

APPLICATION OF A COMBINED NONDESTRUCTIVE EVALUATION APPROACH TO DETECTING SUBGRADE VOIDS BELOW A DAM SPILLWAY

David A. Hollema, Olson Engineering, Inc., Wheat Ridge, Colorado

Larry D. Olson, Olson Engineering, Inc., Wheat Ridge, Colorado

Abstract

The combination of Ground Penetrating Radar (GPR) and Slab Impulse Response (Slab IR) nondestructive evaluation (NDE) methods can be used to improve detection of subgrade voids beneath reinforced concrete slabs. Subgrade voids are typically created by the eroding action of flowing water because of an elevation or otherwise caused pressure gradient. Voids promote cracking and potential for major long-term damage resulting in expensive repairs or replacement. These methods were recently utilized at an alpine dam spillway for detection of potential subgrade voids.

3-Dimensional (3-D) GPR data were analyzed in a “bright spot” fashion by looking for zones where the slab bottom reflection was abnormally strong. The cause of this data signature was attributed to a strong contrast in dielectric between that of wet concrete and that of air or water-filled voids. Slab IR is a model vibration test method and measures the amplitude and frequency of the slab vibration when impacted with an instrumented hammer. Slab areas overlying voids respond with higher amplitudes and lower stiffnesses when impacted. The 3-D GPR and contoured Slab IR results correlated well and the same anomalous areas were discovered in each data set. Coring and video borescope were used for confirmation of NDE delineated voids and proved the success of the methods.

Introduction

Olson Engineering was contracted to perform a nondestructive evaluation (NDE) investigation to attempt to locate potential voids beneath a concrete spillway of an alpine dam in the Rocky Mountains of Colorado. The alpine reservoir is located at a surface elevation of 9886 ft above sea level, has a water capacity of approximately 800 acre-ft, and serves as the consumable water source for a nearby town. An overview photograph of the dam spillway and surrounding mountains is presented in Figure 1.

Prior to the NDE investigation, a drilling program was conducted by the local municipality and confirmed voids underneath the spillway slab. This program was executed after observations indicated seepage from joints and spalls in this area, and after hammer sounding performed by 2 other consulting firms. The drilling was confined to an area between approximately 88 ft to 125 ft downstream of the spillway crest.

Our investigation included a nondestructive evaluation program of the entire spillway (a length of approximately 156 ft) over a width of 52 ft at the spillway crest, decreasing uniformly along the spillway length to a width of 32 ft at the spillway stilling basin. Ground Penetrating Radar (GPR) scanning was performed along the spillway length spaced at 4 ft intervals. Slab Impulse Response (Slab IR) testing was performed on a 2-dimensional grid spaced at 4 ft intervals over the entire area of the spillway. Grid spacing was chosen based on obtaining the highest data density coverage within the budget limits for the investigation.

Coring and video borescope work was performed after our recommendations for probable void locations were given. The results of the drilling program were used in our analysis and interpretation of the Slab IR data and GPR data.



Figure 1.: Overview of the alpine dam spillway

Coring results indicated the thickness of the concrete in the spillway varied from 6.5 inches to 9.5 inches except for one core near the crest of the spillway which measured approximately 14 inches thick. This particular core was expected to have a greater thickness at this location on the spillway based on the spillway design parameters.

Ground Penetrating Radar (GPR) Method

The GPR method involves moving an antenna across a test surface while periodically pulsing the antenna and recording the received echoes, as diagramed in Figure 2 for a typical concrete slab. Pulses are sent out from the GPR computer driving the antenna at a frequency range centered on the design center frequency of the antenna, in this case 400 MegaHertz (MHZ). These electromagnetic wave pulses propagate through the material directly under the antenna, with some energy reflecting back whenever the wave encounters a change in electrical impedance, such as at a rebar or other steel embedment or air-filled void. The antenna then receives these echoes, which are amplified and filtered in the GPR computer, and then digitized and stored. A distance wheel records scan distance across the test surface and embedded features can be located as a given distance from the scan start position. For repetitive scanning, a standard survey is designed and adhered to as field conditions allow to minimize mistakes and to maximize data quality. Daniels expounds on the theory and application of the GPR method (1996).

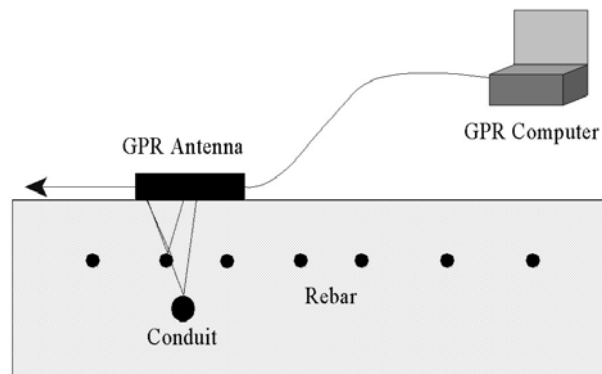


Figure 2.: GPR Schematic

The scans for this investigation were created from pulses sent out at lateral intervals of near 48 pulses per foot. The resulting raw data is in the form of echo amplitude versus time. By inputting the dielectric constant (based on the material being scanned; 9.8 was used for this investigation), and by estimating the signal zero point, the echo time data can be converted to echo depth. If more accurate depth data is required, a depth calibration can be done if an embedment of a known depth is available to scan over. Concrete electromagnetic velocity (dielectric constant) calibration was performed using 8 spillway thickness values obtained from the cores taken. The scans are then typically plotted as waterfall plots of all of the individual data traces collected, with the lightness or darkness (or color) of each point in the plot being set by the amplitude and polarity (positive or negative) of the data at a given depth in each trace. Further, if data are collected along evenly spaced gridlines, a 3-D interpolation can be performed to generate a cubic display of data. This data cube can then be sliced along certain planes (typically XY, XZ, and YZ) to enhance recognition and display of target features. Also, amplitude threshold constraints can be set to allow display of GPR reflections within the given threshold values. Regional features are often more easily recognized when viewing a slice of 3-D interpolated data.

Slab Impulse Response (Slab IR) Method

The Slab Impulse Response (Slab IR) method detects and defines the extent of good versus void/poor support conditions of a slab, but does not provide information on the depth or thickness of void. The method was developed from a force-response vibration test for investigating the integrity of deep foundations and was originally adapted for a slab by a European group.

The Slab IR investigation was conducted from the surface of the concrete spillway. Field equipment included an impulse hammer, Wilcoxson velocity transducer, and an Olson Instruments Freedom NDT PC. The method involved hitting the concrete spillway to generate vibration energy. The 3-lb impulse hammer has a built-in load cell with a plastic head to measure the force of the impact. The vibration response of the concrete to the impact is measured with the velocity transducer held in contact with the concrete close to the point of impact. The outputs from 3 hits of the hammer and the receiver responses were viewed, recorded and processed on an Olson Instruments Freedom NDT PC.

The Olson Instruments Freedom NDT PC performs the Fast Fourier Transform (FFT) Transfer Function operations on the time domain data to produce the mobility plots in frequency domain. Figure 3 is an idealized plot of mobility (vibration velocity amplitude per pound force) as a function of

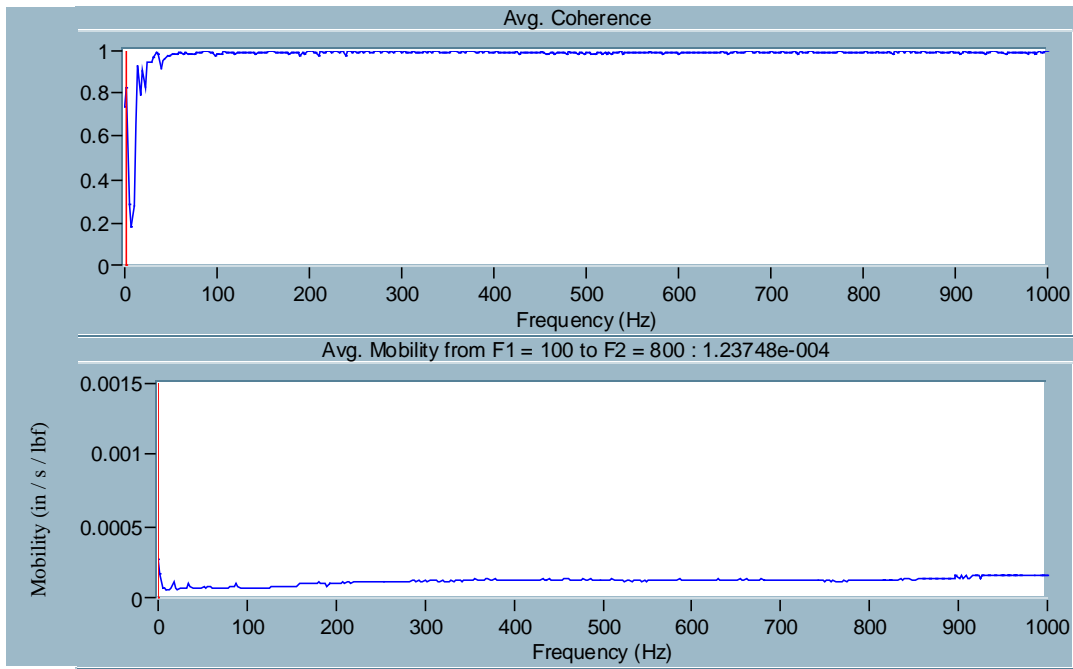


Figure 3.: Example Slab IR plot of mobility indicative of good subgrade support from Test Location 5C

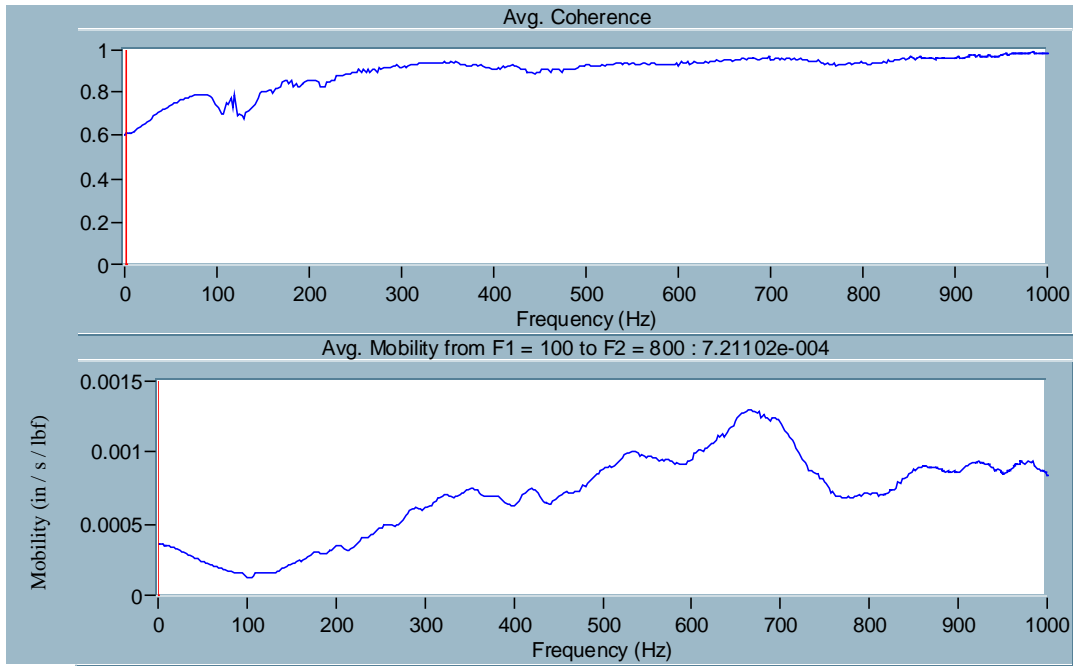


Figure 4.: Example Slab IR plot of mobility indicative of void/poor subgrade support from Test Location 24C

frequency measured in cycles per second or Hertz (Hz) for good subgrade support. The low, and comparatively smooth, mobility is an indicator of good subgrade support conditions. Irregular and higher amplitude mobility indicates a less stiff slab-subgrade support system, indicating poor (void)

support conditions (Figure 4). The top plots are coherence and a value near 1.0 indicates good quality data.

Subgrade support condition evaluation is based on several measured parameters. First, the mean mobility (in/sec/lbf) provides a general indication of the spillway stiffness. Higher mobility may indicate a more flexible and less stiff spillway-subgrade system. Secondly, the shape of the mobility plot at frequencies above the initial straight-line portion of the curve (between 100 to 800 Hz in this investigation) is another indicator of subgrade support conditions. The response curve is more irregular and has a greater mobility for void versus good support conditions due to the decreased damping of the spillway vibration response for a void (Figure 4). Finally, the initial slope of the mobility plot gives the low-strain flexibility (in/lbf) of the spillway-subgrade system. The flexibility is a measurement of how much the spillway moves for a given impact, and the inverse of the flexibility is stiffness. Higher flexibility corresponds to less subgrade support or thinner concrete at the data point. Additional discussion of the Slab IR method and its history is given by Davis (1999).

Other factors typically considered in the Slab IR method include the geometry and thickness of the spillway, the boundary conditions in the vicinity of a test location (including cracks and joints), and the spillway reinforcement. Findings and conclusions on the spillway subgrade support conditions can usually be drawn based on Slab IR results, comparison of data from similar conditions, and/or by correlation with destructive (e.g., core) results. With other factors being constant, thinner spillways are more mobile and flexible than thicker spillways. Regardless of the thickness, the shape of a mobility curve from a point with good subgrade support is generally smooth with no low frequency peaks.

GPR Field Investigation & Example Data

To simplify field data collection for GPR and Slab IR, a nominally 4 x 4 ft grid was established at the spillway. A naming convention was used to designate each grid line in both the north-to-south and east-to-west directions. The centerline of the spillway, running longitudinally for more than 156 ft downstream (north), was named 'C'. Longitudinal lines were designated at 4 ft intervals from right of center eastward as R1 through R6, and at 4 ft intervals from left of center westward as L1 through L6 when looking downstream from the spillway crest. The short east-to-west gridlines (axial lines) began with Line 1 located 2 ft downstream of the reservoir shore edge and continued at 4 ft intervals to line 40, approximately 158 ft downstream of the reservoir shore edge.

The GPR investigation was performed over a nominal length of 156 ft along the concrete spillway. All GPR data were collected using an antenna with a center frequency of 400 MHz and stored in a Geophysical Survey Systems Incorporated (GSSI) SIR-2000 GPR field data collection system. The GPR scanning was performed in 13 lines along the length of the spillway at lines spaced at 4 ft intervals as shown in Figure 5. The actual scanning was split into 2 portions— upper and lower spillway. Initially, scanning was performed at the upper portion of the spillway, from the crest downstream to a distance of 120 ft (Line 30). Next, the lower spillway was scanned, from 116 ft (Line 30) to near 156 ft (Line 41) below the spillway crest. All GPR scans were started 2 ft from the reservoir shore edge and continued downstream. The spillway tapered down uniformly from upstream to downstream causing the two outside lines on both sides of the spillway (L6, L5, R5, and R6) to 'pinch out' at a distance less than 156 ft. The two outside scans on both sides of the spillway are shorter than the nine inside scans.

An example of GPR data recorded along the spillway center is presented in Figure 6. This is a waterfall plot of GPR data recorded along the centerline, 70 - 107 ft downstream of the spillway crest. The waterfall plot presented in the figure was manipulated and analyzed using a 2-D GPR analysis and display software package. Figure 6 shows 3 scan characteristics. The rebar mat ranges from a depth of 0.2 to 0.6 ft (depth in ft. on right hand vertical scale – left hand scale is time in nanoseconds). The slab

bottom reflection is evident at a depth ranging from approximately 0.6 to 0.8 ft. The amplitude of the slab bottom reflection was used for void detection analysis with “bright” and “low” amplitude reflectors shown in Figure 6. Stronger negative amplitudes are indicative of a strong dielectric constant contrast (concrete to air), evidence of potential voids. The core location along the centerline, used for concrete dielectric constant calibration, is shown in the figure as well (near 96 ft). The concrete at this location measured 7.25 inches thick.

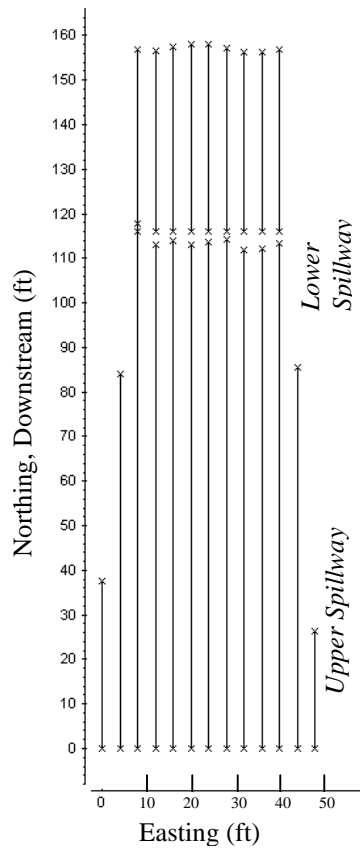


Figure 5.: GPR scan locations for the upper and lower spillway

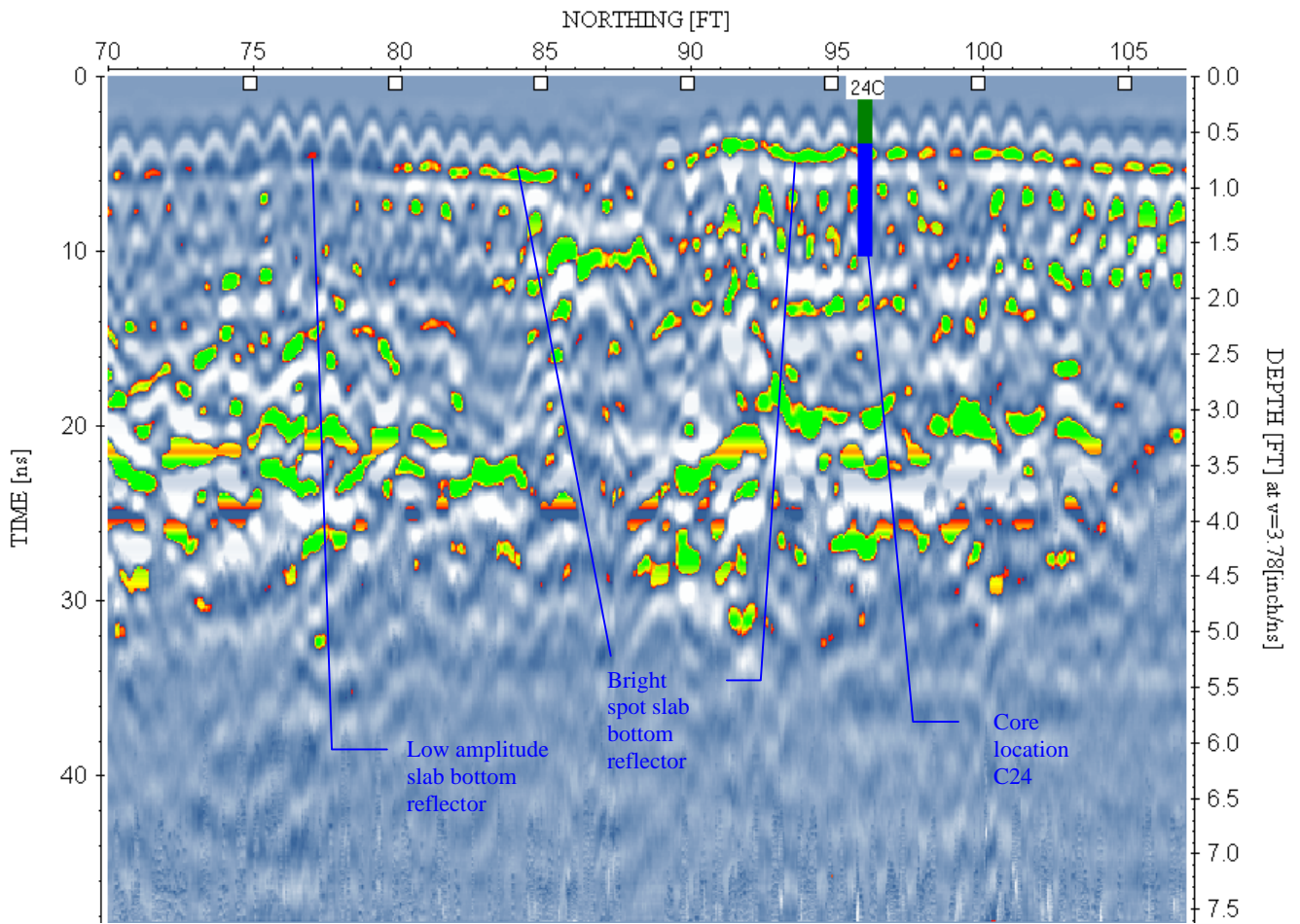


Figure 6.: Example GPR data plot from the centerline, 70 – 107 ft below spillway crest

Slab IR Field Investigation

For the collection of the Slab IR data, 428 data points were taken along the spillway on a grid spaced at 4 ft intervals along the 156 ft tested length of the spillway, and over the entire width of the spillway.

A nominally 4 x 4 ft grid was established at the spillway as described in the previous section and repeated herewith. A naming convention was used to designate each line in both directions. The centerline of the spillway, running longitudinally for more than 156 ft downstream, was named 'C'. Longitudinal lines were designated at 4 ft intervals from right of center eastward as R1 through R6, and at 4 ft intervals from left of center westward as L1 through L6 when looking downstream from the spillway crest. The short east-west trending lines (axial lines) began with Line 1 located 2 ft downstream of the reservoir shore edge and continued at 4 ft intervals to line 40, approximately 158 ft downstream of the reservoir shore edge.

This grid system allowed for the generation of an image contour map that relates each location's mobility to the corresponding mean values of all Slab IR data collected at the site in a relative sense (Figure 7Figure). This image map was created from analyses of mobility and coherence plots examples of which are presented in Figures 3 and 4.

Discussion Of NDE Results

The results of the NDE investigation are presented graphically in Figure 7Figure . Figure 7 presents plan and perspective views of 3-D GPR data showing strong amplitude slab bottom reflection values, an image map contouring the Slab IR relative mobility values, and the core locations performed after the NDE investigation. The Slab IR and GPR results are discussed below.

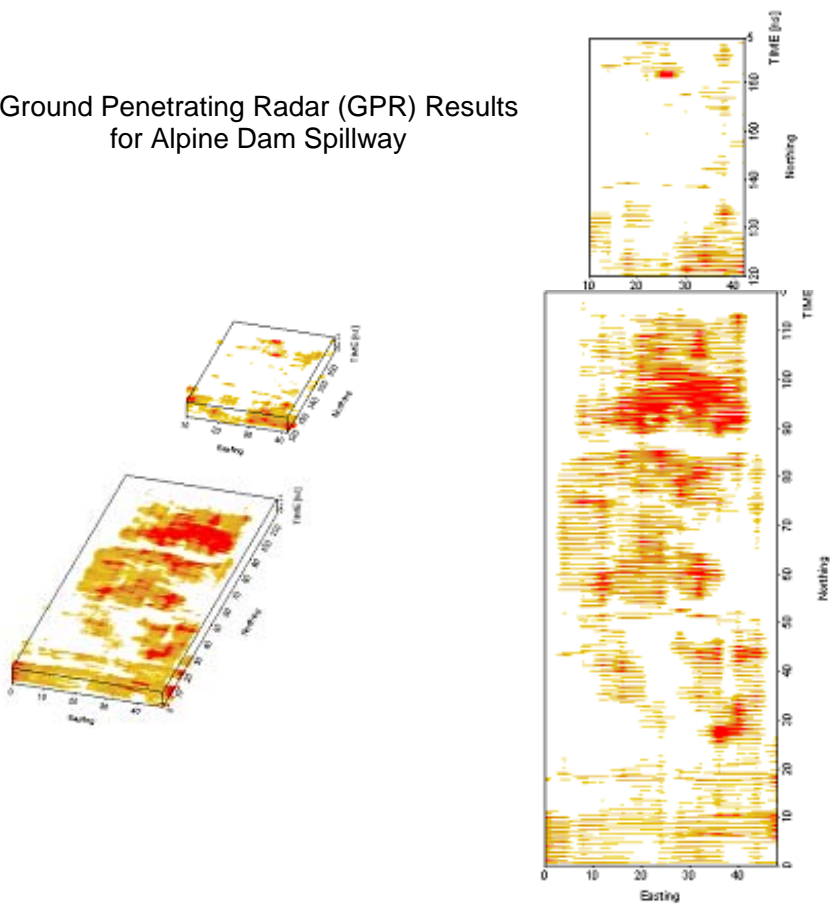
GPR Results

After GPR data collection, the raw data were post-processed in our office to enhance target features and remove background and ambient noise. The digital processing steps for each scan on the upper portion of the spillway included 1) trace zeroing and 2) background noise removal. For the lower portion of the spillway, GPR data also underwent an automatic gain algorithm to normalize trace amplitude from scan to scan.

The GPR data presented in Figure 7 (in both perspective and plan views) show the "bright", strong negative values for slab bottom reflection indicative of void and are the result of 3-D interpolation between the 13 lines scanned. The plots are separated into 2 sections, the upper and lower portions of the spillway. Areas of strong negative amplitude slab-bottom reflection or "bright spots" (red and orange shading in Figure 7) were interpreted as areas of potential voids. These bright spots are evidence of the strong contrast between the electrical properties of concrete and that of water or air-filled void versus the weaker contrast between the electrical properties of concrete and subgrade soil.

From the GPR data, much of the spillway shows evidence of potential voids. The two largest areas are between 55 - 80 and 90 - 110 ft below the spillway crest. Smaller areas of potential void appear in Figure as well. The GPR data did not allow for potential void thickness/depth approximation because of poor void bottom resolution; the core results provided this type of data. Core thicknesses were instrumental in our ability to identify the spillway thickness and hence identify areas of void.

Ground Penetrating Radar (GPR) Results for Alpine Dam Spillway



Slab Impulse Response (Slab IR) Relative Mobility Results for Alpine Dam Spillway

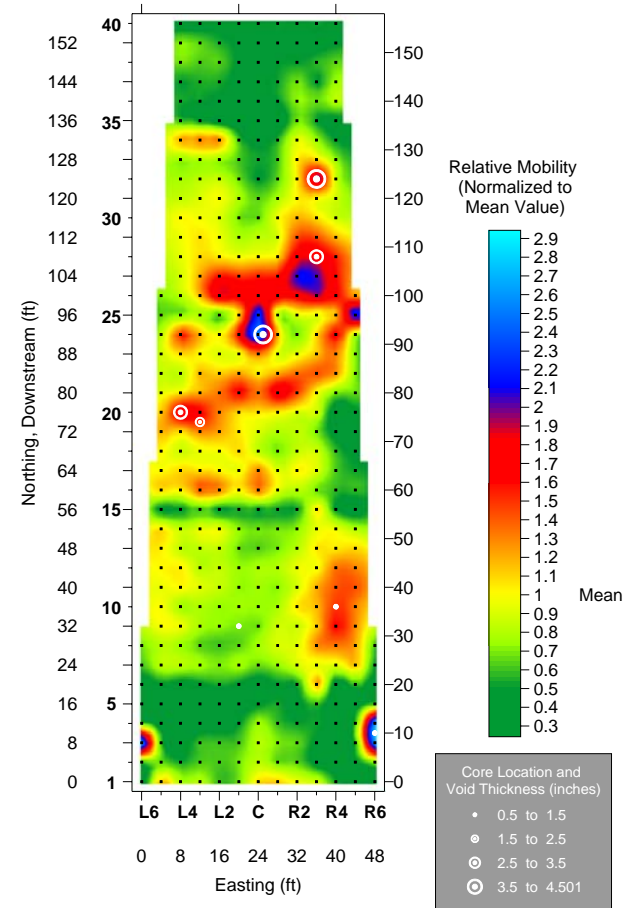


Figure 7.: GPR and Slab IR results for alpine dam spillway

Slab IR and Coring Results

The Slab Impulse Response (Slab IR) evaluation method is fundamentally used for the identification of potential shallow to deeper voids located within or directly below a concrete slab. The Slab IR method cannot identify the actual depth or thickness of a possible void, but can find the plan view location along an investigated portion of spillway in which a void might exist. From the Slab IR data performed on the spillway, an image contour map was created (Figure 7) relating the mobility of all data points to the spillway mean mobility value. These plotted values have been normalized to the mean mobility value recorded at the spillway. This image contour map in Figure 7 presents several sizeable areas for which the mobility is higher than the mean value for the spillway (bright yellow, red, and blue shades). The two largest and potentially most severe areas of void are between 55 - 80 and 90 - 110 ft below the spillway crest (red and blue shades). Based solely on the Slab IR, these areas may indicate potential void beneath the spillway or may reflect a change in slab thickness.

The coring results indicate that concrete thickness varies considerably over the length of the spillway. Comparisons of core data with mean mobility values confirmed small to large voids at Slab IR locations with normalized mobilities ranging from 0.6 and higher. Consequently, all Slab IR data points with normalized mobilities greater than 0.6 are likely to have poor void support conditions. Even lower mobilities may have questionable support as no core encountered good support conditions.

Correlation of Results

The GPR and Slab IR data correlate well as is evident from the plots presented in Figure 7. White areas in the GPR plots (weak amplitude slab bottom reflection) correspond to green areas (low mobility) in the Slab IR image map and suggest locations for better subgrade support. The coring results, Table I, support the NDE data set results. Figure 7 plots the core locations and the size of each symbol relates to the thickness of the corresponding void. Voids were encountered for all locations cored, however, the thinner voids were found in areas of relatively low mobility (Slab IR) and weak slab bottom reflector (GPR) such as core 3/4R6. These areas suggest better subgrade support. One exception was core 3/4R6 where a thin, 0.5 inch thick void was discovered. A proper explanation of this core may be the fact that significant voids are often closely surrounded by areas of good subgrade support, within a 3 to 5 foot radius. Even with NDE results, coring can be a hit or miss operation. The correlated results infer that the Slab IR image map does indeed show locations of potential voids as opposed to changes in slab thickness.

Table I - Core Results

Easting Line	Northing Line	Slab Thickness (upstream side of corehole, inches)	Depth to Firm Soil (upstream side of corehole, inches)	Approximate Void Thickness (inches)
L1	9	9.5	10.6	1.1
C	24	7.3	11.5	4.3
R3	28	6.8	9.9	3.1
R3	32	8.4	12.9	4.5
L4	20	7.3	10.5	3
L3	19/20	7.5	9	1.5
R4	10	6.5	7.5	1
R6	3/4	13.9	14.4	0.5

Video Borescope Confirmation Results

Video borescope probing was performed in the coreholes to provide visual confirmation of the NDE results. Both individual JPEG images as well as VHS recordings were obtained in each corehole. Four images were captured in each of eight boreholes at four different orientations: upstream, west, downstream, and east. The remaining corehole, 3/4R6, was not investigated with the borehole because it had only a ½ inch void and was filled with water to the bottom of the concrete. Figure 8 shows a borescope still-shot from corehole 9L1 (Easting line L1, Northing line 9 - see Figure 7 for location). The spillway concrete, void, and underlying subgrade are all evident in the still-shot. The images recorded with the video borescope showed voids extending some distance from the corehole and proved the NDE results for all coreholes tested.



Figure 8.: Borescope still-shot in corehole 9L1

Conclusions

The combination of GPR and Slab IR was proven to be successful in delineating subgrade voids at the alpine dam spillway. The methods also provide a fast, nondestructive, and inexpensive way to provide both qualitative and quantitative data regarding void location, size, and extent. The coring and corehole borescope investigation verified the accuracy of the NDE methods. The NDE methods are capable of replacing coring as an exploratory technique. However, coring should be performed for confirmation of NDE to validate the data and to build confidence in the general public in the use of remote sensing.

References

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