Jim

United States Department of Agriculture

Natural Resources Conservation Service

11 Campus Boulevard
Suite 200
Newtown Square, PA 19073

Subject: Eng – Geophysical Field Assistance

Date: 29 May 2003

To: Patricia S. Leavenworth
State Conservationist
USDA-NRCS
6515 Watts Road, Suite 200
Madison, Wisconsin 53719-2726

Purpose:
Geophysical surveys were conducted on several earthen dams in southwest Wisconsin using ground-penetrating radar (GPR) and electromagnetic induction (EMI).

Participants:
Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Newtown Square, PA
Phil Hahn, Resource Conservationists, Vernon County LCD, Viroqua, WI
Barbara Lensch, Geologist, USDA-NRCS, Madison, WI
Scott Mueller, Agricultural Engineer, USDA-NRCS, Richland Center, WI

Activities:
All activities were completed during the period of 12 to 15 May 2003.

Summary:

1. The use of GPR to investigate the structural integrity of earthen dams is inappropriate. Clay blankets that cover most earthen dams are relatively thick and highly attenuating to electromagnetic energy. As a consequence, the depth of penetration is restricted and GPR is poorly suited to most investigations.

2. Ground-penetrating radar is well suited to bedrock investigations in areas of sandstone. In addition, GPR can be used to measure the thickness of alluvial deposits. However, GPR [provides no indication as to whether these deposits represent older or recent sedimentation caused by an impoundment structure .

3. EMI is a more appropriate geophysical tool than GPR to investigate the structural integrity of earthen dams. The GEM300 sensor and the EM31 meter produced similar results. The GEM300 sensor is lighter-weight and has a shorter dimension than the EM31 meter. Because of logistical concerns, the GEM300 sensor is preferred for surveys on steep, densely vegetated slopes. Both devices were unable to profile an earthen structure to its base. The resolution of these devices appears sufficient to capture areas of wetter embankment materials and presumably seepage provided a large number of closely spaced observations are made (devices must be operated in the continuous rather than the station-to station mode). However, cavities, joints, or fractures within bedrock, because of their small size or lack of contrast with the surrounding materials, are generally indistinguishable with EMI.

4. The USDA-NRCS has EM34 meters that provide penetration depths of 7.5 to 60 m. However, to obtain these depths, the transmitting and receiving coils must be spaced at distances of 10, 20, or 40 m. These distances would be unmanageable on smaller structures and would create surveying dilemmas on relatively steep, densely vegetated slopes of abutments. In addition, the resolution (equal to the intercoil spacing) of the EM34 meter is too coarse to detect individual joints or small fractured areas in bedrock.

It was my pleasure to work once again in Wisconsin and with members of your fine staff.

With kind regards,

James A. Doolittle
Research Soil Scientist
National Soil Survey Center

cc:
R. Ahrens, Director, USDA-USDA, National Soil Survey Center, Federal Building, Room 152, 100 Centennial Mall North, Lincoln, NE 68508-3866
B. Lensch, Geologist, USDA-NRCS, 6515 Watts Road, Suite 200, Madison, Wisconsin 53719-2726
W. Maresch, Acting Director of Soils Survey Division, USDA-NRCS, Room 4250 South Building, 14th & Independence Ave. SW, Washington, DC 20250
C. Olson, National Leader for Soil Investigations, USDA-USDA, National Soil Survey Center, Federal Building, Room 152, 100 Centennial Mall North, Lincoln, NE 68508-3866
J. Ramsden, State Conservation Engineer, USDA-NRCS, 6515 Watts Road, Suite 200, Madison, Wisconsin 53719-2726
W. Tuttle, Soil Scientist (Geophysical), USDA-NRCS-NSSC, P.O. Box 974, Federal Building, Room 206, 207 West Main Street, Wilkesboro, NC 28697

Equipment:
The radar unit is the Subsurface Interface Radar (SIR) System-2000, manufactured by Geophysical Survey Systems, Inc.[1] Morey (1974), Doolittle (1987), and Daniels (1996) have discussed the use and operation of GPR. The SIR System-2000 consists of a digital control unit (DC-2000) with keypad, VGA video screen, and connector panel. A 12-volt battery powers the system. This unit is backpack portable and, with an antenna, requires two people to operate. A 200 MHz antenna was used in this investigation. The RADAN NT (version 2.0) software program developed by Geophysical Survey Systems, Inc. (2001a), was used to process the radar records.[1] Processing included color transformation, marker editing, distance normalization, and range gain adjustments.

Electromagnetic induction instruments used in this study include the EM31 and EM38DD meters, and the GEM300 sensor. These devices are portable and need only one person to operate. No ground contact is required with these instruments. These devices measured the apparent conductivity of the underlying earthen materials. Values of apparent conductivity are expressed in milliSiemens per meter (mS/m). Lateral resolution is approximately equal to the intercoil spacing.

Geonics Limited manufactures the EM31and EM38DD meters.[1] McNeill (1980) has described the principles of operation for the EM31meter. The EM31 meter has a 3.66 m intercoil spacing and operates at a frequency of 9,810 Hz. When placed on the soil surface, the EM31 meter has theoretical penetration depths of about 3.0 and 6.0 meters in the horizontal and vertical dipole orientations, respectively (McNeill, 1980).

Geonics Limited (2000) has described the operating procedures of the EM38DD meter. The EM38DD meter has a 1-m intercoil spacing and operates at a frequency of 14,600 Hz. It has effective penetration depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively (Geonics Limited, 2000). The EM38DD meter consists of two EM38 meters bolted together and electronically coupled. One meter acts as a master unit (meter that is positioned in the vertical dipole orientation and having both transmitter and receiver activated) and one meter acts as a slave unit (meter that is positioned in the horizontal dipole orientation with only the receiver switched on).

The Geonics DAS70 Data Acquisition System was used to record and store EMI data.[1] The acquisition system consists of an EM31 or EM38DD meter, an Allegro field computer, and a Trimble AG114 GPS receiver. With this data acquisition system, the meter is keypad operated and measurements can either be automatically or manually triggered.

Geophysical Survey Systems, Inc., manufactures the GEM300 multifrequency sensor.[1] Won and others (1996) have described the use and operation of this sensor. This sensor is configured to simultaneously measure up to 16 frequencies between 330 and 20,000 Hz with a fixed coil separation of 1.3 m. With the GEM300 sensor, the penetration depth is considered "skin depth limited." The skin-depth represents the maximum depth of penetration and is frequency and soil dependent: low frequency signals travel farther through conductive mediums than high frequency signals. Theoretical penetration depths of the GEM300 sensor are dependent upon the bulk conductivity of the profiled earthen material(s) and the operating frequencies. Multifrequency sounding theoretically allows multiple depths to be profiled with one pass of the sensor. The sensor is keypad operated and measurements can either be automatically or manually triggered.

To help summarize the results of this study, the SURFER for Windows (version 8) program, developed by Golden Software, Inc.,[1] was used to construct two-dimensional simulations. Grids were created using kriging methods with an octant search.

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[1] Trade names are used to provide specific information. Their mention does not constitute endorsement by USDA-NRCS.

Study Sites:

West Fork Kickapoo, Dam #1

Ground-penetrating radar traverses were conduct on a steeply sloping, wooded site and along the diversion channel on the left abutment of West Fork Kickapoo, Dam #1. The structure, completed in 1964, has created Jersey Valley Lake. It is located in the northeast quarter of Section 13, T. 14 N., R. 4 W. The site is located about three miles northeast of the town of Westby in Vernon County. Other than the embankment materials, the site is located in an area that had been mapped as Stony rock land, steep (Slota, 1969). This miscellaneous soil map unit consists of materials derived from sandstone. Typically, the depth to bedrock is less than 24 inches, but ranges to depths of 42 inches. Ground-penetrating radar was used to help characterize joint and fracture patterns in the underlying Jordan sandstone.

Bad Axe Dam #24

Dam #24, Bad Axe Watershed is located in the southwest quarter of Section 29, T. 12 N., R. 5 W. The site is located along Bull Run about eight miles southwest of the town of Viroqua in Vernon County. The structure was completed in 1967. Other than the embankment materials, the site is located in an area that had been mapped as Stony rock land, steep (Slota, 1969). The Van Oser and Norwalk members of the Jordan Formation are exposed along the left abutment. Both members consist of jointed bedrock.

The dam embankment is about 39 feet high and 320 ft long. Following a severe rainfall event (May 31 to June 1, 2000), slumping and several holes were discovered along both the upstream and downstream portions of the left abutment. The holes were small and less than a few feet in diameter. Near the downstream hole, a debris trail was observed that extended to the creek below the plunge pool. After a significant rainfall event on 14 June 2000, water was observed flowing into holes on the upstream side of the left abutment. However, no water was observed flowing from the hole located on the downstream side of the left abutment. Rehabilitation is in progress. Presently, a grout curtain is being injected into the portion of the dam that adjoins the left abutment.

Klinkner Dam

The site is located in the northeast quarter of Section 9, T. 14 N., R. 3 W. The site is located along Knapp Creek about five miles northeast of the town of Westby in Vernon County. This "dry" dam was completed in 1956. The dam has been overtopped twice. Plans are being considered to raise the dam by 12 ft. Ground-penetrating radar surveys were conducted on both abutments. The GPR survey sites are located in areas that had been mapped as Stony rock land, steep (Slota, 1969). Ground-penetrating radar was used to characterize joint and fracture patterns within the underlying sandstone (Jordan Formation) bedrock.

Dam # 9A

The dam, also know as Brindley Dam, is located in the southeast quarter of Section 11, T. 11 N., R. 2 W. The site is located along Mill Creek about 1 mile northwest of Sabin in Richland County. This "dry" dam was completed in 1962. The area is mapped as Orion silt loam, 0 to 3 percent slopes (Simonson, 2002). The very deep, somewhat poorly drained Orion soil formed in relatively recent stratified alluvium on flood plains. Orion is a member of the coarse-silty, mixed, superactive, nonacid, mesic Aquic Udifluvents family. A portion of the flood plain upstream from the dam was surveyed with both GPR and EMI to determine the thickness of recent fill deposits.

Field Procedures:

West Fork Kickapoo #1

A 40-m traverse line was established on a steeply sloping wooded site overlooking the left abutment. Steep slopes and underbrush reduced survey control and obstructed the GPR survey. Reference flags were inserted in the ground at intervals of about 5-m along the traverse line. A GPR survey was completed using a scanning time of 200 nanoseconds (ns). Soils were moist throughout at the time of this investigation. Assuming a dielectric permittivity of 18 and a velocity of propagation of 0.070 m/ns, a scanning time of 200 ns resulted in a maximum penetration depth of about 7.3 m.

A 500-ft traverse line was also established along the diversion channel on the left abutment. This relatively level and grassed area provided fewer restrictions to the radar survey than did the adjoining, steeply sloping, wooded area. Reference flags were inserted in the ground at intervals of about 10-m for the first 60 meters (about 200-feet). Survey stakes, spaced at intervals of about 15.2 m (50-ft), were used for the remaining 91meters (300 ft). A GPR survey was completed using a scanning time of 100 ns. Based on a known depth to bedrock, the estimated dielectric permittivity was about 17 and the velocity of propagation was about 0.072 m/ns . Using these values, a scanning time of 100 ns resulted in a maximum penetration depth of about 3.6 m.

Bad Axe #24

A grid was established across the structure and portions of the adjoining abutments. Most survey lines were established parallel with the centerline of the structure. One hundred and six survey flags were inserted in the ground and served as reference points (see Figure 1). These flags served as reference points for station-to-station EMI surveys. At each reference point, the elevation of the ground surface was determined with a total station instrument. In Figure 1, the *grout curtain* extends into an area that has been cut into the Jordan sandstone on the left abutment. Also shown in Figure 1 are the approximate locations of the dam's riser and outlet.

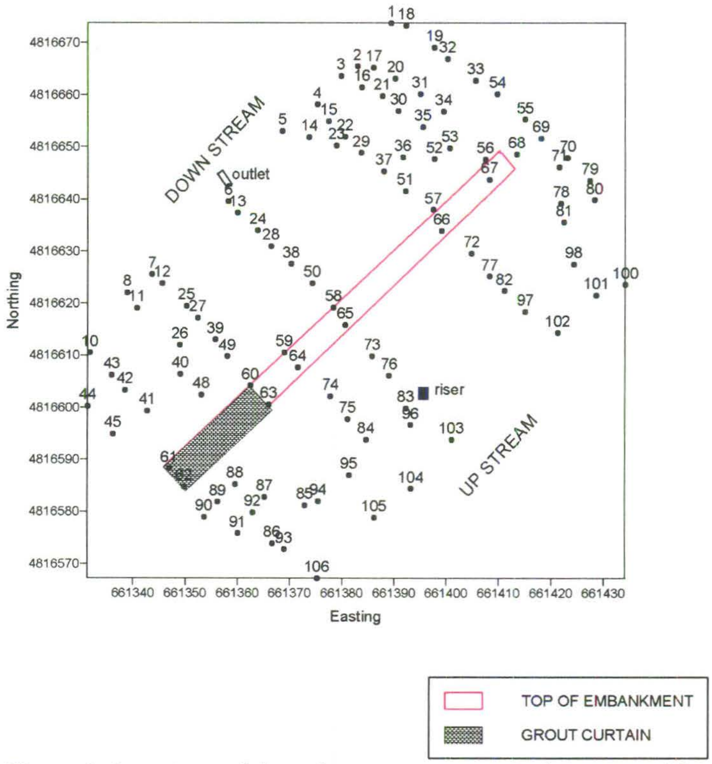

Figure 1. Locations of the reference points on Bad Axe Dam #24.

In addition, a 12-m traverse line was established over the grout curtain. No attempts were made to conduct GPR surveys on other portions of this structure. Reference flags were inserted in the ground at intervals of 2-m. A GPR survey was completed using a scanning time of 80 ns. Assuming a dielectric permittivity of 18 and a velocity of propagation of 0.070 m/ns , a scanning time of 80 ns resulted in a maximum penetration depth of about 2.8 m.

<u>Klinkner Dam</u>
Three radar traverse lines of about 18-, 30-, and 40-m (about 60-, 100-, and 130-ft, respectively) lengths were established near this structure. Two lines were located in wooded areas that had been previously cored on the left and right abutments. One line was located over an exposed fracture that was filled with soil materials along the left abutment. For each traverse line, reference flags were inserted in the ground at intervals of about 3-m (10-ft). Assuming a dielectric permittivity of 18 and a velocity of propagation of about 0.07 m/ns , a scanning time of 150 ns resulted in a maximum depth of penetration of about 5.2 m.

<u>Dam # 9A</u>
Forty-two reference flags were inserted in the ground in a serendipity pattern across a portion of the flood plain that is immediately upstream of the dam. Both EMI and GPR surveys were conducted using the flags as a guide. A GPR survey was completed using a scanning time of 100 ns. The silty soils were saturated at the time of this investigation. Based on a known depth to a buried metallic reflector, for the upper part of the soil, the velocity of propagation was about 0.05 m/ns and the dielectric permittivity was 35. A scanning time of 50 ns resulted in a maximum depth of penetration of about 1.3 m. The EMI survey was conducted with the EM38DD held about 2 inches above the ground surface and its long axis parallel to the direction of traverse.

Results:
<u>West Fork Kickapoo #1</u>
In the undisturbed, steeply sloping area along the left abutment, the 200 MHz antenna provided a detailed record of the underlying Jordan sandstone. Interpretable radar reflections were apparent to depths of about 6.7 m.

Figure 2 is the radar record from this site. The radar record has not been terrain corrected. As such, regardless of slope, the surface appears horizontal. The short, vertical lines at the top of the radar record represent equally spaced (5-m) reference points along the radar traverse. A vertical scale (in meters) appears along the left-hand margin of the record. The vertical scale is based a propagation velocity of 0.070 m/ns.

The planar reflectors evident in this radar record represent stratification and/or sheet joints developed in the sandstone bedrock. Most major reflectors are generally continuous, but vary laterally in amplitude indicating changes in soil and rock properties. The narrow, white vertical breaks in these reflectors are believed to represent larger vertical joints that are filled with more conductive materials.

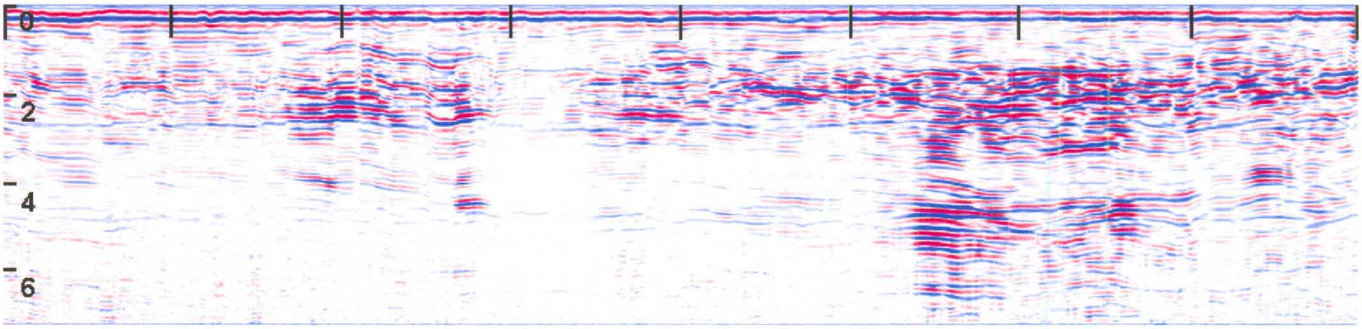

Figure 2. Sheet and vertical joints are evident within Jordan sandstone. The radar record is from the left abutment of Dam #1, West Fork Kickapoo River.

The diversion area was covered with dispersive clays that were mixed with lime-enriched materials. These materials were highly attenuating to the radar energy and restricted penetration depths. Here, interpretable radar reflectors were limited to depths of less than 2.5 m. Below this depth, high levels of low frequency background noise produced ambiguous and uninterruptible reflections. In most areas, the depth to bedrock and the thickness of the dispersive clay layers were distinguishable.

Bad Axe Dam #24

Figure 3 is the radar record from the top of this structure near the grout curtain. The short, vertical lines at the top of the radar record represent equally spaced (2-m) reference points along the radar traverse. A vertical scale (in meters) appears along the left-hand margin of the record. Because of the highly attenuating clay blanket, interpretable reflections were restricted to depths of less than 1.0 m. Below this depth, high levels of low-frequency background noise obscure reflections from subsurface features. The inclined lines in the right-hand portion of this record represent noise from nearby drilling equipment. This radar record best characterizes the inappropriateness and futility of using GPR for the investigation of deep, internal structural features within earthen dams having clay blankets.

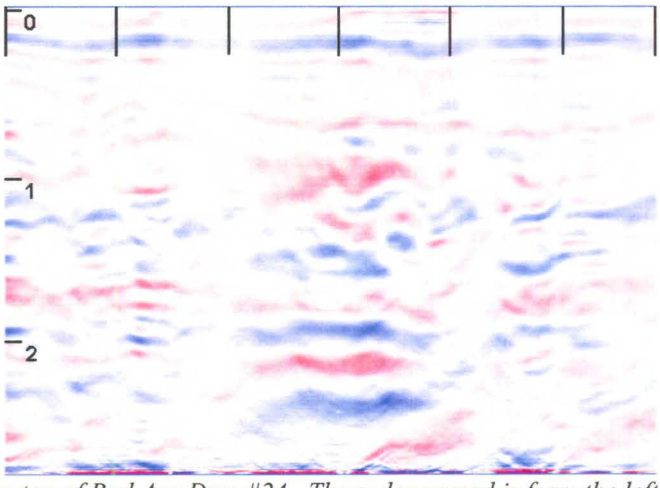

Figure 3. Radar record from the top of Bad Axe Dam #24. The radar record is from the left abutment of the dam where the grout curtain is being injected.

Figure 4 contains a choropleth map that has been overlain on a three-dimensional surface plot of Bad Axe Dam #24. The choropleth map is based on 843 EMI measurements and shows the spatial distribution of apparent conductivity collected with the EM31meter. The meter was held in the deeper-sensing, vertical dipole orientation. Measurements were obtained in the continuous mode. Color variations have been used to show the distribution of apparent conductivity. In Figure 4, the color interval is 2 mS/m.

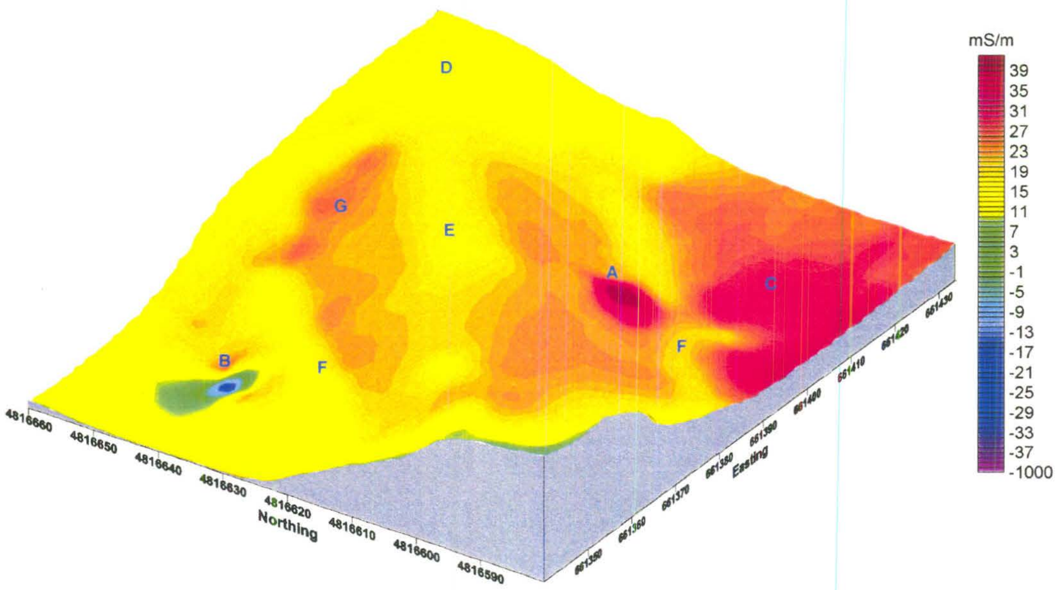

Figure 4. Two-dimensional contour map of apparent conductivity collected with the EM31 meter in the vertical dipole orientation overlaid on a three-dimensional surface map of Bad Axe #24 Dam.

The inlet structure (A) and the outlet pipe (B) are evident near the base of the dam. These features contain metals that interfere with electromagnetic fields and produce anomalous values of apparent conductivity. The upstream pool area (C) is saturated with water. As a consequence, apparent conductivity is higher in the pool area. On the right abutment, depths to resistive sandstone bedrock are relatively shallow. Here (D) values of apparent conductivity are low. A portion of the top of the embankment (E) contains lower values of apparent conductivity. This area had a gravel pad composed of more electrically resistive materials and was drier. Along the left-hand portion of the embankment top, concrete grouting is being injected into the earthen dam. Here, values of apparent conductivity are more similar to the structure's side slopes. The contact between the right hand abutment and the down stream dam embankment was noticeably wet. This contact zone provides a linear pattern of higher apparent conductivity (G) that extends down slope to a bench area. Along the bench, this wetter and more conductivity zone extends laterally along the backside of the bench, which contained ponded water. The outboard edges of benches (F) can be identified by their lower apparent conductivity, which is attributed to drier conditions and/or coarser materials. The map in Figure 4 does indicate areas along the embankment that are moister and receiving seepage.

Figure 5 contains choropleth maps of apparent conductivity collected with the GEM300 sensor and the EM31 meter (lowest set of maps) in the horizontal (left-hand maps) and vertical (right-hand maps) dipole orientations and operated in the station-to-station mode. Each choropleth map is based on 95 EMI measurements. The locations of the measurement points are shown in the upper left map. Color variations have been used to show the distribution of apparent conductivity. In Figure 5, the color interval is 2 mS/m.

Compared with the map shown in Figure 4, which is based on a much larger sample, the spatial patterns in Figure 5 are more disjointed and contain less detail. Based on this comparison, for future surveys of dams, the continuous mode of operation is recommended.

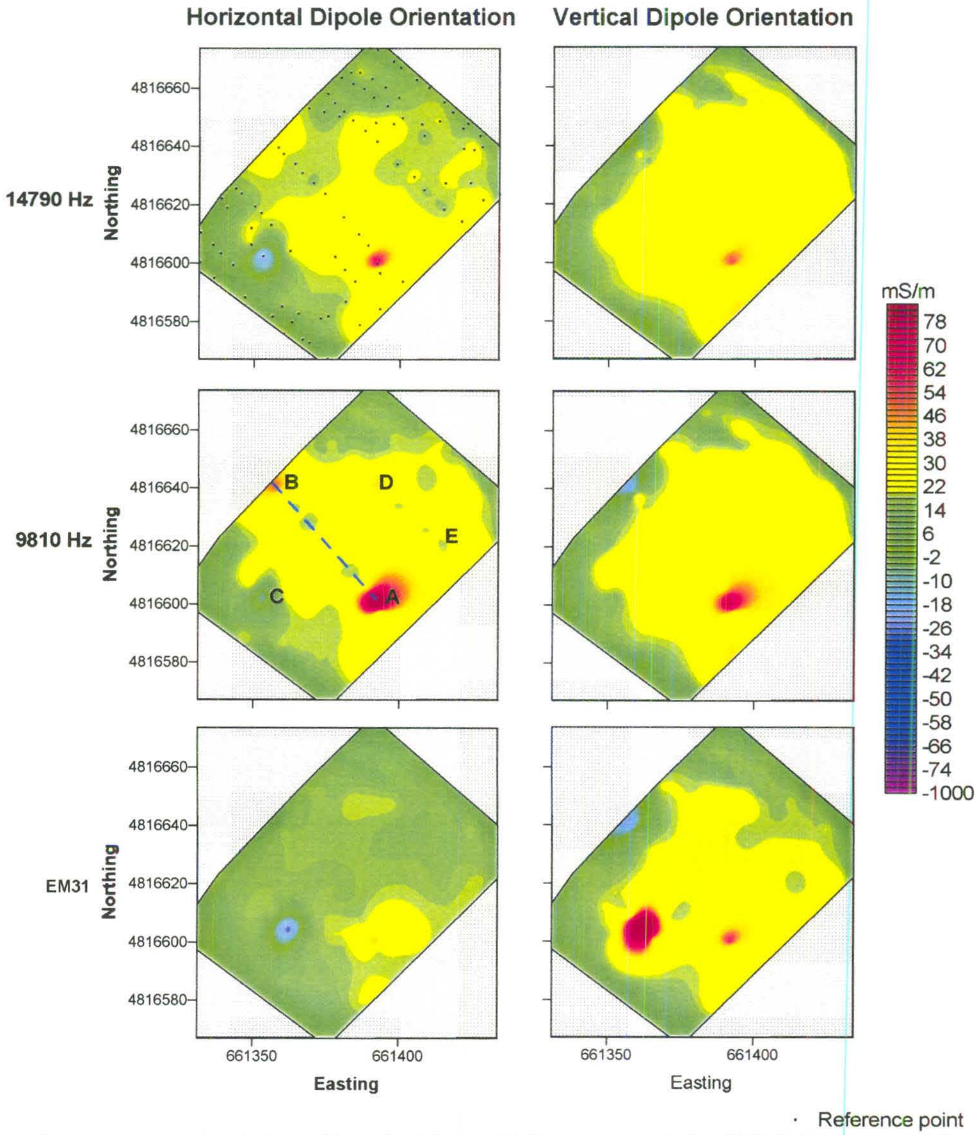

Figure 5. Maps of apparent conductivity collected with the EM31 meter and the GEM300 sensor in the vertical dipole orientation and operated in the station-to-station mode at Bad Axe Dam #24.

Both the EM31 meter and the GEM300 sensor produced similar results and spatial patterns. Regardless of manufacturers purported penetration depth or resolution, each device appears to have responded to similar depth-weighted profiles, and have captured or were responsive to similar features. Regardless of EMI device or dipole orientation used, five anomalous features are identifiable in each map shown in Figure 5. Though labeled on only the middle left-hand map, in each map, the inlet structure (A) and the outlet pipe (B) are evident near the base of the dam. Metallic objects near the grout curtain injection area produced interference and an anomalous EMI response at C. Small, weakly expressed areas of higher (D) and lower (E) apparent conductivity appear on the edge of the dam embankment and indicate possible seepage and shallower depths to resistive materials, respectively.

<u>Klinkner Dam</u>
In the steeply sloping area along the abutments, the 200 MHz antenna provided detailed records of the underlying Jordan sandstone. Though depths as great as 5.5 m were occasionally attained, depths of 3 m were consistently obtained. Figure 6 is the radar record from the right abutment of this earthen dam. The radar record has not been terrain corrected. As such, regardless of slope, the surface appears horizontal. The short, vertical lines at the top of the radar record represent equally spaced (3-m) reference points along the radar traverse. A vertical scale (in meters) appears along the left-hand margin of the record. The vertical scale is based a propagation velocity of 0.07 m/ns.

In this radar record, the multiple, inclined planar reflectors represent stratification and/or sheet joints developed in the sandstone bedrock. Once again, these inclined reflectors vary laterally in amplitude indicating changes in soil and rock properties. Most reflectors are fairly continuous. The narrow, white, vertical zones of no signal returns or breaks represent the presence of vertical joints that are filled with more attenuating materials (clay and moisture). In the central portion of the radar record, between reference points 20 and 80 m (measured from left), the bedrock was excavate and the excavation later backfilled with earthen materials. Though signal amplitudes are weaker and reflections are more disrupted in this portion of the radar record, layering is still evident and probably represents layers of fill material. However, the contact between bedrock and fill materials is ambiguous and difficult to discern.

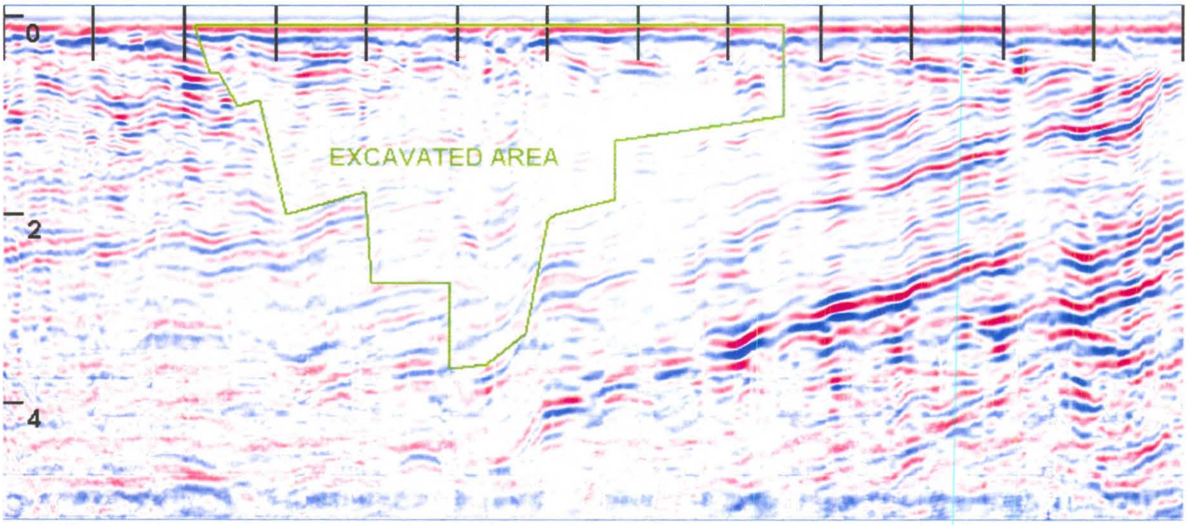

Figure 6. Sheet and vertical joints are evident within Jordan sandstone. The radar record is from the right abutment of Klinkner Dam.

Dam #9A

Figure 7 is the radar record from an area of Orion silt loam. The short, vertical lines at the top of the radar record represent reference points along the radar traverse. A vertical scale (in meters) appears along the left-hand margin of the record. Based on a propagation velocity of 0.05 m/ns and a scanning time of 50 ns, the maximum depth is about 1.25 m.

In Figure 7, a continuous subsurface planar reflector can be traced across a major portion of the radar record. This interface (highlighted with a green line) represents the original channel bottom. The underlying channel bottom materials are highly attenuating and penetration is restricted to the upper part of this layer. The material above this contact is alluvial fill. However, it is unknown whether these deposits represent older or recent sedimentation caused by the structure. In addition to this interface, another interface is evident at depths of 40 to 50 cm. Based on limited core data, this interface represents a buried A horizon. A buried metallic reflector is responsible for the hyperbolic reflection that reverberates next to *A* in Figure 7.

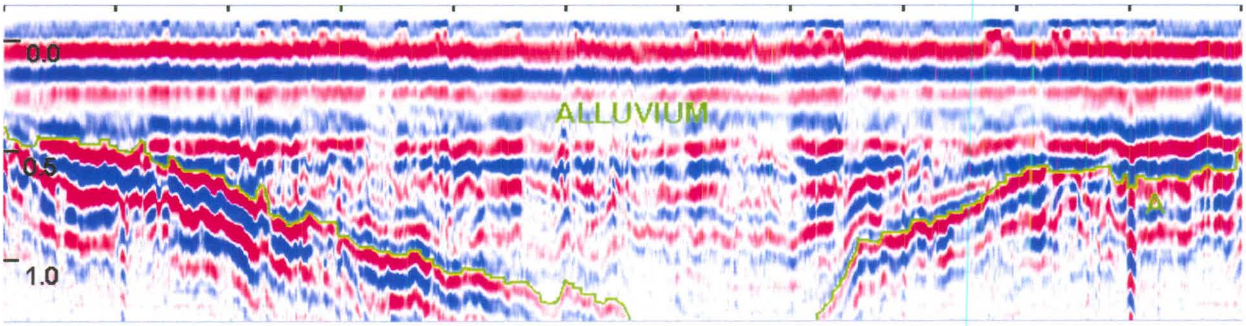

Figure 7. Channel fill deposits in an area of Orion soil.

The depth to the original channel bottom was measured at each of the 42 reference points recorded on the radar records from this site. This data were used to construct the depth of recent alluvial sediments contour map shown in Figure 8. In Figure 8, the contour interval is 20 cm. Also shown in Figure 8 are the locations of Mill Creek, the embankment to Dam #9A, and the reference points.

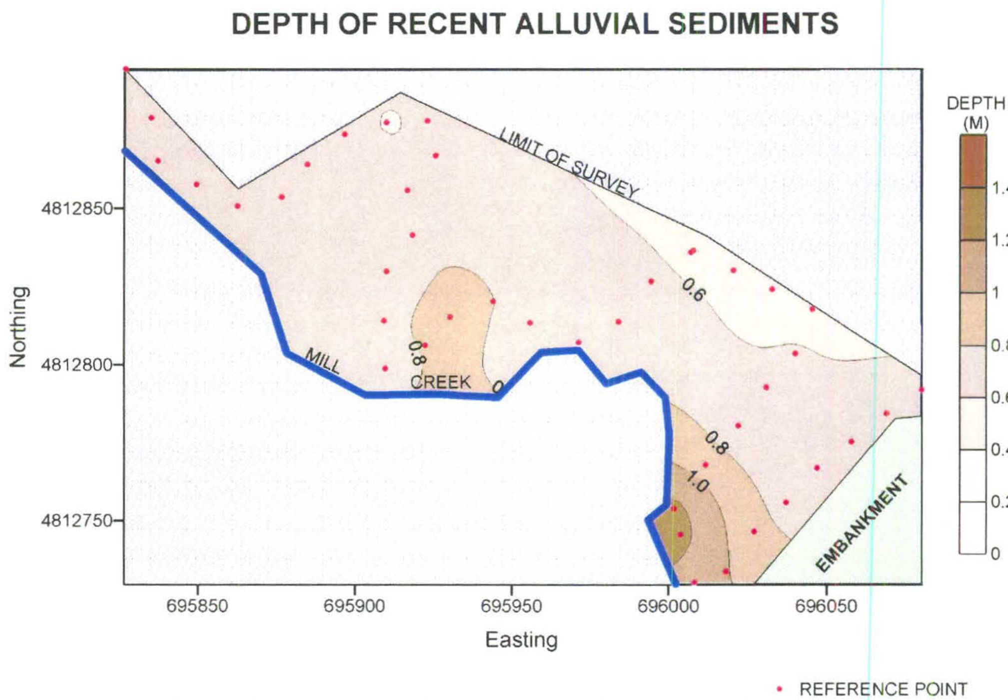

Figure 8. Thickness of alluvial deposits in an area of Orion soil.

Figure 9 contains choropleth maps showing the spatial distribution of apparent conductivity collected with the EM38DD meter. In each map, color variations have been used to show the distribution of apparent conductivity. In each plot the isoline interval is 5 mS/m. To remove spurious measurements and lines, the *grid node editor* of Surfer 8 was used to blank or make slight changes (0.1 to 0.2 mS/m) to some of the measured EMI responses.

Basic statistics for the data collected with the EM38DD meter are shown in Table 1. Apparent conductivity increased and became more variable with increasing penetration depths. Apparent conductivity averaged 10.9 mS/m and 16.8 mS/m for measurements obtained in the shallower-sensing, horizontal and deeper-sensing, vertical dipole orientations, respectively. In the horizontal dipole orientation, apparent conductivity ranged from about –17.3 to 31.4 mS/m with a standard deviation of 3.6 mS/m. In the vertical dipole orientation, apparent conductivity ranged from about –21.3 to 42.2 mS/m with a standard deviation of 5.2 mS/m. Negative measurements reflect interference from a buried metallic object. Negative values were suppressed in the plot of the vertical dipole data (see Figure 9, lower map).

Table 1
Apparent conductivity data collected with the EM38DD meter in an area of Orion silt loam, 0 to 3 % slopes. All values are in mS/m.

	Horizontal Dipole	Vertical Dipole
Average	10.9	16.8
Standard Deviation	3.6	5.2
Minimum	-17.3	-21.3
Maximum	31.4	42.2
25% Quartile	9.0	14.3
75% Quartile	12.8	19.5

The spatial patterns shown in Figure 9 represent difference in soil moisture contents and depths to the original channel bottom materials. Mill Creek is an entrenched stream. Steep slopes border this channel. Soils are better drained and have lower apparent conductivity in areas that adjoin the channel. In areas that are more distant from the channel, soils are more imperfectly drained and the depth to original channel bottom is less. Soils in these areas have higher apparent conductivity. A moderate (r = -483), but significant (.001 level) correlation was found between apparent conductivity (vertical dipole measurements) and depth to the original channel deposits. Though confounded by differences in moisture contents, areas with shallower depths to the original channel deposits have higher apparent conductivity.

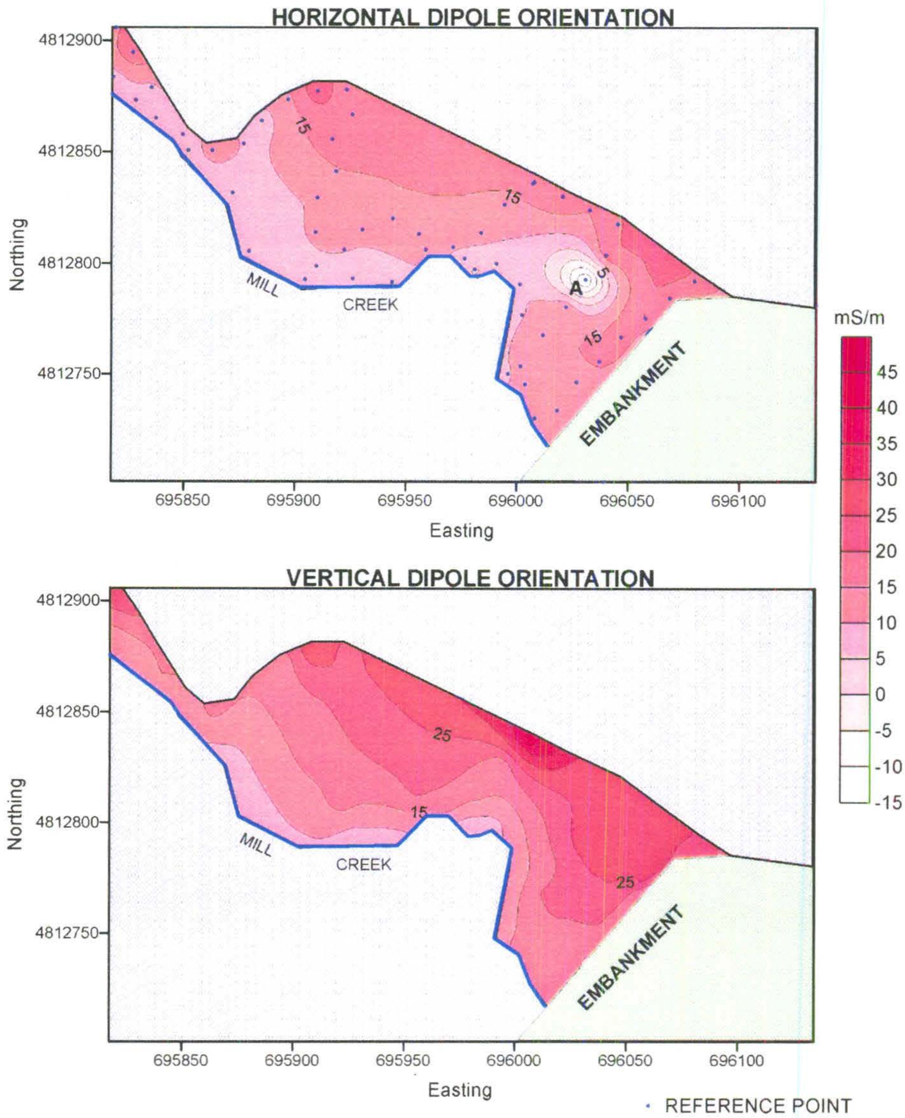

Figure 9. Spatial patterns of apparent conductivity in an area of Orion soil.

Discussion:

Water retention structures such as earthen and rock-filled dams are designed and expected to operate under a steady seepage state. While drainage systems are designed in these structures to collect and discharge seepage water into the downstream channel, excessive, unplanned, and anomalous seepage may threaten the integrity of a structure (Butler and Llopis, 1990). As a large number of earthen structures have exceeded their intended lifetime, there are needs to monitor these structures.

Geophysical methods permit the visualization of trends or localized anomalous conditions missed from all but extremely close-spaced drilling programs (Butler and Llopis, 1990). Geophysical methods, such as direct current (DC) resistivity, transient electromagnetic (TEM) and self-potential (SP), have been used to map seepage paths, monitor temporal and spatial changes in seepage, and help direct remedial measures on earthen dams (Buselli and Lu, 2001; Panthulu et al, 2001). The response of these methods is strongly dependent on changes in moisture contents.

Butler and Llopis (1990) have categorized EMI and GPR as primary and secondary geophysical tools, respectively, for the detection of anomalous seepage in earthen dams. Compared with other geophysical methods, GPR provides the highest resolution of subsurface features. Ground-penetrating radar is suited to shallow (generally less than 5 to 10 m) mapping applications in earthen materials that have low clay and salt contents. Ground-penetrating radar has been used to locate voids and buried pipes (Karastathis et al., 2002), and to monitor the deterioration processes in some concrete dams (Rhim, 2001). In addition, GPR has been used to locate voids and characterize internal structure of coarse-textured embankment materials in dams with a concrete (Silver et al., 1986) or clay (Dominic et al., 1995) core. Because of its dependency on soil properties, the appropriateness of GPR for the investigations of dams is highly variable. At many dam sites, the use of GPR is inappropriate.

In areas of undisturbed soils formed in materials weathered from sandstone, GPR provides a suitable tool to determine soil depths and characterize sheet joints and stratification within bedrock. Sheet joints represent fracturing due to the relief of pressure caused by the removal of overlying rock materials by erosion. Not all sheet joints or stratification will be detected with GPR. Toshioka and others (1995) observed that closed or dry fractures are not easily detected with GPR. However, most larger joints or facture zones are often filled with dissimilar soil materials. These materials often have higher clay and/or water contents than the host rock, and are therefore more visible to GPR.

The detection of anomalous seepage in earthen structures with EMI depends on the size, depth, and nature of the conduit path. Small, deeply buried conduits are more difficult to detect with EMI than large, shallowly buried conduits. Conduit paths are more detectable if the seepage water contains soluble salts that produce anomalously high EMI responses. Fracture zones in bedrock are active seepage conduits. As fractures may be filled with water and clays, they often have higher apparent conductivity than the surrounding unfractured bedrock. Disadvantages of EMI are limited penetration depths, sensitivity to above ground and buried metallic objects, and interference from nearby electrical sources.

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