US Army Corps of Engineers®
Engineer Research and Development Center

Wave-Speed-Based Performance Indicators for Portugues Dam

Ziyad H. Duron, Peter Orme, Spenser Anderson, Henry Diaz-Alvarez, Vincent P. Chiarito, and Mihan H. McKenna

October 2018

Wave-Speed-Based Performance Indicators for Portugues Dam

Henry Diaz-Alvarez, Vincent P. Chiarito, and Mihan H. McKenna

Geotechnical and Structural Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Ziyad H. Duron, Peter Orme and Spenser Anderson

Harvey Mudd College
260 E. Foothill Boulevard
Claremont, CA 91711

Final Report

Approved for public release; distribution is unlimited.

Abstract

Roller Compacted Concrete (RCC) construction techniques are used to raise existing dams and to build new dams. A particular and assumed advantage of the RCC technique is improved homogeneity in concrete condition throughout the dam. An opportunity to evaluate this on a large RCC dam was made available by the U.S. Army Corps of Engineers at Portugues Dam. Through the application of a relatively new testing technique, estimates of a wave-speed-based Performance Indicator (PI) of the dam were obtained. The PI relates wave speeds associated with shear wave propagation in the dam to compression wave speeds for healthy concrete. Values ranging from 1.7-2.2 for Portugues Dam compare favorably to a value of 1.6 for nominal concrete.

Contents

Figures and Tables

Figures

Tables

Preface

This study was conducted for the Office of the Assistant Secretary of the Army for Acquisition, Logistics, and Technology (AASALT) under Project "Remote Assessment of Critical Infrastructure."

The work was performed by the Structural Engineering Branch (GSS) of the Geosciences and Structures Division (GS), U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL). At the time of publication, Mr. Charles W. Ertle was Chief, CEERD-GSS; Mr. James Davis was Chief, CEERD-GS; and Ms. Pamela G. Kinnebrew, CEERD-GZT, was the Technical Director for Military Engineering. The Deputy Director of ERDC-GSL was Dr. William P. Grogan, and the Director was Mr. Bartley P. Durst.

COL Ivan P. Beckman was the Commander of ERDC, and Dr. David W. Pittman was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
atmosphere (standard)	101.325	kilopascals
bars	100	kilopascals
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
inches	0.0254	meters
yards	0.9144	meters

1   Motivation for Current Effort

Performance Based Testing (PBT) of large civil structures has the potential to provide information relevant to the evaluation of a structure's response to hazardous loading conditions. Originally developed during the field investigation of large cable suspension bridges in Maine and in Ohio, the technique has been adapted to large concrete dams and has been demonstrated on both healthy and damaged structures. A distinguishing characteristic of PBT is the use of an excitation source that delivers a large-amplitude, broad-frequency band impulse that induces transient response behavior. The transient nature of the induced responses contains fundamental behavior that can be used for validating numerical models, evaluating structural condition, and predicting response levels in the structure under a wide range of loading conditions.

Portugues Dam is a thick-arch, roller compacted concrete (RCC) dam built in Puerto Rico by the U.S. Army Corps of Engineers and is one of only about 10 such dams in the world. The dam is 220 ft tall and 1230 ft long and has an ogee spillway 140 ft long. Base and crest thicknesses are 111 ft and 30 ft, respectively; and more than 355,000 cubic yards of concrete was used in its construction. The dam was designed as a three-dimensional structure with closed contraction joints and underwent an extensive RCC design and testing program. The tensile strength of the horizontal lift joints plays an important role in the dam's ability to perform under seismic loading, which leads to the focus of the current study.

Dams built by using RCC are assumed to exhibit improved homogeneity over dams built by using traditional block pours, and a measure of the degree of homogeneity present in a dam is wave speed.

This report provides an overview of the PBT performed on Portugues Dam and illustrates the transient behavior across the crest and along one of the monolith blocks. It includes samples of measured responses in the dam, along with results from a Shock Response Spectrum (SRS) analysis that was used to highlight resonances and response shapes in the dam. The report also describes a wave-speed-based Performance Indicator (PI) that can be used to evaluate existing and changing concrete conditions in the dam.

2 Performance-Based Testing of Portugues Dam – Responses and Fundamental Behavior

Portugues Dam is located on the Portugues River three miles northwest of the city of Ponce in Puerto Rico. The dam was completed in early 2014 and provides flood control for a region of more than 40,000 inhabitants and over 13,000 residential structures. Figure 1 is a photograph of the dam at the time of testing during the summer of 2013.

Figure 1. Portugues Dam; photograph taken August 2013 at the conclusion of PBT and prior to completion of the ogee spillway.
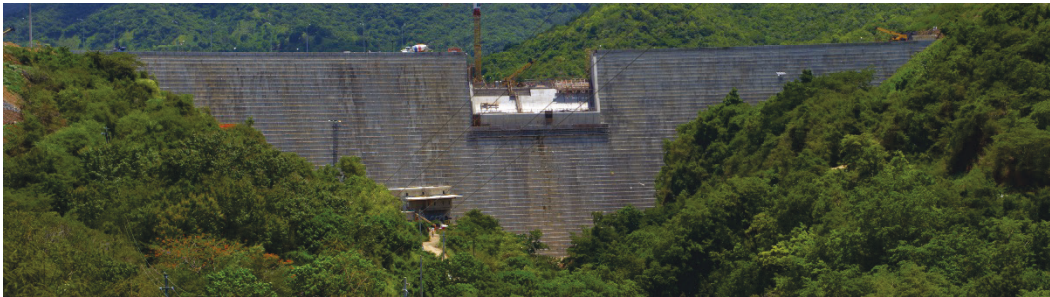
The development of the PBT technique is described in Duron et al. (2013) and its adaptation to a large, concrete multiple-arch dam is described in Goldkamp et al. (2014) and Edelman et al. (2014). Found in the references are specifics regarding instrumentation, particularly those associated with the excitation device that is referred to as a Cold Gas Thruster (CGT); motion sensors; and acquisition systems and parameters. Primary testing at Portugues Dam was conducted using one CGT, but a second CGT was used to investigate potential advantages of multiple (two) devices. A photograph of the CGTs mounted on the crest of the dam is shown in Figure 2.

A typical force pulse delivered to the dam from the CGT is shown in Figure 3.

Peak force levels ranged between 6,000 and 8,000 lb, and repeatability in terms of the pulse width (10 msec) and dissipation was very good for the tests at Portugues Dam. Additional CGT instrumentation included a shock accelerometer that monitored the acceleration induced in the dam at the CGT attachment location; a typical response is shown in Figure 4.

Figure 2. Cold Gas Thrusters mounted onto Portugues Dam.

Figure 3. Typical force pulse delivered by the CGT to the dam.
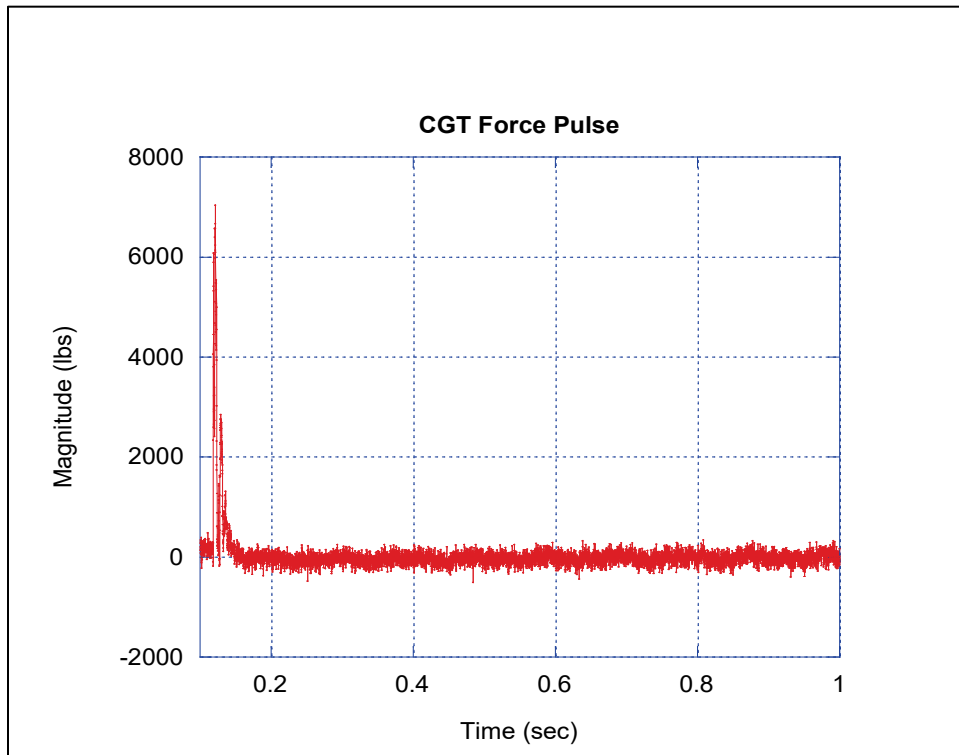
Figure 4. Induced acceleration response at CGT attachment location.
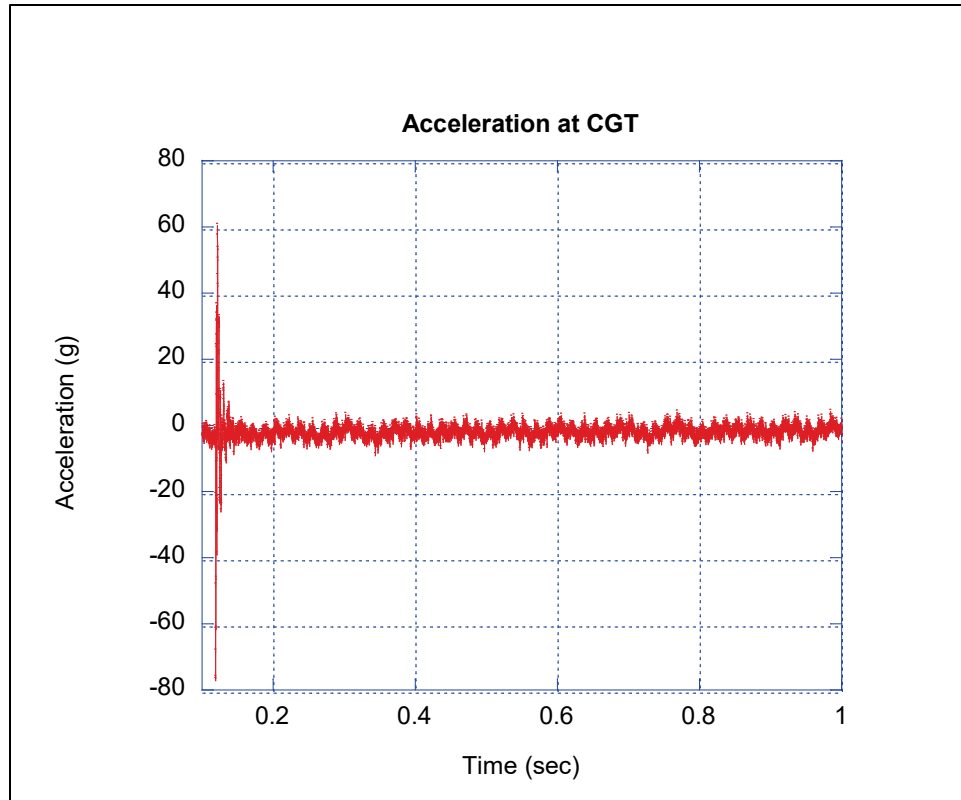
Peak acceleration levels approach 80 g's and are associated with the acceleration of the CGT at load delivery. These levels have been observed in previous PBTs of dams, and the ratio of the peak force and the peak acceleration levels in the measured responses correspond to the mass (or weight) of the CGT itself (approximately 150 lb as configured at Portugues Dam). As a result and based on previous experience with the testing technique and instrumentation, the acceleration levels and overall character of the shock acceleration response are consistent with expected behavior and are indicative of satisfactory CGT performance.

Figure 5 shows the measurement layout used during PBT at the dam, which was designed to capture responses along the crest and along the height of one monolith.

Figure 5. Measurement layout.
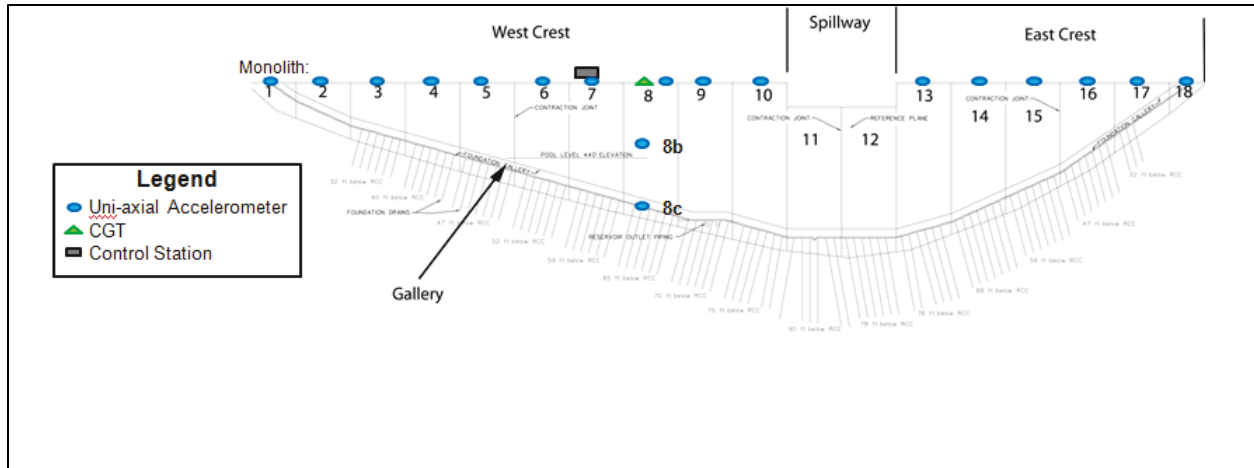
Accelerometers were oriented radially along the crest in the stream direction, and the CGT remained anchored to the crest at monolith No. 8 throughout the test. Sample responses on each side of the spillway are shown in Figure 6.

Figure 6. Sample acceleration responses to CGT force pulse.
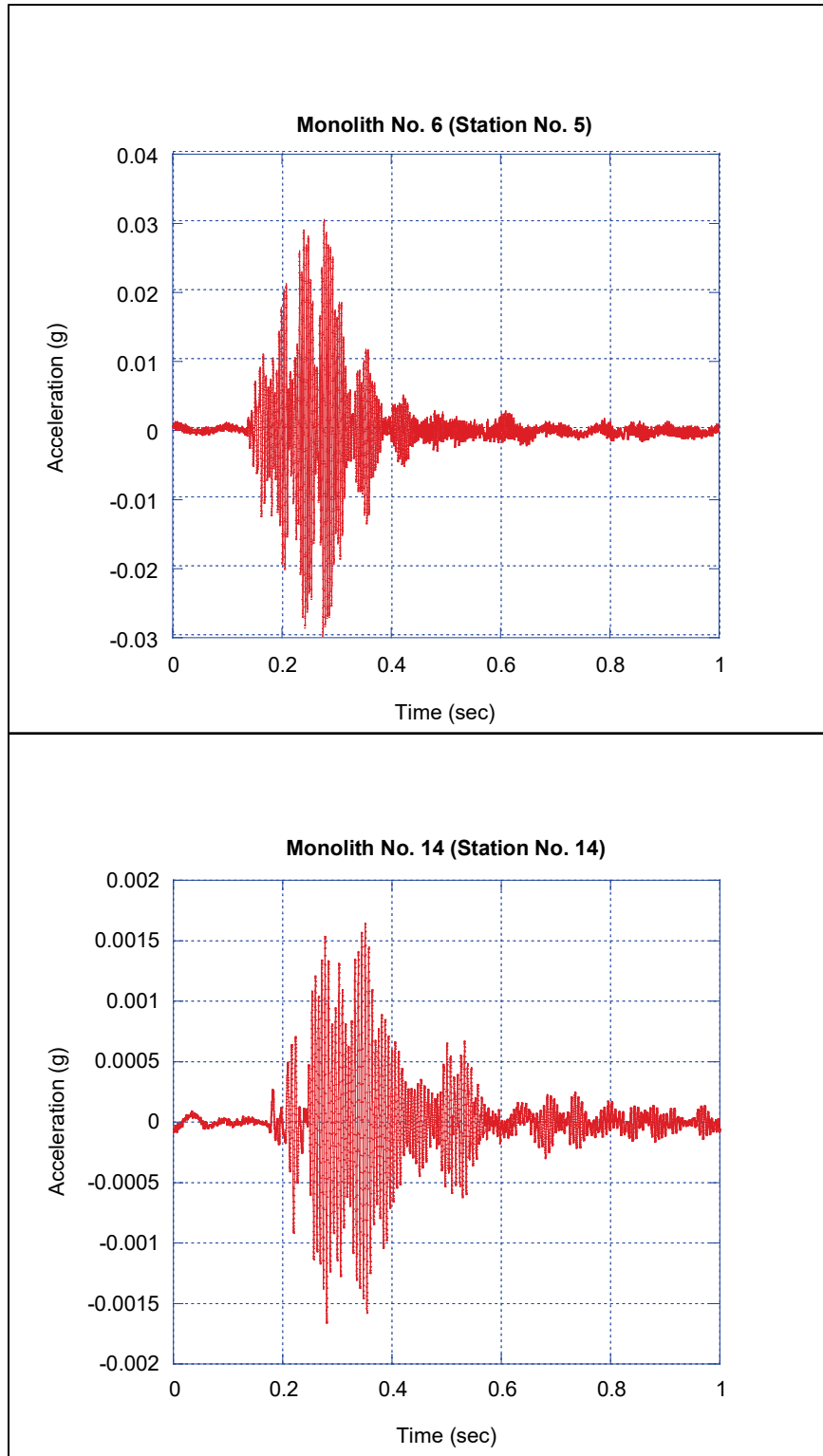
The transient characteristics indicated in these responses are consistent with previous PBTs of dams and illustrate the broad frequency content induced by the CGT. The overall nature of these responses is also consistent with that expected during seismic loading, which highlights a significant advantage of PBT over traditional testing techniques.

PBT is capable of delivering to the dam large-amplitude, short-duration loads, which generate responses that can be considered as impulse responses. These impulse responses, by definition, contain fundamental characteristics of the dam, such as resonant frequencies, that are indications of energy dissipation and relative response levels, which can be used for a variety of applications including model validation, development of performance indicators for assessing and evaluating structural condition, and prediction of response levels to hazardous loadings without the use of a numerical model. All of these applications have been conducted and reported in Duron et al. (2013).

Although the quality of the transient responses captured during PBT at Portugues Dam is considered very high, transients do not normally lend themselves to traditional analysis techniques, such as Fourier techniques. Fortunately, aerospace engineering applications to rocket flight analysis, as well as blast response behavior analysis of structures, have developed tools that can be adapted for evaluating PBT responses on large civil structures. One analysis technique that has been useful in extracting relevant behavior characteristics from the PBT responses is the Shock Response Spectrum (SRS) technique described in Duron et al. (2013).

The SRS analysis technique was used to confirm resonances in the dam and to develop an estimate of the response shape associated with the fundamental resonance. Sample SRS responses for monoliths 6 and 14 are shown in Figure 7.

Figure 7. Sample shock response spectra associated with PBT responses at
monoliths 6 and 14.
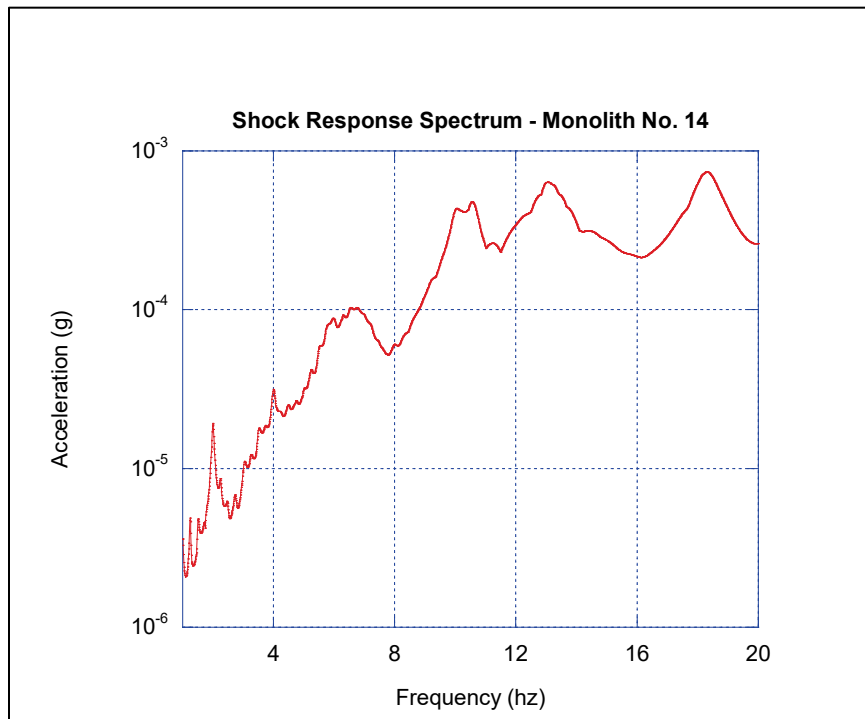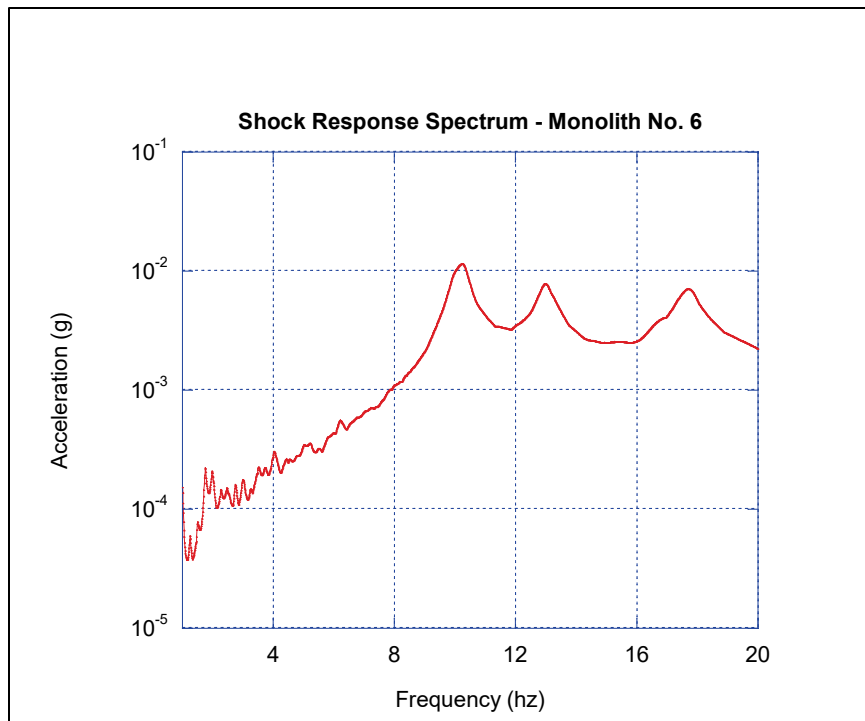
Resonances identified from PBT responses are listed in Table 1.

Table 1. Resonances identified from PBT at Portugues Dam.

Resonance No.	Frequency (Hz)
1	4.8
2	6.6
3	10.2
4	13
5	17.8
6	20.4

These values were confirmed after a review of both power spectral density (PSD) and SRS estimates for each measurement.

A simplified analysis procedure was developed based on SRS responses to obtain an estimate for the response shape associated with the fundamental resonance at 4.8 Hz. The approach takes advantage of the fact that the unique aspect of any response shape lies in the relative amplitudes across the structure and not in the absolute magnitudes of the response. As a result, ratios of SRS response levels can be used to arrive at a response shape defined by relative magnitudes based on a reference location in the dam. Using the SRS response at monolith No. 8 as the reference, an estimate for the response shape at 4.8 Hz was determined, as shown in Figure 8.

Figure 8. Response shape at 4.8 Hz; modal amplitude is normalized to 1 as indicated.

Right Abutment   Left Abutment
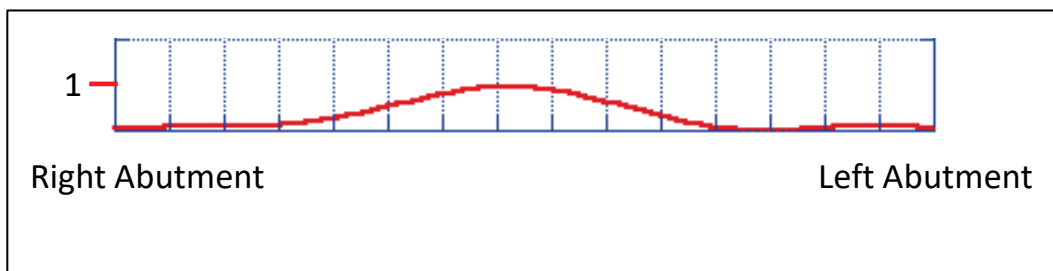
Since the ogee spillway was still under construction during PBT at Portugues Dam, no responses were acquired between monoliths 10 and 13. Nonetheless, the response shape is consistent with expected behavior and illustrates the ability of PBT to extract eigen properties of the dam in a manner consistent with traditional techniques, including the Fourier analysis of forced vibrations in a dam.

3   Wave-Speed-Based Performance Indicators

3.1   Wave-Speed

Wave propagation is the basis for a range of non-destructive evaluation (NDE) techniques that are aimed at uncovering weak or deteriorating concrete in structures. Olson and Sack (2007) describes the application of stress-wave-based methods for evaluating the in-place condition of concrete by using impact echo and spectral analysis of surface waves techniques. In each case, the ability to induce wave propagation and to measure velocities of propagation through the concrete are critical to the overall effectiveness of these or any wave-based NDE technique.

Estimates of wave speed can be used to define a PI that provides baseline and subsequent measures of concrete condition. PBT at Portugues Dam offers a unique opportunity to develop early in its service life indicators for the dam that can be available for future evaluations and condition assessments. Particularly in the aftermath of a significant seismic event, the ability of PBT to produce PIs for assessing and evaluating relative changes in the dam can be an important contribution to decisions regarding continued and safe operations after a hazard event.

To illustrate the ability of PBT to excite wave propagation in the dam, a timing comparison within monolith No. 8 is shown in Figure 9.

Figure 9. Wave propagation in monolith No. 8.
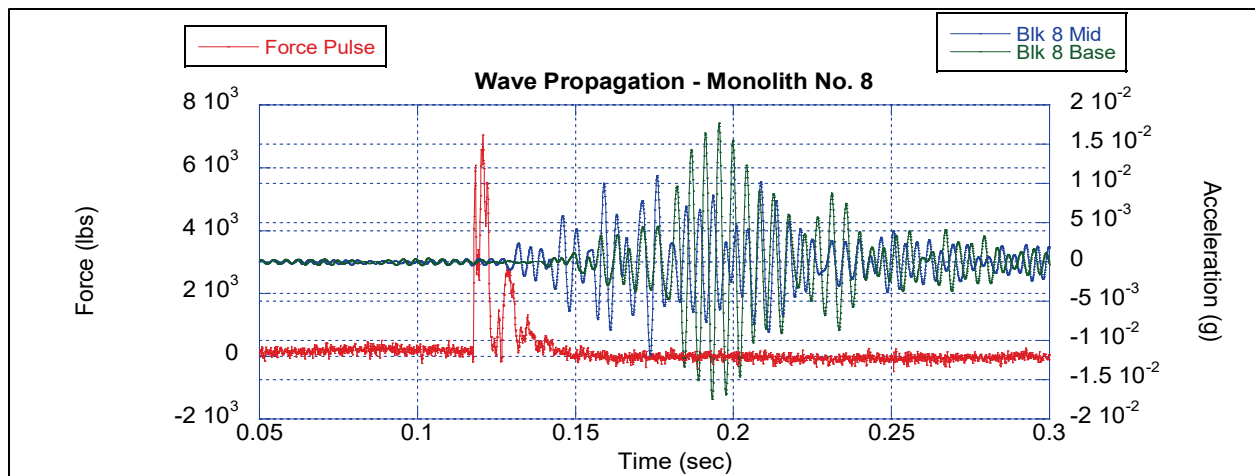
The key to developing wave speed estimates in the dam is identifying accurate and reliable wave arrival times at each measurement location either along the crest or along a single monolith. At Portugues Dam, wave speed estimates were obtained along the crest and in monolith No. 8 by using the measurement layouts shown in Figure 10.

Figure 10. Measurement layouts for determining wave speed estimates along the crest (top) and in monolith No. 8 (bottom) at Portugues Dam; locations 8b and 8c correspond to the mid-height and the base of the monolith, respectively.
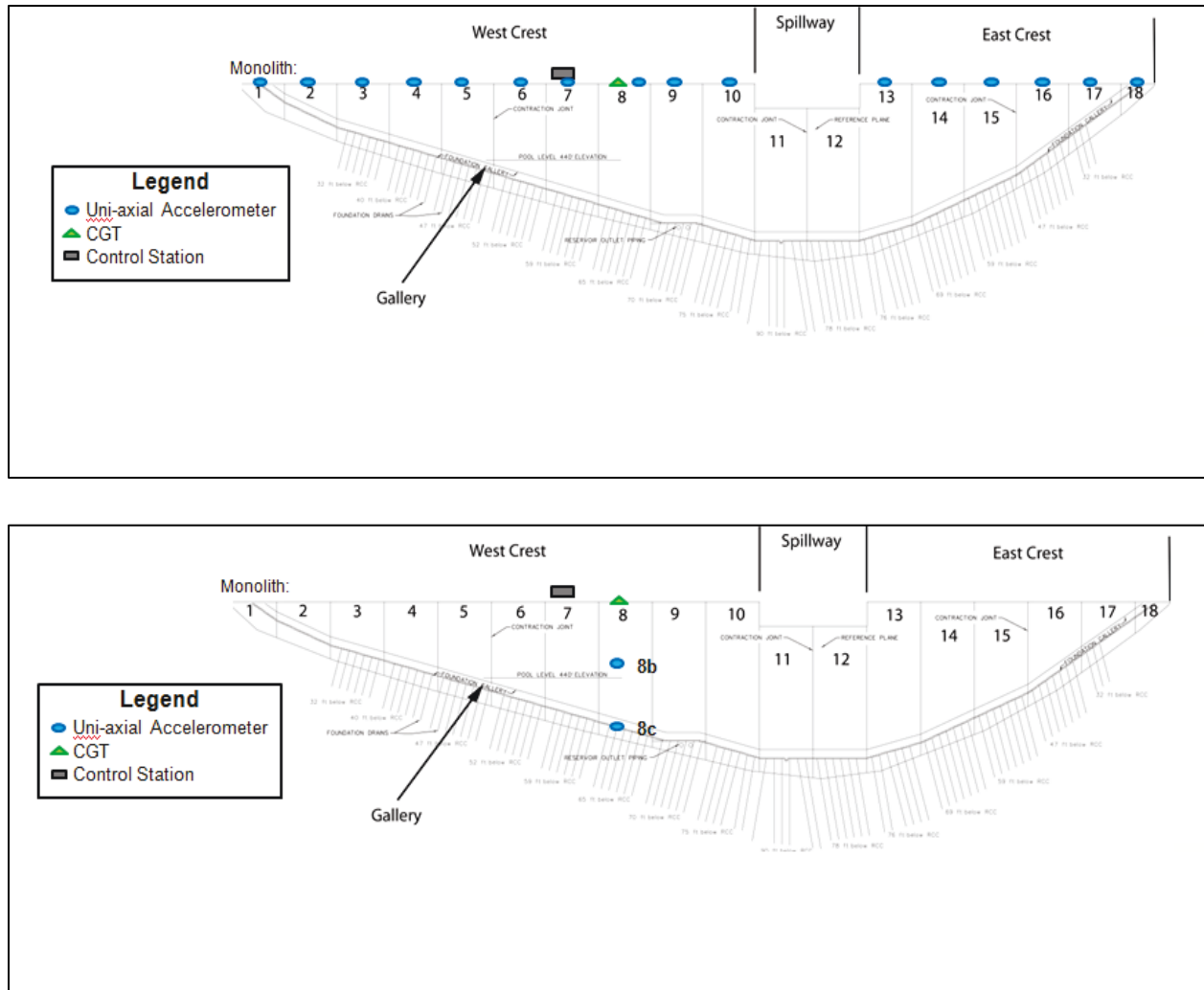
Estimates of wave speed along the west crest and in monolith No. 8 are included in Table 2.

Table 2. Wave speed estimates along the west portion of the crest (top table) and within monolith No. 8 (bottom table). The estimates within monolith No. 8 were obtained from a series of tests that captured responses at the midpoint and the base of the monolith.

Propagation Distance (ft)	Wave Speed Estimate (ft/sec)
52	5870
84	5899
122	5951
182	6431
256	5531
323	5127
390	5394

Propagation Path (ft)	Wave Speed Estimate (ft/sec)
Crest to midpoint (92)	6943
Crest to base (168)	6720
Midpoint to base (76)	6468
Crest to base (168)	6788
Crest to midpoint (92)	6917
Crest to base (168)	6640
Midpoint to base (76)	6333
Crest to midpoint (92)	6970
Crest to base (168)	6720
Midpoint to bas (76)	6440

Wave speed mean and standard deviation values along the crest and within monolith No. 8 are listed in Table 3.

Table 3. Wave speed comparison along crest and within monolith No. 8.

Location	Mean	Standard Deviation
Crest	5828 ft/ sec	429 ft/ sec
Monolith No. 8	6994 ft/ sec	223 ft/ sec

The relatively small statistical variability in these results suggests that a measurable difference exists between the wave speeds along the crest and those within monolith No. 8. Two contributing factors include the presence of contraction joints that the propagating wave must cross as it travels from the point of origin (CGT located on monolith No. 8) along the crest and the absence of these joints in the path traveled by the wave

within monolith No. 8. It is also unclear what effect, if any, is contributed by the reinforced concrete decking (which is actually the crest) over the RCC dam. Differences in wave propagation paths notwithstanding, wave speeds appear to range between 5,828-6,694 ft/sec (1.8-2.04 km/sec).

Hussein and Morgano (1993) describes results from a series of concrete pile tests in which compression waves were introduced with corresponding wave speeds ranging between 9,843-1,4764 ft/sec (3-4.5 km/sec). The tests at Portugues Dam did not introduce compression waves in the concrete due to the orientation of the CGT that delivered its load in shear (thereby producing shear waves) however, the ratio between compression and shear wave speeds for healthy concrete can be used to define a PI for the concrete in the dam.

A wave-speed-based PI can be defined as

$$\frac{Compression\ Wave\ Speed\ \left(\propto \sqrt{E}, Young's\ Mod\right)}{Shear\ Wave\ Speed\ \left(\propto \sqrt{G}, Shear\ Mod\right)} = \sqrt{2(1+\nu)}$$

which for healthy concrete and a nominal Poisson's ratio of 0.2 approaches a value of 1.6.

Assuming the range for compression wave speeds in healthy concrete indicated in Hussein and Morgano (1993) is applicable to the concrete in Portugues Dam, an initial estimated range for the wave-speed-based PI of 1.7-2.2 is obtained.

3.2   Performance Indicator meaning and interpretation

Consider the case of a nominal dam constructed as a perfectly homogeneous monolithic structure. The structure contains no contraction or horizontal lift joints and is immune to crack formation. For this nominal dam, estimates of wave speeds through the concrete can be expected to remain constant throughout its service life with a corresponding PI at or very near to a value of 1.6 (assuming nominal concrete material properties). In this case, the PI value is completely dependent on the material properties of the concrete, since no joints or imperfections are present. Even though in reality the PI is influenced by the combined effects of the concrete's material properties and the condition of the joints in the dam, the nominal case can act as a baseline measurement.

The range of the PI reported for Portugues Dam may be interpreted as follows.

The lower bound of 1.7 is associated with wave propagation across the contraction joints along the crest and, when compared to 1.6, suggests that the combined effects of the material properties and contraction joints mimic those of the nominal dam. In other words, the material properties and joint conditions along the crest are nominal in the sense that the concrete's material properties are likely close to those of nominal concrete, and the contraction joints are sufficiently close to facilitate nominal wave propagation along the crest. On the other hand, the upper bound of 2.2 that corresponds to wave propagation across the horizontal lift joints in a single monolith of Portugues Dam exceeds the baseline by 37.5%, which may be interpreted as follows.

The higher valued PI (2.2 versus the nominal value of 1.6) suggests that, while the compression wave speeds may be at or close to nominal, the shear wave speeds may be less, thus contributing to the larger value. If this interpretation is correct, it may suggest that the horizontal lift joints in the RCC dam contribute to slower propagation speeds in shear. Since the PI depends on the combined effects of the joint and concrete conditions, it cannot be used to separate the effects of presumed changes in joint or concrete conditions on the indicator values. Nonetheless, the lower and upper values of the PI can serve as baseline values for Portugues Dam.

From the perspective of a PI, subsequent or periodic testing that produces variations from known baseline values can contribute to informed inspection and maintenance strategies for the dam. Furthermore, and where appropriate, the indicator may also be used to evaluate numerical model representations of the dam.

4   Summary and Observations

The PBTs conducted on Portugues Dam represent the first of its kind to be conducted on a large RCC dam. A CGT mounted to the crest of the dam delivered impulse loads that induced large-amplitude, broad-frequency-band transient behavior throughout the structure. The type and quality of the measured PBT responses were consistent with previous experiences on other large concrete dams. Subsequent analyses of the measured behavior produced estimates of resonant frequencies and response shapes and facilitated a wave-speed-based PI for assessing and evaluating the condition of the concrete in the dam.

A nominal, homogeneous, monolithic dam provides a basis for evaluating conditions in an actual dam based on wave propagation characteristics observed during PBT. For the nominal dam, the ratio of compression wave to shear wave speeds in concrete is at or very near 1.6 for nominal material properties. This ratio defines a PI that can be measured for any dam and subsequently monitored through periodic PBT. At Portugues Dam, the corresponding wave-speed PI ranged from 1.7 (for propagation across contraction joints) to 2.2 (for propagation across horizontal lift joints). This range can be used as a baseline to evaluate suspected changes in condition after significant hazardous loading events over the life of the dam.

Additional testing on concrete dams is recommended to gain more insight into this PI and its sensitivity to changes in concrete and joint conditions.

References

Duron, Z. H., J. Edelman, M. Goldkamp, P. Orme, and T. Savage. 2013. Performance based testing of large concrete dams. *Journal of Dams Safety* 11(3):9-12.

Edelman, B. J., P. J. Orme, R. M. Goldkamp, T. Savage, and Z. H. Duron. 2014. *Performance based analysis of a large concrete dam.* USSD Annual Meeting and Conference Dams and Extreme Events. San Francisco, CA.

Goldkamp, R. M., T. Savage, B. J. Edelman, P. J. Orme, and Z. H. Duron. 2014. *Performance based testing of a large concrete dam.* 34th USSD Annual Meeting and Conference Dams and Extreme Events. San Francisco, CA.

Hussein, M., and M. Morgano. 1993. *Structural integrity evaluation of concrete piles from stress wave measurements.* The Society for Experimental Mechanics Conference on Nondestructive Testing of Concrete in the Infrastructure. Dearborn, MI.

Olson, L. D., and D. A. Sack. 2007. Nondestructive evaluation of concrete dams and other structures. In *Proceedings of the SPIE*, Volume 2457:113-124. Bellingham, WA: International Society for Optics and Photonics.

REPORT DOCUMENTATION PAGE		*Form Approved* *OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE *(DD-MM-YYYY)* October 2018	2. REPORT TYPE Final	3. DATES COVERED *(From - To)*
4. TITLE AND SUBTITLE Wave-Speed-Based Performance Indicators for Portugues Dam		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Ziyad H. Duron, Peter Orme, Spenser Anderson, Henry Diaz-Alvarez, Vincent P. Chiarito, and Mihan H. McKenna		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER 33143
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Geotechnical and Structures Laboratory U.S. Army Engineer Research and Development Center 3909 Halls Ferry Road Vicksburg, MS 39180-6199		8. PERFORMING ORGANIZATION REPORT NUMBER ERDC/GSL TR-18-28
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Corps of Engineers Washington, DC 20314-1000		10. SPONSOR/MONITOR'S ACRONYM(S) USACE
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Roller Compacted Concrete (RCC) construction techniques are used to raise existing dams and to build new dams. A particular and assumed advantage of the RCC technique is improved homogeneity in concrete condition throughout the dam. An opportunity to evaluate this on a large RCC dam was made available by the U.S. Army Corps of Engineers at Portugues Dam. Through the application of a relatively new testing technique, estimates of a wave-speed-based Performance Indicator (PI) of the dam were obtained. The PI relates wave speeds associated with shear wave propagation in the dam to compression wave speeds for healthy concrete. Values ranging from 1.7-2.2 for Portugues Dam compare favorably to a value of 1.6 for nominal concrete. .

15. SUBJECT TERMS		
Infrasounds Model analysis Dams – Puerto Rico – design and construction	Natural frequencies Dam vibrations CGT Concrete dams Roller compacted concrete – Testing	PBT Portugues Dam RCC Wave propagation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified		25	19b. TELEPHONE NUMBER *(include area code)*