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RESILIENT BEHAVIOUR OF COHESIONLESS SOIL
COMPORTEMENT ELASTIQUE DU SOLS NON-COHERENT

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SYNOPSIS: Cohesionless soils are often used as base or sub-base layers of pavement structures. Their behaviour under traffic induced stresses is both non-linear and anisotropic. The paper describes the resilient testing of six soil type, more or less commonly used in pavements, in a repeated load triaxial apparatus with axial and confining stresses being cycled. On sample measurement of axial and radial strain were used to monitor inherent anisotropy and material non-linearity. Measurements were taken before and after inducing significant stain by the repeated application of an axial loading several thousand times. Non-linearity of response was observed in both resilient and radial deformation and anisotropy was seen to vary confining stress level, deviator stress level and stress-history. A model is proposed to describe most of this observations. It is shown to be good at estimating resilient axial strain and inherent anisotropy but less good at predicting the much smaller values of resilient radial strain.

INTRODUCTION

Cohesionless soils are used in the road construction as sub-base and/or base materials as the working platform and a drainage layer in the pavement structure.It is important to understand the basic mechanical properties of a such a material in order to design a new flexible pavement. The soil is placed in a thin layer and compacted. It is considered that the inherent material characteristics, the compaction and subsequent traffiking may all cause the soil to behave in a significantly non-linear and anisotropic manner. According six materials, soft limestone (SL), gritstone (GS), sand and gravel (SAG) and graded washed river sand (GWRS) and in a dry condition and Fontainebleu sand (FS) and furnace bottom ash (FBA) in a partially saturated condition were tested under a wide range of stress paths using a repeated load triaxial test apparatus. Anisotropy was measured applying cyclic isotropic stress excursions (cyclic cell pressure) of different magnitudes.

Under these isotropic conditions some inherent and stress-history-induced anisotropic behaviour was observed. A new model incorporating anisotropy is proposed

IMPORTANCE OF RESILIENT BEHAVIOUR IN ROAD FOUNDATION DESIGN

The deformation a granular layer under traffic loading is composed of two parts, resilient and permanent. Hence, the stresses observed in a pavement foundation are well below which might cause failure Brown (1981). For a pavement foundation, rutting which is associated with the accumulation of plastic strain is the only failure mode since no bound materials are involved Brown and Selig (1991). However, after constructing upper layers and a number of traffic loads have been applied, the increment of permanent deformation is much smaller than the increment of resilient deformation. It is then the resilient strains which are of concern to the behaviour of the pavement structure built on the granular layer. Therefore, the resilient characteristics of the granular layer in the pavement structure gain importance.

THE REPEATED LOAD TRIAXIAL APPARATUS

The repeated load triaxial apparatus has been used for many years to investigate the behaviour of granular materials although it is not capable of fully producing the stress conditions induced by traffic loading. However, it is simple to operate and simple to interpret results. A triaxial apparatus with a sample of size 150 mm diameter and 300 mm height was developed by Boyce (1976) at Nottingham University which was able to cycle both the deviatoric and confining (cell) stress (Figure 1). Pappin (1979) slightly modified the apparatus in order to apply tensile stress to the granular material. In 1991 the electronic control system was replaced by a digital control system.

The apparatus is able to apply an axial load of 3 kN by a hydraulic actuator at a frequency range of 0-16 Hz. Confining stress is also applied by a fluid pressurized hydraulic actuator at a frequency of 0-2 Hz. Silicone oil is used as the cell fluid due to its low density and its excellent electrical insulation which allows on-sample instrumentation for measurement of axial and radial strain using LVDTs and strain-gauged hoops respectively.

MATERIALS

Different cohesionless soils from fine to coarse were tested, namely soft limestone, sand and gravel, gritstone, Fontainebleau sand, graded washed river sand and furnace bottom ash. Details of the soils tested can be found in Karasahin et al (1993). Gradings of materials are shown in Figure 2.

SAMPLE PREPARATION

A vibrating table was used to to compact each sample, with each of 6 layers being subjected to vibration for 15 seconds (Boyce (1976), Pappin (1979), Hicks and Monismith (1971)) under a surcharge of 30 N. A levelling disc was used during the compaction process in order to apply the compactive effort evenly across the top of the sample. It was seen from previous experience that finer particles tended to migrate

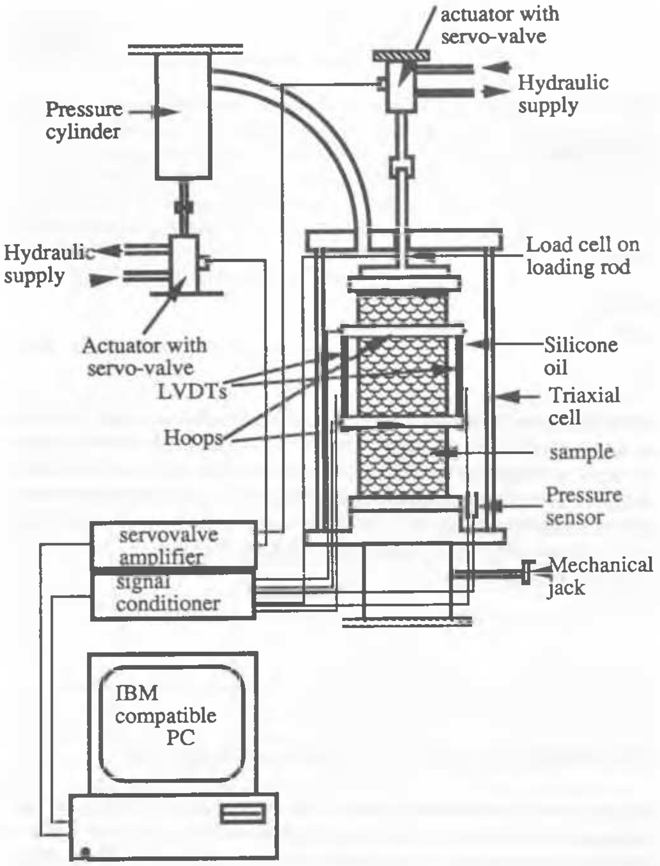

Figure 1.Diagram of the repeated load triaxial apparatus

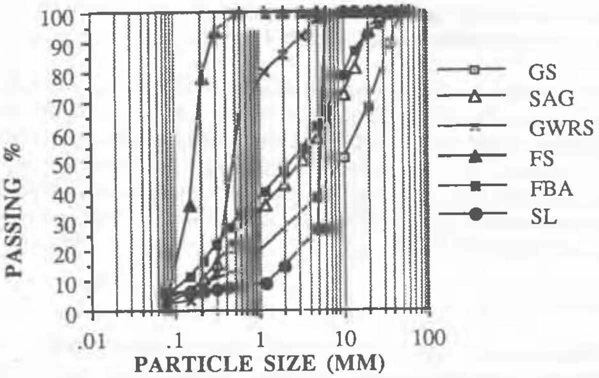

Figure 2. Grading curves

downwards during the compaction whereas coarse particles moved up. In order to prevent this migration, coarse grains were placed at the bottom of the layer before the compaction.

Each sample was enclosed in two latex membranes. During the sample preparation the inner one was held against the porous inner surface of the mould by applying a vacuum. The outer one was added after compaction to cover any possible punctures produced in the inner membrane during the compaction process. An internal partial vacuum was applied to the sample whilst on-sample instrumentation was added to it and prior to application of the external cell pressure.

TEST PROGRAMME

Resilient strain tests were carried out by the application of a wide range of stress paths which are discussed elsewhere Karasahin et al (1993). They included stress paths in which only the axial stress was cycled, paths in which only the cell pressure was cycled and paths with both stresses cycled. Applications of different stress paths at levels well below the failure line have almost no effect on the resilient behaviour of cohesionless soils Kalcheff and Hicks (1973). After a literature review, (Allen and Thompson (1974), Hicks and Monismith (1971) and Brown and Selig (1991)), it was decided to apply 50 cycles to each sample for each stress path and the mean response during the last five cycles was recorded as being representative of resilient behaviour. A loading frequency of 1 Hz was chosen as recommended by Brown and Selig (1991).

MEASUREMENT OF ANISOTROPY

In order to measure the inherent anisotropy of a sample, it was first subjected to a repeated cell pressure application of haversine waveform from a lower stress of 25 kPa to an upper stress increased in 25 kPa increment, ranging from 50 to 225 kPa. 50 cycles were applied to the sample at each stress range. Anisotropy is defined as the ratio of axial strain to radial strain under isotropic pressure and given the symbol n. Next resilient strain tests, in which deviatoric stress was applied, were performed. Then in order to induce stress-history-induced anisotropy, the sample was subjected to a repeated deviatoric stress at the same frequency which caused a plastic strain of about 1%. Lastly the initial stress paths were again applied to the sample in order to see the change in anisotropy.

DISCUSSION OF TEST RESULTS

It is impossible in this paper to give complete results but findings are illustrated with typical data. From the deviatoric stress testing it is clear that the axial strain response is non-linear (Figure 3). Non-linearity increases as the cell pressure decreases.

At high levels of deviatoric stress a disproportionate increase in radial strain was often observed. As the confining pressure increased the radial strain due to deviatoric stress cycling tended to decrease (Figure 4).

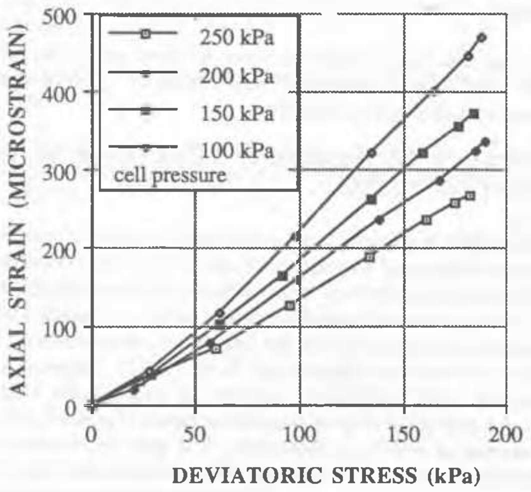

Figure 3. Axial strain results (GWRS)

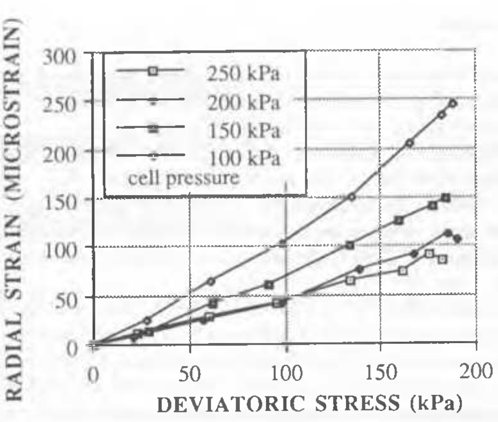

Figure 4. Radial strain results (GWRS)

Cohesionless soil shows more inherent anisotropy during the loading part of a cycle than during unloading (Figure 5). The anisotropy decreases as the isotropic pressure increases.

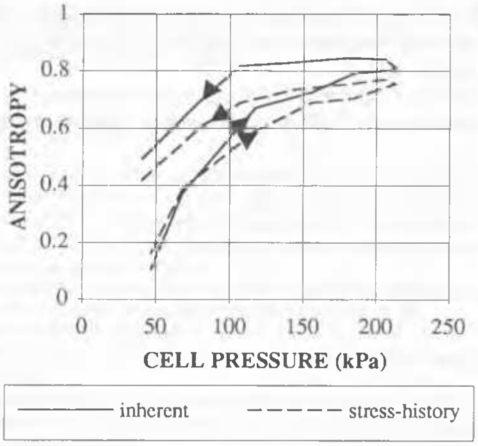

Figure 5. Loading and unloading behaviour (FS)

Stress history has a marked effect on anisotropy. Figure 6 shows the inherent anisotropy before and after the development of permanent strain by deviatoric stress cycling. It is clear that plastic strain has changed the structure of the cohesionless soils. At low levels of stress a higher stress-history-induced anisotropy was obtained (Figure 6). The same stress-induced anisotropy was observed before and after permanent deformation was induced but this is not discussed further here.

A MODEL FOR RESILIENT BEHAVIOUR

A new model which is able to predict results obtained from cycling both stresses is developed for a non-linear cross-anisotropic cohesionless soil. The model considers the effects of inherent anisotropy, which is n in the model. The model needs 13 constants which can be determined from the repeated load triaxial test and are easy to find despite their number (Karasahin (1993)). υ_2 (the effect of horizontal strain on vertical strain) and υ_1 (the effect of horizontal strain on the orthogonal horizontal strain) are obtained from cycling both stresses at the same time. M_r is the resilient modulus which can be determined from repeated deviatoric stress testing under constant cell pressure.

$$\varepsilon_a = \frac{1}{M_r}\left[\left(1 - \frac{2\upsilon_2}{n}\right) p + \left(1 + \frac{\upsilon_2}{n}\right)\frac{2q}{3}\right] \tag{1}$$

$$\varepsilon_r = \frac{1}{nM_r}\left[(1 - \upsilon_1 - \upsilon_2)\, p - (1 - \upsilon_1 - 2\upsilon_2)\frac{q}{3}\right] \tag{2}$$

where p and q the mean and deviatoric stress respectively
ε_a, ε_r are the axial and radial strain respectively

$n = D\left(\frac{p}{p_a}\right)^F$

$\upsilon_1 = 1 - H\left[\left(\frac{p}{p_a}\right)^L \left(\frac{q_m}{p_a}\right)^M \left(\frac{p_a}{p_m}\right)^N\right]$

$\upsilon_2 = R\left[\left(\frac{p}{p_a}\right)^S \left(\frac{p_m}{p_a}\right)^T \left(\frac{p_a}{q_m}\right)^U\right]$

$M_r = A\left[\left(\frac{p_m}{p_a}\right)^B \left(\frac{p_a}{p}\right)^C\right]$

A, B, C, D, F, H, L, M, N, R, S, T, U are model constants

$p = p_2 - p_1$

$p_m = \frac{p_1 + p_2}{2}$

$q_m = \frac{q_1 + q_2}{2}$

p_a = atmospheric pressure introduced to ensure non-dimensional constants

The model can also be written in an incremental form in order to consider the effect of stress-induced anisotropy.

The model is able to predict axial strain due to the cycling of both stresses (see Figure 7). However, for the same stress condition the prediction of radial strain is not as good as the axial strain (Figure 8). The prediction of resilient modulus is also satisfactory. In general predictions from this new model are at least as good as these from other models Karasahin (1993) and, despite the scatter, radial strain prediction by the new model is often better than other approaches. The performance of the model in predicting strain due to cell pressure cycles at elevated deviatoric stress has not been assessed.

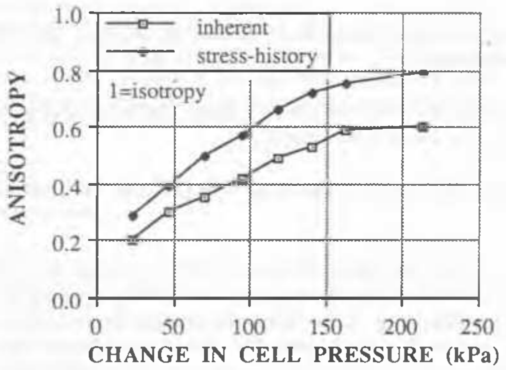

Figure 6. Change in anisotropy (GS)

CONCLUSIONS

- Cohesionless soils show a non-linear anisotropic behaviour under repeated sub-failure loading. The response of cohesionless soils depends on the deviatoric and cell pressure stress levels.

- Anisotropy can be measured by use of a repeated load triaxial apparatus. However, triaxial apparatus which has no facility of cycling

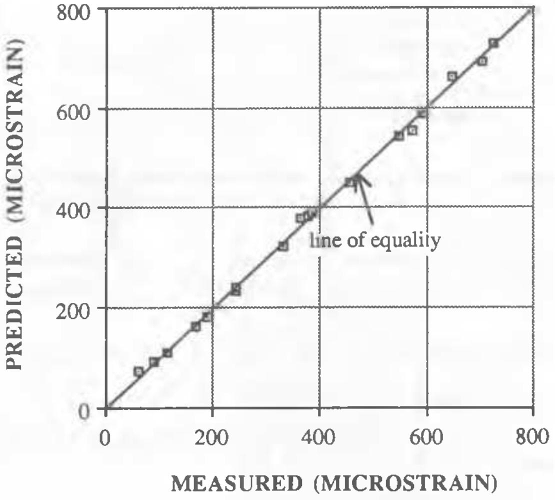

Figure 7. Axial strain predictions (FS)

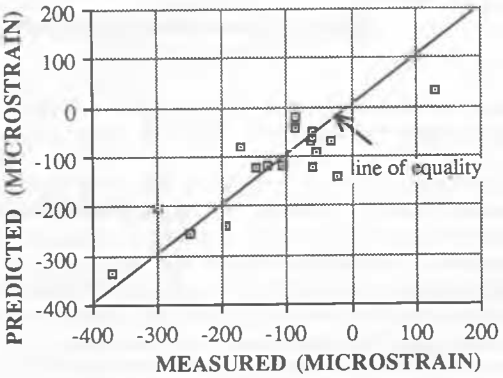

Figure 8. Radial strain predictions (FS)

cell pressure is not capable of measuring inherent anisotropy in cohesionless soil.

- A Stress history which resulted in plastic strain of cohesionless soil can change the inherent anisotropy.

- At low levels of stress anisotropy is higher than at higher level of stress.

- A new model has been developed which is capable of making predictions of resilient strain response to cycled deviatoric and confining stresses together, of the behaviour of under repeated deviatoric stress at constant confining pressure and the inherent anisotropy. It makes a poor prediction of radial strain this may reflect instrumentation error since the measured values of radial strains are very small. However, its ability to model real material behaviour is relatively good in other aspects.

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