Case Study: Shear Wave Velocity Measurements Before and After Dynamic Compaction of Cohesionless Soil Deposits

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SUMMARY

Crosshole shear wave velocity measurements were used to evaluate the effectiveness of dynamic compaction of foundation soils at the Jackson Lake damsite, Wyoming. This investigation method quantitatively assesses the change with depth in the low strain elastic properties of the soils after dynamic compaction. Shear wave velocity measurements from three sites show that shear wave velocities increased within the upper 35 feet (10.7 meters) by approximately 28 percent. Generally, the fine grained silty sand layers showed slightly greater velocity increases than layers with higher percentage of gravels. The investigation demonstrates the ability of crosshole seismic testing to identify changes with depth in the elastic properties of cohesionless soil deposits due to dynamic compaction.

INTRODUCTION

Jackson Lake Dam, constructed in 1911, is located in northwestern Wyoming within the boundaries of the Grand Teton National Park. The dam 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 5,000 ft (1524 m). This dam provides storage and regulation of water for irrigation and flood control; its storage capacity is 847,000 acre-feet.

Dam safety investigations conducted by the U.S. Bureau of Reclamation (USBR) indicated that the dam had a high potential for liquefaction failure of the embankment and/or the foundation soils during earthquake loading. This potential condition is a result of the hydraulic-fill construction of the dam, loose fine-grained lacustrine and alluvial foundation deposits, and the location within a seismically active area. Hazard assessments concerned with total loss of the structure, due to liquefaction, revealed a total economic impact to the Jackson Hole area to be estimated at $0.5 billion (Welsh, et. al., 1987).

Based upon the geologic and seismotectonic conditions, and the environmental impact considerations, the USBR along with National Park officials and public support determined that major modification of Jackson Lake Dam was the best alternative when considering all the various factors. Modification of the dam was divided into two stages: Stage I included removal of the northern two-thirds of the embankment and then shallow densification of the foundation materials exposed beneath the structure; and, Stage II included removal of the remaining north embankment, a combination of shallow and deep treatment of the foundation materials and construction of a zoned embankment to replace the structure.

The method employed for shallow foundation treatment was dynamic compaction, where a 32-ton tamper was repeatedly dropped from a height of 100 ft (30.5 m) over a specified grid. Application of the dynamic compaction consisted of three heavy tamping phases covering the entire grid, and one light (ironing-out) tamping phase. The primary purpose of the dynamic compaction was to densify and stiffen the upper 40 ft (12 m) of relatively low density, loose (cohesionless) foundation soils.

An engineering geophysical investigation was undertaken to evaluate the results of dynamic compaction treatment of the foundation soils present at Jackson Lake damsite. Crosshole shear wave velocity measurements appeared to be the most suitable method to quantitatively assess the amount of change with depth in the low strain elastic properties of the soils after dynamic compaction. Therefore, three crosshole test sites were selected for shear wave velocity measurements to be performed before and after dynamic compaction.

TEST METHOD

The USBR is presently emphasizing the importance of site-specific shear-wave velocity measurements for application in dynamic analysis. 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, the variations are much more prominent than assumed, calculated or predicted velocity trends (Sirles, 1988).

A sophisticated geophysical data acquisition system designed specifically for conducting crosshole seismic testing has been developed to a point where routine measurements are performed under the USBR Safety of Dams program. State-of-the-art equipment utilizing 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. Preparation of boreholes, deviation surveys and the analysis procedures are all conducted in accordance with ASTM standard test procedures for crosshole seismic investigations (1984).

At Jackson Lake damsite crosshole shear wave velocity measurements were performed between borehole triplets prior to and after dynamic compaction using a downhole hammer with reversible impact direction as the shear wave source. The hammer was placed in one drill hole and a vertically oriented geophone located in each companion drill hole. The hammer and both geophones were maintained at depths of equal elevation for each recording and lowered in 2.5-foot (0.76 m) increments to the total depth of each drill hole. Dynamic compaction treatment was intended to have a significant effect to approximately 40 ft (12 m), therefore the drill holes used for crosshole testing extended to approximately 50.0 ft (15 m).

Precompaction measurements were performed at three sites in July 1986 and post compaction measurements were performed in April 1987, also at three sites. Both sets of data acquired at the three sites were from Sector C of Stage I treatment area (Figure 1). The pre- and post-compaction borehole triplet sets were drilled separately and each post compaction triplet was located within approximately 20 ft (6.1 m) of the precompaction set thereby allowing direct comparison of the results.

RESULTS

Foundation materials encountered at the three crosshole test sites are unconsolidated alluvial and fluvio-lacustrine deposits. The thickness of the deposits varies along the dam alignment between 35 ft (10.6 m) near the concrete section to over 600 ft (183 m) at the north end of the dam. Generally, they consist of thin interbedded layers of silt, sand and gravel, and, mixtures thereof. Occasional lenses of clay and organics may be found within these sediments. The deposits are quite varied in consistency and character, both laterally and vertically, although between the boreholes of each crosshole site the materials tested appear to be consistent.

The primary purpose of this investigation was to measure the change in S-wave (shear wave) velocity with depth due to dynamic compaction treatment of the soils present at Sector C. Table 1 lists the triplet of boreholes used during pre- and post-compaction crosshole testing and the range of shear wave velocities obtained in both the construction-fill and natural soils (Sirles, 1988).

Data listed in Table 1 are shown in graphic form on figures 2, 3 and 4 which represents the range of values obtained. The data indicate a significant effect on measured shear wave velocities due to dynamic compaction efforts. To illustrate the observed change in S-wave velocity with depth for pre- vs. post-compaction test results, percent differences were calculated at each depth interval for each crosshole test site and are shown in Figure 5. Due to the complex soil stratigraphy present at the damsite, direct correlation of percent differences in S-wave velocity with material type was complex. However, if all three sets of crosshole velocity results are compared some significant trends in the data can be seen. Figure 5 shows that within the fill material there is approximately a 10 to 16 percent increase in S-wave velocity. For the variety of alluvial and fluvio-lacustrine sediments the increase varies between 15 and 43 percent in the upper 30 to 35 ft (9.1 to 10.7 m), and below that the percent increase is between 20 and 0 percent to a depth of approximately 47.5 ft (14.5 m) (Fig. 5). The data also show similar trends within the upper 20 ft (6 m) between Sites 1 and 2; and, very similar trends below 20 ft (6 m) between Sites 2 and 3. This is attributed to similar soil composition and stratigraphy between the sites at the corresponding depths.

Generally, within the upper 30 ft (9.1 m) at the crosshole sites investigated S-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. Overall, there is an average increase in shear wave velocity of 28 percent in the upper 30 ft (9.1 m) of soils at all three crosshole sites. Due to relatively similar soil stratigraphy at crosshole Sites 2 and 3, there appears to be very good correlation of velocity layering, as well as percent difference from the pre- and post-compaction surveys. However, both Sites 2 and 3 are dissimilar from Site 1 where fine grained materials have an increase in shear wave velocity between 31 and 34 percent (Fig. 2 and 5).

CONCLUSIONS

Shear wave velocities obtained by the crosshole method prior to dynamic compaction of foundation soils range from 420 to 772 ft/s (128 to 235 m/s). Post-compaction survey results show an increase of the range in velocities obtained from 547 to 916 ft/s (167 to 279 m/s), respectively, for the same foundation materials. These data indicate an overall increase in pre- vs. post-compaction shear wave velocity measurements of approximately 28 percent for the upper 30 to 35 ft (9.1 to 10.7 m). Below that depth the change in velocity is less pronounced where the percent increase is consistently less than 20 percent to a depth of 47.5 ft (14.5 m). Due to a complex soil stratigraphy present at the damsite the absolute percent increase in velocity varies considerably with both depth and material type. However, the crosshole-seismic technique, which evaluates a relatively small volume of material at any depth, is well suited for evaluating these conditions and the resolution of the velocity profile is relatively straight forward. The quality of crosshole data obtained at Sector C was exceptional, for both pre- and post-compaction surveys, which results in a high degree of confidence in the shear wave velocities obtained.

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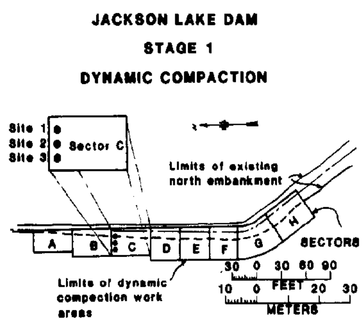

FIG. 1. Location map for crosshole test sites at Jackson Lake damsite, Wyoming.

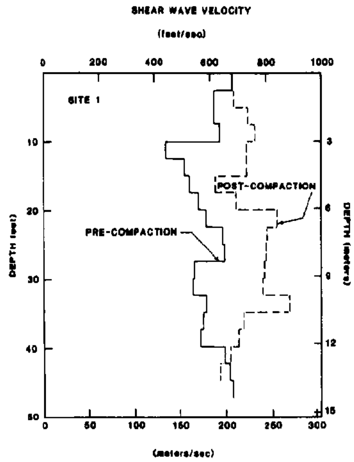

FIG. 2. Site 1 shear wave velocity profile.

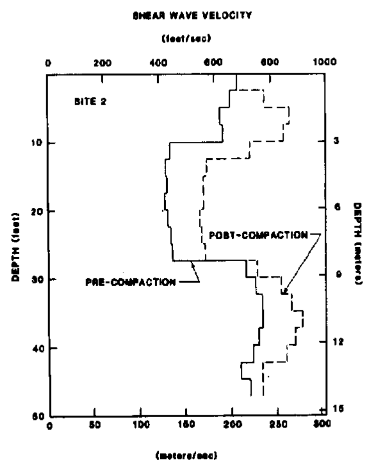

FIG. 3. Site 2 shear wave velocity profile.

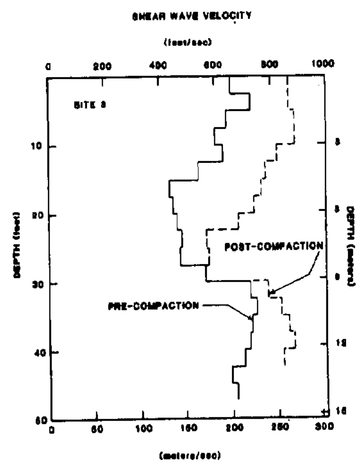

FIG. 4. Site 3 shear wave velocity profile.

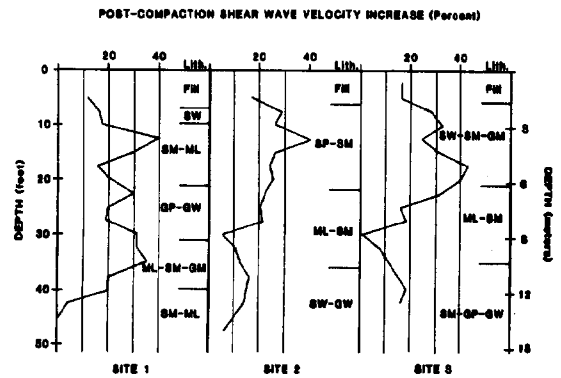

FIG. 5. Percent increase in shear wave velocities after dynamic compaction. Lithologies are presented in the Unified Soil Classification system.

Table 1. Precompaction and postcompaction shear wave velocities.

		S-WAVE VELOCITY ft/s (m/s)	
	Crosshole Triplet	Construction Fill	Soil Deposits
SITE 1			
Pre-	1 X 2 X 3	614-677 (187-206)	439-682 (134-208)
Post-	1A X 2A X 3A	683-760 (208-232)	619-885 (189-270)
SITE 2			
Pre-	4 X 5 X 6	619-681 (189-208)	420-772 (128-235)
Post-	4A X 5A X 6A	779-870 (237-265)	547-916 (166-279)
SITE 3			
Pre-	7 X 8 X 9	638-727 (194-222)	434-745 (132-227)
Post-	7A X 8A X 9A	864-886 (263-270)	563-882 (171-269)