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Influence of cementation and density on G_{max} for sand

L'influence de cimentation et la densité sur G_{max} pour le sable

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ABSTRACT

This paper presents data on the variation of G_{max} with stress level and density for uncemented and cemented sands. This has been obtained using a technique developed by the authors for the continuous monitoring of G_{max} during consolidation and shearing in triaxial tests. This technique has been used to investigate the variation of G_{max} for Toyoura sand and a carbonate sand subject to a range of stress paths. The results for these uncemented sands are broadly consistent with other published data but suggest that the effects of mean effective stress, p′, are not being correctly predicted by existing empirical relations at higher stress levels. Further tests have been performed on the carbonate sand which has been artifically cemented and prepared at a range of cement contents and densities. It has been found that existing empirical expressions are generally poor at estimating G_{max}. An equation has been developed that relates G_{max} to density, stress level and cement content. The paper presents briefly the methodology, some typical results and some comparisons with existing empirical approaches for estimating G_{max}.

RÉSUMÉ

Ce papier présente des données sur la variation de G_{max} avec le contrainte et la densité pour les sables et les sables cimentés. Ceci a été l'obtenu utilisant une technique développée par les auteurs pour l'interception continue de G_{max} pendant la consolidation et tondre dans les tests triaxiaux. Cette technique a été utilisée pour examiner la variation de G_{max} pour le sable de Toyoura et un sable de carbonate à une gamme de contrainte. Les résultats pour ces sables sont globalement conforme aux autres données publiées mais suggèrent que les effets de tension efficace moyenne, p′, ne sont pas correctement prédit par les relations empiriques existantes aux plus hauts contrainte. Plus les essai ont été exécutés sur le sable de carbonate qui a été artifically a cimenté et préparé à une gamme de contenus de ciment et aux densités. Il a été trouvé que les expressions empiriques existantes sont généralement pauvres à estimer de G_{max}. Une équation a été développée cela relate G_{max} à la densité, la contrainte et le contenu de ciment. Le papier présente brièvement la méthodologie, quelques résultats typiques et quelques comparaisons avec les approches empiriques existantes pour estimer de G_{max}.

1 INTRODUCTION

Interest in the small strain behaviour of soil has increased in recent years as the significance of this on ground deformations has become more widely appreciated. During the last few years improvements in measurement techniques have shown that there is significant non-linear behaviour even in the small strain range. It has been suggested that to characterise the small strain behaviour the modulus at very small strains, G_{max}, where the behaviour appears to be linear elastic, should be routinely measured (e.g. Atkinson, 2000). The factors which influence G_{max} include the recent stress-strain history, anisotropy, ageing or creep, relaxation, and cementation. This paper is particularly concerned with the investigation and quantification of the effects of cementation in sandy soils. The effect of various cementing agents on sandy soils has been investigated in several studies (e.g. Chiang & Chae, 1972, Acar & El-Tahir, 1986, Dobry et al., 1988, Saxena et al., 1988, Chang & Wood 1992, Fernandez & Santamarina, 2001, Salvati, 2002). The empirical relations proposed by these authors give widely different predictions for the effects of cementation on G_{max}, and there is a need for more data and a better understanding of how cementation affects the small strain modulus.

2 MATERIALS AND METHOD

Two uncemented sands were used in the initial stages of this study, Toyoura Sand and a carbonate sand from Australia's North West Shelf. Cemented samples were prepared by mixing the carbonate sand with gypsum and water. The grain size distributions of the tested materials are shown in Figure 1. Cemented samples were prepared with dry unit weights, γ_d of 13, 15 and 17 kN/m^3 and cement contents of 10%, 20% and 30%. To produce specified unit weights the soil mixture was placed in a cylinder and compressed as described by Huang and Airey (1991). Uncemented carbonate sand specimens were prepared with the same unit weights, γ_d = 13, 15 and 17 kN/m^3, by first compressing the sand in a similar way to the cemented specimens. Toyoura sand specimens were prepared with a range of relative densities by pluviation of dry sand. The specific gravities (G_s) of Toyoura sand and carbonate sand were 2.65 and 2.75 respectively. The carbonate content of the carbonate sand was greater than 90%.

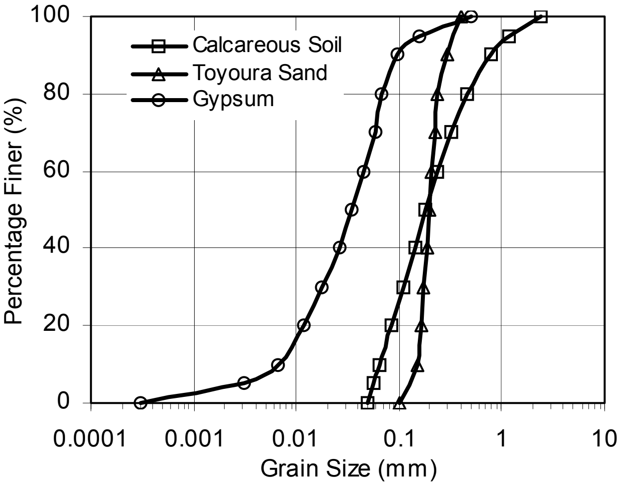

Figure 1 Grain size distributions

After setting up in the triaxial cell all specimens were saturated using elevated back pressures. The uncemented specimens were subjected to a range of stress paths under fully drained conditions that included isotropic compression to the maximum capacity of the triaxial cell, paths at constant deviator stress, constant mean effective stress, and constant axial stress. Each test concluded by drained shearing of the specimens to failure with constant confining stress. The cemented specimens were isotropically compressed to an effective confining stress of 300 kPa before shearing drained to failure. All specimens were subjected to at least one unload-reload loop before failure.

All specimens were instrumented with internal Hall Effect transducers and Bender elements to investigate the small strain response. The Bender elements were used to determine G_{max} continuously throughout both shearing and consolidation using the procedures discussed by Mohsin & Airey (2003). This method uses an input Chirp type waveform consisting of sine waves of frequencies of 8 kHz, 13 kHz and 20 kHz. A cross correlation between input and output signals is performed and the peaks in the cross correlation recorded. It has been found (Mohsin & Airey, 2003) that this technique gives a reliable indication of the travel time provided the correct peak in the cross correlation can be identified.

3 RESULTS

3.1 *Uncemented Sand*

Toyoura sand was used in this study because it has been investigated by many researchers and data on G_{max} have been reported from a variety of test types. Figure 2 shows some results obtained during isotropic compression for specimens with a wide range of relative densities.

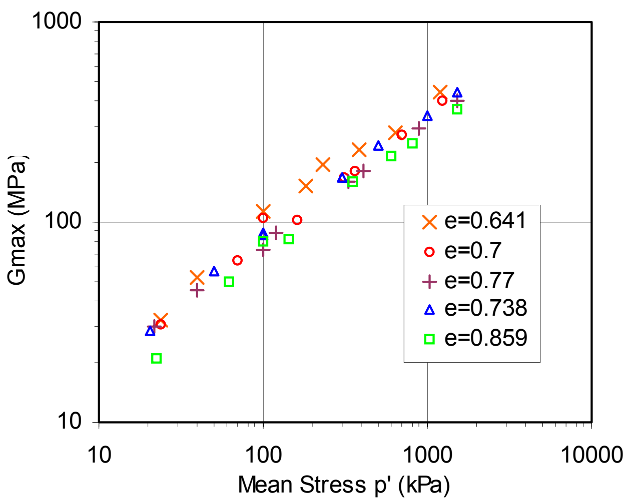

Figure 2 Variation of G_{max} during isotropic compression, Toyoura sand

The data shown in Figure 2 are generally consistent with previously published data (e.g. Yamashita et al., 2001). However, it was noticed that the widely published empirical relations for G_{max} underpredicted the data at higher effective stresses, and did not account for the influence of deviator stress. Using all the data from tests performed in this study a least squares fit procedure was used to determine a new relationship that could better describe the variation of G_{max} as a function of void ratio, e, mean effective stress, p′, and deviator stress, q, given by:

$$\frac{G_{max}}{p_r} = 4786 \left(\frac{p'}{p_r}\right)^{0.56} e^{-1.16} \left(1+\frac{q}{p'}\right)^{0.02} \qquad (1)$$

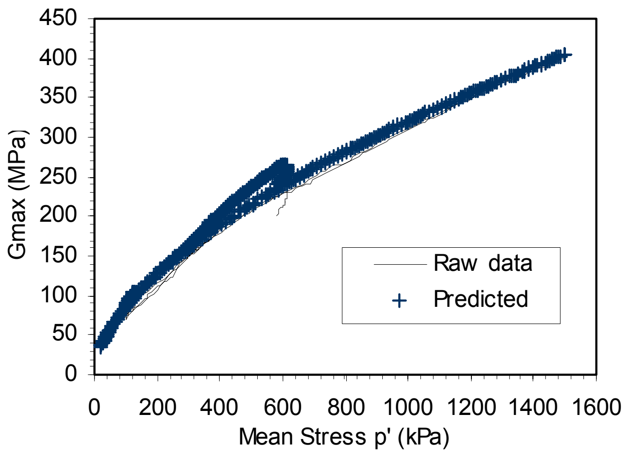

Figure 3 Comparison of measured and predicted G_{max}, Toyoura sand

where p_r is a reference stress, taken as 1 kPa. The predicted response from this equation is compared with the experimental data from a typical test in Figure 3. This test involved isotropic compression to 1500 kPa, isotropic unloading to 300 kPa, and then a drained shear tests at a constant confining stress of 300 kPa. It can be seen that Equation 1 gives an excellent prediction for all stages of this test.

The variation of G_{max} during isotropic compression for the carbonate sand is shown in Figure 4. In the key on this Figure the value following “g” is the percentage of gypsum (by dry weight) and following “u” the dry unit weight. Comparison with Figure 2 indicates that the data generally lie above those for Toyoura sand. This can be explained in part by the high stresses needed to produce the specimens. It can also be seen that the moduli of the carbonate sand on unloading are greater than during initial compression, unlike Toyoura sand which gave identical moduli on loading and unloading. This difference is a consequence of the void ratio changes that occur during compression for the carbonate sand. The effect of the different initial unit weights is more evident in the variation of G_{max} during drained shear tests shown in Figure 5. This shows G_{max} increasing with mean effective stress until the peak strength is reached after which G_{max} drops off more rapidly. A similar pattern is evident for the Toyoura sand in Figure 3. Following a similar procedure to that used for the Toyoura sand, a best fit relation was derived to describe the variation of G_{max} which is given as follows:

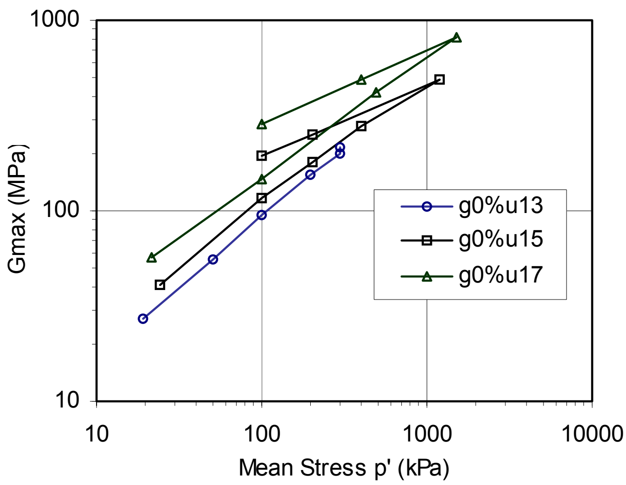

Figure 4 Variation of G_{max} during isotropic compression, carbonate sand

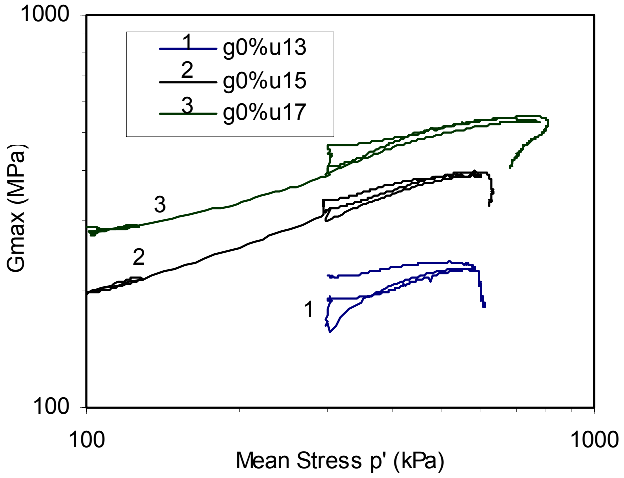

Figure 5 Variation of G_{max} during comprssion and shear, carbonate sand

$$\frac{G_{max}}{p_r} = 23404 \left(\frac{p'}{p_r}\right)^{0.38} e^{-1.33} \left(1+\frac{q}{p'}\right)^{-0.06} \qquad (2)$$

A comparison of the predictions of Equation 2 with the experimental data from the carbonate sand is shown in Figure 6. Both results shown are for specimens subjected to isotropic compression followed by a drained shear test to failure at a mean effective stress of 300 kPa. In one case the specimen experienced a maximum isotropic effective stress of 1500 kPa before unloading to the effective stress of 300 kPa. Figure 6 shows that G_{max} reduces from the isotropic response during shearing, whereas for Toyoura sand (Fig. 3) it increases, and this is reflected in the different exponents on the stress ratio term in Equations 1 and 2. It is also apparent that the predictions for the carbonate sand are less capable of reproducing the observed behaviour. This is because the simple power law relation with void ratio which can reproduce the large scale effects of differences in void ratio is not sufficiently sensitive to the effects of over-consolidation.

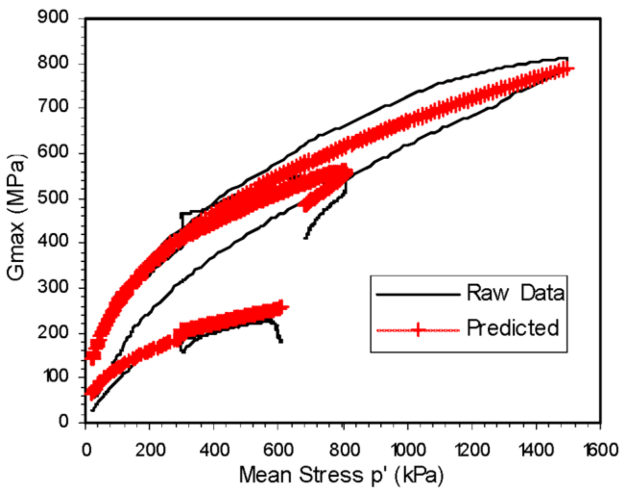

Figure 6 Comparison of measured and predicted G_{max}, Carbonate sand

3.2 *Cemented sand*

Figure 7 shows the effect of cementation on G_{max}. It can be seen from the figure that increasing the cement content leads to very significant increases in G_{max}. The uncemented sand data given in Figure 4 show a range of G_{max} from 100 MPa to 300 MPa at a mean effective stress of 100 kPa, whereas the cemented specimens have given G_{max} values from 200 MPa to 2500 MPa at the same stress level. Figure 7 further shows that the effectiveness

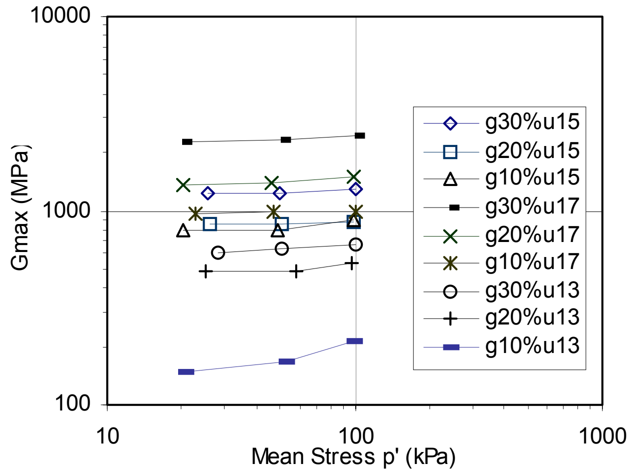

Figure 7 Effect of cement content and unit weight on G_{max}

of a given amount of cementation increases dramatically with the dry unit weight. The figure shows that the three curves for gypsum contents of 10%, 20% and 30% for γ_d = 17 kN/m^3 lie above the curves for γ_d = 15 kN/m^3, which in turn lie above the three curves for γ_d = 13 kN/m^3. Another feature of the results shown in Figure 7 is the independence of G_{max} from the effective confining stress. This is in contrast to the strong dependence of G_{max} on mean effective stress for uncemented sands. The general pattern of behaviour shown in Figure 7 has been reported in several other studies (e.g. Fernandez & Santamarina, 2001).

Using the data from all the G_{max} measurements covering the full range of cement contents and unit weights a best fit relation has been formulated for the gypsum cemented sand. This relation has the form:

$$\left(\frac{G_{max}}{p_r}\right)_{cemented} = \left(\frac{G_{max}}{p_r}\right)_{uncemented} + \left(\frac{G_{max}}{p_r}\right)_{*} \qquad (3)$$

where the uncemented term is given by Equation 2 and

$$\left(\frac{G_{max}}{p_r}\right)_{*} = 16047\,(GC)^{1.08} \left(\frac{p'}{p_r}\right)^{0.01} e^{-2.42} \left(1+\frac{q}{p'}\right)^{0.02} \qquad (4)$$

with GC = % gypsum by dry weight. Comparisons between the values of G_{max} predicted by Equation 3 and the experimental data are shown in Figure 8 for a wide range of cement contents and unit weights. For all the curves shown, the specimens were isotropically compressed to 300 kPa before being sheared drained at constant confining stress. Considering the wide range of cement contents and unit weights and the simple power law relations used in Equations 2 and 4 the agreement is very encouraging. Only part of the shear test responses are shown in Figure 8 because, as the specimens approached failure, the discrepancy between the predicted and measured data increased. This can be explained by a breakdown of the cementation bonds as the specimens are sheared. Because of the breakdown of cementation the data used to derive Equation 4 were limited to the isotropic compression stages and the initial linear portion of the stress-strain responses. Although not explored in detail here it can be noted that Equations 3 and 4, coupled with the continuous recording of G_{max} in these tests, enables the degradation of cementation to be estimated as cemented specimens are subjected to a range of stress paths. Mohsin & Airey (2005) have shown that when this procedure is followed the degradation of cement content for the tests reported here follows an exponential decay with shear strain, and the rate of decay is independent of initial cement content.

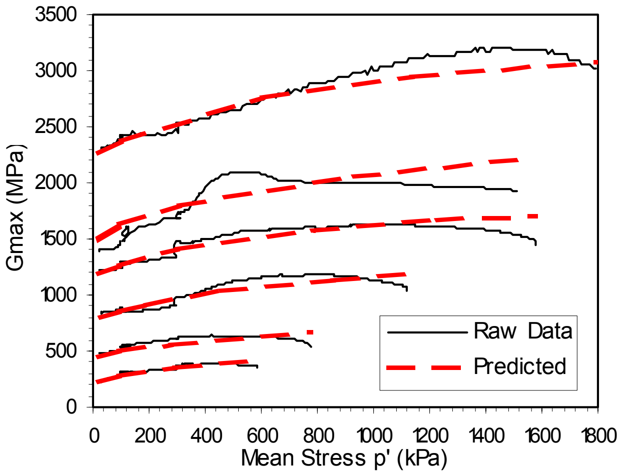

Figure 8 Comparison of measured and predicted G_{max}, Cemented sand

4 DISCUSSION

Many authors have tested cemented sands in the past, although not usually for as large a range of density and cement content as considered in the current study. These authors, listed in Table 1, have generally followed a similar methodology and produced relations to describe the variation of G_{max} with stress, void ratio and cement content.

Table 1 List of studies reporting relations for G_{max} of cemented sands

Study	Key to Figure 9
Current study	1
Shambu (2003)	2
Salvati (2001)	3
Fernandez & Santamarina (2001)	4
Chang & Woods (1992)	5
Saxena et al (1988)	6
Dobry et al (1988)	7
Acar & El-Tahir (1986)	8
Chiang & Chae (1972)	9

Figure 9 shows a comparison of the predictions of the various equations referred to in Table 1 for a gypsum content of 20% and an initial unit weight of 13 kN/m^3. Curve 1 is the prediction from Equation 4 which gives reasonable agreement with the data for this cementation and density. It can be seen that there is a very wide range in the predicted responses for G_{max}. This may in part reflect the different cementing agents used in other studies. To allow for this an attempt has been made to determine the cement content equivalent to a gypsum cement content of 20%. This was based on values of the unconfined compressive strength for different cement contents. As the effectiveness of the cement is likely to be a function of the sand characteristics some differences would be expected, however, the large range in the predictions is difficult to explain.

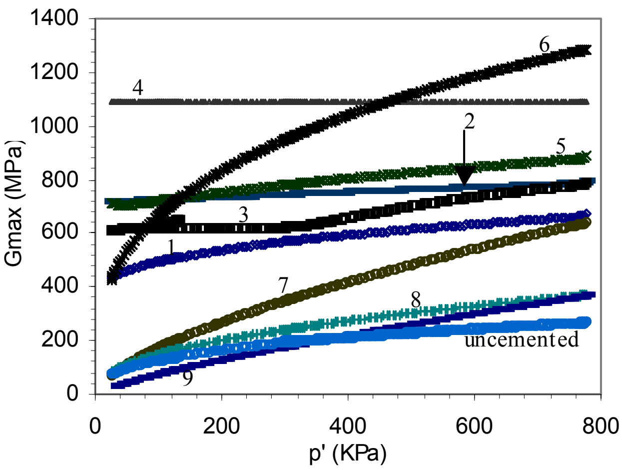

Figure 9 Comparison of published relations between G_{max} and p′ for cemented sands using 20% gypsum and γ_d = 13 kN/m^3

5 SUMMARY

By automating the recording of G_{max} during triaxial tests its variation with stress state, void ratio, and cement content has been investigated. This has enabled new empirical relations for G_{max} to be formulated. The method gives reasonable values for uncemented sands and it appears to offer great promise as a means of tracking cementation degradation.

It has been shown that existing empirical relations for cemented sands, including the relation proposed in this paper, give a wide range of predictions, and consequently they are of little general predictive value. Further study is needed to quantify the factors responsible for the different relationships between G_{max} and cement content.

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