Soil-type estimation beneath a coastal protection levee, using resistivity and shear wave velocity.

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Summary

Unconsolidated Holocene deltaic sediments comprise levee foundation soils in New Orleans, USA. Whereas geotechnical tests at point locations are indispensable for evaluating soil stability, the highly variable sedimentary facies of the Mississippi delta create difficulties to predict soil conditions between test locations. Combined electrical resistivity and seismic shear wave studies, calibrated to geotechnical data, may provide an efficient methodology to predict soil types between geotechnical sites at shallow depths (0- 10 m).

The London Avenue Canal levee flank of New Orleans, which failed in the aftermath of Hurricane Katrina, 2005, presents a suitable site in which to pioneer these geophysical relationships. Preliminary cross-plots show electrically resistive, high-shear-wave velocity areas interpreted as low-permeability, resistive silt. In brackish coastal environments, low-resistivity and low-shear-wave-velocity areas may indicate both saturated, unconsolidated sands and low-rigidity clays.

Introduction

Established methods for levee assessments involve invasive techniques such as borings and penetration tests. However, invasive techniques are expensive and do not provide the laterally continuous data necessary in geologically heterogeneous depositional environments, such as the Mississippi River Delta. Non-invasive geophysical techniques provide nearly continuous measurements of physical properties that aid in the evaluation of levee safety. The application of resistivity and surface wave analysis to levee evaluation has proven useful in determining changes in lithology, grain size, and water saturation (e.g., Burton and Cannia, 2011 ; Dunbar et al., 2007). An integrated geophysical approach combining shear wave velocity and resistivity provides a more accurate description of soil type than the individual properties alone (Hayashi et al., 2013).

Seismic and Electrical Resistivity Acquisition

Acquisition of seismic data was conducted using an active source and an array of 23 geophones, each possessing a resonant frequency of 4.5 Hz. At each shot point five separate shot gathers were recorded for 26 seconds while the ground was struck by between 7 and 13 hammer blows. Shotpoints were spaced 12 m apart. The acquisition procedure of using multiple energy inputs eliminates the assumption that the surface wave observed in the data originated from the same source wave (Park et al., 2001). Resistivity measurements were acquired using a capacitively coupled resistivity (CCR) system (Geometrics, 2001). The CCR method obtains resistivity measurements in a dipole-dipole configuration.

Figure 1: (Top) Site of investigation is the London Avenue Canal levee in London Park, New Orleans, LA. (Bottom) The long black line marks the location along which we derive resistivity (Figure 5), and shorter white line marks the length of the seismic profile (Figure 7). The locations of the boring logs, B-32 and 3-LUG, are marked with arrows at 128 and 159 meters, respectively, along the profile.

Data Processing

Seismic data were pre-processed using a Common-MidPoint Cross Correlation (CMPCC) workflow (Hayashi and Suzuki, 2004) in order to improve lateral resolution from 12 m to 1.5 m. Dispersion curves were created using the MASW processing technique pioneered by Park et al. (1999), manually picked along the maximum and then inverted for a shear wave velocity profile using a nearest neighbor algorithm (Wathelet, 2008). The 1D shear wave velocity profiles are interpolated together using a kriging method to create a pseudo 2D profile (Figure 2).

The resistivity profile data are combined with the 1D shear wave velocity inversions to generate cross-plots. Cross-plots are combined with US Army Corps of Engineers' (USACE) boring log data and linear interpolations of soil type (USACE, 1989). Linear interpolations are based on the wells intersecting our surveys (Figure 1) and 2 wells (~50-75 m) to the NE and SE.

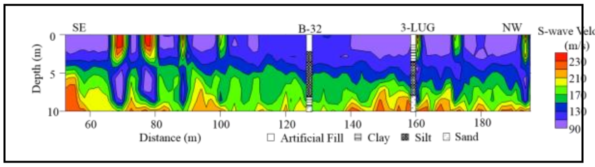

Figure 2: Pseudo-2D shear-wave velocity profile (only where CMPCC fold is greater than 150). Contour interval is 20 m/s. Distance along the x-axis is in the same coordinate system as the resistivity profile. A shallow 0-4 m low-velocity zone thickens to the NW (increasing distance), consistent with the deposition of a lacustrine wedge (USACE, 1989). Low-velocity lenses exist to the SE between 70-80 m.

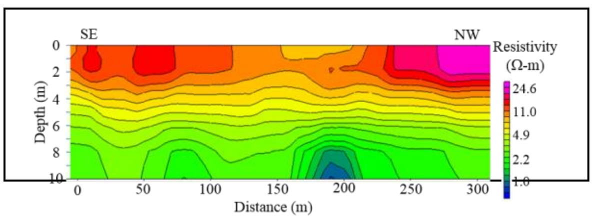

Figure 3: 2D Resistivity profile created from the CCR survey. The resistivity of the soil appears to be vertically partitioned into a resistive layer in the upper 3-5 meters, and a more conductive layer below. The S-wave velocity profile indicates a similar 2 layer model (Figure 2). Also, the deep conductive zone around 200 m matches the higher velocities (Figure 2).

Interpretation

Using a polynomial approximation (Hayashi et al., 2013), soil types can be estimated by a cross-plot of S-wave velocity and resistivity. Predicted soil types correspond well to those described in the boring logs (USACE, 1989**).** We find that 2/3 of sand fall within Hayashi et al.'s (2013) predicted zone, whereas all clay and silt fall in the range of clay; silt was not originally described as a soil type by Hayashi et al. (2013). However, predictions of soil types between borings, determined by only linearly interpolating boring log data do not always match the expected soil types predicted using polynomial approximation. By a simple linear interpolation approach, areas such as the low velocity lenses (~70 m; Figure 2) are interpreted to consist of sand silt and clay, even though the cross-plots alone would suggest the area majority to contain clay. But, because the polynomial approximation does match the soil type observed in the boring sites, we presume it to provide a better estimate.

The phreatic zone could also explain low resistivity zones The resistivity drop at 5 m depth (Figure 3) may likely be caused by the transition to soils under the water table. The deep conductive zone and high shear-wave velocity zone around 175 m along the survey line is indicative of a saturated sand, which matches the observed sands of 3-LUG (Hayashi et al., 2014), and could be saturated by brackish water from Lake Pontchartrain.

Results

Initial cross-plots of electrical resistivity and S-wave velocities (Figure 4) show that deep sands in the boring logs (Figure 2) tend to display higher S-wave velocities and lower resistivity values, whereas clays are slightly more resistive, but provide a lower shear-wave velocity. Clay is the most widely distributed soil type in the cross-plots (Figure 4).

It appears that polynomial approximations created from the Japanese database can be suitably applied to the soils of the Mississippi River delta system. Boring log data fit reasonably well with the Hayashi et al. (2013) polynomial approximation (Figure 4a), where 2/3 of soil samples fall within their respective bounds. In addition, a new demarcation line can be drawn (Figure 4b) to separate sand and silt; for this case, the statistical split of soil type exists at about 2/3 the predicted type. This represents a new classification system that could be used for the Mississippi delta in future surveys.

Discussion

Statistically assessing the soil type is possible using the polynomial approximation method developed for Japanese soils, especially when looking to differentiate sand from finer sediment. However, subdividing clay soils into sub-types still poses a challenge, as clay exhibits a large range of resistivities and shear wave velocities. Clays, and organic clays in particular, pose a risk to the stability of levee foundations during flooding events, as was seen during Hurricane Katrina

Consideration must be given to the relatively small sample size used for this study. The study was limited by the fact that only two boring logs exist along the profile to ground truth soil type estimates. Whereas the soil type integer calculated for the seismic and resistivity data at the boring sites matched well with the boring logs, the linear interpolations should be taken with an expectation for error.

One of the reasons for conducting the geophysical survey is

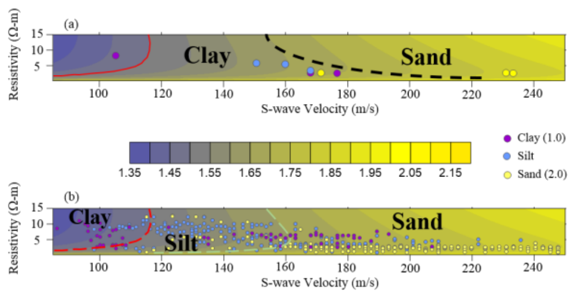

Figure 4: Cross-plots of resistivity and shear wave velocity. The color scale represents a polynomial approximation (Hayashi et al., 2013). Clay and sand soil types are separated by a dashed black line introduced by Hayashi et al. (2013). Colored circles indicate soil types determined either from (a) boring logs or (b) linear interpolations between wells (Figure 1), and placed at their respective coordinates (Vs,resistivity), as determined from Figure 2. The dashed lines (b) are used to demark the zones expected for clay (<1.5), silt (1.5-1.65), and sand (>1.65). In both plots, a red line marks the 1.5 contour.

to detect lateral heterogeneity, and relying only on a linear interpolation between boring sites negates this idea. The quality and error associated with the resistivity and seismic data set contributes to inaccuracies associated with soil type interpretations made by the polynomial approximation.

The lack of additional geotechnical data such as grain size distribution or standard penetrating tests inhibit this study from tying resistivity and S-wave velocity to other geotechnical measurements of foundation soils in the Mississippi delta. Lateral homogeneity is assumed in the direction perpendicular to the survey, as the borings were projected onto the profiles. The seismic data also neglected to use a single source wave during acquisition, and the cross-correlation and processing of 26-second-long traces is a resource-intense method.

Conclusions

The prediction of soil types from shear wave velocity and resistivity is possible on a statistical basis. The polynomial approximation developed for soil types in the foundation soils of Japanese levees can be used to identify soils from the Mississippi river delta. However, the small grain size of the Mississippi delta needs a modified classification system. Further identification of silt from sand and clay predication are possible by further subdivision of the existing polynomial approximation.

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