# RESISTIVITY AND SHEAR WAVE VELOCITY AS A PREDICTIVE TOOL OF SEDIMENT TYPE IN COASTAL LEVEE FOUNDATION SOILS

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## Abstract

Levee foundation soils in New Orleans, USA, are composed of unconsolidated Holocene deltaic sediments. Traditionally, geotechnical tests at point locations can identify the more unstable zones, but cannot predict accurately the laterally heterogeneous facies of the Mississippi delta. Together, electrical resistivity and seismic shear wave studies can aid in the interpretation of different soil types between geotechnical sites. In such highly conductive, coastal soils, resistivity measurements are limited to shallow depths, but remain useful for describing variations in saturation and the presence of clays. Similar studies conducted in Japanese fluvial and Australian calcrete environments do not consider the influence of brackish water in coastal settings.

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 in a coastal setting. Shear wave velocity and resistivity are related to soil properties through Hertz-Mindlin Theory and Archie's Law. 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. Published polynomial approximations to similar cross-plots must be modified for use in the near-surface sediments of the Mississippi River Delta. We present new relationships between soil type, resistivity, and shear wave velocity to distinguish the three main sediment groups found in deltaic environments: sand, silt, and 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 (eg. 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).

The shear wave velocity and resistivity of the sediments in the levee foundation soils are affected by many physical properties. Porosity is a shared physical property used to calculate a soil's resistivity and elastic shear wave velocities, expressed in Archie's Equation (Archie, 1942) and Hertz-Mindlin theory (Mindlin, 1949) respectively. However, other physical properties can influence these measurements. In the case of resistivity, water saturation has a greater effect on conductivity than porosity (Worthington, 1985). However, a 20% change in water saturation will cause less than 2%

change in the shear wave velocity (Dvorkin et al., 1999). We expect to observe high velocity, low electrical resistivity in the case of saturated sands, low resistivity values and low-velocities for clays, and intermediate values of resistivity and velocity for silt. At shallower depth with less saturation, sands and silts should possess higher resistivities, and lower shear wave velocities (Wilkens and Richardson, 1998). Applying this understanding to cross-plots of resistivity and shear wave velocity aids in the interpretation of soil type comprising the levee foundation soils.

## Investigation Site and Data Acquisition

***London Avenue Canal***

Resistivity and surface wave surveys were conducted along the flank of the levee, as a survey along the crest of the London Avenue engineered levee is impractical. The levee bounding the outflow canal consists of buried steel pylons that could affect resistivity measurements. The general design plans from the 1989 construction include boring logs used in this study to ground truth our data (USACE, 1989). The survey site is located near the northern shore of Lake Pontchartrain, a brackish lake connected to the Gulf of Mexico (Figure 1).


**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.

***Seismic Acquisition***

Acquisition of seismic data was conducted using a multichannel survey with an active source and an array of 23 geophones, each possessing a resonant frequency of 4.5 Hz. To make one gather, instead of vertically stacking each individual, shot all channels recorded for 26 seconds while the ground was struck by between 7 and 13 hammer blows. Five gathers were created at each shotpoint to be used for analysis and stacked during processing. 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). This is corrected during processing through cross correlation, discussed later. The geometry of the seismic survey is detailed in Table 1.

**Table 1:** Acquisition Parameters

| **Seismic Method** | |
|---|---|
| Acquisition Date | Jun-1-2012 |
| Source-Receiver offset | 12 -78 m |
| Shotpoint advancement | 12 m |
| Number of shotpoints | 16 |
| Geophone separation | 3 m |
| Geophones | 23, Mark Products L-10B 4.5 Hz Vertical Sensor |
| Seismograph | 24-Channel, 24-bit resolution, R24 Geometrics Strataview |
| Sample Rate, record length | 2000 S/s, 26 s |
| Seismic Source | 7-13 vertical blows: ~15.25 cm x ~15.25 cm x ~2.5 cm (6 x 6 x 1 in) aluminum plate; using ~4.5 kg (10 lb) sledgehammer |
| **Resistivity Acquisition** | |
| Acquisition Date | Dec-17-2013 |
| System | Geometrics OhmMapper: 5 receivers, 1 transmitter; Towed by Ford E-series van |
| Operating Frequency | 16.5 kHz |
| Array Style | Dipole-Dipole |
| Sample Rate | 2 S/s |
| Transmitter-Receiver offset | Short: 10-30 m<br>Long: 20-40 m |
| Receiver Spacing | Short: 2.5 m<br>Long: 5 m |

***Resistivity Acquisition***

Resistivity measurements were acquired using a capacitively coupled resistivity (CCR) system (Geometrics, 2001). The CCR method obtains resistivity measurements in a dipole-dipole configuration. Due to the high conductivity of the soils in the New Orleans area, the skin depth using the Geometrics Ohmmapper is limited by the operating frequency. Using the approximation for skin depth in meters, $500 * \sqrt{\rho/f}$ , where f is the operating frequency, and $\rho$, the average resistivity of the soils, is assumed to be 6.5 ohm-m, then the signal from the OhmMapper should decay to a strength of 1/e, at about 10 m depth. Two surveys using short and long array setups (Table 1) were run and processed together. The longer array assisted in making observations to a depth of 10 m in the foundation soils. Both reverse and forward profiles were collected and processed together.

## 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 meters to 1.5 meters. First, the signal from each receiver is cross-correlated with the others in each original gather, thereby measuring the similarity around a CMP instead of the midpoint of the array. Next, after performing cross-correlations for all gathers at all shotpoints, cross-correlation pairs with the same distance between receivers and sharing a CMP are stacked and then placed into new CMP gathers ordered by increasing spacing around the common midpoint. Finally, CMP gathers are then processed in Seismic Unix (Stockwell, 1999). Dispersion curves were created using the MASW processing technique pioneered by Park et al. (1999), and manually picked along the maximum (Figure 2).

A geometric fold of at least 30, or a CMPCC fold of 150, was required to pick the dispersion curve. CMPCC fold is calculated as the sum of all cross-correlation pairs for all offsets at a given cmp. Geometric fold—the number of cross-correlation pairs with unique shotpoints—are a factor of 1/5 that of the CMPCC fold as a result of obtaining 5 gathers per array. However, the necessary geometric fold of 30 is only established over a distance of 142.5 meters (Figure 3). Dispersion curves are then inverted for a shear wave velocity profile using a nearest neighbor algorithm (Wathelet, 2008). S-wave velocity profiles containing 5 layers over a half space are generated.

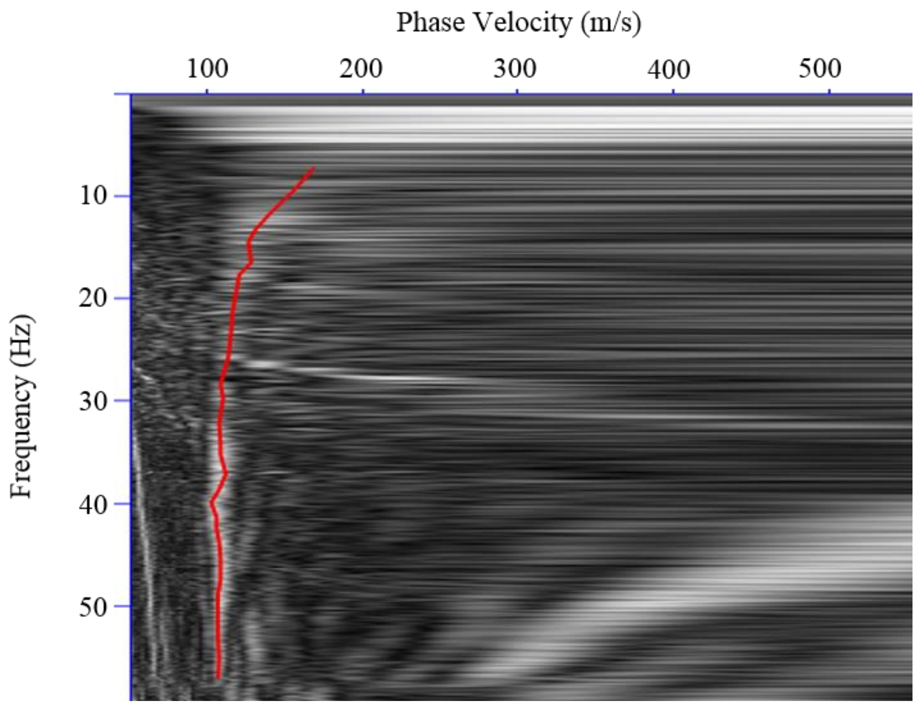


**Figure 2:** Phase velocity analysis of CMP at the boring site for B-32. Dispersion curves were created using the SU program *suphasevel* and gained with *suamp (Stockwell, 1999)*. Increased noise at frequencies below 12 Hz make interpretation of dispersion curves difficult.

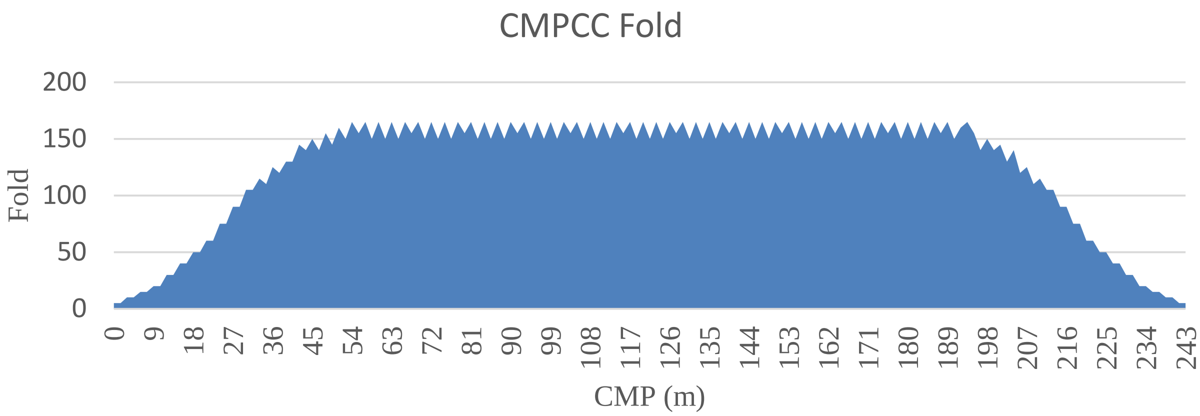


**Figure 3:** CMPCC fold of seismic data, with each acquisition gather treated as a unique event. The idealized zone of data collection (fold > 150) exists between 52.5 and 195 meters. 96 CMPs fall within the zone and are inverted for shear wave velocity.

The resistivity profile (Figure 4) is 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. The 1D shear wave velocity profiles are interpolated together using a kriging method to create a pseudo 2D profile (Figure 5).

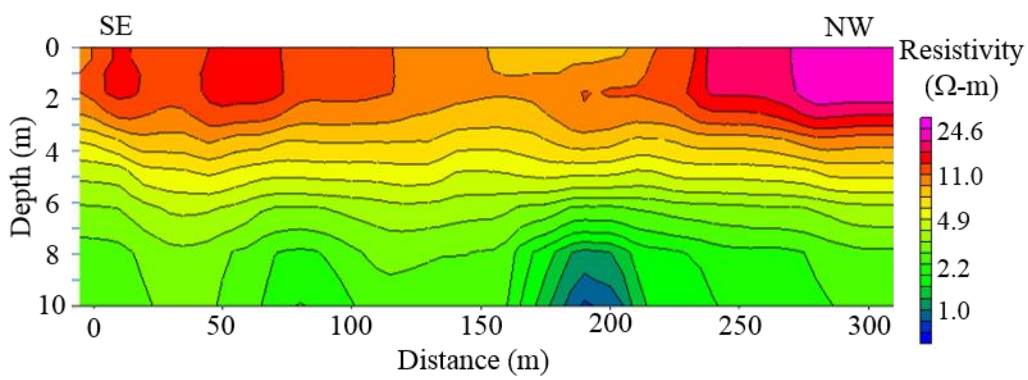


**Figure 4:** 2D Resistivity profile created from the CCR survey. The resistivity of the soil appears to be vertically partitioned into a resistive layer in the upper 3-5 meters, and a more conductive layer below. The S-wave velocity profile indicates a similar 2 layer model (Figure 5). Also, the deep conductive zone around 200 m matches the higher velocities (Figure 5).

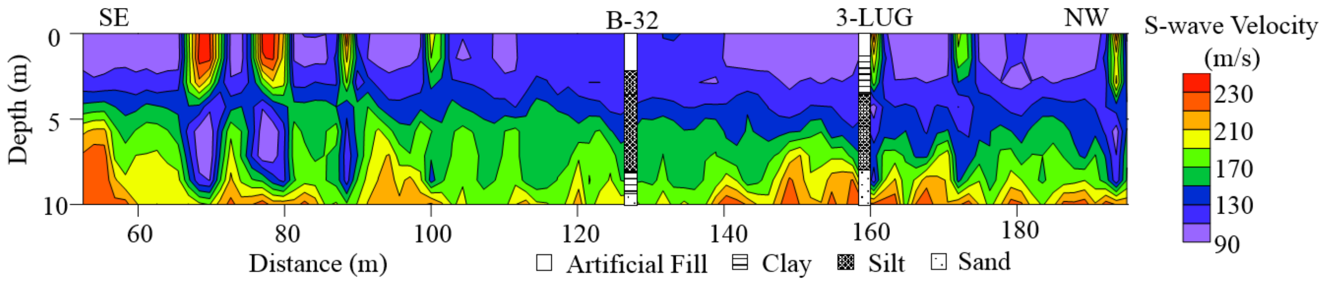


**Figure 5:** Pseudo-2D shear-wave velocity profile (only where CMPCC fold is greater than 150). Contour interval is 20 m/s. Distance along the x-axis is in the same coordinate system as the resistivity profile (Figure 4). A shallow 0-4 m low-velocity zone thickens to the NW (increasing distance), consistent with the deposition of a lacustrine wedge (USACE, 1989). Low-velocity lenses exist to the SE between 70-80 m.

## Interpretation

Using a polynomial approximation (Hayashi et al., 2013), soil types can be estimated by a cross-plot of S-wave velocity and resistivity (Figure 6a); estimated soil types correspond well to the soil types described in the boring logs (USACE, 1989). We find that 2/3 of sand fall within Hayashi et al.'s 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). Whereas the boring log data correspond to the polynomial approximation of soil type, the USACE linear interpolations (1989) do not match with the approximation in every case. Areas such as the low velocity lenses (~70 m) are interpreted by the linear interpolations to consist of sand silt and clay, even though the cross-plots (Figure 6b) would suggest the area majority to contain clay.

The phreatic zone could also explain low resistivity zones (Figure 4). The resistivity drop at 5 m depth (Figure 4) 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 $\rho$ and S-wave velocities (Figure 6) show that deep sands in the boring logs (Figure 5) tend to higher S-wave velocities and lower resistivity values, whereas clays are slightly more resistive, but provide a slower shear-wave velocity. Clay is the most widely distributed soil type in the cross-plots (Figure 6). However, the average values for clay remain, as predicted, on the lower end of the cross-plot spectrum, shown (Table 2).

**Table 2:** Values and standard deviation ($\sigma$) of resistivity and S-wave velocity for each soil type used to generate the cross-plots.

| | Clay | | Silt | | Sand | |
|---|---|---|---|---|---|---|
| | Vs | $\rho$ (ohm-m) | Vs (m/s) | $\rho$ (ohm-m) | Vs | $\rho$ (ohm-m) |
| Mean | 142.4 | 5.9 | 152.0 | 5.9 | 198.5 | 2.8 |
| $\sigma$ | 34.11 | 2.05 | 32.18 | 2.95 | 33.66 | 1.93 |

Boring log data fits reasonably well with the Hayashi et al. (2013) polynomial approximation (Figure 6a), where 2/3 of soil samples fall within their respective bounds (Hayashi et al., 2013). It appears that polynomial approximations created from the Japanese database can be suitably applied to the soils of the Mississippi River delta system. By matching the soil type boundaries to the polynomial approximation and assuming that the soil types from the linear approximation are correct, new demarcation lines can be drawn (Figure 6b). A separation can be made between sand and silt, in which the statistical split of soil type exists at about 2/3 the predicted type (Figure 7). This represents a new classification system that could be used for the Mississippi delta.

## Discussion

Statistically assessing the soil type is possible using the polynomial approximation method developed for Japanese soils, especially when looking to differentiate sand from smaller sediment. However, distinguishing clay soils pose a challenge, as they exhibit 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 (Hicks, 2011, Rogers et al., 2008). It is possible the values identified as clays in the linear interpolation are either silt or a mix of silt and clay. The USACE linear interpolation of soil type (1989) may not be entirely accurate as it does match with the soil types determined by the Hayashi et al. polynomial approximation (2013). The polynomial approximation does match the soil type observed in theboring sites, and is presumed to be a better estimation than the linear interpretation.

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 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.

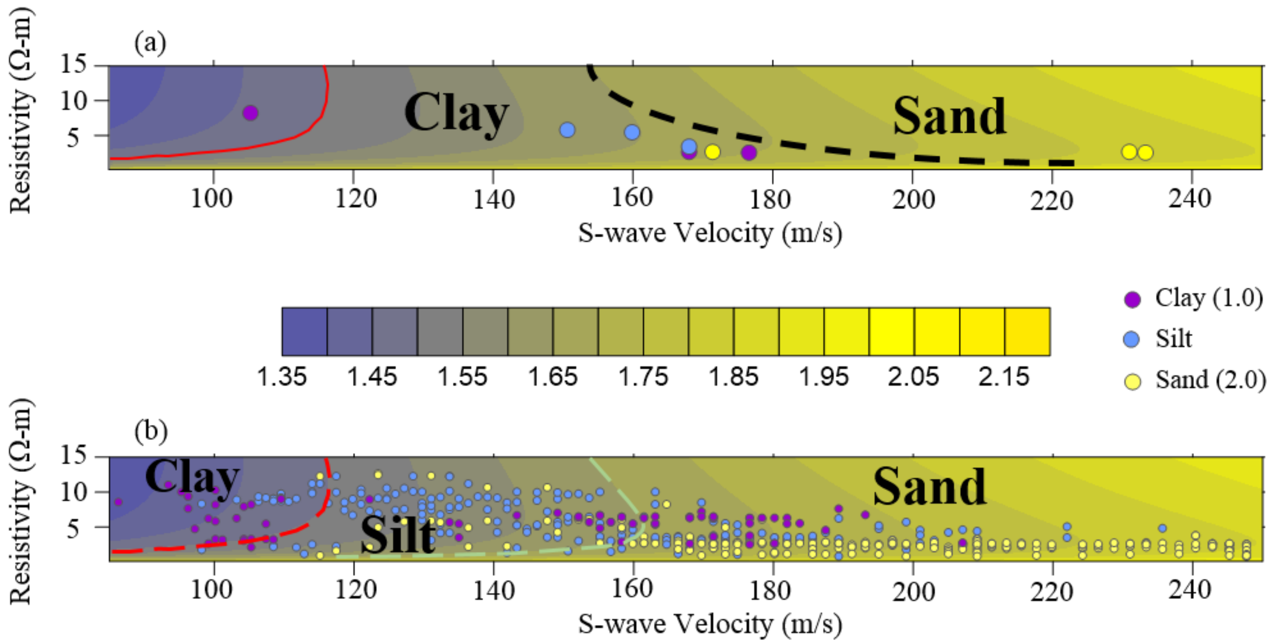


**Figure 6:** Cross-plots of resistivity and shear wave velocity. The color scale represents a polynomial approximation (Hayashi et al., 2013). Clay and sand soil types are separated by a dashed black line introduced by Hayashi et al. (2013). Colored circles indicate soil types determined either from (a) boring logs or (b) linear interpolations between wells (Figure 1), and placed at their respective coordinates (Vs,$\rho$), as determined from Figure 4 and 5. 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.

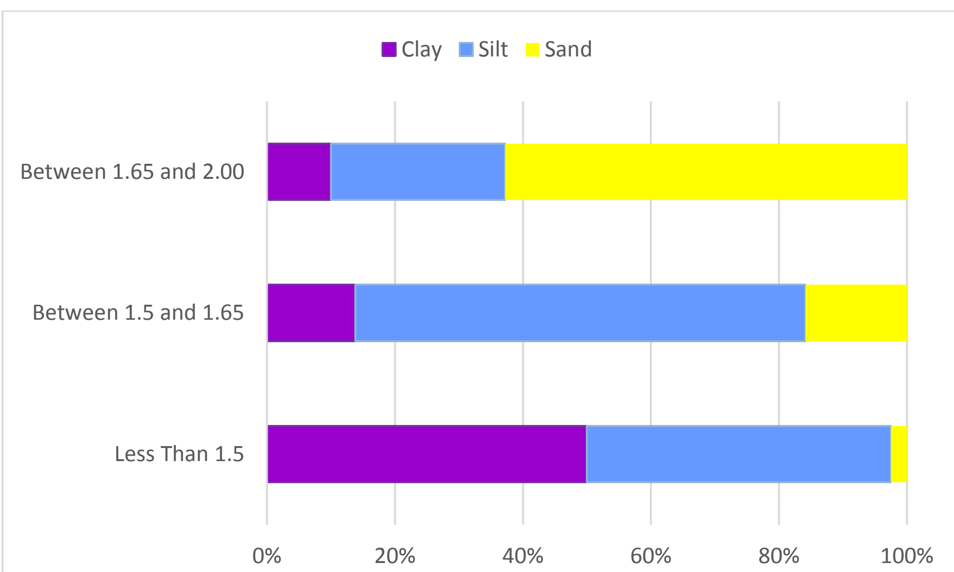


**Figure 7:** Distribution of the three sediment types separated by the newly proposed demarcation values of the polynomial approximation. About 2/3 of the cross-plot data points identified by linear interpolation fall within the correct bounds for sand and silt, while half of points with an integer less than 1.5 correctly were correctly identified as clay.

## Conclusion

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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