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Test to Extract Soil Properties Using the Seismic Hammer^{TM} Active Seismic Source

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Abstract

Geologic material properties are necessary parameters for ground motion modeling and are difficult and expensive to obtain via traditional methods. Alternative methods to estimate soil properties require a measurement of the ground's response to a force. A possible method of obtaining these measurements is active-source seismic surveys, but measurements of the ground response at the source must also be available. The potential of seismic sources to obtain soil properties is limited, however, by the repeatability of the source. Explosives, and hammer surveys are not repeatable because of variable ground coupling or swing strength. On the other hand, the Seismic Hammer™(SH) is consistent in the amount of energy it inputs into the ground. In addition, it leaves large physical depressions as a result of ground compaction. The volume of ground compaction varies by location. Here, we hypothesize that physical depressions left in the earth by the SH correlate to energy recorded by nearby geophones, and therefore are a measurement of soil physical properties. Using measurements of the volume of shot holes, we compare the spatial distribution of the volume of ground compacted between the different shot locations. We then examine energy recorded by the nearest 50 geophones and compare the change in amplitude across hits at the same location. Finally, we use the percent difference between the energy recorded by the first and later hits at a location to test for a correlation to the volume of the shot depressions. We find that:

- Ground compaction at the shot-depression does cluster geographically, but does not correlate to known surface features.

- Energy recorded by nearby geophones reflects ground refusal after several hits.

- There is no correlation to shot volume and changes in energy at particular shot locations. Deeper material properties (i.e. below the depth of surface compaction) may be contributing to the changes in energy propagation.

- Without further processing of the data, shot-depression volumes are insufficient to understanding ground response to the SH. Without an accurate understanding of the ground response, we cannot extract material properties in conjunction with the SH survey. Additional processing including picking direct arrivals and static corrections may yield positive results.

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Introduction

Geologic material properties are necessary parameters for ground motion modeling and may be measurable by active-seismic surveys with consistent source and measurable ground response. Vibrator systems, for example, commonly output material properties such as ground stiffness and viscosity. These outputs are estimated from the accelerations of the reaction mass and baseplate [1], and are possible because the force exerted on the ground is known, as well as the reaction of the ground to the force. Unlike vibrator systems, the Seismic Hammer^{TM} (SH) does not provide ground motion data from a reaction-mass accelerometer. However, the SH does provide a consistent, repeatable seismic source with measurable effects on the soil. The SH (Figure 1) is a weight-drop seismic source with a constant mass of 13,000 kg and a constant drop-height of 1.5 m. This leads to a consistent potential energy of the system at 191,00 Joules.

Here we hypothesize that the volume of the shot depression left by the SH correlates to energy recorded by nearby geophones. With such a correlation, we would expect to be able to extract information on material properties. To test our hypothesis, we address the following research questions: 1) Does ground compaction reflect a change in geology? 2) Can we link compaction to energy recorded by geophones? 3) Are the ground effects consistent enough to allow energy comparisons across shot locations? The following section details the data collection and measurements of shot depressions. Subsequently, we describe the analysis and results for each of the above research questions.

Figure 1. The 13,000 kg Seismic Hammer^{TM}

Field Measurements

We use data collected during project Frey Chimney at the Nevada National Security Site (NNSS). The survey consists of 280 shot points with 1000 Sunfull 2-Hz, 3-component geophones along a hybrid 2D-3D array. Figure 2 shows the layout of the source shot locations included in this analysis. Line 500 extends from the southwest to the northeast, while Line 600 is perpendicular to Line 500. The SH is a modified pile driver with a 13,000 kg mass dropped from 1.5 m. Each hit from the hammer depresses the ground until "refusal", when, in theory, compaction ceases and the maximum amount of energy propagates through the ground. During the survey, we measured the depth of the shot-depression after each of a series of about 8 hits. Occasionally the hammer became tilted at an angle greater than 10 degrees from vertical and had to be repositioned. These locations were not included in the analysis. Figure 3 is a photograph of one of the valid shot points. Although the hammer for this shot remained nearly vertical, compaction was uneven at the base of the hammer. In such cases, we obtain the depth on each side and in the middle of the shot-depression and calculate the average volume based on the three depths.

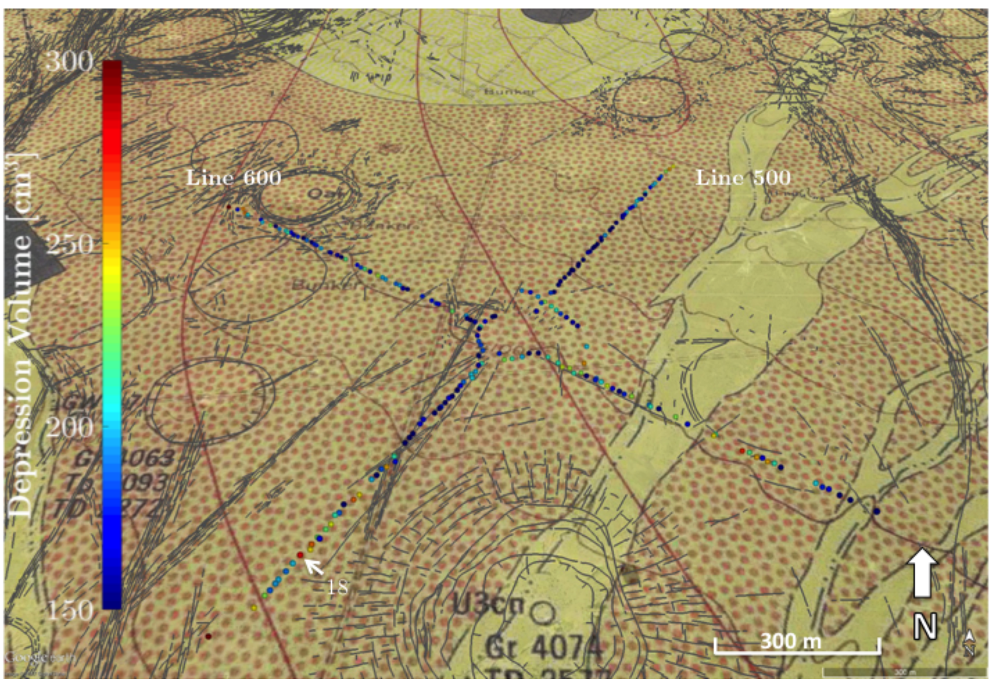

Figure 2. Volumes of shot depressions. We only measure volume for shots in which the hammer remained nearly vertical. Gaps represent shots in which the hammer became tilted and had to be repositioned. Underlain is a geologic map of the area [2], as well as known faulting (gray lines)[3].

Figure 3. Example of depression left after successive hits in shot location 18. Here the ground compacted more to one side. See Figure 2 for location.

Methods

We conduct all of our analysis with the 50 closest geophones for each shot location. We look for evidence of compaction and refusal using two methods. First, we find the energy recorded by the nearest geophones. To do this, we sum the energy of the three components of ground motion and then integrate across times. To avoid including noise and scattering, we cut the records to include 0.25 seconds of signal. After summation, we have one value in units of $(cm/s)^2$ for each of the geophones.

Next, we compare total energy across hits at a particular source point. For this step, we omit the geophones from the first 25 meters because of the large difference in energy between these geophones, which may reflect nonlinear effects, and are not a focus of this study. This removes the first 4-8 geophones of the nearest 50 to the source. To find the total energy for each hit, we sum across the remaining geophones.

We look for a correlation with the shot-depression volumes by examining the percent difference in the total energy from uncompacted ground to the point of refusal. The first hit is on uncompacted ground and is the hit with the least amount of seismic wave energy. At refusal, the ground ceases to compact significantly and the maximum amount of energy is directed as seismic waves. Using the total energy, we find the percent difference between the first hit and the hit with maximum total energy. We then compare the percent difference in energy between shots to test for correlation in shot-depression volume.

Finally, we perform frequency domain analysis to look for any marked frequency content changes. For example, if all the low frequencies are the same but high frequency content changes across shots. We conduct three different analyses to examine the frequency domain. First, we find the Power Spectral Density (PSD). Next, we find the spectral ratio between the first and nth hit. Finally, we take the average of the spectral ratio of the penultimate and first hit for all shots along Line 500.

Results

We first hypothesize that ground compaction reflects a change in geology. To test this hypothesis, we find the volumes of shot depressions and plot the results by location. Figure 2 shows the volumes of all shots in which the hammer remained nearly vertical (was not repositioned during the acquisition of data). Higher volumes represent greater compaction. We note that there are geographic areas where the compaction is greater and could indicate different underlying alluvium. Shots with greater compaction volume are clustered together, suggesting that this could be an indicator of local soil properties. When we compare to the underlain geologic map on Figure 2 [2], we note that Line 600 crosses over younger quaternary alluvium, but that the large volume differences to the southwest of Line 500 do not correspond to any overall change in the geology. However, there is some loose correspondence with faulting in the area (gray lines [3]). The larger volumes on Line 500 are all to the west of a fault line. Larger volumes in the northwest on Line 600 correspond to an area disturbed by nearby craters.

Second, we hypothesize that successive hits transfer greater amounts of energy into seismic waves until the soil reaches maximum compaction. This is the point of refusal, when the energy in the seismic waves stabilizes. Figure 4 shows the energy calculated for all hits of shot 18 with amplitude versus offset. The location of shot 18 is the southwest corner of one of the 2D lines and represents a shot depression with a higher volume (see Figure 2). While all hits show the same relative pattern, the first hit is significantly less energetic than the second. Later hits continue to increase the amount of energy recorded but at a decreasing rate. This is indicative of continued ground compaction until about hit 5. Hits $5-9$ all show similar amplitudes, indicating that the ground has reached refusal. This pattern was consistent across shots, although the number of shots to reach refusal varied. Figure 5 shows the total energy for shot 18. Here, the decreasing slope also indicates refusal as hits 5-9 all remain around 1600 $(\mathrm{cm/s})^2$. Figure 6 shows the histogram of the number of hits until refusal as indicated by the summed energy plots. While the majority of shot locations required 8 hits, overall the number required ranged from 4 to 9 hits to refusal.

Finally, we hypothesize that the percent difference in energy between the initial hit and a hit at refusal correlates with shot-depression depth. We plot the percent difference against shot depression volume for all shots along an individual line. Figures 7(a) and 7(b) show the results for Lines 500 and 600, respectively. We note that in Line 500 there appear to be two populations in the data that we label population A and B and plot the geographic locations in Figure 9. Population A largely consists of consecutive shot locations 1-50. We separate the two populations and find the linear regression of each in Figure 8. Population A shows a weak linear trend of increasing percent difference with increasing volume. Later shots in population B, however, do not show a clear relationship between volume and percent difference. Line 600 (Figure 7(b)) had no apparent linear relationship among any consecutive series of shot points. This could indicate that deeper material properties impact the attenuation of energy.

Figure 10 shows the PSD (top) and spectral ratio (bottom) for a representative shot. Seismic energy is stabel at low frequencies but variable at high frequencies between subsequent hits. Low frequencies (<200 Hz) dominate the spectra as a whole. Below about 125 Hertz both plots show increasing energy with progressive shots. Later shots are also closer together, indicating refusal. Higher frequencies vary more widely, with hit 9 unexpectedly decreasing in energy between frequencies of about 240 to 375 Hertz. While this demonstrates that compaction impacts higher frequencies more heavily, most of the overall energy is in the lower frequencies, mitigating the effect when the total energy is summed.

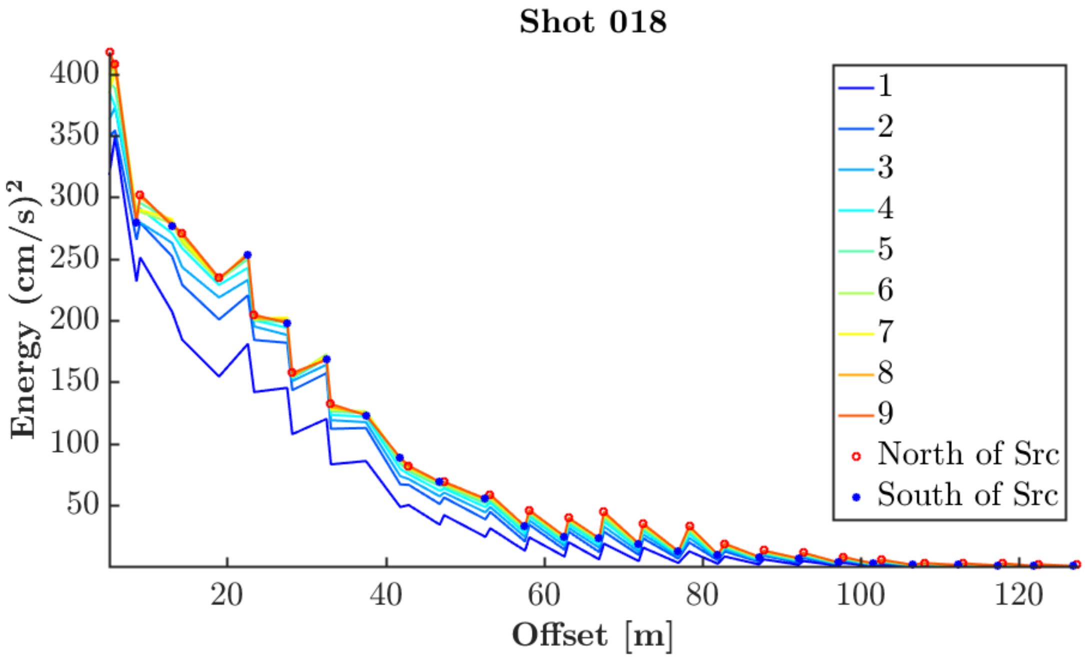

Figure 4. Energy calculated for the nearest 50 inline geophones. Individual geophone locations shown as * on the last hit and indicate position relative to source. Geophones south of the source follow geophones to the north and explain the jagged appearance of the lines. Hits after the 5th show very little difference and are consistent with ground refusal.

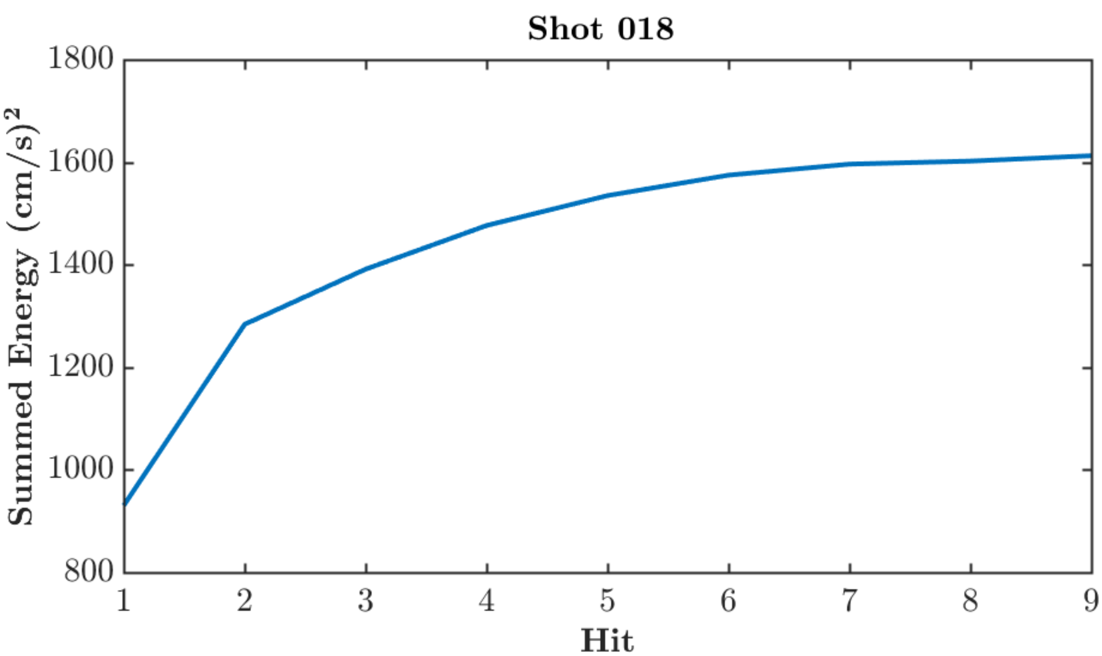

Figure 5. Total energy per hit, omitting receivers less than 25 meters from the source. Energy begins to level off at about hit 5, consistent with Figure 4.

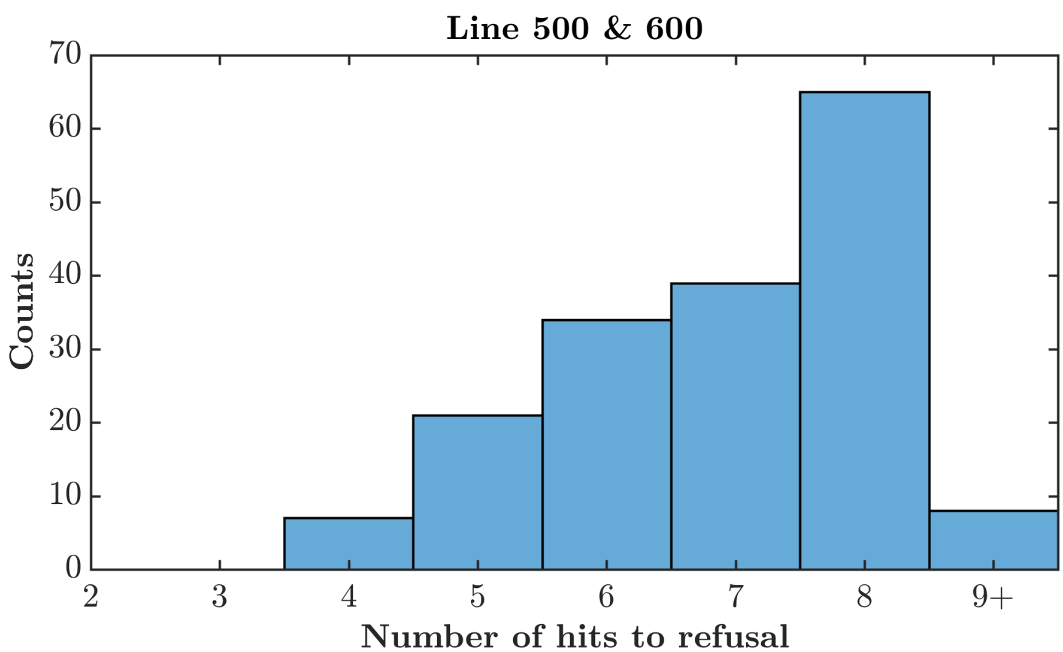

Figure 6. Historam plot of the number of hits before reaching refusal. Shots that did not conclusively indicate refusal are included in the 9+ bin.

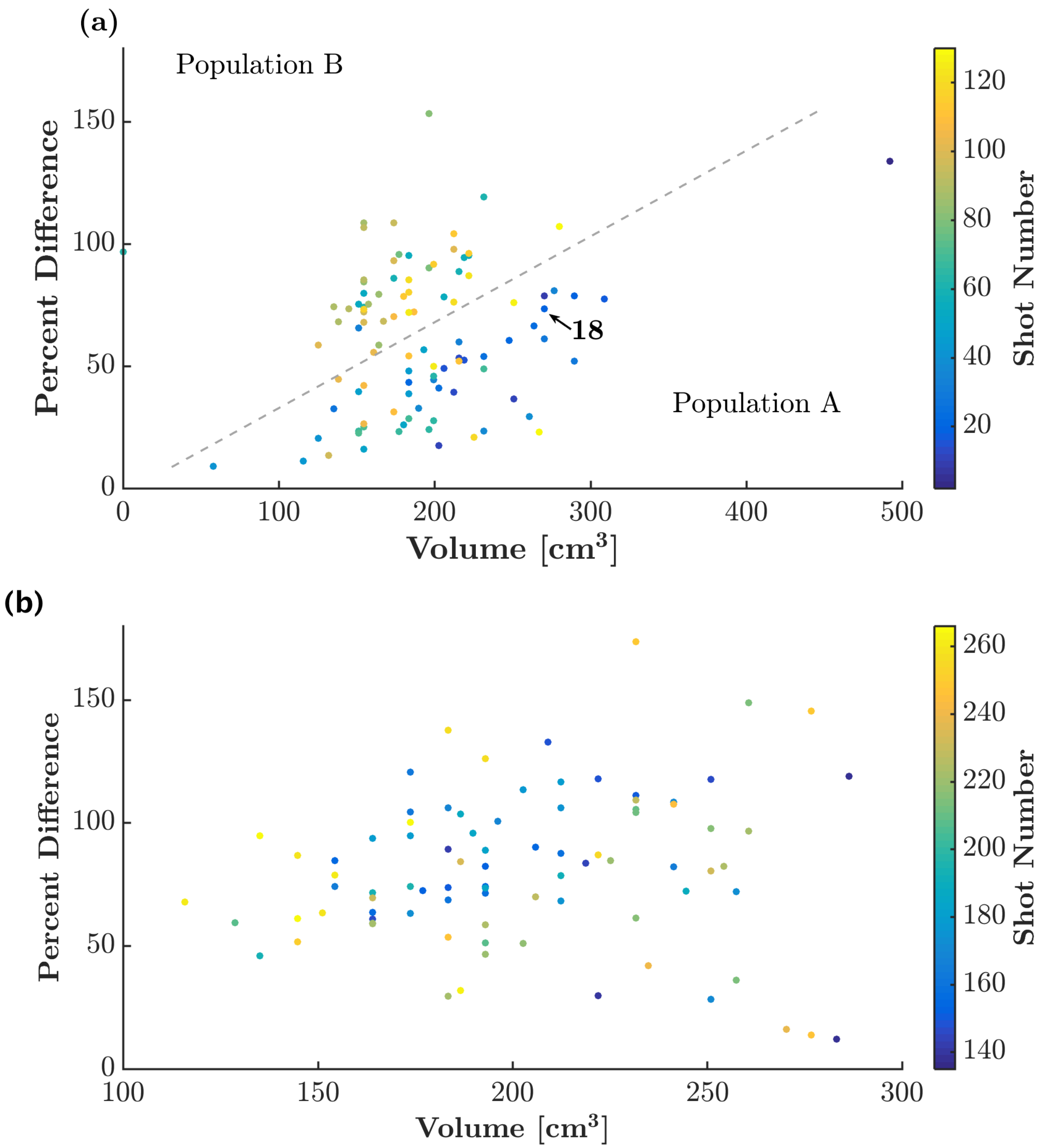

Figure 7. Percent Difference vs shot depression volume for (a)Line 500 and (b) Line 600. The dashed line in (a) divides two apparent populations for Line 500.

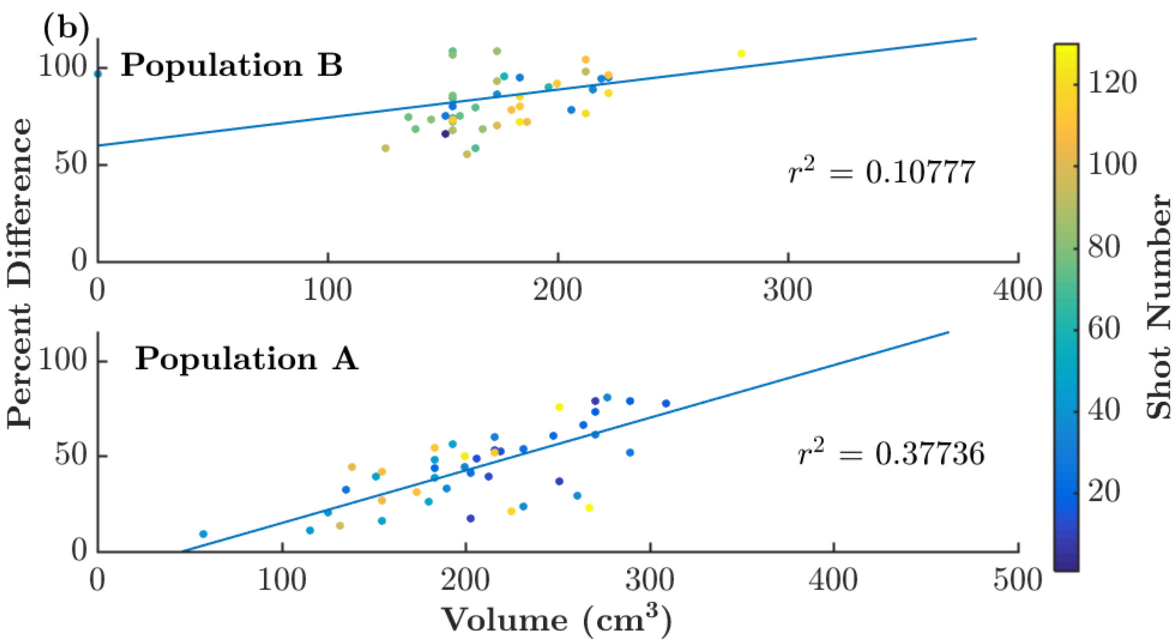

Figure 8. Percent Difference vs shot depression volume for Line 500 separated into two populations.

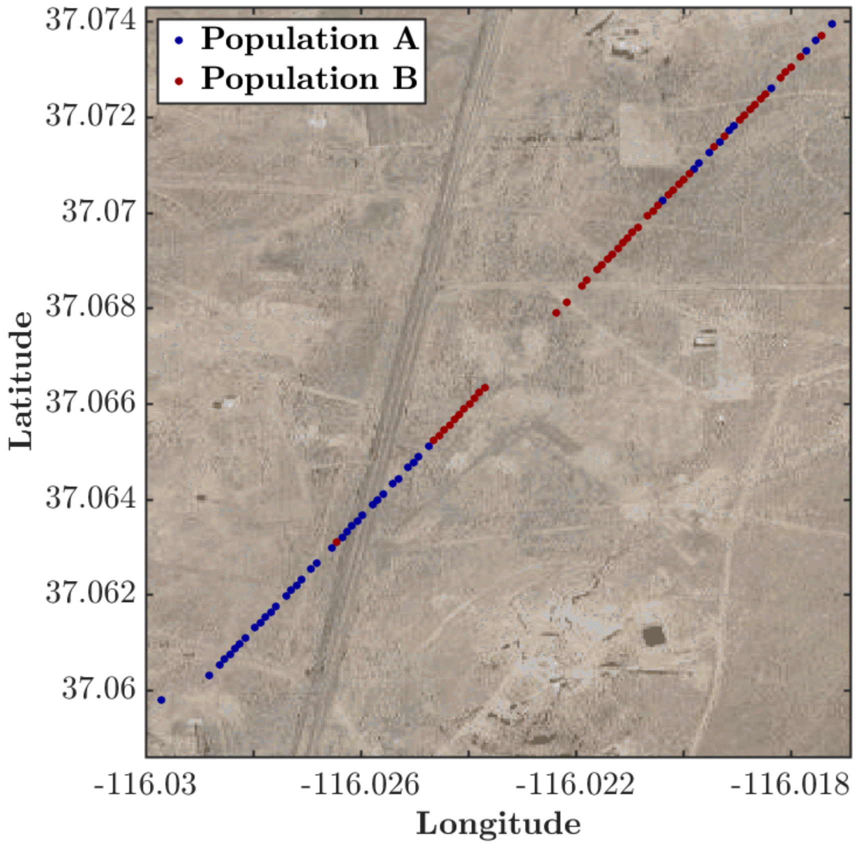

Figure 9. Geographical locations of 2 populations in Figure 7(a). Population A is the group of shots under the dashed line in Figure 7(a).

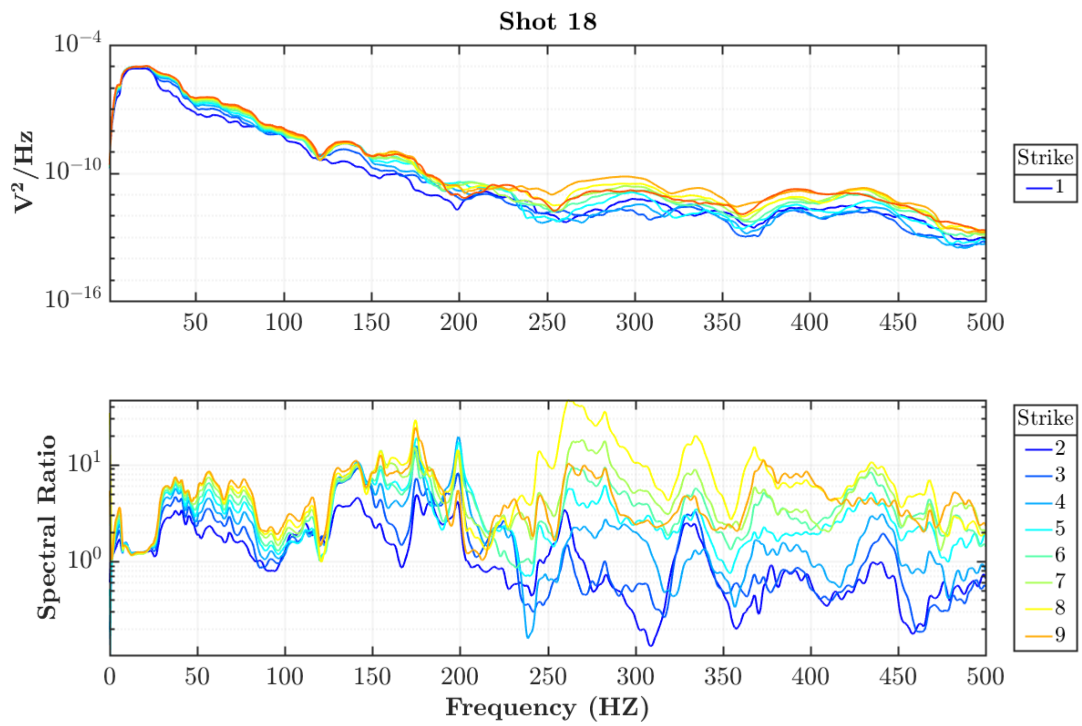

Figure 10. Example PSD (top) and spectral ratios (bottom). For the spectral ratio we divide the nth hit by the first.

Conclusions

We make the following conclusions regarding correlation of the shot-hole depressions left by the SH to energy recorded by nearby geophones:

1. While shot-hole depressions are clustered, they do not correlate definitively to known surface features.
2. The SH outputs progressively more seismic energy into the seismic wave field until soil refusal is met.
3. Shot-hole depression volume does not correlate with energy put in the ground. This indicates that SH radiated energy is sensitive to changing material properties at depths greater than the shot-hole depression. However, more robust processing of data may improve results.

Recommendations

1. We cut all data at the same times to roughly include direct arrivals. More sophisticated picking may show a better correlation.

2. Perform station correction based on radiation and attenuation.

3. On future surveys, perform a cone penetration test (CPT) before and after the last hit at each shot location. The CPT would measure soil geotechnical properties to several meters below the level of surface compaction, perhaps illuminating the role of deeper soil compaction.

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