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Identification of Potential Seepage Locations along the Herbert Hoover Dike, Lake Okeechobee FL, by Electromagnetic Geophysical Methods. Prediction and Confirmation.

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ABSTRACT

This case history demonstrates the use of electromagnetic (EM) induction methods to examine known seepage locations and then predict future ones along the Herbert Hoover Dike (HHD) in south central Florida. The HHD forms an embankment dam 20 to 30 feet high and 140 miles long surrounding Lake Okeechobee. Approximately 26 miles of embankment was surveyed with EM induction. The objective of the EM survey was to identify active and potential foundation seepage locations and conduits. Areas of greater conductivity were often associated with seepage locations observed during a record high water event in October, 1995. These problems included boils and piping of foundation and embankment materials. One great benefit of this investigation was that large areas of competent dike foundations could be separated from areas containing potential problems requiring additional examination.

KEYWORDS

Electromagnetic, Seepage, Piping, Embankment Dam, Geophysical, Dam Safety

INTRODUCTION

Project Background

Prior to reclamation efforts in the late 1800's, Lake Okeechobee regularly overflowed it's southern shore providing water to the long, wide flow way known as the Florida Everglades. Increasing agricultural demand for use of the rich, organic soil brought economic growth and development to the area. Canals were constructed to drain the land, and a low "muck" levee was constructed along the south shore of the lake. Initial construction of the federal project began in 1932 after two devastating hurricanes in 1926 and 1928. During these events, storm surges on the lake overtopped the locally constructed levees. These disasters resulted in the loss of approximately 2,700 lives and over $80 million in property damages. The present embankment section was completed in the 1960's. During this construction phase, the lake was completely encircled and embankment crest elevations were raised. The lake covers approximately 730 square miles and is normally less than 15 feet deep. In the area of study, water levels vary from 0 - 7 feet above the current surrounding ground levels. The project currently provides flood protection, navigation, water supply and water storage for a large portion of central and south Florida.

Problem Definition

The US Army Corps of Engineers, Jacksonville District, produced a report in 1986. Using existing data, it was determined that there was a potential for seepage problems in the embankment foundation. The combination of a hydraulic fill embankment over a peat and porous limestone foundation resulted in a structure susceptible to seepage damage. A second report was released in 1993 by Jacksonville District restating the vulnerability of the embankment and foundation to breaching due to a piping failure at lake levels far below

Standard Project Flood (SPF). A Major Rehabilitation Evaluation Report (MRER) was funded in October, 1994 to perform subsurface explorations, surveys, laboratory analyses and probabilistic geotechnical analyses for seepage and slope stability. In order to accomplish this task with limited resources, the project was divided into eight reaches as shown in Fig. 1. The 22 miles of Reach 1 were deemed the most critical due to it's susceptibility to seepage damage, topography and proximity to populated areas. The majority of effort was focused on Reach 1 and to a much lesser degree Reaches 2 - 7. In order to maximize core boring efforts to drill in the areas most prone to seepage damage, the Jacksonville District, in conjunction with the US Army Corps of Engineers Waterways Experiment Station (WES), tried five different alternatives to supplement core borings. Cone Penetrometer Testing (CPT) and four geophysical methods were selected for trials beginning in January, 1995. The first phase was a two week trial to test the suitability of the different methods. The second "production" phase took three weeks and was completed in August, 1995.

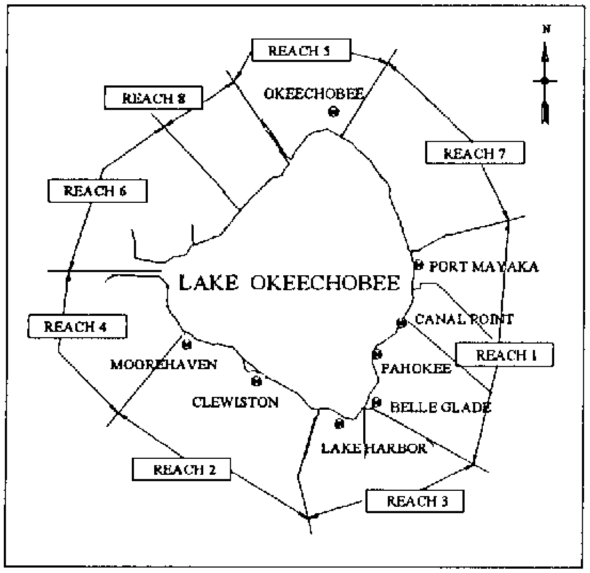

Fig. 1 Project Site Plan.

COMPARISON OF EXPLORATION METHODS

In addition to core borings and CPTs, four geophysical exploration methods (resistivity, ground penetrating radar, self potential, and electromagnetic induction) were used to obtain subsurface data. The objective of the first phase investigation was to determine which method could best characterize materials and locate active or potential seepage paths. The alternative methods were tested for suitability at a test section in Reach 1 just north of the city of Pahokee where documented long term water seeps existed and embankment foundation properties were known. The target depth for the zone of primary investigations was 5 to 20 feet at the toe of the embankment.

Core Borings

Core borings (Standard Penetration Testing (SPT) and drive sampling) were the standard tools for the HHD explorations. Core borings provide material samples for inspection and laboratory testing . Another advantage of core borings is that piezometers can be installed for a minimal extra cost. Because core borings are expensive and time consuming, they were drilled for the present MRER seepage exploration on 3,000 foot or greater spacing. This spacing will miss anomalies in the embankment and foundation that may exist between the core boring locations.

Cone Penetrometer

The WES cone penetrometer truck was brought on site in March, 1995. Cone Penetrometer Testing (CPT) was expected to produce continuous soil classifications, continuous SPT values, and continuous piezometric values from each of the exploration locations. The continuous classification of materials and the continuous standard blow counts produced by the cone penetrometer were excellent. However, the CPT's were not deemed suitable in this application since they were not able to penetrate the soil horizons of the rocky or gravely materials of most interest, and the truck was not able to operate on soft ground at the toe of the embankment.

Resistivity

Different subsurface materials can be characterized by their electrical resistance properties. The application of the resistivity method consists of placing a series of metal electrodes into the ground arranged in a prescribed manner. An electrical current is passed through two electrodes and the voltage potential is measured across two other electrodes. By varying the distance and geometry between the electrodes, the electrical properties of volumes of material at increasing depths in the subsurface can be established. This can be repeated at a succession of points along a linear array. Newly developed instrumentation for resistivity investigations was utilized in this test effort. Using this equipment, several long and continuous subsurface high resolution (for the method) resistivity profiles were acquired at the test site. The depth of intense investigation was 3 to 30 feet. However, analysis of the data did not reveal that the seepage areas could be discerned from areas where no water permeability problems existed. As a consequence, this method was not applied during the second phase of the investigation.

Ground Penetrating Radar

Areas which are underlain by granular material are often favorable sites for Ground Penetrating Radar (GPR) investigations. The depth of interrogation by this method is highly dependent on the percentage and type of clay contained in the subsurface material. Generally, clay exhibits changes in the dielectric that can greatly attenuate and modify the broadcasted radar wave. The test site proved to be suitable for GPR. This geophysical method involves transmitting a high frequency pulse (50 Kilo Hertz in this case) into the ground. At the test site, GPR penetration depths of 14 to 17 feet were achieved. Subsurface GPR profiles at the test site displayed boundaries in substantial agreement with material boundaries determined by core borings. The reflection coefficients (percentage of the pulse returned) at boundaries varies considerably in a lateral fashion. This effect is interpreted as the result of significant changes in the dielectric properties of the material rather than large resistivity variations. In addition, the absorption characteristics of the strata differs substantially. This implies that significant material changes in the sediments are present which can be illuminated and displayed. Although the results of the GPR investigation were of high quality and displayed notable lateral variations in subsurface conditions, no direct correlation between foundation seepage locations and the GPR stratigraphy could be determined.

Self Potential

The location of seepage under earthen structures can often be determined by self potential techniques. Flowing fluid will create a streaming electrical potential which can be measured. This data is generally collected by employing two special electrodes, one a fixed reference and the other placed in locations along a traverse. The electrical potential in mill Volts is measured between the electrodes at each place. To achieve a measurable potential, a water head differential of at least several tens of feet is generally required. At the test site, the head differential was significantly less than 10 feet. No measurable electrical potential could be identified that was the result of seepage. Therefore, the self potential technique was not used in further studies.

Electromagnetic

The results of the electromagnetic investigation produced significant results in direct detection of seeps and local high ground water conditions under the embankment. In this application, a Geonics EM-31 was used to broadcast a continuous wave electromagnetic field into the subsurface. This signal interacts with and then induces eddy currents in the subsurface materials and fluids. These currents then generate secondary electromagnetic fields which can then be detected. Contrasting material types and dissimilar soil moisture concentrations produce differing electrical induction effects. As a result, if the lateral subsurface soil resitivity remains reasonably constant for reasonable distances, then any variations displayed in the conductivity results can be largely the result of lateral changes in subsurface moisture conditions. The electromagnetic field investigation was designed to achieve an average depth of significant material influence in the area of 14 to 16 feet in the subsurface. Consequently, it was feasible to gain a qualitative idea of lateral increases or decreases in the ground water table or moisture content along the embankment. Using this method, it was possible to directly detect and measure local seepage sites under the embankment toe.

ELECTROMAGNETIC SURVEYING

Production Reaches 2 and 3

The electromagnetic induction method was used in August, 1995 along the toe of the embankment in Reaches 2 and 3. Refer to the reference map shown in Fig. 2 (locations are referenced to water control structures such as spillway structure S-77). The Geonics EM 31 was mounted on a plastic trailer and towed about 20 feet behind a Global Positioning System (GPS) equipped all terrain vehicle. EM induction data and differentially corrected positions were collected every 2 seconds, with a forward speed of 2.5 to 3 miles per hour. As a result, it was possible to categorize large sections of the levee system in regard to seepage locations and the relative level of water saturation in the zone of induction investigation. Lake levels at this time were between elevations 16.3 and 16.4 feet. Significant regional and local variations in subsurface moisture content at a constant depth of investigation were documented.

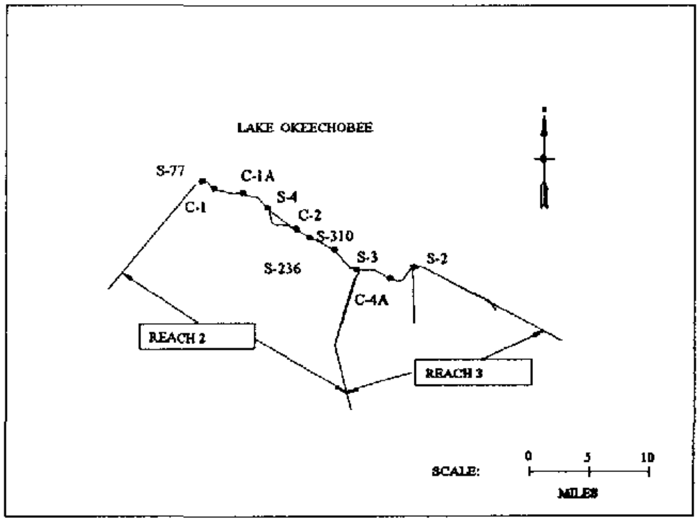

Fig. 2. Reference map of Reaches 2 and 3.

Presentation and Analysis of Results

The collected and processed data is presented against distance to demonstrate lateral changes in subsurface moisture content. This is exhibited by the computed conductivity values in millSiems per meter (MS/M). In this investigation, the observed values ranged from 10 to 25 MS/M for the dry to less saturated areas, to measurements of 40 to over 70 MS/M for the well saturated regions in the subsurface. In addition, an "in-phase" measurement may be extracted from the data. These additional computations are chiefly a response to highly conductive materials in the subsurface such as metal pipes and cables. Very large metal pipes generally generate a very sharp electrical conductivity peak. This feature can be used to easily distinguish metallic conductivity anomalies from responses due to seepage sources within the dike. In this investigation, electrical conductivity values greater than 45 to 50 MS/M indicate the subsurface (within the zone of instrument interrogation) is well saturated. For the purposes of graphical presentation, the values shown in this report represent the average of 50 values plotted as a point. Although individual peaks are not represented, this does not detract from the interpretation of large areas of several thousand feet.

Section from S-77 to S-4. This represents the western eight miles of the area of consideration. A typical cross section of the embankment, MRR2-E, is shown in Fig. 3. The geologic conditions in this area are generally sand overlying layers of shell and limestone. The sand also contains varying percentages of shell. The shell and limestone layers are very pervious relative to the sand. Meyer (1971) also found this area had the highest transmissivity of five sites studied along the south shore of the lake from Moorehaven east to Canal Point. (See Fig. 1.). The deep excavation on the lake side of the embankment is the borrow canal. The ditch between the embankment and U.S. 27 serves as both a seepage control ditch and surface runoff interceptor. These excavations intersect some of the shell and rock layers in the foundation.

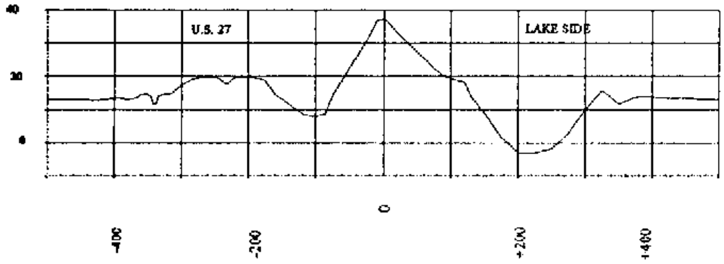

Fig. 3. Cross section MRR2-E. Distances and elevations in feet.

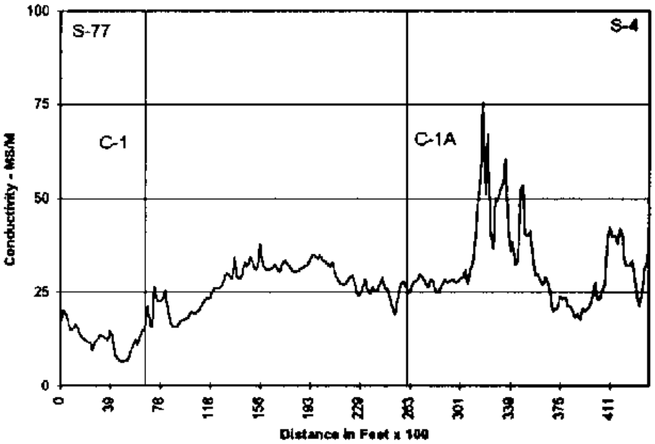

Fig. 4. EM results from S-77 to S-4.

Figure 4 represents data along the section from S-77 to S-4. Only one area in this section was considered for future study. The sustained peaks from distance 301 to 339 represent anomalous conditions in the foundation. Some of these areas registered a high in-phase measurement, indicating metal pipes in the subsurface.

Section from S-4 to S-236. Figure 5 represents the middle eight miles of data collected. Cross section MRR2-E is also representative of this section. The geologic conditions in this area are similar with sand overlying layers of shell and limestone. This area represents a transition with increasing silt in the upper sand layers and lenses of peat at the natural ground surface. Anomalies from about distance 20 to 60 and at 135 were noted as significant. Also noted was the increase in background conductivity to about 35 MS/M, indicating a broad lateral change in the subsurface moisture content or changes in the groundwater surface elevation. Anomalies from distance 332 to 395 are characterized similarly, with a noted increase in background conductivity.

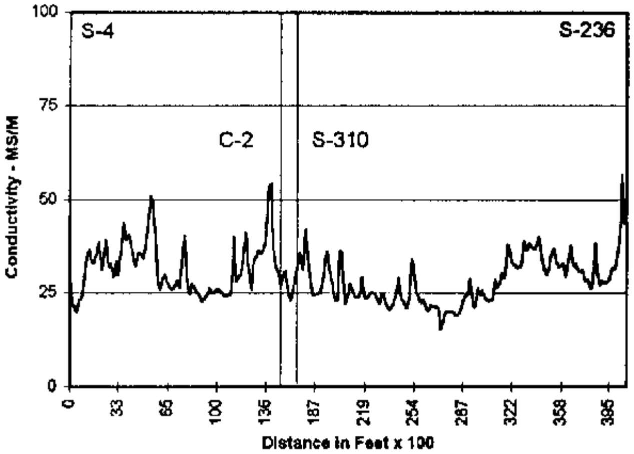

Fig. 5. EM results from S-4 to S-236.

Section from S-236 to S-2. This represents the easternmost ten miles of data collected. A typical cross section, MRR3-A, is shown in Fig. 6. The foundation conditions in this section are markedly different from that in the western two sections. A thick surficial layer of peat overlays a layer of silt. Below the silt are interbedded layers of sand and limestone. As in other areas, the percentage of shell in the sand layers can be significant. Also, note the depth of the drainage ditches between U.S. 27 and the embankment.

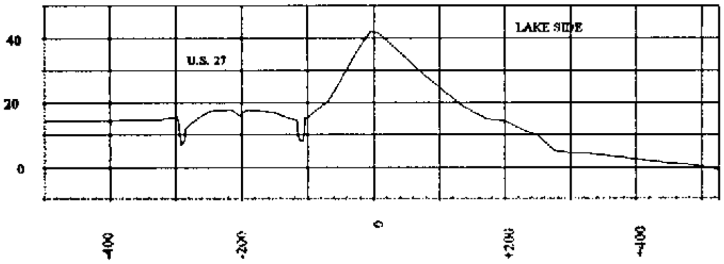

Fig. 6. Cross section MRR3-A. Distances and elevations in feet.

The most apparent feature of the EM data in Fig. 7 is the pronounced sustained peak at distance 174. These large anomalies with conductivity values from 75 to nearly 100 MS/M indicated largely saturated subsurface conditions. This also inferred that larger hydraulic conductivities existed at depths below the region of inquiry. The background conductivities of 30 - 40 ms/m between S-236 and S-3 are a result of the generally higher ground water table along this portion of the embankment.

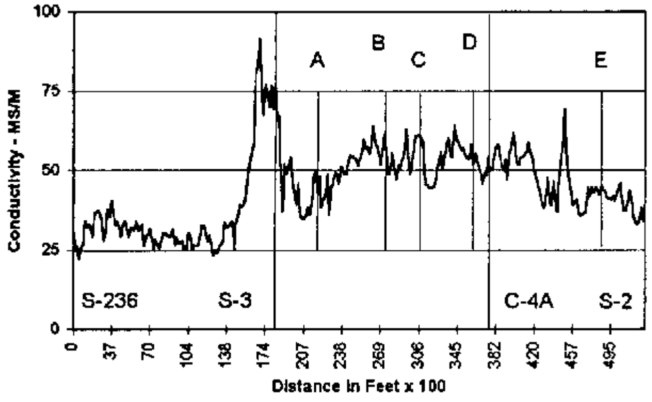

Fig. 7. EM results from S-236 to S-2.

The area at distance 174 was investigated by both core borings and downhole video in September, 1995. The limestone was chalky and very porous with a unit weight of 105 pounds per cubic foot (pcf). Competent limestone in this area is generally 130 to 150 pcf. Visible flow was observed in the video. Clouds of silt and some sand particles were observed to move laterally at different levels within the limestone. Sand and shell that fell into the bottom of the boring were observed to "boil" from flow at the bottom of the hole. Another significant factor at this site was the large borrow ditch shown in Fig. 8 at cross section MRR2-G.

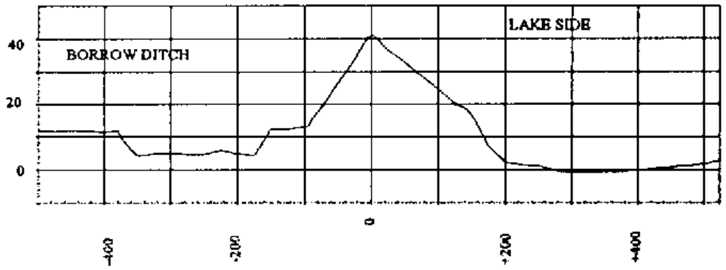

Fig. 8. Cross section MRR2-G. Distances and elevations in feet.

A broad area of numerous anomalies were encountered east of S-3 in Fig. 7. Conductivities from 45 to 75 MS/M were common, with a background of approximately 50 MS/M. This is representative of very saturated subsurface conditions and an elevated groundwater table. Many of the peaks were located in regions of visible groundwater seepage. Note that at this time, the lake level was at 16.4 feet and the existing ground surface in this area (section MRR3-A) was approximately elevation 15.0. This section was expected to demonstrate the highest hydraulic conductivity.

CONCLUSIONS

High Water Event of 1995

Two months after completing the second phase geophysical survey of Reaches 2 and 3, Lake Okeechobee reached it's highest level in almost 50 years during late October and early November of 1995. The high daily average lake level recorded during this period was elevation 18.8 feet, NGVD. This corresponded roughly to a "30 year event". Lake elevations are typically between elevation 14 and 15 feet. Daily inspections were performed on the embankment and water control structures. This was in accordance with the Jacksonville District Dam Safety Program and the project's Emergency Action Plan (EAP). Nine general areas of seepage and piping were observed. There were four in Reach 1 and five in Reach 3. The worst of these sites had several pipes in the landside drainage ditch and boils were noted at some of the drainage culverts under U.S. Highway 27.

Comparison to High Water Event Damages

Damage to the embankment is defined as excessive seepage or piping. Damage was observed in Reaches 1 and 3. Since Reach 1 was not part of the EM survey, only damage to Reach 3 will be relevant to this comparison with one exception. There were five main areas of damage in Reach 3. They are labeled in Fig. 7 as "A", "B", "C", "D" and "E". Other areas of saturated berms were encountered in Reach 3; but, points A through E were the only locations where there was visible flow exiting the slope or piping of material.

Point A. This was an area where a large volume of seepage was exiting along the downstream berm at elev. 15 ft for about 200 feet. There was no piping of material (flow was clear); however, the quantity of seepage was excessive and cause for concern.

Point B. This was an area about 1500 feet long where there were several dozen pipes exiting into the toe ditch with significant movement of material. This area had the most severe damage. Several of the pipes had caved in, causing depressions to extend from the ditch into the toe of the embankment about 25 feet away. Several small and one large sinkhole developed on the crest of the embankment. The large sinkhole was 3 feet in diameter by 6 feet deep. Probing with a steel rod indicated a cavity for an additional 5 to 6 feet before resistance was encountered. Sinkholes were also found in the crest of the embankment between points B, C, and D.

Point C. This area was approximately 2500 feet long where the downstream slope of the embankment experienced varying degrees of seepage without movement of material.

Point D. This was an area where several seeps exited the berm and a boil developed at elevation 15.5 ft. The boil piped material at first and then flowed clear. It is interesting to note that the embankment section was measured at 280 feet from the lake shore to the boil with a head of approximately three feet. This indicated that there was almost a direct connection to the lake, with less than three feet of head lost in almost 300 feet.

Point E. This was an area where two different types of problems emerged. Through seepage exited the slope at the berm and flowed clear. Also, in the adjacent ditch two areas were flowing into the ditch at the toe of the embankment. There was a strong sulfur odor and a white stain covered the organic soils in the area. This water was likely from below the confining silt layer, indicating flow from the foundation rock below through an open conduit that had formed by fracturing the silt layer below the peat.

Comment on Reach 1. One item of interest was an area of seepage in Reach 1. This area was approximately two miles north of the geophysical test site. During the High Water Event, excessive seepage exited the slope at approximately elevation 14 ft. Subsequent excavation of this area revealed an abandoned 6 inch diameter cast iron water supply pipe. Even though the pipe had been plugged with concrete, it had formed a "roof" for a flow channel which had developed over time. In a structure of this age and size, locating abandoned pipes is an important issue. A pipe of this size and depth would have been detected had this area been surveyed using the same EM methods as were used in Reaches 2 and 3.

Comparison to Known Geology

There is an apparent relationship between the EM values, the topography, the foundation materials, and the embankment materials. The higher conductivity values appear to be primarily caused by seepage through the embankment. Five separate cases can be presented for combinations of foundation and embankment conditions which contribute either to the high or low EM readings.

Case 1. In the western portion of Reach 2 from S-77 to S-4, the EM values are low, indicating a dry toe. Both the embankment and foundation are composed primarily of pervious shelly materials which drain the seepage into the foundation and keep the embankment toe dry as shown in Fig. 9.

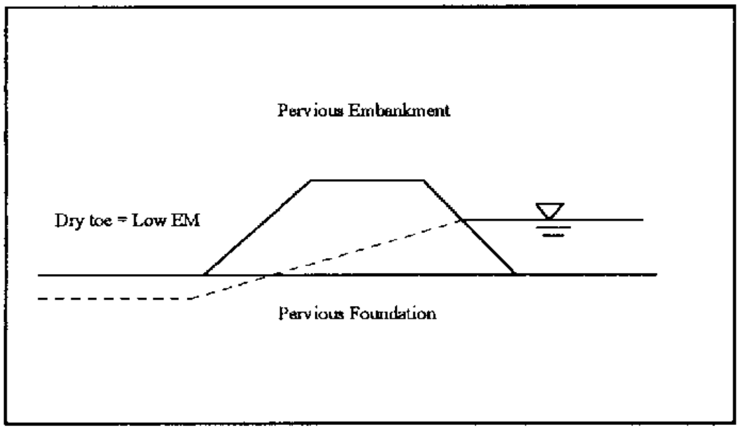

Fig. 9. Case 1. Pervious embankment over pervious foundation.

Case 2. From S-4 to S-236, the readings are increasing slightly. There is a pervious to semi-pervious embankment overlying a confining layer. This is the general condition existing in Reach 3. Water from the lake, seeping into the embankment can't drain into the foundation because of the confining layer. The seepage is forced to exit the toe of the embankment. This results in a wet toe and high EM values as shown in Fig. 10.

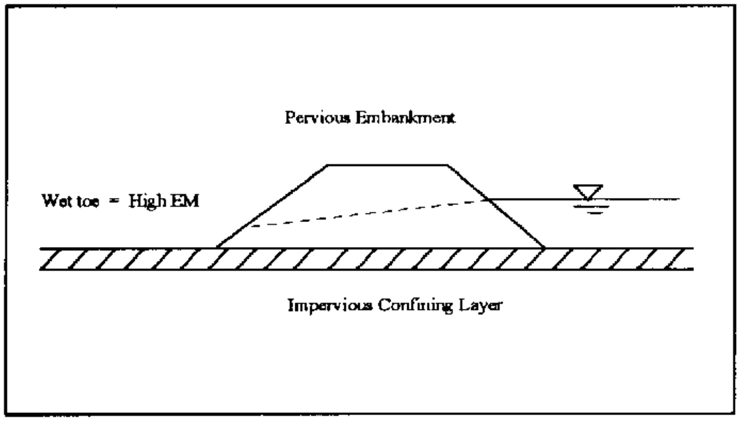

Fig. 10. Case 2. Pervious embankment over impervious foundation.

Case 3. From S-3 to C-4A a dramatic change takes place. Gravely layers within the embankment are highly pervious and serve as conduits to supply seepage water directly to the toe of the embankment. This results in a wet toe and very high EM values as shown in Fig. 11. This condition is also particularly hazardous since a significant head drop occurs in a short distance across the downstream portion of the embankment.

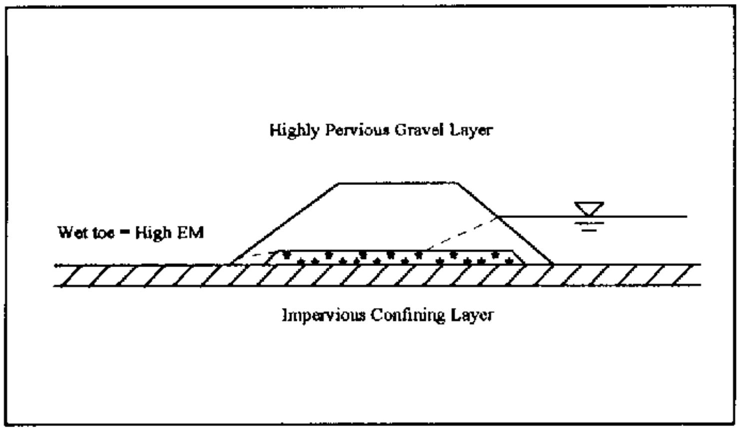

Fig. 11. Case 3. Highly pervious gravel layer in embankment.

Case 4. Based on experiences from core borings and piezometer readings in Reach 1, a fourth condition can be presented. This condition exists sporadically along the embankment where the toe was constructed of clayey or silty materials. This material acts as a downstream impervious blanket which raises the piezometric level within the embankment as shown in Fig. 12. This results in a wet toe and high EM values.

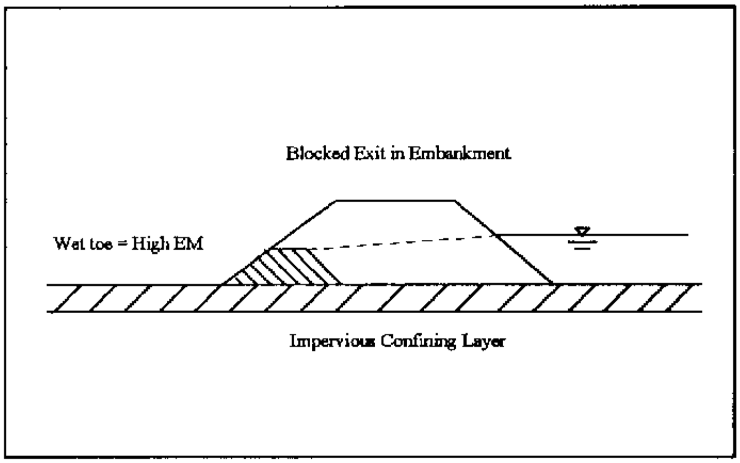

Fig. 12. Case 4. Blocked Exit.

Case 5. Another local anomaly which can be detected is artesian flow from limestone layers beneath the embankment. This occurs where the confining layer has been heaved or fractured (usually in a ditch bottom). These fractures serve as conduits for seepage up through the confining layer into the toe of the embankment. This results in a wet toe and high EM values as shown in Fig. 13.

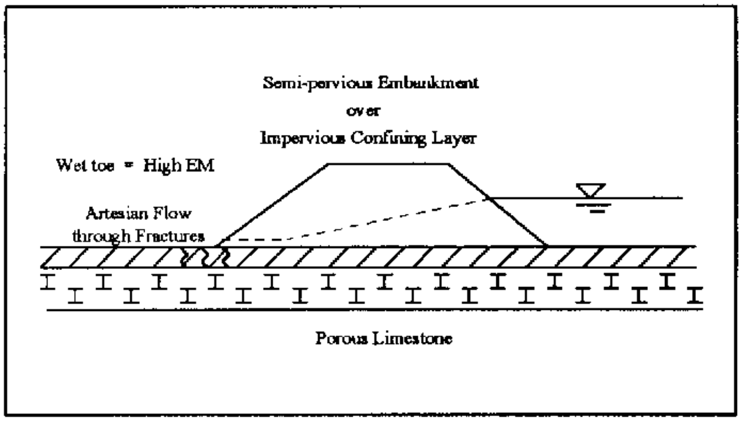

Fig. 13. Case 5. Artesian Flow.

POST HIGH WATER EVENT ACTIVITIES

Remedial Repairs at Damage Locations

Core borings were obtained in December, 1995 at each of these sites both in the crest and at the landside toe. Peizometers were also installed. Temporary repairs at the Lake Harbor sites consisted of removing 2 - 4 feet of peat off the landside berm. The berm and drainage ditch were then backfilled with filter stone. At point E on Fig. 7, a line of relief wells 12 inches in diameter and 10 feet deep were drilled along a 300 foot section and backfilled with filter stone. The stone columns were connected by a 3 foot by 3 foot ditch to drain into the existing ditch.

Use of EM to establish Repair Limits

EM surveying could assist in identifying the boundaries of each remedial solution to be constructed, such as the limits of a filter blanket or relief wells. The main purpose would be to locate transition points or boundaries in the geological conditions. Conventional core borings could then be concentrated in these boundary areas.

Potential for Future Applications

Since it is financially impractical to instrument all of HHD with a close regular spacing of conventional instruments such as piezometers, EM could be used to establish a baseline conductivity around the perimeter of the embankment at a common lake level such as elevation 15 or 16 ft. This would allow examination of areas of the embankment relative to each other. As observed in the Reach 2 to Reach 3 transition, Reach 3 was clearly more conductive than Reach 2 and Reach 3 experienced piping problems at a lake level of 18.5 ft whereas Reach 2 did not. Re-examination after a high water level event could reveal changes in conductivity relating to a worsening condition. Higher EM values could reflect the removal of smaller material from gap graded soils, development of fractures in the confining layer, or lengthening of existing pipes in the embankment.

SUMMARY

Geophysical methods can be used to aid in the characterizations of subsurface conditions. These methods are best combined with conventional exploration methods such as core borings and piezometers for a more complete picture of the subsurface conditions. In many cases, however, it is difficult to determine before hand what geophysical method will work best at any given site. At Herbert Hoover Dike, a geophysical test program determined that EM surveying was best suited to aid in the characterization of seepage locations. The subsequent EM survey of Reaches 2 and 3 was able to classify the materials along the levee toe according to their relative moisture contents. This provided additional information which led to the conclusion that a wet toe implies active seepage potential. During the subsequent high water event, the seepage problems seen were in areas where the EM survey had implied high seepage potential. It should also be noted, however, that data from piezometers installed in completed core borings was the single most effective tool in understanding the seepage problems associated with the project.

Some key advantages of the EM method are:

1. EM investigations are useful in differentiating large segments of an earthen embankment dam. This can assist in classifying potential problem areas from those less inclined to have seepage problems.

2. It can provide a continuous log of the moisture conditions (no gaps in the data), it can proceed rapidly (2.5 miles per hour), and it is relatively inexpensive considering the per mile cost. It is the only method available that has the potential to characterize the entire 140 miles of HHD at a minimal cost.

3. It could be used to examine degradation of the embankment and foundation over time to monitor changes in saturated or unsaturated areas. This potential dam safety tool could give an indication of performance after a number of high water events.

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