CHAPTER - 9

CONCLUSION AND RECOMMENDATION

9.1 Introduction

The works carried out in this research are briefly summarised, conclusions are drawn and some suggestions for further study are made in this chapter.

The main objectives of this research were to investigate the small strain shear stiffness ($G_{\text{max}}$) behaviour of cemented sand and degradation of cement bonds due to loading. The artificially cemented carbonate sand with different gypsum contents, and Toyuora sand have been studied in this research. Triaxial tests on cemented and uncemented sand were performed to investigate small strain stiffness behaviour. Empirical relationships for $G_{\text{max}}$ were established and attempts were made to predict the cement degradation of cemented sand during loading.

9.2 Conclusion

9.2.1 Sample Preparation

The mould and specimen manufacturing technique developed in this study was able to produce uniform and repeatable specimens at various pre-determined densities and gypsum contents. UCS tests to investigate the reliability of the specimens have shown that manufacturing process is satisfactory. This specimen manufacturing technique enabled the effects of cementation and density on the soil behaviour to be examined separately.

9.2.2 Measurement Accuracy

The data acquisition system and accuracy of data played a major role in recording the material response during testing i.e. in compression and in shearing. The accuracy of data depended on the calibrations, resolutions, stability of signals in the hardware and electric noise levels of different measurement devices. Use of a high speed computer (266MHz Pentium CPU), GPIB board and 16bit A/D card enabled reasonably accurate data to be recorded.
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9.2.3 Test Control Program
In this research a triaxial test control program has been modified and rewritten to make the test fully automated. The modifications included subroutines for different stress path test, data logging criteria, on screen display of different stress strain graphs, on screen monitoring of the test, provision for remote control of the tests via internet, provision to remotely access the data during the test, successful incorporation of digital oscilloscope, function generator, bender elements, Hall effect transducers, GDS pressure and volume controllers etc.

9.2.4 Automation of $G_{\text{max}}$ Measurement
In this research one subroutine for cross-correlation technique has been incorporated into the test control programme and automation of $G_{\text{max}}$ measurements has been done successfully using two bender elements. The procedure gives a consistent, reliable and continuous trace of $G_{\text{max}}$ for any stress-path in triaxial testing. The details of this technique have been given in Chapter 5.

9.2.5 Bender Element Performance
The performance of bender element was found to be reliable and consistent in this research subjected to the optimum frequency that has been selected for the tested material and the chosen waveform.

9.2.6 Tests on Toyoura Sand
In this research the validity of automated $G_{\text{max}}$ measurements procedure were checked by performing the triaxial tests on Toyoura sand. The results have been compared with other published data on this sand and the data from this study matched well with published data indicating the reliability of the new method.

9.2.7 Tests on Uncemented Carbonate Sand
Tests on uncemented sand paved the way to understand the behaviour of cemented carbonate sand. Test results on uncemented carbonate sand constituted the part of $G_{\text{max}}$ relationship of cemented carbonate sand.

9.2.8 Creep Triaxial Test
The effects of creep at different stress levels (S) were investigated on cemented carbonate sand. It was found that creep causes increase in axial and volumetric strain, loss of cementation and $G_{\text{max}}$ decreases with the increase of stress level during creep period.
9.2.9 Effect of Density
$G_{\text{max}}$ and peak deviator stress increase with the increase of density for cemented carbonate sand and for the same degree of cementation.

9.2.10 Effect of Cementation
$G_{\text{max}}$ and peak deviator stress increase with the increase of cementation and for the same density cemented carbonate sand. It was observed that degradation of cementation hence reduction in $G_{\text{max}}$ occurs from the early stage of shearing.

9.2.11 Compression or Expansion Behaviour
$G_{\text{max}}$ response for isotropic compression for Toyuora sand and uncemented carbonate sand is similar i.e. $G_{\text{max}}$ increases with the increase of $p'$. But the isotropic expansion response of $G_{\text{max}}$ for Toyuora sand and uncemented carbonate sand is not similar. For Toyuora sand during isotropic expansion $G_{\text{max}}$ follow the same path as of isotropic compression. But for uncemented carbonate sand during isotropic expansion $G_{\text{max}}$ follows the path above the isotropic compression. It suggests that there occurs some plastic volumetric strain at end of isotropic compression.

9.2.12 Small Strain Behaviour
At very small strains during shearing $G_{\text{max}}$ remains unchanged for cemented carbonate sand. The stress strain behaviour for Toyuora sand and cemented or uncemented carbonate sand were observed to be linear.

9.2.13 Shearing Behaviour
For Toyuora sand and uncemented carbonate sand $G_{\text{max}}$ increases during shearing with axial strain up to point, after that $G_{\text{max}}$ starts to decrease and reach to an ultimate state of $G_{\text{max}}$. This threshold point could be the yield point or the peak deviator stress point. But for cemented carbonate sand $G_{\text{max}}$ starts to decrease from the beginning of shearing with the breakdown of cementation. The reduction of $G_{\text{max}}$ accelerates once the sample passes the peak deviator stress point and eventually meets with ultimate $G_{\text{max}}$ state of uncemented carbonate sand.

9.3 Suggestion for Further Study
9.3.1 Different Stress Path Study
This research work concentrated on specimens with three different constant density and three different cement content under a constant effective confining stress i.e. $\sigma_c' = 300$ kPa. The effective confining stress has an important influence on the stress-strain behaviour of both uncemented and cemented soil. Due to the limitations of the triaxial
cell, proving ring and time, tests with higher effective confining stresses than 300 kPa have not been investigated. Therefore it would be interesting and fruitful to investigate the $G_{\text{max}}$ behaviour, degradation of cement content for different effective confining stress and for different stress path and increase the small strain $G_{\text{max}}$ database.

9.3.2 Study of Natural Cemented Sand

In this research only artificially cemented carbonate sand has been investigated. It would be worthwhile to conduct some tests on naturally cemented sand using bender elements and compare the results with this study. It would provide the opportunity to check whether the $G_{\text{max}}$ measurements on artificially cemented sand have been over estimated or not.

9.3.3 Study of Different Cementing Agent

In this research only one cementing agent (Gypsum) has been used to prepare the artificially cemented sand. Therefore stiffness behaviour has been investigated for one type of cemented sand. An investigation of other artificially cemented sands using different cementing agents can be conducted to correlate the degree of cementation between various cementing agents. Also further theoretical study to understand why different cementing agents have different effects.

9.3.4 Investigation of other $G_{\text{max}}$ Measurement Method

In this research a method of $G_{\text{max}}$ measurement has been developed using cross-correlation technique, which is a semi-automatic method. Attempts could be made to explore other methods of $G_{\text{max}}$ measurement, to come up with a fully automated $G_{\text{max}}$ measurement procedure. A fully automated $G_{\text{max}}$ measurement procedure may be practically difficult but it is worthwhile to give a try.
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