MPC-694

October 11, 2022

Project Title

Calibrating Ground Response Analyses Beneath an Instrumented Bridge using the I-15 Borehole Array and Ground Motions from the Magna Earthquake

University

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Research Needs

On March 18, 2020 a magnitude 5.7 earthquake struck the Salt Lake Valley near Magna, Utah*. *While it lasted less than 10 seconds and no deaths were reported, this relatively small earthquake caused over $600 million in damage and exposed vulnerabilities in Utah's housing, education, lifeline, and infrastructure networks. Effects from the Magna earthquake are even more shocking when viewed with an understanding that Utah's "big one", an expected 7.0-plus magnitude earthquake, would release approximately 90 times more energy than the Magna earthquake, and that we are hundreds of years overdue for a large earthquake along multiple sections of the Wasatch Fault. It has been estimated that approximately 80% of Utah's 3.2-million population lives within 15 miles of the Wasatch Fault, which essentially runs right underneath the heavily developed I-15 corridor between Nephi and Brigham City. This leaves the people and infrastructure of Utah precariously exposed to significant seismic risk. In fact, a study conducted in 2015 by the Earthquake Engineering Research Institute (EERI 2015) revealed that a magnitude 7.0 earthquake along the Salt Lake City segment of the Wasatch Fault would result in approximately: 2,500 deaths, 8,000 injuries, 84,000 displaced households, and $33 billion in economic losses. Furthermore, the Utah Department of Transportation (UDOT) has identified strong ground shaking, soil liquefaction, and rock slides caused by earthquakes as significant contributors to the overall risk faced by transportation infrastructure in the state (UDOT 2020).

The M5.7 2020 Magna earthquake is the best ever recorded earthquake in the Basin and Range extensional tectonic regime. More than 160 strong motion/broadband seismic stations recorded the mainshock out to epicentral distances of more than 600 km. The highest recorded peak ground acceleration (PGA) was recorded at station LKC, 4.4 km from the epicenter, where one horizontal component recorded a PGA = 0.54 g's and the geometric mean PGA of the two horizontal components was 0.43 g's (Wong et al. 2021). Additionally, ***important ground motions were recorded by a geotechnical borehole array installed near the intersection of I-15, I-80 and SR-201 in Salt Lake City (Youd et al. 2003).*** This borehole array recorded the Magna earthquake ground motions at both the surface and at a depth of 400 feet below the surface. As discussed in more detail below, borehole arrays play a key role in understanding seismic site response and in calibrating numerical ground response models. This particular borehole array is even more valuable, as it lies in close proximity to a flyover bridge from WB I-80 to WB SR-201 (i.e., UDOT bridge C-846) that is instrumented with 18 accelerometers (a combination of triaxial, biaxial and uniaxial) that recorded the structural response of the bridge during the Magna earthquake (Halling and Petty 2001). ***There is a need to study the ground motions recorded by the I-15 borehole array during the Magna mainshock and its aftershocks as a means to calibrate seismic ground response models that can inform numerical ground response modeling throughout the Salt Lake Valley, particularly at bridge sites where shaking was not recorded.*** These numerical ground response models can then be expanded in the future (not a part of the present proposal) to include soil-structure interaction modeling for various bridges throughout the valley, with calibrations performed using the structural response recorded on bridge C-846. ***The ability to accurately model the recorded ground shaking during the Magna earthquake (i.e., backward analyses) will allow for greater confidence in forward predictions of future, more damaging earthquakes. This will benefit seismic hazard studies not only in Utah, but also nationally and internationally through increased understanding of how to build site-specific 3D ground models and how to best perform site-specific 2D and 3D numerical wave propagation simulations know as ground response analyses (GRAs).***

Research Objectives

The overarching research objective of this proposal is to perform numerical 2D and 3D GRAs for the I-15 borehole array and instrumented bridge site using a large, site-specific 3D shear wave velocity (Vs) model. The GRAs will be calibrated at small- to moderate-strains using the ground motions recorded by the borehole array throughout its lifetime and during the 2020 M5.7 Magna earthquake and its aftershocks. Note that only a portion of the Magna earthquake mainshock was recorded by the borehole array due to power loss on a communication line and a full buffer on the main recorder. While this is unfortunate, two M4.6 aftershocks were recorded and will be valuable to the study. Furthermore, calibrating the numerical GRAs at small-strains is of great importance and consistent with the work done a many other borehole array sites around the world, and these efforts will not be affected by the partial main shock recordings. As noted above, the ability to accurately model the small- to moderate-strain recorded ground shaking during the Magna earthquake sequence (i.e., backward analyses) will allow for greater confidence in forward predictions of future, more damaging earthquakes with highly nonlinear wave propagation. ***Key aspects of this research that make it unique include the development of a large (~ 1 km^2), site-specific 3D Vs model using the procedures recently developed in my research group (i.e., Hallal and Cox 2021a and 2021b) and performing 2D/3D GRAs based on this model using a proven 3D wave propagation software. Our research group has recently been using the open-source code SeismoVLAB for this purpose (e.g., Hallal and Cox 2022).*** Sub-objectives that will be accomplished throughout the research project are detailed in chronological order below:

1. Prepare a database of small- to moderate-strain ground motions recorded by the 0-ft and 400-ft borehole array stations during their complete installation lifetime, including aftershocks of the 2020 Magna earthquake.
2. Calculate empirical transfer functions (ETFs) between the 0-ft and 400-ft borehole stations for all small-strain ground motions in the database.
3. Perform non-invasive seismic site characterization around the borehole array using a combination of MASW, MAM, and HVSR methods with the goal of developing Vs profiles down to bedrock.
4. Develop a pseudo-3D Vs model for the site that extends at least 500 m in each direction from the borehole array.
5. Use the 3D Vs model to perform 2D and 3D numerical, linear-viscoelastic GRAs to obtain theoretical transfer functions (TTFs) between the 0-ft and 400-ft borehole array stations.
6. Compare the ETFs with the TTFs as a means to refine and calibrate the subsurface 3D Vs model and the numerical, linear-viscoelastic GRAs prior to performing larger strain GRAs.
7. Perform GRAs for the moderate-strain GMs recorded by the biggest aftershocks of the 2020 Magna earthquake (e.g., two M4.6 events from 18 March 2020) and compare ETFs with TTFs.
8. Investigate the partially-recorded borehole array GMs for the main shock of the 2020 Magna earthquake to determine if they can be of use for further nonlinear calibration of the GRAs.
9. Prepare a database of ground motions recorded by the bridge instrumentation in preparation for future soil-structure interaction modeling, which will not be completed in the work plan of the present research proposal.
10. Disseminate research findings through peer-reviewed journal and conference publications.

Research Methods

GRAs are commonly performed in an attempt to estimate the site-specific, frequency-dependent amplification of seismic waves (i.e., site effects) as they travel from bedrock through soil to the ground surface. The importance of accurately predicting site effects for engineering infrastructure projects in seismically active regions cannot be overstated. A large body of research on site response over the past decade has focused on our abilities to replicate recorded ground motions at borehole/downhole array sites, where both the input (rock) and output (surface) ground motions are known. While several studies have shown that 1D GRAs can successfully model key features of the recorded response at some downhole array sites (e.g., Kim and Hashash, 2013; Tao and Rathje, 2020), all researchers have noted that the computed and recorded amplitudes cannot be matched at many sites (e.g., Afshari and Stewart, 2019; Boore, 2004; Kaklamanos et al., 2013; Thompson et al., 2009). While the findings from these studies vary somewhat, ***on average more than 50% of borehole array sites are poorly modeled using 1D GRAs, with actual percentages varying between approximately 30% to 80%. Thus, 2D and***

3D GRAs need to be investigated as a means to better model seismic site response. The borehole array studies noted above have predominantly focused on small-strain ground motions, indicating that challenges associated with modeling nonlinear soil behavior are not the first problem that must be solved, but rather limitations associated with understanding small-strain soil properties and how they vary spatially across the site.

The lack of cost-effective and reliable site characterization methods to quantify spatial variability in subsurface conditions, particularly regarding Vs measurements needed for 3D GRAs, is an impediment to future progress in allowing reliable site response modeling. Indeed, even at our most studied downhole array sites in the U.S., Japan, and elsewhere globally, we are generally limited to 1D representations of Vs. This simply isn't adequate to enable robust 3D GRAs. ***While the exact areal extent required to adequately capture important 3D subsurface structure influencing site response is an open research question, and certainly site-dependent, recent research by Hallal and Cox (2021b and 2022) suggests that 3D subsurface models need to be at least 400m x 400m to adequately model low frequency/long wavelength shaking, with deeper, softer sites requiring larger incorporated areas, perhaps as large as 1km x 1km.*** As noted above, my research team has recently developed a method called the H/V geostatistical approach for generating large, site-specific 3D Vs models and demonstrated its application at two U.S. borehole array sites (Hallal and Cox 2021a and 2021b). Furthermore, we have used these large 3D Vs models to investigate the area influencing site response by performing 1D, 2D, and 3D GRAs (Hallal and Cox 2022). To my knowledge, the 3D Vs models developed by my research team at the Treasure Island and Delaney Park downhole array sites are the only 3D Vs models available at any borehole array sites in the world that extend deep enough and over large enough areas to enable meaningful comparisons between 3D GRAs and recorded ground motions. ***In this research, we will develop a large, 3D Vs model at the I-15 borehole array site using similar procedures to Hallal and Cox (2021a). This will make the I-15 borehole array site quite unique among worldwide borehole array sites and allow for more accurate 2D and 3D GRAs***.

By far, 1D wave propagation is the most widely used approach for simulating site effects. The equivalent linear method (as embodied, for example, in the widely used program SHAKE91; Idriss and Sun, 1991) and the nonlinear site response analysis method (as embodied, for example, in the widely used program DEEPSOIL; Hashash et al, 2020) are routinely used in engineering practice. These approaches have well established procedure for developing the requisite input parameters, and they have been used for both site-specific and broader regional studies to develop site amplification functions for use in building codes (Harmon et al, 2019, Hashash et al, 2020). However, our research community has long recognized the limitations of 1D GRAs and devoted extensive efforts to study 2D and 3D GRAs (e.g., Abell et al. 2018, Assimaki et al. 2005, de la Torre et al. 2019, de la Torre et al. 2021, Jeremic et al. 2013, Makra & Chavez-Garcia 2016, Riano et al. 2020, Thompson et al. 2012). ***Despite significant progress that has been made in modeling 3D GRAs, there remains a missing link between the site characterization efforts necessary to develop large 3D models and the availability of computationally efficient numerical modeling tools that are broadly accessible to the engineering community. However, my research team has recently been able to bridge this gap by combining large-scale, site-specific 3D Vs models with powerful, open-source 3D wave propagation software and high-performance computing.*** Specifically, we have used SeismoVLAB (Kusanovic et al. 2020) to accurately capture multi-dimensional site response recorded by the Treasure Island downhole array (Hallal and Cox 2022). We will expand upon these efforts by performing similar GRAs at the I-15 borehole array site.

Expected Outcomes

Expected outcomes from the project include:

(a) first-time application of advanced, large-scale, site-specific 3D Vs model development in the state of Utah,

(b) better 2D/3D GRA modeling procedures for the soft, Bonneville Clay deposits underlying much of the Salt Lake Valley,

(c) better understanding of the site-specific, frequency-dependent loads imparted to transportation infrastructure during the Magna earthquake and in future, larger earthquakes, and

(d) the ability to perform future soil-structure interaction modeling for various bridges throughout the valley, with calibrations performed using the structural response recorded on bridge C-846.

These outcomes will benefit seismic hazard studies not only in Utah, but also nationally and internationally through increased understanding of how to build site-specific 3D ground models and how to better perform site-specific 2D and 3D numerical GRAs.

Relevance to Strategic Goals

State of Good Repair – Ensure the U.S. proactively maintains critical transportation infrastructure in a state of good repair.

This research will help to ensure that the U.S. proactively maintains critical transportation infrastructure in a state of good repair by providing guidelines and tools to researchers and practitioners looking to evaluate the seismic resiliency of aging bridges. As noted above, UDOT has identified strong ground shaking, soil liquefaction, and rock slides caused by earthquakes as significant contributors to the overall risk faced by transportation infrastructure in the state (UDOT 2020). Other states with significant seismic hazard, such as Alaska, Arkansas, Californian, Oregon, South Carolina, Tennessee, and Washington, face similar challenges in evaluating and mitigating risk to their aging bridge inventories.

Educational Benefits

One M.S. student will be support on this research and will be responsible for most of the analyses. However, it is anticipated that at least five USU graduate students will be involved in the field testing required to develop the 3D Vs model beneath the I-15 borehole array. Furthermore, I plan to involve students from my Fall 2022 In-Situ Site Characterization course in the field testing and use the data we collect for example datasets related to horizontal-to-vertical spectral ratio (H/V or HVSR) testing, multi-channel analysis of surface waves (MASW) testing, and microtremor array measurements (MAM) testing. Furthermore, I plan to incorporate some of the GRA analyses into my Spring 2023 Earthquake Engineering course as examples of more complex site response studies than the typically-taught 1D GRA approach.

Technology Transfer

Technology transfer and broad dissemination of research findings is an important objective of this research effort. I seek to better understand and improve site-specific 2D/3D GRAs both inside Utah and across a larger international community. In order for these research efforts to have an impact on practice they must be disseminated to a broad audience through peer reviewed journal and conference publications. I have demonstrated a commitment to this principal throughout my career, with over 100 peer reviewed publications.

Work Plan

The work plan includes efforts that will be put forth to achieve each of the sub-objectives listed above. Each sub-objective represents a major task that must be completed in chronological order for the research to move forward. The expected completion dates for each task, expressed in the anticipated months from the starting date of the project, are provided in brackets, below, at the end of each task:

1. Prepare a database of small- to moderate-strain ground motions recorded by the 0-ft and 400-ft borehole array stations during their complete installation lifetime, including after-shocks of the 2020 Magna earthquake. [2 months]
2. Calculate empirical transfer functions (ETFs) between the 0-ft and 400-ft borehole stations for all small-strain ground motions in the database. [3 months]
3. Perform non-invasive seismic site characterization around the borehole array using a combination of MASW, MAM, and HVSR methods with the goal of developing Vs profiles down to bedrock. [3 months]
4. Develop a pseudo-3D Vs model for the site that extends at least 500 m in each direction from the borehole array. [5 months]
5. Use the 3D Vs model to perform 2D and 3D numerical, linear-viscoelastic GRAs to obtain theoretical transfer functions (TTFs) between the 0-ft and 400-ft borehole array stations. [7 months]
6. Compare the ETFs with the TTFs as a means to refine and calibrate the subsurface 3D Vs model and the numerical, linear-viscoelastic GRAs prior to performing larger strain GRAs. [8 months]
7. Perform GRAs for the moderate-strain GMs recorded by the biggest aftershocks of the 2020 Magna earthquake (e.g., two M4.6 events from 18 March 2020) and compare ETFs with TTFs. [9 months]
8. Investigate the partially-recorded borehole array GMs for the main shock of the 2020 Magna earthquake to determine if they can be of use for further nonlinear calibration of the GRAs. [9 months]
9. Prepare a database of ground motions recorded by the bridge instrumentation in preparation for future soil-structure interaction modeling, which will not be completed in the work plan of the present research proposal. [10 months]
10. Disseminate research findings through peer-reviewed journal and conference publications. [10 months]

Project Cost

Total Project Costs:	$120,000
MPC Funds Requested:	$ 60,000
Matching Funds:	$ 60,000
Source of Matching Funds:	Utah State University

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