Detection of stress-induced velocity anisotropy in unconsolidated sands

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Velocity anisotropy in rocks and soft sediments can indicate stress anisotropy and can 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, σ_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 σ_z inside the sample was 0.2 the stress at the piston in the z direction. The stresses in x and y, σ_x and σ_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 σ_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,

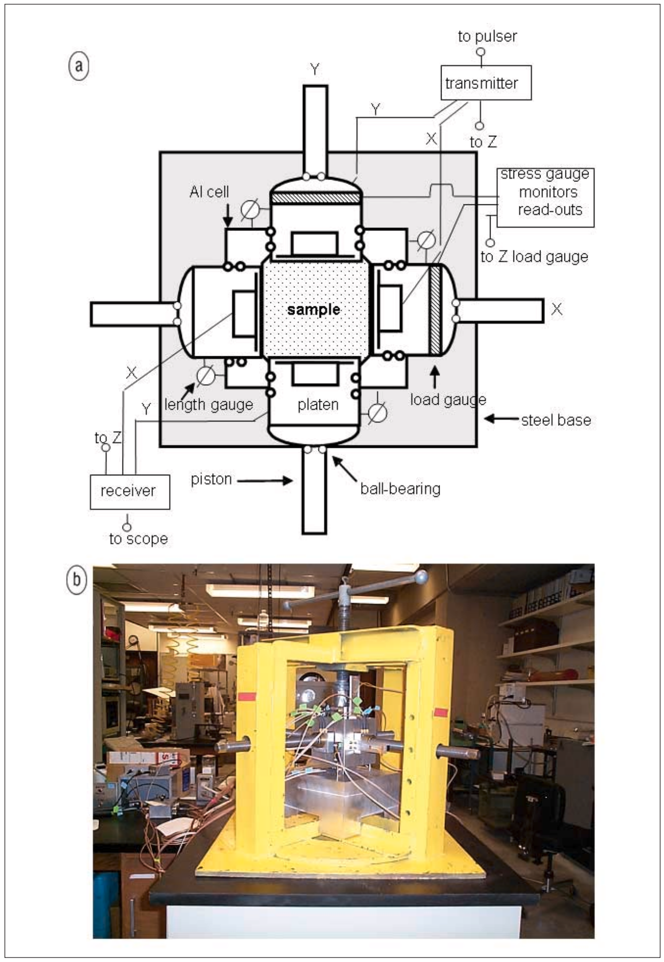

Figure 1. *Polyaxial apparatus: (a) plan view on the x-y plane, and (b) picture.*

Table 1. *Sample characteristics.*

	Samples		
	Finest-grained	**Fine-grained**	**Coarse-grained**
ρ(g/cc)	2.606	2.629	2.613
Grain size average (mm)	0.25	0.39	0.91
Packing	Natural stratification	Slight stratification	Nonstratification
φ	0.45	0.42	0.41

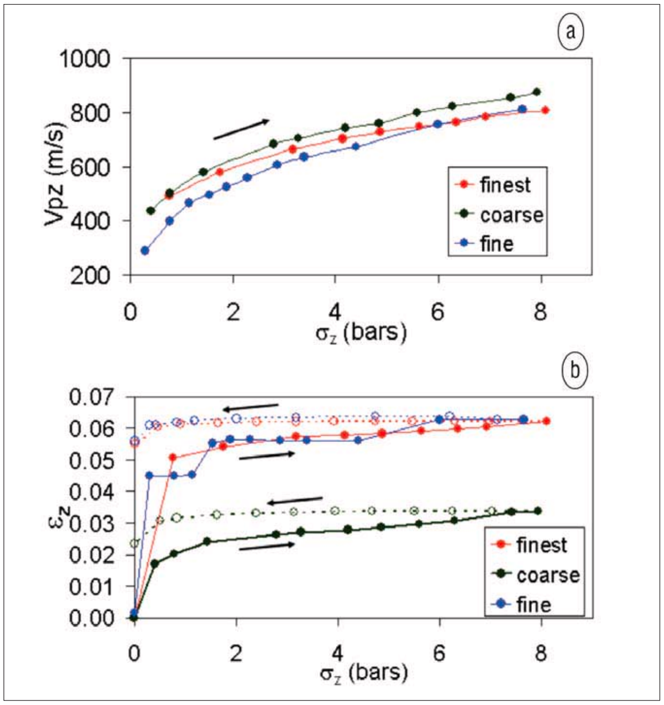

Figure 2. *(a) Compressional velocity in the z direction,* V_{Pz}*, versus* σ_z *during loading. (b) Strain in the z direction,* σ_z*, versus applied stress,* σ_z*, during loading and unloading. (Filled symbols=loading path; open symbols=unloading path).*

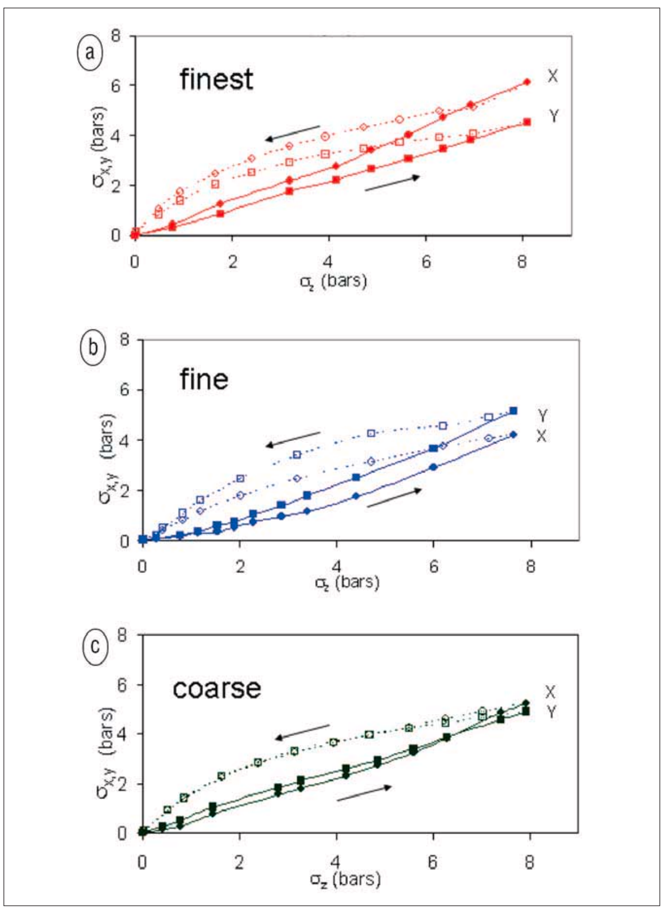

Figure 3. *Applied stress (*σ_z*) and induced stress response (*σ_x *and* σ_y*) for (a) the finest-grained sample,* ϕ*= 0.45, the fine-grained sample,* ϕ*= 0.42, and (b) the coarse-grained sample,* ϕ*= 0.41. (The x and y directions are indicated with circles and squares, respectively; filled symbols=loading path; open symbols=unloading path).*

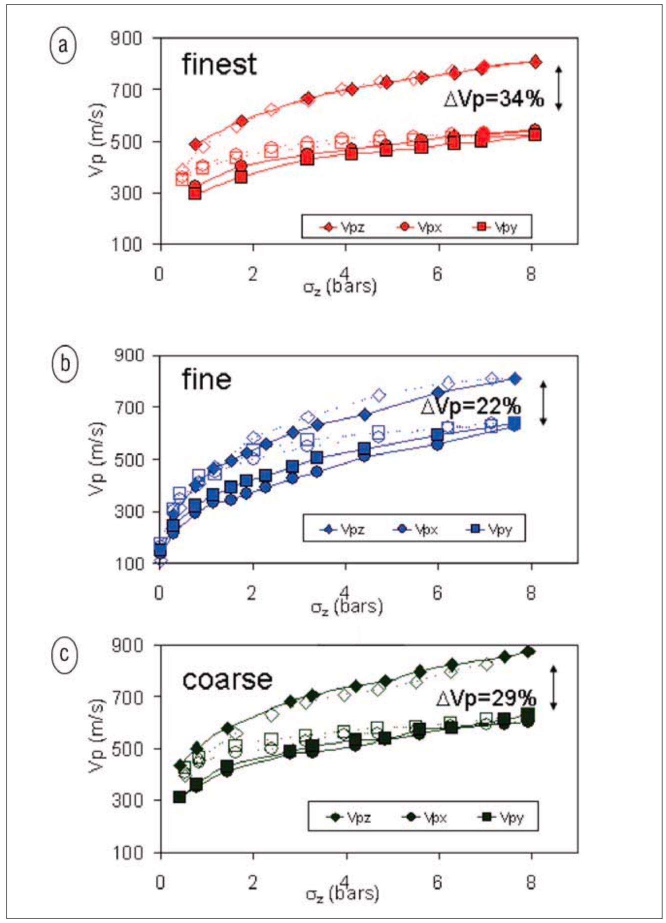

Figure 4. V_P *versus applied stress,* σ_z*, for (a) the finest-grained sample, (b) the fine-grained sample, and (b) the coarse-grained sample. (The x, y, and z directions are indicated with circles, squares, and diamonds, respectively; filled symbols=loading path; open symbols=unloading path).*

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, σ_x and σ_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 (ΔV_P) as

$$\Delta\sigma = \frac{\sigma_z - \text{average}\left(\sigma_x, \sigma_y\right)}{\sigma_z} * 100 \quad (1)$$

$$\Delta V_P = \frac{V_{Pz} - \text{average}\left(V_{Px}, V_{Py}\right)}{V_{Pz}} * 100 \quad (2)$$

We found that ΔV_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 ΔV_P versus $\Delta\sigma$ in Figure 5. For loading and unloading, ΔV_P varied linearly with $\Delta\sigma$ at σ_z higher than 0.4 bars for the finest-grained and coarse-grained samples, and at σ_z higher than 1 bar for the fine-grained sample. The finest-grained sand sample, with natural stratification, had higher ΔV_P, evident in Figure 4. The fine-grained, with slight stratification, had the lowest ΔV_P. The coarse-grained, nonstratified sand, had intermediate ΔV_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 ΔV_P. The coarse-grained sample seems to be intermediate mechanically stable, with intermediate ΔV_P.

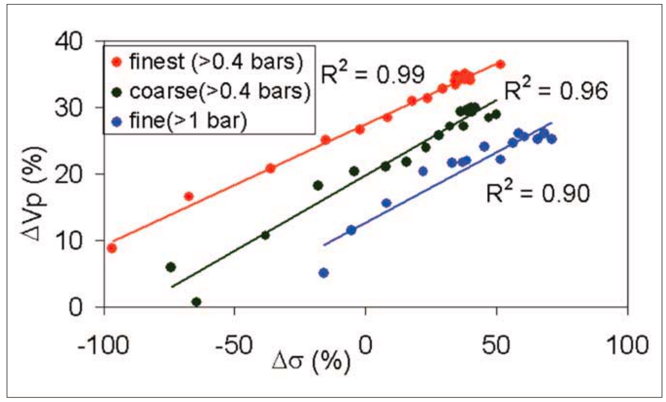

Figure 5. ΔV_P *as a function of* $\Delta\sigma$*: solid lines are linear regression fits through the data of the form* $\Delta V_P = C_1 + C_2\Delta\sigma$*, with* C_1 *= (27.4, 12.7, 19.8),* C_2 *= (0.18, 0.21, 023), and* R^2 *= (0.99, 0.90, 0.96) for the finest-grained sand, fine-grained sand, and coarse-grained sand, respectively. (Red symbols=finest-grained sand sample; blue symbols=fine-grained sand sample; dark green symbols=coarse-grained sand sample).*

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_{Pz}, 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.

Suggested reading. "Comparison of Young's moduli of dense sand and gravel measured by dynamic and static methods" by AnhDan et al. (*Geotechnical Testing Journal*, 2002). "Stratification in poured granular heaps" by Baxter et al. (*Nature*, 1998). "Mechanisms of granular spontaneous stratification and segregation in two-dimensional silos" by Cizeau et al. (*Physical Review E*, 1999). "On the use of multi-directional piezoelectric transducers in triaxial testing" by Fioravante et al. (*Geotechnical Testing Journal*, 2001). "Inherent and stress-state-induced anisotropy in very small strain stiffness of a sand gravel" by Jiang et al. (*Geotechnique*, 1997). "Spontaneous stratification in granular mixtures" by Makse et al. (*Nature*, 1997). "Stress-induced velocity anisotropy in rock: an experimental study" by Nur and Simmons (*Journal of Geophysical Research*, 1969). "Stress anisotropy and wave propagation: a micromechanical view" by Santamarina and Cascante (*Canadian Geotechnical Journal*, 1996). "Stress-induced azimuthal anisotropy in borehole flexural waves" by Sinha and Kostek (GEOPHYSICS, 1996). "Relationship Between Ko and Overconsolidation Ratio—A Theoretical Approach" by Sivakumar et al. (*Geotechnique*, 2001). "Intrinsic and stress-induced velocity anisotropy in unconsolidated sands" by Vega (PhD thesis, Stanford University, 2003). "Acoustic velocity and attenuation of rocks; isotropy, intrinsic anisotropy, and stress-induced anisotropy" by Yin (PhD thesis, Stanford University, 1993). "Stress-induced anisotropic Gmax of sands and its measurements" by Zeng (*Journal of Geotechnical and Geoenvironmental Engineering*, 1999). TLE

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