BUREAU OF RECLAMATION

Evaluation of Laser Doppler Vibrometry for Long-Range Remotely-Sensed (Touch-Free) Seismic Data Acquisition

Science and Technology Program
Research and Development Office
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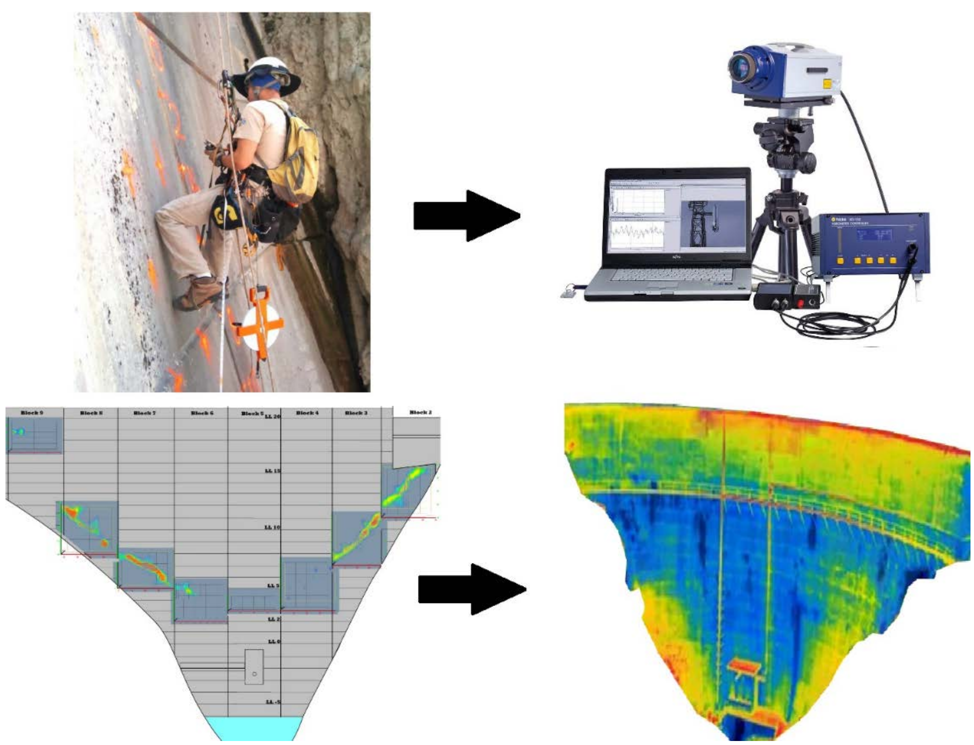

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14. ABSTRACT ***The location and severity of concrete defects and damage is usually poorly understood. New technologies are needed to facilitate rapid identification and characterization of concrete defects/damage/deterioration in a significantly more efficient and spatially comprehensive fashion than typical techniques currently used. Laser Doppler Vibrometry (LDV) is one potential technology that could achieve these goals. This scoping-level research project consisted of a literature and technology review to assess the current state of the art in LDV sensing hardware and techniques and their capabilities and applications for non-destructive testing and evaluation of concrete structures. Results of this scoping-level research project indicate that active LDV techniques hold significant promise in the ability to help address many of Reclamation's technical challenges related to the assessment and maintenance of aging concrete infrastructure.***

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JUSTIN RITTGERS Digitally signed by JUSTIN RITTGERS
Date: 2020.05.04 18:06:22 -06'00'

Prepared by: Justin B Rittgers, Geophysicist
Engineering Geology and Geophysics Group, Technical Service Center, 86-68320

DANIEL LIECHTY Digitally signed by DANIEL LIECHTY
Date: 2020.05.04 21:20:05 -06'00'

Peer Review: Daniel Liechty, Geophysicist
Engineering Geology and Geophysics Group, 86-68320

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Acronyms and Abbreviations

1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional
4D	Four-Dimensional
ASR	Alkali-Silica Reaction
AV	Ambient Vibration
CSLDV	continuous-scan Laser Doppler Vibrometry
CSM	Colorado School of Mines
FHWA	Federal Highways Administration
HVSR	Horizontal-Vertical Spectral Ratio Analysis
LDV	Laser Doppler Vibrometry
MASW	Multi-Channel Analysis Of Surface-Waves
MEMS	Micro Electro-Mechanical Sensors
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Testing
O&M	Operations And Maintenance
PLDV	Point Laser Doppler Vibrometry
Reclamation	US Bureau of Reclamation
ReMi	Refraction Microtremor
RSV	Remote Sensing Vibrometer
SASW	Single-Channel Analysis of Surface-Waves (SASW)
SLDV	Scanning Laser Doppler Vibrometry
UAV	Unmanned Aerial Vehicles
USACE	US Army Corps of Engineers

Executive Summary

Problem

The US Bureau of Reclamation (Reclamation) has several large concrete dams and other large concrete infrastructural components considered to be "high-risk" due to their critical functions and locations relative to large downstream population centers (e.g., large economic losses and loss of life for downstream populations in the event of a catastrophic failure). Many of these structures are in various states of deterioration (e.g., experiencing wear and tear due to repetitive impact and motion damage or other cyclic phenomena such as freeze-thaw), increasing the probability of failures in certain plausible scenarios. The location, spatial extent and severity of concrete defects are usually poorly understood, and typical assessment methods are often conducted "blindly" (e.g., random placement of focused surveys and coreholes without the use of additional information or prior knowledge of defect location/severity). As a result, there is the ever-present chance of underestimating the severity of damage to these structures and the subsequent overly liberal estimate of safety factors/risk.

New technologies are needed to facilitate rapid identification and characterization of concrete defects/damage/deterioration in a significantly more efficient and spatially comprehensive fashion than typical techniques currently used (e.g., spot-checking conditions via standard geophysical techniques or drilling/coring programs). Laser Doppler Vibrometry (LDV) is one potential technology that could achieve these goals and is the focus of this scoping-level research project.

Research Approach

This scoping-level research project consisted of a literature and technology review to assess the current state of the art in LDV sensing hardware and techniques and their capabilities and applications for non-destructive testing and evaluation of concrete structures. This scoping-level effort also aimed to assess Reclamation's current capabilities for conducting LDV studies by evaluating current resources, capabilities, and needs to support future research involving LDV. Lastly, several existing geophysical datasets collected (and planned for FY20) at a variety of Reclamation facilities have been identified that would offer valuable ground-truthing for future LDV field studies.

Results and Recommended Next Steps

Results of this scoping-level research project indicate that active LDV techniques hold significant promise in the ability to help address many of Reclamation's technical challenges related to the assessment and maintenance of aging concrete infrastructure. Initial reviews of existing data, hardware, and software indicate that future research efforts are readily feasible using existing resources and rented LDV equipment.

It is highly recommended that further conducting-level research efforts be funded and pursued to more closely evaluate and develop LDV capabilities at Reclamation.

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Problem Statement and Research Goals

Reclamation has several large concrete dams and other large concrete infrastructural components considered to be “high-risk” due to their critical functions and locations relative to large downstream population centers (e.g., large economic losses and loss of life for downstream populations in the event of a catastrophic failure). Damage and deterioration of concrete structures poses several safety and economic risks related to aging critical infrastructure and is oftentimes very difficult and costly to assess comprehensively using typical visual inspection and invasive techniques.

In the case of large concrete structures, distributed defects such as alkali-silica reaction (ASR) and cyclical freeze-thaw deterioration processes exacerbate maintenance challenges and the probability of certain failure modes. More localized issues can also increase the probability of certain structural failures, or simply lead to poorly performing structures, decreased water storage or conveyance capacity, and operations and maintenance (O&M) challenges and related costs. Some of these localized structural issues include poor bonding of adjacent concrete pours (“bad lift-lines”), concrete placement issues resulting in honey-combing and poor aggregate bonding, delaminations from underlying reinforcement, and the development of localized cracking due to interior stresses resulting from differential settlement processes, hydrostatic loading or differential curing, and thermal expansion/contraction processes.

New technologies are needed to facilitate rapid identification and characterization of concrete defects/damage/deterioration in a significantly more efficient and spatially comprehensive fashion than typical techniques currently used (e.g., spot-checking conditions via standard geophysical techniques or drilling/coring programs). Laser Doppler Vibrometry (LDV) is one potential technology that could achieve these goals and is the focus of this scoping-level literature and technology review.

The primary goals of this scoping level research project are to answer the following questions:

1. Perform a literature review to determine current state of the art of LDV defect detection and imaging for remote-sensing assessment of material defects, and to determine the required LDV system(s) and supporting hardware/software.
2. Assess the feasibility of various approaches to data collection.
3. Determine realistic technical limitations of LDV for collection of touch-free seismic data (e.g., environmental conditions requirements, typical signal-to-noise ratios, line-of-sight range limits, spatiotemporal resolutions, practical data bandwidths, etc.) on large concrete structures.
4. Determine realistic logistical limitations, typical data production rates, costs of field-scale implementation of the technique (e.g., required hardware/software, time for data collection, processing, etc. to produce data coverage and data quality results similar to standard seismic survey approaches), logistical benefits and limitations of field implementation, and estimate benefit/cost ratios in comparison to other more typical survey techniques, options, and possible outcomes.
5. If deemed a promising technology, prepare a research proposal for FY21+ funding to support a follow-up conducting-level research effort.

Background

LDV Overview

Laser Doppler Vibrometry is a nondestructive, nonintrusive, and noncontact (i.e., “touch-free”) approach to sensing and recording of vibrational energy on the surface of a remote target or object. LDV has its roots in remote fluid velocity measurement experiments carried out in 1960 (Yeh & Cummins, 1964), and is one of many remote sensing technologies that has been researched and developed for several decades (Drain 1980; Halliwell 1979; Oldengram et. al 1973; Buchhave 1975; Bank and Hathaway 1980).

Most recent advancements have involved improvement and expansion of hardware capabilities and subsequent modeling techniques for various applications. Most of these efforts have been related to the use of LDV in lab and production settings. Specifically, LDV has traditionally been researched and developed for applications in structural and modal shape analysis of physical prototypes, in-service devices (e.g., machinery components), medical imaging applications, and for damage detection and analysis relevant to small-scale non-destructive testing (NDT) and evaluation of micro to meso-targets (e.g., fracture detection and mapping in composites, modal shape and vibration analysis of objects, etc.).

In its most basic form, LDV involves pointing a laser beam at a target object or surface and recording back-scattered laser light with a photodetector located at or directly next to the laser source. Here, the back-scattered light experiences a doppler shift if the target surface is moving or vibrating in the same direction as the laser beam (e.g., towards or away from the laser source). This doppler shift, similar to how a police radar gun operates to record velocity of a vehicle or moving object, is a phenomenon where the wavelengths of light or sound that are reflected off of a surface become either stretched or compressed by the relative velocity of the reflecting surface (relative to the source and observation point that is typically stationary relative to the target surface or object). The recorded signal at the photodetector is a combination of the source and reference laser beams, and the back-scattered light with doppler shifts (Figure 1). The combination of these three laser beams results in a beat frequency that is proportional to the doppler frequency shift (i.e., frequency beating due to two sinusoids of slightly different frequency). The final signal is a frequency-modulated voltage signal of the target’s vibration amplitude and frequency versus time.

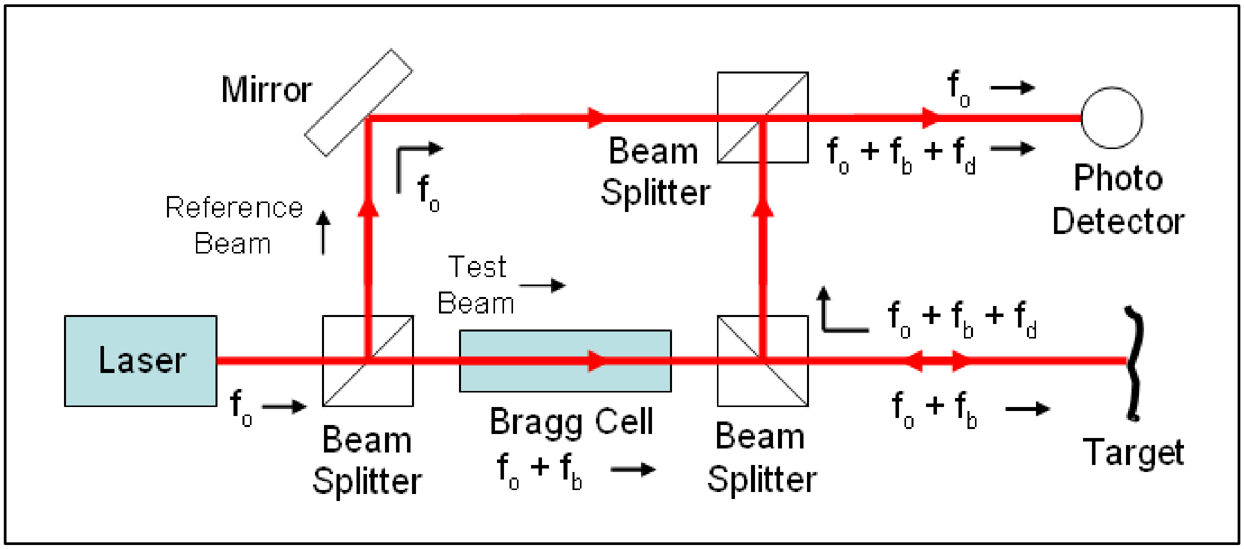

Figure 1. Schematic of LDV concept, from (Laderaranch, 2014).

The amount of stretching or compression that occurs is linearly dependent upon the velocity of the reflecting surface in the same direction of the impinging wave-front (e.g., lateral motion perpendicular to the laser or sound wave-front does not create a doppler shift effect). Stretching and compressing the wavelengths are also referred to as red-shift and blue-shift, respectively, which refers to the visible effect of doppler shifting visible light. To an observer, this stretching and compression is observed as a change in frequency of light (or sound, such as is audibly experienced when an ambulance drives by with sirens on).

In the case of vibrations with particle motions that are perpendicular to an object or target's surface (i.e., the surface normal vector), doppler shifts can be observed concurrently as a series of red and blue shifts that follow the frequency and intensity of vibrations. Here, the amount of doppler shifting (e.g., the amount of frequency shift) is proportional to particle velocity or amplitude of vibrations, and the periodicity of the doppler shift red-blue cycles is directly proportional to the frequency of the vibrations being observed. Therefore, backscattered laser light signals with this series of doppler shifts can be recorded and used to reconstruct the target's vibration signal (particle velocity versus time). The end effect is the ability to quantitatively record vibrations or translational motions of targets by means of remote sensing (i.e., without the need to physically touch the target with a sensor) using laser light.

LDV systems come in various configurations and sizes for various applications. These range from miniature devices with fiberoptic guided laser beams used for delicate medical applications (Buunen & Vlaming, 1981; Terasaki, et al., 2001; Marchionni, Scalise, Ercoli, & Tomasini, 2013) to large laboratory instrumetns that are configured with single or muliple-beam laser heads that can be set to aim at specific loctions, or can be pre-programmed to scan a 2D target surface to record multiple test points sequentially (Halkon & Rothberg, 2017; Fu, Guo, & Phua, 2011; Poittevin, Picart, Faure, Gautier, & Pézerat, 2015; MacPherson, et al., 2007; Maia, Almeida, Urgueira, & Sampaio, 2011; O'Malley, Woods, Judge, & Vignola, 2009; Kilpatrick & Markov, 2008; Castellini & Santolini, 1998).

Scanning LDV (SLDV) is typically implemented by means of incrementally holding a laser beam at a given location, collecting data, and then quickly moving to the next test point and repeating the measurement. Other researchers have developed novel approaches to colecting multipoint LDV data with a single laser beam using rotating mirors and high-speed swept measurements. This technique, also referred to as continuous-scan LDV (CSLDV), has many different applications related to modal shape analysis and impact excitation vibration testing where transient waves are recorded as they propigate across the surface of a test target (Sriram, Craig, & Hanagud, 1990; Stanbridge & Ewins, 1999; Ribichini, Di Maio, Stanbridge, & Ewins, 2008; Allen & Sracic, 2010). Additionally, the use of multi-beam LDV systems has been developed to enable the measurment of particle motions in 3D (e.g., not simply in the normal vector direction of the laser/surface, but now capable of capturing horizontal components of motion that are parallel to the target surface). This has impications in terms of fullwavefield modeling and elastic modulus extraction for each test point (Pourahmadian & Guzina, 2018).

Figure 2. Image of an LDV lab experimental setup: Scan of a nuclear graphite block experiencing bulk and surface wave propagation. The wavefield simultaneously captured form the block surface by three LDV units placed at different angles is subsequently fed to an inverse-elasticity algorithm to reconstruct the position, size, and shape of defects (e.g. internal damage due to thermal gradients) that may have developed in the interior of the block, from (Pourahmadian & Guzina, 2018).

Potential Applications and Benefits Specific to Concrete Infrastructure

One of the primary advantages of LDV over the use of more traditional vibration measurement sensors such as an accelerometer, is that the LDV can be directed at targets that are difficult or otherwise dangerous to physically access, or that may be too small, too hot, or energized with voltages or currents too high to safely attach a physical transducer too. In some cases, touch-free sensing is required in order to avoid either damaging or altering the state of free vibration of the target. Also, the LDV makes the vibration measurement without mass-loading the target, which is especially important for MEMS devices or characterization of small components that would otherwise be affected by attaching a sensor (e.g., the use of LDV for imaging modal shapes or damage of the tympanic membrane or more commonly referred to as the “ear drum,” (Buunen & Vlaming, 1981; Terasaki, et al., 2001; Marchionni, Scalise, Ercoli, & Tomasini, 2013).

LDV technology could be deployed for collection of various active and passive seismic survey types, including active and passive seismic surface-wave interferometry surveys, seismic refraction tomography surveys, and seismic reflection surveys, all without the need for wired geophone systems that are limited in the number of sensor channels, geometric configurations, and the need for physical access to sensor locations. The use of long-range LDV could completely alleviate the need for complex ropes access team preparations for seismic data collection on large concrete or rock face surfaces, as was done on the downstream face of Seminoe Dam in Wyoming, as shown in Figure 3.

Application of this technology could significantly augment or even eventually replace current industry standard approaches for conducting various types of seismic surveys with numerous applications directly relevant to Reclamation’s Mission. This would translate to immense cost savings, increases in data coverage and production rates, and overall value of information obtained from various seismic surveying efforts.

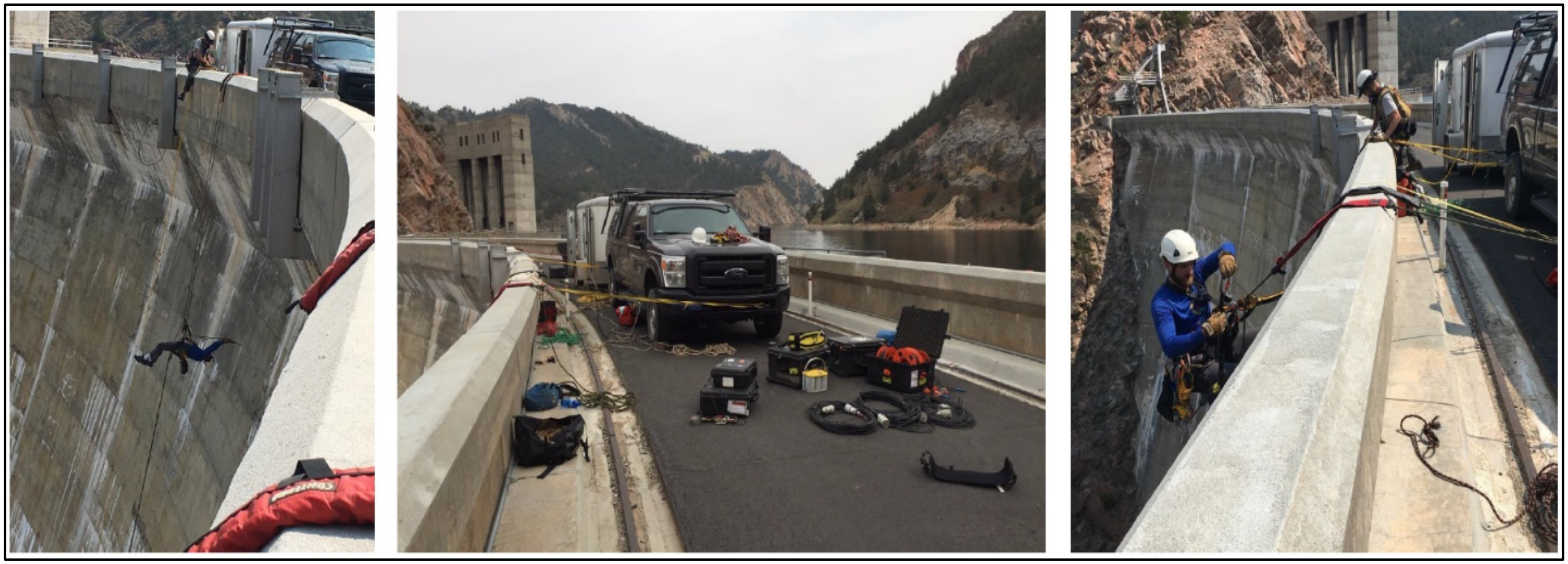

Figure 3. Photos showing complex ropes access team preparations for seismic data collection along vertical transects on the downstream face of Seminoe Dam in Wyoming.

A particularly poignant benefit from the application of this technology is the potential to rapidly detect and image defects, damage, and deterioration across large vertical concrete structures or large infrastructural components without the need to access or touch the target structure's surface with sensors, and potentially without the need to apply active seismic sources across the structure's surface (e.g., alleviate the need for ropes team access for placement of geophones and hammer impacts). Hence, this approach could potentially allow for extremely rapid, cost effective, and spatiotemporally comprehensive assessment and imaging of concrete structures throughout Reclamation's entire inventory of infrastructure.

If deemed a successful approach to collection of "touch-free" (remotely-sensed) seismic data, LDV technology could be used to more comprehensively assess the state of disrepair of critical infrastructure and high-risk structures/miscellaneous structures, and help to guide and optimize repair and mitigation efforts. Additionally, the results of application of this technology could help to guide efficient and intelligent design and placement of more costly and invasive investigations, including the placement of coreholes along the crest of concrete dams, or across the vertical/sub-vertical faces of concrete structures.

Manual LDV Surveys

Manual LDV surveying (e.g., manually aimed laser beam with the use of an aiming scope or camera for spotting the visible laser point) is one common approach to recording vibration data on remote targets. In the case of invisible infrared laser beams, a thermal infrared camera can be used for sighting and aiming the laser measurement point. Manual surveys can be combined with rotary mirror sets that synchronize with rotating machinery or moving targets for sake of measuring vibrational information during uninterrupted use of the component. While more time-consuming than automated aiming and data collection approaches, single or multi-beam manual surveys still enable a comprehensive set of testing capabilities. In addition to health monitoring of parts in use, there are several NDT and geophysical survey types that could be performed using manual LDV techniques.

Active Source Seismic Surveying with LDV

LDV could be used to augment or eventually replace more expensive and less comprehensive seismic surveying techniques on large concrete structures. In the case of active-source (e.g., impactive or impulsive energy) seismic imaging and testing methods, LDV would require physical access to within some proximity of the surface area to be tested/interrogated (e.g., would potentially require ropes access for application of active impactive seismic sources to test surface).

In some cases, scanning LDV or continuous scanning LDV data collection techniques may be feasible to support extremely fast seismic surveying and imaging techniques applied to large concrete structures. Active seismic techniques that could be supported by the use of LDV include the following:

- One, two, three, and four-dimensional (1D, 2D, 3D, and 4D, respectively) Seismic surface-wave imaging with the use of dispersion analysis
- Backscatter analysis of surface-waves for detection of subsurface flaws, inclusions or voids

- 2D/3D/4D surface-based seismic refraction tomography
- 2D/3D/4D surface-to-borehole seismic refraction tomography
- 2D/3D/4D seismic reflection imaging
- Impulse response testing for natural frequency verification
- 2D surficial defect/damage mapping by means of surface vibration excitation amplitude and attenuation testing

One example of how LDV could be used to significantly reduce data collection time and costs involves the use of LDV for through-dam seismic tomography surveying. LDV could be used for 2D/3D/4D imaging and monitoring of large structures for deterioration or damage by means of placing a downhole seismic source within a corehole or within the reservoir on the upstream side of the dam, and using LDV across the downstream face of the structure to record signal transmission times.

This concept is depicted in Figure 4, where Seminoe Dam is shown in cross-sectional view showing various possible though-dam seismic tomography surveys that could be conducted extremely rapidly with the use if a borehole seismic source placed within a corehole inside the dam and LDV recorded data across the downstream face and top of the dam. In the figure, ray-paths are approximated as straight lines from source to recording points location along the top and face of the structure. The sources are located along the upstream face of the structure (either under water or above waterline). Similar types of surveys can be conducted or augmented with the use of hammer impactive or vibrational sources placed at the bottom and top of the structure, or on the face of the structure using ropes access support.

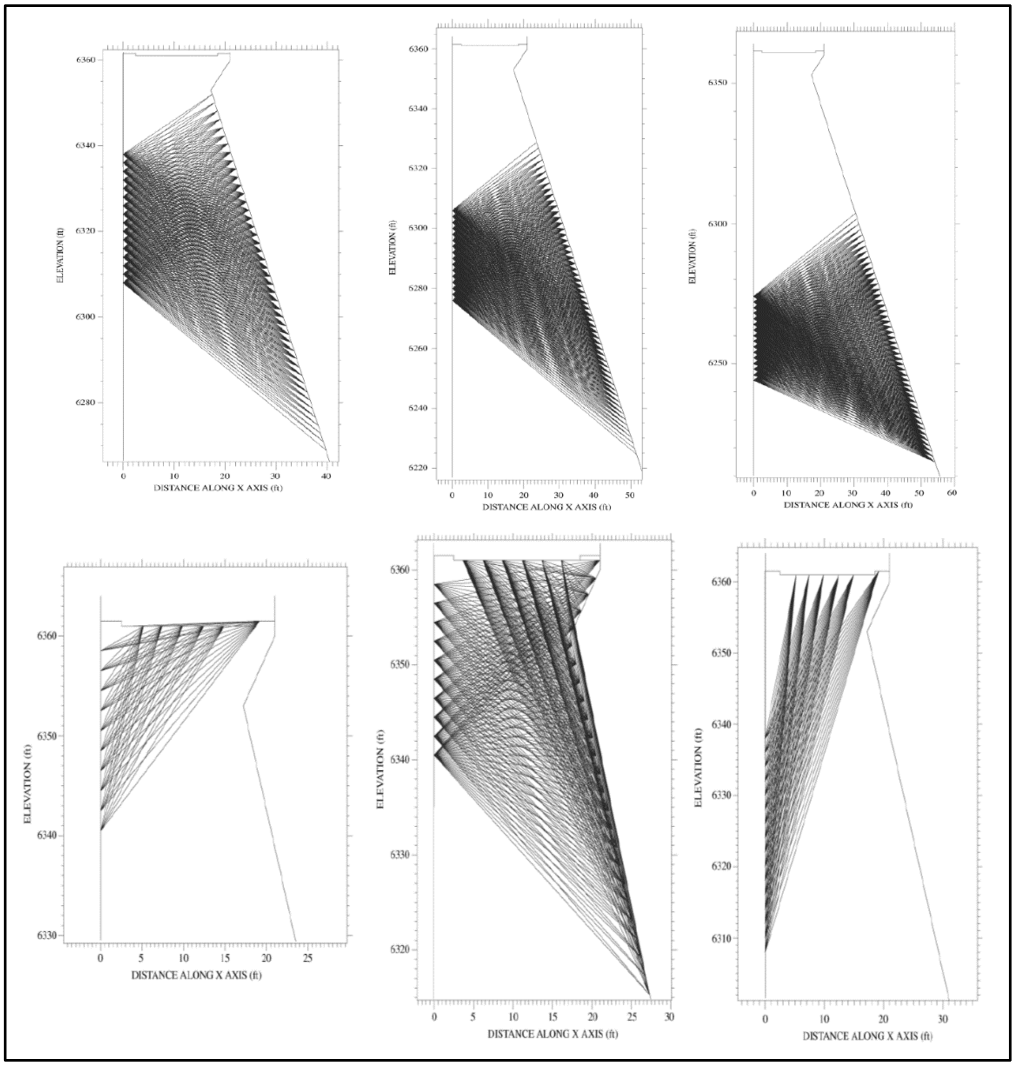

Figure 4. Six different schematics of Seminoe Dam in cross-sectional view showing various possible though-dam seismic tomography surveys that could be conducted extremely rapidly with the use of a borehole seismic source placed within a corehole inside the dam and LDV recorded data across the downstream face and top of the dam.

Passive Seismic Interferometry Surveying and Imaging with LDV

Passive seismic interferometry imaging generally consists of recording background vibrational noise with multiple sensors (at least two) at various points along a line or grid simultaneously and time-synchronized, such that the recorded wave propagation between sensor points can be used to reconstruct material properties (i.e., seismic shear-wave velocity and attenuation information) of the medium between and beneath the sensors. In some “passive” techniques, an active seismic source (impulsive or oscillatory forcing) is required to generate adequate vibrational energy. In these cases, a “passive” data collection and processing approach is used (e.g., data is not triggered or otherwise time-synchronized with the impulse or oscillatory vibration source), but an active energy source is required, nonetheless.

There are various passive seismic imaging reconstruction techniques including back-scatter analysis of surface waves and surface-wave dispersion imaging processes like multi-channel analysis of surface-waves (MASW) and Refraction Microtremor (ReMi). These industry-standard passive seismic data analysis and modeling workflows allow for the reconstruction of shear-wave velocity distributions between and beneath sensing points. This offers a means to interrogate the surface and subsurface of objects for damage or changes in material properties.

In the case of passive seismic surveys using LDV, it is possible that no proximal physical access to the area to be tested/interrogated would be necessary, as a passive seismic source (e.g., background noise) would be monitored via remote sensing by a LDV system located at a large distance from the surface of interest. LDV for passive seismic data collection could theoretically be conducted from up to several hundreds of meters away from the surface of interest. Here, the practical limitations are the requirement for direct line-of-sight of the test surface, and minimal obliquity of the surface relative to the laser beam (sensitive to line-of-site vibrational displacements only), adequate reflectivity of the surface, and non-excessive speckle noise (i.e., related to the spatial scale-length of roughness of the target surface with respect to the wavelength of the LDV laser source used), as discussed by (Rothberg, 2006; Vass, et al., 2008).

One particular study on the topic of surfacewave interferometry in lab setting was presented by (Hayashi & Nishizawa, 2001) and again for surface waves and other modes of seismic wave propigation within heterogeneous rock samples in a laboratory setting (Nishizawa, Satoh, Lei, & Kuwahara, 1997).

Ambient Vibration Amplitude and Phase Monitoring with LDV

In addition to seismic imaging techniques that focus on mapping the spatial distribution of physical properties (e.g., seismic velocity) of a target object or subsurface geologic volume of Earth material, passive LDV data collection has many applications related to structural health monitoring and characterization of mechanical properties of specific structures or objects or machinery such as motors or power tools (Bendel, Fischer, & Schuessler, 2004).

Determination of Natural and Resonant Frequencies of Objects and Structures

Passive vibration and displacement data collected by means of LDV can be used for simple vibration analysis, such as impulse excitation vibration analysis for characterizing fundamental frequency and higher mode harmonics of target objects. Impulse responses and swept oscillatory forcing of objects can be recorded to develop the response spectra of infrastructure, which is a critical component to modeling of structure response to strong motion loading (e.g., how will a dam shake in the event of an earthquake). This topic alone is an area of upmost interest to civil and geotechnical engineers at Reclamation and partner agencies (Chugh, 2019).

NDT and Damage Detection

Additionally, ambient LDV monitoring of targets can be used for detection of changes in data signatures for parts in motion or under cyclic stress loading for identification of vibrational signatures indicative of change in component health or development of fatigue damage (e.g., acoustic emissions from damaged areas under load). LDV can additionally be used for mapping of shallow defects across large areas that exhibit changes in surface wave propagation characteristics (e.g., damaged areas oftentimes exhibit higher amplitude and changes in phase relative to undamaged areas), such as discussed by Fu, Guo, & Phua, (2011); Kessler, Spearing, Atalla, Cesnik, & Soutis, (2002); Maia, Almeida, Urgueira, & Sampaio, 2011; and Khan, Stanbridge, & Ewins, (1999).

One poignant testing approach of interest for future research is the use of scanning LDV for collecting passive 3D particle motions at various test points for utilization in horizontal-vertical spectral ratio analysis (HVSR) and mechanical properties imaging of large surfaces, as discussed by Fisher, Heisig, & Kappel, (2019); and Gallipoli, Mucciarelli, Castro, Monachesi, & Contri, (2004). Looking at the variations in amlitude and phase of vertical versus horizontal particle motions at a given single test point contains information about the mechanical properties (e.g., elastic moduli) of the test material beneath that test point. Thus, three-axis LDV systems could be used to scan the surface of a target and detect spatial variations of HVSR values that are idicative of damged areas or components only using passive vibrational signals or repeated imacts or ocsilatory forcing of the target to generate addequate vibrational energy during scanning.

Semi-Automated and Continuous Scanning LDV Surveys

In addition to manual single-point and manual scanning LDV surveys, automated scanning LDV surveys and continuous scanning LDV are conducted by means of mounting an LDV unit on a tripod configured with stepping-motors or similar guidance and aiming system platform that controls aiming of the LDV laser sensing points across a target surface or object and during data collection using pre-programmed sensing point locations or sweep functions. The system sweeps through these various pre-determined sensing points sequentially during data collection. In scanning-mode, LDV data are typically exported directly to supporting software that generates images of the characteristics of recorded vibrations across the target surface. Scanning LDV can be augmented or replaced by the use of multi-beam systems that have sufficient measurement points for a given application (e.g., imaging modal deflection shapes of a car door being shut), such as discussed in Dikmen & Basdogan, (2008).

This approach to data collection opens several opportunities for enhancing seismic survey data coverage and resolutions of interest, such as scanning large surfaces for areas of deterioration or damage (e.g., large concrete structures). There is also the possibility of capturing transient wave events as they propagate along a CSLDV scan line, which has several implications in terms of the use of CSLDV for seismic imaging techniques that use active sources or passive background vibrational noise for signal.

Imaging Transient Wavefields and Modal Shapes with LDV

A large application of passive LDV is also for imaging modal shapes of vibrating objects or machinery components during uninterrupted use (e.g., wind turbine blades or spinning plates or rotors). Many techniques and data processing algorithms have been developed for modal shape and ambient vibration analysis, as discussed in Sriram, Craig, & Hanagud, (1990); Halkon & Rothberg, (2014); Sever, Stanbridge, & Ewins, (2006); Dietzhausen, Bendel, & Scelles, (2003); and Cookson & Bandyopadhyay, (1980).

In some approaches to modal shape analysis with LDV, a multi-point laser is used (MacPherson, et al., 2007) or matrix laser systems (Kilpatrick & Markov, 2008) to record deflection shapes at various points simultaneously. Other reserchers have implmented CSLDV surveys for colleting modal shape information with single-beam LDV systems, including Allen & Sracic, (2010); Stanbridge & Ewins, (1999); Stanbridge, Martarelli, & Ewins, (2004); and La, Choi, Wang, Kim, & Park, (2003).

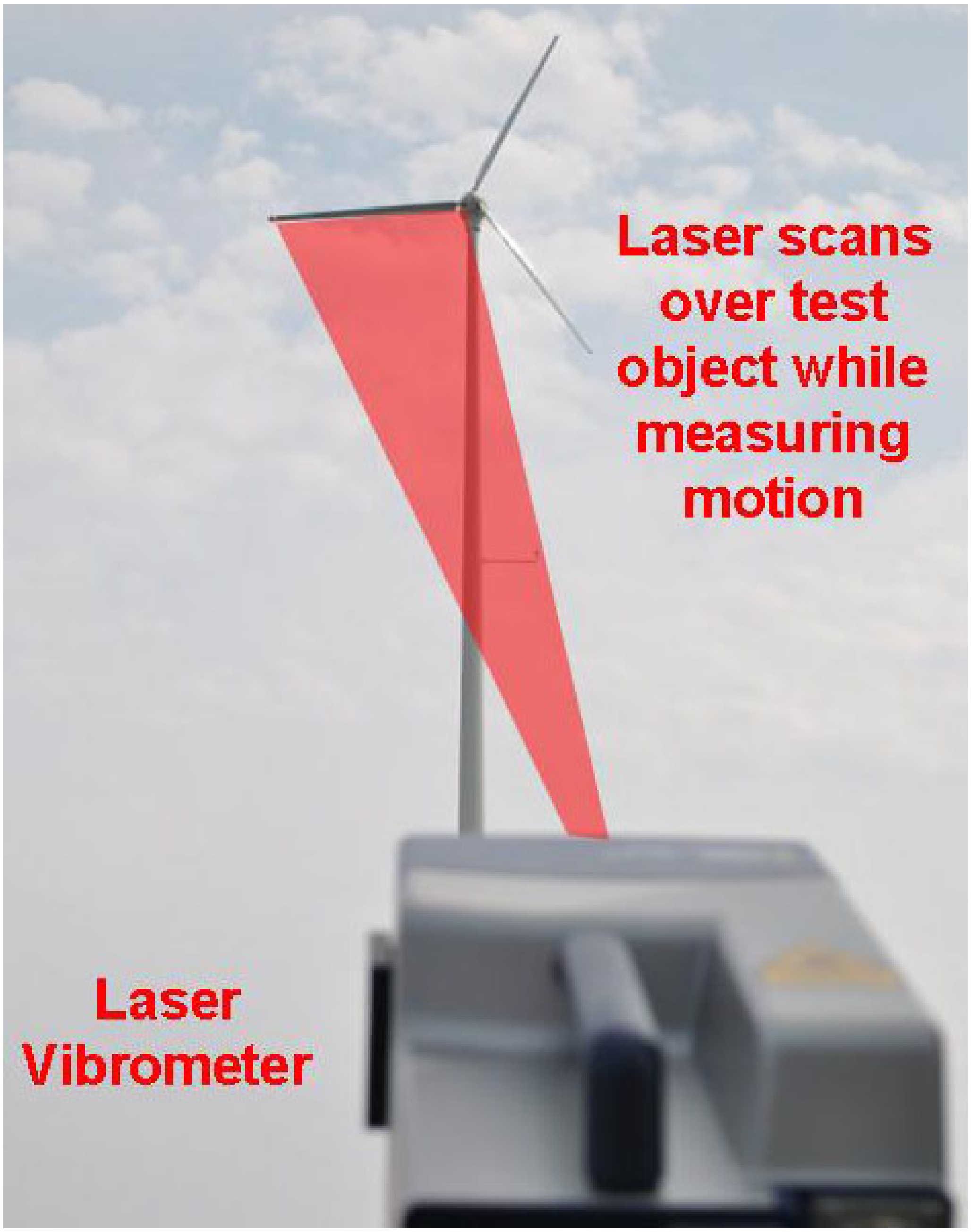

Figure 5. Schematic of CSLDV data collection along the entire length of a rotating wind turbine blade during uninterrupted service. Modal shapes and structural health monitoring of the blades can be rapidly determined with this application of LDV (from Allen M.S., 2010).

In the NDT and NDE industries, vibrational excitation of the surface of test materials or targets for sake of vibrational and modal analysis (and damage detection) can be achieved with the use of pulsed-laser ablation (where ablation is defined as the removal or destruction of material from an object by vaporization, chipping, or other erosive processes). Here, a laser pulse is utilized to generate vibrational impulse responses in the local vicinity of the laser point. LDV is then used to record the resultant vibration field around the impingement point. In some cases, sub-ablation energy laser pulses are used to avoid mechanically altering or damaging the test surface while still achieving adequate induced vibrations for NDT assessments at a given test point (Hosoya, Kajiwara, & Hosokawa, 2012; Philp, Booth, & Perry, 1995; Castellini, Revel, Scalise, & De Andrade, 1999).

Previous Work and Existing Resources

General Previous LDV Work from Industry and Academia

While over 100 publications on the general topic of LDV were reviewed, an extensive presentation of the literature review is beyond the scope of this report. However, it should be stated that several notable publications related to the use of active LDV for civil engineering and NDT applications were identified.

As mentioned above, extensive industry-based and academic-based research and development of LDV technologies and NDT and non-destructive evaluation (NDE) techniques, including various approaches to recording active-source vibrations and passive vibration and deformation studies has already been conducted. As stated above, LDV has its roots in remote fluid velocity measurement experiments carried out in 1960 (Yeh & Cummins, 1964), and the first sets of experiments were carried out shortly thereafter to record vibrational motions (Drain 1980; Halliwell 1979; Oldengram et. al 1973; Buchhave 1975; Bank and Hathaway 1980). There are several peer reviewed journals that revolve around optical sensing physics and various applications within the NDT industry, much with a focus on micro-scale assessments of material properties and health condition monitoring within the aerospace and automotive industries.

Some NDT applications involve the use of LDV for NDT approaches to damage detection in laboratory settings, most commonly utilized in the automotive and aerospace industries but have several appliations beyond damage detection and characterization (Allen & Sracic, 2010; Allen M., 2010; Bendel, Fischer, & Schuessler, 2004; Castellini, Revel, Scalise, & De Andrade, 1999; Cookson & Bandyopadhyay, 1980; Dikmen & Basdogan, 2008; Fu, Guo, & Phua, 2011; Gallipoli, Mucciarelli, Castro, Monachesi, & Contri, 2004; Stanbridge, Martarelli, & Ewins, 2004; Ribichini, Di Maio, Stanbridge, & Ewins, 2008; Poittevin, Picart, Faure, Gautier, & Pézerat, 2015; O'Malley, Woods, Judge, & Vignola, 2009; and Maia, Almeida, Urgueira, & Sampaio, 2011).

Other novel applications of LDV include the assessment of fruit ripeness (Terasaki , et al., 2001) and for imaging and characterization of fresco artworks (Castellini, Paone, & Tomasini, 1996). There has also been significant cross-over into the use of LDV for medical imaging applications, including the use of LDV for imaging modal shapes or damage of very small internal organs such as the tympanic membrane or more commonly referred to as the “ear drum,” (Buunen & Vlaming, 1981; Marchionni, Scalise, Ercoli, & Tomasini, 2013).

Previous LDV Work Specific to Concrete and Civil Infrastructure

Although many of the data collection and analysis techniques discussed above are potentially relevant to concrete structures and civil infrastructure assessments, there are only a few examples where active LDV has been applied successfully in civil engineering type field settings, where LDV recorded vibrational data can be used for conventional seismic imaging techniques applied to concrete or asphalt surfaces. The Federal Highways Administration (FHWA) recently sponsored a review of post-hazard assessment of highway structures using various remote sensing technologies (Jalinoos, et al., 2019). Applications of remote sensing for infrastructure assessment is discussed at length, and while the use of LDV is not covered in detail, the following excerpt related to the use of LDV on bridges from Jalinoos, et al. (2019) is worth quoting at length:

> *“Measurement of dynamic vibration of bridges is of significant importance in identifying current condition of critical bridge members. During an extreme hazard situation, such as hurricane, dynamic deflection of a bridge can be measured quite accurately by tools such as Laser Doppler Vibrometer (LDV) without directly accessing the bridge element to be monitored (Tabatabai et al. 1998, Nassif et al. 2005). A LDV system is a non-contact portable instrument that measures surface vibration through the principle of interferometry (Doppler Effect) and can provide both velocity and displacement measurement with time (Chen 2018). Nassif et al. (2005) have shown that LDV measurement of deflection in girders of a bridge is comparable to that carried out by contact sensors such as geophone sensor. Helmerich et al. (2012) also used LDV to measure deformation of masonry arch bridges under test loads. The vibrations from points and regions of crucial structural importance to a bridge can be systematically collected remotely by using three types of laser vibrometers: (i) Point LDV (PLDV), (ii) Scanning LDV (SLDV) and (iii) Remote Sensing Vibrometer (RSV). In this set up, PLDV is used to calibrate the SLDV to provide a vibration signature for a spatial region; while RSV is employed to generate the vibration curve for one focal point for a long-time duration. The space and time-evolved vibration map collected using these three laser vibrometers yields a valuable temporal and spectral signature of the structure of a bridge due to the extremely high resolutions in the space and frequency domains. All these high-resolution vibration measurements can be done as automatically programmed from as far as up to 1,000 ft (305 m) using the most advanced models of laser vibrometers. When used during strong winds and hurricanes, space and time-evolved vibration maps of long-span bridges, such as suspension bridges, will serve as extremely valuable datasets (that are not currently available) to verify current design guidelines and potential modes of failure of these bridges.”*

Another study was performed to evaluate the use of LDV for ambient vibrational (AV) analysis of tall buildings (Jolivet, Gueguen, Michel, & Schveitzer, 2008). According to the authors, "most of AV surveys consist of installing accelerometers or velocimeters in the target building and recording ambient vibrations using digital and handheld acquisition system. It can also be worthwhile and safe to have the possibility to get the resonance frequency of buildings using remote system: worthwhile because of the repeatability of the measurements without entering in buildings, and safe in case of post-earthquake assessment of the building integrity when aftershocks are able to collapse the damage buildings," (Jolivet, Gueguen, Michel, & Schveitzer, 2008). As depicted in Figure 6, data were recorded at various locations laong the building façade in order to evaluate the natural frequency and response spectra of various building components.

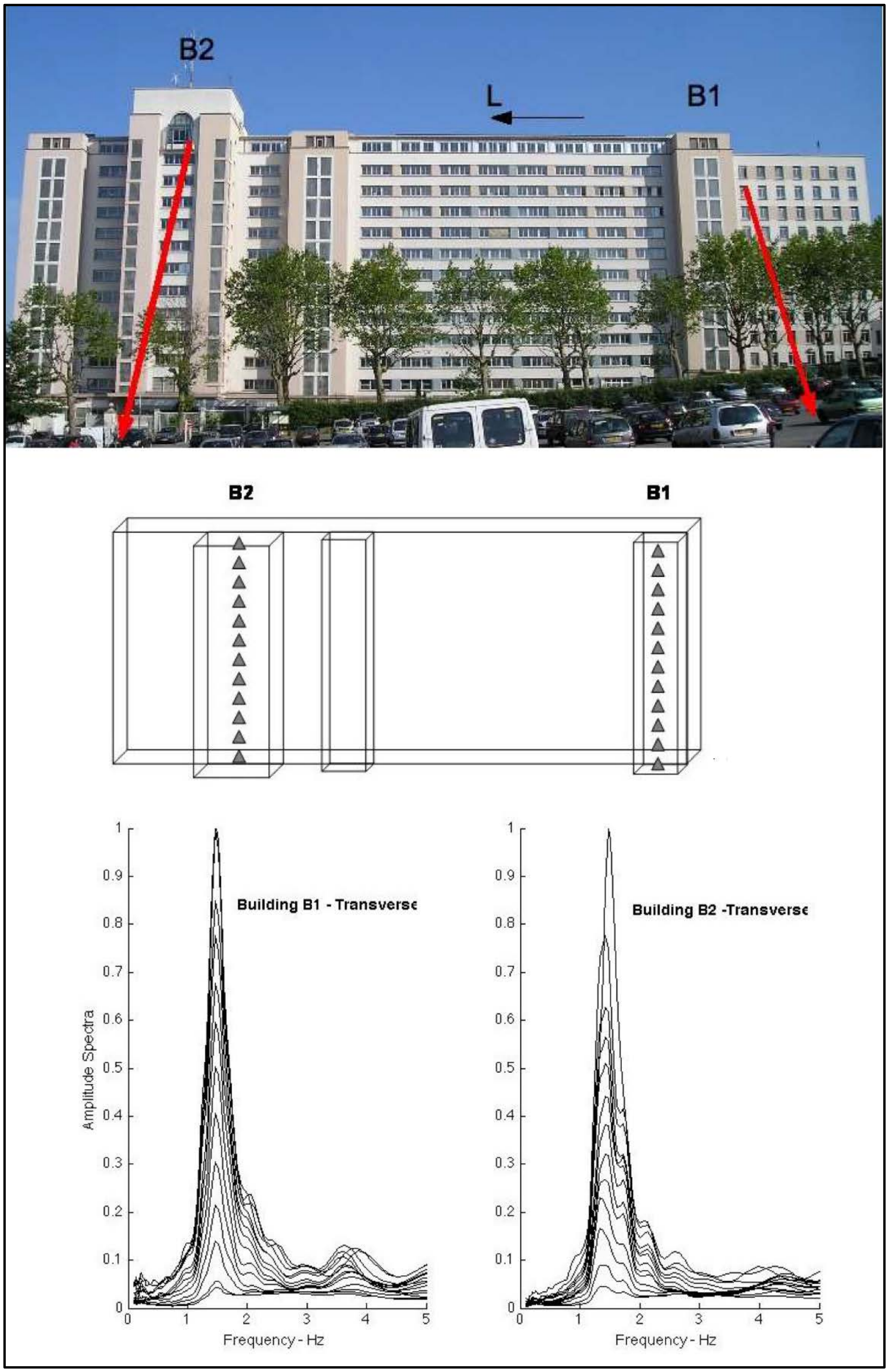

Figure 6. Photo showing a target RC building near Paris France used for ambient vibration analysis with two example long-range LDV sensing laser beams indicated with red lines (top photo), a schematic of the building and various test points placed along two vertical lines B1 and B2 that follow two stairwells (center), and the resultant amplitude spectra for vibrations recorded along B1 and B2 at various floors of the building (bottom).

Additionally, LDV has been researched for the sake of seismic field data collection and to evaluate LDV performance in field settings relative to industry standard contact seismic sensors (i.e., geophones). Specifically, Dräbenstedt, et al. (2016) conducted an experiment using a vehicle-mounted LDV system and recorded impactive seismic source data at various offsets to reconstruct a typical shot gather used for shallow seismic imaging (e.g., refraction tomography). In this study, the researchers successfully compare LDV data with seismic data recorded using industry-standard geophone sensors in order to compare the two data types side-by-side and evaluate the use of LDV for low frequency (e.g., 0-250Hz) seismic surveying. As part of this study, Dräbenstedt, et al. (2016) collected active-source seismic surveyig data with both a linear array of 48 geophones coupled to the ground with spikes, and with an infrared LDV system. Direct data comparisons were made to evaluate the resulting LDV data. In Figure 7, a single timeseries of LDV data (e.g., a seismic "trace") is plotted side-by-side with a seismic trace recorded using a geophone at a common meaurment point. The close match between the two signals is visibly apparent in the figure.

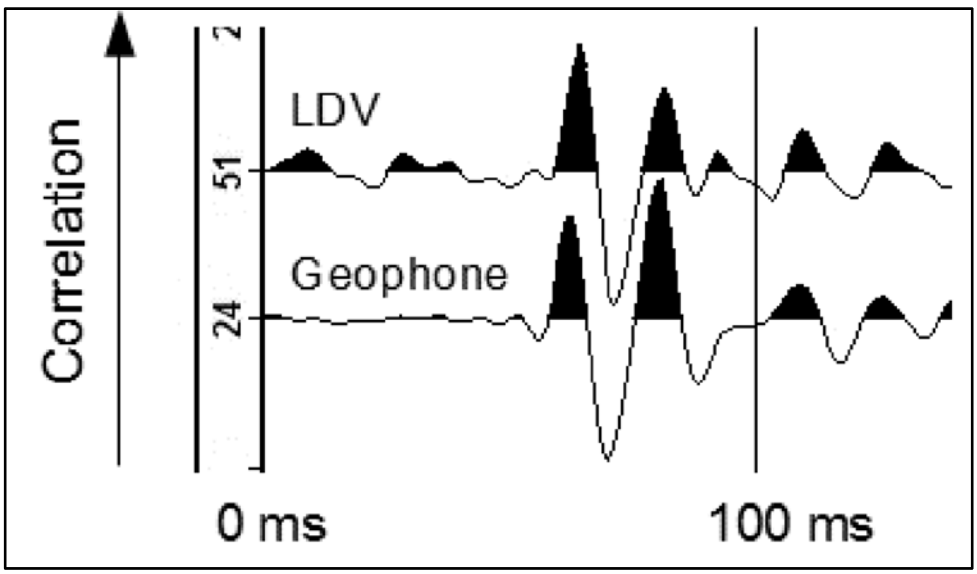

Figure 7. Comparison of LDV data and geophone data for a vibroseis swept source recorded at the same location (from Dräbenstedt, et al. 2016).

Similarly, a composite seismic shot record (also referred to as a shot gather) recorded using an LDV system is plotted in Figure 8. Here, a reference geophone data trace is plotted near the center of the 48 channel shot gather for comparison. As indicated in the shot gather, several seismic wave types are succesfully recorded (refracted body waes, surface waves, air-waves, and reflected body waves) and data signals from known geologic interfaces are visible in the record (from Dräbenstedt, et al. 2016). This indicates that LDV can be used at short offsets (e.g. several feet) to successfully record high-quality seismic exploration data to help supprot subsurface seismic or related ultrasonic imaging techniques.

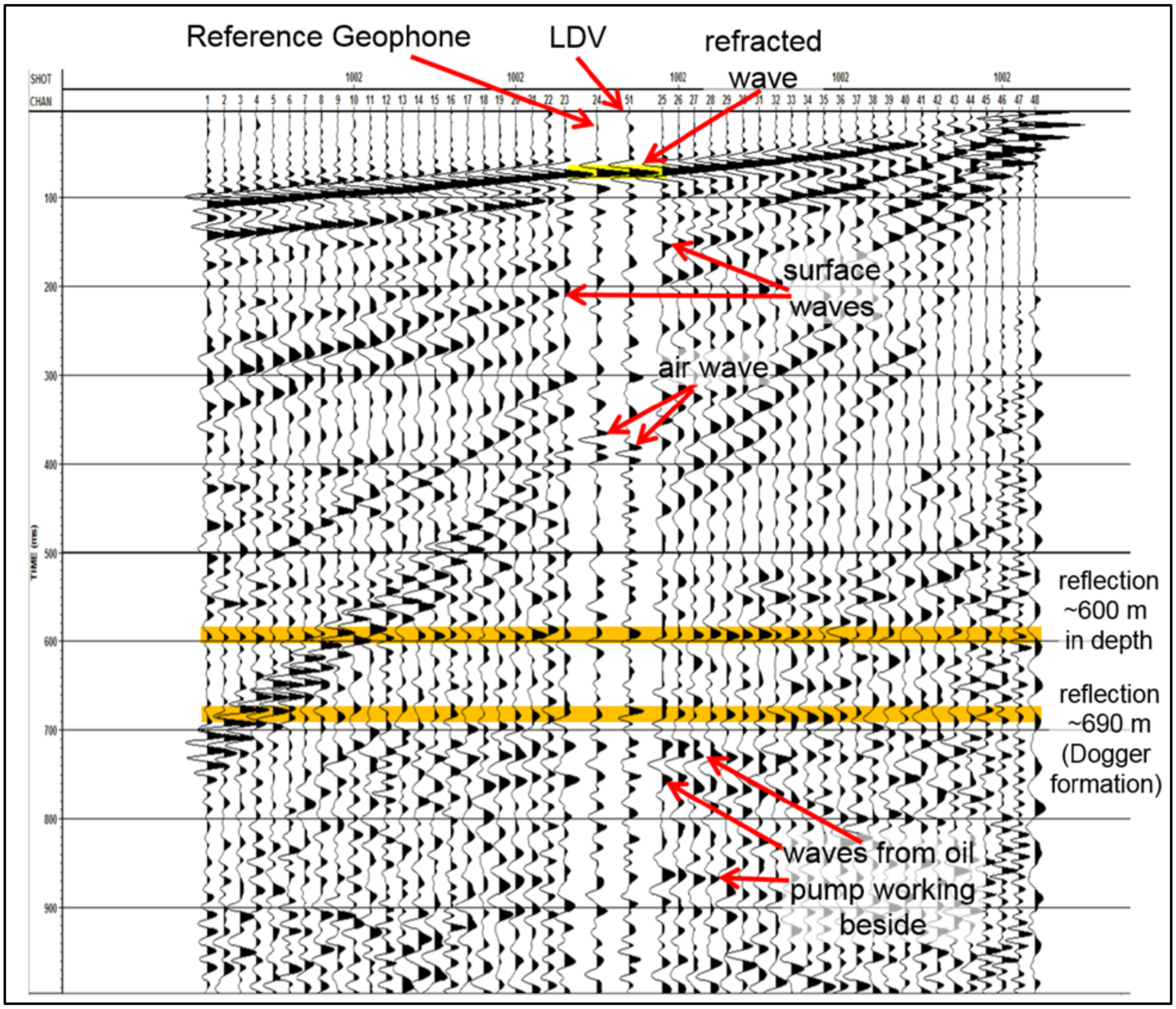

Figure 8. A composite seismic shot gather recorded using LDV. A reference geophone data trace is plotted near the center of the 48 channel shot gather for comparison. As indicated in the shot gather, several seismic wave types are recorded (refracted body waes, surface waves, air-waves, and reflected body waves) and data signals from known geologic interfaces are visible in the record (from Dräbenstedt, et al. 2016).

Another study was performed to investigate the use of LDV for delineation and mapping of damage on large civil structures with the use of remote active-source vibrational excitation (Swanson & Rettowski, 2020). This study focused on the use of LDV for mapping damaged areas across the surface of concrete targets using remote impulsive or oscillatory excitation of target structures (e.g., hammer impact or demolition jack-hammer vibrations placed on the target structure outside the area of LDV measurement scanning). The study indicated promising results in terms of identifying surficial or shallow subsurface damaged zones simply based on the amplitude and frequency responses at various measurement points.

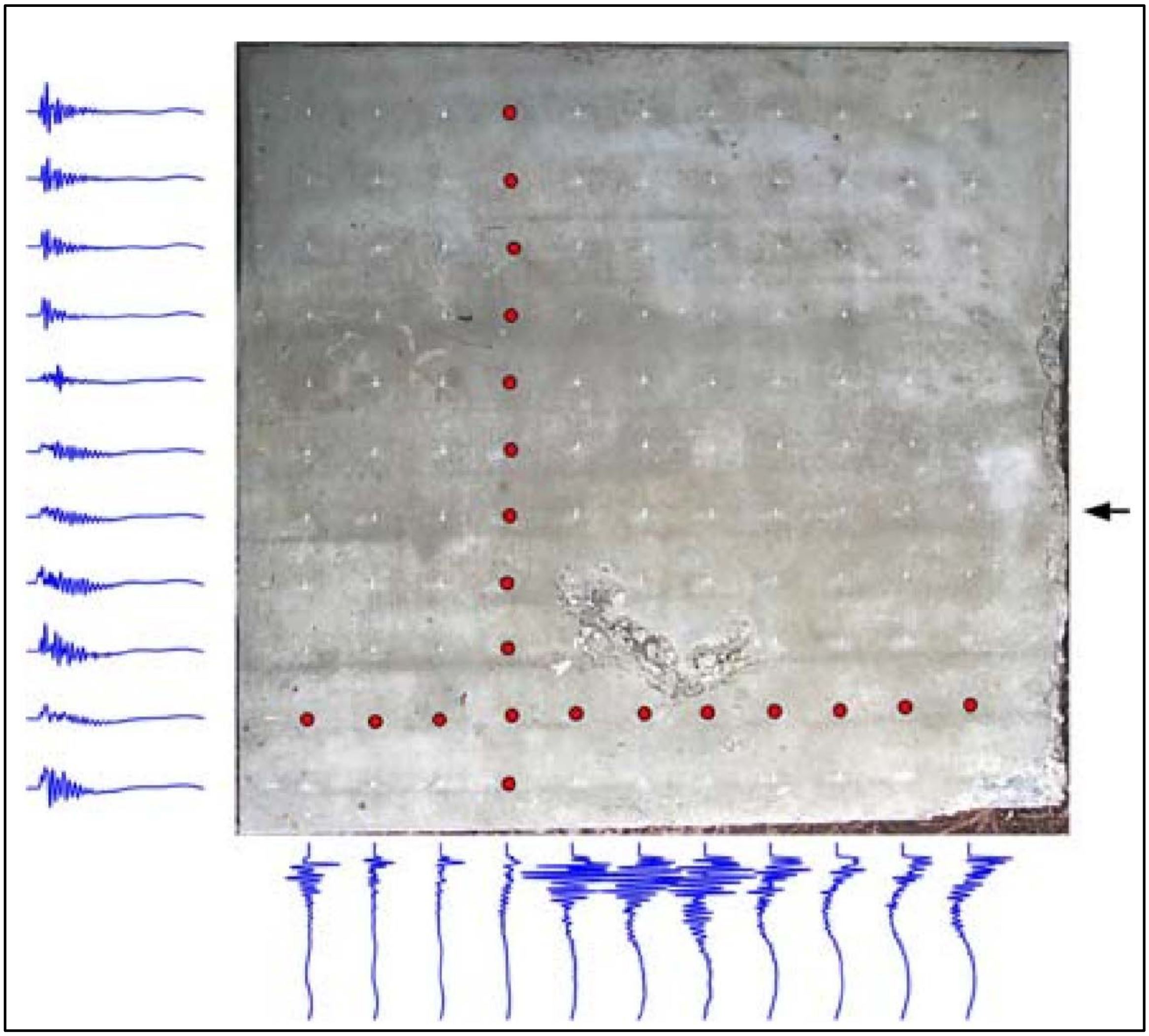

Figure 9. Profiles showing the time series LDV data for the corresponding row and column of test points indicated with red dots. An impactive hammer source was generated on the side of the slab at the location indicated with the black arrow. There is clear variations in raw data for damaged areas versus intact concrete areas (from Swanson & Rettowski, 2020).

Another novel area of research related to the use of LDV for large-scale data collection is the use of unmanned aerial vehicles (UAV) for airborne deployment of LDV sensors. This topic is very new and is generally motivated by the concept of decreasing cost and logistical challenges related to field seismic data collection in energy exploration applications (e.g. to record seismic data from the air for ground surface locations difficult to physically access for deployment of more standard contact-based sensors). However, this concept could potentially have implications on the use of LDV for large civil structures, where long offsets may be problematic for ground-based (e.g., tripod-mounted) LDV systems, or where long-range line-of-sight or laser beam impingement angles become problematic (i.e., doppler shift signal strength drops off with increasing laser beam incidence angle from normal vector of the test surface).

Researchers at the Colorado School of Mines have recently investigated the use of UAV collected touch-free seismic data using LDV systems and stereo video footage enhanced with motion detection algorithms to reconstruct particle motions in 3D (Rapstine & Sava, 2019; Rapstine & Sava, CWP-921, 2019; Rapstine & Sava, CWP-877, 2019). Another related topic ws researched on the use of LDV for orbital seismology applications in space exploration, with a focus on characterizing and dealing with speckle noise from distant rough surfaces (Courville, 2019). A depiction of an impulse response experiment on an asteroid is shown in Figure 10, where a simulated wavefield is propigated through the body from impact point to an LDV measurement point on the opposite side of th target. This research has direct implications on the use of LDV for distant concrete structures with rough surfaces that may be complicated by speckle noise.

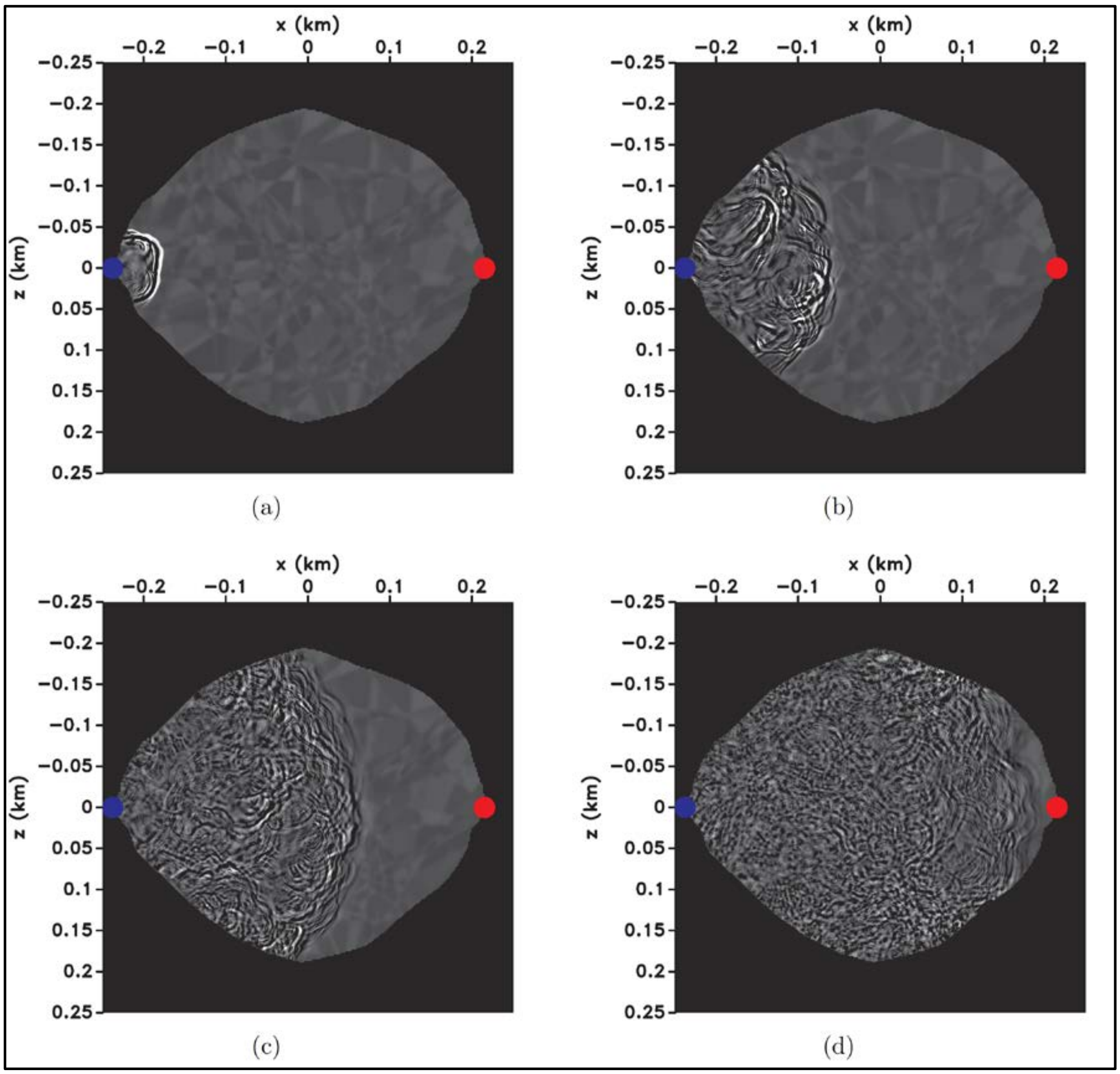

Figure 10. Wavefield snapshots from an impactor with an efficiency of 10−3 at t = 0.15 s, t = 0.45 s, t = 0.75 s, and t = 1.05 s after impact respectively. The blue dot indicates the impact location, and the red dot indicates the LDV recording location, taken from (Courville, 2019).

Existing LDV Hardware and Technology Resources Specific to Concrete Infrastructure

As part of this scoping-level study, research into commercially available technologies and hardware/system solutions related to LDV were researched. Several communications were made with leading US-based manufacturers of LDV systems and software. Several conference calls were held to discuss the capabilities, functionality, and limitations of commercially available LDV systems. Quotes for rental and purchase of these systems were obtained for just a handful of systems that are capable of long-range sensing applicable to Reclamation's large infrastructure inventory.

One of the primary long-range LDV systems that have been identified is the RSV-150 manufactured by Polytec Inc.[1]. As depicted in Figure 11, the PolyTec RSV-150 LDV system is a long-range and portable system. The RSV-150 was identified as one of the most promising long-range LDV systems with a reported range of up to 300m (almost 1000ft away from target) and reported velocity and displacement sensitivity and resolution that match industry standard contact-based sensors such as geophones. This single-beam system is configurable with multi-channel data acquisition hubs and multiple time-synchronized LDV sensor heads in order to perform multi-beam tests. Similar sensors exist, such as the OptoMET Nova-Remote-Sense SWIR Digital LDV with reported ranges up to 300m. The OptoMET Nova-Remote-Sense SWIR Digital LDV also has a scanning version that has reported range of up to 100m from the target surface.

During conversations with PolyTec representative Rob Warmbold on July 23rd, 2019, quotes for rental of a single-beam RSV-150 system is approximately $4000 per week, and was quoted at $63,150 for a single beam system, or $126,300 for a 4-channel system and two LDV sensors. During a conference call with OMS Corporation representative Amit Lal on July 23rd , 2019, a similar system was discussed, and an informal verbal estimate was provided for a dual-beam system that would need to be custom-built for approximately $150,000. Additional research needs to be performed to establish if continuous scanning is feasible with a single RSV-150 or similar units by means of mounting on specialized tripods or with the use of refractive or reflective optics controllers.

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[1] Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

Figure 11. Image of the PolyTec Inc. RSV-150M system with compact data acquisition system and simple USB computer interface. The image shows waveforms and spectral content of vibrations of a remote cell tower antenna several hundred feet away from the tripod-mounted sensor head, taken from (PolyTec, 2019).

In addition to commercially available units for rental or purchase, at least two potential external research partners have been identified that already posses and actively conduct lab-based research with the use of LDV systems. These entities include the Colorado School of Mines (CSM) Geophysics Department, and federal colleagues at the US Army Corps of Engineers (USACE). Specifically, CSM researchers have a PolyTec ISV-500 LDV system with short-to-intermediate ranges of up to 3m. The USACE has a similar unit. CSM also has another LDV system of unknown make/model that has a reported range of up to 20m for intermediate to long-range applications.

Existing Reclamation Resources Specific to Concrete Infrastructure

Reclamation has not performed previous work related specifically to LDV. However, Reclamation TSC geophysicists commonly implement SASW and other seismic survey types, and Reclamation owns several standard seismic data collection systems that can be made available for testing in subsequent research efforts.

Additionally, extensive industry-based and academic-based research and development of LDV devices and nondestructive testing and evaluation techniques, including “long-range” systems (up to 100's of meters range from target surfaces) have been conducted and developed. Several commercially available hardware options (Laser Vibrometers) applicable to this research are available for rental or purchase, as discussed above for the RSV-150 and OptoMET Nova-Remote-Sense SWIR Digital LDV systems. A recent review of relevant international LDV technology and applications is provided by Rothberg et. al (2016).

Existing seismic imaging datasets are available for ground truthing of future field-testing of LDV on concrete structures, including Seminoe Dam in Wyoming (Liechty & Rittgers, 2019), and East Canyon Dam in Utah (Liechty D. , 2014). Seismic SASW imaging surveys have already been conducted at both structures along their downstream faces via rope-team access and manual surveying techniques. An example showing the seismic data coverage at East Canyon dam is shown in Figure 12. Additionally, extensive seismic surveying data coverage is proposed for an upcoming FY20 field survey at Seminoe Dam, as indicated in Figure 13.

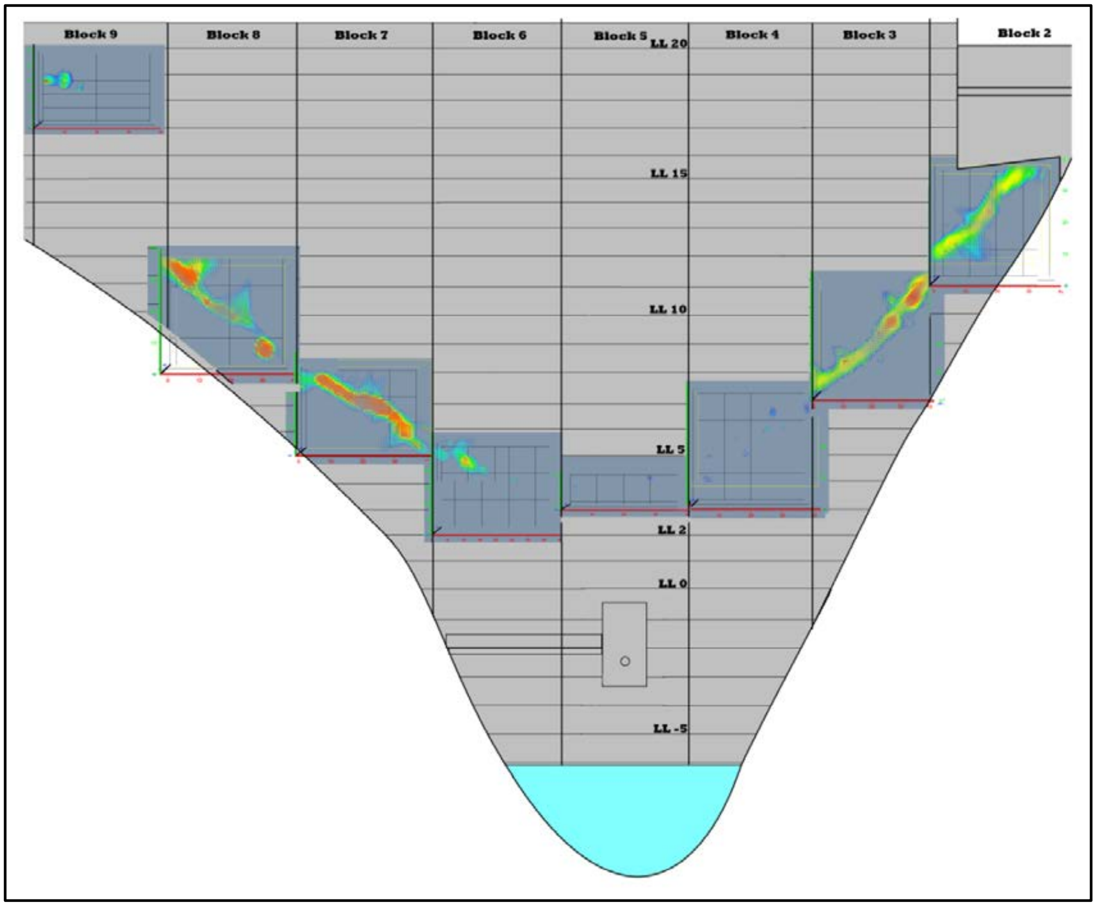

Figure 12. Schematic of the downstream face of East Canyon Dam showing 8 blocks that were surveyed with manual SASW by a ropes access team. The spatial distribution of low seismic velocities associated with a visible crack that spans virtually the entire width of the dam can be seen. Areas of red are interpreted as more extensive cracking/damaged volumes of concrete.

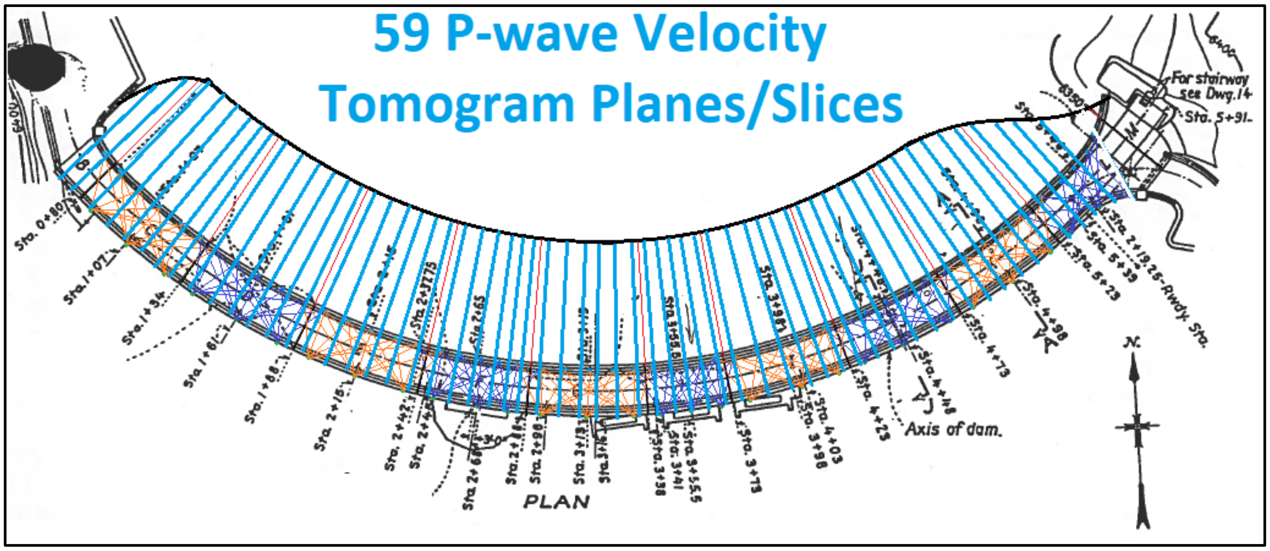

Figure 13. Map-view schematic showing approximately 60 vertical seismic survey transects that were proposed as manual ropes-team seismic survey line locations for an FY20 study at Seminoe Dam.

Challenges and Limitations of LDV Specific to Concrete Infrastructure

One of the main challenges of long-rang LDV is “speckle noise” witch is related to the roughness of the test surface relative to the wavelength of the LDV laser light used for vibration detection. This phenomenon is one of the main challenges related to collection of LDV data on concrete surfaces and distant targets, due to the nature of roughness of concrete surfaces. In some cases, this may require the use of retoreflective tape or installation/mounting of rigid refectors in order to overcome axcessive speckle noise and record a strong reflected laser signal from distant targets. The speckle noise issue becomes exacerbated by increased target offsets, mainly do to the increased area of laser impingment at greater distances. A significant amount of research has been conducted on this topic, in an effort to better understand and account for or remove speckle noise in LDV data (e.g., see Courville, 2019).

In the Dräbenstedt, et al. (2016) study focussed on mobile seismic data collection, the authors discuss some of the challenges related to the collection of seismic energy within the typical frequency range of active seismic imaging techniques. Here, they state “the detection of seismic waves is an application which has not been investigated so far because seismic waves outside laboratory scales are usually analyzed at low frequencies between approximately 1 Hz and 250 Hz and require velocity resolutions in the range below 1 nm/s/√Hz. Thermal displacements and air turbulence have critical influences to LDV measurements at this low-frequency range leading to noise levels of several 100 nm/√Hz. Commonly seismic waves are measured with highly sensitive inertial sensors (geophones or Micro Electro-Mechanical Sensors (MEMS)).”

Modern LDV systems, such as the RSV-150 system by PolyTec Inc., have been developed with selectable resolutions and sensitivity ranges (by means of optics and signal amplification and processing) such that they exhibit adequate sensitivities for seismic data collection at long distances of up to 300m. There is still the challenge, however, related to noise induced by atmospheric influences on the recorded LDV light phase (i.e., temperature and water vapor or wind distortions in realistic field conditions).

Benefits and Costs of LDV Specific to Concrete Infrastructure

If deemed a successful approach to collection of “touch-free” remotely-sensed seismic data on Reclamation’s large concrete structures, LDV technology could be used to more comprehensively assess the state of disrepair of critical infrastructure and high-risk structures/miscellaneous structures, and help to guide and optimize repair and mitigation efforts. Additionally, the results of application of this technology could help to guide efficient and intelligent design and placement of more costly and invasive investigations, including the placement of coreholes along the crest of concrete dams, or across the vertical/sub-vertical faces of concrete structures. Figure 14 presents conceptual benefits of the use of LDV rather than manual seismic surveying on large concrete structures, where the need for physical access and placement of contact-based transducer sensors is replaced by a remote LDV system and computer (top), and the resulting data coverage goes from spatially limited to more spatially comprehensive (bottom).

As an example of the potential cost savings related to the use of LDV compared to other more techniques, we can draw from a recently completed Dam Safety Program-funded research project conducted by Dan Liechty of Reclamation Technical Service Center’s Engineering Geology and Geophysics Group (Liechty & Rittgers, 2019). Here, various geophysical imaging techniques were evaluated for their ability to detect and map ASR deterioration that has been a known issue at Seminoe Dam for several years. The main component of this research project involved the use of Reclamation’s Ropes Access Team for obtaining physical access to the face of Seminoe Dam in order to enable data collection (Figure 15).

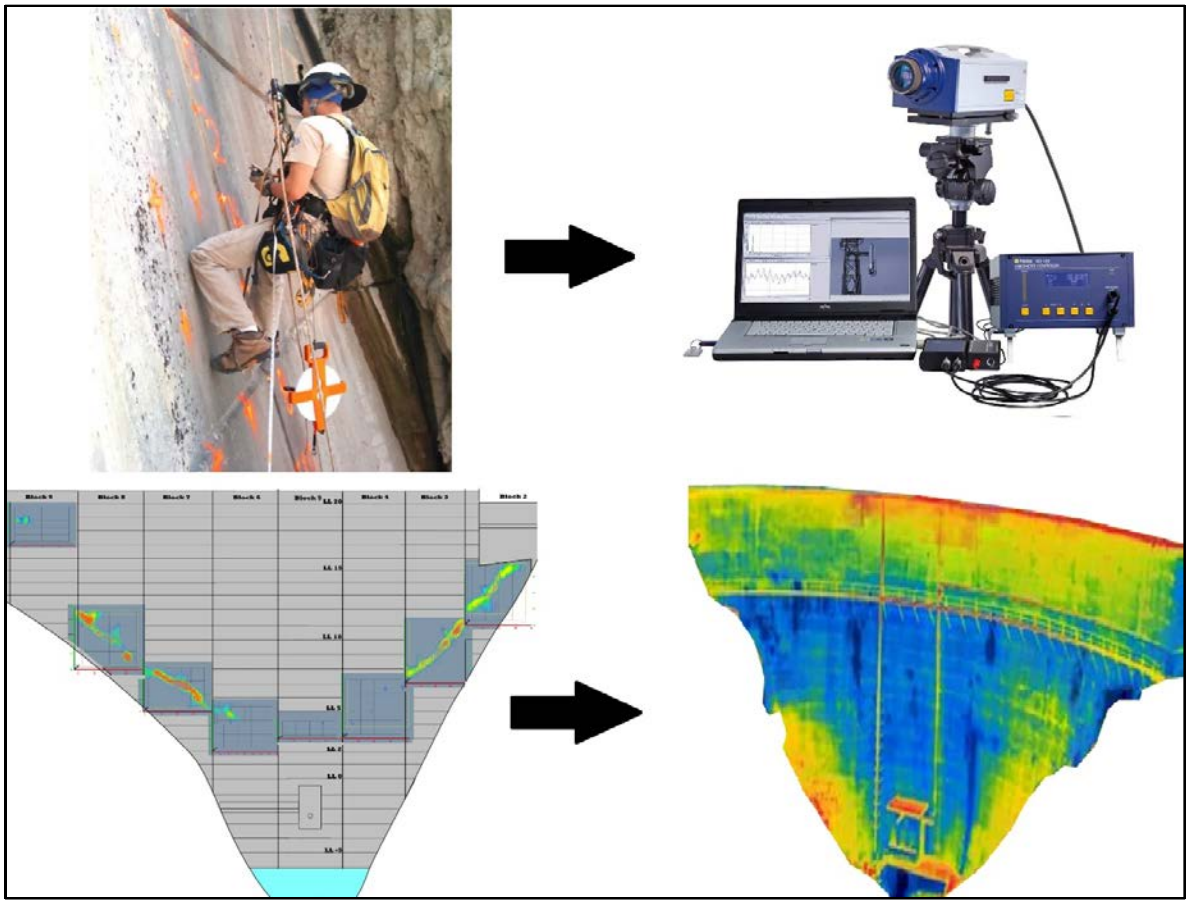

Figure 14. Conceptual benefits of the use of LDV rather than manual seismic surveying on large concrete structures, where the need for physical access and placement of contact-based transducer sensors is replaced by a remote LDV system and computer (top), and the resulting data coverage goes from spatially limited to more spatially comprehensive (bottom).

While several geophysical imaging techniques were deemed successful for imaging ASR deteriorations, the resulting data coverage was very limited (data only collected along two sections of the dam, as depicted in Figure 16), the data were extremely time-consuming to collect (ropes preparations and data collection activities took a multi-person crew several days to complete), and the costs associated with data collection were more than $75,000. Data processing, modeling and reporting brought the entire project budget to just slightly less than $160,000, so a single surveying technique could be deemed to cost one third of this overall project budget (~$60,000), and since two transects of each data type were collected, we could estimate the total cost per transect as $30,000 per technique.

Figure 15. Photos showing ropes access supported geophysical data collection along a vertical seismic survey transect mounted down the face of Seminoe Dam in Wyoming. These data were collected as part of a research project related to ASR detection with the use of various geophysical techniques.

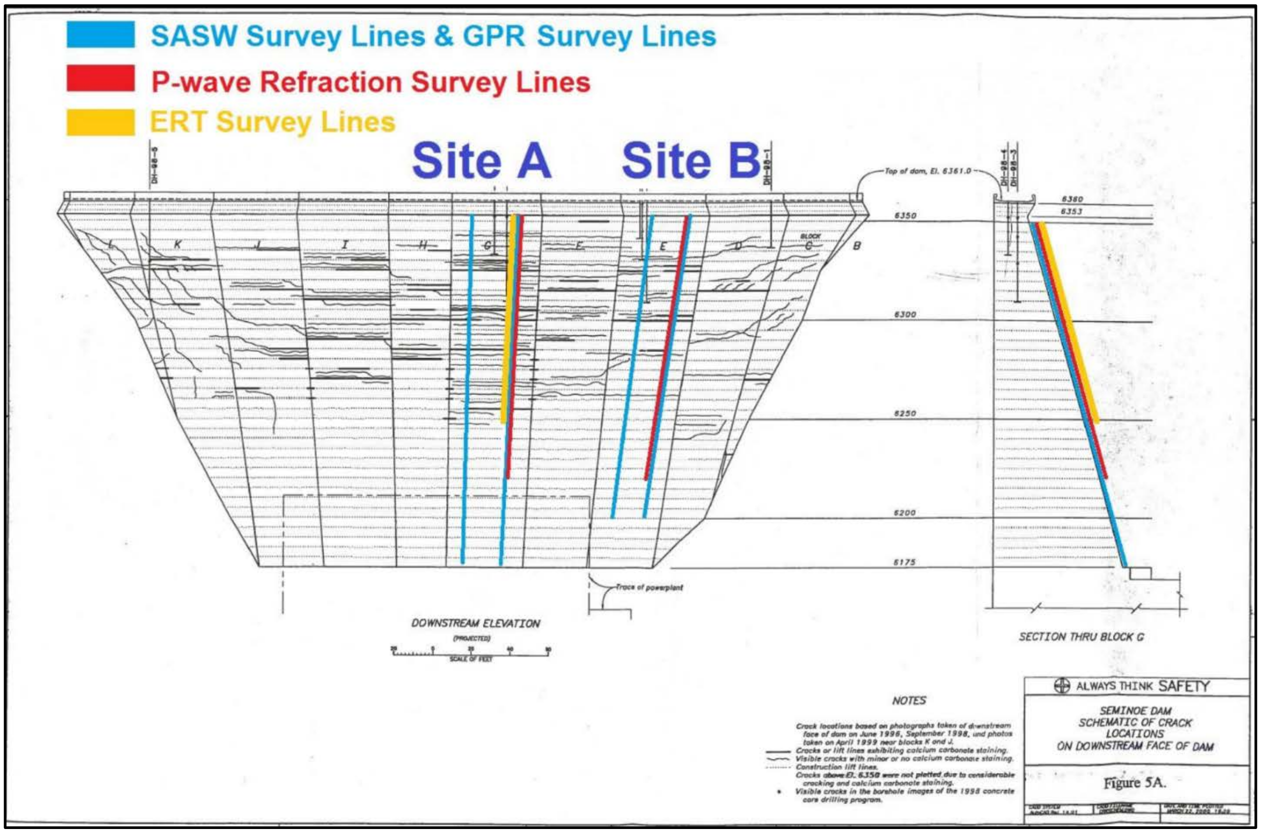

Figure 16. Schematic of the downstream face of Seminoe Dam (left) and cross-sectional side-view (right) depicting the locations of various geophysical surveys conducted as part of a Dam Safety Program Technology Development research project. These three data types with fairly minimal data coverages cost approximately $75,000 to collect, required physical access along the length of each transect, took several days to collect, and took several weeks to process the resulting data (Liechty & Rittgers, 2019).

One of the four main geophysical surveying techniques evaluated in the Seminoe Dam study was Single-Channel Analysis of Surface-Waves (SASW), which is a surface-wave interferometry technique that relies on two sensors and an impactive hammer seismic source. The survey is most commonly conducted manually, by means of two piezoelectric transducers mounted on a bar and pressed against the test surface. A hammer impact is generated off-end of the two recording transducers to generate surface-waves that propagate past/through the two sensors (see Figure 17). The resulting seismic data collected with the two receivers is used to develop a 1D s-wave velocity model (e.g., a Vs sounding at the center point of each test). The test is typically repeated at several locations along survey lines or grids and the resulting 1D model set is merged graphically to create a 2D cross-section or 3D volume of seismic shear-wave velocity distribution. Velocity variations and patterns are then interpreted for structural information and flaws or damage indicated by low velocity zones or areas that exhibit high seismic attenuation.

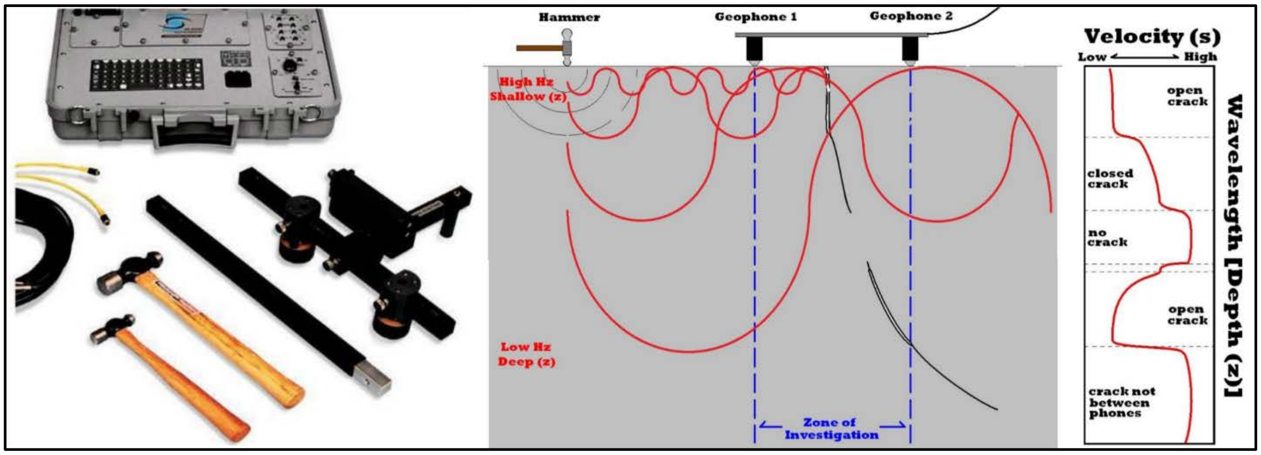

Figure 17. SASW recording equipment consisting of rugged computer, transducer bar, hammers, and cables (left photo), and schematic of the SASW survey technique and resulting 1D Vs model.

If we consider a direct comparison of labor costs for SASW data collection using this standard manual transducer contact approach versus LDV data collection for this Seminoe study, we need to consider the required impactive source near the sensing points. In this case, there may not be a vast difference in cost of piezoelectric transducer versus LDV, since a ropes team is still required. There is the possible benefit of not needing to carry an SASW system, and simply hit the test surface when queued (or trigger from the hammer).

However, it remains to be seen in future research weather or not passive surface-wave interferometry with LDV can be implemented to achieve the same sensitivity and resolution of active-source/manual SASW scanning. If this is possible, then we can assume that LDV data could be collected by a single person remotely and without the need for physical access/ropes team support (e.g., using only background ambient noise or a repeated impactive source placed somewhere away from the test point such as at the base of the dam below a vertical survey transect). This approach would save significant labor costs to collect each transect of data coverage. In this case, manual aiming and recording of passive SASW data with a dual-beam LDV system would take approximately 45 seconds at each test point. In this case, each 200ft tall SASW survey transect consisted of nominally 35 1D soundings (test locations), as shown in Figure 18, and would therefore only take LDV 26 minutes to collect these data.

Passive SASW with LDV sensing could hypothetically be collected by a single person using a tripod-mounted LDV system in less than 24hrs, providing comprehensive data coverage of the entire downstream face of a concrete dam, and data analysis could be partially or fully automated, providing results in matter of hours. Using the estimated 45 seconds per testing point (manual aiming, we can extrapolate using the dimensions of the downstream face of Seminoe dam, which is approximately 400ft across by 200ft tall. In a 24-hour period of time, the entire face of Seminoe could hypothetically be scanned with 2000 test points at nominally 5ft spacings in both the vertical and horizontal directions. The addition of pre-programmed fully automated data acquisition via step-motors and automatic aiming, the time required to collect passive SASW data per test point could be reduced dramatically, enabling even higher data coverage densities and corresponding survey resolutions acquired during the same timeframe.

Once capabilities are fully developed, this approach would cost less than $10,000 to complete at most structures (including travel and labor/non-labor costs related to data collection). A simple comparison of data collection labor costs suggests that passive seismic scanning with multi-beam LDV systems would cost only ~15% of the more expensive approach to geophysical data collection. Depending on the type of seismic data collected (e.g., passive seismic interferometry), data analysis (e.g., post-processing of waveforms and calculation of Vs) could be made semi or fully automated. This automation would potentially help to further reduce costs associated with processing and reporting of results.

Furthermore, if manual SASW surveys were implemented in order to achieve a similar data coverage provided by comprehensive LDV scanning, the resulting costs would scale accordingly. To achieve this data coverage density using manual SASW would hypothetically require the same number of vertical ropes-access surveys to be conducted. This would result in an approximate total cost of $35,000 X 80=$2,800,000. Using this estimated value, a cost savings factor of 280X would be achieved with the use of LDV scanning with manual aiming. This factor could likely be multiplied by 10 if automated aiming and data collection were fully realized.

While the above cost comparison is only hypothetical, it points to the inherent value of first implementing a more rapid and spatially comprehensive screening approach like LDV in order to better guide subsequent more expensive techniques (e.g., geophysical imaging surveys). LDV alone cannot replace these other more expensive imaging techniques, but it could be used to help identify the need for these other approaches and help guide placement of other data collection efforts (including core placement for sample extraction).

It should be noted here that there is still uncertainty of whether or not LDV-based passive seismic interferometry techniques could be used to partially or fully replace contact-based SASW surveys using only background ambient vibrational noise or with the use of a remotely-placed and repetitive active seismic source. Specifically, it has yet to be determined if the high-frequency and high-resolution SASW results presented in Figure 18 could be reproduced using only LDV with passive energy or an active source placed tens to hundreds of feet away from LDV measurement point(s). The high frequencies generally required to produce SASW results on concrete structures like that shown in Figure 18 would be a technical challenge and will require future research initiatives to fully evaluate.

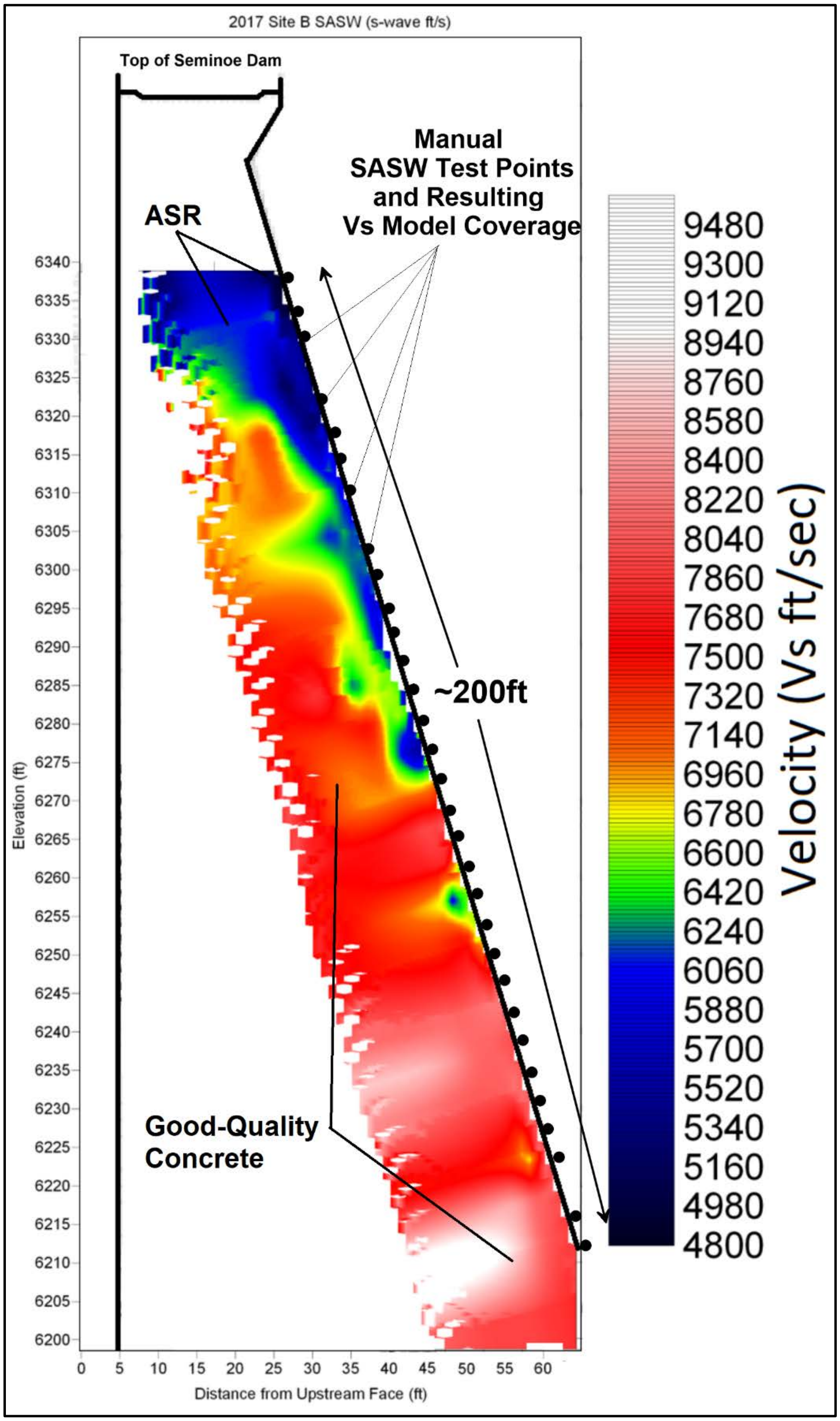

Figure 18. Schematic of Seminoe Dam in cross-section at Site A SASW survey location. The SASW testing locations and resulting s-wave velocity models are depicted. ASR deterioration of the concrete structure can be seen as low velocities concentrated near the top of the dam.

Conclusions

Based upon the literature and technology review performed as a part of this scoping-level research project, it is apparent that LDV could be applied to rapidly identify locations of concrete defects/damage/deterioration in a far more efficient and spatially comprehensive fashion compared to typical geophysical surveying and other invasive techniques currently used (e.g. spot-checking conditions via standard geophysical techniques or drilling/coring programs).

While there is still much to learn on the practical limitations of LDV for large infrastructure assessment efforts, LDV offers promise as a means to remotely interrogate entire surfaces of large structures and interior volumes of material properties (located within appropriate line-of-site and environmental conditions of the LDV sensor) in a comprehensive fashion within 24 to 48 hours using only tripod-mounted sensor. This would by far surpass current seismic data collection and damage/deterioration detection and mapping production rates, would add value of information obtained from field exploration efforts, and would likely drastically improve the benefit/cost ratios of operational and maintenance efforts conducted by Reclamation and other stakeholders.

In addition to lab-based testing and development of analysis techniques, subsequent research efforts could immediately incorporate data collection at large structures, adding value to the results obtained. At a minimum, LDV technology could provide a means to rapidly categorize and prioritize large numbers of structures/components within Reclamation's inventory for subsequent inspection and/or repair efforts. Furthermore, this technology could be extended to long-term (repeated) monitoring and change-detection at a given structure.

Several commercial long-range LDV systems are available for rental or purchase, with off-the-shelf and integrated data acquisition and analysis software available. PolyTec Inc., Colorado School of Mines researchers, and USACE researchers have all voiced interest in supporting and partnering on future conducting-level LDV research initiatives.

Recommendations for Next Steps

The primary recommendation stemming from this scoping level effort is to support continuation of LDV research by funding subsequent conducting-level research activities.

Specific recommendations for next steps include the following:

1. Conduct various lab-based tests with engineered concrete targets
2. Obtain core samples and assess LDV sensitivity to various factors, types of damage, and material property variations
3. Assess the limits of sensitivity and resolution of LDV in active and passive seismic experiments
4. Further assess the usability and limitations of specific hardware available for rental

5. Identify field-scale structures and area office partners that are candidates for field testing of LDV, and carry out large-scale imaging on select structure(s).
6. Further develop data collection techniques and analysis and modeling software to provide quantitative material and defect properties (e.g., elastic moduli estimation) in manual and/or continuous scanning modes of data collection.

Potential External Partners for Future Research

The following non-Reclamation entities have been identified as possible future external partners and collaborators for future research endeavors (all have voiced interest in supporting and partnering on future conducting-level LDV research initiatives):

- PolyTec Inc.: Rob Warmbold, Technical support and US territories manager, Irvine, CA.
- Colorado School of Mines researchers: Geophysics Department Professors Paul Sava and Jeffrey Shragge (and graduate students), Golden, CO
- USACE researchers: Dan Costley, Research Mechanical Engineer, US Army Engineer Research and Development Center, Vicksburg, MS

References

Allen, M. (2010, August 31). *Experimental setup for CSLDV test.* Retrieved from wikipedia.org: https://en.wikipedia.org/w/index.php?curid=28649877

Allen, M. S., & Sracic, M. W. (2010). A New Method for Processing Impact Excited Continuous-Scan Laser Doppler Vibrometer Measurements. *Mechanical Systems and Signal Processing, 24*(3), 721–735.

Bank, G., & Hathaway, G. T. (1980). A revolutionary 3-D interferometric vibrational mode display. *Audio Engineering Society Convention 66.* Audio Engineering Society.

Bendel, K., Fischer, M., & Schuessler, M. (2004). Vibrational analysis of power tools using a novel three-dimensional scanning vibrometer. Vibrational analysis of power tools using a novel three-dimensional scanning vibrometer. *Sixth International Conference on Vibration Measurements by Laser Techniques: Advances and Applications. 5503.* Ancona, Italy: SPIE. doi:https://doi.org/10.1117/12.579525

Buchhave, P. (1975). Laser Doppler velocimeter with variable optical frequency shift. *Optics & Laser Technology, 7*(11), 11-6.

Buunen , T. J., & Vlaming , M. S. (1981). Laser–Doppler velocity meter applied to tympanic membrane vibrations in cat. *Journal of the Acoustical Society of America, 69*(3), 744-50.

Castellini, P., & Santolini, C. (1998). Vibration measurements on blades of a naval propeller rotating in water with tracking laser vibrometer. *Measurement, 24*(1), 43-54.

Castellini, P., Paone, N., & Tomasini, E. P. (1996). The laser doppler vibrometer as an instrument for nonintrusive diagnostic of works of art: application to fresco paintings. *Optics and Lasers in Engineering, 25*(4), 227-46.

Castellini, P., Revel, G. M., Scalise, L., & De Andrade, R. M. (1999). Experimental and numerical investigation on structural effects of laser pulses for modal parameter measurement. *Opt. Lasers Eng., 32,* 565–581.

Chugh, A. (2019, June 18). Verbal Correspondence: discussions of response spectra of dams and structures related to strong motion responses .

Cookson, R. A., & Bandyopadhyay, P. (1980). A fiber-optic laser-Doppler probe for vibration analysis of rotating machines. *Journal of Engineering for Power, 102*(3), 607-12.

Courville, S. (2019). TOWARD ORBITAL SEISMOLOGY: THEORY FOR SPECKLE NOISE REDUCTION IN LASER DOPPLER VIBROMETER MEASUREMENTS ON DISTANT ROUGH SURFACES. *PH.D. Thesis*. Golden, Colorado.

Dietzhausen, H., Bendel, K., & Scelles, N. (2003). Tracking scanning laser Doppler vibrometers: extending laser vibrometry to arbitrarily moving objects. *Proceedings of IMAC XXI*, (p. Paper #168). Kissimmee, Florida.

Dikmen, E., & Basdogan, I. (2008). Material characteristics of a vehicle door seal and its effect on vehicle vibrations. *Vehicle System Dynamics, 46*(11), 975-990. doi:10.1080/00423110701689610

Dräbenstedt, A., Cao, X., Polom, U., Pätzold, F., Zeller, T., Hecker, P., . . . Rembe, C. (2016). Mobile seismic exploration. *12th International Conference on Vibration Measurements by Laser. 1740*, p. 030001. AIP Publishing.

Drain, L. (1980). *The Laser Doppler Technique - Chapter 9.* London: Wiley.

Fisher, B. N., Heisig, P. M., & Kappel, W. M. (2019). *Horizontal-to-Vertical Spectral Ratio Soundings and Depth-to-Bedrock Data for Geohydrology and Water Quality Investigation of the Unconsolidated Aquifers in the Enfield Creek Valley, Town of Enfield, Tompkins County, New York.* U.S. Geological Survey data release. doi:https://doi.org/10.5066/P9ZFTDFY

Fu, Y., Guo, M., & Phua, P. B. (2011). Acousto-optical signal processing; Interferometry; Nondestructive testing; Vibration analysis; Detector arrays; Laser beams; Laser scattering; Laser sources; Optical components; Optical design. *Appl. Opt., 50*, 1280–1288.

Fu, Y., Guo, M., & Phua, P. B. (2011). Multipoint laser Doppler vibrometry with single detector: principles, implementations, and signal analyses. *Appl. Opt., 50*, 1280-1288.

Gallipoli, M., Mucciarelli, M., Castro, R., Monachesi, G., & Contri, P. (2004). Structure, soil–structure response and effects of damage based on observations of horizontal-to-vertical spectral ratios of microtremors. *Soil Dynamics and Earthquake Engineering, 24*, 487–495. doi:10.1016/j.soildyn.2003.11.009

Halkon, B. J., & Rothberg, S. J. (2014). Angular -pitch and yaw- vibration measurements directly from rotors using laser vibrometry. *Mechanical Systems and Signal Processing, 46*(2), 344-60.

Halkon, B. J., & Rothberg, S. J. (2017). Taking laser Doppler vibrometry off the tripod: correction of measurements affected by instrument vibration. *Optics and Lasers in Engineering., 91*, 16-23.

Halliwell , N. A. (1979). Laser-doppler measurement of vibrating surfaces: A portable instrument. *Journal of Sound and Vibration, 62*(2), 312-5.

Hayashi, K., & Nishizawa, O. (2001). Laboratory Studies of Surface Waves Using a Laser Doppler Vibrometer. doi:10.3997/2352-8265.20140030

Hosoya, N., Kajiwara, I., & Hosokawa, T. (2012). Vibration testing based on impulse response excited by pulsed-laser ablation: Measurement of frequency response function with detection-free input. *J. Sound Vib., 331*, 1355–1365.

Jalinoos, F., Agrawal, A. K., Brooks, C., Amjadian, M., Banach, D., Boren, E. J., . . . Ahlborn, T. (2019). *FHWA-HIF-20-004: Post-Hazard Engineering Assessment of Highway Structures using Remote Sensing Technologies.* The City College of New York. McLean, VA: FHWA Research, Development, and Technology Turner-Fairbank Highway Research Center.

Jolivet, V., Gueguen, P., Michel, C., & Schveitzer, A. (2008). ON THE FULL SCALE DYNAMIC BEHAVIOUR OF RC-BUILDINGS USING COHERENT LASER RADAR VIBROMETER. *The 14th World Conference on Earthquake Engineering.* Beijing, China.

Kessler, S. S., Spearing, S. M., Atalla, M. J., Cesnik, C. E., & Soutis, C. (2002). Damage detection in composite materials using frequency response methods. *Composites Part B: Engineering, 33*(1), 87-95.

Khan, A. Z., Stanbridge, A. B., & Ewins, D. J. (1999). Detecting damage in vibrating structures with a scanning LDV. *Optics and Lasers in Engineering, 32*(6), 583-92.

Kilpatrick, J. M., & Markov, V. (2008). Matrix laser vibrometer for transient modal imaging and rapid nondestructive testing. In E. P. Tomasini (Ed.), *Eighth International Conference on Vibration Measurements by Laser Techniques: Advances and Applications.*, (p. 709809). doi:10.1117/12.802929

La, J., Choi, J., Wang, S., Kim, K., & Park, K. (2003). Continuous scanning laser Doppler vibrometer for mode shape analysis. *Optical Engineering, 42*(3), 730-7.

Laderaranch, N. (2014, 11 22). *Basic schematic of a laser Doppler vibrometer.* Retrieved 7 10, 2019, from Wikimedia Commons, the free media repository: https://commons.wikimedia.org/w/index.php?title=File:LDV_Schematic.png&oldid=140228219

Liechty, D. (2014). *Technical Memorandum 85-833000-2014-15: Geophysical Investigations; Spectral Analysis of Surface Waves (SASW) Surveys, East Canyon Dam SASW Crack Investigation.* Denver, CO: US Bureaeu of Reclamation.

Liechty, D., & Rittgers, J. (2019). *Geophysical Surveys: NDE Techniques to Model ASR and Freeze-Thaw Affected Concrete; Seminoe Dam ASR Investigation for S&T Research.* Dnver: US Bureau of Reclamation.

MacPherson, W. N., Reeves, M., Towers, D. P., Moore, A. J., Jones, J. D., Dale, M., & Edwards,, C. (2007). Multipoint laser vibrometer for modal analysis. *Appl. Opt., 46*, 3126-3132.

Maia, N. M., Almeida, R. A., Urgueira, A. P., & Sampaio, R. P. (2011). Damage detection and quantification using transmissibility. *Mech. Syst. Sig. Process., 25*, 2475–2483.

Marchionni , P., Scalise , L., Ercoli , I., & Tomasini , E. P. (2013). An optical measurement method for the simultaneous assessment of respiration and heart rates in preterm infants. *Review of Scientific Instruments, 84*(12).

Nishizawa, O., Satoh, T., Lei, X., & Kuwahara, Y. (1997). Laboratory studies of seismic wave propagation in inhomogeneous media using a laser doppler vibrometer. *Bulletin of the Seismological Society of America, 87*(4), 809-823.

O'Malley, P., Woods, T., Judge, J., & Vignola, J. (2009). Five-axis scanning laser vibrometry for three-dimensional measurements of non-planar surfaces. *Meas. Sci. Technol., 20*.

Oldengarm , J., Van Krieken, A. H., & Raterink , H. J. (1973). Laser Doppler velocimeter with optical frequency shifting. *Optics & Laser Technology, 5*(6), 249-52.

Philp, W. R., Booth, D. J., & Perry, N. D. (1995). Single pulse laser excitation of structural vibration using power densities below the surface ablation threshold. *J. Sound Vib., 185*, 643–654.

Poittevin, J., Picart, P., Faure, C., Gautier, F., & Pézerat, C. (2015). Multi-point vibrometer based on high-speed digital in-line holography. *Appl. Opt., 54*, 3185-3196.

PolyTec. (2019, 7 23). *RSV-150 Specifications Data Sheet.* Retrieved from www.polytec.com: https://www.acoutronic.se/pdf/vibration/Polytec_RSV-150_datasheet.pdf

Pourahmadian, F., & Guzina, B. B. (2018). On the elastic anatomy of heterogeneous fractures in rock. *Int. J. Rock. Mech. Min. Sci., 106*, 259-268.

Rapstine, T., & Sava, P. (2019). *Airborne seismic monitoring using stereo vision.* Colorado School of Mines, Geophysics. Golden, Colorado: Center for Wave Phenomena.

Rapstine, T., & Sava, P. (2019). *Contactless seismic acquisition using stereo vision.* Colorado School of Mines, Geophysics. Golden, Colorado: Center for Wave Phenomena.

Rapstine, T., & Sava, P. (2019). *Towards airborne seismic data acquisition.* Colorado School of Mines, Geophysics. Golden, Colorado: Center for Wave Phenomena.

Ribichini, R., Di Maio, D., Stanbridge, A. B., & Ewins, D. J. (2008). Impact Testing With a Continuously-Scanning LDV. *26th International Modal Analysis Conference (IMAC XXVI)* . Orlando.

Rothberg , S. (2006). Numerical simulation of speckle noise in laser vibrometry. *Applied Optics, 45*(19), 4523-33.

Sever, I. A., Stanbridge, A. B., & Ewins, D. J. (2006). Turbomachinery blade vibration measurements with tracking LDV under rotation. *7th International Conference on*

Vibration Measurements by Laser Techniques (pp. 63450L-63450L). NA: International Society for Optics and Photonics.

Sriram, P., Craig, J. I., & Hanagud, S. (1990). Scanning laser Doppler vibrometer for modal testing. *International Journal of Analytical and Experimental Modal Analysis, 5*, 155–167.

Stanbridge, A. B., & Ewins, D. J. (1999). Modal testing using a scanning laser Doppler vibrometer. *Mechanical Systems and Signal Processing, 13*(2), 255–70.

Stanbridge, A. B., Martarelli, M., & Ewins, D. J. (2004). Measuring area vibration mode shapes with a continuous-scan LDV. *Measurement, 35*(2), 181-9.

Swanson, P., & Rettowski, J. (2020). *Damage Delineation in Structures Using Laser Vibrometry And Remote Excitation.* Spokane, WA: National Institute for Occupational Safety and Health.

Terasaki , S., Wada, N., Sakurai , N., Muramatsu , N., Yamamoto , R., & Nevins , D. J. (2001). Nondestructive measurement of kiwifruit ripeness using a laser Doppler vibrometer. *Transactions of the ASAE, 44*(1), 81.

Vass, J., Šmíd, R., Randall, R. B., Sovka, P., Cristalli, C., & Torcianti, B. (2008). Avoidance of speckle noise in laser vibrometry by the use of kurtosis ratio: Application to mechanical fault diagnostics. *Mechanical Systems and Signal Processing, 22*(3), 647-71.

Yeh, Y., & Cummins, H. Z. (1964). Localized fluid flow measurements with an He–Ne laser spectrometer. *Applied Physics Letters, 4*(10), 176-8.