Velocity anisotropy in rocks and soft sediments can indicate stress anisotropy and be more sensitive to stress in soft sediments than in rocks. Most of the experimental studies on velocity anisotropy in soft sediments have been focused in the S-wave response. However, S-waves are highly attenuated in soft sediments under field conditions. P-waves are less attenuated and frequently acquired using in-situ geophysical methods. Hence, detecting stress anisotropy with P-waves in soft sediments would be of great value.

The purpose of this paper is to show that stress anisotropy can be detected using P-wave velocity anisotropy in unconsolidated sands. We measure stress-induced velocity anisotropy in uniaxial strain tests. These tests can simulate underground compaction in the approximation of no lateral displacement, where the applied compressive stress corresponds to the overburden. To study different textures, the experiments are performed with three different grain sizes and packings. For all packings, we find a linear dependence of velocity anisotropy with stress anisotropy. We also observe a nonelastic behavior of strain-stress.

**Experimental setup.** For this study, we used a polyaxial apparatus (Figure 1) to facilitate velocity and strain measurements in unconsolidated sands. We measured velocity, stress, and strain, during loading and unloading, in three perpendicular directions (x, y, and z) under uniaxial strain conditions. In these tests, a compressive stress was applied in the vertical (z) direction, $\sigma_z$, while the platens in the x and y directions remained fixed.

The samples were held in a cubic aluminum cell of 12.1 cm on each external side and 7.5-9 cm (as the lengths vary from sample to sample) on each internal side. On the six faces of the cell, there were six platens (5 cm × 5 cm × 4 cm) that contained piezoelectric transducers to transmit and record the acoustic P-waves with a central frequency of 1 MHz. The side of each loading piston in contact with the platens, had ball bearing caps to allow for slight unevenness in the sample. The stress measured at the pistons can significantly differ from the stress inside the samples. This discrepancy is due to stress distribution in the samples, and the apparatus configuration. The stress distribution in granular materials is not yet well understood, and either the measured or estimated stresses cannot be taken as absolute values. For the uniaxial strain test, we estimated that $\sigma_z$ inside the sample was 0.2 the stress at the piston in the z direction. The stresses in x and y, $\sigma_x$ and $\sigma_y$, were the same inside the sample and at the pistons. Here, we report our results using the estimated stresses inside the samples. These stresses for $\sigma_z$ (0-8 bars) correspond to the first 30 m of depth.

**Samples and sample preparation.** We used three dry sands: Two beach sands, one with an average grain size of 0.25 mm and grain density 2.606 g/cc and another with an average grain size of 0.39 mm and grain density of 2.629 g/cc, and a construction sand with an average grain size of 0.91 mm and grain density 2.613 g/cc (Table 1). The initial porosity was 0.45, 0.42, 0.45, 0.42, 0.41.
and 0.41 for the finest-grained sample, the fine-grained sample, and the coarse-grained sample, respectively.

In the sample preparation, we poured the grains vertically into the cell and tamped the sand pile. We found that the finest-grained sample showed natural stratification, with roughly horizontal layers. This natural stratification has been seen in mixtures of (a) large rounded grains and small rough grains, and (b) various grain sizes with similar grain shapes. It has also been shown that this stratification is mechanically unstable. Finally, the fine-grained sample showed slight stratification, and the coarse-grained sample showed a more random texture.

**Grain size effect and porosity.** Grain size and porosity seem to affect the \( V_p \) response. Figure 2a shows \( V_p \) in the z direction (\( V_{pz} \)). Velocities in the coarse-grained sample are slightly higher than velocities in the other two samples. Higher velocities observed in the coarse-grained sample appear to be related to both porosity and grain size. The coarse-grained sample had lower porosity than the finest-grained sample, while the coarse-grained and fine-grained samples had the same porosity and different grain size (Table 1).

The strain measured at stresses higher than 0.4 bars showed hysteresis for all sands corresponding to nonelastic behavior, in contrast to the elastic behavior found in sands and gravels at stresses lower than 1.5 bars. Figure 2b shows that the finest-grained and fine-grain sample deformed most significantly during the first stress step, which might be due to their initial stratification. The coarse-grained sample, which had more random packing, deformed more gradually.
**Induced stress anisotropy.** As the applied stress increased in the z direction, it induced compressive stresses in the orthogonal (x-y) directions. Figure 3 shows that the induced compressive stresses, $\sigma_x$ and $\sigma_y$, were lower during loading (normal consolidation) than unloading (overconsolidation), which coincides with previous results on stress behavior in soils. The stress hysteresis also corresponds to the strain hysteresis shown in Figure 2b. Grain rearrangements and a tighter packing led to an induced stress accumulation in the x and y directions that remained during overconsolidation.

**Velocity anisotropy.** Figure 4 shows the velocities in the x, y, and z directions as a function of applied stress for (a) the finest-grained sample, (b) the fine-grained sample, and (c) the coarse-grained sample. As previously observed, there was a significant velocity anisotropy in all sands. The highest velocity, $V_{pz}$, was in the direction of applied stress. The other two lower perpendicular velocities, $V_{px}$ and $V_{py}$, were roughly the same but smaller than $V_{pz}$. As pointed out before, the finest-grain sample had a clean stratification. In an isotropic stress field, we might expect the horizontal velocities to be larger than the vertical. These results indicate that stress anisotropy has a more significant effect on the velocity than the textural anisotropy. In addition, velocities during unloading were higher than during loading. This velocity hysteresis was more notable in the directions of the induced stresses (x and y) than in the applied stress direction (z). This coincides with the stress hysteresis pattern found in Figure 3. In addition, our sands showed a faster $V_p$ increase for stresses lower than 3 bars, and a slower $V_p$ increase for stresses higher than 3 bars.

**Induced stress and velocity anisotropy.** We defined relative stress anisotropy ($\Delta \sigma$) and relative velocity anisotropy ($\Delta V_p$) as

$$\Delta \sigma = \frac{\sigma - \text{average}(\sigma_x, \sigma_y)}{\sigma_z} \times 100$$

(1)

$$\Delta V_p = \frac{V_{pz} - \text{average}(V_{px}, V_{py})}{V_{pz}} \times 100$$

(2)

We found that $\Delta V_p$ was almost constant during loading, and it decreased significantly during unloading. $\Delta \sigma$ is consistent with previous work and roughly constant during loading and decreased during unloading. To investigate the relationship between velocity anisotropy and stress anisotropy, we plot $\Delta V_p$ versus $\Delta \sigma$ in Figure 5. For loading and unloading, $\Delta V_p$ varied linearly with $\Delta \sigma$ at $\sigma_z$ higher than 0.4 bars for the finest-grained and coarse-grained samples, and at $\sigma_z$ higher than 1 bar for the fine-grained sample. The finest-grained sand sample, with natural stratification, had higher $\Delta V_p$, evident in Figure 4. The fine-grained, with slight stratification, had the lowest $\Delta V_p$. The coarse-grained, nonstratified sand, had intermediate $\Delta V_p$ between the other two samples. This result suggests that the finest-grained sample originally had a less stable intrinsic anisotropy packing that was broken with the stress anisotropy, an observation consistent with previous descriptions of natural stratification. It also suggests that the slight stratification may be due to layers of segregation that had more mechanically stable packing with lower $\Delta V_p$. The coarse-grained sample seems to be intermediate mechanically stable, with intermediate $\Delta V_p$.

Our results confirm that the change in velocity anisotropy is a consequence of variations in stress anisotropy. During loading, the induced stress, in the x and y directions, increased proportionately with the applied stress while the stress anisotropy remained constant. Consequently, velocity anisotropy also remained constant. During unloading, the induced stresses in the xy plane did not relax proportional to the decreasing applied stress, resulting in a decrease in stress anisotropy. This stress accumulation in the xy plane, during overconsolidation, led to higher velocities in that plane and lower velocity anisotropy.
Conclusions. Our findings have potential application in P-wave seismic studies in soft sediments. We found P-wave velocity anisotropy to be indicative of stress anisotropy in three different sands. Each separate sand sample displayed a linear dependence of velocity anisotropy with stress anisotropy. $V_P$ showed a steep slope at low applied stress and a flatter slope at higher stress. The results suggested that velocity anisotropy is more significantly affected by stress anisotropy than by textural anisotropy. However, the initial texture in the sands seemed to only slightly affect the final stress-induced velocity anisotropy. In addition, porosity and grain size influenced $V_P$, which was higher in the coarse-grained sample (with the lowest porosity) than in the two finer grained samples.

The strain showed ductile behavior during loading and unloading for both sands, complementing to previous studies. Nevertheless, we were unable to discriminate whether the difference in strain was due to grain size, packing, and sorting or some combination of those factors. Future research will study the effect of these factors in the strain as in the velocity anisotropy behavior.


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