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Evaluation of a low-cost instrument for ambient vibration testing of concrete gravity dams

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ABSTRACT

Short-term deployments of a low-cost triaxial velocimeter were conducted to assess its suitability for ambient vibration testing and operational modal analysis of a large concrete gravity dam. Prior to field deployment, the velocimeter was collocated with industry-standard instruments in a controlled setting to facilitate verification of the recordings. The velocity time series were compared, and the low-cost instrument recordings exhibit significant differences compared with those recorded by the industry-standard instrument. Spectra were also compared in the frequency domain and the low-cost velocimeter was found to accurately record the dominant frequency content; however, these spectra are limited to frequencies below 50 Hz due to the low sampling rate of the velocimeter. The velocimeter was then deployed as a standalone instrument at a large concrete gravity dam for approximately 20 minutes of data acquisition at two locations: (i) a public pathway above the dam crest and (ii) at a free field approximately 100 m downstream of the dam. Estimates of resonant frequencies were made based on observed spectral shapes; however, confidence in these estimates was compromised by significant low-frequency drift, poor time synchronization between channels, and the possible presence of machinery excitation. Although the low-cost velocimeter may be suitable for certain applications, several important limitations are identified, which include: (i) apparent lack of reliable time synchronization, (ii) limited user interface which increases the likelihood of user error, (iii) reliance on an external power source which complicates field deployment, (iv) low sampling rate, and (v) greater susceptibility to instrument malfunction.

Keywords: *Raspberry Shake; Ambient Vibration Testing; Concrete Gravity Dam; Instrumentation*

1. INTRODUCTION

Major seismic upgrades of dams are becoming more common due to an improved understanding of seismic hazard and an aging inventory. Such projects target improvements to the seismic performance of dams and often include finite-element models to evaluate dynamic structural response to earthquake ground motions. Earthquake-induced structural demands in these models are sensitive to their dynamic properties; therefore, it is important to validate the behavior of these models with real-world data. Such validation is readily accomplished via examination of vibration data recorded from across the dam [1]; however, such testing programs typically require the deployment of multiple high-precision instruments with high associated instrumentation costs [2]. In recent years, low-cost velocimeters have become widely available; this study examines the performance of one such instrument, the Raspberry Shake (RS).

This study consists of a verification in a controlled environment and field deployment at a large dam. First, the RS was deployed with two collocated industry-standard instruments—Sensequake Larze vibration monitors—to benchmark the performance of the RS. In the second stage of the study, the RS was deployed as a stand-alone instrument at two locations on publicly accessible portions of a large concrete gravity dam. The objective of the data collection from this deployment was to estimate the resonant frequencies in the instream direction of the dam monolith and thereby assess the suitability of the RS for this task.

2. BACKGROUND

2.1. Low-cost instrument: Raspberry Shake 3D

There are several different models of RS instruments available; this study used a single RS-3D—which can record triaxial vibrations and is the RS model best suited for low-amplitude ambient noise environments. The RS contains three orthogonal velocity sensors, a digitizer, and an onboard computer (Raspberry Pi 3, Model B) integrated into a single 140 mm x 135 mm x 60 mm enclosure with a total weight of 0.6 kg. The RS has a bandwidth of -3 dB from 0.7–39 Hz, sensitivity of 3.60E+08 counts/m/s and clip level of approximately 8 388 608 counts (24-bit). The instrument has a minimum detection threshold of 0.03 μm/s root mean square from 1–20 Hz [3]. One main limitation of the RS is that it can only record at a sampling frequency of 100 Hz; therefore, the highest frequency signal which can be recorded, i.e., the Nyquist frequency, is 50 Hz. The RS was deployed with a GPS antenna because this was anticipated to provide the best synchronization between channels and the lowest time drift [3].

2.2. Industry-standard instrument: Sensequake Larze

Sensequake Larze vibration monitors were used as reference industry-standard instruments. The Larze vibration monitors have two types of internal vibration sensors: a triaxial velocimeter with a range of ±120 mm/s and bandwidth of 3 dB up to 1500 Hz—depending on the sampling frequency—and a triaxial accelerometer with a 3 dB bandwidth up to 1000 Hz [4]. Data is recorded on six channels: three velocity channels and three acceleration channels.

Together, the velocimeters and accelerometers can facilitate accurate vibration acquisition across a broad spectrum of frequencies and a range of vibration amplitudes. Both sensors have low levels of self-noise with the accelerometers estimated to have 20 $\mu g/Hz^{1/2}$ and the velocimeters estimated to have 10-2 $\mu g/Hz^{1/2}$ from 1 to 20 Hz [4]. Nominal sampling frequencies of 400 Hz were used in this study. While data was recorded using both the accelerometers and velocimeters, only the velocity data is presented herein because the velocimeters perform better than the accelerometers in ambient noise environments, i.e., not strong earthquake ground motion, and because the velocity data provides the most direct comparison with the RS, which only records velocities.

2.3. Applications by others

2.3.1. Seismic instrumentation and structural health monitoring

The RS is a low-cost triaxial velocity sensor based around the Raspberry Pi processor. Because of its relatively low cost, the RS has been deployed to a wide variety of projects from seismology to structural health monitoring. For embankment dams, RS instruments have been used to develop frameworks for structural health monitoring and detection of internal erosion in a laboratory setting [5]. Others have used the RS-4D, which is best suited for recording earthquake ground motion, for the purpose of seismic network densification and have found that although the RS-4D has relatively high levels of self-noise, it is suitable for densifying networks designed for studies of strong ground motions, e.g., from large earthquakes with small rupture distances [6].

2.3.2. Operational modal analysis of rock formations

Comparisons between the Raspberry Shake (RS) and an industry-leading broadband seismometer (Trillium Compact 20s) for identifying resonant frequencies of natural rock arches in Utah showed that the RS exhibited several limitations, including inconvenient deployment, a larger footprint, and higher self-noise levels. Despite these drawbacks, the RS provided natural frequency estimates that closely matched those obtained from the higher-end instrument [2].

2.4. Novelty of application to dams

Although the RS has been deployed for a variety of scientific applications, to the author's knowledge, no previous studies have attempted to estimate the dynamic properties of a large concrete gravity dam using the RS. The dynamic response of concrete dams presents several unique challenges compared with structural health monitoring of buildings, bridges, and other structures due to their low-amplitude vibrations, high resonant frequencies, and significant environmental noise from spillway release and hydropower generation.

3. METHODS

3.1. Deployments

This study consists of verification tests and a field deployment. First, the RS was deployed with two collocated industry-standard instruments (Sensequake Larze vibration monitors) for four hours of data acquisition in a high-noise environment. Then the RS and Sensequake were tested in a low-noise environment with transient impulses applied. In the second stage of the study, the RS was deployed as a stand-alone instrument at two locations on publicly accessible portions of a large concrete gravity dam.

3.2. Field setup procedure

At each location, data collection with the RS velocimeter proceeded as follows:

1. The portable power supply was turned on and connected to the field laptop which was then powered on;
2. The RS was connected to the laptop via ethernet cable;
3. The RS GPS antenna was connected to the RS;
4. The RS was levelled using three levelling pins and a built-in bubble level and recording channels were oriented to be orthogonal to the axis of the dam (crossvalley; instream; and vertical);
5. All wires were cleared from the perimeter of the RS and a testing area was delineated around the RS;
6. The RS was plugged into the portable power supply; and
7. Data was collected during ambient operating conditions on all three recording channels.

3.3. Data pre-processing

Following the deployment, the velocity data from the devices was accessed via micro-USB. For the RS, the data was converted from units of counts to m/s. A linear detrend was applied to all time series (all three directions and both instruments).

4. VERIFICATION WITH COLLOCATED INDUSTRY-STANDARD INSTRUMENTS

4.1. Deployment description

In the first deployment, which was intended to verify the accuracy of the RS recordings, the RS was deployed with collocated Larze vibration monitors in a controlled setting. Two tests were conducted: (i) 4-hour duration in a high-noise environment with 2 collocated Larze instruments recording at 400 Hz and (ii) 5-minute durations in a low-noise environment with 1 collocated Larze instrument recording at 100 Hz and 1200 Hz. All instruments were oriented in the same direction and were emplaced within approximately 0.5 m of each other.

4.2. High-noise vibration environment analysis and observations

Velocity time series data for the high-noise test is shown in Figure 1. Several features were noted in the time series, first, there is strong agreement in the timing of wave train arrivals between the two Larze instruments; however, some differences in the amplitudes of transient events (spikes) are apparent between Larze instruments.

The timing data reported by the RS was insufficient to synchronize the recordings with the Larze instruments in the time domain. The RS time series were visually examined with various frequency filters applied; however, the resemblance to the Larze recordings was too poor to determine manual time offsets to align the waveforms from the RS with those from the Larze instruments. Efforts to align the recordings in the time domain were made more challenging because the large amplitude transient events recorded by the Larze instruments are not apparent in the RS recordings.

Other irregularities are present in the RS recordings. These include a low-frequency oscillation of the RS recording which does not appear in the Larze recordings. In addition, examination of the number of samples recorded in each direction (instream, crossvalley, and vertical), indicate that each channel of the RS recorded different numbers of samples. Channel differences of approximately 1 sample per minute were observed in these and other experimental deployments.

The recordings were also compared in the frequency domain with Fourier amplitude spectra computed via fast Fourier transformations (FFT), as shown in Figure 3, and power spectral densities estimated via the maximum entropy method (MEM), as shown in Figure 4 [7]. The results indicate that there is strong agreement between all three devices, with nearly identical Fourier amplitudes between 1–45 Hz. At higher frequencies, the RS has significantly lower Fourier amplitudes and exhibits roll-off of the amplitudes up to the Nyquist frequency which occurs at 50 Hz. Conversely, at lower frequencies, the RS has larger Fourier amplitudes than the Larze instruments; these correspond to the low-frequency oscillations observed in the RS time series. MEM-based power spectral densities were computed and indicate that all three instruments recorded vibration data with similar distributions of power within frequencies which are important for the dynamic response of concrete dams to earthquakes, approximately 2–40 Hz.

4.3. Low-noise vibration environment analysis and observations

A second test was conducted in a low-noise environment using the RS and a single collocated Larze instrument. Recordings were made for 5 minutes with manual excitation delivered via small impact hammer on the supporting surface. The Larze instrument sampled at both 100 Hz and 1200 Hz. For both sampling frequencies, the transient events induced by the impact hammer exhibit different arrival times and amplitudes between the Larze and RS instruments, as shown in Figure 2.

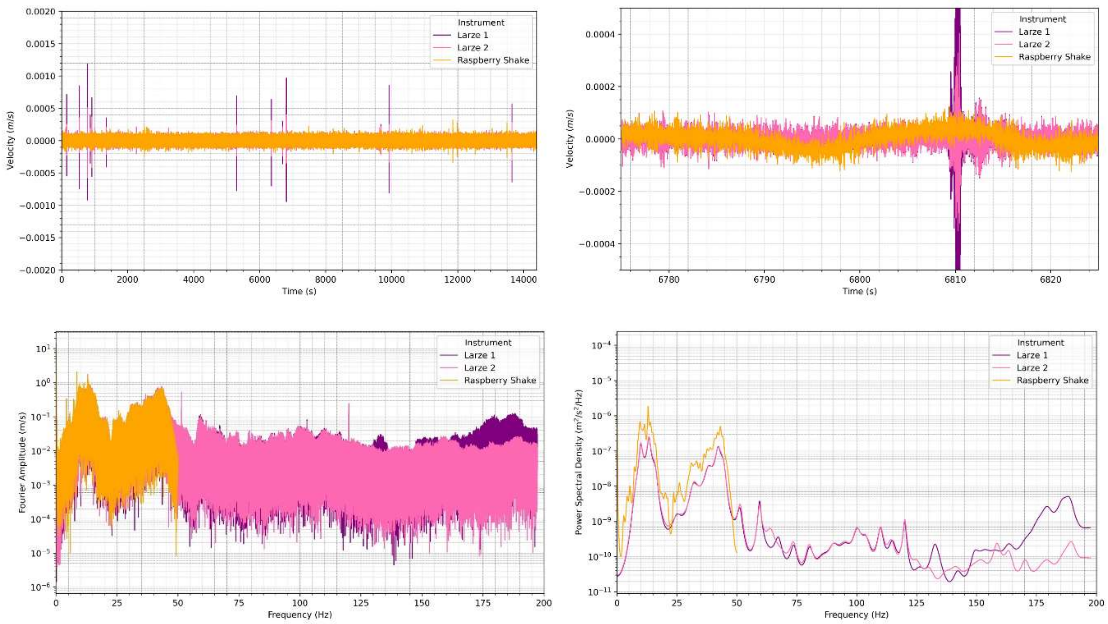

Figure 1. High-noise environment vibration data recorded by the Larze and Raspberry Shake instruments from a collocated deployment with the Larze instruments recording at 400 Hz. Top left: velocity time series; top right: velocity time series during transient impulse; bottom left: FFT; bottom right: MEM-based PSD.

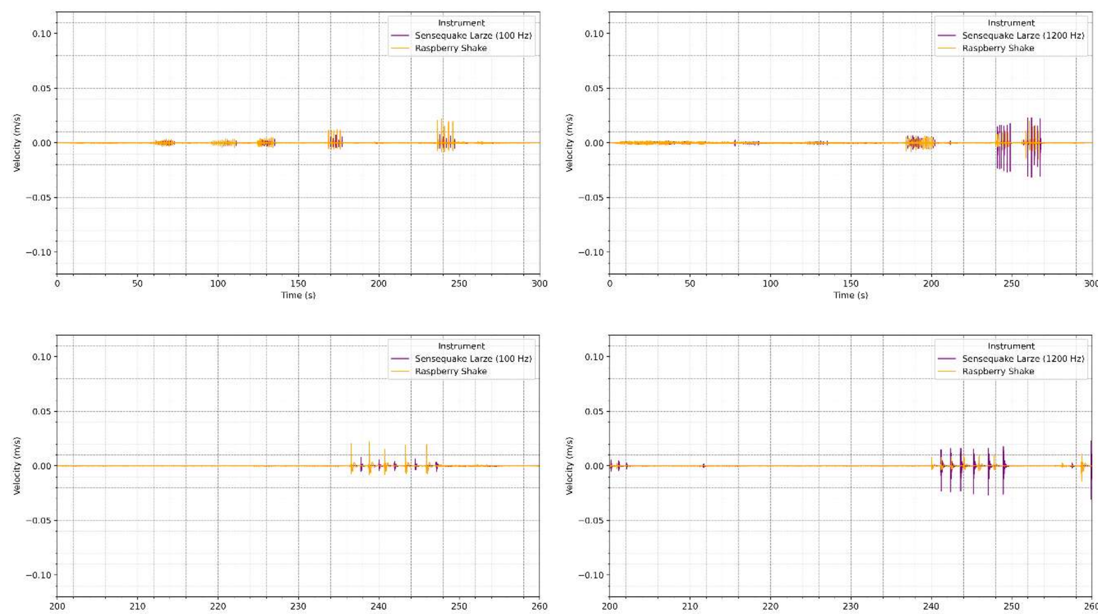

Figure 2. Low-noise environment vibration data recorded by the Larze and Raspberry Shake instruments from a collocated deployment. Top left: full recording with Larze sampling at 100 Hz; top right: full recording with Larze sampling at 1200 Hz; bottom left: transient segment of recording with Larze sampling at 100 Hz; bottom right: transient segment of recording with Larze sampling at 1200 Hz.

5. STANDALONE DEPLOYMENTS OF RASPBERRY SHAKE

5.1. Deployment description

A field deployment was then conducted at a large concrete gravity dam with the RS used as a standalone instrument. Data acquisition was conducted at two locations: (i) from a public pathway above the dam crest approximately midway along the length of the overflow spillway; and (ii) free field approximately 100 m downstream of the overflow spillway. The location selected at the dam crest was at 1/3 span of the elevated arch-supported pathway between two piers, and therefore this location is expected to exhibit resonances associated with the dam body, pier structure, and the elevated bridge superstructure. The free field location was selected on smooth cobble-sized rocks downstream of the stilling basin at the toe of the dam.

Data was collected on all three instrument channels for a duration of 20 minutes at each location during ambient operating conditions with approximately 1.5 cubic meters per second of release through the low-level outlet (there is no power generation at this dam). It was observed that the reservoir was near full pool and no irregular activities or events were noted which could have perturbed the ambient data collected at either location.

5.2. Vibration analysis and observations

The RS time series data exhibits significant low-frequency drift, both at the free field location and at the dam crest, as shown in Figure 3. For the dam crest, which was expected to exhibit excitation due to release of water through the low-level outlet, the amplitudes of vibrations are relatively large, particularly in the instream and vertical directions. Concerningly, transient wave trains at the free field location appear to have different arrival times in each of the three directions, which indicates poor time synchronization between the channels—this may have been worsened by operation from a portable power supply during the field deployment.

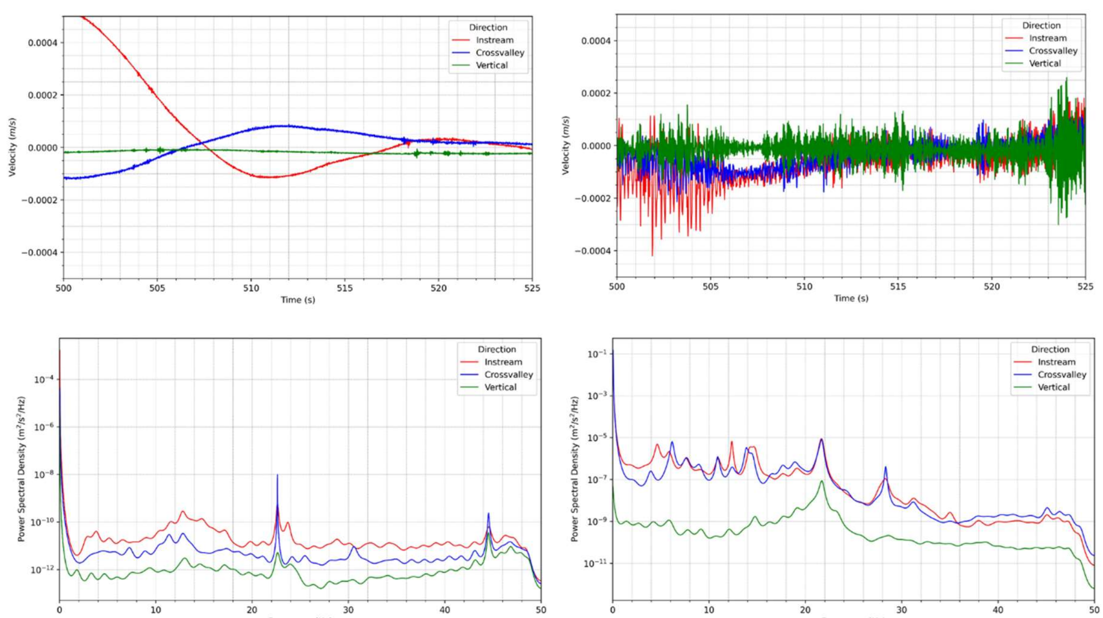

Figure 3. Vibration data recorded by the Raspberry Shake instrument from a standalone deployment. Top left: example segment of velocity time series from the free field location; top right: example segment of velocity time series from the dam crest; bottom left**:** MEM-based PSD at the free field location; bottom right: MEM-based PSD at the dam crest.

MEM-based power spectral density estimates were also examined for recordings at both the free field location and the dam crest. At the free field location, two prominent peaks are apparent at approximately 22.5 Hz and 44.5 Hz. These peaks appear for all three directions and are also apparent at the dam crest location. These peaks are suspected to correspond to excitation frequencies of rotating machinery.

For the dam crest, the MEM-based power spectral densities indicate the possible presence of several resonances, including instream dam resonances at approximately 4.5 Hz and 12 Hz and a suspected crossvalley pier resonance at approximately 6 Hz. However, attributing these resonances to specific component behavior is challenging due to the influence of multiple components (dam body, piers, and elevated arch bridge superstructure) which may have contributed to the resonant response at this location.

Because only a single instrument was deployed, it was not possible to definitively differentiate vibrations related to structural resonances from those with other origins. The lack of clear explanation for spectral peaks emphasizes the advantages of deploying multiple reliably time-synchronized instruments which would have resulted in greater confidence for interpreting structural responses. However, if multiple RS instruments had been deployed, unreliable time synchronization between instruments may have impeded the computation of cross-correlations between instruments. Finally, low-frequency drift, poor time synchronization, and different sample counts between channels limits confidence in the results and makes it difficult to use observations of suspected resonant behaviour to support consequential engineering decisions.

Practical considerations of the RS deployment were also important. The cumbersome mobilization of multiple pieces of equipment in the field likely degraded the success of the deployment and may have contributed to data quality issues resulting from improper tightening of leveling legs or incorrect time synchronization. Complicated protocols to start and stop recording resulted in additional testing time. Reliance on an external power supply and field laptop meant that outdoor testing could only be completed during clear, dry, and warm weather conditions.

6. CONCLUSIONS

This study used a single low-cost Raspberry Shake 3D to record ambient vibrations on a large concrete gravity dam to evaluate the performance of the instruments for ambient vibration testing. In stage one of the study, the Raspberry Shake was collocated with two industry-standard instruments to verify the velocity recordings from the Raspberry Shake. The Raspberry Shake recordings were found to have several important limitations.

First, the time synchronization of the Raspberry Shake was found to be too poor to synchronize the recordings automatically or manually with those of the industry-standard instruments. The failure to achieve time synchronization of the Raspberry Shake is attributed to multiple factors. The user interface for Raspberry Shake is relatively difficult to use and there is limited ability to control the precise start and stop times of data acquisition, especially when moving between multiple locations in the field. Furthermore, because the time series from the Raspberry Shake may differ to the extent that they no longer resemble the industry-standard instrument recordings—even with various frequency filters applied—it can be impractical to synchronize the recordings and compare the records in the time domain.

Once transformed to the frequency domain, there was found to be general agreement between the frequency content of the low-cost and industry-standard instruments; however, several limitations were identified. The Raspberry Shake recordings were contaminated by low-frequency oscillations which caused spectral distortions below approximately 1 Hz—a characteristic typical of low-cost sensors. Furthermore, the low sampling frequency of the Raspberry Shake (100 Hz) limited the spectra to frequencies below 50 Hz and significant roll-off was observed at frequencies above 45 Hz.

When deployed as a standalone instrument at a large concrete gravity dam, the Raspberry Shake was found to be able to record velocities with sufficient accuracy to infer suspected resonant behavior of various structures. However, the deployment suffered from several limitations related to the performance of the Raspberry Shake. Despite these limitations, the Raspberry Shake may be suitable for ambient vibration testing under certain conditions: (i) preliminary or exploratory testing to make estimates of structural resonances or vibration amplitudes, (ii) locations which are indoor, have access to permanent power supplies, and feature a line of sight with the sky to support GPS timing, and (iii) for deployments in remote locations or with short notice when state-of-the-art or industry-standard instruments may not be readily available.

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