DEPTH TO BEDROCK AND SHEAR-WAVE VELOCITY PROFILING IN STE. GENEVIEVE, MISSOURI

M.S. THESIS PROPOSAL

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Abstract

A scientific experiment has been designed to use the gravity, refraction, and the Multi-Channel Analysis of Surface Waves (MASW) techniques to determine the depth to bedrock and shear wave velocity at selected sites around the historical Old Brick House in Ste. Genevieve, MO. The area has historical buildings including the Old Brick House that predate the 1811-1812 earthquakes in the New Madrid seismic zone. Visual inspection of these buildings has been used to estimate magnitudes of those historic earthquakes and estimate the hazard posed by the New Madrid seismic zone. Published hazard estimates from the visual inspection approach tend to lower New Madrid seismic hazard, contrary to other studies based on observed seismic intensity decay with distance such as Cramer and Boyd (2014). The proposed experiment will help address how soil site response might affect expected ground motions and damage observations in the historic section of Ste. Genevieve. The gravity technique will be the main technique used to estimate soil thickness over bedrock. Refraction and MASW techniques will be restricted to a few sites due to the paved roads or residential buildings. The refraction survey will be used as a constraint for the gravity survey to estimate the depth to bedrock while the MASW survey will independently provide shear wave velocity from generated surface-waves traveling along the refraction spread. The depth to bedrock and the shear wave velocity will help us understand the response of soil (amplification or de-amplification) to earthquake shaking. This study will advance our understanding of soil response at the historic buildings and the findings from this study can be used for calculating site amplification and updating hazard maps and estimates in historic Ste. Genevieve (not part of this proposal).

Introduction

Ste. Genevieve, Missouri experienced the historic 1811-1812 earthquake sequence. Different studies using observed seismic intensities resulted in different magnitude estimates for those earthquakes. Johnston and Schweig (1996) obtained values around 8.0 while other studies like Nuttli (1973), Hough et al. (2000), Street (1982), and Kochkin and Crandell (2004) showed the magnitudes to be around 7.0. These variations in magnitude estimates show the importance of an on-site study in that region to better constrain likely ground motions from New Madrid earthquakes for comparison to observed building damage. Cramer et. al. (2017) showed in their study for the St. Louis, MO-IL area that an on-site characterization of depth to bedrock, and the measurement of compressional and shear wave velocities provide a better understanding of the effect of large earthquakes in any region and a measure of any future threat posed.

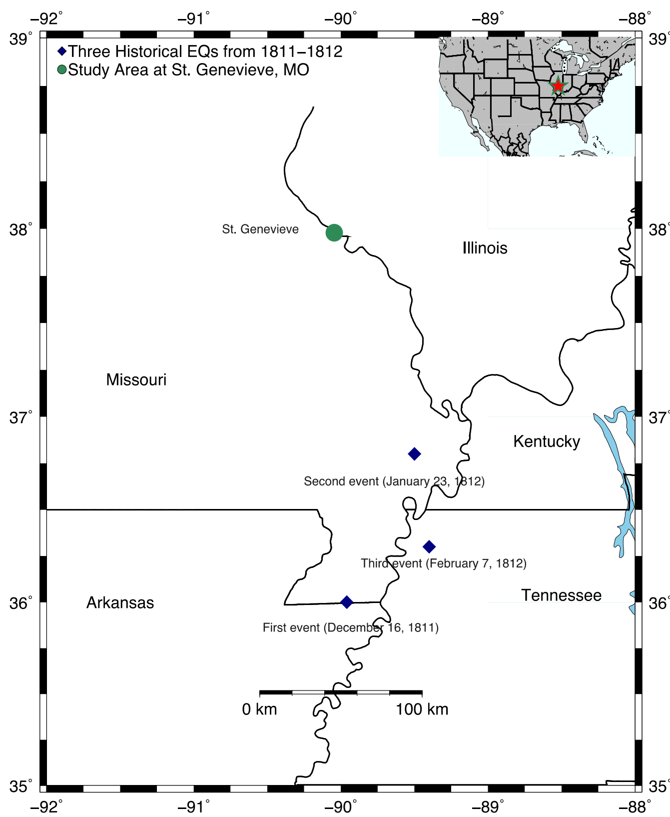

Figure 1: Study area at Ste. Genevieve, Missouri relative to the three historical earthquakes from 1811-1812, Bakun and Hopper (2004). Red star on the inserted US map represents the study area

Kochkin and Crandell (2004) used the physical damage to the historic buildings in their study to calculate the magnitude of 1811-1812 earthquakes. Most of the historic buildings that were surveyed by them are located in Ste. Genevieve, Missouri (about 100 km north of New Madrid). The position of the study area relative to the three historic earthquakes is shown in Figure 1.

Downtown Ste. Genevieve has one historic brick building (the Old Brick House) and two other historic houses. Additionally, two more houses having French vertical log style construction are located just south of downtown and predate the 1811-1812 earthquakes. The presence of these damaged buildings, having different construction styles and resistance to earthquake shaking are indication of the effect of 1811-1812 earthquakes. Because the buildings are still in existence, perhaps ground motions were smaller there than expected. Alternatively, maybe site conditions were conducive to smaller ground motions. Performing a site survey for shear wave velocity and depth to bedrock could clarify these ambiguities.

We know that the depth to bedrock and shear wave velocity estimation are two important inputs for calculating site amplification in a region. Abbot and Louie (2000) mentioned in their paper that knowing the depth to bedrock is helpful for seismic hazard analysis of sedimentary basins. Kawase and Aki (1989) showed that both basin shape (i.e. depth to bedrock) and velocity contrast within the alluvium were essential parameters needed to model ground motion in the Mexico City basin. The density contrast between bedrock and unconsolidated and/or poorly consolidated sediments allows the determination of depth to bedrock. Depth can be inferred from the spatial distribution and amplitude of the gravity anomaly. Many researchers have used this technique for hydrologic, geothermal, mineral, and exploration problems (Abbott and Louie, 2000). The Old Brick House is located in an urban area having residential buildings around it. Even though different methods like reflection, drilling, gravity, refraction etc. are available for calculating depth of bedrock, the paved roads and residential areas there make it undesirable to use methods other than the gravity. We, therefore, propose to use the gravity survey as the principal technique to determine the depth of bedrock in Ste. Genevieve. Seismic refraction and MASW techniques will be used only at selected sites upon approval to measure the P wave (Burger and Burger, 1992; Fowler, 1990) and S wave (Xia et. al., 1999; Socco et. al., 2010) velocities, respectively.

Methodology

We have identified eight prospective locations around the Old Brick House to conduct the gravity, refraction, and MASW surveys together (Figure 2). Even though a reflection survey could provide a direct measurement of the depth over bedrock throughout the town, running a reflection survey will be undesirable due to the urban infrastructure. The result from the refraction survey at constant points will give us an independent measure for the depth over bedrock. The gravity technique will also give us a measurement for relative soil thickness. The measurement from the refraction survey will help us evaluate the density contrast that we will use for interpreting the gravity measurements and will be adjusted accordingly. Once we get our adjusted density contrast for that region, we will complete the rest of the survey using the gravity technique following the profiles (red lines) in Figure 2. MASW at our control sites will independently provide shear wave velocity.

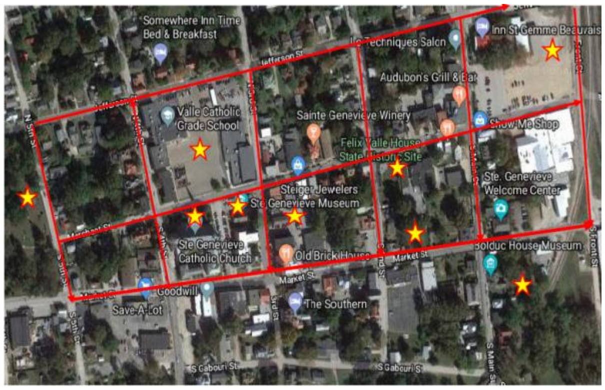

Figure 2: The stars represent the proposed locations for running all three surveys together. The red lines represent the profiles for running gravity survey following the roads around the Old Brick House in Ste. Genevieve, MO (photo base from Google earth).

Gravity measurement:

The first step in a gravity survey is to establish a base station. It is desirable to return to the base station within one hour over the duration of the survey to adjust for the drift and tidal effect. Once the base station is established, elevation, position and dial reading of the gravimeter are recorded for each station. This will be repeated until three consecutive readings are found within 0.1 dial division to make sure the meter is stable (Burger et. al., 2006). A differential GPS could be used to determine the elevation and position. Burger et. al., (2006) mentioned that determining elevation must be known to within 25-30 cm to maintain Bouguer anomaly values that are accurate to better than 0.1 mGal. For different depths in our proposed region, using a density contrast of 0.67 gm/cm^3, the theoretically calculated gravity anomalies for an infinite slab are as below.

Depth (m)	Calculated Anomaly (mGal)
3	0.0843
10	0.2809
30	0.8428

This suggests that to obtain a depth resolution of 3 m, the gravity survey needs to have better than 0.1 mGal accuracy, which implies the elevation of each station must be determined to better than

10-20 cm (a few tenths of a foot), which can be obtained with the external antenna on the GPS system that CERI has.

Refraction Survey:

The depth of penetration in a seismic refraction survey is approximately 1/5th of the length of geophone spread, including offset shots. So, if we want to see 3 m deep, we'll need a minimum of 15 m seismic spread. Similarly, for 10 m and 30 m, we'll need 50 m and 150 m of spread respectively. There will be two shots (multiple shots can also be used), one at each end of the spread using an active source (a sledgehammer). The end geophone will be moved inward by one-half an interval between two geophones, positioning the shot on the end. In that case, the forward and reverse traveling time should be identical (Geometrics 2018). Once the survey is done, the result will be a travel time curve showing the signal arrival time at each geophone vs distance that can be interpreted for seismic velocity and interface depth.

MASW (Multichannel Analysis of Surface Waves) Survey:

The field procedure for MASW matches with a traditional refraction survey. Both the refraction and the MASW measurements can be conducted with the same equipment. An active source is used for active surveying along with 24 channels with an engineering seismograph. Due to the dispersive nature of surface waves, a dispersion curve will be obtained for each spread. Xia et. al. (1999) explained the inversion procedure of the dispersion curve in their paper to obtain the shear wave velocity of a particular sub-surface. A layered earth model is considered for this purpose. MASW can be used in three modes- active, passive, combined (active and passive to observe to a lower frequency). We plan to use the combined method for our study since it will help us obtain both shallow and deep V_s information simultaneously (Park et. al., 2007). SurfSeis software that we are planning to use has a built-in function to complete the inversion. In this case, we don't need to do the inversion manually.

Gravity Data Processing

Gravity is affected by various factors and we need to correct those effects so that the residual gravity will be due to subsurface density variation only. Following (Burger et. al., 2006), the correction includes the latitude correction, free air correction, Bouguer correction, and terrain correction. The complete form of the equation to calculate the Bouguer anomaly (Δg_B) incorporating the GRS67 formula and the free-air and Bouguer correction is

Δg_B = {g_{obs} – [978031.85(1 + 0.005278895 $sin^2 \Phi + 0.000023462\, sin^4 \Phi$)] + [(0.3086 – 0.04193 ρ) z]}, (1)

The ρ in equation (1) is called the Bouguer density and its value is usually considered to be 2.67 g/cm^3, z is the thickness of the infinite slab. Final unit for Bouguer anomaly will be in mGal. Terrain correction will be calculated separately following Hammer (1939) and will be added to the observed gravity. Including terrain correction, the equation to calculate Bouguer anomaly is expressed as

$\Delta g_B = g_{obs} - g_n + \mathrm{F}A_{corr} - B_{corr} + \mathrm{TC}$ (2)

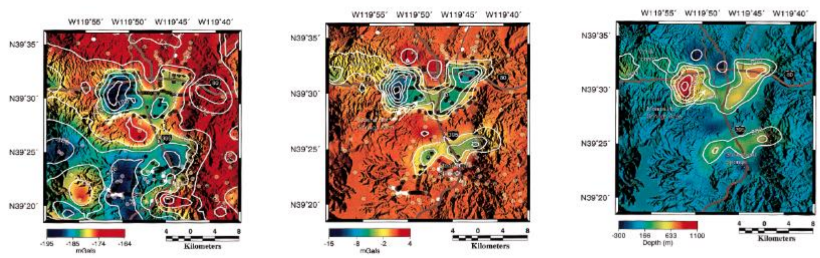

Figure 3: The first figure is showing Reno–Truckee Meadows complete Bouguer gravity map. The second one shows the residual basin gravity and the third one shows Depth-to-bedrock for the same region (Abbott and Louie, 2000)

Analyzing the Anomaly

To get a residual anomaly, we may need to remove a regional trend from the data. Surfaces of various orders can be calculated to represent the good regional trend (Burger et. al., 2006). Polynomial fitting is a standard procedure and can be done using MATLAB. Usually, a polynomial fit no higher than third order is used to remove regional trends (Burger et al., 2006). Once all the corrections are done, and the regional trend is removed, the depth to bedrock can be estimated using the following equation,

$\Delta g_B = 2\pi\mathrm{G}\,(\rho_c d_z)$ (3)

where Δg_B is the observed anomaly (known from gravity survey), G is the universal gravitational constant, ρ_c is the density contrast between subsurface soil and bedrock (known or measured), and d_z is the depth to bedrock (to be calculated). d_z will be calculated from the seismic survey as well for selected locations and will be compared to d_z from the gravity survey. This comparison will help modify ρ_c accordingly. GRAVMAG software can also be used to make different models to compare with the observed data for finally accepting one that matches the data.

Refraction Data Processing

Once refraction data are collected, the dataset will be analyzed using the SeisImager/2DTM software package to pick the first arrival (similar to Figure 4). The package has a specific module called Pickwin, that will be used to pick the arrivals. The output file can be saved in SEG-2 format and the picks in an ASCII file. If we plot time vs distance, we can identify the intercept time (t_i) from the plot. The intercept time will be used to calculate the thickness of the bedrock by the following equation:

$$h_1 = \frac{t_i}{2} \frac{V_2 V_1}{(V_2^2 - V_1^2)^{1/2}} \tag{4}$$

where $V_1$and V_2 are the velocities of the first layer and second layer respectively that can be calculated from the slope of the time-distance curve plotted before (Burger et. al., 2006).

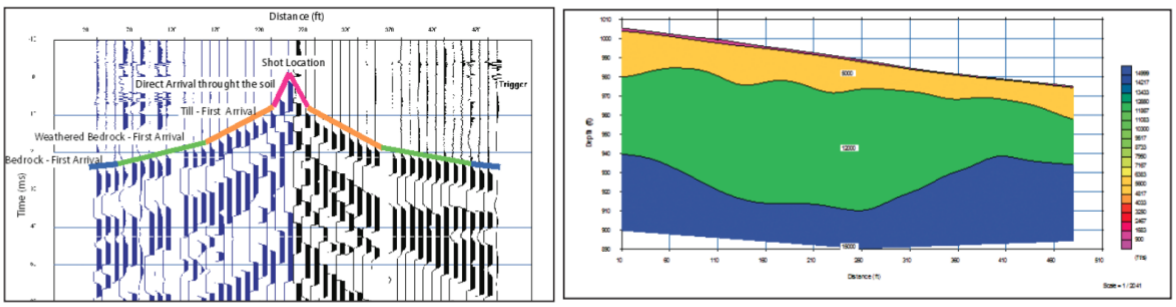

Figure 4: The left figure is showing field data from a refraction survey and the right figure is showing the corresponding depth to bedrock modeled from that data (Hart D., 2011)

MASW Data Processing

The MASW data processing can be divided into Pre-processing and Main-processing steps. In the pre-processing step, the file format will be changed according to the software configuration internally and the source/receiver geometry will be completed by the software. In this method, the Rayleigh wave phase velocity is calculated using a characteristic equation in its non-linear form as follows:

$$\mathrm{F}\,(f_j, C_{Rj}, \boldsymbol{V_s}, \boldsymbol{V_p}, \rho, \boldsymbol{h}) = 0 \tag{5}$$

where f_j is the frequency in Hz, C_{Rj} is the Rayleigh wave phase velocity, $\boldsymbol{V_s}$ is the shear wave velocity vector, $\boldsymbol{V_p}$ is the P wave velocity vector, ρ is the density vector and $\boldsymbol{h}$ is the thickness vector. The dispersion curve will be the Rayleigh wave phase velocities depending on different frequencies. For inversion, data **d** = Rayleigh wave phase velocities at m different frequencies, model S-wave velocities can be represented by vector **x** of length n, and the Jacobian matrix **J** will be a matrix of m by n having first-order partial derivatives of Rayleigh wave phase velocities $\boldsymbol{C_R}$ with respect to shear wave velocities. The final inversion equation will be in the form of

$$\mathbf{J\Delta x = \Delta b}, \tag{6}$$

where $$\mathbf{J}_s = \left[-\frac{\partial F / \partial V_{si}}{\partial F / \partial C_R} |_{f=f_j} \right] \tag{7}$$

Our target will be to determine $\mathbf{\Delta x}$ using $\mathbf{J}$ and $\mathbf{\Delta b}$**.** Since the model C_{Rj} in equation (5) is a non-linear function, we need to linearize equation (5) by Taylor-series expansion. In equation (6), $\mathbf{\Delta b = b - \boldsymbol{C_R}(\boldsymbol{x_0})}$ and is the difference between measured data and the model response to the initial S wave velocity estimation $\boldsymbol{x_0}$. $\mathbf{\Delta x}$ is the modification of the initial estimation. Equation (6) is solved by the optimization technique (Xia et. al., 1999). The steps for the software to process the data commonly consist of the following steps.

Data Acquisition > Data Conversion > Encoding Field Geometry > Dispersion Analysis > Inversion > S- Velocity Profile.

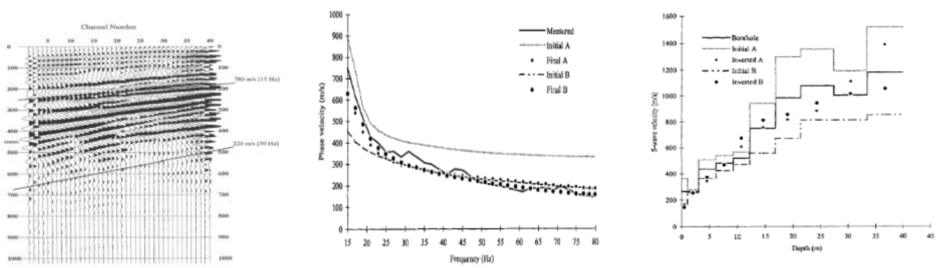

Figure 5: The leftmost figure is a field data from MASW survey, the middle one shows the phase velocity calculated from that data, the rightmost one shows the inverted shear wave velocity for that region (Xia et. al., 1999).

Equipment

We are going to use a differential GPS with an external antenna to determine elevation, latitude, and longitude, and the GRAVMAG software for Matlab or Python. For the refraction survey, we will use Geometrics Geodes (24 channels seismographs) along with a field computer, geophones and spread cable, a sledgehammer as the active source, trigger cable, and striking plate. We will use a SeisImager/2DTM software package to analyze refraction data and the software SurfSeis for analyzing MASW data.

Cost, Contacts and Proposed Timeline

Gasoline, hotel room and (maybe) a rental gravimeter (for better perfection) are needed. We have been talking to Mr. Gary Patterson, Director, Education & Outreach, CERI. He has some contacts that we hope will be helpful to get permission for the survey in that region.

Summer 2018	Getting Permission; Brown Bag Presentation
Fall 2018	Data Collection, Data Processing
Spring 2019	Finding Results, Starting to write a paper based on the work and the thesis
Summer 2019	Completing the papers and the thesis. Defending the Thesis
August 2019	Graduation

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