Site-Specific Shear Wave Velocity Determinations for Geotechnical Engineering Applications

Phil C. Sirles and Andy Viksne**

Abstract

Shear wave velocity values obtained from in situ measurements are used to compute the low strain soil shear modulus required as an input parameter in advanced finite-element programs for dynamic analysis of earth dams and for foundation materials in the evaluation of site liquefaction potential. Site-specific shear wave velocity measurements of approximately 50 U.S. Bureau of Reclamation crosshole seismic investigations show that significant variations in shear wave velocity exist with depth and that these variations qualitatively correlate with material type and structural loading conditions. Six case histories included represent the variety of studies and applications of shear wave velocity determinations used for Bureau of Reclamation projects. These case studies demonstrate the substantial variation of in situ shear wave velocity obtained with depth as well as from site-to-site.

Introduction

Dynamic analysis of embankment dams for liquefaction potential and/or seismic stability requires the knowledge of subsurface earth material properties in order to predict accurately ground accelerations expected to occur during earthquake loading. Elastic properties, such as shear wave velocity, are the key parameters in the determination of the dynamic response of an embankment dam as well as site liquefaction potential. Seismic methods, such as crosshole, uphole, and downhole, utilizing boreholes and polarized or directional energy sources have been used for a number of years by the U.S. Bureau of Reclamation (Bureau) to obtain in situ shear wave velocity measurements of various earth materials such as embankment dams and foundations (Viksne, 1976). However, with the development by the Bureau of a state-of--the-art sophisticated geophysical data acquisition system, designed specifically for conducting crosshole seismic investigations, shear wave velocity determinations have been made utilizing the crosshole method exclusively during the past decade. Because of the need for the shear wave values to be reliable and accurate, the methodology for the data acquisition has seen a number of significant improvements and standardization to the point where an ASTM Standard (1984) has been promulgated for "Crosshole Seismic Testing." Consequently, the Bureau has developed its own procedures for preparation of boreholes for geophysical testing based on the ASTM Standard and adheres to these guidelines for its site-specific shear wave velocity determinations.

To date, approximately 50 different and unique sites (Figure 1) have been investigated, and shear wave velocity profiles have been determined at a number of locations for each site. Discussion of six of these studies, each associated with embankment dams, follows and illustrates the fact that the velocity-depth distribution is indeed complex and site dependent. These six sites represent a variety of embankment dams and foundation conditions. They are located throughout the western United States as follows, Casitas and Senator Wash Dams in California, Cold Springs Dam in Oregon, Rye Patch Dam in Nevada, Steinaker Dam in Utah, and, Jackson Lake Dam in Wyoming.

Case Studies

Casitas Dam

Casitas Dam, an embankment dam in southern California approximately 6 miles (9.6 km) northwest of the city of Ventura, was completed in 1959, and is a zoned

*U.S. Bureau of Reclamation, MC D-3611, P.O. Box 25007, Denver, CO, 80225.

Fig. 1. USBR Crosshole shear wave velocity test locations.

earthfill structure with a structural height of 334 ft (102 m), a hydraulic height of 261 ft (79.5 m), and a crest length of 2000 ft (610 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 adjacent to three embankment structures: Squaw Lake Dike, North Dike, and Senator Wash Dam, which is the moderately to intensely weathered sandstone, siltstone, and claystone strata of the Sespe Formation.

Crosshole shear wave velocity profiles were determined at three downstream locations for dynamic analysis and site liquefaction potential. The variation in shear wave velocity distribution with depth obtained at each test location correlates well with the materials present based on geologic logs and SPT (Standard Penetration Test) tests conducted in companion drill holes (Sirles, 1988a). Shear wave velocities range from 884 to 1942 ft/s (269—592 m/s) and although this represents a relatively wide range in velocities, within each respective alluvial unit or within the bedrock, the range in velocities obtained is much narrower (Figure 2). Figure 2 illustrates that velocities obtained for those foundation materials (alluvium) underneath the embankment exhibit the effect of overburden loading by the structure. Here, the in situ velocities are higher, by approximately 30 percent, for the same alluvial materials encountered both at the toe of the structure and near the outlet works.

Senator Wash Dam

Senator Wash Reservoir, located along the California side of the Colorado River and completed in 1966, is created by three embankment structures: Squaw Lake Dike, North Dike, and Senator Wash Dam which is the main embankment section. The dam has a structural height of 94 ft (29 m), hydraulic height of 80 ft (24.4 m) and a crest length of 2342 ft (714 m). The structure is rolled, three-zone earthfill embankment. Foundation materials beneath the main embankment section consist of greater than 200 ft (61 m) of uncemented sand and gravel alluvial channel deposits. Bedrock at the dam site, which forms both the abutment foundations, consists of hard and dense, but highly fractured andesite-flow rocks.

Crosshole shear wave velocity measurements were performed at three locations along the downstream toe of Senator Wash Dam to identify continuity of foundation materials and their potential for liquefaction. The elastic properties of the subsurface material exhibit good correlation along the downstream toe of the embankment, as shown in the cross-sectional view that parallels the dam centerline (Figure 3). Although there is a large variation in the range of the depth distribution and the shear wave velocities obtained, this wide range primarily reflects the different stiffnesses associated wtih the various alluvial soil types and other materials present.

Shear wave velocities measured in the alluvial soils range from 331 to 1683 ft/s (101—513 m/s), however, a few thin caliche layers exist where the shear wave velocities obtained range between 1750 and 2203 ft/s (533—671.5 m/s). As illustrated in Figure 3, the velocities measured with the upper 30 to 40 ft (9—12 m) range from 331 to 583 ft/s (101—178 m/s) which is a narrow range indicative of very low rigidity and potentially liquefiable soils. Below approximately 40 ft (12 m), the shear wave velocity distribution generally increases with depth, with a few (relatively) low velocity zones present as well as the high velocity caliche layers. Velocities obtained within the andesitic bedrock range from 14% to 1693 ft/s (456—516 m/s). These velocities are slightly low for volcanic rock, but the low velocity is attributed to the high degree of fracturing and moderate weathering.

Cold Springs Dam

Cold Springs Dam in northcentral Oregon was completed in 1908, and is a zoned earthfill embankment with a structural height of 115 ft (35 m), hydraulic height of 85 ft (26 m), and a crest length of 3450 ft (1051.5 m).

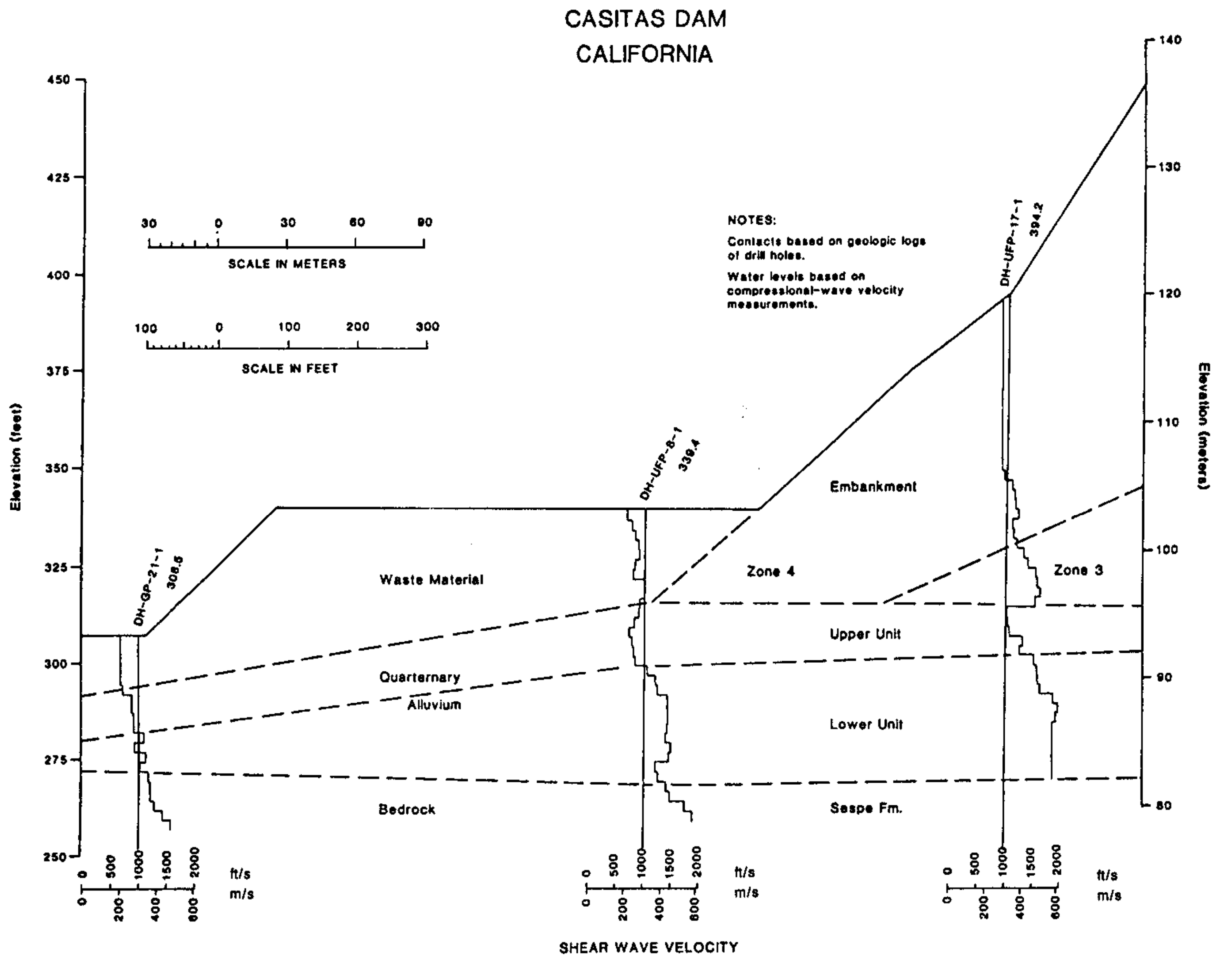

Fig. 2. Cross-sectional view, Casitas Dam, California.

its, and the elevation to which structural loading has the effect of increasing in situ shear wave velocity (approximately 3985 ft or 1215 m).

Steinaker Dam

Steinaker Dam, completed in 1962, is located offstream in Steinaker Draw 3.5 miles north of Vemal, Utah. The dam is a rolled, zoned earthfill embankment with a structural height of 162.2 ft (49 m), hydraulic height of 142 ft (43 m) and a crest length of 1997 ft (609 m). The dam is founded on alluvial channel deposits, approximately 90 ft (27 m) thick in the maximum section across the valley, and bedrock on both abutments. The alluvium is primarily composed of loose, poorly graded, very fine-grained sand, with a few interbedded silt and silty sand layers. Artesian conditions exist within the bedrock, which is weathered shale (Mowry Formation) and sandstone (Frontier Sandstone).

The quality of seismic waveform data obtained from a crosshole test location mid-slope on the downstream face of the embankment was exceptional. Figure 8 displays waveforms acquired at 2.5 foot (0.76 m) depth intervals between 57.5 and 105 ft (17.5—32 m). These waveforms represent field data and although only one polarized shear wave is displayed for each depth interval, first arrival time of the shear wave energy (depicted with a V) is easy to identify. A gradual increase in arrival time can be seen in zone 3 embankment materials which consist of selected miscellaneous materials compacted in 1 ft (0.3 m) layers. However, in the foundation soil deposits, the direct arrivals are considerably delayed, particularly between 82.5 and 92.5 ft (25—28 m). The low amplitude of the compressional wave arrival below 62.5 ft (19 m) indicates P-wave *energy* propagating through the interstitial pore fluid.

By converting shear wave arrival times into velocities utilizing borehole directional survey data, very good correlation between the geologic drill hole log data and seismic-wave velocity data is obtained (Figure 9). The range of shear wave velocities obtained within each material type investigated is representative of the in situ stiffness. That is, zone 3 material shear wave velocities range from 1021 to 1974 ft/s (311—602 m/s) with an irregular velocity/depth distribution; zone 1 material shear wave velocities range from 1374 to 1901 ft/s (419—579 m/s); and, shear wave velocities in the alluvial deposits range from 590 to 806 ft/s (180–246 m/s) with only slight variations in the velocity/depth distribution.

The general trend is for the seismic wave velocity to increase and then decrease with depth for each material layer (zone) encountered in the embankment. The reason for this trend is unknown. In the alluvium, some layers of sand are very loose and poorly-graded, and, both the shear wave velocities and the SPT blow count data are low. This is indicative of a high potential for liquefaction failure of the foundation materials if earthquake loading should occur.

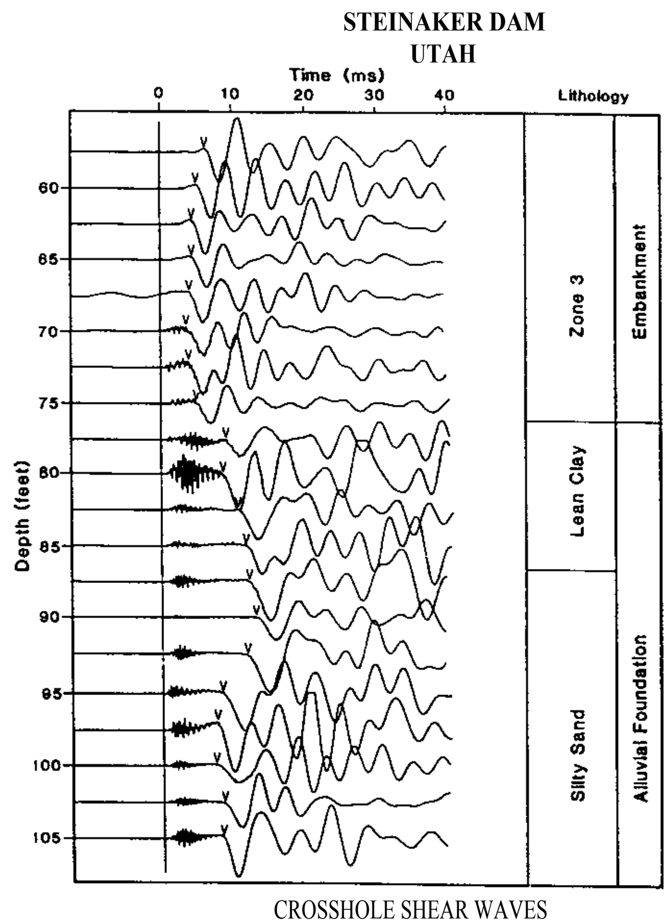

FIG. 8. Crosshole shear waves, Steinaker Dam, Utah.

Jackson Lake Dam

Jackson Lake Dam, located in north-western Wyoming within the boundaries of the Grand Teton National Park, was constructed in 1911, and is a composite structure consisting of a concrete section (combination spillway and outlet works), a short embankment section to the south, and a long embankment section to the north for a total length of approximately 5000 ft (1524 m). Foundation materials encountered at three crosshole test site locations (Figure 10) are unconsolidated alluvial and fluvio-lacustrine deposits. Generally, they consist of thin interbedded layers of silt, sand and gravel, and, mixtures thereof. Occasional lenses of clay and organics may be

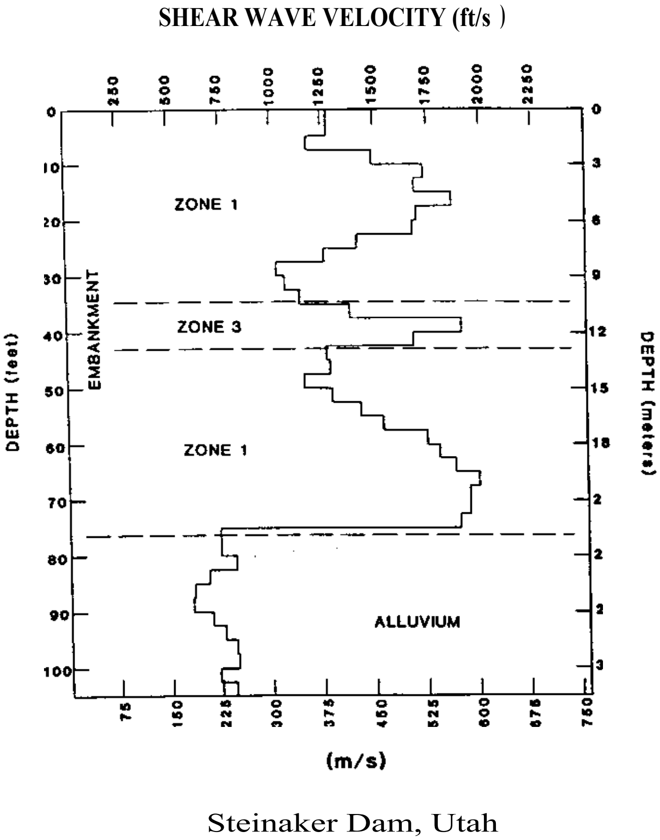

FIG. 9. Shear wave velocity profile, Steinaker Dam, Utah.

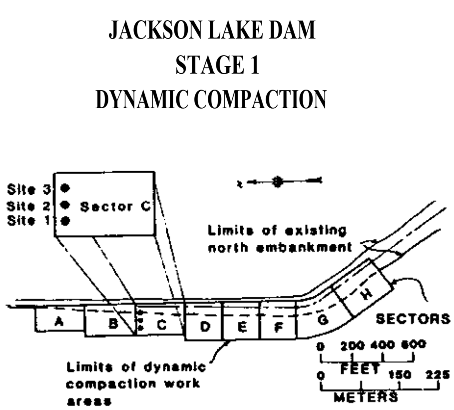

FIG. 10. Site plan for Stage I dynamic compaction work and three crosshole test sites located in Sector C, Jackson lake Dam, Wyoming.

found within these sediments. The deposits are quite varied in consistency and character both laterally and vertically.

This crosshole investigation represents shear wave velocity values obtained after the entire embankment was removed such that dynamic compaction treatment of the foundation soils could be performed prior to construction of a new zoned earthfill embankment. Results of in situ crosshole testing, conducted before and after the dynamic compaction treatment, are presented in Figures II, 12, and 13, and also listed in Table I (Sirles, 1988b). Each figure illustrates both of the data sets that were obtained prior-to and after the dynamic compaction treatment of the foundation soils. These results indicate a significant effect on measured in situ shear wave velocities due to dynamic compaction efforts. To illustrate the observed change in shear wave velocity with depth for pre- versus post-compaction test results, percent differences were calculated at each depth interval for all crosshole tests. The results are plotted in Figure 14 for each crosshole test location. Because of complex soil stratigraphy present at this damsite, direct correlation of percent difference in shear wave velocity with material type was difficult. However, if all three sets of crosshole velocity results are compared some general trends in the data can be observed. Figure 14 shows that within the fill material

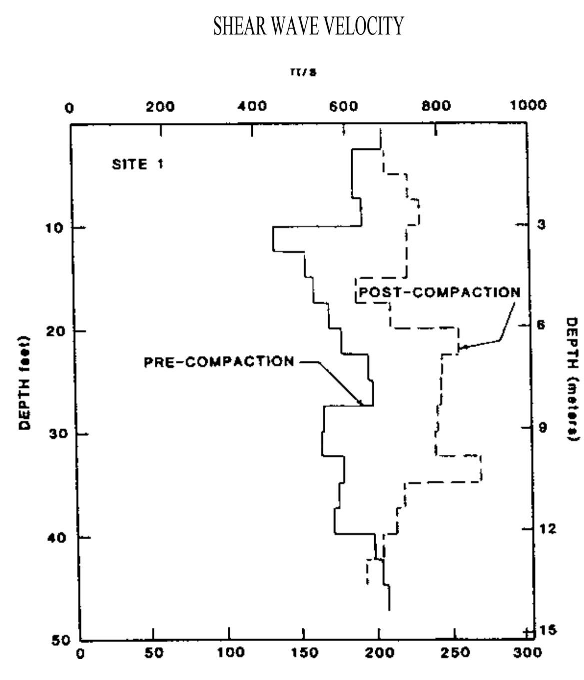

FIG. I I. Site 1—Pre- and post-compaction shear wave veloc ity profiles, Jackson Lake Dam, Wyoming.

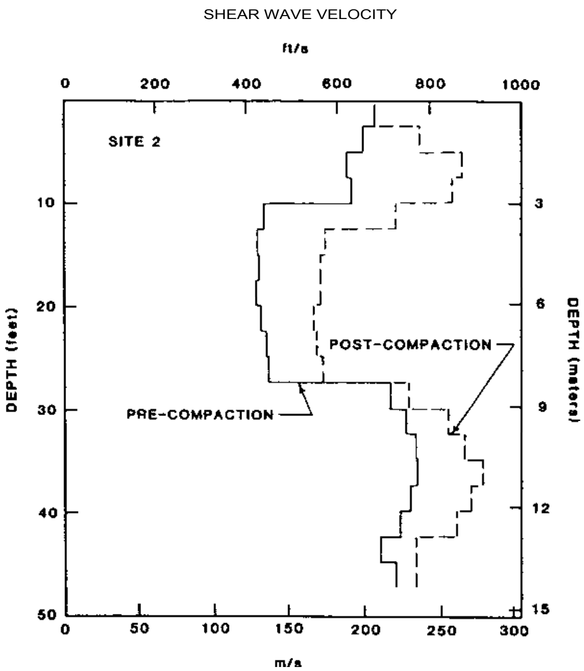

FIG. 12. Site 2—Pre- and post-compaction shear wave velocity profiles, Jackson Lake Dam, Wyoming.

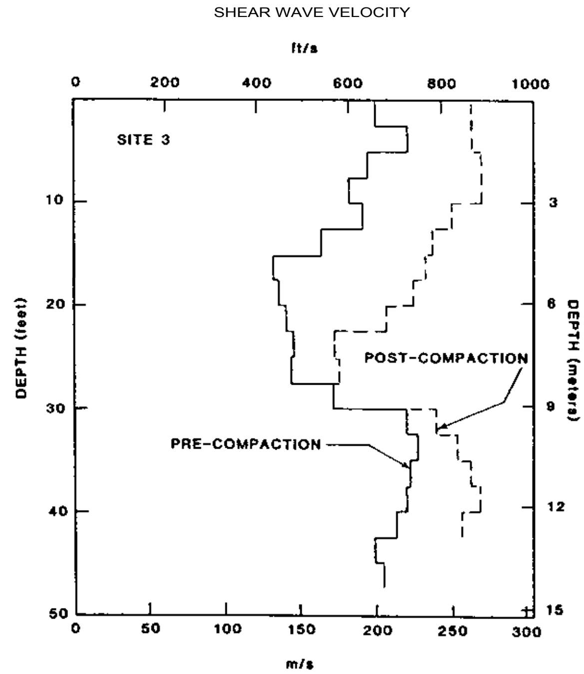

FIG. 13. Site 3—Pre- and post-compaction shear wave velocity profiles, Jackson Lake Dam, Wyoming.

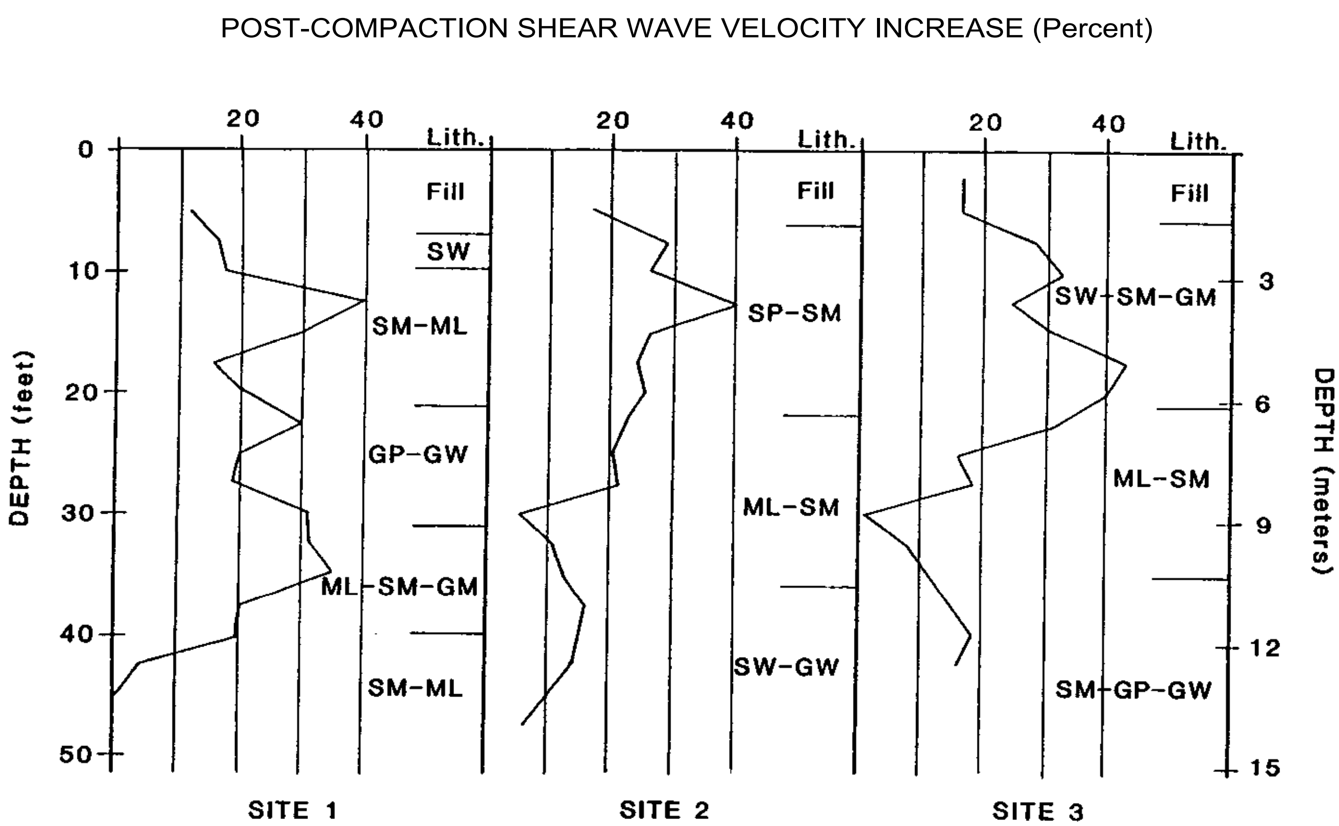

Fig. 14. Post-compaction percent increase in shear wave velocity for Sites I, 2 and 3.

Table 1. Shear wave velocity ft/s (m/s)

	Construction fill	Soil deposits
Site 1		
Pre-	614-677 (187-206)	439-682 (134-208)
Post-	683-760 (208-232)	619-885 (189-270)
Site 2		
Pre-	619-681 (189-208)	420-772 (128-235)
Post-	779-870 (237-265)	547-916 (166-279)
Site 3		
Pre-	638-727 (194-222)	434-745 (132-227)
Post-	864-886 (263-270)	563-882 (171-269)

the increase in shear wave velocity is in the 10 to 16 percent range. For the variety of alluvial and fluvio-lacustrine sediments investigated the increase varies between 15 and 43 percent in the upper 30 to 35 ft (9 to 10.5 m). Below that depth they typically decreased from 20 to 0 percent to a depth of 47 ft (14 m). The data also define similar trends within the upper 20 ft (6 m) for Sites 1 and 2; and, very similar trends below 20 ft (6 m) for Sites 2 and 3. This trend is attributed to similar soil composition and stratigraphy between the sites at these depths.

Overall, in the upper 30 ft (10 m) shear wave velocity increases appear to correlate with material types such that the greatest increases occur in fine-grained deposits of silt and sand; and smaller increases occur in coarse layers of gravels with sand. Also, the average increase in shear wave velocity is 28 percent in the upper 30 ft (10 m) of soils at all three crosshole sites. Because the soil stratigraphy at crosshole Sites 2 and 3 is relatively similar, the correlation of both the velocity layering and percent difference for the pre- and post-compaction survey results appears to be very good. However, these two sites are dissimilar from Site I with respect to velocity layering and percent difference where fine grained materials have an increase in shear wave velocity between 31 and 34 percent.

Conclusions

Site-specific shear wave velocity measurements of approximately 50 U.S. Bureau of Reclamation crosshole seismic investigations show that significant variations in shear wave velocity exist with depth and that these variations qualitatively correlate with material type and structural loading conditions. Six case studies intended to illustrate the variety of applications and utilization of crosshole seismic investigations, which were selected from the 50 Bureau investigations, demonstrate just how substantial the variation of in situ shear wave velocity may be with depth and also from site-to-site. They also emphasize that no definitive trend becomes obvious in the shear wave velocities obtained with depth, but rather, that the near-surface shear wave velocity distribution is indeed complex and site dependent.

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