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SHEAR WAVE VELOCITY DEVELOPMENT IN NATURAL SAND UNDER TRIAXIAL LOADING

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ABSTRACT

Accurate definition of shear wave velocity (Vs) and small shear modulus (G_{max}) is of high importance for solving any kind of geotechnical problems using modern software solutions. Abundance of experimental results have been accumulated to define the initial maximum shear modulus, however the interpretation of shear wave data measured in deformed/sheared soil has not been considered so far. This study used a triaxial apparatus equipped with bender elements to monitor the development of Vs during triaxial experiments of the cohesionless natural sand. Sandy soil specimens were prepared using wet-tamping method varying the initial relative densities, from Dr=30% to Dr=80%, then confined at four levels of initial effective stress p0 = 50, 100, 200 and 400kPa before application of loading. Loading rate of 0.2mm/min was applied in drained and undrained conditions, while the Vs was monitored during the tests for defined points of axial deformation. The experimental results revealed that the Vs values for the specimens in drained conditions tend to approach each other and merge at large axial strains. Additionally, the axial strains at which the peak Vs is measured is found to be aligned with the axial strain at which the specimen transfers for compaction to dilation. In the case of undrained monotonic test, the peak values of Vs are occurring for higher axial strain values, while the merge of results is not measured at least not within the observed range of 15% axial strain. For both sets of results significant density dependence is noticed, more pronounced in the case of undrained conditions.

Keywords: shear wave velocity, bender elements, triaxial experiments, sand sample.

INTRODUCTION

Small-strain shear modulus (G_{max}) is the fundamental parameter required for dynamic analyses of various geotechnical problems. Accurate determination of G_{max} is essential for ensuring reliable modelling of soil behaviour under different loading conditions. Among the various methods available for determining shear modulus, the use of shear wave velocities (V_s) has emerged as the most widely adopted and reliable approach. Shear wave velocity measurements provide a non-destructive and highly accurate means of evaluating the small-strain stiffness of soils, making them an essential tool in geotechnical and seismic engineering.

In geotechnical engineering, the use of bender elements (BE) to measure shear wave velocity (Vs) was first introduced by (Shirley and Hampton, 1978). Since then, numerous researchers have developed and implemented bender element systems in their laboratories, applying them to a wide range of soil types (Deniz, 2008), (Piriyakul, Pochalard, 2012), (Suwal, Kuwano, 2013). For verification of accuracy and reliability of the BE method, techniques such as resonant column tests and torsional shear tests have been extensively used (Dyvik, Madshus, 1985), (Youn, Jun-Ung et al., 2008). One of the key advantages of bender elements is their non-destructive nature, which allows repeated measurements to be taken throughout the course of an experiment. This capability enables researchers to monitor the evolution of shear modulus over time, providing valuable insights into soil behaviour under various loading conditions (Dutta et al., 2020). Despite the widespread application of bender elements, comprehensive studies investigating the propagation of S-waves in both intact and sheared/deformed soils remain limited in the literature.

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The small-strain shear modulus (G_0) is commonly determined using the following equation (1):

$$G_o = \rho V_S^2 \quad (1)$$

where ρ represents the dry density of the soil sample, and Vs is the shear wave velocity. This equation is derived from the theory of elasticity under the assumption that the soil behaves as an isotropic and homogeneous medium. However, there is no universal agreement on its applicability when soils undergo shearing beyond the small-strain elastic range. Due to these uncertainties, the present study focuses its analysis on terms of shear wave velocity rather than directly relying on the small-strain shear modulus equation.

MATERIAL AND TESTING PROGRAM

The soil material used in this study represents a natural fluvial sand, the so-called "Skopje sand", that has been frequently tested in the laboratory for dynamics of soils and foundation, UKIM-IZIIS and a lot of reports have already been published using this sand (Bojadjieva, 2015), (Kitanovski, et al. 2023). It consists mainly of silica oxides (about 78%) with particles of subangular shape. With only 2% fines it is highly uniform with mean grain size of d_{50}=0.26mm and a uniformity coefficient Cu=1.8. The void ratios were determined using ASTM D4253-00 standards, where e_{min}=0.51 and e_{max}=0.95, at mean pressure p=0kPa. Since it is a natural sand, small differences in each batch can be expected.

The testing program is consisted of two groups with 12 experiments paired by the drainage conditions (Table 1). All soil samples in the triaxial apparatus were reconstituted using the wet-tamping method with an initial water content of 3% (Tatsuoka et al., 1986), height /diameter ratio of around 2, into roughly three groups of initial relative densities. To achieve a better saturation, all samples were first saturated using CO2 and then deaired water was applied to a B-value≥0.95. Consolidation of the soil specimens was done at four levels 50, 100, 200 and 400kPa until stabilization of the volume change. The monotonic load was applied using deformation control with a rate of 0.2mm/min.

Table 1 Soil properties, parameters, compaction state

Effective stress (KPa)	Relative density Dr (%)		
Monotonic drained tests			
50	32.03	56.50	73.00
100	27.14	48.15	74.65
200	33.38	53.53	74.19
400	31.14	47.21	64.00

Effective stress (KPa)	Relative density Dr (%)		
Monotonic undrained tests			
50	31.89	52.15	77.10
100	33.88	54.36	72.32
200	32.64	50.02	76.89
400	35.86	59.62	78.41

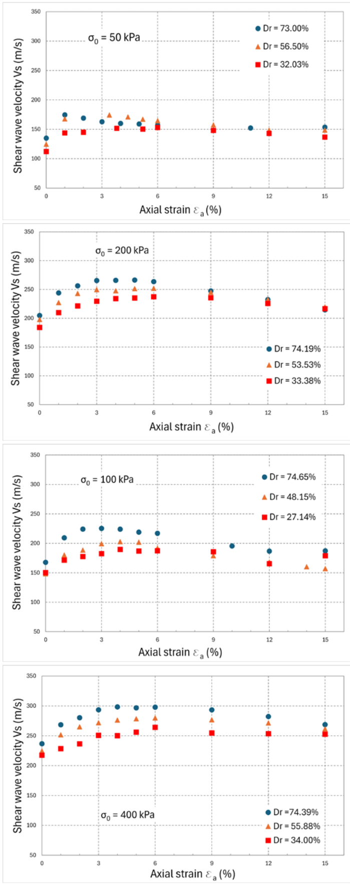

Figure 1 *Evolution of shear wave velocity (Vs) with axial strain (ε_a) during drained triaxial compression experiments*

BENDER ELEMENT RESULTS - DRAINED MONOTONIC TEST

The evolution of Vs with ε_a for soil samples under monotonic loading in drained conditions is presented in Figure 1 grouped by the initial effective stress (50, 100, 200 and 400kPa). The initial increase of Vs for axial strain from 0 to 1% is distinct in all cases with a rate between 10 and 25%. This increase is higher for soil sample consolidated with lower values of initial effective stress (σ0) and decreases with the increase of effective stress (Figure 2). In the literature this initial increase in Vs often is attributed to the rise in σ'_1 and thus, the increase in p' (Dutta et al. 2020), (Stokoe et al.,1985). The obtained peak shear wave velocity (Vs,peak) corresponds with axial strain where the specimen progresses from contractive to dilative phase. Styler and Howe [10] noticed the same correlation of Vs,peak when investigating the Fraser river sand. As in the case of volumetric change the axial strain at which the Vs,peak occur is mainly dependent on the initial relative density. The ratio between the initial shear wave value and the peak shear wave (Vs/ Vs,peak) is presented on Figure 3, but no clear trendline can be constructed as the values fluctuate between 0.7 and 0.8. Maybe with additional investigations this dilemma can be resolved.

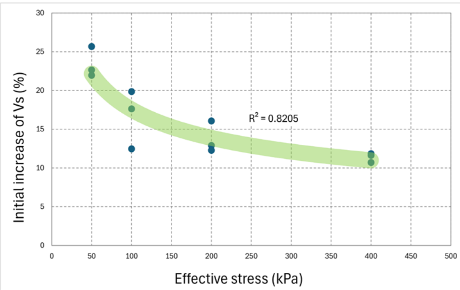

Figure 2 *Dependence of initial increase of Vs from initial effective stress (σ_o)*

Finaly, from Figure 1 we can conclude that for specimens prepared at different initial void ratios (e_0), the shear wave velocity (Vs) values tend to converge during shearing and become similar at higher levels of axial strain. This merger happens sooner in the case of lower σ_0, and it is prolongated as the initial effective stress increases (Dutta et al. 2020).

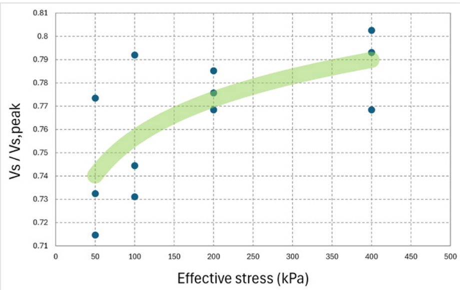

Figure 3 *Dependence of Vs/Vs,peak ratio on initial effective stress (σ_o) - drained tests*

BENDER ELEMENT RESULTS-UNDRAINED MONOTONIC TEST

In the case of undrained monotonic tests, the evolution of shear wave velocity (Vs) with axial strain (ε_a) differs significantly from that observed in drained condition tests (Figure 4). This difference arises due to the pore water pressure buildup in undrained conditions, which affects the effective stress and, consequently, the soil stiffness. The initial distinct increase in Vs observed in the previous case was not present in this set of experiments. The increase is continuous at a steady rate up to certain axial strain after which it flattens and remains more or less constant. Additionally, the convergence of shear wave velocity values didn't occur, at least not within the observed range of 15% axial strain. Figure 5 presents the ratio of Vs/ Vs,peak as a function of initial effective stress. Similar to the previous case, some scattering of results is observed, with indications of a trendline. Although further investigation is needed, it can be noted that the ratio tends to increase with increasing initial effective stress.

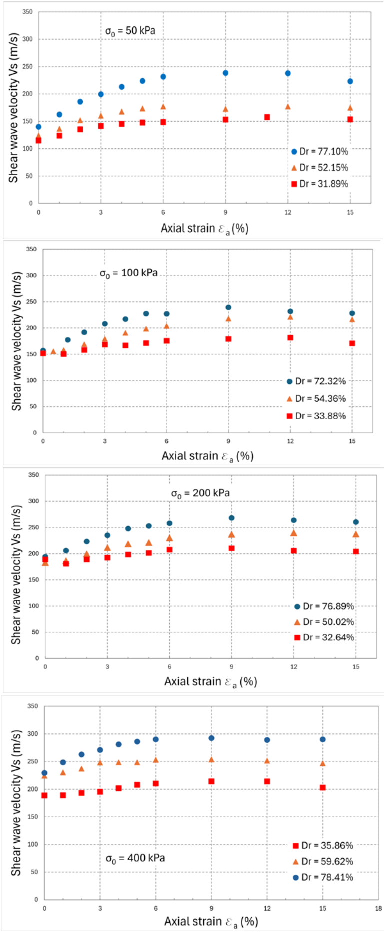

Figure 4 *Evolution of shear wave velocity (Vs) with axial strain (ε_a) during undrained triaxial compression experiments*

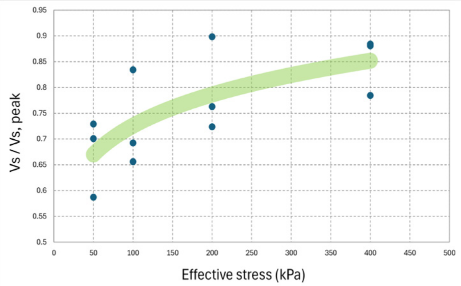

Figure 5 *Dependence of Vs/Vs,peak ratio on initial effective stress (σ_o) - undrained tests*

CONCLUSIONS

This study investigates the development of shear wave velocity during monotonic triaxial compression under both drained and undrained conditions for cohesionless natural material. The experiments were conducted using bender elements mounted on a triaxial apparatus. Based on the experimental results for the tested materials and the applied testing method, the following conclusions can be drawn:

- The test results suggest that the measurement of Vs is significantly affected by the load-deformation history of the intact soil specimen (Lawrence, 1965).
- The initial increase of shear wave velocity in the drained monotonic test is pressure-dependent and tends to decrease as the effective pressure decreases (σ_o). This type of increase of Vs is not observed in the set of undrained experiments.
- In the case of monotonic drained test using the investigated natural fluvial sand, the Vs values for samples prepared with different initial void ratios tend to approach one another and merge at large axial strain. This convergence of shear wave velocities does not occur in the case of undrained monotonic tests.
- In the case of drained monotonic tests the axial strain at Vs,peak is similar to the axial strain at which changes in the specimen's fabric occur, marking the point at which the sample begins to exhibit dilative behavior.
- The increase of Vs in undrained monotonic experiments continues up to certain axial strain after which it remains more or less constant.

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