APPLICATION OF CROSS- PLOT ANALYSIS ON A LEVEE USING TIME LAPSE SEISMIC REFRACTION TOMOGRAPHY AND ELECTRICAL RESISTIVITY TOMOGRAPHY.

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Abstract

Out of the estimated 100,000 miles of levees in the United States a staggering 91% of these levees are not in an acceptable condition. Levee failures due to flood from hurricanes or heavy rainfalls occur without early warning and cause catastrophic damage. Therefore, the development of rapid assessment system of levees is greatly required to delineate weak locations and prioritize compromised locations. This study implements the use of surface based time-lapse geophysical methods known as seismic refraction tomography (SRT) and electrical resistivity tomography (ERT) on the Francis Levee Site. The Francis Levee site is located in Bolivar County, 0.5 miles west of Francis, Mississippi. The Francis Levee site was affected by the 2011 Mississippi river flood with multiple sand boil formations at the toe of the clay apron on the landside. Multiple geophysical surveys were conducted during spring 2014. It should be noted that similar methods of investigation are also applicable on earthen dams. The large number of dams in the United States and their risk of failure is alarming considering their old age and engineering design. Out of the 75,000 earthen dams in the US reported by the National Dam Inventory (2009), 56,000 are privately owned and do not undergo through investigation. This statistics necessitates the development of rapid and economical method of integrity assessment.

INTRODUCTION

The 2011 flood report by the Mississippi Levee Board, identified as many as twelve areas associated with seepage. The Francis levee site is one of the locations affected by the flood. Francis levee site (Station 150, 34° 5'9.48"N, 90°51'52.56"W) is located 0.8 kilometers west of Francis, Mississippi. During the 2011 flood event, three main sand boils were observed and mitigated by the construction of sand bag berms. After the initial mitigation, the US Army Corps of Engineers (USACE) extended the berm of the levee and constructed 16 relief wells. Figure 1 shows the location of the Francis Levee site on a Google map and an aerial photograph taken during the mitigation of the levee. This site was chosen for the geophysical study due to its close proximity to the University of Mississippi and the availability of borehole information.
Nimrod (2011) noted during the 2011 flooding the first sand boil surfaced at toe of the (berm) apron on the landside of the levee inside a drainage trench. The sand boil was mitigated with sand bags and by impounding water above the seepage area. After the first sand boil was mitigated, two additional sand boils surfaced 90 m to the northeast of the first one. Sand bags were used to mitigate these new sand boils. Figure 2 shows the locations of the three sand boils with red dots and a photograph of one of the later sand boils.

The rapid assessment of the potential hazards associated with earthen dam and levee failures requires advanced screening tools to delineate, classify, and prioritize compromised locations. Screening such a large number of dams and levees requires the use of some type of remote sensing and/or geophysical technique. Geophysical methods provide a means of evaluating large areas of the subsurface rapidly. The results are can be used to optimize drilling requirements. Geophysical methods are also non-destructive and non-invasive with a simple and portable setup.
The overall objective of this study is to advance the use of remote sensing and multiple geophysical techniques for the early identification of compromised zones in levees. Geophysical monitoring and condition assessment of the Francis Levee was conducted with the use of different methods including seismic refraction tomography (SRT), electrical resistivity tomography (ERT), multichannel analysis of surface waves (MASW), electromagnetic (EM34) survey, and remote sensing surveys. The first phase of this study was conducted in the Spring 2014. Addition sets of measurement were planned for Fall 2014 during low water level but were not conducted due to weather and logistical problems.

In this paper, preliminary results from seismic refraction tomography (SRT) and electrical resistivity tomography (ERT) from the first set of surveys (Spring, 2014) at the Francis Levee site is presented. Focus will be on identifying seepage paths that start on the waterside of the levee and are responsible for the sand boil formations on the landside.

Uyank (2011) divided factors that can affect seismic velocities through soils and rocks into three main groups. Lithological properties of soils (grain sizes, grain shape, grain type, grain size distribution, amount of compaction, amount of consolidation and cementation), physical properties of soils (porosity, permeability, density, degree of saturation, pressure, and temperature), and elastic properties of soils (shear modulus (G), bulk modulus (K), Young modulus (E), Poisson’s ratio (ν) and Lamé constant (λ)). All these factors are interrelated and affect the seismic velocity of soils. Therefore, analyzing 2D velocity distribution tomograms obtained from seismic refraction surveys provides valuable information on the integrity of the subsurface of dams and levees (Kim et. al., 2011, Bedrosian et. al., 2012, Moustafa et. al., 2012). In Particular, we expect that subsurface zones with higher permeability will have lower p-wave velocity. An area of seepage with fines washed out will have a high resistivity area if it is not fully saturated.

Electrical resistivity is a physical material property that represents the material’s ability to oppose the flow of electrical current. The resistivity of a given soil (sand/clay) can have a wide range values due to differing porosity (ϕ), saturation (S_w), pore fluid resistivity (ρ_w), and the presence of clay content. This makes electrical resistivity an ideal method in the early detection of subsurface seepage through dams and levees (Cho et. al., 2007, Sjödahl et. al, 2008, Chinedu et al., 2013 Lin et. al., 2014, Al-Fares, 2014). Case (2012) applied the electrical resistivity method to a model embankment dam where resistivity tomograms are used to infer the subsurface conditions and assist in the resolution of zones susceptible to preferential flow.

**SURVEY SETUPS AND PROCESSING**

The data acquisition for seismic refraction surveying requires placing a line of multiple geophones on the ground surface and creating seismic waves using an impact source at a shot point location. The geophones record direct and refracted energies which are stored as waveform using a seismograph. The first arrival time is the relevant information required from the data. The first arrival time is the time it takes for the first seismic energy to travel from the source to a geophone. These first arrival times are determined for all geophones of the spread and are used to determine the velocity of seismic waves in the subsurface.
For the P-wave seismic refraction surveys, 48 vertical component 10 Hz geophones with 2 m spacing were used. The whole length of each survey line is covered using a 24-geophone roll-along. Data were collected with a sample interval of 0.125 msec and a record length of 2 sec. Shot records were collected 1 m offset from the first and last geophones and in between all geophones.

Depending on the quality of the data, multiple shot records might be obtained at one location and added together to increase the signal to noise ratio. An 8 lbs sledgehammer was used as a seismic source. Rayfract™, commercially available software, was used for the inversion of all seismic refraction data. Surfer™, commercially available imaging software, was used to build the tomograms after processing with Rayfract™. After first arrival times are picked, an inversion technique is implemented and a 2-D velocity tomogram is obtained which is a station location (distance) versus depth image showing the velocity distribution in the subsurface. The velocity tomogram is plotted using color scales depending on the value of the velocity obtained for each grid after processing the first arrival times. In addition to the velocity tomogram, a ray coverage tomogram, a plot showing the number of rays passing through the grids used to obtain the velocity tomogram is obtained. A high number of ray coverage is an indication that more rays traveled through that area of the subsurface. Low ray coverage on the other hand is an indication that the rays avoided to travel through that location and took a preferred high velocity path in the surrounding subsurface.

In this study, the electrical resistivity method is used to study the distribution of electrical properties in the subsurface by injecting electrical current and measuring the induced potential at various locations along the ground surface. The final product is a 2D distance versus depth electrical resistivity distribution tomogram. Electrical resistivity surveys were conducted using 112 electrodes with 1 m spacing. Dipole-dipole electrode configuration was chosen. Case (2012) showed that the dipole-dipole electrode configuration has a higher sensitivity to horizontal changes, depth of investigation, and horizontal data coverage. The whole length of each survey line is covered using a 56-electrodes roll-along. EarthImager 2D, a commercially available inversion software, was used for the inversion and imaging of all the electrical resistivity data.

**RESULTS**

Both the P-wave seismic refraction and electrical resistivity surveys were conducted along three 478 m long lines. Figure 3(a) shows the location of the three survey lines and the sand boils. Survey line 1 is on the water side of the levee, survey line 2 is on the berm of the levee and between the levee and the first sand boil, survey line 3 is on the landside of the levee and between the first sand boil and the two sets of sand boils. Each survey line starts at the northern end and progresses southward parallel to the levee.

To cover the entire 478 m length of each survey line, eight roll-along spreads for the seismic refraction and six roll-along spreads of electrical resistivity surveys were conducted. In this paper, results from three locations (rolls) along each line will be presented. The three selected locations are shown in Figure 3(b). These locations are chosen because they show anomalies that might be associated with a pathway for seepage responsible for the formation of the three sand boils on the land side of the levee.
The white line in Figure 3(b) represents the inside edge of a meander belt from an old river channel composed of complex deposits and sedimentary structures. Figure 4(a) represents a typical cross-section of a meander belt (Saucier, 1994). The cross section shows that the old river channel is filled with vertical structures of medium-course sand and gravel at the bottom, fine-medium grained sand in the middle, and a very fine grained silt and sand at the top. There is a ridge and swale formation in the top silt and sand layer with swale fill clays. There are also clay drapes in between each vertical structure. Measuring from the edge of the natural levee the ridge and swale formation ranges from 6m to 9m of depth. The depth from the bottom of the ridge and swale formation to the bottom of the old river channel is site specific and ranges from 18m to 24m.
An example of borehole information close to the three survey lines and inside the meander belt is shown in Figure 4(b). The borehole goes to a depth of 15m (50ft). Considering the 2m clay layer on the top is natural soil deposit after the ridge and swale formation, the bottom of the borehole lies just below the ridge and swale formation and inside the fine-medium grained sand layer in the middle.

After the 2011 flood event, the U.S. Army Corps of Engineers (USACE) mitigated the problem with an installation of water relief wells on the landside of the levee at the end of the apron (berm). Ground water elevation readings from all the relief wells were measured alongside geophysical measurements. Figure 5 shows the average ground water elevation based on the well readings and the above sea level (ASL) elevations of the three survey lines. Based on the ground water elevation shown in Figure 5 and the borehole information in Figure 4(b), the sand layer is fully saturated.

![Figure 5](image)

**Figure 5** Ground water elevations from well readings

P-wave seismic refraction data was processed using a travel (arrival) time plot analysis for the survey on the water side. Water saturated soils commonly have p-wave seismic velocity of 1500m/s or higher. Based on the travel time plot analysis shown in Figure 6, the subsurface is interpreted to be a two-layer structure. The depth of the water saturated soil with a P-wave velocity of 1667m/s is at a depth of about 8m. The saturated zone predicted from the seismic data is much deeper than one on predicated based on the ground water elevation from the well readings.

![Figure 6](image)

**Figure 6** Travel time plot analysis for survey line 1 (336m to 430m)
Based on the depth of the 2nd layer obtained from the travel time analysis, an initial model for tomography processing is produced with the 1666m/s is close to 8m (Figure 7). The resulting P-wave velocity tomogram in meters/second is shown on the right of Figure 7. There are two velocity anomalies with lower velocity between 15m and 25m of depth annotated with the box.

Figure 7 Initial model based on arrival time plot and associated velocity tomogram.

The same survey location in Figure 7 (336m – 430m) is processed again using the 1D-gradient smooth initial model obtained from Rayfract™. Figure 8 shows the Rayfract™ initial model on the top and the associated velocity tomogram on the bottom left and the ray coverage on the bottom right. The velocity tomogram shows similar features to the velocity tomogram in Figure 7 except for the less pronounced anomaly on the left. This indicates that the tomography results are not controlled by the initial model. Rayfract™ generated initial models are therefore used for all refraction processing.

Figure 8 Rayfract™ initial model and inversion results
The velocity tomogram in Figure 8, indicates a P-wave velocity ranging from 350 m/s near the surface to 3000 m/s at 34 m below the surface. Comparing to the borehole information, suggest that the soil between the surface and the 500 m/s contour is clay at the top overlying a mixture of clayey silt to silty sand. Below the 500m/s contour line it is mostly sand. The 1500-1800 m/s P-wave velocity is usually used as indicator of ground water level, because the speed of sound in water is close to 1500 m/s. Seismic interpretation based on the velocity tomogram indicates that the saturated zone is at a depth of around 14m for the first half of the survey line. This depth is in much deeper to what would be predicted from the well readings.

With increasing depth, elastic properties such as bulk modulus will increase due to the added compaction of the overburden pressure (effective stress). An increase in bulk modulus with depth will cause an increase in P-wave velocity with depth. However, lithology can have an effect. Unsaturated sand is expected to have a lower P-wave velocity compared to clay due to high porosity and low bulk modulus. There is a pull down in the 1500 m/s velocity contour annotated with the white box in Figure 8. This location has a lower velocity compared to adjacent material at the same depth. The same location is indicated on the ray coverage tomogram (shown on the bottom right of Figure 8) with an area of low ray coverage. A combination of low P-wave velocity and low ray coverage is an indication of weak compaction or possible void formation due to an internal erosion (washing out of fines) caused by seepage. Seismic waves travel through a preferred path of high P-wave velocity, which can be associated with good compaction (high bulk modulus). When seismic waves encounter low velocity zones, they travel through surrounding areas with higher velocity zones and do not go through the low velocity zones which leads to the formation of localized low ray coverage areas as shown in Figure 8. Another possible reason for the low velocity area could be a zone of high pore pressure causing a decrease in the effective stress of the area and therefore dropping the velocity.

The results for the seismic surveying on the berm of the levee are shown in Figure 9. The P-wave velocity tomogram is on the left and the ray coverage tomogram on the right for. The above sea level elevation of the berm (line 2) is 4 m higher than the elevation on the waterside (line 1). This is due to the 4 m sand layer used for the construction of the berm. The water table indicated by the 1500 m/s contour line is at a deeper depth of 20m which is located 2m shallower on survey line 1. There is an anomaly of low velocity and low ray coverage indicated within the white box. The depth of the anomaly is too shallow to be seepage path associated with the sand boil formation.
Figure 9 P-wave velocity (left) and ray coverage tomogram (right) for Line 2 (336m – 430m)

The results of the p-wave seismic refraction survey on the landside of the levee, line 3 (192m – 286m), is shown in Figure 10. The p-wave velocity tomogram is on the left and the ray coverage tomogram on the right. Surface elevation of survey line 3 is 2m below survey line 1 and 6m below survey line 2. The ground water table (1500 m/s contour line) is located at a depth of 13 m which is consistent with the observation on the other seismic surveys. The white box indicates an anomaly with a low P-wave velocity and low ray coverage which we interpret as an indication of a weak zone in the subsurface.

Figure 10 P-wave velocity (left) and ray coverage tomogram (right) for Line 3 (192m - 286m)

The electrical resistivity tomogram for Line 1 (336m - 430m) is shown in Figure 11. The electrical resistivity values are given in Ohm-m. Borehole information is added on the left of Figure 11 to aid with the interpretation of the result. The broken lines on the figure indicate different layers that are observed based on resistivity values.
In Figure 11, the low resistivity region between the top surface and the first broken line is an indication of the clay and silty sand layer. The same location is indicated in Figure 8 between the surface and the 500m/s contour line. Mavok, Mukerji, and Dvorkin (1998) showed that clays have lower resistivity (higher conductivity) than sands due to their high cation exchange capacity. In sands, electrical conductivity is solely based on the conductivity of the pore fluid; whereas in clays, in addition to the pore fluid electrical conductivity takes place through the charged and interconnected surface of the clays.

The borehole indicates sand at depths greater than 5m. The resistivity data shows a layer between 4m and 8m consistent with sand. However, there is a drop in resistivity to 5-10 Ohm-m within the sand zone at a depth of 8m. Calculation using Archie’s first law was made to check if such a low velocity in the sand layer can be achieved by a fully saturated clean sand. Using an electrical resistivity of 15 Ohm-m for the pore fluid and cementation factor for sand between 1.8 and 2, it requires unrealistic porosity to achieve a resistivity lower than 10 Ohm-m for clean sand only due to saturated water. This suggests that there must be a mixture of clay in the sand layer not indicated in the borehole information. The low resistivity structure may be due to the swale fill clays in the vertical structure of the meander geomorphology. The black broken box in the resistivity tomogram indicates the location of the seismic anomaly shown in Figure 8. There is no anomaly at that location indicating a possible location of seepage.

The electrical resistivity survey on the berm of the levee did not yield usable information due to high noise in the data. This problem is due to the high contact resistance of the top dry sand layer. Electrical resistivity survey works when there is good contact between the electrodes and the ground. Attempts were made to reduce the contact resistance by pouring salt water around the electrodes but only slight reduction around the electrodes was observed which did not improve the overall quality of the data.

**SUMMARY**

Multiple geophysical methods were conducted at the Francis Levee site. In this paper, part of seismic refraction tomography and electrical resistivity tomography results that focus on identifying seepage paths responsible for sand boil formations were presented.
Although electrical resistivity surveys are not completed as planned, results from seismic refraction tomography show an indication of a possible seepage path that can be associated with the three sand boil formations. The location of low P-wave velocity and low ray coverage anomalies observed in the seismic refraction results are shown with the green circles in Figure 12. A possible seepage path is drawn by connecting these anomalies. The three sand boils indicated with the blue circles are in close proximity to the estimates seepage path. It should be noted that the seepage path is perpendicular to the levee and follows the trend of the meander belt. Flow path parallel to the meander is expected because the soil deposit inside the meander has low compaction and high permeability compared to the native ground. Water can flow through the highly permeable sand and gravely sand and cause sand boil formations at locations where the overburden clay layer is thin.

![Figure 12 Possible seepage path](image)

It is possible that water flows from the waterside to the landside through the path shown in Figure 12. At places where the overburden clay layer is thin above the seepage path, water can flow to the surface causing sand boil formations.

**REFERENCES**


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