MEASURING THE VARIATION OF SOIL MECHANICAL PROPERTIES WITH TREATMENT AND TIME IN A COMPACTION CONTROL AND REPAIR EXPERIMENT.

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ABSTRACT

This paper investigates the use of critical state soil parameters measured in a simple shear box to characterise the state of two soils subject to different compaction control and repair regimes. It is shown that the compressibility and void ratio parameters are strong functions of the void ratio and degree of saturation at the critical stress, and can be used to distinguish between the different treatments.

1. INTRODUCTION

A large scale compaction control and repair experiment is being carried out in Central Queensland, with the main experimental work centred on two sites at Biloela and Emerald. Six different treatments are being imposed, consisting of varying degrees of initial compaction and subsequent repair practices. A multi-disciplinary team has measured a wide range of soil and crop parameters in order to assess various methods of investigating compaction, its effects and its repair.

The Biloela site is on the Biloela Research Station, and consists of a black cracking soil formed on an alluvium, and is classified as a Vertisol. The Emerald site is on the Emerald Research Station, and the soil type is clasified as a shallow basaltic black earth, and is the same as in the major cropping areas of the Central Highlands. The farming practices being used are as realistic as is possible on small sites.

This paper reports measurements of soil mechanical properties measured on samples taken principally from the Biloela site. Some of these parameters can differentiate between the uncompacted, compacted and current best advice treatments and show how the soils vary with time.

These measured properties are parameters defined within the framework of the Cambridge critical state theory, which was initially derived for saturated clays in the civil engineering environment. It is well established there, and offers a powerful conceptual framework which deals with the mechanical behaviour and volume change behaviour of such soils under generalised conditions of loading.

Its application to unsaturated soils in the agricultural context has been discussed by a number of authors. There have been, until very recently, very few measurements presented in the literature of the relevant parameters, and their dependence on the state of the soil (that is, moisture content, density, stress history). The work of Leeson and Campbell (1983) considered two Scottish soils, and demonstrated the effect of water content on the gradient of the virgin compression line, which is expressed in terms of void ratio and the logarithm of applied stress, and concluded that the critical state theory can be extended to unsaturated agricultural soils. Hettiaratchi (1987) considered a sand, a loam and a clay soil and investigated the influence of microstructure, volume change and moisture status on soil strength, and demonstrated that the relevant state boundary surfaces of critical state theory for unsaturated soils could be determined. Kirby (1989) measured yield surfaces and the critical state condition on four unsaturated agricultural soils and demonstrated that these soils displayed yield and deformation behaviour qualitatively consistent with the critical state concept. In a later paper, Kirby (1991) measured critical state parameters of undisturbed samples of several Vertisols and investigated the inter-relationships and variability among the various parameters, and the dependence of the parameters on the state of the soil. Also, Petersen (1993) investigated the variation of critical state parameters using two different loam soils. Current work by Bakker (1994) has been directed at establishing critical state parameters and yield surfaces for a Vertisol and to investigate their dependence on moisture content and stress history.

Apart from Kirby, all these authors have used a triaxial apparatus to make their measurements, and all have commented on the tedious and slow processes required. This apparatus has the advantage that the stress state within the sample is completely defined. Kirby (1989) showed that a soil sample stressed in a split shear box, which is a much simpler and easier apparatus to use, displayed a behaviour analogous to critical state behaviour. The state of stress in a split shear box is unknown, and so boundary stresses have to be used to construct the critical state space. Recent work by Bakker et al (1994) using a simple shear box, which imposes a more uniform and predictable stress field, has also demonstrated critical state like behaviour in terms of boundary stresses. The simple shear box is limited, in that because of the particular stress fields it creates it cannot impose general stress paths defined by possible and practical combinations of shear and normal stresses.

For the results presented here, the approach of Bakker is followed in which the state of stress of the soil is expressed in terms of total stresses applied at the boundaries viz the applied normal stress, σ, and the applied shear stress, τ, rather than the effective octahedral stresses. Also the compressibility is expressed in terms of the void ratio e as opposed to specific volume due to the reactive nature of the clay soils to be examined. This represents a transformation of the Cambridge critical state concept to a critical state space defined by the applied total boundary stresses. Therefore, the relevant parameters necessary to describe the behaviour of the soil are themselves an analogue of the Cambridge critical state parameters and will be presented next for reasons of clarity.

By analogy with the critical state concept, the yield behaviour of the soil can be represented in e-σ-τ space. This model can be more conveniently represented by 2-dimensional diagrams of the e-ln σ and the τ-σ relationships. These relationships are illustrated in Figures 1 and 2 along with the relevant parameters which define their geometry.

These parameters include state parameters (the current void ratio and stresses) and the current pre-consolidation stress, P_c. When soil is compressed there is a slight reduction in void ratio for stresses below P_c, but after P_c is exceeded void ratio decreases markedly (Figure 2). Therefore, P_c is related to the strength of the soil, and can be found at the intersection of the tangents of the elastic section and the plastic section of the NCL. P_c also describes the maximum past stresses to which the soil was subject and therefore is related to the stress history of the soil. The corresponding void ratio at this stress is defined as the critical void ratio, e_{pc} (Kirby, 1989).

Property parameters can also be defined, and these include the compression index, λ_{bs}, and the rebound index, K_{bs}. These two parameters describe the volume change characteristics and are defined in Figure 2. The NCL in Figure 2 is fully described by

$$e = N_{bs} - \lambda_{bs} \ln \sigma \qquad ......(1)$$

where N_{bs}(capital nu) is defined as the void ratio at $\sigma = 1$ kPa.

The CSL in Figure 2 is described by,

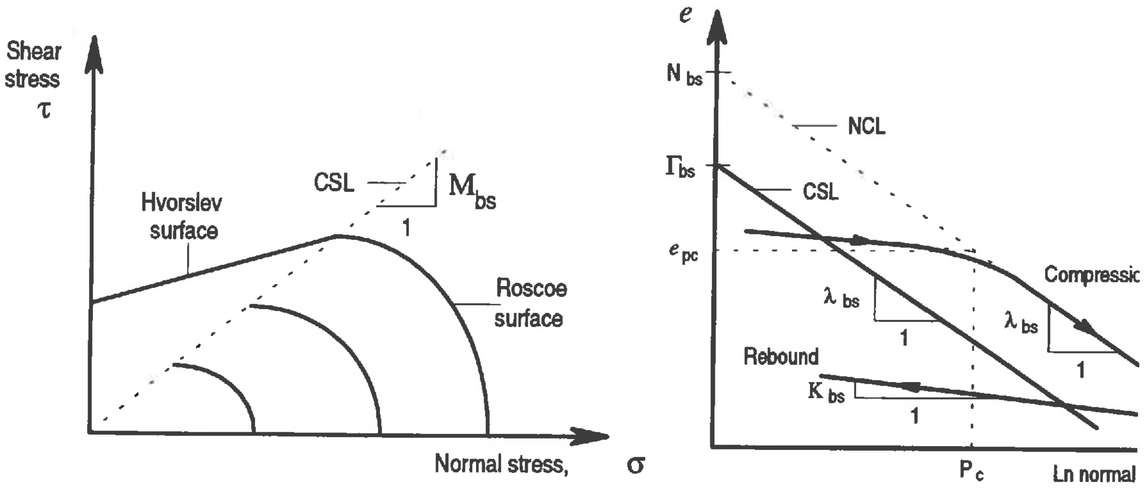
$$e = \Gamma_{bs} - \lambda_{bs} \ln \sigma \qquad \text{..........(2)}$$

where Γ_{bs} (capital gamma) is defined as the void ratio at $\sigma = 1$ kPa.

The slope of the critical state line in shear stress/normal stress space is described by

$$\tau = M_{bs}\sigma \qquad \text{..........(3)}$$

as shown in Figure 1.



FIGURES 1 and 2 Yield surface projection in σ - τ space and NCL and CSL projection in e - ln σ space

The subscript $_{bs}$ is used on all these parameters to emphasise that they have been derived using boundary stresses rather than the octahedral stresses on which critical state theory is based.

High values of λ_{bs} denote a soil which is compressible, because the increment of normal stress required to reduce void ratio by a given amount is decreased.

Higher values of N_{bs} imply that a soil is stronger, because it can support a stress of 1kPa at a higher void ratio, and because the volume of state space enclosed by the boundary surfaces extends to higher values of stress.

Higher values of Γ_{bs} similarly imply a stronger soil.

A number of authors including Leeson and Campbell (1983), Kirby (1989, 1991b) and Bakker (1994) have demonstrated that the above described parameters can be expected to vary according to the state (moisture content, degree of saturation) of an unsaturated soil while Hettiaratchi (1987) showed that the microstructural state and moisture content greatly influenced the behaviour of an unsaturated soil.

Soil behaviour in the present context refers to the mechanical behaviour as opposed to the electro-chemical behaviour. Hettiaratchi (1987) developed a simple model which dealt with those aspects of electro-chemical behaviour concerned with the micro-structure of a clay loam soil, and identified two extremes of microstructural state. These are "remoulded" and "cemented", and are identified respectively with soils as prepared in the laboratory, and field soils which have not been disturbed following saturation.

2. METHODS AND PROCEDURES

2.1 FIELD SAMPLING

Field (undisturbed or cemented) samples were collected for testing in the simple shear box to enable the relevant critical state parameters to be determined.

These samples were collected using thin walled sampling tubes, fabricated from sheet metal, 65 mm in breadth by 105 mm in length and 40 mm in height. The tubes were greased on the inside and then pushed into the soil and subsequently excavated and then sealed and wrapped to prevent moisture loss. They were then transported to Toowoomba for testing and when not required immediately, were stored in a refrigerator at 4^{0} C. For testing the sample was removed from the tube and then trimmed to the appropriate size. The samples were therefore tested at their field moisture contents.

2.2 REMOULDED SAMPLE PREPARATION

To provide information on the effect of microstructural state on soil strength, remoulded samples were prepared in the laboratory using loam soil from the Biloela experimental site and then shear and compression tested in the shear box.

Remoulded samples were prepared over a range of predetermined moisture contents (10 - 35 %) by adding a calculated amount of distilled water to a known mass of dry soil constituents. The resulting wet sample was placed in a polythene bag, sealed and then kneaded to distribute the moisture evenly. This disturbance constitutes the remoulding process and parallels that reported by Hettiaratchi (1987). The sample was then left to equilibrate for 48 hours and subsequently tested for moisture content.

2.3 MEASUREMENT OF CRITICAL STATE PARAMETERS

Undisturbed samples were tested for strength and compressibility at the field moisture contents. Eight samples were collected at each depth and this allowed four over-consolidation ratios to be sampled at both constant volume and constant load, thus eight tests were completed at each depth. After each test the samples were individually tested for moisture content by the oven drying method. Identical tests were performed on remoulded samples at each moisture content and each sample subsequently tested for moisture content.

2.4 UNI-AXIAL COMPRESSION TEST

Uni-axial compression was achieved by the application of only the normal stress prior to shearing. The shear box is stress controlled and the maximum allowable normal stress that could be applied to the sample was 300 kPa. For the field samples a maximum normal consolidation stress of 200 kPa was applied. This represented typical stress levels being applied to the soil by the compacting equipment. For remoulded samples a range of maximum normal consolidation stresses was applied, viz 100, 200 and 300 kPa.

Soil response in the compression test is measured by the void ratio, *e*. By plotting *e* as a function of the logarithm of applied stress, ln σ, values for λ_{bs}, K_{bs}, Γ_{bs}, N_{bs}, P_c and e_{pc} were determined.

3. RESULTS AND DISCUSSION

The results of these measurements can be grouped according to the site, the preparation, the time and the treatment, as follows:

Biloela

Remoulded Samples

Field Samples
June 1993, uncompacted and compacted (initial characterisation)
December 1993, uncompacted, compacted and current best advice
June 1994, uncompacted, compacted and current best advice

Emerald

Field Samples
March 1994, uncompacted and compacted (initial characterisation)

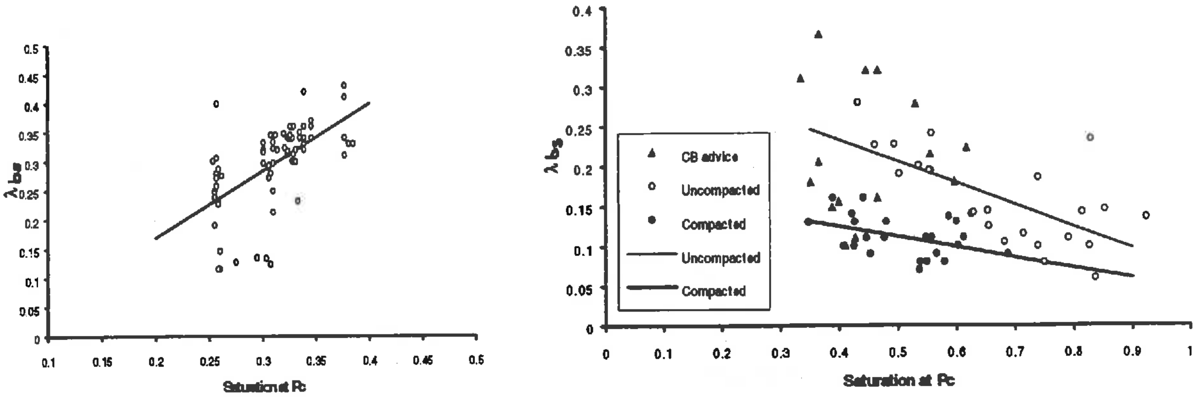
The total program of measurements has generated a large amount of data on the variation of the critical state parameters with soil type, microstructure, treatment, time and moisture content. The measurements of most interest here are those which reveal differences between treatments and with time.

3.1 BILOELA RESULTS

The two most significant independent variables were found to be the void ratio e_{pc} at the preconsolidation stress P_c, and the degree of saturation S_{epc} at the preconsolidation stress. The microstructural state of the soil was also found to have a significant effect on the variation of the parameters with e_{pc} and S_{epc}.

We have chosen therefore to present only a sample of the results which illustrate these variations. They are for the Biloela soil in its remoulded state, and as sampled in the field in December 1993.

Figures 3 and 4 show, respectively, the variation of λ_{bs} with S_{epc} for the remoulded and the field soil. It is obvious that the compressibility of the remoulded and cemented forms of this soil have opposite responses to the saturation at P_c. The remoulded soil becomes more compressible as the saturation increases, and its compressibility is always greater than that of the cemented soil. A highly saturated field soil has a low compressibility. This result is the same as that reported by Leeson and Campbell (1983) for loam soils, and by Kirby (1991b) for Vertisols. As expected, the compressibility of the uncompacted field soil is greater than that of the compacted soil. For both remoulded and cemented soils, other data (not given here) shows that the compressibility increases with e_{pc}. When the variation of λ_{bs} with S_{epc} and e_{pc} is considered, straight lines as defined below can be fitted to the data.



FIGURES 3 and 4 Compression index, λ_{bs}, versus saturation at the pre-consolidation stress .

For Figure 3, the remoulded soil

$$\lambda_{bs} = -0.566 + 0.437\, e_{pc} + 0.347\, S_{epc} \qquad (R^2=0.506)$$

For the field soil (December 1993) in Figure 4, which is

(a) uncompacted

$$\lambda_{bs} = 0.0871 + 0.120\, e_{pc} - 0.0946\, S_{epc} \qquad (R^2=0.478)$$

(b) compacted

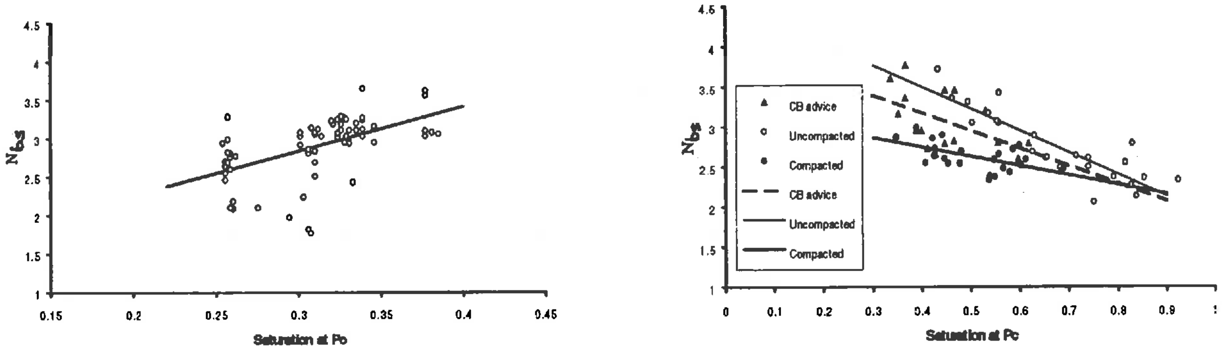
$$\lambda_{bs} = -0.172 + 0.245\, e_{pc} - 0.00071\, S_{epc} \qquad (R^2=0.608)$$

(c) current best advice

$$\lambda_{bs} = -1.24 + 0.70\, e_{pc} - 1.201\, S_{epc} \qquad (R^2=0.807)$$

Differences between the initial compacted and uncompacted treatments in June 1993 were minimal, with the uncompacted samples being slightly more compressible at higher void ratios. The December 1993 samples described above show substantial differences between the treatments.

Figure 5 and 6 show how N_{bs} varies with S_{epc} for the remoulded soil and the field soil respectively. Again, the variation of this parameter with S_{epc} is the opposite for the two microstructural states. At low saturations the field soil when uncompacted has a higher void ratio than the remoulded or compacted soil, which is as expected. N_{bs} was also found to be an increasing function of e_{pc} for both cemented and remoulded soils, and the lines of best fit to the data were as follows.



FIGURES 5 and 6 NCL void ratio at $\sigma = 1$ kPa, N_{bs}, versus saturation at the pre-consolidation stress

For Figure 5, the remoulded soil

$$N_{bs} = -2.02 + 2.71\, e_{pc} + 0.801\, S_{epc} \qquad (R^2=0.499)$$

For Figure 6, the field soil in December 1993

(a) uncompacted

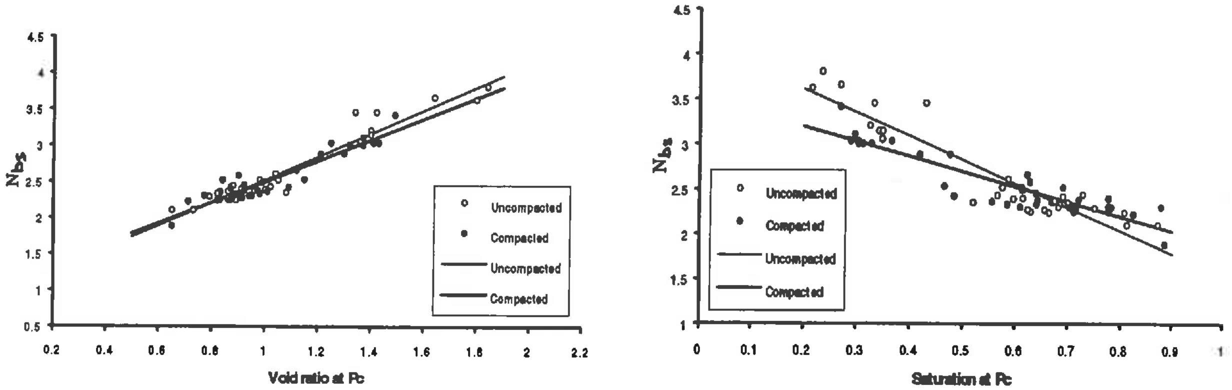
$$N_{bs} = 1.67 + 1.38\, e_{pc} - 0.698\, S_{epc} \qquad (R^2=0.854)$$

(b) compacted

$$N_{bs} = 0.368 + 2.01\, e_{pc} - 0.126\, S_{epc} \qquad (R^2=0.837)$$

(c) current best advice

$$N_{bs} = 2.24 + 2.93\, e_{pc} - 3.32\, S_{epc} \qquad (R^2=0.784)$$



FIGURES 7 and 8 NCL void ratio at $\sigma = 1$ kPa, N_{bs}, versus void ratio and saturation at the pre-consolidation stress - June 1993.

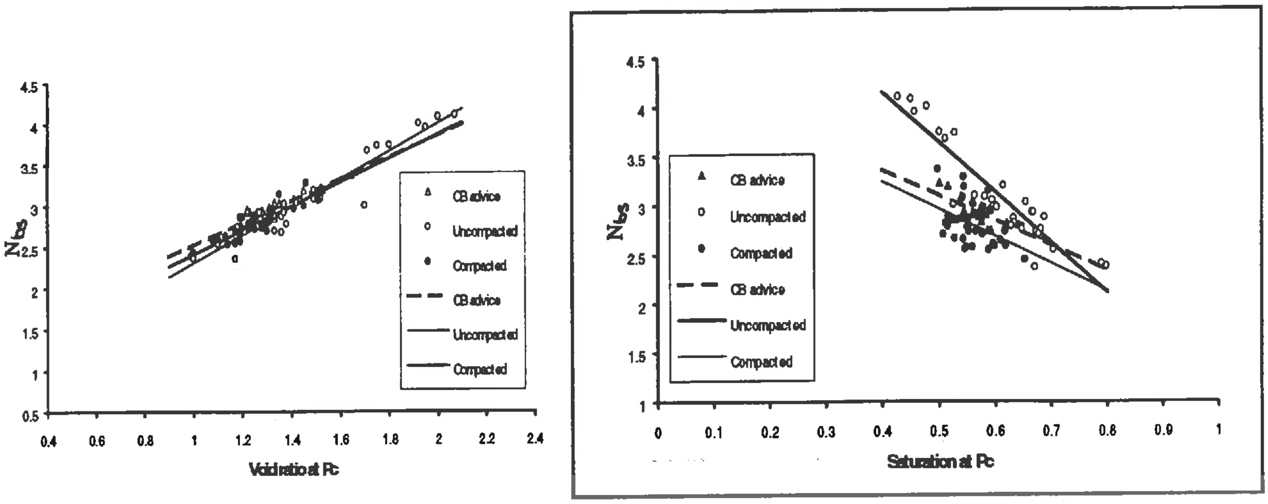
Figure 7 shows that there were no significant differences between the treatments in June 1993 when plotted as functions of e_{pc}. However, plotting against S_{epc} as shown in Figure 8 reveals differences, with the compacted soil becoming stronger at high saturations.

The two void ratio parameters Γ_{bs} and N_{bs} are highly correlated, with a typical R^2 in excess of 0.9. For instance, the uncompacted field soil in December 1993 yielded the following relationship between Γ_{bs} and N_{bs}.

$$\Gamma_{bs} = 0.147 + 0.884\, N_{bs} \qquad (R^2=0.924)$$

The relationship for the other treatments was not statistically different from this, and a similar conclusion could be drawn across all times and treatments. N_{bs} is a reliable predictor of Γ_{bs}, and so the location of the critical state line is not an additional independent parameter useful for distinguishing between treatments. The slope of the critical state line, M_{bs}, did not show any consistent variation with treatment or time, and is therefore also not useful as a measurement of the degree of compaction.

The field samples taken in June 1994 were wetter than any of the previous samples, and moisture content was not adjusted before testing. However, the parameter S_{epc} can be used to correct for this uncontrolled moisture content because it is defined at a known point (P_c) and therefore depends on both the moisture content and stress history of the soil. Figures 9 and 10 show N_{bs} plotted as a function of e_{pc} and S_{epc} respectively for the samples taken in June 1994. Plotting against S_{epc} clearly reveals the differences between the treatments.



FIGURES 9 and 10 NCL void ratio at $\sigma = 1$ kPa, N_{bs}, versus void ratio and saturation at the pre-consolidation stress - June 1994.

3.2 FURTHER COMMENTS

The major changes in the parameters were measured after the first six months or between June 1993 and December 1993 with only a few slight changes measured in the following six months to June 1994. After the first six months, the soil had increased in strength and had decreased in compressibility over all treatments.

The uncompacted treatment was found to have a higher degree of variability in void ratio than both the current best advice and compacted treatments.

Differences between the uncompacted and compacted treatments at Emerald were found in all the parameters. These differences became more apparent when compared with the level of saturation. A significant difference in the parameters, P_C, λ_{bs}, N_{bs} and Γ_{bs} was found between the surface and the subsoil samples in the compacted treatment. This difference was not found in the parameter M_{bs} or in the separation of the intercepts N_{bs} and Γ_{bs}. The uncompacted samples were more compressible and more likely to compress when sheared and required a lower level of stress for failure. Therefore the uncompacted treatment is more susceptible to compaction. The surface of the compacted treatment was less compressible and had a higher strength than the subsoil and this could aid in preventing damage to the subsoil.

4. CONCLUSIONS

It is possible to use simply measured critical state parameters based on boundary stresses applied by a simple shear box to distinguish between compacted, uncompacted and current best advice treatments for the field soils investigated in this work.

For all treatments, the compressibility λ_{bs} and the normal compression parameter N_{bs} are highly correlated with the void ratio e_{pc} at the critical stress P_c, and the degree of saturation S_{epc} at this void ratio. S_{epc} depends on the stress history of the soil and its current moisture content, and was found to assist in differentiating between treatments for soils with high moisture contents.

In terms of these parameters, the behaviour of a remoulded soil is quite different from that of a field soil. λ_{bs} is found to increase with e_{pc} rather than decrease. The critical state parameter

Γ_{bs} is highly correlated with the normal compression parameter N_{bs}, and so it cannot be used as an additional soil parameter. The slope of the critical state line, M_{bs}, did not show any consistent variation with treatment or any of the independent variables.

5. REFERENCES

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