain deformation. In addition, based on Equation (9) the plastic strain equal to 9.91% at 100 cycles for the ratio of the threshold stress, R_f of 31%. Thus, based on this test result, the R_{TS} is 31% in the case of $\sigma'_c \leq$ 40 kPa.

The plastic strain for high confining pressure soil condition achieve the plastic strain less than 10% axial strain at 100 cycles is for R_f = 38.6%. Its threshold stress is higher compare to lower effective stress. The higher the confining pressure or effective stress the higher the threshold stress will be.

V. Evaluation Of Threshold Stress Ratio

Threshold stress is needed as a limit stress induced into the highway pavement layers when designing the pavement thickness for construction. The ratio of the threshold stress, R_{TS} can be estimated based on Plasticity Index (PI) of soil [25] for simplification evaluation (refer to Equation 4 and 5). For PI equal to 28% for this subgrade soil, thus R_{TS} equal to 0.4062. It means that the threshold stress ratio of this soil is 40.62% if predicted by PI value. The cyclic stress ratio, R_f is any value in the range of 0.3062% to 0.5062%. However, for thoroughly analyses of the threshold stress of the soil, the results from the triaxial testing, was utilized to develop the threshold stress which then used for design of the highway formation thickness. By a complete evaluation of the threshold stress of the soil subgrade for formations highway construction expectedly fulfil the construction service life satisfaction. In this investigation, the threshold stress is based on the development of plastic strain with the number of load cycles set at different cyclic stress ratios. Fig. 5 shows the plastic strains of the samples correspond to the cyclic stress level, R_f. The value of R_f at which a rapid increasing of the plastic strain occurs, is taken as threshold stress ratio value. Data from unconfined cyclic compression tests are also indicated in Fig. 5. For this unconfined test, for R_f > 60% the specimen will failed before 100 cycles. On the basis of change point for partially saturated soil at zero confinement, the threshold stress was located at R_f = 60%.

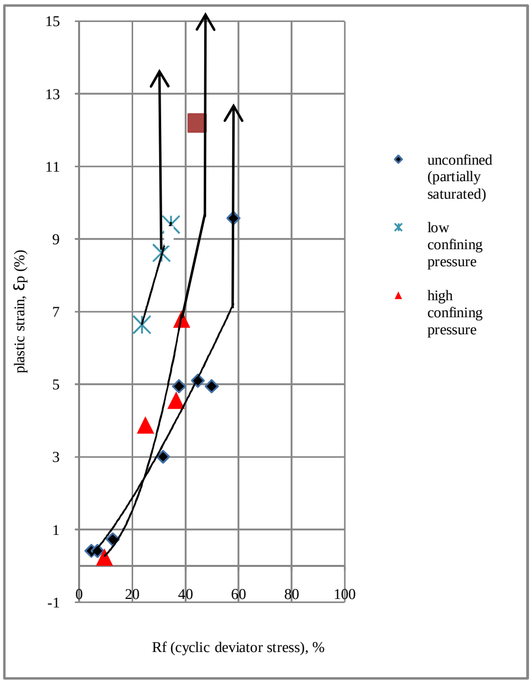

Fig. 5 Plastic strain versus cyclic deviator stress

The line drawn through the low confining pressure or low all-round pressure point actually drawn on the strength of the three points corresponding to the test with σ_c' = 26kPa, 30kPa and 40 kPa. This is because these tests exhibit a normalized behaviour and can be normalized into a narrow zone as shown in Fig. 6. The figure is the normalized behaviour of the pore water pressure development for low effective stress corresponds to the σ_c' = 26kPa, 30kPa and 40 kPa. In addition, the sample O, P and Q have been cycled in the threshold stress ratio range of predicted R_{TS}. The remaining data do not fit in this category and this data has also shown a sudden increase in incremental plastic strain for $R_f > R_{TS}$ and fail before 100 cycles.

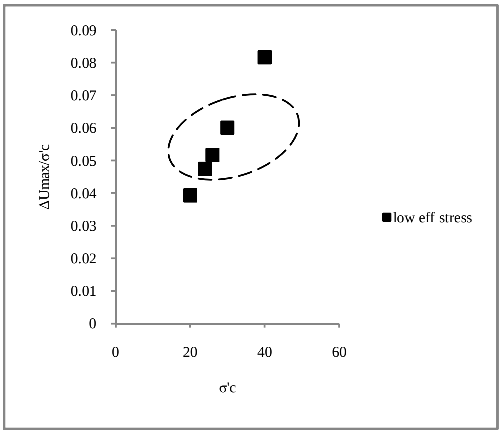

Fig. 6 Variations of $\Delta U_{max}/\sigma'_c$ with σ'_c for low effective stress

Thus, based on plastic strain criterion, the threshold stress of the compacted clay with sand soil is 30% where the low confining pressure is taken into account, due to the confining pressure for highway formation is commonly less than 35 kPa [15, 18]. As well as for high confining pressure the threshold stress ratio can also be determined. It is equal to 38.638% as shown also in Fig. 5.

VI. Summary

The threshold stress has been determined for normally consolidated clay as subgrade soil that have the cohesion, c'= 92.98 kPa and the angle of friction, Ø = 32^0. Based on plastic strain criteria to evaluate the threshold stress of the subgrade soil, the results can be concluded as follows.

- In the case of the highway formations design development which commonly having lower confining pressure from Consolidated Undrained test, the ratio of threshold stress, R_{TS} value obtained equal to 31%, as can be seen in Fig. 3 and Equation (7).
- For Unconfined condition of the partial saturated subgrade soil is having the ratio of threshold stress, R_{TS} value equal to 60%. The response of the partially saturated soils for high confining pressure is equal to 38.638% as shown in Fig. 4 and based on Equation (13).

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