Shallow Marine MASW: a Case History and Lessons Learned

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ABSTRACT

The concrete spillway associated with a small dam in Rapid City, South Dakota has evidenced persistent seepage since its construction in the 1970's. Visual inspection appears to indicate signs of worsening seepage. Geotechnical borings from dam pre-construction as well as modern boring logs taken on either side of the spillway have been consulted; however, budgetary, access, and logistical constraints restricted a more in-depth geotechnical boring program. A geophysical investigation was ordered to better define the subsurface stratigraphy. This data would be used to perform seepage/flow net analysis and determine some remedial solutions to mitigate seepage and extend the life of the structure.

Seismic surface wave techniques were employed in a shallow marine environment to map depth to bedrock between available boreholes. Hydrophone streamers with 1m and 3m receiver spacing were used as receiver arrays. MASW and microtremor data were collected using various sources located on both the marine (within the river) and land (adjacent the spillway) sides of the rolling receiver arrays. CMP gathers were constructed using data from four different source-receiver array configurations. Geotechnical borings were used to constrain the inverse model and verify interpretation of the geophysical data.

A traditional means of collecting 2D MASW data utilizes a "walkaway" test to determine a single optimal source-receiver offset per survey profile. We show that multiple source-receiver offsets, and receiver-receiver spacings, were necessary to generate complete surface wave dispersion curves suitable for modeling total depth of investigation. We present challenges observed during the data collection, modeling of the data, and interpretation caused by using this traditionally land-based method in a marine environment.

INTRODUCTION

The Canyon Lake Dam, located in western Rapid City, South Dakota has experienced seepage since the mid 1980s. Seepage is visibly evident on the spillway face and boils have been noted in the stilling pool. Other seepage paths have been inferred by dye testing. Mitigation methods such as grout injection, installation of a filter berm over the stilling pool and a shallow cutoff wall have shown moderate, but temporary success to slow seepage. None of these measures controlled the problem to the satisfaction of the City of Rapid City. Continued evidence of seepage prompted a detailed evaluation of Canyon Lake Dam, with the goal of developing a repair or replacement regime.

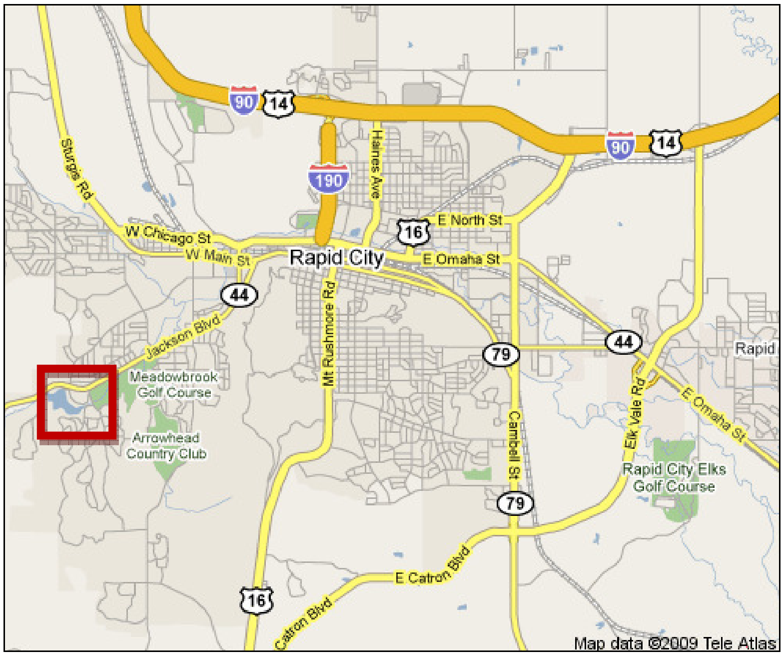

Figure 1: Project Location Map. Approximate location of test area outlined in red.

One interpreted seepage path lies along the contact between the 200 foot concrete spillway and subsurface materials. The southern portion of the spillway and south abutment are founded on limestone bedrock, while the remainder of the spillway and north abutment is constructed on a compacted clay core founded on alluvial materials. The limestone bedrock outcrops immediately south of the spillway and southern abutment.

As part of the geotechnical evaluation of the project site, a geophysical survey was conducted to help map subsurface geology beneath the spillway area. Geologic borings had been conducted several times throughout the lifetime of the dam, but provided conflicting and sparse information. The goal of the geophysical survey was to provide information between boreholes, and generate a 2D cross-section profile showing depth to bedrock beneath the spillway structure.

GEOPHYSICAL METHODOLOGY

Using geophysical methods to map depth to bedrock is a fairly common practice (Redpath, 1973, Lankston, 1990). Many geophysical techniques are appropriate for this broad application, but can generally be narrowed based on site-specific conditions and/or geology. Due to logistical and budgetary constraints, it was necessary to plan, execute, and deliver results within a very short timeframe.

The area chosen for the geophysical survey was located immediately east of the spillway, within the concrete and rip-rap stilling pond (Figure 2). Fieldwork was conducted in October, 2008, and water was not yet at freezing conditions. Water depths ranged from 3-5 ft. Fine-grained materials, such as clay, reduced the effectiveness of ground penetrating radar (GPR). Cultural interference from the reinforced concrete structures, fences, and utilities precluded the use of electrical and electromagnetic geophysical techniques. Additionally, the concrete and rip-rap overlying alluvial sediments would have been difficult to accurately model using traditional gravity, seismic reflection and seismic refraction methods.

Figure 2: Site Photo. Location of MASW work area highlighted in red.

Previously a component of seismic energy that was considered a nuisance to overcome during exploration seismic surveys, surface waves may be used by engineers and geoscientists to calculate the vertical shear-wave velocity profile. The spectral-analysis-of-surface-waves (SASW) method has been used successfully for civil engineering projects, notably for pavement thickness calculation (Gucunski et al, 1996, Nazarian et al 1983). In recent years seismic surface wave surveys have become popular non-destructive techniques that can be used to determine the vertical shear-wave velocity profile (Martin et al., 2005; Park et al., 1999; Louie, 2001).

Surface wave methods can be broadly characterized as being active or passive, depending on the energy source used. Active techniques include the SASW and multi-channel-analysis-of-surface-waves (MASW) methods. Passive methods include the refraction microtremor and array microtremor techniques. The basis of both categories of surface wave surveys concerns the dispersive characteristic of Rayleigh waves as they travel through a layered medium. The Rayleigh-wave phase velocity is related to the material properties, notably shear-wave velocity. The variation of phase velocity with frequency or wavelength is called dispersion.

Surface wave testing consists of collecting surface-wave phase data in the field, generating the dispersion curve, and then using iterative forward or inverse modeling techniques to back-calculate the corresponding shear-wave velocity profile. Further detailed descriptions about the SASW method can be found in Joh, 1997; MASW in Park, 1999; and microtremor survey methods in Louie, 2001.

Geophysical equipment used during this investigation consisted of a Geometrics Geode 24-channel signal enhancement seismograph, 10 Hz hydrophones spaced 1 and 3m apart, seismic, a heavy digging bar / tamping rod and 16-lb sledge hammer with an aluminum plate. The final seismic record at each shot point was the result of stacking 3-7 multiple shots to increase the signal to noise ratio. All seismic records were stored on the hard disk of a laptop computer. All geophone and shot point locations were measured using a 100m tape measure, and fixed hydrophone spacing along the hydrophone cable, for spatial control. Relative elevations of each geophone location were not acquired due to minimal relief in the zone of interest.

A 2D MASW profile is constructed by combining multiple 1D MASW soundings. A number of geophones are aligned in a linear array with a source located at some fixed distance beyond one of the end geophones. A source (such as a sledgehammer or weight drop) is impacted against the ground surface while a seismograph records ground motion data. This generates 1D MASW data, with the shear-wave velocity vs. depth profile coinciding with the center of the receiver array. The entire source-receiver array is moved, or "rolled" a fixed distance along the survey profile and the process repeated (Figure 3). Source-receiver offset distance is typically determined by means of a "walkaway" test where the source is moved away from a static array until the desired balance of surface-wave energy and frequency bandwidth is reached. Interpreting the results of the walkaway test can be difficult to do in the field. Therefore, we recommend several source-receiver array offsets be used to maximize the bandwidth of the recorded signal.

Surface wave data was collected by arranging the hydrophone streamer in a linear array and impacting either the heavy tamping rod or sledgehammer against the ground surface as a seismic source (the "shot"). To maximize the amount of data available for interpretation and modeling, several source-receiver array types were evaluated:

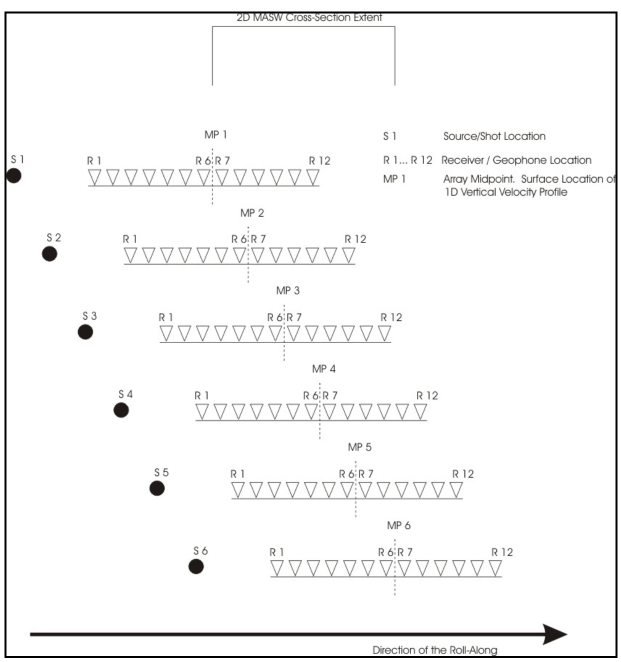

Figure 3. Example of seismic roll-along method as applied to 2D MASW profiling

(1) a static array with the 3m hydrophone cable unmoving, moving the shot from off the north end of the array southward through the receiver array, with a shot location immediately adjacent to each hydrophone. This simulates the "walk-through" technique borrowed from seismic reflection surveys. Passive seismic data was also collected using this array, using nearby traffic noise as an energy source.

(2) a 3m receiver array where the source (tamping rod) was kept fixed 3m south of the receiving array, and both the source and receiver array were moved north in 1m increments until constrained by site access (the northwestern pond shown in Figure 2). This is analogous to a "roll-along" common offset gather from seismic reflection surveys.

(3) a rolling 3m receiver array where the sledgehammer was used on the northern end of the array while rolling the source and receiver array to the south at 1m increment per shot

(4) a similar array to (3), but utilizing a 1m hydrophone streamer and rolling 2m at a time.

DATA ANALYSIS

A total of fifty-six (56) MASW shot records were acquired using the 3m hydrophone streamer with various source-receiver offsets. Thirty-two (32) shots were acquired using the 1m hydrophone streamer. Surface-wave data were processed using software produced by the OYO Corporation, Geogiga Technology Corporation, and the Kansas Geological Survey. An iterative modeling process was used to generate S-wave velocity models for each 1D MASW shot location. Surface waves were separated from the body (compressional P-wave and shear S-wave) wave via a wavefield transform (Figure 4). Picking a dispersion curve in the frequency domain yields a Rayleigh wave velocity curve. Multiple dispersion curves were generated during the course of the data reduction process. Inverse-modeling of the combined dispersion curves generated a 1-D shear wave velocity vs. depth sounding per each test location (Figure 5). The passive microtremor data was processed first in an effort to constrain the MASW velocity models. Available geotechnical data was also used to help constrain the velocity model, as well as provide initial guides to the number of expected geologic units and approximate depth ranges.

During this process an initial velocity model was created based on general characteristics of the dispersion curve. The theoretical dispersion curve was then generated using the 1-D modeling algorithm and compared to the field dispersion curve. Adjustments are then made to the thickness and velocities of each layer and the process repeated until an acceptable fit to the field data is obtained (Xia et. al, 1999).

2D models were generated via two methods: gridding and plotting of each individual inverted 1D MASW profile, as well as performing a 2D inversion that uses the previous 1D sounding as the starting model for each subsequent 1D inversion. This limits the distance-extent of the profile to the midpoints of the extreme 1D soundings (illustrated in Figure 3). Thus, data processed in this manner will not yield a cross-section beneath the entire length of the survey profile.

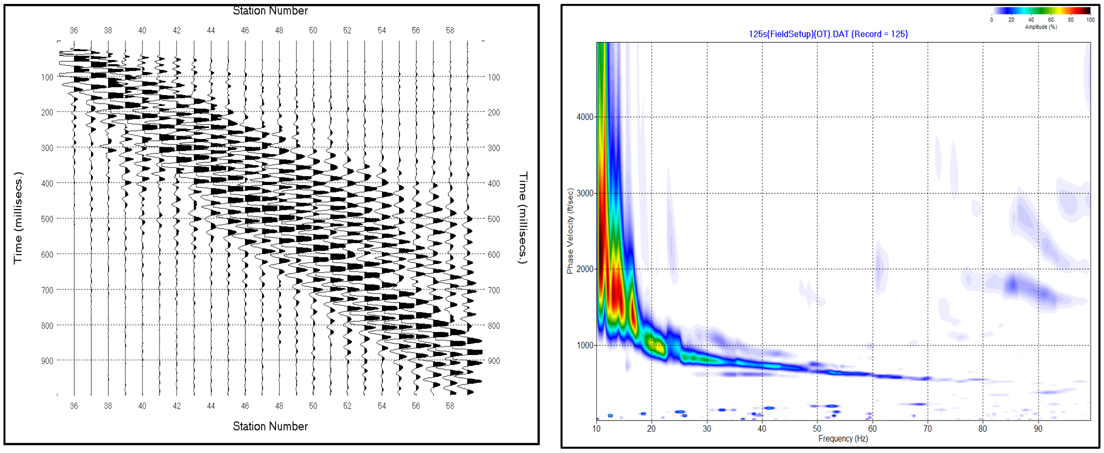

Figure 4. Raw shot record (left); results of wavefield transform for dispersion analysis (right)

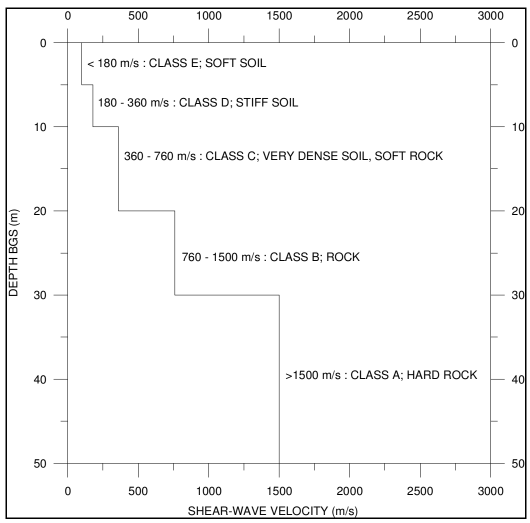

FIGURE 5. Example synthetic 1D shear-wave velocity model

Additional 2D models were calculated by importing all 1D shot records, and re-sorting the raw shot gathers from shot-receiver into midpoint-offset coordinates (Yilmaz, 1997), a process termed common midpoint (CMP) sorting. This extends the effective survey length of the 2D cross-sectional profile. The processing sequence for processing the CMP gathers was identical to processing the raw shot gathers: apply a wavefield transform to pick a 1D dispersion curve, and invert that dispersion curve in 1D or 2D as described above for the common offset section.

RESULTS

2D MASW results are shown in Figure 6. Gridded 2D MASW data are presented as color-contour plots. Red and orange colors represent bedrock velocity values; blue and green represent soil and engineered fill velocity ranges. The yellow contours indicate the velocity gradient associated with the transition zone between soil and rock materials. Profile distance and depths are presented in meters (m); velocity in meters per second (m/s). There was no relief along the survey profile and the ground surface was assigned a relative elevation of 0m. Profiles are presented with a 2:1 vertical exaggeration. All stationing refers to 0m as being the intersection of the concrete subsurface retaining wall and southern wall of the dam structure (see Figure 2).

Figure 6a illustrates data processed using velocity data associated with the mid-point of each 1D sounding as described in Figure 3. This is a conventional MASW processing and analysis method (Park, 1999). Due to logistical constraints (the wall to the south and pond to the north, shown in Figure 2), velocity data is only available beneath the central portion of the survey profile (stations 15-45m). Additionally, data quality was poor, due to ambient noise levels, relatively weak seismic source, and the presence of the concrete structure attenuating fundamental-mode surface wave energy. Preliminary review of this data was of little value to this investigation. Over the 30m profile length shown below, depth ranges for the bedrock contact is highly variable and not consistent with regional geology. The extreme end of the profile (45m) appears to show a trend with a steeply dipping bedrock contact; however, without additional data this could equally have been interpreted as an artifact of the data, such as interpreted near station 23 along the survey profile in 6a.

However, by collecting several different source-receiver arrays and integrating them during data processing, a better 2D profile was constructed. Resorting all data into CMP gathers prior to dispersion curve analysis extends the profile very close to the ends of the survey profile (stations 3-75m), as shown in Figure 6b. Additionally, the inclusion of more data points (CMP gathers) increases data redundancy and confidence in the modeled results. The resulting velocity model makes more sense, geologically, than that shown in Figure 6a, above. Between stations 42 and 47 (m), there is a 5m elevation drop in the interpreted bedrock unit, which coincides with the limited boring information and confirmed the preliminary geotechnical interpretation. Figure 7, from the submitted geotechnical report, summarizes the geotechnical interpretation.

SUMMARY

A MASW survey was conducted to image depth to bedrock beneath alluvium and fill materials. Quality of data was poor. This is primarily attributed to higher levels of background noise than ideal (moving water directly adjacent from the spillway) and relatively weak surface waves travelling beneath the surface of the water. Higher resolution data was obtained using the 1m hydrophone streamer, due to the closer receiver spacing and proximity of far hydrophones to the source. However, use of the 3m hydrophone streamer extended the effective length of the receiver array, allowing longer wavelength surface waves to be observed, increasing the depth of investigation. Combination of the different receiver arrays yielded a geologic model whose soil/overburden-bedrock contact is observed. With few exceptions, the surface-wave methodology was incapable of generating Vs models past depths of 18m. For future investigations of this type we would anticipate the use of a larger seismic source to overcome the poor signal-noise ratio. The use of CMP gathers was invaluable during this investigations and allowed us to a geologically valid model resulted in the model shown in Figure 6.

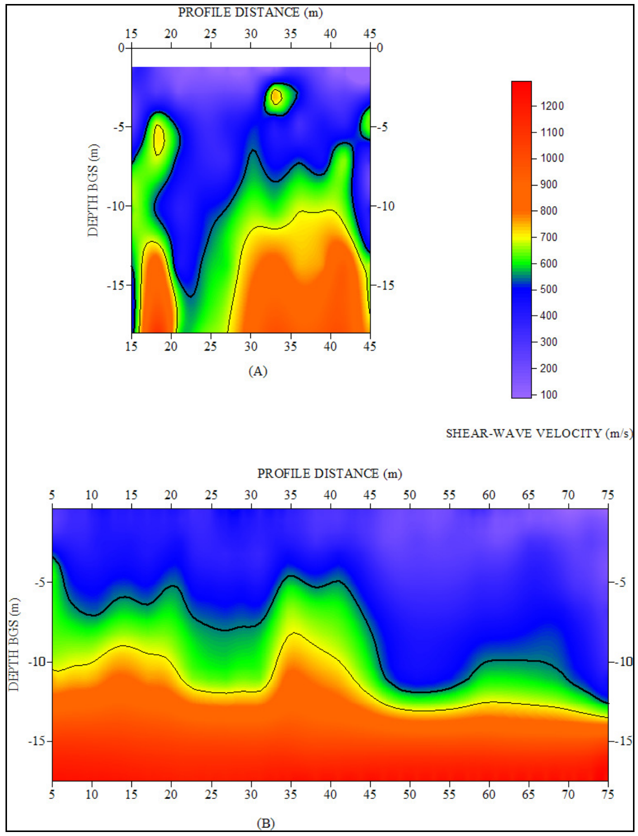

FIGURE 6. Gridded shear-wave velocity data. 6a (top) demonstrates conventional 2D MASW data processing, and 6b (bottom) the results of MASW processing of the sorted CMP gathers. Note extension of profile length and smoother geologic model.

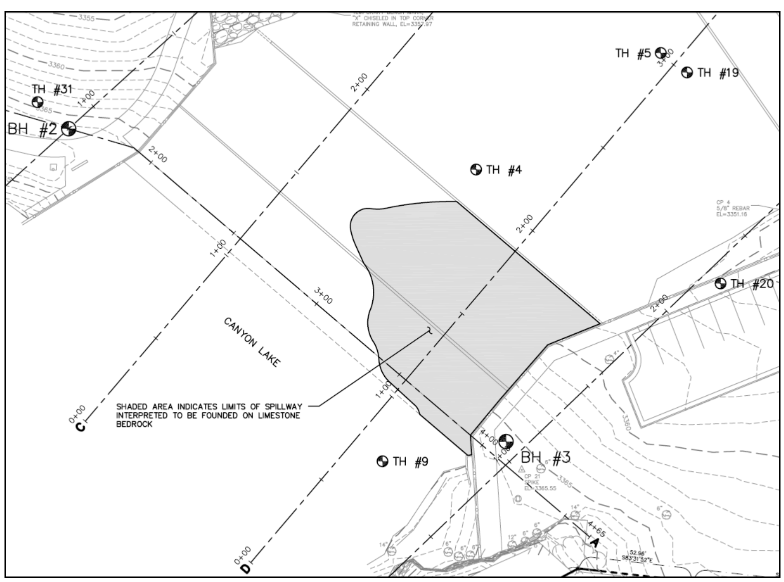

FIGURE 7. Summary geological interpretation

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