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Effects of fines on stress–strain behaviour of sands

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ABSTRACT

A series of bender element tests for small-strain range and stress-controlled dynamic triaxial tests for higher-strain range have been conducted on clean sand and sandy soils sourced from Christchurch, New Zealand. The sandy soils were prepared by mixing clean sand with three different percentages of fines (particle diameter ≤ 75μm) contents. Thus, the testing program was designed to quantify the effects of fines on the shear wave velocity, V_s, stress-strain relationship, and corresponding modulus and damping properties at different relative densities. Shear wave velocity of silty sand is shown to be significantly smaller than the respective values for clean sands at the same void ratio, *e*. However, the difference in the nonlinear behaviour of clean sand and sandy soils was small. For loose samples prepared at an identical relative density, the behaviour of clean sand was less nonlinear as compared to sandy soils with higher fines content. This difference in the nonlinear behaviour of clean sand and sandy soils was negligible for dense soils. In order to establish a common basis for comparison of behaviour of clean sands and sands with fines, equivalent granular void ratio, e^*, is employed. Therefore, modelling of the variability of shear wave velocity, modulus reduction and damping curves versus void ratio for clean sands and sands with fines, irrespective of their fines content, is achievable.

Keywords: fines content, stress-strain, shear wave velocity, shear modulus, damping, equivalent granular void ratio

1 INTRODUCTION

Soil properties that exert considerable influence on wave propagation include stiffness, damping, Poisson's ratio, and density. Of these, stiffness which is proportional to shear wave velocity V_s, and damping *h*, are the most important. Because of nonlinear nature of stress-strain behaviour of soils, the stiffness and damping of soils change under dynamic load conditions, with increasing strain amplitude. While these properties are not dynamic per se, the term "dynamic soil properties" is commonly used in the geotechnical earthquake engineering field to describe soil stiffness and damping.

Nonlinear dynamic soil properties can be influenced by different factors. These factors can be grouped into two categories: i) loading conditions and, ii) material type. Considerable attention has been given to the characterization of soil modulus and damping properties of different soil types under varying load conditions and soil type. These include the influence of strain amplitude, mean effective confining pressure, soil type (plasticity index), loading frequency, and number of cycles, among others (Darendeli 2001; Iwasaki and Tatsuoka 1977; Seed and Idriss 1970; Stokoe et al. 1999). Previous studies however have not systematically examined the influence of fines content on shear wave velocity, V_s, stiffness, *G*, and, damping, *h*, of sands.

Generally, shear modulus, *G*, decreases with increasing strain amplitude. The relationship between shear modulus and shearing strain amplitude is commonly characterised by shear modulus reduction curve or a normalized shear modulus attenuation curve. Hardin and Drnevich(1972) and Darendeli (2001) have reported a list of parameters and their relative importance in terms of affecting normalized modulus reduction curve. Strain amplitude, mean effective confining pressure, soil type and plasticity have been found to be the most important factors exerting a great influence on the shape of normalized curves.

Moreover, the nonlinearity in the stress-strain relationship results in energy dissipation per cycle of loading and hence an increase in material damping ratio, *h*. The main source of energy dissipation is friction between soil particles in addition to viscosity. Hysteretic damping increases with increasing strain amplitude (*Figure 4*). In addition to important factors influencing normalized modulus reduction curves, the influence of number of loading cycles is also found to be significant for damping ratio curve (Darendeli 2001; Hardin and Drnevich 1972).

Shear modulus at small strains is referred to as small-strain shear modulus, G_{max} or G_0. Various types of laboratory techniques have been developed to measure the small-strain shear modulus, G_{max} (e.g. torsional shear and resonant column tests). Beside these techniques, wave propagation methods (e.g. ultra-sonic and bender element tests) have also drawn an increasing attention in determination of soil modulus; after determining the wave propagation velocity, the small-strain shear modulus can be calculated as:

$$G_{\max} = \rho . V_s^2 \tag{1}$$

where ρ is soil density and V_s is shear wave velocity. Therefore parameters affecting shear wave velocity can directly affect maximum shear modulus and vice versa. Moreover, previous studies (Hardin and Drnevich 1972) have reported that for many types of soil G_{max} can also be calculated from the general expression:

$$G_{\max} = A . f(e) . (OCR)^K \bar{\sigma}_0^n \tag{2}$$

where A is a constant, e void ratio, OCR overconsolidation ratio, K is dependent to plasticity index, σ_0 mean principal effective stress and n is a fitting parameter. Hence, it is observed that void ratio and mean principal effective stress are the most important factors influencing the variation of G_{max}.

Since void ratio is one of important factors influencing modulus, it is commonly used as a state variable to determine dynamic properties of soil. However recent studies show that it may not be a good parameter for characterizing the behaviour of sands in the presence of fines content. This is due to the fact that void ratio can be regarded as an index of mass density whereas mechanical properties of soil such as stiffness are functions of grain contact density (i.e. a measure of transfer of intergranular forces) (Thevanayagam and Mohan 2000). To obtain single trends regardless of fines content, the concept of equivalent granular void ratio can be utilized (Thevanayagam and Liang 2001). Hence, a unique value of equivalent granular void ratio, e^*, for sand with varying fines content exist which can be correlated to e.g. a unique shear wave velocity.

$$e^* = \frac{e + (1-b) f_c}{1 - (1-b) f_c} \tag{3}$$

where b is the fraction of fines content which is active in the transfer of force between grains and f_c is fines content. The common method for obtaining b-value is back calculation. Therefore, a value of b that lets e.g. the shear wave velocity be similar at a constant value of e^*, independent of the soil fines content, is desirable (e.g. more details in Cubrinovski and Rees 2008; Rahman et al. 2008).

Particular attention is given in this paper to the effects of fines content on shear wave velocity, normalized shear modulus and damping curves. Moreover, in order to establish a common basis for comparison of behaviour of clean sands and sands with fines, equivalent granular void ratio, e^*, is employed.

2 EXPERIMENTATION

A series of cyclic drained triaxial tests have been conducted on sand obtained from Fitzgerald Avenue Site in Christchurch, New Zealand. Samples were prepared with variable fines content: 0%, 10%, 20% and, 30%. Each specimen was re-used for testing because of limited material available. The tested soil was dried and gently ground after each test. The details of testing material and procedure are given below.

2.1 Tested Material

Clean sand and fines content were sourced from Christchurch, New Zealand. Fine silty particles (particle diameter ≤ 75μm) were found not to be plastic. The table below lists the properties of granular material and finer material.

Table 1: The properties of the material tested

Material	f_c (%)	D_{50}[a] (mm)	D_{10}[a] (mm)	e_{max}	e_{min}
FB-0	0	0.168	0.089	0.935	0.628
FB-10	10	-	-	0.908	0.579
FB-20	20	-	-	0.882	0.528
FB-30	30	-	-	0.855	0.427

[a] After Rees (2009)

2.2 Experimental Procedure

A Seiken Inc. dynamic triaxial equipment combined with bender elements was used in this work. The confining pressure was kept constant at a value of 100 kPa. Compression-extension cycles were imposed by a Servo controller at a constant frequency under drained conditions. The force applied to the specimen and the displacement at the top of the specimen was recorded in addition to cell pressure and volume change. For very low shear strain range a pair of bender elements were utilized to calculate shear wave velocity.

Moist tamping method was used for specimen preparation. A total of 10 layers of predetermined quantities of moist soil were worked into a prescribed thickness of ~10mm. CO_2 was percolated up through the specimen using pressure. The percolation was continued for a period of 30 minutes for low fines content soils, or up to two hours for the soils having higher percentage of fines. Then de-aerated water was flushed through the sample and then it was saturated using a 100 kPa back pressure and left overnight. The soil sample was considered saturated when the Skempton *B*-value was equal to or more than 0.95. Maximum and minimum void ratio attainable by this method was variable for sands with different fines content (Table 1).

3 EFFECTS OF FINES ON SHEAR WAVE VELOCITY

The bender element method was originally developed by Shirley in 1975 to obtain shear wave velocity V_s, and hence small strain shear modulus G_{max}. The use of bender element to measure shear wave velocity is popular due to its simplicity and optimal soil-transducer coupling. Generally there are two parameters to be measured i.e. travel length and travel time. The element's tip-to-tip distance is suggested by previous studies as the travel length (Lee and Santamarina 2005; Leong et al. 2005). While on the other hand, it is not an easy task to obtain precisely the travel time. Different methods are suggested including first arrival time, peak to peak, cross-correlation of input and output signals, and cross-power of transmitter and receiver signals. First arrival and peak-to-peak methods were used in this study and it was found that the difference between these two methods is within 10% error.

Shear wave velocities, V_s, obtained from bender element tests are plotted in Figure 1, versus void ratio for different specimens having variable fines content and void ratio. A linear ($V_s = a + b \, . \, e$) relationship is assumed to exist for the correlation. High value of correlation coefficient ($R^2 > 0.93$) illustrates the good correlation between shear wave velocity and void ratio assuming a linear relationship.

It is noted that shear wave velocity decreases with increase of fines content for specimens having similar void ratio. This is expected due to arrangement of finer particles in the matrix of granular material. It is possible that smaller particles sit in void space created by larger sand grains and do not participate in the transfer of force between particles during travel of sinusoidal wave triggered by bender element. To obtain shear wave velocity values for similar void ratios regardless of fines content, the fines influence factor *b* or the percentage of fines content that actively participate in the force transfer is desirable. Hence the concept of equivalent granular void ratio can be utilized and a unique value of equivalent granular void ratio, *e**, for sand with varying fines content can be obtained that is correlated to a unique shear wave velocity.

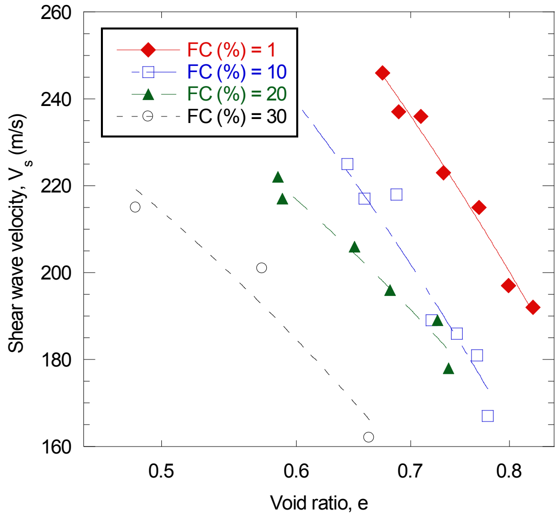

Figure 1. Linear best fit to shear wave velocity vs void ratio

The *b*-value can be obtained by various methods such as back analysis (Thevanayagam and Liang 2001), correlation with soil properties (Kanagalingam and Thevanayagam 2005; Rees 2009); prediction from soil properties (Rahman et al. 2012) etc., however the most common method is back calculation and used in this study. First step is to define the clean sand benchmark curve which in this case is the solid line in Figure 1. Then the equivalent granular void ratio *e** is calculated using equation 3 for all test specimens using *b* = 0.00 – 1.00 in increments of 0.01. The distance *d* from the benchmark response curve for each V_s corresponding to specimen *e** is measured and the obtained *d* value is squared. Mean squared error value will then be evaluated. The lowest value is identified, and corresponding *b* is chosen as the best fit for the fines influence factor (Figure 2a). A *b = 0.57* was obtained using the back calculation procedure and shear wave velocity data.

Employing this value, *e** can be evaluated using equation 3. Shear wave velocity versus equivalent granular void ratio, e*, is then plotted in Figure 2b. A linear line is fit to all test results and compared against the linear best fit of clean sands (dashed line). It is observed that with the adoption of *e** as a state measure, effects of fines can be normalized for sands up to a fines content of 30% and shear wave velocity can be evaluated regardless of fines content.

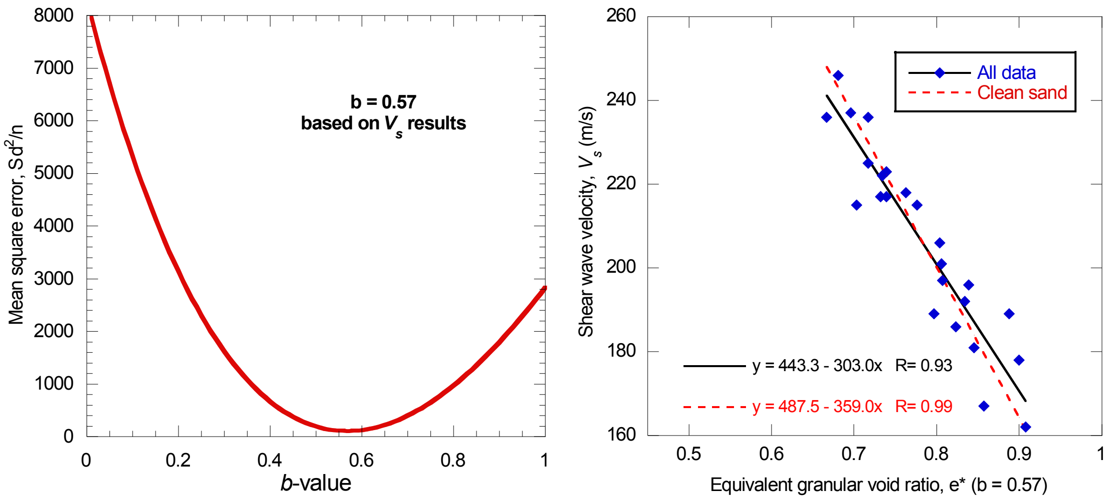

Figure 2. a) Determination of the best fit b-value based on shear wave velocity results, b) Shear wave velocity vs equivalent granular void ratio with b = 0.57

4 EFFECTS OF FINES ON NORMALIZED MODULUS REDUCTION AND DAMPING CURVES

For the sake of brevity only normalized modulus reduction curves are plotted for two different density states, i.e. medium loose, and dense in Figure 3. The secant Young's moduli obtained from cyclic triaxial tests are normalized by measured modulus value at strain ε = 0.002%. However, it is possible to evaluate shear modulus reduction curves assuming a Poisson's ratio for soil. The normalized modulus curves in Figure 3 give good indication of how fines can affect the nonlinearity in soil. It may be noticed that the effect of fines content on these curves is not significant especially for denser specimens. A somehow more linear behaviour is apparent for sand samples with lower fines percentage i.e. slower reduction with increase of strain level whilst they even have higher void ratios in these figures. General tendency for modulus curves is in comparison with the trend found for shear wave velocity correlation with void ratio. It should be noted that the curves in Figure 3 are normalized curves; fine particle can have a significant influence on the shape of modulus reduction curves similar to the effect on shear wave velocity (Figure 1).

It is illustrated in Figure 3 that for strain levels higher than about ε = 0.1%, the curves are coming to a single curve regardless of fines content existent in the sand matrix. This means that sands may exhibit similar behaviour independent of their fines content at higher strain levels.

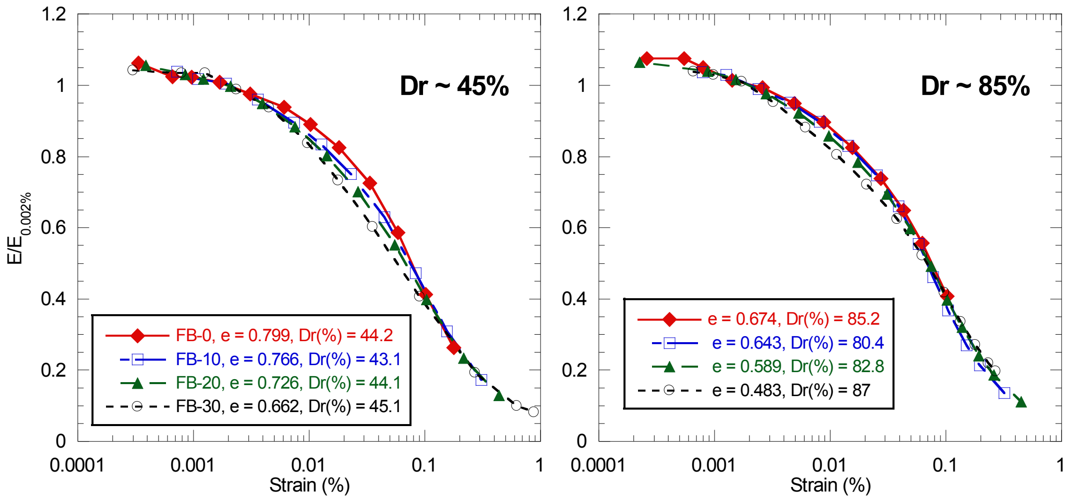

Figure 3. Normalized curves for loose and dense sands with varying fines content

A similar trend was found in the influence of fines content on damping ratio curves. In Figure 4 damping ratio curves are plotted for similar relative densities (i.e. Dr = 45 & 85%). Higher damping ratio is observed for sands with higher fines although in this case they are prepared with lower void ratios.

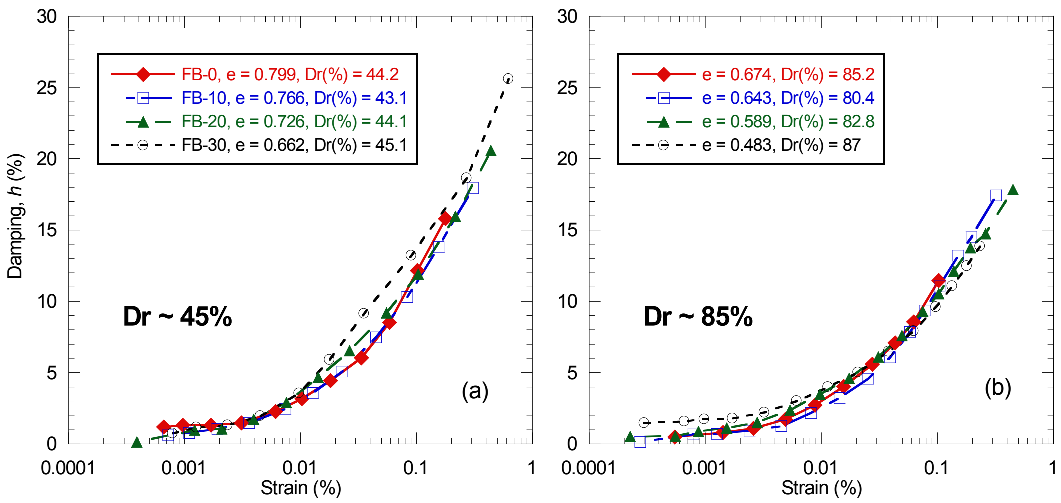

Figure 4. Damping curves for loose and dense sands with varying fines content

5 CONCLUSION

A series of cyclic triaxial tests on sandy soils with variable amount of fines were used to study the effects of non-plastic fines on dynamic properties of sands sourced from Christchurch, New Zealand. The findings can be summarized as follows:

- Shear wave velocity reduces as fines are added to clean sand. Employing equivalent granular void ratio concept, it is possible to find a unique shear wave velocity equation regardless of fines content
- Fines content have marginal influence on normalized modulus reduction and damping curves. However, clean sands exhibit a somehow more linear behaviour i.e. slower reduction with increase of strain.
- Modulus reduction curve collapses to single trends for higher strain levels showing a similar behaviour regardless of fines content at strain higher than ε = 0.1%.

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