SEISMIC REFLECTION: UPSTREAM, DOWNSTREAM, AND ON EARTHEN DAMS AND DIKES

Richard D. Miller, Kansas Geological Survey, University of Kansas, Lawrence, KS
Richard D. Markiewicz and Lisa Block, U.S. Bureau of Reclamation, Denver, CO
Steve Hartung, U.S. Army Corps of Engineers, Little Rock, AR
William E. Hancock, U.S. Army Corps of Engineers, Seattle, WA
Julian Ivanov and Jianghai Xia, Kansas Geological Survey, University of Kansas, Lawrence, KS

Abstract

High-resolution seismic reflection has been used successfully to characterize material and investigate a variety of problems associated with earthen dams and abutments. Limitations and challenges of seismic reflection when interrogating these structures and lithologies are nontrivial and require very critical thinking. Seismic reflection has proved an effective tool for mapping confining units for integration into the cutoff wall at the Keechelus Dam in Cle Elum, Washington; mapping lithologies and bedrock structures for earthquake retrofitting at Bend, Oregon; delineating karst in bedrock beneath the dam core responsible for subsidence on the upstream side of a major flood control structure at Clearwater Dam, Missouri; and detecting high permeability zones within a glacial outwash embankment of a water retention dam near Enumclaw, Washington. Extreme geometries and material variability associated with any man-made structure are the most formidable challenge to seismically imaging. Inconsistent source wavelets, out-of-the-plane energy, extreme statics (topography and velocity based), and source noise (disproportionately high percentage of surface waves) are all problems that are not unique to earthen dams, dikes, and levees, but they are certainly more prevalent with those types of structures. Success of the technique in these settings is source characteristics and spatial oversampling.

Introduction

Earthen structures used for water retention are susceptible to failures related to overtopping, seepage, and structural degradation. Overtopping failures are predominantly related to erosion or scouring. Seepage occurs when water is allowed to move through or beneath the structure and generally result in boiling and/or piping. Failures of the structure generally result for instability of the foundation, but structural failures can be the result of seepage. Cracks and settlements are generally indicators of increased failure potential. Physical characteristics are key to a structures breach potential and there are a variety of very effective tools to assess a structures breach potential once those parameters are known (Wahl, 1997). Defining the key characteristics for these three dimensional structures in a fashion that does not adversely affect the capabilities of the structure is the difficult part. Regardless of the failure type, key to dam/levee safety lies in the integrity and characteristics of the core.

Noninvasive testing of dams and levees has predominantly focused on electrical and EM methods (Dobecki et al., 1988). In cases where seismic has been used, refraction or first arrival analysis has been the preferred method (Dutta, 1984). There are a few cases where seismic reflection has proven to be an effective and efficient method of interrogating the internal geometries and associated anomalies in seismic material characteristics in earthen structures (Nie et al., 2001; Woolery et al., 2001; Llopis et al., 1995; Dakoulas, 1993; Miller and Markiewicz, 2000, 2001; Miller et al., 2004). Reduced strength related to anomalous zones within or below the earthen structures could represent unsafe conditions.

Understanding and quantifying the properties of shallow subsurface materials are critical for characterizations and associated models used to guide design and retrofitting of structures to withstand...
expected ground motions. Dam safety is always a high priority for any dam owner. Concerns about performance during potential earthquakes and flood events have prompted many owners to embark on extensive drilling and geophysical site characterization programs to provide improved properties for site response models. Prioritizing the risk of individual structures has generally been based on potential of liquefiable foundation materials, increased flow in weirs, sinkholes, or changes in local seismicity making characterization a reaction rather than a preemptive activity.

In support of the U.S. Army Corps of Engineers’ and U.S. Bureau of Reclamation’s strong commitment to dam safety, new and/or adaptations of existing technologies are being identified and evaluated at sites with both physical characteristics conducive to those technologies and failure potential. Proven correlation between acoustic properties and stiffness/rigidity is the basis for developing and implementing field-efficient, laterally continuous, non-invasive methods to accurately measure the seismic wavefield. As well, routine non-invasive appraisal of dam/dike core integrity is feasible and could prove quite valuable in some settings. Ultimately, the goal of these kinds of research efforts is to define technologies and parameters for implementing those technologies that allow identification of localized anomalous material zones—indicative of either dissolution activity, piping, or non-uniform compaction/settling—prior to surface expressions. Seismic techniques hold vast potential for imaging and measuring materials in a fashion applicable to evaluations of dam integrity.

This paper summarizes seismic reflection studies at four different sites where problems or potential problems with dam structures had been identified. Bureau dams studied included Wickiup in west-central Oregon and Keechelus in west-central Washington. Investigations at Wickiup were designed to map potential fault features suggested from regional potential fields studies. At Keechelus voids discovered in the dam structure initiated a series of geophysical surveys with the reflection survey designed to identify the location and geometry of a competent aquitard to anchor the new dams cutoff wall. Clearwater Dam in southeastern Missouri and Mud Mountain Dam in western Washington are the two Corps dams included in this paper. The Clearwater Dam experienced a sinkhole on the upstream face which required immediate attention and concern for the integrity of the Mud Mountain Dam under high water conditions was raised with the discovery of highly permeable boulder lens in the upstream face of the abutment.

Study Sites

Wickiup Dam, Bend Oregon

Wickiup Dam, dikes, and appurtenant structures were constructed between 1939 and 1949 and are located 30 miles southwest of Bend, Oregon, in Deschutes County, on the Deschutes River. Inflows to the reservoir are significantly impacted by releases from Crane Prairie Dam, located approximately 2 miles upstream from Wickiup Reservoir. The dam is a zoned, rolled earthfill embankment and has a structural height of 100 feet. The foundation of the dam consists of volcanic bedrock (primarily basalt) overlain by layers of sands, gravels, silts and clays, with variable amounts of volcanic debris (lava, tuff breccia, and pumice). The majority of the 13,860-foot long dam is less than 40 feet high. Seepage and major leaks through the foundation of the dam have been a continual problem since the first filling of the reservoir.

High-resolution seismic reflection was one of a variety of geophysical techniques employed at Wickiup Dam. Seismic reflection data were intended to delineate the bedrock surface and provide improved correlations between existing as well as future boreholes. High-resolution seismic reflection techniques possessed the necessary resolution potential to both map the bedrock surface and delineate the intricate bedding geometries likely present but perhaps undetected in the borehole data at this site. Of secondary concern was faulting interpreted from potential fields data to be present at the surface of bedrock.
**Keechelus Dam, Easton, Washington**

Seismic reflection surveys were conducted at Keechelus Dam, near Easton, Washington, as part of corrective action investigations by the Bureau of Reclamation. Approximately 7,450 line feet of seismic reflection surveys were conducted along the embankment toe and in the wetland area southeast and downstream of the dam. A detailed knowledge of the subsurface geology in these areas was determined necessary and would impact the design of a modified or replacement embankment at this site. Corrective action activities include drilling, test pitting, and geological mapping in the areas targeted for reflection surveying. The reflection survey was conducted to provide information about the likely configuration of the top of bedrock (Tertiary Rhyolites as encountered in previous explorations) and possible glacial Outwash/Lacustrine/Alluvial zones above bedrock.

Keechelus Dam is located at the headwaters of the Yakima River, immediately east of Snoqualmie Summit, Washington. The dam, constructed during the 1912 through 1916 time period, is a zoned, rolled earth fill embankment at the outlet of a natural glacial lake. It is classified as a high risk dam by the U.S. Bureau of Reclamation due to the potential number of lives that could be lost and the potential environmental and cultural destruction that would occur if the dam were to fail.

**Clearwater Dam, Clearwater, Missouri**

Clearwater Lake Dam, 30 miles northwest of Popular Bluff, Missouri, was designed and constructed in the early 1940s as a control structure across the Black River. During the design and building of the cutoff trench two distinct and unique sets of enlarged joints were discovered in the limestone bedrock. Additional drilling suggested the joints were extremely localized and inferred to only extend several tens of feet beyond the cutoff trench excavation. Based on the trench and drill findings, the joints were filled with concrete consistent with the dam building practices of that time.

On January 14, 2003, project personnel working at Clearwater Lake found a 10 ft diameter by 10 ft deep sinkhole. A sinkhole of this nature and location represented a threat to dam integrity and prompted a response by the dam owner. On January 17, 2003, a backhoe excavated the sinkhole down to 25 ft below ground surface where the diameter of the subsidence feature narrowed to 3 ft. The 25 ft deep excavation was backfilled with a clay plug, returning the dam surface to original grade. On February 15, 2003, with the first sizeable rainfall (1.2 in) since the installation of the clay plug came subsidence of the clay plug (3 in around the perimeter and 6 in at the center). The backfilled sinkhole has been under constant surveillance since it formed with no evidence of downstream seepage, upstream slumps, cracks, or whirlpools. Soil engineers describe the 6-ft thick clay blanket covering the upstream slope as being very compacted and probably hiding a void that likely formed during the summer of 2002 and then finally collapsed in January, forming the sinkhole.

**Mud Mountain Dam, Enumclaw, Washington**

Mud Mountain Dam was originally designed in the 1930s for flood control on the White River which heads at Carbon Glacier on the flanks of Mt. Rainier. Springs, seeps, and increased material saturations were observed during periods of elevated pool levels. Considered changes to pool storage and use would require elevated pool levels more frequently and sustained for longer periods of time. The potential of a seepage-induced failure of the reservoir rim similar to the 1918 landslide at Masonry Pool on the Cedar River prompted concern for the integrity of the Mud Mountain Dam.

The two 1250 ft seismic lines were located along one active and one inactive haul road intersecting at an oblique angle north and east of the dam and approximately parallel to the current river channel. The primary targets of the seismic reflection survey were the bedrock surface topography and any cut/fill features within the 300 to 600 ft of unconsolidated materials that lay between bedrock and the ground surface. Imaging intra-till features in areas with near total saturation has been successfully
done using basic reflection techniques (Hunter et al., 1984). The lack of saturated fine-grained surface materials drastically complicates the effectiveness and resolution potential of shallow reflection.

The lines were deployed in hopes of imaging a long path channel (Big Springs) suspected to possess at least 150 ft relative elevation difference in the top of bedrock representing an interglacial course of the ancestral White River (U.S. Army Corps of Engineers, 1986). Of equal interest is any subsurface expression of a localized outcrop of boulders in the side hill approximately 20 ft below and 150 ft northwest of the road where the data was acquired. A chimney sink exposed on the top of a nearby could be suggestive of deeper sediment erosion.

Data Acquisition and Processing

Each survey employed data acquisition equipment and parameters unique to the requirements of the study and consistent with the state-of-the-art at that time. Determining the spread lengths, receiver and shot spacings, and roll-along strategies were all based on well documented procedures (Hunter et al 1984; Steeples and Miller, 1990).

- For the Wickiup study 24-fold data were acquired on the upstream side of the dam and dike structure using a standard CMP roll-along technique employing a 48-channel Geometrics Strataview and variable sized charges of Kinepak high explosive. Shot ranged from 1/6 to 1 lb and were buried 5 below ground surface, receiver spreads included 6-40 Hz geophones in a 3 ft inline array with both shots and receive stations separated by 10 ft.
- At Keechelus, nominal 24-fold data were acquired on a 96-channel Geometrics StrataView seismograph using a 96-channel rolling, fixed-spread configuration with 5 ft receiver and 10 ft shot spacing. Seismic energy was generated by a single or pair of blasting caps (depending on in-field analysis of energy penetration) 5 ft to 8 ft below ground surface and detected by two 40 Hz marsh phones planted 1 to 3 ft below the ground surface.
- For Clearwater Dam, a pair of 120-channel lines with two 40 Hz L28E geophones per receiver station recorded three 10 second, 25 to 250 Hz IVI minivib sweeps were recorded at each shot station. All ground stations were separated by 4 ft with data recorded on a 24-bit, 240-channel Geometrics Strataview seismograph with a StrataVisor NZC controller.
- The Mud Mountain data were acquired on a 48-channel EG&G Geometrics 2401x seismograph. The sources were an 8-gauge auger gun (Healey et al., 1991) and an IVI minivib1 while the receivers for all the data were three Mark Products L28E 40 Hz were receivers offset from 20 ft to 204 ft from the source with 8 ft station spacing.

High-resolution seismic reflection data, by its very nature, lends itself to over-processing, inappropriate processing, and minimal involvement processing. Interpretations of high-resolution shallow reflection data must take into consideration not only the geologic information available, but also each step of the processing flow and the presence of reflection events on raw unprocessed data. Processing for the reflection portion of this study included only operations or processes that enhanced signal-to-noise-ratio and/or resolution as determined by evaluation of high confidence reflections interpreted directly on shot gathers (Figure 1) For the most part, processing of high resolution shallow reflection data is a matter of scaling down conventional processing techniques and methods; however, without extreme attention to details, conventional processing approaches will produce undesirable artifacts. In-field processing of the reflection data resulted in correlated shot gathers that were subject to a variety of scaling and filtering operations. In-field processing was coincident with data acquisition and did not impact the full day field schedules.

The basic architecture and sequence of processing steps followed during the generation of the final stacked sections were similar to conventional petroleum exploration flows (Yilmaz, 1987). The primary exceptions related to the step-by-step QC necessary for the highest confidence interpretations of
shallow features and realization of full resolution potential (Miller and Steeples, 1991). Specific distinctions relate to the emphasis placed on velocity analysis (Miller, 1992), lack of extensive wavelet processing, care and precision placed on muting, step-by-step analysis of effects of each operation on reflected energy, limiting statics operations to maximum shifts no greater than one-quarter wavelength of the dominant reflection energy with large correlation windows, and coincident iterative velocity and statics analysis.

Results

Unequivocal identification and verification of reflections on shot gathers is not only necessary, it is mandatory for meaningful interpretations of near-surface seismic data. The most conclusive means to both verify and analyze reflections is to match modeled NMO curves (based on uphole velocity information when possible) with reflection hyperbola interpreted on shot gathers. This combination incorporates ground truth (borehole-determined velocity), geometric curve fitting (forward and inverse modeling), and event identification directly from single-fold shot gather data. Too many times the power of seismic processing software and lack of careful attention to detail results in stacked seismic reflection data that inaccurately represent the subsurface, and is justified by happenstance, consistency with existing drill data, and geologists’ models.

Wickiup

CMP stacked data from this line are of excellent quality (Figure 2). Most pronounced is the west-dipping bedrock surface reflection and the channel feature within the unconsolidated sediment section. Shallow reflections (<250 ft) appear relatively flat with only minor (small scale) apparent variations in lithology or structure. This shallow portion of the geologic section is where almost all the drill data has sampled. Extending those interpretations based on drill data alone would have likely resulted a significantly different image of the subsurface than is evident on the stacked section. Many of the subtle details are difficult to distinguish on this 1 to 3 vertical exaggeration (Figure 2). The 2000 ft wide and 300 ft deep channel feature centered on CMP 720 at about 150 msec is quite dramatic and suggestive of a high volume of water moving through the ancestral Deschutes River system. Most of the bedding apparent within this channel is relatively flat, likely indicative of a low energy depositional environment resulting from a shift in the main river channel. Clearly the older sediments (>250 ft) were deposited during dramatic swings in the river’s position and water volume.
Keechelus

Geometries resolved with the CMP stacked section provides unique insight into the contact between lacustrine and till sediments beneath this wetlands area (Figure 3). A high amplitude and frequency reflection marks the boundary between the Quaternary lacustrine and till boundary and is hydrologically significant to construction of a new dam and the potential to install an effective cut-off. The channel-looking feature on the northwest end of the profile separates a near surface where outwash sediments overlay lacustrine sediments from an area void of outwash sediments. This distinction will add significant detail to the engineering design of the new dam structure.

Figure 2. Wickiup Dam stacked section with a vertical exaggeration of 1 to 3.
Figure 3. CMP stacked section from Keechelus Dam, Washington. The strong reflection event between 20 and 40 msec is interpreted as the boundary between Quaternary fill and lacustrine sediments. The complex geometries and discontinuous bed observed on this stacked section is consistent with the geology in this area as well as the shot gathers.
**Clearwater**

Starting at the top of the section beneath the sinkhole, a downdropped reflection can be seen at about 50 ms with equates to about 45 ft (Figure 4). This zone is about 15 ft wide and extends from about station 8 ft right to 8 ft left of the sinkhole, from here it drifts strongly to the right side. At about 70 ft it appears to widen from 10 ft left of the sinkhole to over 40 ft right of the sinkhole. Looking deeper into the section the “chimney” or subsidence-altered zone appears to meander around stronger or more resistant layers, with these stronger layers forming bridges or in some cases subsiding intact. At the top of the clay core, interpreted at about 80 ms (~100 ft) the subsiding materials have left either the top or a reflective layer near the top offset a bit. The void or less competent area in the subsurface continues to move right where at the bedrock surface correlates with a set of what appear to be fractures located between 80 ft and 20 ft right of the sinkhole. These inferred fractures correlated quite closely to the projection of the enlarged joints observed during dam construction.

![Figure 4. Interpreted CMP stack of line P1 showing key layers and abnormalities.](image)

**Mud Mountain**

Cut-and-fill features in the Vashon Lake Bed (VLB) sequences appear to extend from stations 1040 and 1110 and from stations 1210 and 1280 on the CMP stacked section with the potential for very unsorted piles of material (possibly similar to boulder outcrops on both flanks of the embayment) deposited in channels between stations 1075 and 1105 (Figure 5). The depths of these channels are around 50 to 75 ft. Cuts into the VLB across the expanse of the embayment is likely more common than the presence of complete VLB and deltaic sequences as observed in the borehole 34 as identified on the CMP stacked section.

A basin or closed low in the bedrock surface is evident beneath well 38 with a low extending westward off the end of the seismic profile. The closed low or basin beneath well 38 could act as an isolated conduit for the movement of fluid.
Figure 5. Interpreted CEP stacked section of line 3 at Mud Mountain Dam, Washington. This interpretation suggests a large mound of till that completely removes labeled sediments near the bridge.
Conclusions

High-resolution seismic reflection has proven an effective tool in these traditionally challenging near-surface settings. Dominant frequencies were observed clearly exceeding 200 Hz to depths over 1000 ft on some of the data presented here. Dramatic bedding geometries, completely unexpected based on drill data alone, were imaged at these sites. Incorporation of these seismic reflection data with other information provided an excellent compliment to existing borehole data, providing a solid scientific basis for interpretations and projections of structural response to various pool scenarios.

References


