SHEAR WAVE VELOCITY MEASUREMENTS IN EMBANKMENT DAMS

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ABSTRACT

The U.S. Bureau of Reclamation (USBR) is presently emphasizing the importance of site-specific shear-wave velocity measurements for application in dynamic analyses of embankment dams. Results of approximately 50 USBR crosshole-seismic investigations show that significant variations in shear wave velocity exist with depth, and that these measured variations qualitatively correlate with material type and structural loading conditions; however, they are much more prominent than assumed, calculated or predicted velocity trends. Four case studies are presented where measured shear-wave velocity profiles are compared with standard penetration test data, material type and computed peak accelerations. The results illustrate that the near surface shear-wave velocity distribution, and consequently the accelerations expected to occur, are indeed complex and site dependent.

INTRODUCTION

Dynamic analyses of embankment dams for liquefaction potential or seismic-stability requires the knowledge of subsurface material properties in order to accurately predict ground accelerations expected to occur during earthquake loading. Elastic properties of soil deposits overlying bedrock are among the most important input parameters for dynamic studies. Not only are the values of these elastic properties important, but perhaps more significant is their distribution with depth. Subsurface modeling of these site-specific elastic properties through theoretical predictions or correlation principles (e.g., depth, SPT-N value or material type) can result in substantial differences in computed strong ground motions (Aubeny, 1984). However, the severity of ground shaking can accurately be evaluated using one, two, or three dimensional analysis with a high degree of confidence when utilizing well defined (measured) subsurface material elastic properties.

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Currently, the USBR is emphasizing the importance of site-specific, shear-wave velocity measurements to better understand how the observed variations in shear wave velocity with depth affect ground accelerations. This paper is intended to: 1) Illustrate significant variations in measured shear-wave velocity with depth obtained at four dams located in the western United States; 2) Qualitatively compare these observations with material type and corrected SPT N-values; and, 3) Demonstrate how these variations in shear wave velocity affect peak ground accelerations. For the purpose of first-cut approximations at the response of a soil column to earthquake loading expected to occur at a particular site, the equivalent-linear method as programmed in SHAKE (Schnabel et al., 1972) was used for these analyses. Nonlinear, strain dependent properties for modulus and damping were incorporated in the analyses. The case histories reported herein represent only a fraction of site-specific investigations conducted for dynamic analysis of embankment dams by the USBR. Figure 1 shows the location of dams and other structures where crosshole shear-wave velocity measurements have been performed.

FIGURE 4. USBR crosshole-seismic investigations.

TEST METHOD

Equipment and analysis procedures used for crosshole investigations have been developed to a point where routine measurements are performed under the USBR Safety of Dams program. During the past decade the USBR has developed a sophisticated geophysical data acquisition system designed specifically for conducting crosshole seismic investigations. State-of-the-art equipment is utilized for the surveys such that downhole compressional- and shear-wave sources are used in conjunction with downhole hydrophones and vertically oriented geophones, respectively. This field set-up allows optimum generation and recovery of the respective wave energy. Wireline winches are used to transmit downhole signals to a high-resolution, digital recording system, which provides means for fast efficient data acquisition. Data acquired in the field are stored on floppy diskettes allowing analysis to be performed with desktop computer software.

The preparation of boreholes, deviation surveys and the analysis procedures are all conducted in accordance with ASTM (1984) standard test procedures for crosshole seismic investigations. USBR crosshole investigations are typically performed at a minimum of two sites; one on the crest or at a predetermined "critical" mid-slope location, and one near the downstream toe of the embankment. There are several advantages to utilizing two crosshole test sites:

1) Obtain measurements within the embankment
2) Obtain measurements within the foundation materials-
   - while under static load beneath the structure
   - while in a free-field condition at the toe
3) Verify lateral continuity of elastic properties
4) Allow dynamic response analyses to be performed with in situ velocities at the toe and through the embankment

CASE HISTORIES

In the presentation of the following case studies in situ velocity profiles obtained for each investigation are plotted and compared with: Peak accelerations for the foundation materials (base motion for the embankment), computed by the equivalent-linear method; standard penetration test data (where available), corrected for overburden and energy delivered to the drill rod (SPT $N_{1(60)}$); and laboratory soil types presented in the Unified Soil Classification system (USC). These case studies were selected to illustrate the aforementioned advantages to performing crosshole investigations.

<u>COLD SPRINGS DAM</u> - Cold Springs Dam, located in north-central Oregon and completed in 1908, is a zoned earthfill embankment. It has a structural height of 115 ft (35 m), hydraulic height of 85 ft (26 m) and a crest length of 3,450 ft (1050.5 m) at elevation 629.8 ft (192 m). Foundation materials consists of two alluvial soil units: An upper unit composed of loose, clean-sands and silts; and, a lower unit which is composed of dense to very dense gravels with interbedded sandy silt layers. The alluvium is approximately 40 ft (12.2 m) thick and overlies bedrock which is fractured basalt.

Crosshole velocity measurements were performed at the downstream toe and a mid-slope location on the embankment and the results are presented in Figures 2 and 3, respectively (Sirles, 1987). Shear wave velocities measured in the embankment steadily increase with depth from 544 to 865 fps (166-264 mps). The shear wave velocities obtained in the foundation materials delineate the different stiffnesses of the two alluvial units with distinct ranges in velocity: Within the upper unit they range from 361 to 737 feet/second (fps) (110-225 meters/second (mps)) at the toe of the structure, and from 526 to 890 fps (160-271 mps) beneath the embankment; and, within the lower unit they range from 929 to 1,670 fps (283-509 mps), which includes the measurements at the toe and beneath the embankment. These data show the effect of structural loading which has increased the velocity in the upper alluvial soils by approximately 55 percent. The figures show an irregular velocity/depth distribution which corresponds to variable materials and SPT-N values. The basaltic bedrock at the sites has an average velocity of 2,953 fps (900 mps) with a trend of slightly increasing velocity with depth.

To approximate the accelerations expected to occur at Cold Springs Dam the Pacoima-Taft II modified accelerogram was selected to model the base excitation. The record was scaled to .61g to adjust the maximum acceleration of the record (0.75g) to an appropriate amplitude for the site. As shown in Figure 2 there is considerable amplification of the input base motion as it propagates to the ground surface. The strong base excitation beneath the embankment is amplified in the lower alluvial unit, and then damped out in the upper alluvial unit (Figure 3).

<u>RYE PATCH DAM</u> - Rye Patch Dam, located in central Nevada and completed in 1936, is a rolled earthfill embankment. It has a structural height of 78 ft (23.8 m), hydraulic height of 70 ft (21.3 m) and crest length of 1,074 ft (327.4 m). The embankment is composed of a (variable) firm to hard clay, sand, and gravel mixture. Foundation materials are alluvial deposits consisting of very loose to very dense poorly graded sand, silty-sand, silt and

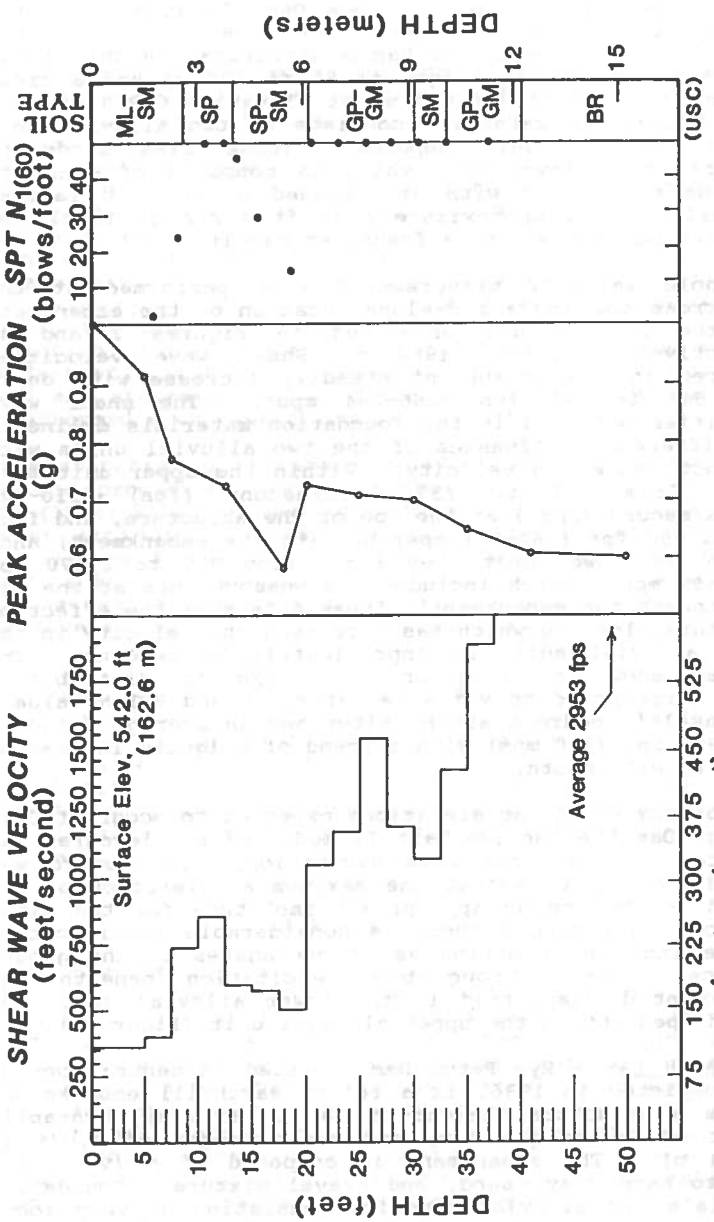

FIGURE 2. Cold Springs Dam, Oregon. Downstream toe section. BR indicates bedrock.

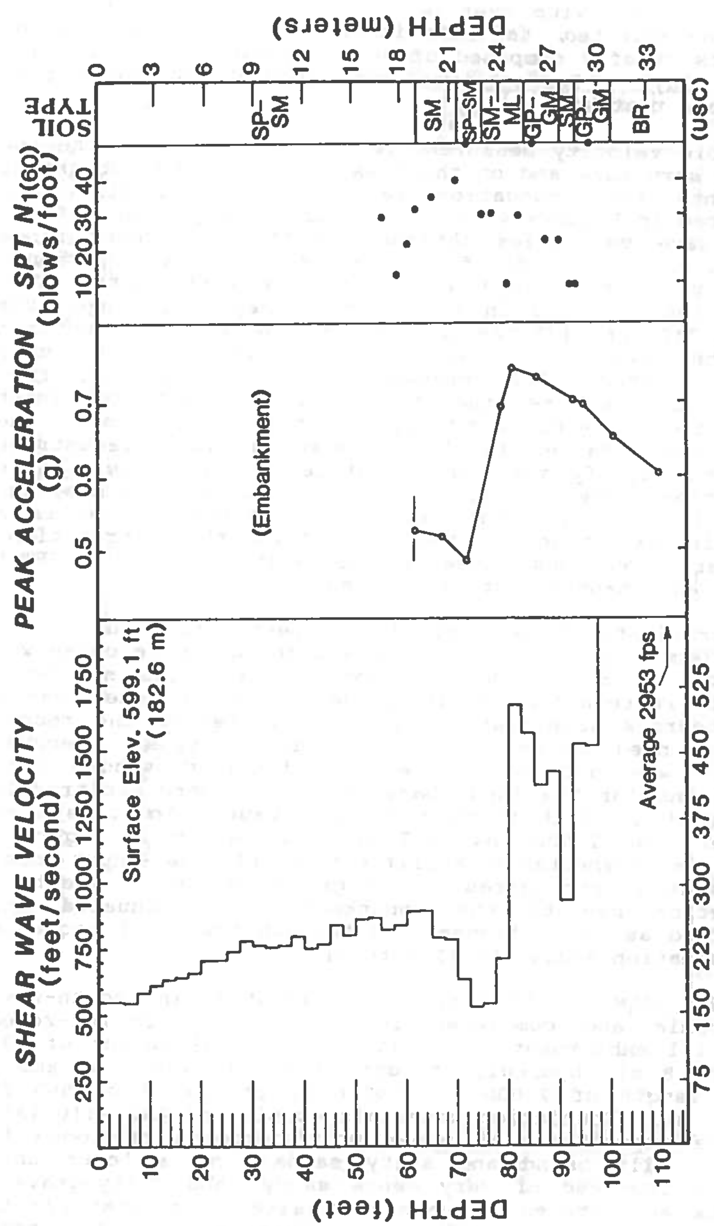

FIGURE 3. Cold Springs Dam, Oregon. Mid-slope embankment section. BR indicates bedrock.

clay. The alluvium overlies an extremely thick sequence of non-indurated to semi-indurated, fluvio-lacustrine deposits chiefly composed of stiff to hard silt, clay and sandy clay. Bedrock was not encountered at either crosshole test site.

Crosshole velocity measurements were performed at the toe of the structure and on the crest, through the embankment and into the foundation materials; the results are presented in Figures 4 and 5, respectively (Sirles, 1986). Shear wave velocities obtained in the embankment range from 1,023 to 1,359 fps (312-414 mps), and although slightly varied they tend to increase with depth. The velocities measured in the alluvial deposits range from 586 to 740 fps (179-226 mps) at the toe of the structure; and they range from 949 to 1,005 fps (289-306 mps) directly beneath the embankment. It can be seen from these two test sites that the alluvium beneath the crest has a higher velocity by approximately 33 percent. The velocities obtained in the thin-bedded fluvio-lacustrine sediments typify the varied nature of materials. Here velocities range from 1,040 to 1,840 fps (317-561 mps) and there is no consistent trend, but rather, there is a dramatic variation in the velocity/depth distribution. The variation does, however, correlate well with SPT-N values and changing material types.

To approximate the accelerations expected to occur at Rye Patch Dam a synthetic near-field bedrock accelerogram was selected to model the base excitation. The synthetic record, representing a magnitude 7.5 earthquake, has a peak bedrock acceleration of .63g, therefore the record did not need to be scaled for this analysis. Because bedrock was not encountered at either crosshole site elevations for the input base excitation were arbitrarily chosen at a depth where the shear wave velocities were greater than 1,500 fps (457 mps). As shown in Figure 4 there is respectable amplification of the input base motion as it propagates to the ground surface. The base excitation beneath the embankment is attenuated <u>and</u> amplified as it is transmitted through the thick sequence of foundation sediments (Figure 5).

<u>CASITAS DAM</u> - Casitas Dam, located in south-west California and completed in 1959, is a rolled-zoned earthfill embankment. It has a structural height of 334 ft (101.8 m), hydraulic height of 261 ft (79.5 m) and a crest length of 2,000 ft (609.6 m) at elevation 585 ft (178.3 m). Foundation materials consist of two alluvial-terrace deposits: An upper unit composed of loose to medium, silt, sand and silty sands; and a lower unit chiefly composed of very dense sandy- and silty-gravel. Bedrock encountered at each test site is moderately- to intensely-weathered sandstone, siltstone, and claystone

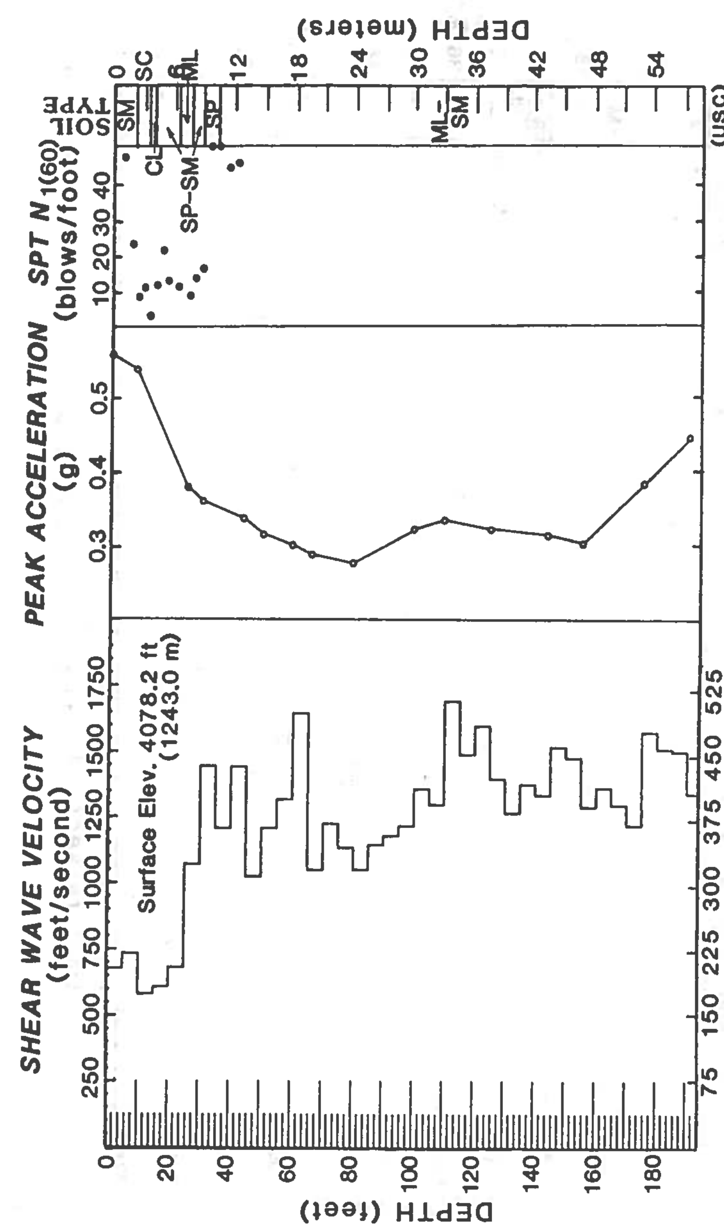

FIGURE 4. Rye Patch Dam, Nevada. Downstream toe section.

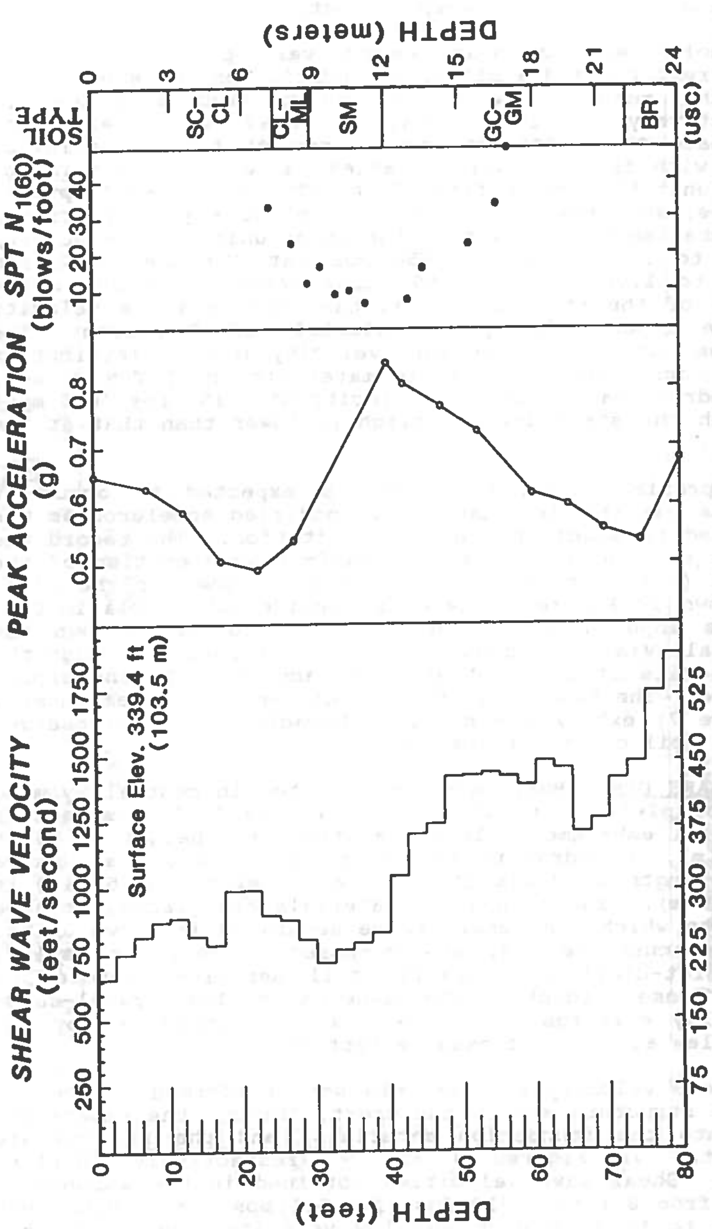

FIGURE 6. Casitas Dam, California. Downstream toe section. BR indicates bedrock.

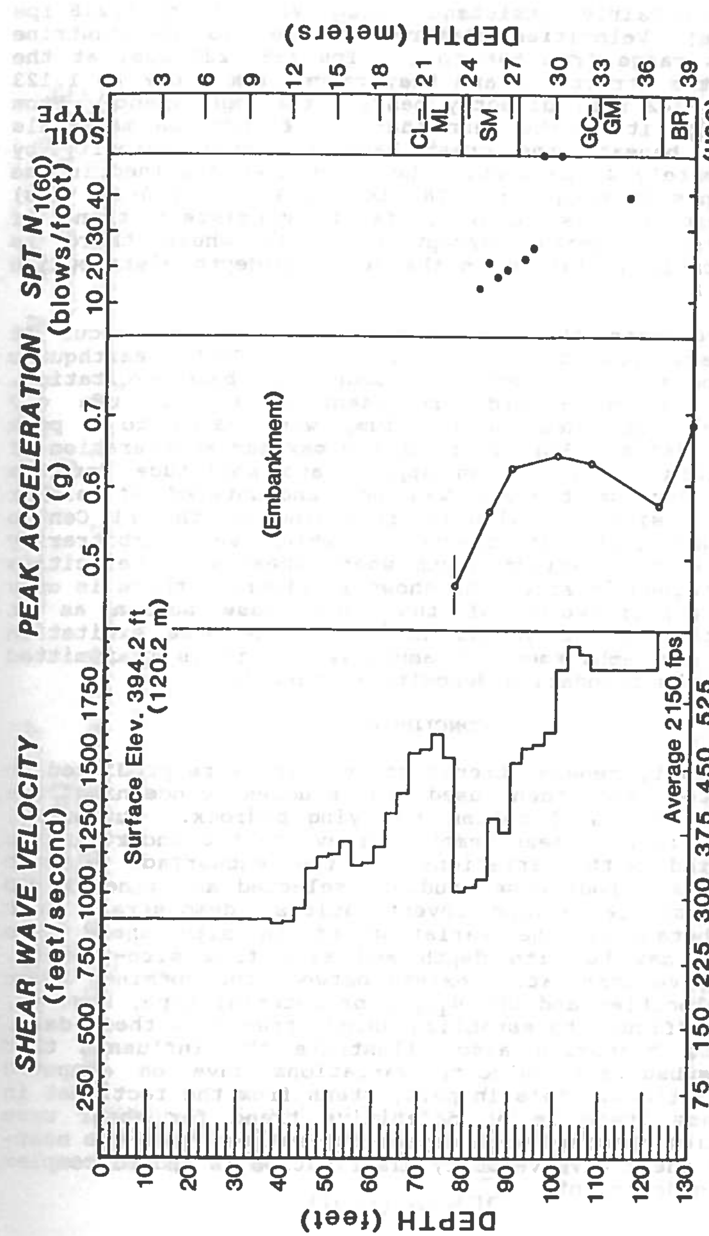

FIGURE 7. Casitas Dam, California. Mid-slope embankment section. BR indicates bedrock.

there is a fairly consistent average velocity of 1,218 fps (371 mps). Velocities measured in the fluvio-lacustrine deposits range from 596 to 737 fps (182-225 mps) at the toe of the structure; and they range from 1,062 to 1,123 fps (324-342 mps) directly beneath the embankment. From these data it can be seen that the foundation materials directly beneath the crest have a higher velocity by approximately 40 percent. The velocities obtained in the till deposits range from 788 to 1,123 fps (240-342 mps) and there appears to be a fairly consistent trend of increasing velocity, except at depth where there is considerable variation in the velocity/depth distribution (Figure 8).

To approximate the accelerations expected to occur at Bull Lake Dam the El Centro 1940 South earthquake accelerogram was selected to model the base excitation. The El Centro record, representing a magnitude 6.7 earthquake recorded on alluvium, was scaled to a peak acceleration of .30g to adjust the maximum acceleration of the record (.35g) to an appropriate amplitude for the site. Because bedrock was not encountered at either crosshole site the alluvial-recording of the El Centro event was input at elevations which were arbitrarily chosen as the maximum depth where shear wave velocities were obtained in situ. As shown in Figure 8 there is only slight amplification of the input base motion as it propagates to the ground surface. The base excitation beneath the embankment is amplified as it is transmitted through the foundation deposits (Figure 9).

CONCLUSIONS

In the past, general trends of velocity were predicted or calculated and then used in studies concerning the dynamics of a soil column overlying bedrock. Currently, reliable in situ measurements alleviate the uncertainties associated with variations in the subsurface elastic properties. Four case studies, selected among nearly 50 USBR crosshole-seismic investigations, demonstrate just how substantial the variation of in situ shear wave velocity may be with depth and also from site-to-site. Qualitative correlation exists between the obtained shear wave velocities and SPT $N_{1(60)}$ or material type, however, it is difficult to establish unique trends to these data. The case histories also illustrate the influence that these subsurface velocity variations have on computed ground motions. This in part, stems from the fact that in each case there is no definitive trend for shear wave velocities obtained with depth; but rather, that the near-surface shear wave velocity distribution is indeed complex and site dependent.

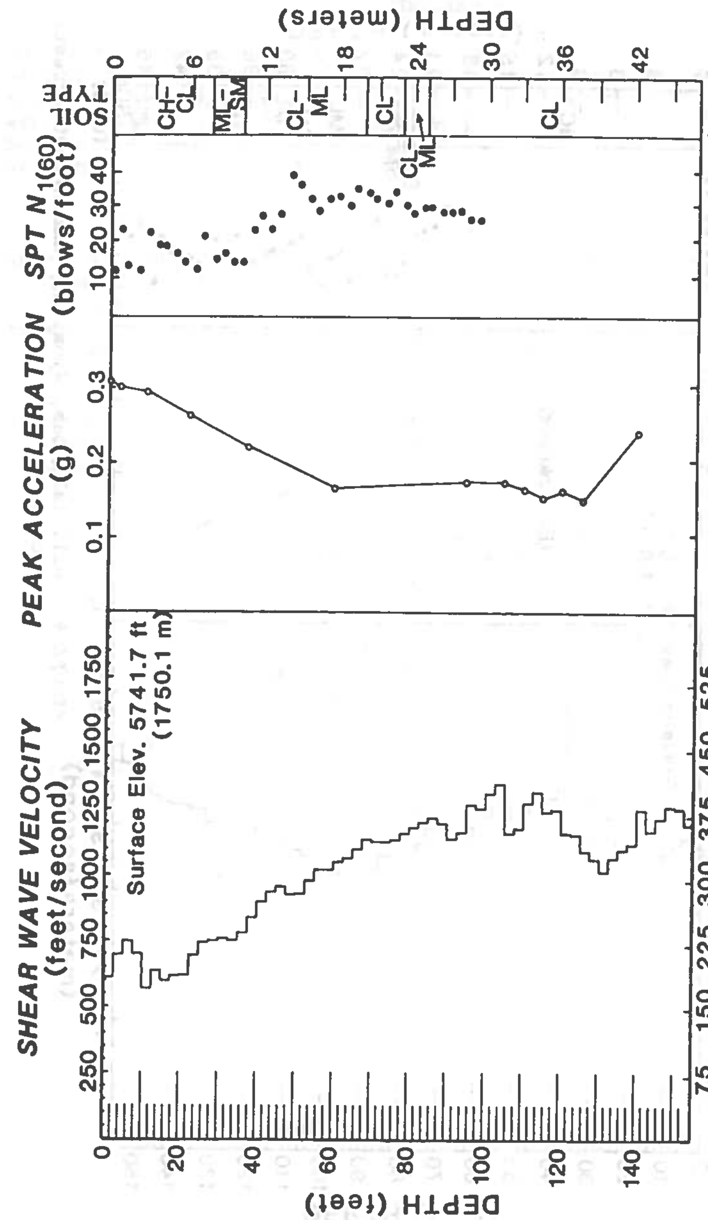

FIGURE 8. Bull Lake Dam, Wyoming. Downstream toe section.

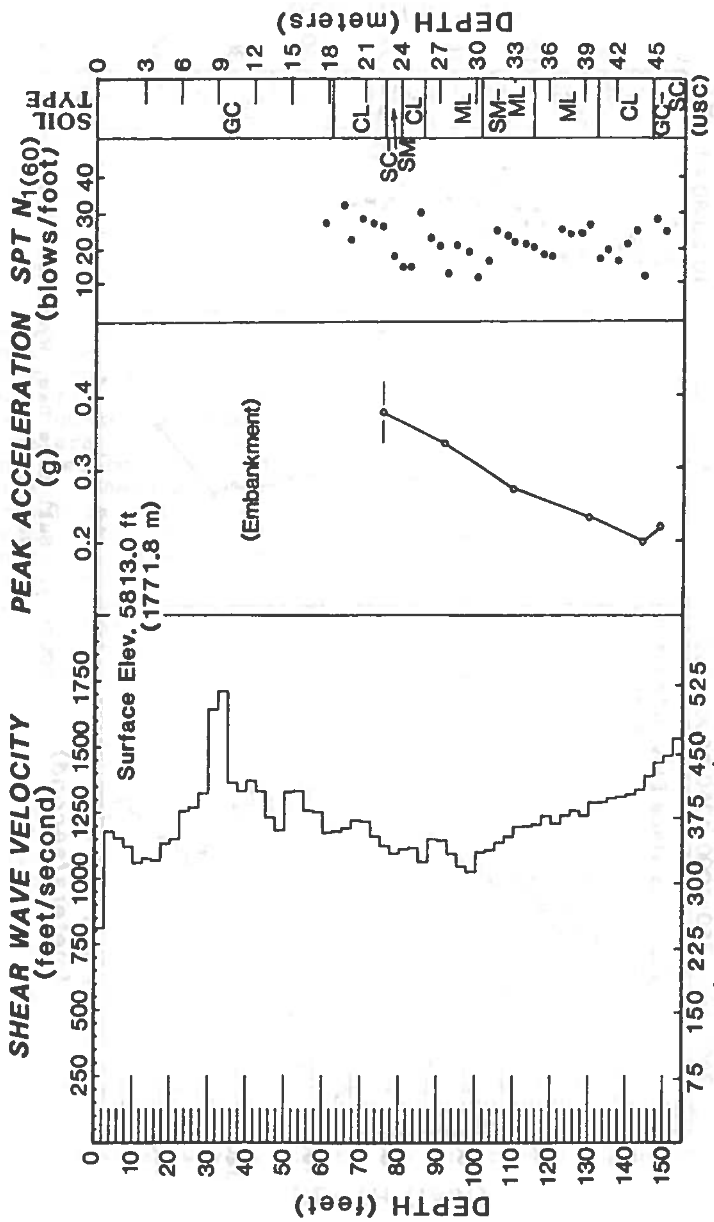

FIGURE 9. Bull Lake Dam, Wyoming. Embankment (crest) section.

ACKNOWLEDGEMENTS

The author greatly appreciates the help and guidance in preparing this document by Andy Viksne and Dave Route in the USBR Geophysics Section. Insight and support for the study were provided by Messrs. R.L. Dewey, J. L. Nettleton, and L.J. Von Thun of the Embankment Dams Branch, USBR, and thanks are extended to them.

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