Stratification in loose sediments and its seismic signature
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Summary
In this paper we present a study on stratification as a source of intrinsic anisotropy in sediments using Vp. We compare velocity anisotropy and textural anisotropy for different sediment packs. We use the spatial autocorrelation function and its variation with direction to characterize the stratification texture from images of samples. We found that velocity anisotropy reveals internal packing.

Introduction
In nature, there is stratification in many sedimentary structures. Stratification in mixtures of sediments that contain clay minerals is probably affected by the crystal structures. In general, these mixtures can be very complex. In this study, we focus on the stratification anisotropy in packing of poured sediments.

It has been found that grain size and shape, and deposition speed determine packing. Makse et al., 1997 and Cizeau et al, 1999 have shown that natural stratification occurs in poured granular mixtures of large rounded and small rough grains. However, Baxter et al., 1998 reported that natural stratification also occurs in mixtures of same grain shape and various grain sizes for a relatively low deposition speed.

Acoustic velocities, which are widely used in geophysical studies, are sensitive to both stress anisotropy (Nur and Simmons, 1969; Yin, 1993; Vega et al., 2000) as well as intrinsic anisotropy. The purpose of this paper is to explore compressional velocity and its relation with packing in poured sediments. We seek to answer whether different packings created with poured sediments are detectable with Vp measured under isotropic stress.

Methods
In order to study Vp and its relation with packing, we used a polyaxial apparatus to measure Vp and strain (ε) at three perpendicular directions in sand and glass bead samples. We also implemented Fourier transform based codes to compute the spatial autocorrelation function and its directional dependence of the sample images.

Experimental procedure
We used a polyaxial apparatus (Yin, 1993), adapted and improved to make Vp and ε measurements in unconsolidated materials (Vega et al., 2003). The principal frequency of the piezoelectric crystals for P-wave generation was 1 MHz. In the experimental tests, we attempted to apply the same stress in all three directions, σz ≈ σx ≈ σy in order to create an isotropic stress. Vp and ε were measured in the Z, X, and Y directions, Vpz, Vpx, and Vpy, and εz, εx, and εy, respectively.

We used a beach sand with an average grain size of 0.25 mm and grain density 2.060 g/cc and glass beads of 0.25-0.3 mm (MO-SCI Corporation), 0.5-0.6 mm and 2.794-3.327 mm (Cataphote, INC). Table 1 summarizes characteristic of the samples used in this study.

All samples were poured in the vertical direction (Z) into the aluminum cell for the polyaxial apparatus. We prepared two different samples with the sand, one was only poured and the other was initially poured and then rotated 90° around the horizontal direction X, i.e. Z and Y directions were exchanged in the final configuration. In addition, we made replicas of the samples in transparent plastic containers and took photographs of them as we cannot take photography inside the apparatus cell. As illustrated in Figure 1, images for the XZ (back and front), ZY (back and front), and XY (top) planes were taken (Figure 1).

We implemented a code that calculates the autocorrelation function of images at azimuth angles between 0° to 180°. For each azimuth, the correlation length is estimated as the lag at which the autocorrelation function falls to e⁻¹ its value at zero lag. Finally, we calculate the anisotropy ratio (AR), defined as the ratio between the maximum and the minimum correlation length. The median correlation length is also estimated.

We processed the images in the ZX plane (back and front), ZY (back and front), and XY (top) for all the samples. We used the following steps: (1) the best and more
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representative image of the sample on the chosen plane and side was selected, (2) the image in gray scale was used, (3) the image histogram was equalized, and then (4) filtered until a reasonable median correlation length of at least two grains was obtained, this process was made to reduce the very small grain scale features but retain the layer stratification textures, and finally (5) the anisotropy ratio and the angles of the autocorrelation anisotropy were calculated. In addition, we created an image of a hexagonal 2D packing and we followed the same process, to validate it with a known granular pack.

Figure 1: Image sketch example for ZX and XY planes (SCS sample).

Results

Velocity anisotropy

Figure 2 shows compressional velocities as a function of the mean applied stress, $\sigma$. As can be seen in the graphs, most of the samples presented velocity anisotropy in. In the SCS sample (Figure 2a), Vpx and Vpy were equal and higher than Vpz. In the SCR sample (Figure 2b), Vpz and Vpy were similar and lower than Vpx. This result indeed revealed different intrinsic anisotropy between the two sand samples, which was expected.

In general, Vpz was lower than Vpx and Vpy for the glass beads samples. In the GB1 (Figure 2c), all three velocities were similar. In the GB2 sample (Figure 2d), the velocity anisotropy behavior was similar to the SCS. Finally, in the GB3 sample (Figure 2e), all three perpendicular velocities were different with a change in Vpx and Vpy at 32 bars.

Textural anisotropy interpretation

We first described the sample images and then estimated their autocorrelation function anisotropy (textural anisotropy), summarized as follow: The SCS sample presented natural stratification as can be seen in Figure 1. Roughly horizontal layers (parallel to the XY plane) are spontaneously created every time that this sand is poured. On the contrary, the resulting packing for the SCR sample was more complex as grains under and after the rotation slipped due to gravity.

Figure 2: Vp versus mean stress, $\sigma$. Vpz, Vpx, and Vpy are the Vp velocities in the Z, X, and Y axes. Sand samples are plotted at the same scale, and glass bead samples are plotted at the same corresponding scale: (a) SCS, (b) SCR, (c) GB1, (d) GB2, and (e) GB3.

The GB1 sample showed light segregation on the ZX and ZY planes, and almost homogenous texture on the XY plane. Moreover, the GB2 seemed to have a high level of segregation on the ZX and ZY planes, and random appearance on the XY plane. In contrast, GB3 sample images presented some layers on the bottom and on the vertical edges combined with some diagonal aligned beads on the ZY and ZX planes. On the XY plane, this sample also showed aligned beads on the walls, and a general orientation to the center. On the whole so far the description of texture in images is qualitative. We attempted to quantify the characterization of stratification texture using the spatial autocorrelation function and its variation with direction.

Figure 3 shows a typical output of the image processing used in this paper: (a) image of the GB1 sample in the XY plane, (b) results on the top right, anisotropy ratio, median correlation length in pixels and in mm, angles with the maximum correlation length, and angles with the minimum correlation length, (c) autocorrelation function of the equalized and filtered image, and (d) autocorrelation function as a function of the lag (correlation distance in pixels) for azimuth angles from 0° to 180°. We found that the maximum values of AR corresponded to the SCS.
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sample in the ZX and ZY planes, and to the SCR sample in the XY plane. Nevertheless, the different values of AR for sand, glass beads, and image pack suggest that AR must be relative to the type of sample, or sample composition.

Figure 4 shows the image processing for a 2D hexagonal pack (numerically created). This packing is also equivalent to hcp (hexagonal close pack) and the ts (tetragonal-sphenoidal pack) in 3D, because in 2D these two packs are not distinguishable. Moreover, its autocorrelation function is periodic. We found that the maximum correlation was parallel to the Z direction, and the minimum correlation was in the direction of the hexagon sides. This result agrees with the velocity anisotropy of an hcp pack, which is $V_{pz} \neq V_{px} = V_{py}$ with ZY symmetry plane. However, it may not always be the case that textural anisotropy coincides with acoustic anisotropy.

**Velocity anisotropy and packing**

We define velocity anisotropy value as the relative difference between two perpendicular velocities

$$\Delta V_{ij} = \frac{V_{pj} - V_{pi}}{V_{pi}} \times 100$$

where $i, j = z, x, or y$, for $i \neq j$. In Figure 5, the velocity anisotropy values at the initial stress are compared with the corresponding AR. We found the same relative tendency of $\Delta V$ and AR for each sample, i.e. for a high $\Delta V$ a relative high AR and so on. We also found two general trends between $\Delta V$ and AR in Figure 5d, excluding GB2 and SCS samples in the ZY plane. One of the trends contains all the data from the XY plane, which suggests that there might be a relation between $\Delta V$ and AR in this plane. However, for the other planes trends are not differentially clear. In addition, $\Delta V$ and AR vary with sample, i.e. with packing type. On the other hand, we also found that $\Delta V$ changes slightly with stress, which might be related with grains rearrangement during loading and unloading. However, it was not possible to calculate AR as function of stress because pictures cannot be taken inside the apparatus cell.

**Discussion**

**Velocity anisotropy**

The velocity anisotropy found in the samples shows that textures in poured sediments present intrinsic anisotropy that can be detectable with $V_p$. For instance, in the SCS sample, with natural stratification, the lower velocity $V_p$ was in the direction perpendicular to the layers. This result indicates that the velocity responds to the internal structure of the sample. In addition, in the SCR, the highest velocity $V_p$ was in the direction of the rotation axis that had some remaining layers. Furthermore, the sample with the lowest $\Delta V$, GB1, was the one with the least visual apparent segregation in the pictures. The sample with the highest $\Delta V$, GB2, was the one with the most apparent segregation. These results also suggest that there is a relation between velocity anisotropy and packing, although most of the packings were complex to describe.

For all the samples, $\Delta V$ was higher than the error of velocity measurement (1%) in 11 of the 15 measures. For that reason, we can assume that the samples presented velocity anisotropy.

![Image processing: (a) GB1 sample image in the XY plane, (b) corresponding AR, median correlation length and azimuth angles, (c) autocorrelation function of the equalized and filtered image, and (d) autocorrelation function as a function of lag for azimuth angles between 0° to 180°.](image)

**Textural anisotropy interpretation**

We found that the SCS sample showed a textural anisotropy that had a higher correlation on the XY plane, i.e. 0° and 180° on ZX and ZY, and lower in the Z direction. This result agrees with the velocity anisotropy in this sample, which was $V_{pz} < V_{px} = V_{py}$. In the XY plane, AR is relatively lower than the other planes. The SCR sample showed a more complex textural anisotropy: there was not a clear direction of the maximum and minimum correlation on the ZX and ZY planes, while the maximum correlation was in the X direction. This last result coincides with $V_{pz} > V_{py}$ for this sample.

The GB1 sample had a textural anisotropy with a maximum correlation perpendicular to the Z direction and a minimum correlation around 30° of Z; on the XY plane there is not a clear orientation. GB2 showed similar textural anisotropy to the GB1 on the ZX and ZY planes but with higher AR.
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This result agrees with the visual observation that the GB2 presented more segregation than GB1. On the XY plane, the maximum correlation was in the X direction but with lower AR to the other planes, which can imply a lower relative anisotropy in XY. GB3 had a maximum correlation perpendicular to the Z direction and the minimum slightly varies from ZX and ZY, around the Z direction. On the XY plane, the maximum and the minimum correlation were close to the Y direction, i.e. no clear textural anisotropy was seen. In general, these results mostly agree with the velocity anisotropy seen in the glass beads samples. That is, the maximum correlation was perpendicular to the Z direction corresponding to a Vpz lower than the Vpx and Vpy.

Conclusions

All the results indicate that velocity anisotropy and grain packing textures are related. The anisotropy ratio calculated from spatial autocorrelation function of images gives an estimation of packing structure. The results also suggest that if there is a relation between ΔV and AR, it might also depend on the sample composition. In other words, it seems that velocity anisotropy is closely associated with the intrinsic texture anisotropy. Thus, if it were possible to separate the intrinsic anisotropy effect and stress anisotropy effect from velocity anisotropy, it would be possible to improve seismic processing and interpretation.

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References


