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In Situ Observations of Seismic Wave Propagation

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In Situ Observations of Seismic Wave Propagation

A Thesis submitted in partial satisfaction of the requirements for the degree Master of Science in Earth Science

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June 2017

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June 2017

ABSTRACT

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by

Kenneth Stewart Hudson

Instrumented geotechnical field sites are designed to capture the infrequent but critically important in situ case histories of ground response, deformation, and liquefaction during significant earthquakes that generate high intensity ground shaking and large strains. The University of California at Santa Barbara has been monitoring densely instrumented geotechnical array field sites for almost three decades, with continuous recording now for more than a decade. When seismic waves travel into soil with sufficiently large ground motions, the soil behaves nonlinearly meaning the shear modulus of the material decreases from the linear value observed during weak ground motions. The degraded shear modulus can continue to affect a site for a period of time by changing the soil response during smaller ground motions after the large event. Decreased shear modulus is inferred when a decrease of shear wave velocity between two sensors in a vertical downhole array is observed. This velocity is calculated by measuring the difference in shear wave arrival times between the sensors using normalized cross correlation. The trend of decreasing shear wave velocity with increasing peak ground acceleration is observed at multiple geotechnical array field sites. The length of time the decreased velocity remains following stronger shaking is analyzed

using more than 450 events over more than a decade at the Wildlife Liquefaction Array (WLA). Using both monthly and yearly velocity averages between sensors, there is evidence that suggests the shear wave velocity remains low over a period of months following larger significant shaking events at the site. In addition, at WLA there is evidence that the decrease in shear wave velocity can be detected at ground motion levels as low as 20 cm/s^2.

Additionally at the Garner Valley Downhole Array, a permanent cross-hole experiment is used to measure velocity changes in the soil with changing water table height. An underground hammer source swings once a week and is recorded on two geophones at the same depth in a line adjacent to the source. Data collected from December 2010 to June 2012 and again from August 2015 to June 2017 is analyzed. That results shows a strong correlation between water table height and the shear wave velocity in the sediment, with changes of almost 5% over the course of seasonal water table variation.

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Introduction

Granular Earth materials have been known to exhibit nonlinear response due to large strain deformation in laboratory experiments since the 1970s (Seed and Idriss, 1970; Hadrin and Drnevich, 1972a, b; Vucetic, 1994; Guyer and Johnson, 1999; Ostrovsky and Johnson, 2001). Although the physics of nonlinear behavior is not well understood, the relationship between the elastic modulus and applied strain level is well quantified by laboratory experiments (Ostrovsky and Johnson, 2001) and is used in seismic hazard assessments to predict how a site will behave during strong ground motions. It is thought that the physical origin of nonlinear behavior is related to the bonding between grains, and not within the individual grains (Guyer and Johnson, 1999). Nonlinear effects are evidenced by an immediate decrease in shear modulus of the material during excitation by an elastic wave with a large enough effective strain. This is manifest as a reduction in the material's shear wave phase velocity and is referred to by Johnson and Sutin as nonlinear fast dynamics (2005). Recently, studies have become focused on *in situ* experiments of nonlinear effects during both induced ground motions (Lawrence et al., 2008; Lawrence et al., 2009) and strong ground motion events (Beresnev and Wen, 1996; Pavlenko and Irikura, 2002; Sawazaki et al., 2006; Karabulut and Bouchon, 2007).

Nonlinear effects observed by Ten Cate et al. in 2000 include a time-dependent recovery process occurring in the material broadly referred to as nonequilibrium dynamics (TenCate et al., 2004). *In situ* studies of the long-term damage to soil observe recovery processes lasting hours (Lawrence et al., 2009) while others appear to last for years (Sawazaki et al. 2006). This study seeks to further constrain the nonequilibrium state following strong ground motions by observing unique *in situ* shear wave velocities at sites during small to medium intensity shaking generated by earthquakes at several downhole arrays, building on the work of Steidl, Civilini and Seale (2014).

Methods

The shear wave velocity changes observed in this study are calculated from the difference in arrival times (time lag) between accelerometers at different depths located in geotechnical downhole arrays. A geotechnical downhole array is a site with multiple boreholes, each containing accelerometers (and sometimes pore pressure transducer) at different depths (Figure 1).

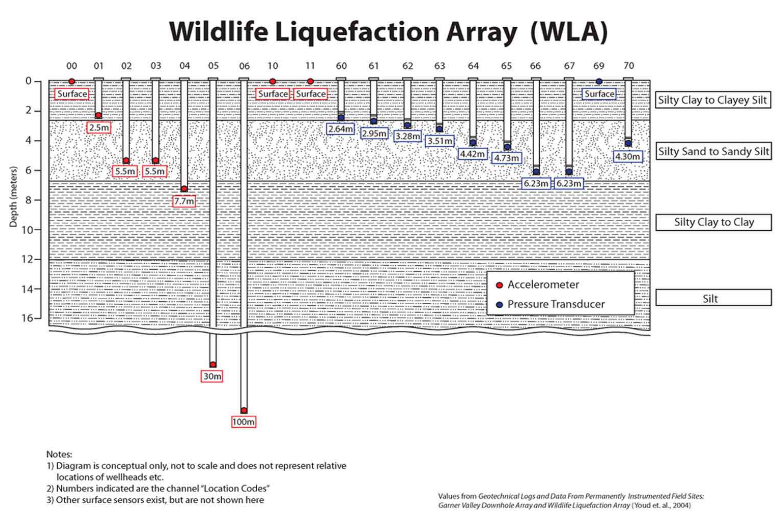


Figure 1: Cross section of Wildlife Liquefaction Array (WLA) located on the west bank of the Alamo River 13 km north of Brawley, California. It is a typical example of a geotechnical down-hole array and one used extensively in this study

Data are extracted from the UCSB data portal (http://www.nees.ucsb.edu/data-portal) as a .csv file, which is then converted to MATLAB for analysis. The s-wave arrival is manually or automatically selected within MATLAB and cross correlation of the waveforms with 1 second, 2 second, and 5 second time windows around the arrival time is computed for the East and the North components. This is accomplished by cutting the data to half the window size before s-wave arrival and half the window size after. The time lag is calculated by running a cross-correlation between two waveforms at separate vertical array sensors. To discard incorrect cross-correlations, the time lags are checked against a preselected difference in s-wave arrivals, rejecting the time lag if it is not within 20% of the expected s-wave arrivals' time difference. This serves to get rid of values that are known to be incorrect because of a variety of reasons that causes the two waveforms to be falsely cross correlated including but not limited to emergent arrivals due to the source mechanism and s-wave polarity, noise, and contamination by the p-wave arrivals in the window prior to the s-wave arrival. If none of the calculated time lags are discarded, there will be six values for the time lag (one for each of the three windows for both the North and East components). This method is being used on several different sites in the UCSB geotechnical array program, including the Delaney Park Array in downtown Anchorage, Alaska (DPK); and the Wildlife Liquefaction Array (WLA), Borrego Valley Array (BVDA), and Garner Valley Array (GVDA) all located in southern California. See Appendix for full lists of events used.

Time lags are converted to shear wave phase velocity by dividing the time lag by distance between the accelerometers used in the cross correlation; the shear modulus is then inferred from the shear wave velocity as proportional to its square due to the relation

$$v_s = \sqrt{G/\rho},$$

where v_s is the shear wave phase velocity, G is the shear modulus, and ρ is the density of the elastic material. The s-waves are assumed to arrive vertically at the site, any difference in arrival times caused by directionality of the plane waves is averaged out by the number of events used. The results are plotted comparing s-wave velocity against peak ground acceleration (PGA) and s-wave velocity against date/time of event.

Results

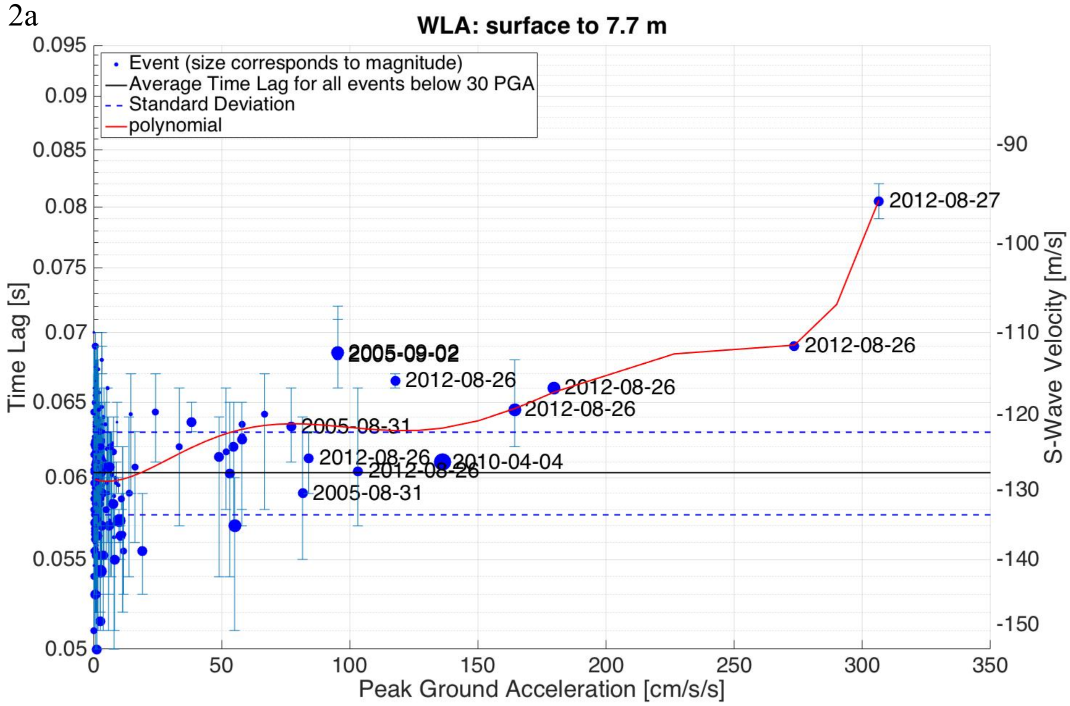
WLA:

At WLA, s-wave velocities were calculated for more than 450 events occurring from January 2005 to June 2016 between the surface to GL-7.7 meter at the 2004 main site and 1982 "T-hut" site, and between the 2004 main site surface to GL-30 meter, surface to GL-100 meter, GL-30 to GL-100 meter, and GL-7.7 to GL-30 meter accelerometers (GL = ground level). Nonequilibrium fast dynamics were observed during several large events, showing a trend of increasing time lag (decreasing s-wave velocity) with increasing PGA (Figure 2). The largest ground motions produced between each sensor had differing reduction in the shear wave velocity (Table 1).

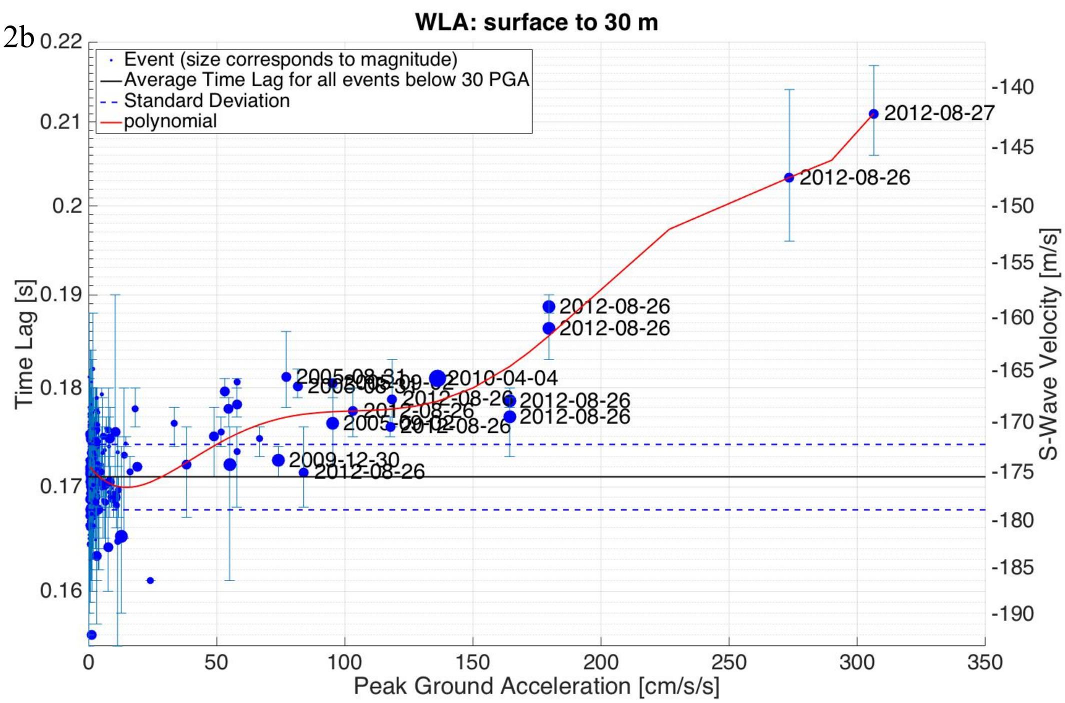
Sensor pairs	Average time lag of events <30 Gals (s)	Standard Deviation of time lags	Largest event's time lag (s)	Percent increase of time lag
0m-7.7m	0.0605	0.002549	0.0805	33.10%
0m-7.7m T-hut	0.0633	0.003543	0.0890	40.60%
0m-30m	0.1710	0.003232	0.2110	23.40%
0m-100m	0.4207	0.03876	0.4725	12.30%
7.7m-30m	0.1099	0.003805	0.1280	16.50%
30m-100m	0.2485	0.002370	0.2610	5.00%

Table 1: Percent increase of time lags between the largest calculated time lag between two sensors and the average time lag of events with surface accelerations less than 30 cm/s^2.

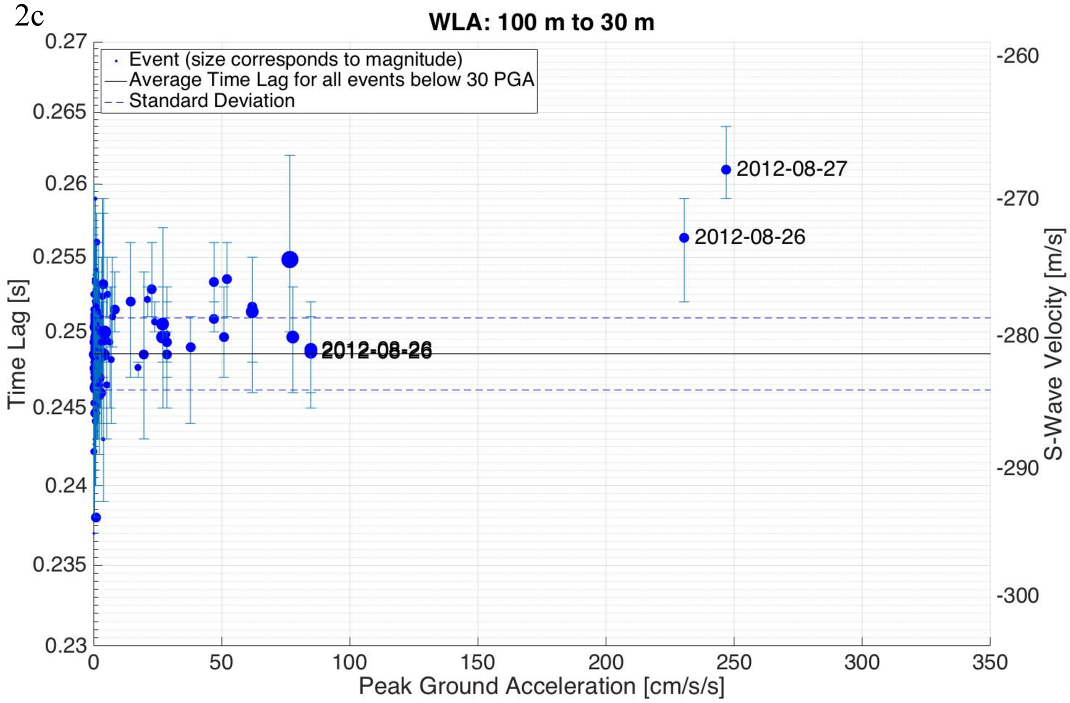
2a


WLA: surface to 7.7 m
Event (size corresponds to magnitude)
Average Time Lag for all events below 30 PGA
Standard Deviation
polynomial
Time Lag [s]
S-Wave Velocity [m/s]
Peak Ground Acceleration [cm/s/s]
2012-08-27
2012-08-26
2005-09-02
2012-08-26
2012-08-26
2012-08-26
2005-08-31
2012-08-26
2012-08-26
2010-04-04
2005-08-31

2b


WLA: surface to 30 m
Event (size corresponds to magnitude)
Average Time Lag for all events below 30 PGA
Standard Deviation
polynomial
Time Lag [s]
S-Wave Velocity [m/s]
Peak Ground Acceleration [cm/s/s]
2012-08-27
2012-08-26
2012-08-26
2012-08-26
2010-04-04
2012-08-26
2012-08-26
2009-12-30
2012-08-26

2c



2d

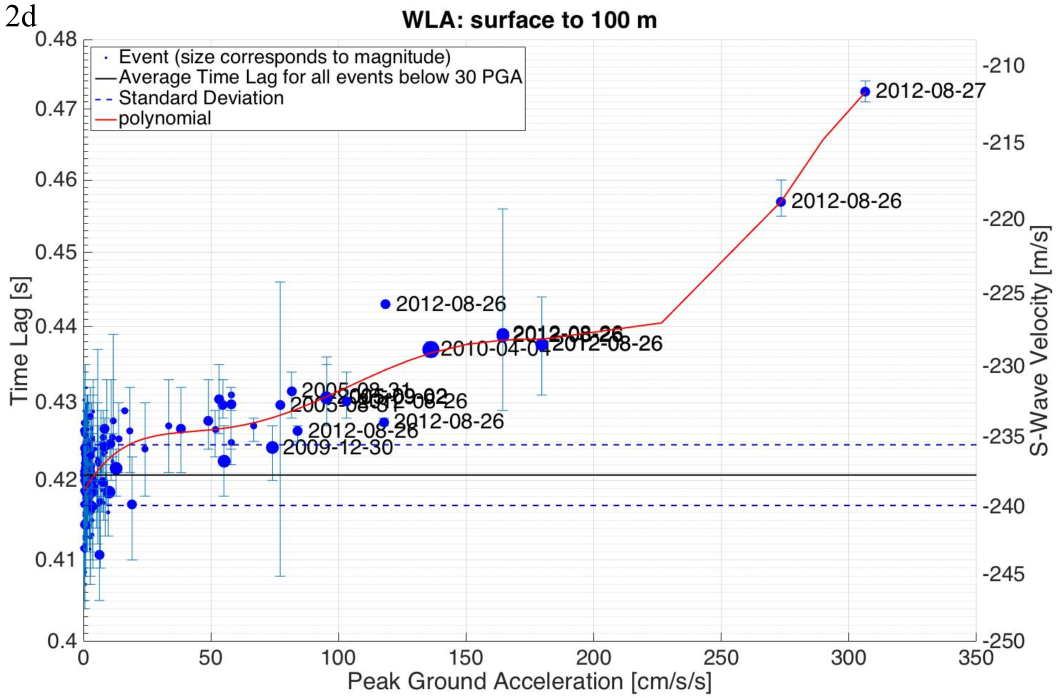


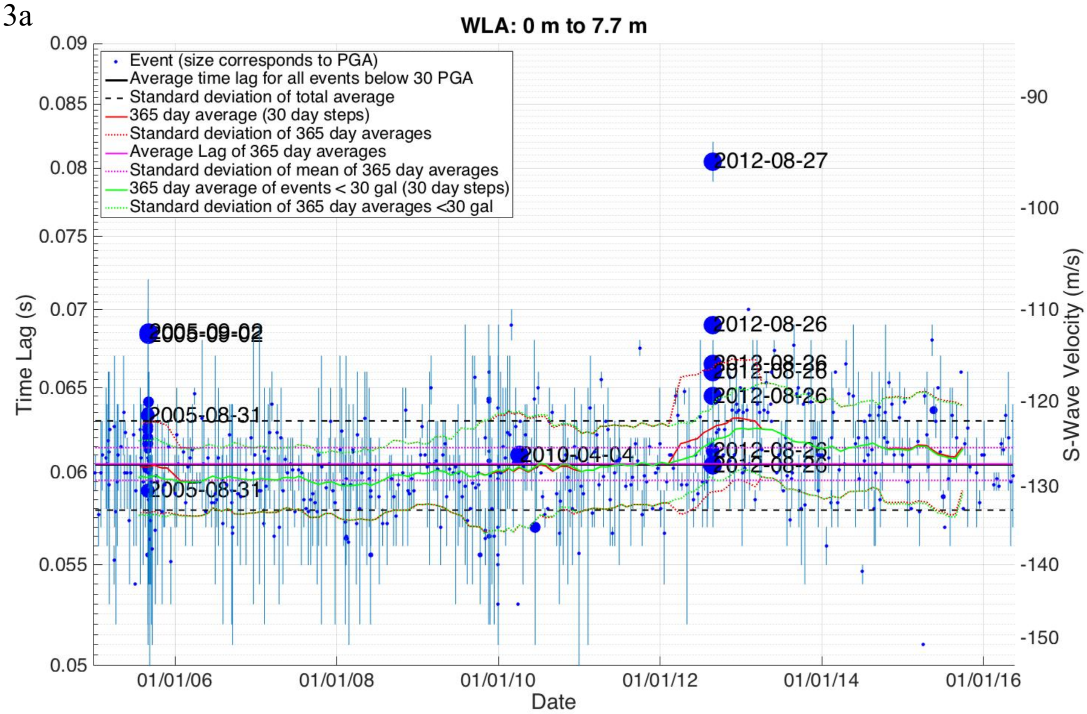
Figure 2: Results showing time lag between 4 pairs of vertical accelerometers from WLA. The error bars extend from the lowest value found during cross correlation to the highest, and the point on that line is the mean of all the values found during cross correlation.

A large swarm of events in August of 2012 produced several M_w 4 or greater earthquakes less than 15 km away from the WLA that generated ground motions above 0.1G in eight occurrences, the largest being ~0.3G. Each of the strong ground motion events induced nonlinearity in the soil at the WLA and caused nonlinearity during distinctly separate, weak ground motion events (<30 Gals). The nonlinearity during weak ground motions persisted in the shallow pairings of sensors for several years (Figure 3). The GL-30 to GL-100 meters sensor pairings do not show a long term degradation (Figure 3c). The degree of the reduction of shear modulus observed from these figures is determined by how much the moving yearly average of all events less than 30 Gals deviates from the average of all the events in the data set.

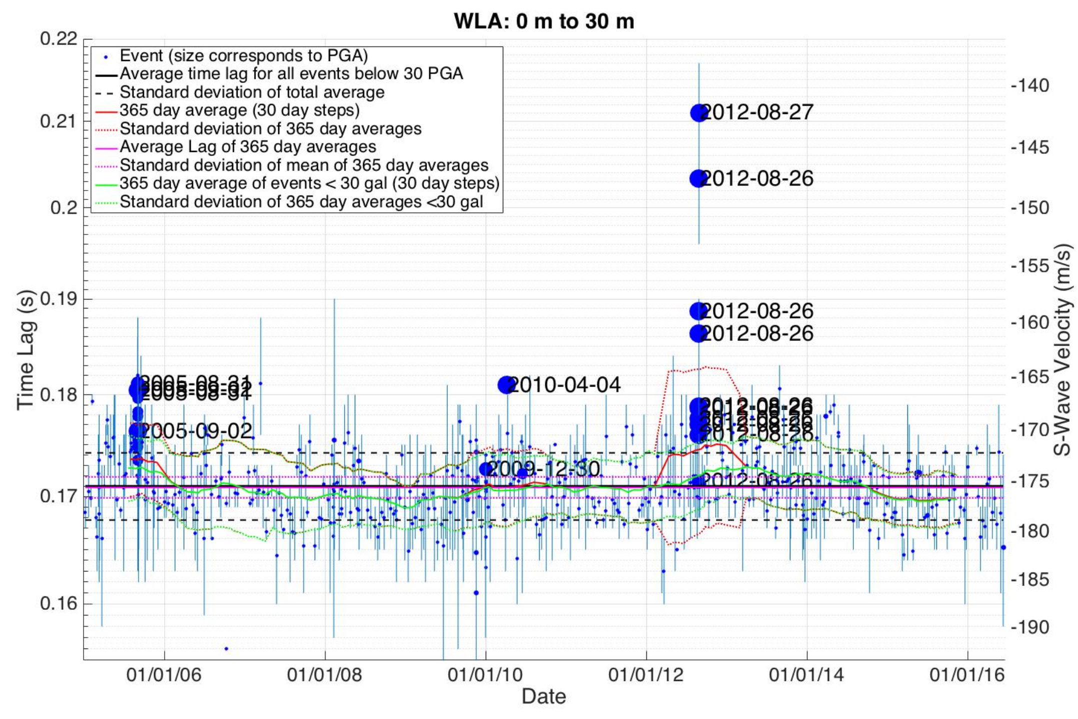
GVDA:

At the Garner Valley Downhole Array (GVDA), significant nonlinearity is observed during five events that exceeded 30 Gals, giving an increase of 40% in time lag between the <30 Gals average and the largest (165 Gals) event, when using the surface and GL-15 meter sensors. Plotting the time lag against date of event displays a varying moving average that stays within the standard deviation of the mean. There is an increase during large events, but it recovers fairly quickly and is not statistically significant. The largest motions occurred at the beginning of the time series and there are no records of the s-wave velocity before then in the data set therefore it is not known if the site is already in a state of degraded shear modulus.

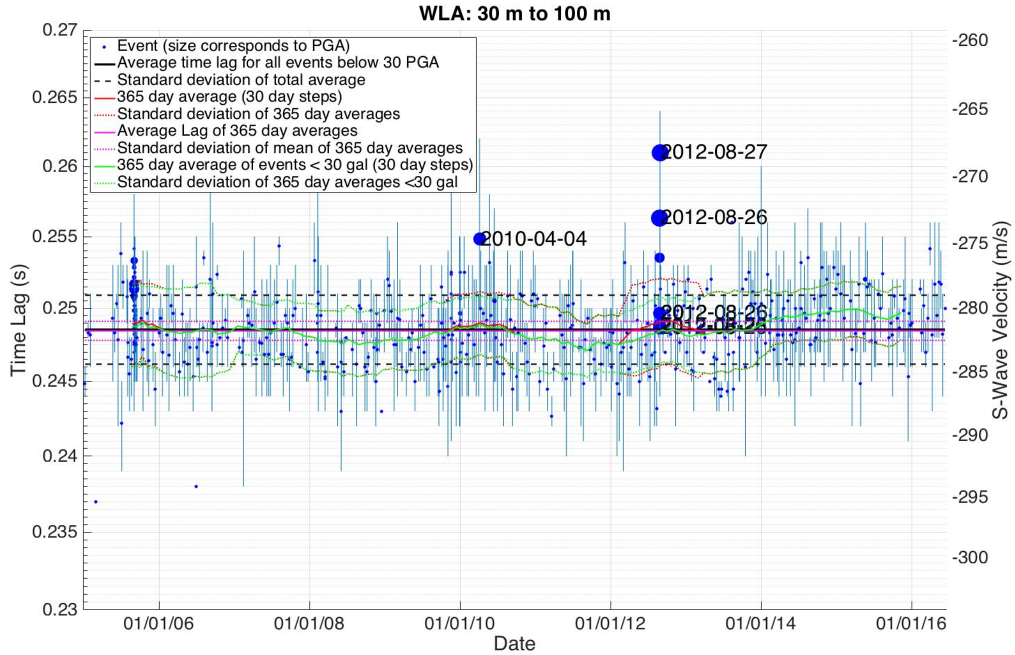
3a


WLA: 0 m to 7.7 m
Event (size corresponds to PGA)
Average time lag for all events below 30 PGA
Standard deviation of total average
365 day average (30 day steps)
Standard deviation of 365 day averages
Average Lag of 365 day averages
Standard deviation of mean of 365 day averages
365 day average of events < 30 gal (30 day steps)
Standard deviation of 365 day averages <30 gal
Time Lag (s)
S-Wave Velocity (m/s)
Date
0.09
0.085
0.08
0.075
0.07
0.065
0.06
0.055
0.05
-90
-100
-110
-120
-130
-140
-150
01/01/06
01/01/08
01/01/10
01/01/12
01/01/14
01/01/16
2012-08-27
2005-09-02
2012-08-26
2005-08-31
2010-04-04

3b


WLA: 0 m to 30 m
Event (size corresponds to PGA)
Average time lag for all events below 30 PGA
Standard deviation of total average
365 day average (30 day steps)
Standard deviation of 365 day averages
Average Lag of 365 day averages
Standard deviation of mean of 365 day averages
365 day average of events < 30 gal (30 day steps)
Standard deviation of 365 day averages <30 gal
Time Lag (s)
S-Wave Velocity (m/s)
Date
0.22
0.21
0.2
0.19
0.18
0.17
0.16
-140
-145
-150
-155
-160
-165
-170
-175
-180
-185
-190
01/01/06
01/01/08
01/01/10
01/01/12
01/01/14
01/01/16
2012-08-27
2012-08-26
2005-08-31
2010-04-04
2005-09-02
2009-12-30

3c



3d

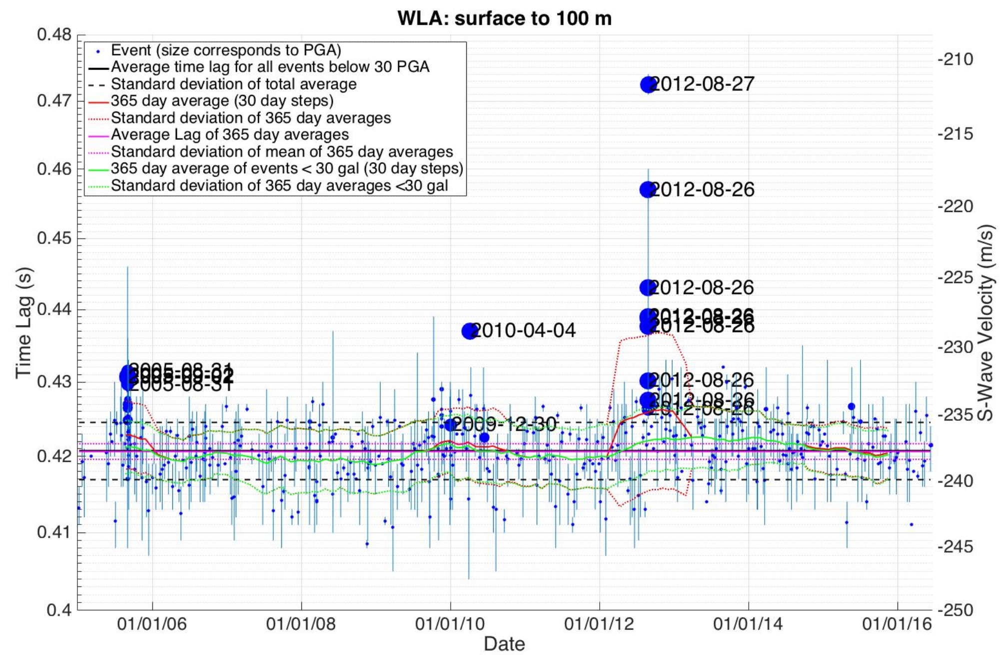
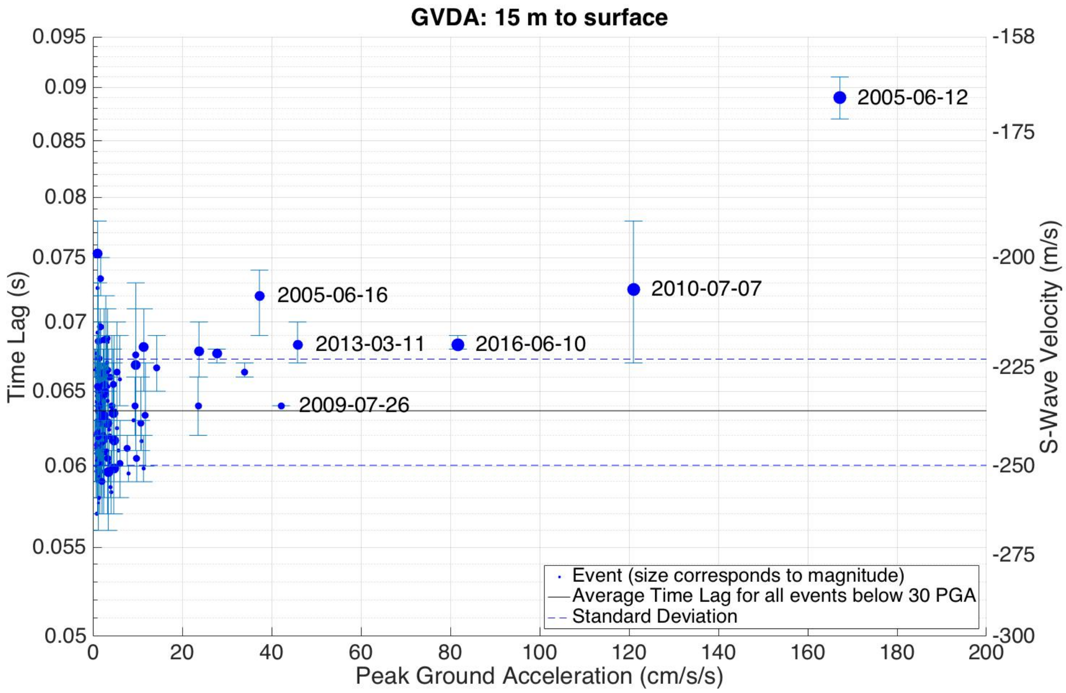


Figure 3: Results showing time lag between 4 pairs of vertical accelerometers from WLA against date of event. The events are plotted in the same format as Figure 2. While individual events vary greatly due to imperfections in the cross correlation, moving yearly averages show that the s-wave velocity decreases after large events.



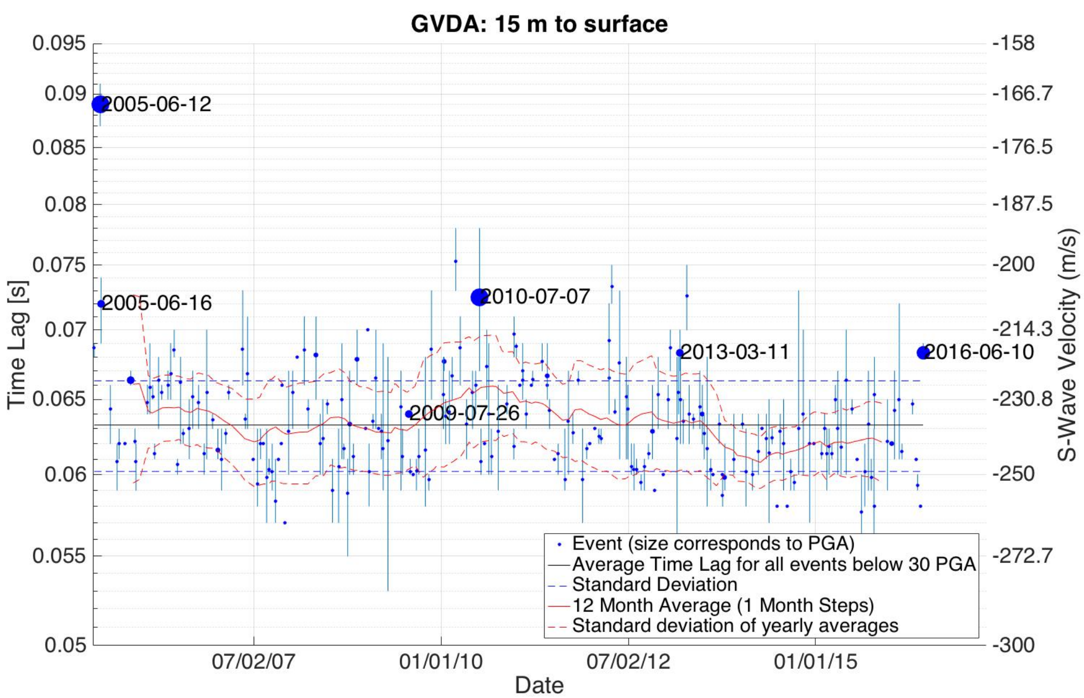


Figure 4: Results from GVDA. Clear evidence of nonlinearity at increased PGA. Data is plotted in the same manner as the previous WLA figures.

DPK:

A reduced s-wave velocity between the surface and GL-10.7 meter accelerometer by more than the standard deviation of the small event average velocity at the array in Anchorage, Alaska suggest that the site experienced nonlinear behavior during the recent January 2017 earthquake (Figure 5). None of the deeper sensors show any significant change in velocity during this event. No other events in the records reduce the shear wave velocity and therefore there is no other nonlinearity observed at the site. Due to lack of events since the recent nonlinear response at DPK, there is not sufficient data to observe a longer lasting slow dynamics recovery.

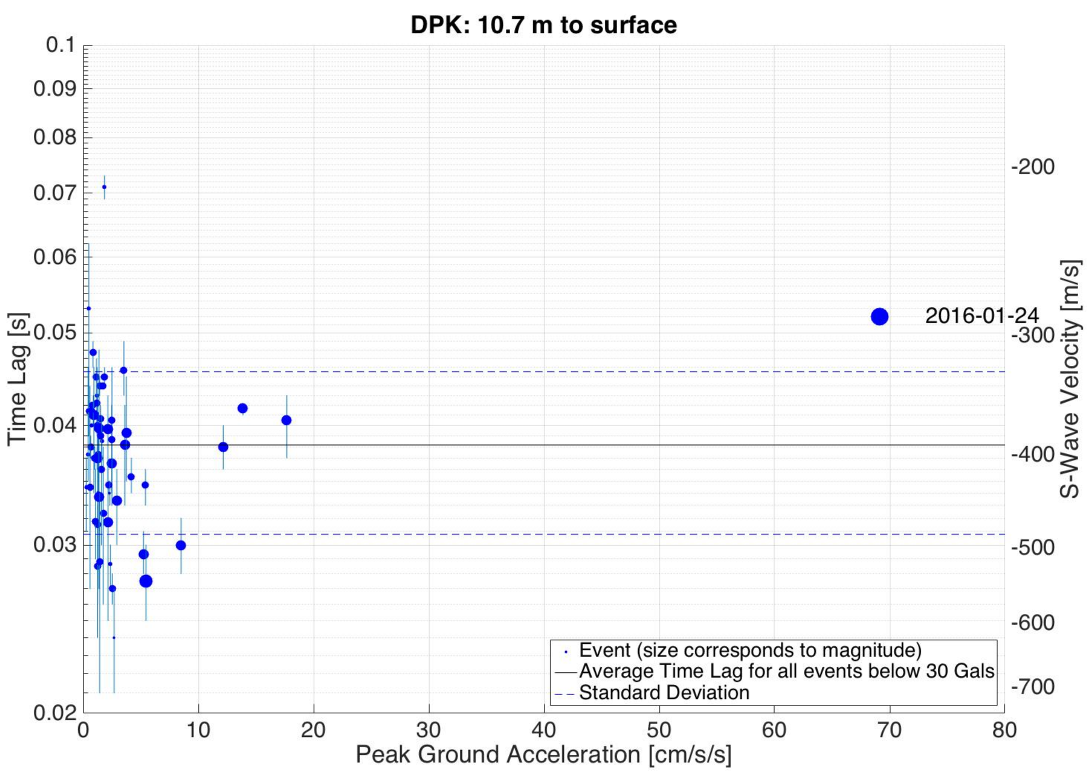
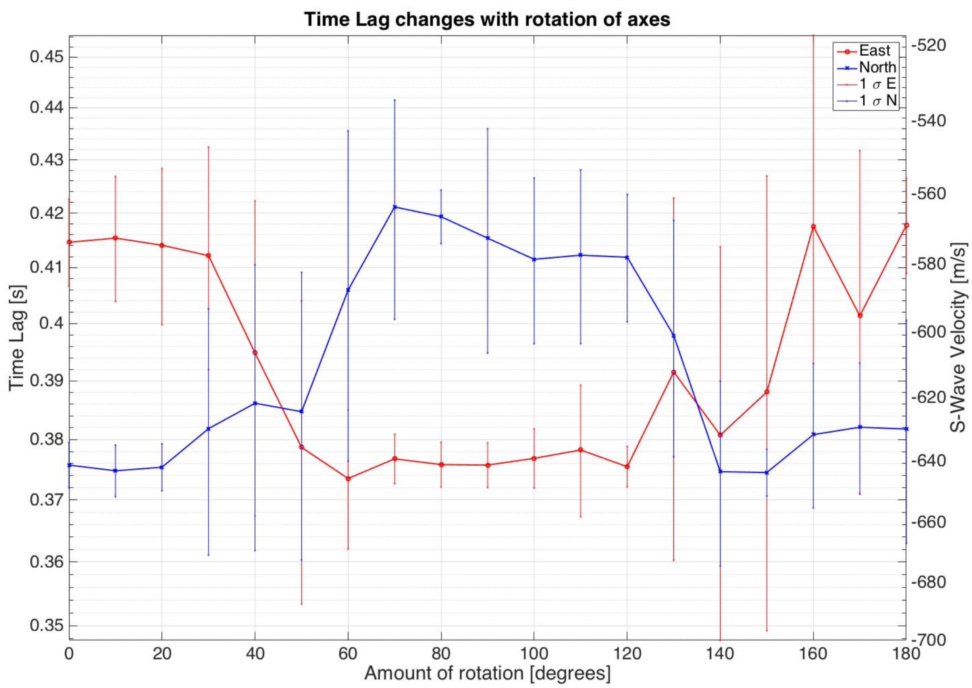


Figure 5: Results from DPK. Plotted in the same format as the previous two stations' data.

BVDA:

Data from the Borrego Valley Downhole Array (BVDA) has not shown any signs of nonlinearity even though there have been 3 events that produced motions greater than 30 Gals at the site. BVDA does experience a significant difference in shear wave velocity between it's north and east components, with the north component 10% slower than the east component in both the surface to 139 meter and surface to 238 meter sensor pairings (Figure 6a, 7b,c). BVDA does not display any anisotropy between the 19.4-meter and surface sensors (Figure 7a).

6a



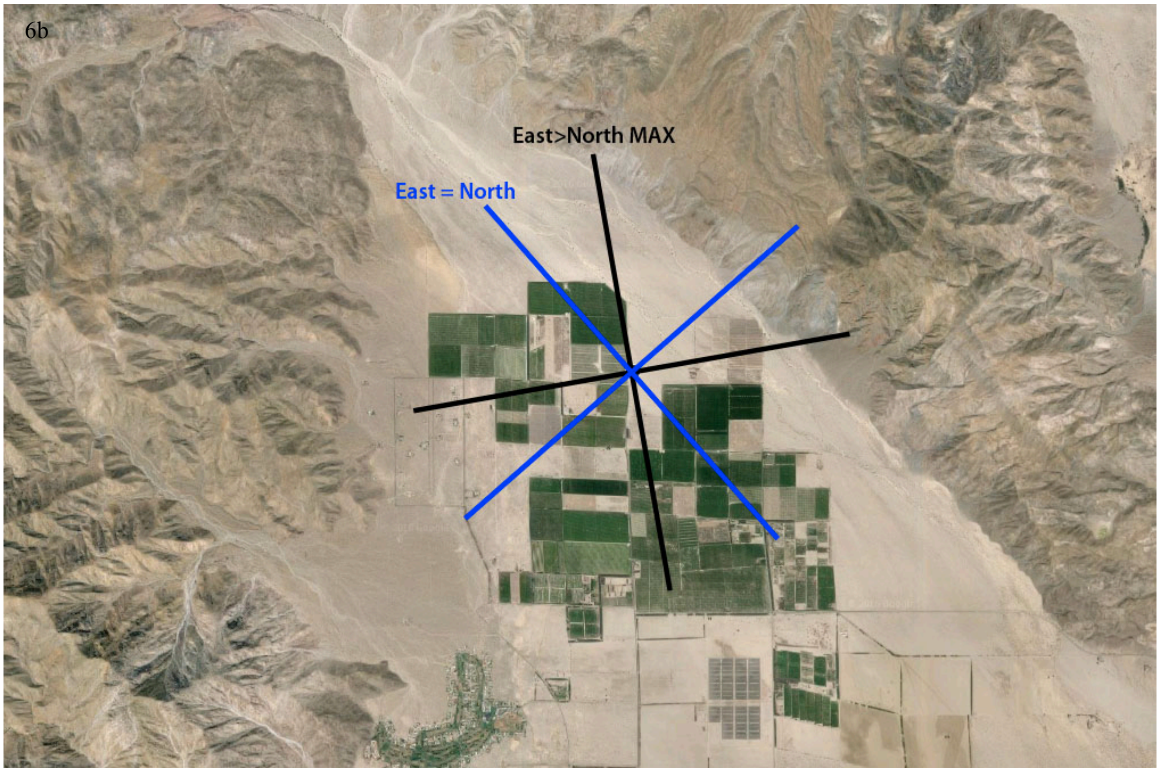


Figure 6: Anisotropy at BVDA. 6a: The velocity changes with respect to degree of rotation counterclockwise from North. 6b: The orientation where velocities in both components are equal.

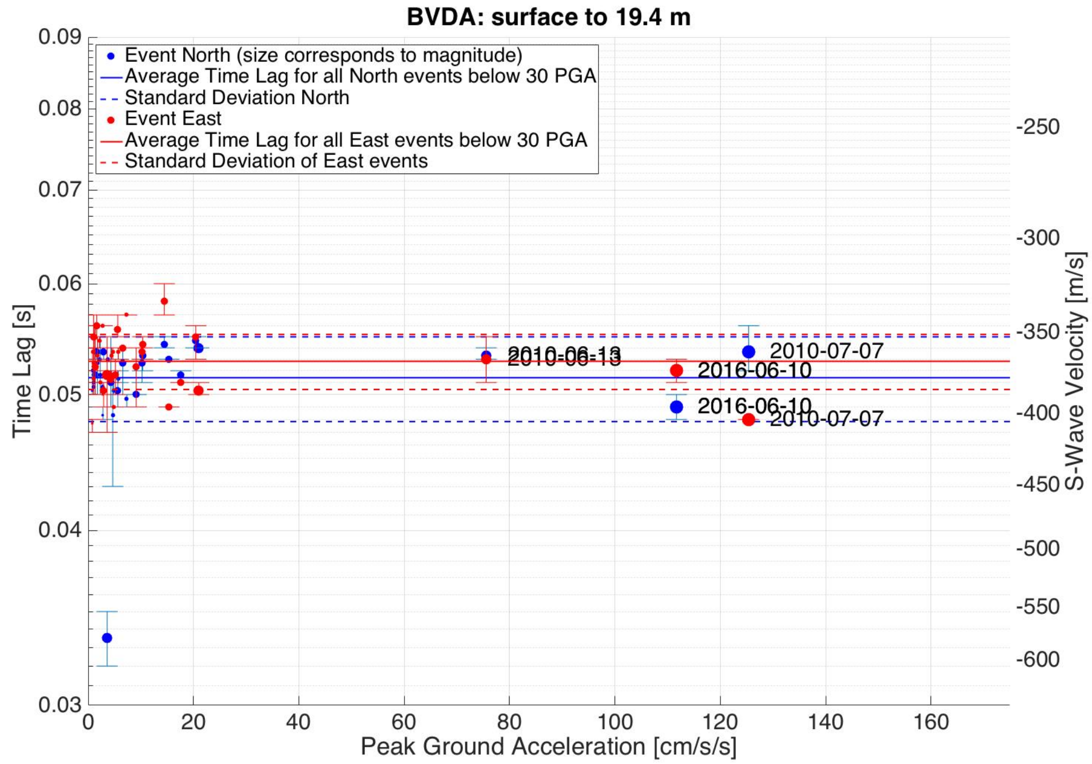
To test the anisotropy between the East and North sensors, each event's raw accelerometer data is rotated at ten-degree intervals by multiplying a rotation matrix to the East and North data vectors compiled into a matrix. Each rotated data set then was processed and average time lags were computed for all the events (Figure 6a).

$$A' = R * A$$

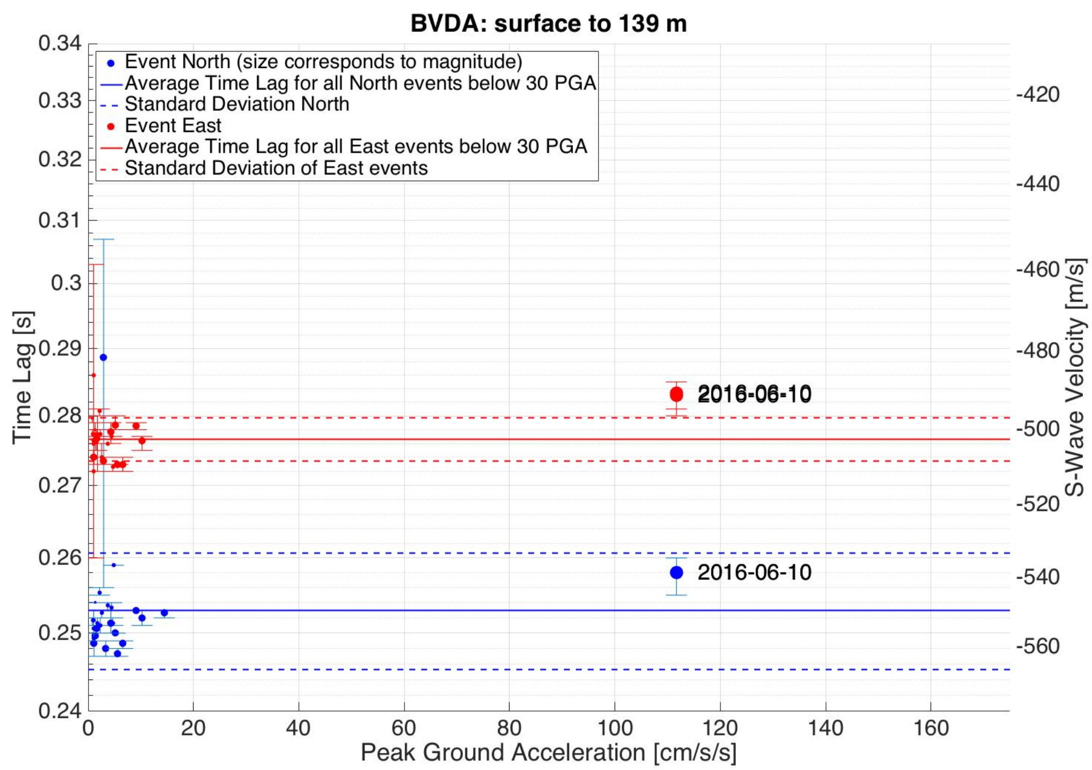
$$\begin{bmatrix} A'_{11} A'_{21} \\ \vdots \quad \vdots \\ A'_{n1} A'_{n2} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} A_{11} A_{21} \\ \vdots \quad \vdots \\ A_{n1} A_{n2} \end{bmatrix}$$

A_{n1} represents the East vector time series and A_{n2} represents the North vector time series.

7a


BVDA: surface to 19.4 m
Event North (size corresponds to magnitude)
Average Time Lag for all North events below 30 PGA
Standard Deviation North
Event East
Average Time Lag for all East events below 30 PGA
Standard Deviation of East events
2010-06-13
2010-07-07
2016-06-10
Time Lag [s]
S-Wave Velocity [m/s]
Peak Ground Acceleration [cm/s/s]

7b


BVDA: surface to 139 m
Event North (size corresponds to magnitude)
Average Time Lag for all North events below 30 PGA
Standard Deviation North
Event East
Average Time Lag for all East events below 30 PGA
Standard Deviation of East events
2016-06-10
Time Lag [s]
S-Wave Velocity [m/s]
Peak Ground Acceleration [cm/s/s]

7c

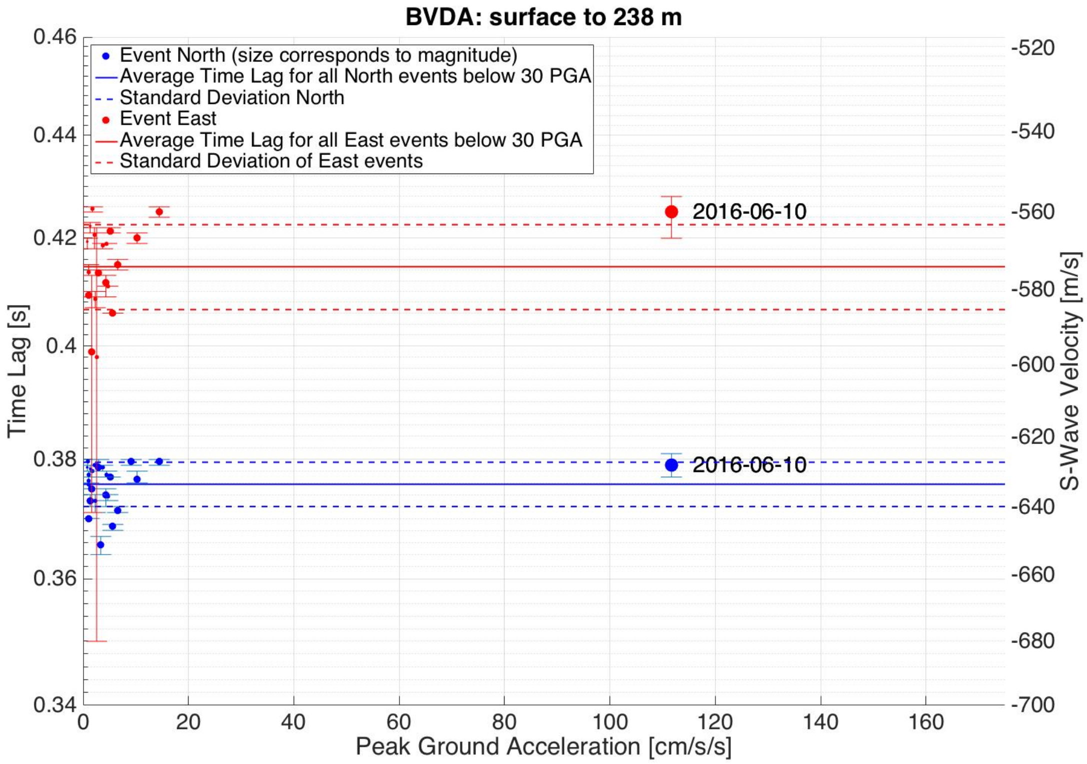


Figure 7: Events recorded at BVDA split into their two horizontal components and plotted with time lag against PGA. 7a: The shallowest pairing of sensors (19.4-surface) does not show any difference between the two components and no nonlinearity during the large ground motions produced during the June 10, 2016 earthquake. 7b,c: The deeper pairings of sensors have a large difference between the East and North components, about 10%. These are plotted with the same format as all previous figures.

Discussion

The *in situ* observational data previously discussed gives insight into nonlinear and nonequilibrium effects along with the time dependent recovery process of the material after sufficient excitation has occurred. Large strains induced during strong ground motions at WLA, GVDA, and DPK caused physical damage to the soil observed from the reduction in the shear strength of the material associated with the reduction of shear wave velocity between vertical accelerometers. At the WLA site, there is some evidence that the damage to the soil was not immediately healed, with the average shear-wave velocity remaining low for at least two years. Looking at only the events with PGA under 30 Gals, where even these weaker events had average shear wave velocities that remained low over the two years following the large strain events, supports this evidence. Normally, these events are not expected to exhibit reduced shear-wave velocity. These results confirm other observations of a recovery process in which granular Earth materials return to their original state given sufficient time that has been found both during *in situ* (Lawrence et al. 2009) and laboratory experiments (Johnson and Jia, 2005). Johnson and Jia (2005) performed a slow dynamics recovery experiment under two different effective pressures and found that both returned to their normalized shear modulus after about 10,000 seconds, shorter than the recovery observed in this study. Lawrence et al. (2009) did an induced nonlinear test and found the recovery process only lasted one day. The reason both the lab and induced tests have a much shorter recovery period than these results is likely due to their tests not using earthquake induced strong motion data, but locally generated point source motions at the surface instead. The local point source motions likely do not cause degradation in as large an area as earthquakes, so the local materials are able to recover quickly relative to damage caused by earthquake generated plane waves propagating up from depth over the region. Sawazaki et al. (2006) found two sites that had a reduction of the peak frequency during strong earthquake motion that took a few years for the values to recover, similar to the results presented here.

The WLA data confirms nonlinear fast dynamics and slow recovery in the best resolution of all the data sets due to its 10-year long recording history and continuous functionality of its instruments during that time. The high strain excitation in the nearby 2012 swarm demonstrated the longest lasting recovery, as seen from the reduced s-wave velocity in the two years of motions under 30 Gals following the swarm. This leads us to interpret the nonequilibrium slow dynamic process as one that can last for several years after significant damage has been sustained in the granular Earth material, but that it is still not a permanent effect as we see a return of the average shear modulus to its original value after about three years. Another unique observation at WLA was the depth at which nonlinear effects occurred. In most previous studies and models, nonlinear effects are limited to lower strength soils and the upper few meters at a site. Nonlinearity was still observed with a shear wave velocity reduction of five percent between the GL-30 and GL-100 meter sensors. Although the shear modulus is reduced much less than in the shallower sediments, we are able to surmise that even the deeper and stronger material can display nonlinear fast dynamics.

The GVDA site confirms nonlinearity much in the same way that the WLA data does. Events that create large ground motions between 15 meters and the surface cause damage in the material and reduce its shear strength significantly. The GVDA site provides decent resolution during a ten year period, but not as many well-recorded events have occurred there than at WLA, partly due to the higher noise characteristics of the older vintage of borehole sensor at the GVDA site.

The DPK site has one event with evidence of nonlinearity in the soft upper layer of soil as well, but not between the lower depth sensor pairings. This is likely because of the lack of data at the site because there are only four events with ground motions larger than 20 Gals, therefore the deeper material has not had large enough strains to cause nonlinearity. One hypothesis is that higher stiffness materials need higher ground motions (effective strains) in order to cause damage to and reduction of the shear modulus.

The BVDA site does not display any nonlinearity even though it has experienced some ground motions greater than the threshold for nonlinearity found at the previous sites (~30 Gals). Velocity measurements at the sight indicate it has a faster wave velocity and therefore larger shear modulus when compared to that of the other sites, so although we expected to find less nonlinear behavior during the greater than 30 Gal ground motions, we did not expect to find no nonlinearity because we demonstrate fast dynamics with stiffer material in deeper materials of other sites. We have no clear answer to this question that is raised by the lack of damage to the site during high strains, but it indicates that soil shear strength is not the only variable that affects nonlinear behavior. The sediments at BVDA are significantly stiffer and compositionally different enough from WLA and GVDA to still behave linearly up to 100 Gals of ground motion. The different depositional environment likely plays a role in this. Comparing GVDA to WLA, which has a higher V_s30 (GVDA V_s30 ~ 250 m/s; WLA V_s30 ~ 170 m/s), supports the claim that nonlinearity is not entirely determined by stiffness because GVDA appears to experience greater levels of fast dynamics.

The anisotropy is an interesting observation that merits discussion. It could possibly be caused by long-term damage in the direction parallel to the nearby San Jacinto fault trending 50 degrees west of north. Because the fault is near, tectonic stresses might have caused fractures in parallel to the direction we find the anisotropy. Fractures inhibiting the travel of seismic waves through the bedrock would cause a phase velocity slowing and apparent drop in shear modulus in one direction relative to another. Another cause of anisotropy could be the orientation of the sedimentary bedding in the valley. If the anisotropy is truly more nonequilibrium recovery in one direction than another, we would expect to find increasing amounts of nonlinearity in the shallower materials, but instead we find a constant anisotropy in the deeper sediment and very little in the shallow sediments. This results suggests that the deeper materials have been subjected to more faulting damage than the shallow sediment and it is not related to nonlinear behavior, but instead could be the effects of permanent fault zone damage over time.

A possible source of error in our calculations of the average shear wave velocity or time lag could come from ignoring the time dependent recovery process that we have been studying. It is observed that small events after large shaking exhibit a reduced shear wave velocity; therefore we cannot assume the maximum shear modulus (G_{max}) of the sight is related to the average shear wave velocity at the site during events that are below 30 Gals. A true G_{max} at the site can only be determined by measuring the shear wave velocity when there is absolutely no memory of previous nonlinearity in the soil. Viewing the moving average of shear wave velocity at WLA indicates that during long periods without strong ground motions, the value appears below the total average for shear velocities from all the small events recorded. Therefore, the actual s-wave velocity is likely faster than is calculated, which would produce even larger percentages of velocity reduction at the site. This conclusion implies that the quantified nonlinearity presented in this study likely underestimate how much actual nonlinearity is occurring and the recovery time is even longer than inferred. Therefore, we take these results as minimum estimates for the true effects of nonlinearity. It may be challenging to find the true G_{max} because the material takes so long to recover, it could be slightly under the influence of earthquakes in years past, such as the 1987 superstition hills earthquake that liquefied the site, so we leave the results as a minimum estimate without trying to infer what the maximum extent could be.

Conclusion

This study has demonstrated *in situ* observations of nonlinear and nonequilibrium effects in soil with varying degrees of shear strength during strong ground motions recorded at various down-hole arrays. It also suggests a slow recovery process that can last months and possibly to years after significant damage has been done to granular Earth materials at multiple sights. At the WLA site nonlinearity was consistently detected at accelerations as low as 30 Gals and there is up to a 40% increase in time lag during the largest ground motions. We also discovered a possible effect of long-term anisotropic damage at the BVDA site that needs further examination.

How water table height affects shear wave velocity in soil

Introduction

The permanently installed cross-hole experiment at the Garner Valley Downhole Array and Wildlife Liquefaction Array were placed in order to further constrain how long it takes for Earth materials to recover their shear modulus after larger earthquakes. Since their installation, there has not been any large ground motion at either site, but it was discovered that as the water table varied with the seasons, the shear wave velocity changed. This sparked our following study of pore fluid pressure on shear wave velocity.

The physical processes involved in seismic wave velocity reduction are poorly understood and are very difficult to model. There are many potential sources of seismic energy absorption in rock and unconsolidated sediment including but not limited to frictional affects and pore fluid saturation. Many previous studies have found that pore fluids have strong effects on attenuation in rocks; Tittmann et al (1972) showed that by removing the trace amounts of water vapor present in rocks at room humidity, the attenuation decreases by an order of magnitude. Born (1941) found that when water saturation was reduced to below one percent in sandstone, attenuation was decreased and became frequency dependent with similar results from Gardner et al (1964) in Berea sandstone. Seismic velocity and attenuation in granite and limestone is a function of pore fluid viscosity as studied by Nur and Simmons (1970) and Nur (1971) and interpreted as shear relaxation (Walsh, 1969) or intercrack flow (O'Connell and Budiansky, 1977). Measurements of P and S wave attenuation were first measured in dry and saturated sandstone by Toksöz et al in 1979 and Johnston et al (1979) concluded that the dominant mechanism for attenuation in both the wet and dry rock was frictional sliding.

There is a general agreement that rocks with pore fluids present have a greater amount of seismic attenuation than dry rocks, but the mechanisms responsible for this effect are disputed. There have also been few *in situ* studies of how water table height affects seismic wave velocity and no long-term studies on how seasonal changes to pore fluid pressure with changing water table height affect attenuation. West and Menkey (2001) performed a study observing changing water table height during the cycle of the tides on a sandy beach and found that saturated layers showed changing wave velocity with changing water table height, attributing increased pore fluid pressure to a reduced shear modulus. This project is intended to bring more *in situ* data forward and to examine how changes in pore fluid pressure over months and years (due to rainfall and drought) affect shear wave velocity.

Methods

The Wildlife Liquefaction Array and Garner Valley Downhole Array, two different downhole arrays in Southern California, have permanently deployed cross-hole experiments that are used in this study. Shear wave velocity is found from the cross-hole experiment by measuring the time it takes the waves to travel from a source to two geophones all located at the same depth. Using the distance between the sensors and the time difference, an average shear wave velocity between the two sensors is calculated. At Garner Valley the setup includes a solenoid powered dual directional hammer located at five meters in depth and four geophones, two of which are located at five meters and the other two directly above those at two meters depth (Figure 8). The hammer is triggered to swing both upwards and downwards once a week, Sundays at 7:30 AM local time.

The Wildlife Liquefaction Array also has a cross-hole experiment running once a week. It has a hammer source at 4.6 meters depth and three geophones at the same depth at 3.21 meters, 6.28 meters, and 9.38 meters in a straight line away from the source along with another geophone above the farthest geophone at 2.5 meters depth (Figure 9).

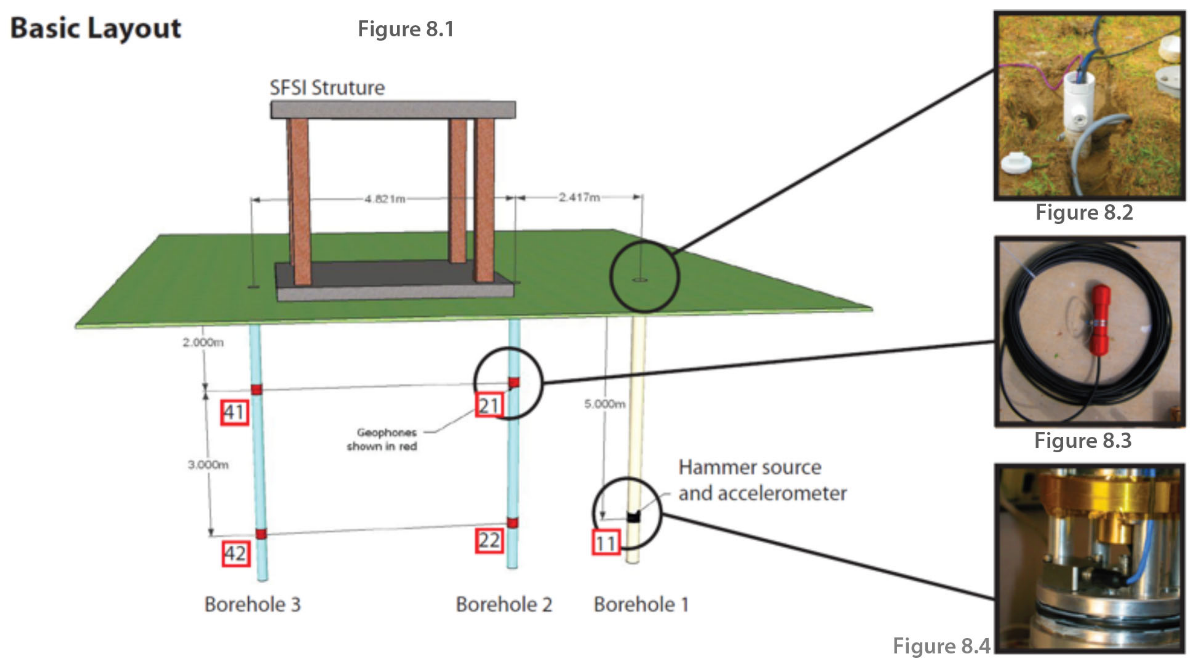


Figure 8.1: The basic layout of the cross-hole experiment at GVDA. 8.2: Top of borehole casing. 8.3: Depiction of one of the four Geospace GS-20DX 14 hz, uniaxial Geophones. 8.4: Close-up of the duel-directional solenoid driven hammer

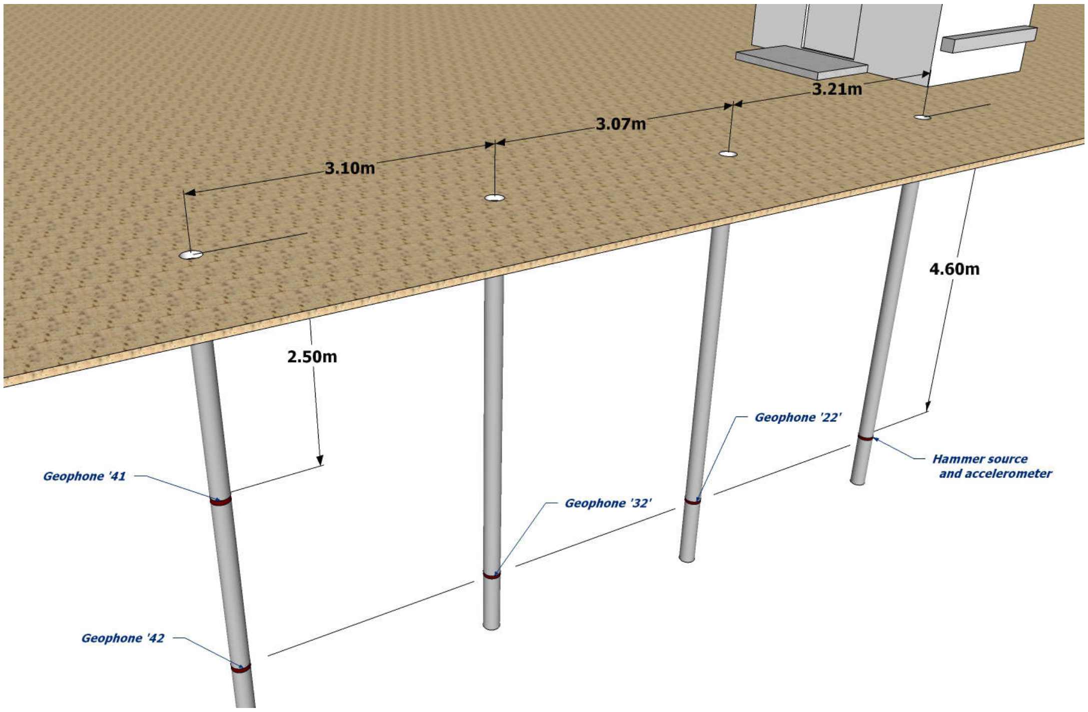


Figure 9: Layout of cross-hole experiment at WLA

At GVDA, the hammer was swung from December 7, 2010 to June 18, 2012, then from August 9, 2015 to May 14, 2017. The hammer swung every day during the 2010-2012 window and once a week from August 2015 to July 2017. The data is stored as miniSEED files on the servers at the Earth Research Institute. MATLAB scripts extract the data and convert it to a useable format. A Short Term Average over Long Term Average (STA/LTA) moving algorithm detects when the upswing and downswing arrivals occur during the closest geophone's record and then one second windows around those arrival times are created to use for cross correlation. Geophones 42 and 22 (Figure 8a) then have their arrival time windows cross-correlated together and using the difference in arrival times and the distance between the sensors, the shear wave velocity is calculated. The sample rate of the geophones is 2000 samples per second (sps), or every 5×10^{-4} seconds. Waves travelling at ~200 m/s (the approximate velocity at 5 meters depth) recorded at 2000 sps by geophones spaced ~5 m take 0.025 seconds, or 50 samples to cover that distance. If the s-wave speed is increased to 205 m/s, it takes ~0.0244 seconds, a difference of 6 x 10^{-4} seconds, only about one sample less to cover the distance. This gives a velocity change detection resolution of about 5 m/s with the 2000 sps data acquisition.

Water table and rainfall data during the time period of interest were also collected from a pore pressure transducer, barometric pressure sensor, and rainfall sensor. The pore pressure transducer and barometric pressure sensor are used to calculate the water table height every day during the periods when the hammer was active.

The same methods are used for the WLA data, except no rainfall data was included in the analysis.

Results

The shear wave velocity at GVDA varies between 209 and 225 meters per second. Figure 10 shows the wave velocity and water table height during the two periods the hammer was active for the up swing and down swing. There is a clear trend between rising water table height and decreasing shear wave velocity and vice versa during both time periods. Note that the water table height is always above the geophones that are used in the calculations.

Figure 11 shows the recent hammer swing data with rainfall plotted as well. During the winter storms in early 2017 that brought the water table height above 2 meters occur at the same time that the wave velocity decreases by almost 5%.

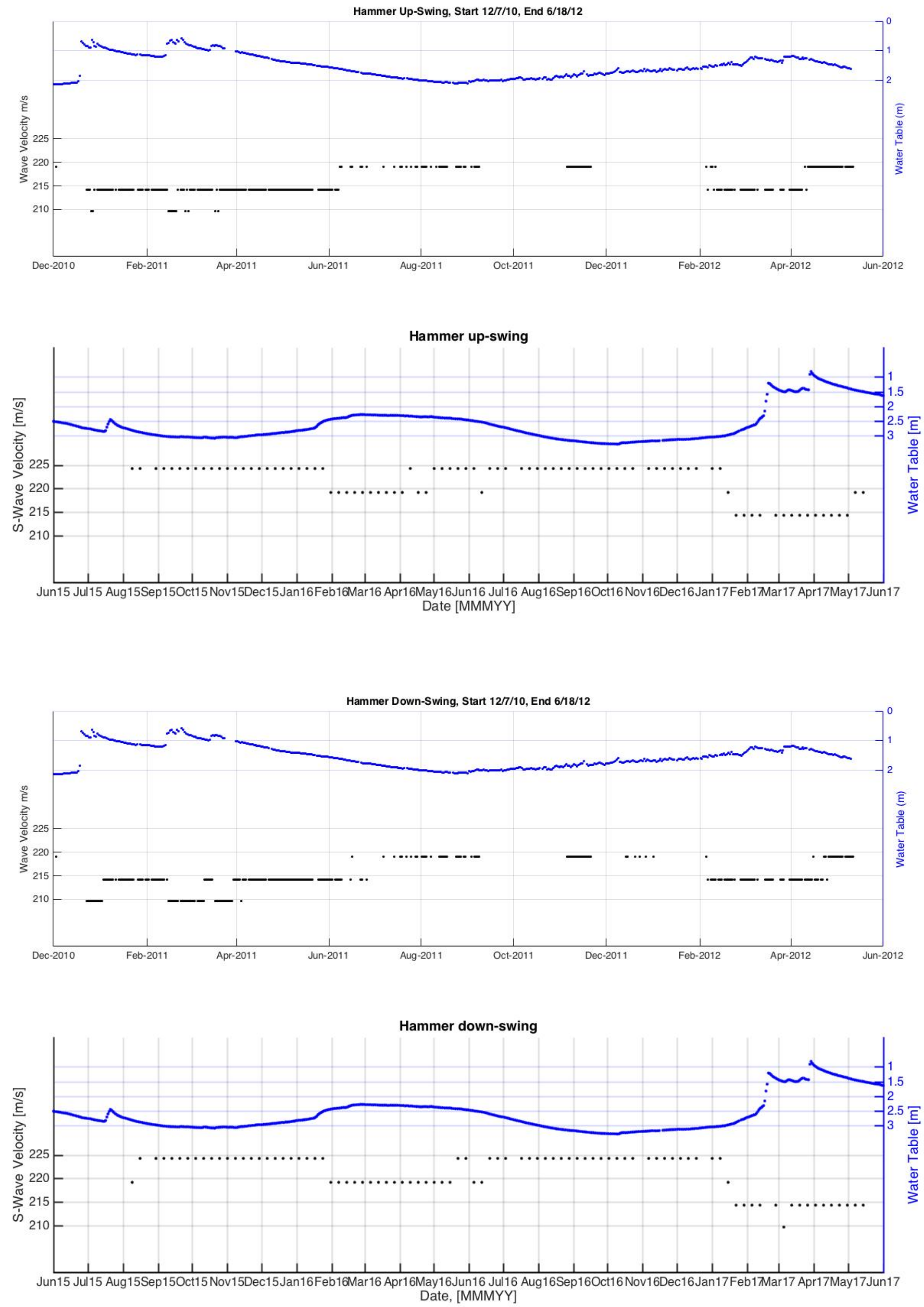


Figure 10: Water table height and shear wave velocity versus date

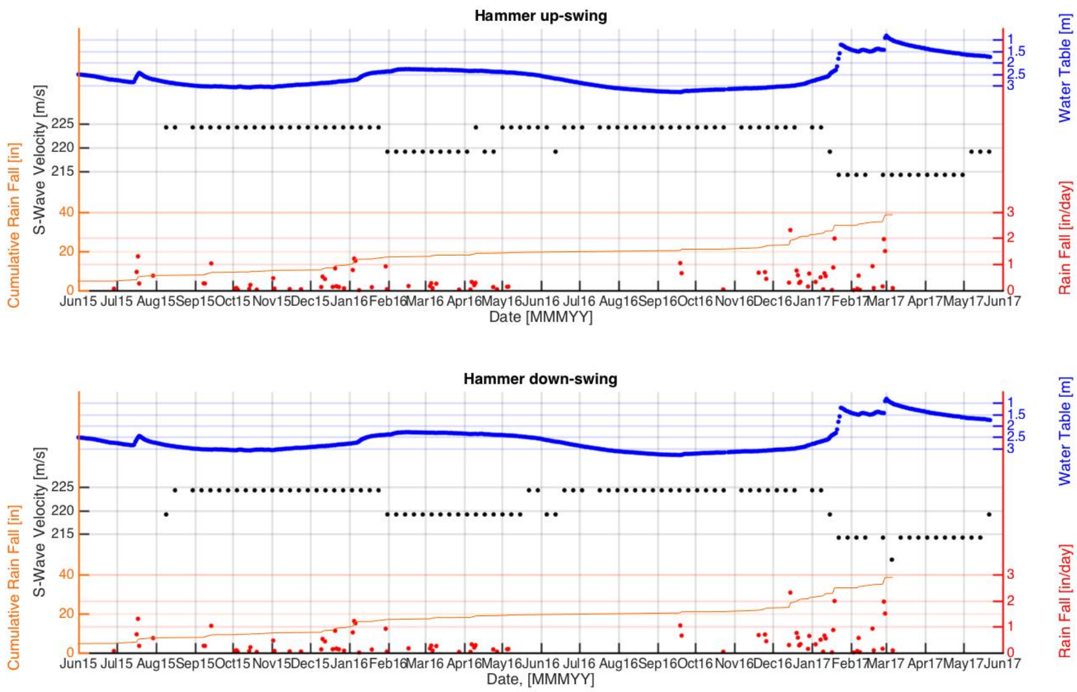
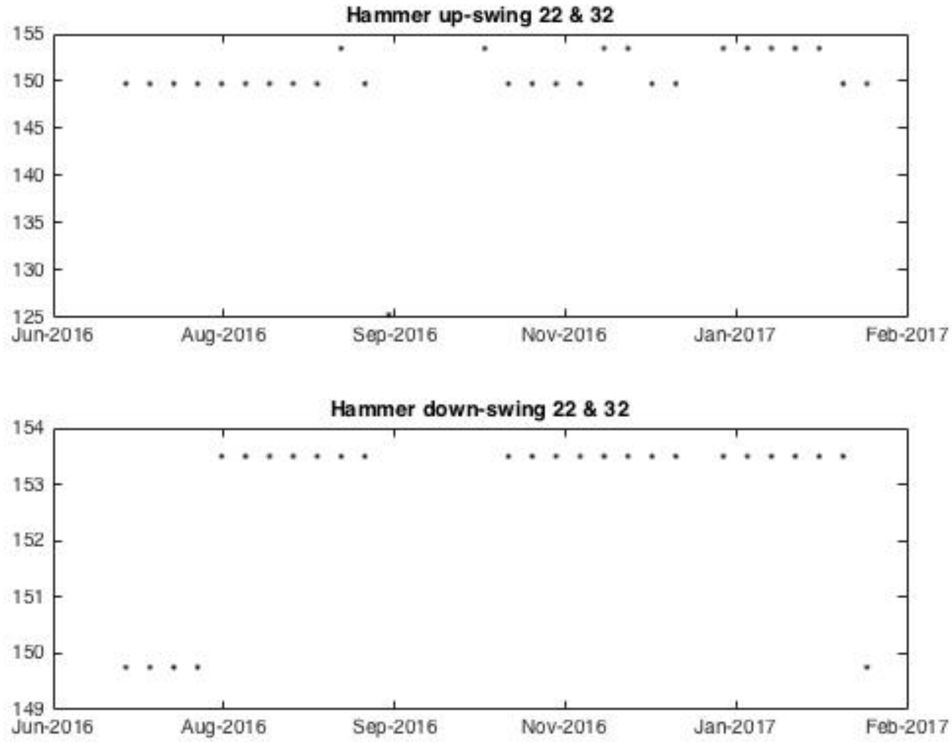


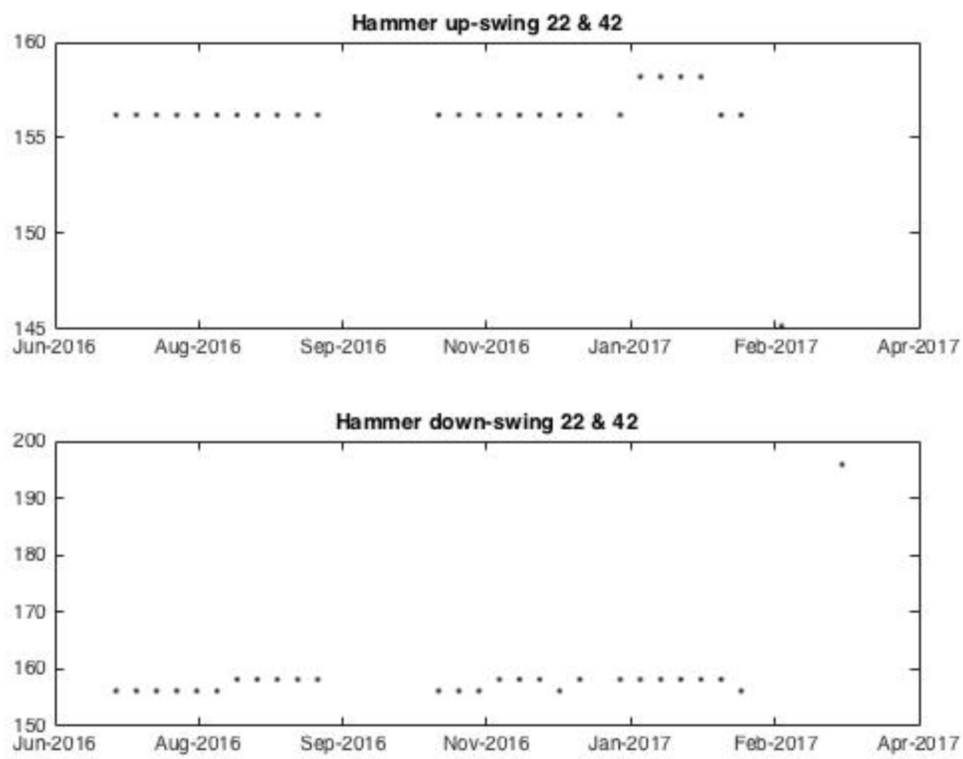
Figure 11: Water table height, s-wave velocity, and rainfall versus date

The data from WLA did not produce any meaningful results. The s-wave arrivals are more emergent than the impulsive signal at GVDA and have a long coda after the arrival that make the cross correlation have a very difficult to get an accurate time difference. Because of this issue, it was not possible to analyze the data from the WLA cross-hole array using these cross-correlations methods. Figure 12 displays the velocity data that was resolved; the velocity varies between 149 and 165 m/s. There is a slightly higher resolution because of the slower average shear wave velocity at this site relative to the GVDA, approximately 4 m/s between intervals.

12.1


Hammer up-swing 22 & 32
155
150
145
140
135
130
125
Jun-2016
Aug-2016
Sep-2016
Nov-2016
Jan-2017
Feb-2017
Hammer down-swing 22 & 32
154
153
152
151
150
149
Jun-2016
Aug-2016
Sep-2016
Nov-2016
Jan-2017
Feb-2017

12.2


Hammer up-swing 22 & 42
160
155
150
145
Jun-2016
Aug-2016
Sep-2016
Nov-2016
Jan-2017
Feb-2017
Apr-2017
Hammer down-swing 22 & 42
200
190
180
170
160
150
Jun-2016
Aug-2016
Sep-2016
Nov-2016
Jan-2017
Feb-2017
Apr-2017

12.3

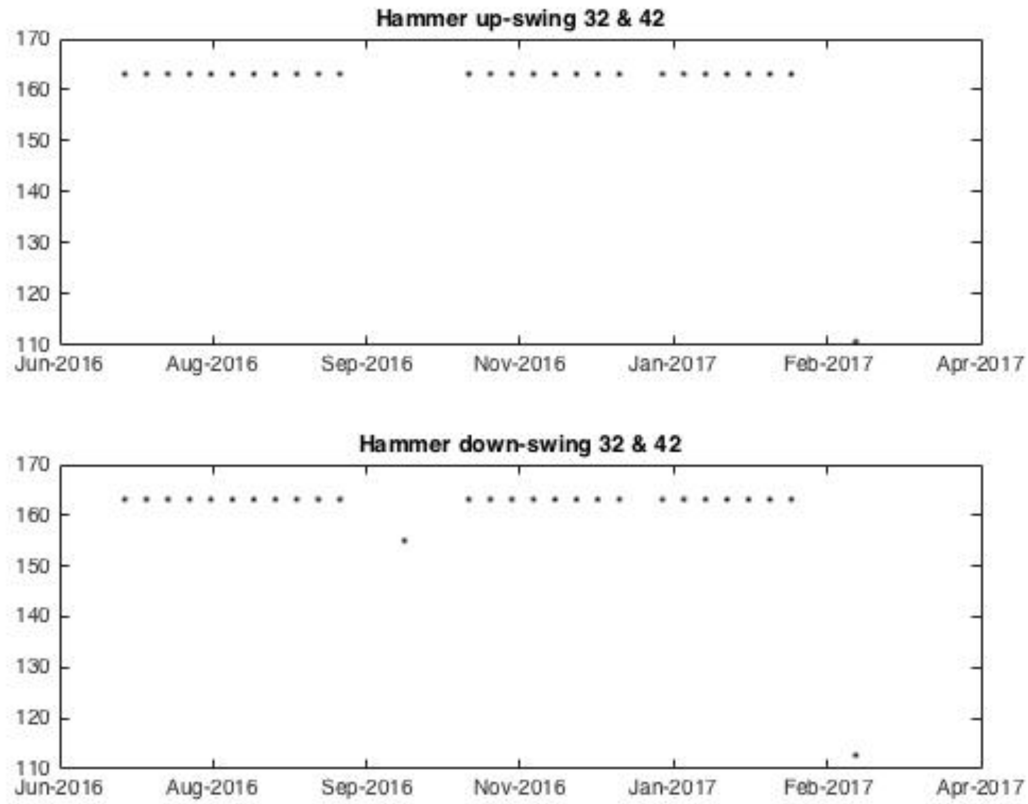


Figure 12: The WLA results comparing shear wave velocity and date. There are a few outliers, and a few dates missing because hammer source was not triggered.

Discussion

The data from GVDA shows a strong visual correlation between water table height and the shear wave velocity of the material. The higher the water table, the slower the shear wave velocity. Because the geophones are always below the water table at this site, the presence of pore fluids or lack thereof is likely not the causation of the velocity changes observed. Instead, larger fluid pressures due to the increased height of the overlying water column likely causes it. Because the density of the material is staying constant, the assumption is that the shear modulus of the material is changing with the pore fluid pressure. Fluid pressure reduces the effective stress in the sediment likely because of reduced friction between grains causing a reduction in shear wave velocity to occur. Just as shear strength increases with compaction and consolidation of sediment, increased pore fluid pressure acts in the reverse and decreases the shear modulus in these near-surface unconsolidated sediments.

Conclusion

The cross-hole experiment has provided evidence that over long periods of droughts and heavy rains, change in the height of the water table cause changes in the shear wave velocity. This is a phenomenon that should be carefully considered when examining shallow shear wave velocity studies because it can change results from one time of the year to another by 5%.

This analysis shows that studying nonlinear change in the shear modulus using the cross-hole arrays is promising in the future because the resolution, ~5 m/s at GVDA and 4 m/s at WLA, is fine enough to detect small changes in the s-wave velocity. It will be useful as a tool for studying the slow recovery of the modulus after strong ground motions at the two sites.

References

Seed, H.B., and I. M. Idriss (1970). Report No. ERIC 70-10, *Soil moduli and damping factors for dynamic response analysis*, Earthquake Engineering Research Center, University of California, Berkeley.

Hardin, B. O., and V. P. Drnevich (1972a). Shear modulus and damping in soil: Measurement and parameter effects, *J. Soil Mech. Found. Div. ASCE* **98**, 603–624.

Hardin, B. O., and V. P. Drnevich (1972b). Shear modulus and damping in soil: Design equations and curves, *J. Soil Mech. Found. Div. ASCE* **98**, 667–692.

Vucetic, M. (1994). Cyclis threshold shear strains in soil *J. Geotech. Eng.* **120**, 2208-2228.

Guyer, R. A., and P. A. Johnson (1999). The astonishing case of mesoscopic elastic nonlinearity, *Physics Today* **52**, 30–35.

Ostrovsky, L., and P. A. Johnson (2001). Dynamic nonlinear elasticity in geomaterials, *La Rivista del Nuovo Cimento* **24**, 1–46.

Beresnev, I. A., and K. L. Wen (1996). Nonlinear soil response—a reality? *Bull. Seismol. Soc. Am.* **86**, 1964–1978.

Johnson, P. A., and A. Sutin (2005). Slow dynamics and anomalous fast dynamics in diverse solids, *J. Acoust. Soc. Am.* **117**, 124–130.

Lawrence, Z., P. Bodin, C. A. Langston, F. Pearce, J. Gomberg, P. A. Johnson, F. Y. Menq, and T. Brackman (2008). Induced dynamic nonlinear ground response at Garner Valley, California, *Bull. Seismol. Soc. Am.* **98**, 1412–1428.

Lawrence, Z., Bodin, P., and C.A. Langston (2009). In Situ Measurments of Nonlinear and Nonequilibrium Dynamics in Shallow, Unconsolidated Sediments, *Bull. Seismol. Soc. Am.* **99**, 1650-1670.

Pavlenko, O. and K. Irikura (2002). Nonlinearity in the response of soils in the 1995 Kobe earthquake in vertical components of records, *Soil. Dyn. Earthq. Eng.* **22**, 967-975.

Karabulut, H. and M. Couchon (2007). Spatial variablitiy and nonlinearity of strong ground motion near a fault, *Geophys. J. Int.* **170**, 262-274.

Sawazaki, K. H., H. Sato, H. Nakahara, and T. Nishimura (2006). Temporal change in site response caused by earthquake strong motion as revealed from coda spectral ratio measurement, *Geophys. Res. Lett.* **33**, L21303.

Steidl, J. H., F. Civilini, and S. Seale (2014). What have we learned after a decade of experiments and monitoring at the NEES@UCSB permanently instrumented field sites? Proc. of the 10th U.S. National Conference on Earthquake Engineering,Anchorage, Alaska, 21–25 July 2014.

TenCate, J. A., E. Smith, and R. A. Guyer (2000). Universal slow dynamics in granular solids, *Phys. Rev. Lett.* **85**, 1020–1023.

TenCate, J. A., D. Pasqualini, S. Habib, K. Heitmann, D. Higdon, and P. A. Johnson (2004). Nonlinear and nonequilibrium dynamics in geomaterials, *Phys. Rev. Lett.* **93**, doi 10.1103/PhysRevLett .93.065501.

Johnson, P. A., and X. Jia (2005). Nonlinear dynamics, granular media and dynamic earthquake triggering, *Nature* **437**, 871–874.

Tittman, B.R., Abdel-Gawad, M., and Housley, R.M., (1972). Elastic velocity and Q measurements on Apollo 12, 14, and 15 rocks, *Proc. 3td Lunar Sci. Conf.* p. 2565-2575.

Born, W.T., (1941). The attenuation constant of earth materials: Geophysics. 6, p. 132-148.

Gardner, G. H. F., Wyllie, M. R. J., and Droschak, D. M., (1964). Effects of pressure and fluid saturation on the attenuation of elastic waves in sands, *J. Petr. Tech*., **16**, p. 189-198.

Nur, A., and Simmons, G., (1970). The effect of viscosity of a fluid phase on velocity in low porosity rocks, *Earth Plan. Sci. Lett.*, **7** p. 99-108.

Nur, A., (1971). Visocus phase in rocks and the low-velocity zone, *J. Geophys. Res.*, **76**, p. 1270-1277.

Walsh, J. B., (1969). New analysis of attenuation in partially melted rock, *J. Geophys. Res.* **74**, p. 4333-4337.

O'Connel, R. J., and Budiansky, B., (1977). Viscoelastic properties of fluid-saturated cracked solids, *J. Geophys. Res.*, **82**, p. 5719-5736.

Toksöz, M. N., Johnston, D. H., and Timur, A., (1979). Attenuation of seismic waves in dry and saturated rocks. I. Laboratory measurments, *Geophysics*. **44**, p. 681-690.

Johnston , D. H., Toksöz, M. N., and Timur, A., (1979). Attenuation of seismic waves in dry and saturated rocks: II. Mechanisms, *Geophysics*. **44**, p. 691-711.

West, M. and Menke, W., (2001). Fluid-Induced Changes in Shear Velocity from Surface Waves. Proc., Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), Denver, Co., p. 21-28.

Appendix

List of events for WLA

Event ID	Magnitude	Date	Time	PGA (cm/s/s)
10078833	2.8	5-Feb-05	23:37:31	3.897683719
10082213	2.15	23-Feb-05	10:59:59	0.075699261
10083485	1.85	28-Feb-05	10:36:10	0.135863701
10095673	2.03	30-Apr-05	20:20:24	1.245626327
10099425	1.3	14-May-05	1:26:09	0.139578539
10100369	2.47	17-May-05	11:17:55	2.757776709
10147473	1.95	14-Oct-05	9:19:46	1.076597504
12212727	1.22	9-Jul-05	21:08:36	0.442628402
12216915	3.65	1-Sep-05	13:49:59	19.78952722
12217067	4.5	2-Sep-05	1:27:08	44.85613467
12217251	4	31-Aug-05	23:33:29	17.25049849
12217483	2.37	1-Sep-05	12:49:16	1.882052785
14116860	2.35	6-Jan-05	5:32:06	3.631476864
14120096	2.61	20-Jan-05	15:45:57	0.398245126
14122488	2.79	31-Jan-05	14:05:20	0.144097796
14130500	2.15	6-Mar-05	3:46:25	3.711938315
14131160	2.33	10-Mar-05	3:28:01	3.556985852
14131164	1.79	10-Mar-05	3:29:07	0.929588349
14131336	2.01	11-Mar-05	6:02:41	1.042907096
14133048	3.7	22-Mar-05	8:55:05	0.321069433
14134948	1.83	31-Mar-05	13:23:02	0.209114711
14135412	2.1	2-Apr-05	18:03:51	0.052836851
14136548	2.2	9-Apr-05	10:08:31	0.817007075
14137688	2.48	14-Apr-05	18:45:14	2.880245765
14138696	1.73	19-Apr-05	12:37:56	1.473222683
14146956	4.06	21-May-05	0:39:32	0.931448713
14148548	1.77	30-May-05	11:06:17	1.291534329
14150780	1.72	9-Jun-05	16:43:49	0.676244076
14154508	1.3	15-Jun-05	8:09:11	0.121665265
14158980	1.67	28-Jun-05	22:59:16	0.507897414
14160072	3.18	3-Jul-05	13:16:36	0.19371168
14166684	1.53	28-Jul-05	13:05:56	0.276611053
14167612	2.92	31-Jul-05	21:04:17	5.532483315
14167736	2.03	1-Aug-05	6:27:30	4.311184985
14171572	1.5	10-Aug-05	4:52:22	0.238934711
14174988	1.64	20-Aug-05	4:46:26	0.452531929
14177900	3.66	31-Aug-05	15:35:27	15.37707654
14178184	4.59	31-Aug-05	22:47:35	34.004179

14178188	4.45	31-Aug-05	22:50:13	24.44973691
14178212	4.1	31-Aug-05	23:07:06	16.30658576
14178236	4.33	31-Aug-05	23:27:22	20.41976985
14178248	4.48	31-Aug-05	23:32:01	21.26697816
14178348	2.01	1-Sep-05	0:28:55	0.638957935
14178404	2.86	1-Sep-05	1:03:06	3.582089978
14178576	2.03	1-Sep-05	2:27:22	0.859472943
14178692	2.07	1-Sep-05	3:47:23	2.579603147
14178764	3.01	1-Sep-05	4:29:12	7.818107634
14178856	2.25	1-Sep-05	5:53:32	2.219325237
14178904	2.34	1-Sep-05	6:30:47	2.786468277
14179288	3.68	1-Sep-05	13:48:15	19.79902254
14179292	4.48	1-Sep-05	13:50:10	19.78613937
14179296	2.3	1-Sep-05	14:02:59	1.341840726
14179308	2.14	1-Sep-05	14:13:36	1.574895883
14179736	5.11	2-Sep-05	1:27:10	44.85561301
14179896	2.35	2-Sep-05	2:31:37	3.861395818
14179924	3.76	2-Sep-05	2:46:25	15.12556363
14181136	2.27	3-Sep-05	11:23:36	4.719674907
14181328	2.24	4-Sep-05	2:08:16	5.102521878
14181376	1.43	4-Sep-05	4:20:42	0.626994606
14181508	1.79	4-Sep-05	13:01:01	1.023811897
14181596	2.2	4-Sep-05	19:32:35	1.235046522
14181636	1.62	4-Sep-05	22:52:32	0.345384021
14181756	3.83	5-Sep-05	8:53:43	16.60627386
14181936	3.17	5-Sep-05	23:49:27	10.65736112
14182084	2.36	6-Sep-05	12:41:05	7.03029483
14182980	2.83	8-Sep-05	22:49:47	7.99874469
14184304	2.85	13-Sep-05	5:46:53	6.47989362
14185020	2.25	15-Sep-05	22:43:30	0.478942494
14185980	2.47	20-Sep-05	9:08:32	1.129075918
14190156	2.04	4-Oct-05	15:16:46	0.852611741
14190524	1.49	5-Oct-05	21:02:33	0.135236803
14196288	1.36	3-Nov-05	22:33:50	0.234279137
14197476	2.67	11-Nov-05	2:04:35	0.564461513
14198024	3.4	14-Nov-05	22:00:16	0.817842385
14201640	2.59	2-Dec-05	16:25:11	0.4042065
14203892	2.41	13-Dec-05	8:32:04	1.886002423
14206552	2.48	31-Dec-05	17:52:37	8.020440455
10168489	3.09	7-Feb-06	10:11:46	0.845964601
10179981	1.62	23-Apr-06	20:58:01	0.570418076
10181465	2.24	3-May-06	15:43:22	0.953313948
10182629	1.54	11-May-06	10:29:42	0.184436963

10184117	1.18	20-May-06	18:38:30	0.39722225
10185797	1.9	31-May-06	2:41:34	0.686508804
10200661	1.42	6-Aug-06	0:21:02	0.239139293
10206481	3.01	5-Sep-06	15:22:58	0.73184139
10207681	4.05	14-Sep-06	0:11:05	3.222080468
10207737	3.64	14-Sep-06	1:25:14	2.72248286
10208533	3.03	18-Sep-06	1:33:46	4.299129243
10215765	3.65	3-Nov-06	16:12:12	4.299129243
10218081	2.68	18-Nov-06	1:24:26	6.743783815
10222033	2.06	10-Dec-06	1:02:11	0.461754274
10223437	1.56	21-Dec-06	3:23:35	0.203026169
10224381	2.18	29-Dec-06	0:13:34	3.313627322
12250499	1.3	18-Sep-06	1:35:58	0.349002023
14206552	2.48	31-Dec-05	17:52:37	8.020440455
14207812	2.27	8-Jan-06	22:21:41	2.566214389
14209064	1.38	17-Jan-06	4:14:26	0.301754859
14213068	2.16	17-Feb-06	20:45:41	0.287859801
14214948	1.86	1-Mar-06	6:13:45	0.099990896
14216484	1.84	10-Mar-06	19:53:34	0.33775017
14217884	3.65	20-Mar-06	17:16:19	1.322223136
14219560	2.38	30-Mar-06	6:20:24	1.410712813
14220956	2.18	9-Apr-06	14:09:14	7.050613442
14233344	1.35	15-Jun-06	0:36:54	0.401838109
14236768	4.37	30-Jun-06	0:28:03	2.573981514
14237056	3.43	30-Jun-06	15:20:49	0.66429725
14237352	1.54	1-Jul-06	16:07:47	0.291037468
14238908	1.46	8-Jul-06	21:15:33	0.143631002
14240484	1.66	15-Jul-06	23:54:01	0.950145147
14244008	3	1-Aug-06	9:16:20	0.23899002
14247608	2.5	22-Aug-06	7:27:03	2.610356902
14255632	4.01	9-Oct-06	20:26:48	0.711052193
14255732	1.55	10-Oct-06	8:55:23	0.109868753
14257776	1.08	23-Oct-06	5:01:20	0.604215753
14263712	4.11	29-Nov-06	21:10:52	1.37599097
10230177	1.36	5-Feb-07	18:48:10	0.213558705
10230869	4.29	9-Feb-07	3:33:42	2.177315522
10231745	3.75	14-Feb-07	8:51:11	1.221580297
10233213	3.16	25-Feb-07	11:59:41	0.272143996
10235657	1.45	14-Mar-07	12:32:57	0.281201324
10237673	3.62	25-Mar-07	17:51:44	1.223001432
10247269	1.81	14-May-07	23:17:20	5.381729925
10250169	3.38	25-May-07	11:35:29	0.776890368
10255277	2.21	16-Jun-07	16:41:27	0.539443862

10257545	1.46	25-Jun-07	6:45:33	0.189167242
10262593	1.57	14-Jul-07	10:35:41	0.326468198
10265733	1.69	25-Jul-07	16:19:49	0.835655599
10272337	1.46	25-Aug-07	23:37:07	0.818807387
10276753	1.75	6-Sep-07	3:16:47	0.593995205
10280537	1.6	14-Sep-07	21:38:16	0.330499228
10283729	1.49	4-Oct-07	14:57:04	0.58433643
10284797	1.72	11-Oct-07	22:38:25	0.870836267
10295165	1.53	16-Dec-07	2:58:32	0.264027079
10296573	1.76	24-Dec-07	15:20:55	1.366784528
14277904	1.65	5-Mar-07	12:08:06	2.523775279
14283328	2.6	8-Apr-07	3:21:54	0.17193335
14285168	4.41	15-Apr-07	22:57:26	3.076839201
14287268	2.49	25-Apr-07	9:15:52	0.530539131
14288764	1.95	3-May-07	5:57:24	1.48511556
14296624	2.1	7-Jun-07	15:16:11	0.448582053
14311556	1.3	5-Aug-07	22:32:40	0.733112915
14313648	2.42	15-Aug-07	17:06:46	0.468027999
14325436	1.36	25-Sep-07	7:29:45	0.260650727
14330028	1.84	24-Oct-07	8:38:42	0.840499194
14333364	1.34	15-Nov-07	23:34:32	0.201188843
14335156	1.32	27-Nov-07	19:35:27	0.425947298
14336152	2.03	4-Dec-07	18:23:44	0.34929702
10312485	1.87	15-Mar-08	20:47:41	2.116532549
10318249	2.1	14-Apr-08	16:26:15	1.047333382
10320373	1.2	25-Apr-08	3:46:15	0.292562466
10326721	3.2	26-May-08	18:08:10	0.156587361
10343721	2.03	15-Aug-08	20:31:39	1.067771718
10345861	1.54	27-Aug-08	8:36:56	0.480087352
10347049	2.58	4-Sep-08	11:03:34	0.355070602
10348693	1.35	13-Sep-08	22:40:20	0.394138646
10352673	1.2	6-Oct-08	0:40:15	0.235863301
10355961	1.54	25-Oct-08	20:43:55	0.270398447
10358229	1.8	8-Nov-08	2:31:55	0.635005375
10366461	1.31	15-Dec-08	1:24:51	0.131830089
10368325	4.52	28-Dec-08	5:17:05	1.923108822
12330567	5.4	9-Feb-08	7:12:07	9.898383756
14343064	2.1	15-Jan-08	23:41:39	0.268899499
14344452	3.44	24-Jan-08	1:01:36	2.306776809
14345572	1.38	1-Feb-08	2:46:27	0.160907814
14346868	5.1	9-Feb-08	7:12:07	9.898045788
14346872	3.86	9-Feb-08	7:28:43	0.582585227
14347204	3	9-Feb-08	17:12:45	0.099858672

14348584	3.42	12-Feb-08	4:23:27	0.285618249
14348588	4.97	12-Feb-08	4:32:40	8.497265966
14348592	4.04	12-Feb-08	4:40:48	0.860727825
14348596	3.27	12-Feb-08	4:42:52	0.306938258
14352540	3.62	25-Feb-08	1:59:17	0.304749677
14354336	1.07	5-Mar-08	4:39:32	0.19400189
14358796	4.18	29-Mar-08	22:01:45	0.841491395
14359772	3.27	3-Apr-08	14:09:27	0.194712595
14366884	1.18	7-May-08	18:32:01	0.271171832
14368984	1.33	16-May-08	3:01:27	0.181768839
14371920	2.65	2-Jun-08	4:51:03	6.147654197
14372604	2.33	3-Jun-08	6:52:23	3.403240595
14372736	2.68	3-Jun-08	15:16:31	3.715577023
14375044	1.91	14-Jun-08	23:47:31	0.828153314
14376800	1	24-Jun-08	13:43:10	0.31783584
14380240	3.03	11-Jul-08	13:28:30	0.244387048
14383504	1.43	26-Jul-08	23:25:24	0.583625377
14394980	1.13	26-Sep-08	1:00:12	0.270462761
14403636	1.35	17-Nov-08	1:14:45	0.773595474
14404512	4.98	20-Nov-08	19:23:03	3.547756909
14405496	2.27	25-Nov-08	20:06:51	2.502356775
14407632	2.62	4-Dec-08	16:07:22	3.326802833
10372525	2.59	21-Jan-09	7:42:17	2.015701696
10378301	1.29	23-Feb-09	12:14:25	0.182482522
10379461	2.66	2-Mar-09	19:48:10	0.594152232
10400553	1.63	25-Apr-09	17:19:40	0.650555319
10405121	1.32	5-May-09	3:33:11	0.325271376
10407801	2.03	12-May-09	7:57:22	0.839596331
10433897	2.28	2-Jul-09	18:57:09	2.671083252
10436545	1.29	9-Jul-09	7:06:54	0.176552613
10478741	3.42	10-Oct-09	6:38:38	5.04370567
10480157	2.33	12-Oct-09	23:31:13	0.880469988
10484413	1.54	23-Oct-09	2:46:10	0.621657578
10488845	3.01	2-Nov-09	4:15:24	0.384838647
10489253	4.13	2-Nov-09	19:27:28	1.629183264
10490325	3.79	3-Nov-09	7:36:54	6.623162598
14418960	1.56	2-Feb-09	0:06:51	0.45694371
14421008	1.2	13-Feb-09	19:36:59	0.559078659
14429648	1.26	14-Mar-09	9:10:25	0.511204873
14433456	4.77	24-Mar-09	11:55:37	5.427520067
14439848	1.67	1-Apr-09	17:42:01	0.169664691
14444312	2.46	14-Apr-09	17:05:17	0.783258719
14463168	1.6	26-May-09	3:58:37	1.42222777

14472624	1.57	12-Jun-09	10:25:22	0.154265666
14489680	1.59	21-Jul-09	23:33:01	0.164751522
14494800	1.46	3-Aug-09	1:23:48	0.461592611
14499528	3.54	12-Aug-09	23:49:03	0.584557665
14502908	1.29	27-Aug-09	8:00:17	0.190296714
14506716	1.43	5-Sep-09	14:15:15	0.205539963
14510556	2.06	14-Sep-09	23:54:27	1.3396627
14512436	5.08	19-Sep-09	22:55:20	2.789175208
14513028	1.27	20-Sep-09	21:13:35	0.796345523
14519364	2	2-Oct-09	21:26:24	2.046002069
14519412	2.2	2-Oct-09	21:29:49	1.781022501
14545540	3.31	17-Nov-09	23:05:26	11.47945773
14545572	3.14	17-Nov-09	23:07:06	7.894064399
14545612	1.2	17-Nov-09	23:12:23	0.104163884
14545820	3.36	18-Nov-09	0:43:50	13.15174914
14545844	1.5	18-Nov-09	0:47:44	0.227065459
14546284	2.67	18-Nov-09	10:34:17	14.61831034
14548804	1.48	24-Nov-09	4:41:32	0.600938056
14557828	1.7	12-Dec-09	10:36:36	1.090084968
14564844	1.46	28-Dec-09	16:29:32	0.469711078
14565580	3.53	30-Dec-09	17:54:15	0.909121382
14565620	5.8	30-Dec-09	18:48:58	42.40788308
14565636	4.77	30-Dec-09	18:53:24	6.46516841
14565660	4.03	30-Dec-09	19:07:42	2.985944028
14565668	3.35	30-Dec-09	19:10:04	1.414174764
14566212	3.05	31-Dec-09	0:49:10	0.195064144
24085759	1.55	2-Dec-09	3:12:54	0.448553132
24677759	3.13	30-Dec-09	18:58:07	0.379092762
10158162	3.14	11-Jun-10	9:42:18	0.190232738
10532501	3.37	20-Jan-10	11:51:48	0.274069341
10540973	1.92	10-Feb-10	22:45:07	0.161978054
10545469	1.89	20-Feb-10	22:19:28	0.161978054
10597293	3.66	10-Apr-10	9:51:58	2.407775288
10627653	4.16	21-Apr-10	10:37:13	2.944193783
10659325	3.14	9-May-10	17:58:47	0.188598975
10719229	3.11	21-Jun-10	12:26:17	0.273304038
10729325	3.59	30-Jun-10	8:03:01	0.706844142
10757205	3.49	20-Jul-10	10:18:03	0.302400519
10765405	1.74	30-Jul-10	3:32:40	0.495188449
10775325	1.42	11-Aug-10	5:12:50	0.430249399
10781821	1.68	19-Aug-10	2:18:46	1.090479455
10790557	1.06	1-Sep-10	13:06:34	0.105289394
10795941	1.56	11-Sep-10	10:45:09	0.194499171

10836669	1.55	10-Nov-10	7:02:27	0.371540621
10860557	3.36	21-Dec-10	11:01:50	0.435545846
10864749	3.8	30-Dec-10	17:37:22	0.681009719
14566876	3.24	1-Jan-10	2:33:44	0.225199224
14570852	4.08	10-Jan-10	6:35:56	1.217531409
14584300	1.38	2-Feb-10	10:38:09	0.301056747
14595780	3.45	1-Mar-10	6:21:10	0.720990983
14598228	4.02	9-Mar-10	4:18:23	2.665363287
14602180	1.63	19-Mar-10	9:23:00	0.993931058
14606268	4.16	31-Mar-10	9:20:29	0.593017449
14688260	3.46	1-May-10	8:43:04	1.326486915
14718764	4.88	22-May-10	17:33:15	6.91238964
14728444	3.63	30-May-10	12:22:31	0.155821582
14745580	5.72	15-Jun-10	4:26:56	28.55694156
14845092	1.42	21-Sep-10	2:59:55	0.616724016
14851956	3.12	2-Oct-10	20:18:22	0.448552454
14856420	3.2	8-Oct-10	3:27:19	0.687157896
14864436	1.26	20-Oct-10	1:16:51	0.252184958
14870876	3	29-Oct-10	18:37:09	0.647384207
14884428	1.68	20-Nov-10	14:25:51	0.717424082
14888716	1.23	1-Dec-10	4:16:30	0.112726619
14895060	3.66	10-Dec-10	17:16:08	0.6191478
30557759	6.6	4-Apr-10	22:41:10	81.69547963
34357759	1.34	10-Jul-10	11:30:28	0.322687699
10871509	1.07	10-Jan-11	4:50:01	0.172241303
10877213	1.2	20-Jan-11	13:37:21	0.178487172
10906157	1	10-Mar-11	3:35:38	0.33488433
10911725	1.58	21-Mar-11	15:35:19	0.409244808
10922941	1.06	10-Apr-11	10:05:17	0.043363455
10929453	1.1	20-Apr-11	4:45:13	0.296146214
10962013	1.57	20-Jun-11	6:15:24	0.285446166
10985317	1.42	31-Jul-11	12:37:02	0.149798529
10996077	1.22	21-Aug-11	10:46:47	0.288668648
11000165	1.26	30-Aug-11	8:55:11	0.153353298
11004901	1.15	11-Sep-11	4:02:14	0.334467171
11009861	1.86	21-Sep-11	6:25:35	0.450572177
11022701	1.87	20-Oct-11	10:27:46	0.337142701
11027181	1.73	30-Oct-11	7:01:42	0.459985599
11045125	1.34	20-Dec-11	22:33:35	0.163473963
11047765	1.55	30-Dec-11	2:29:43	2.461289492
14932292	2.04	9-Feb-11	12:24:14	0.148987305
14937820	1.3	20-Feb-11	2:31:44	0.382857753
14942388	1.38	28-Feb-11	11:18:01	0.771905277

14960116	1.94	30-Mar-11	21:19:00	0.31307974
14977388	1.43	29-Apr-11	21:23:32	0.795103024
14982660	1.19	10-May-11	16:25:22	0.398341454
14988228	1.62	20-May-11	2:48:20	0.857964508
14993812	1.54	31-May-11	0:50:03	0.188866662
14999212	1.58	10-Jun-11	7:47:22	1.132058453
15009444	2.02	30-Jun-11	6:42:48	0.175493951
15010260	2.32	1-Jul-11	20:50:43	2.116716355
15057772	1.37	1-Oct-11	2:08:48	0.341699599
15062076	3.06	11-Oct-11	13:25:26	0.524151961
15075444	1.15	14-Nov-11	9:47:11	0.29979411
15080340	1.54	28-Nov-11	10:35:56	0.152075855
15084884	1.48	10-Dec-11	21:06:09	0.659981456
11049413	1.45	4-Jan-12	5:57:55	0.15579343
11065613	3	11-Feb-12	9:46:37	1.155132741
11069397	1.59	20-Feb-12	8:18:14	0.346672098
11078482	1.39	10-Mar-12	23:53:38	0.480776764
11082378	1.02	21-Mar-12	1:45:06	0.428408647
11090394	3.12	8-Apr-12	8:15:18	0.6752865
11129306	1.26	30-Jun-12	8:32:37	0.201779445
11134290	1.53	10-Jul-12	13:19:45	0.315701854
11206602	1.96	21-Nov-12	10:36:51	7.135926721
15099108	1.14	19-Jan-12	6:07:25	0.150740604
15103948	1.39	31-Jan-12	12:20:32	0.312868048
15117065	1.67	2-Mar-12	9:42:06	0.212926232
15137561	1.12	19-Apr-12	15:39:22	0.200728925
15142633	2.24	1-May-12	12:39:57	1.145239313
15147225	1.32	10-May-12	16:45:49	0.222481521
15156665	1.46	30-May-12	15:59:52	0.228070252
15162001	1.57	8-Jun-12	19:54:29	0.399061914
15166801	1.41	20-Jun-12	12:15:31	0.146305469
15180609	1.34	19-Jul-12	21:00:15	0.326051959
15185489	2.06	31-Jul-12	12:36:13	2.156131782
15187057	3.33	3-Aug-12	18:05:26	2.090744061
15190729	1.86	11-Aug-12	2:23:59	1.544069266
15194825	3.4	19-Aug-12	3:43:41	0.654108012
15199593	4.59	26-Aug-12	19:19:54	31.82165862
15199681	5.32	26-Aug-12	19:31:13	91.54302213
15199721	4.33	26-Aug-12	19:40:03	28.72969551
15200489	4.25	26-Aug-12	21:15:18	76.45588945
15201537	4.61	26-Aug-12	23:33:14	231.8316209
15202921	4.9	27-Aug-12	4:41:26	272.0059878
15208097	2.84	30-Aug-12	10:18:47	2.305899691

15213401	1.77	10-Sep-12	11:53:57	0.656968076
15218673	1.67	20-Sep-12	18:26:05	1.057737688
15227337	1.34	10-Oct-12	6:19:01	0.32921775
15232649	1.49	20-Oct-12	1:29:44	0.20804945
15243569	2.62	10-Nov-12	23:31:16	0.342438462
15243617	1.84	11-Nov-12	2:24:42	1.077917586
15254369	2.65	2-Dec-12	1:59:49	0.316477007
15261353	1.34	10-Dec-12	7:51:42	0.175780009
15261377	1.51	10-Dec-12	8:09:20	0.666532084
15266745	1.32	21-Dec-12	21:18:49	0.233898946
15268713	1.03	29-Dec-12	6:29:53	0.233652331
37088500	5.5	26-Aug-12	20:57:48	138.1184308
11277698	1.5	3-Apr-13	2:08:36	0.130761781
11284050	1.65	12-Apr-13	22:38:55	0.687349179
11321426	1.5	19-Jun-13	4:55:27	0.505533779
11322570	1.67	20-Jun-13	20:53:44	1.214855967
11328994	1.87	2-Jul-13	2:00:23	0.738670126
11332138	2.23	9-Jul-13	2:43:59	3.089786367
11336962	1.16	19-Jul-13	23:56:19	0.795125111
11339938	3.05	26-Jul-13	14:00:41	1.911944695
11347826	3.92	10-Aug-13	14:09:18	1.501439592
11351930	1.44	17-Aug-13	15:00:22	1.000170119
11362402	1.21	10-Sep-13	15:19:30	0.306719933
11364890	1.32	15-Sep-13	15:03:28	1.012516327
11366154	3.22	18-Sep-13	12:53:36	0.328701115
11371586	3.71	30-Sep-13	4:23:25	5.017797468
11375346	1.99	9-Oct-13	17:11:23	0.663672883
11378554	2.43	15-Oct-13	13:31:49	1.272920885
11379770	1.75	17-Oct-13	14:18:50	0.316838161
11385946	1.2	1-Nov-13	0:08:23	1.229077448
11390866	1.15	12-Nov-13	18:49:05	1.549340842
11393730	1.26	21-Nov-13	15:14:36	0.129633724
11397090	3.16	30-Nov-13	15:10:16	0.229070792
11407962	1.17	31-Dec-13	8:35:45	0.663089025
15270505	1.52	5-Jan-13	11:34:17	0.16444583
15271873	1.41	10-Jan-13	10:24:55	3.386094921
15274049	1.71	16-Jan-13	21:33:26	0.441146229
15278273	1.43	27-Jan-13	17:19:02	0.184120219
15280945	1.15	3-Feb-13	13:04:41	0.179282925
15282833	1.87	7-Feb-13	15:04:24	3.245084096
15293777	1.67	4-Mar-13	19:30:22	0.103850714
15303153	1.75	13-Mar-13	16:53:33	1.850020263
15332225	1.87	25-Apr-13	4:31:44	0.41707475

15336185	1.7	2-May-13	0:33:17	0.466195609
15341889	1.32	13-May-13	2:44:02	0.795867164
15344465	3.54	17-May-13	3:07:42	1.744872846
15346033	2.8	19-May-13	15:44:33	4.840334207
15351425	2.08	30-May-13	4:14:52	1.83119759
15357673	1.63	10-Jun-13	0:29:22	0.699234147
15394233	1.65	20-Aug-13	1:52:49	1.262200463
15398473	1.34	28-Aug-13	7:40:21	1.359322941
15442937	1.06	11-Dec-13	9:47:28	0.324322634
15444201	1.08	15-Dec-13	6:55:55	1.035008238
15446089	2.02	21-Dec-13	11:03:12	1.14594533
11415922	2.49	20-Jan-14	19:40:00	0.488143717
11419386	1.49	31-Jan-14	2:48:17	0.490665107
11423178	1.63	11-Feb-14	10:49:58	0.927890167
15466865	1.37	14-Feb-14	6:55:17	0.628577072
15468297	2	19-Feb-14	5:38:29	2.931459844
15471305	1.77	1-Mar-14	21:32:56	0.938055403
15475865	1.62	14-Mar-14	4:52:28	0.293777827
15477937	1.65	20-Mar-14	6:29:50	1.353227677
15500385	2.08	11-May-14	5:09:43	0.33123881
15504329	2.11	22-May-14	8:07:12	1.576139475
15507529	1.75	1-Jun-14	9:16:27	2.440560902
15511897	3.19	14-Jun-14	6:41:08	2.36767867
15519025	1.3	3-Jul-14	5:58:39	0.238904519
15525177	1.72	11-Jul-14	5:26:10	0.367823636
15525257	1.48	11-Jul-14	7:11:42	0.666951524
15532585	2.26	30-Jul-14	0:20:20	1.70141233
15534681	1.82	5-Aug-14	4:56:07	0.961042329
15538321	2.65	14-Aug-14	13:58:33	0.272491887
37043071	1.87	21-Sep-14	7:55:43	0.714498707
37046455	1.24	30-Sep-14	19:53:24	0.53492546
37060735	2	13-Nov-14	18:27:20	1.676306026
37063063	1.82	21-Nov-14	9:36:56	0.439414044
37210760	3.17	11-Apr-14	23:53:11	0.260584625
37215008	1.82	20-Apr-14	9:53:05	0.587198193
37219392	2.4	3-May-14	3:37:36	2.780311562
37233264	2.73	18-Jun-14	3:30:40	1.34727093
37248544	3.09	20-Jul-14	9:18:22	0.390175012
37261160	1.06	24-Aug-14	6:43:41	0.109554187
37262720	1.18	30-Aug-14	5:43:15	0.557309882
37267960	1.15	14-Sep-14	10:47:10	0.238536669
37268456	1.46	15-Sep-14	21:30:01	0.619966485
37278008	2.6	11-Oct-14	8:24:56	0.832106172

37279184	1.52	14-Oct-14	23:22:43	0.974352353
37281168	1.18	22-Oct-14	9:59:22	0.157225893
37284280	1.23	1-Nov-14	1:30:14	0.336508006
37296992	1.91	17-Dec-14	15:55:09	1.010912694
37300024	2.39	29-Dec-14	15:01:08	0.539372156
37113807	1.67	9-Mar-15	7:48:23	0.251965438
37148639	1.2	20-Apr-15	13:36:55	0.551692179
37152447	1.32	27-Apr-15	22:01:50	2.769654194
37166079	4.1	21-May-15	3:15:20	17.27893613
37196663	3.57	2-Jul-15	19:38:30	6.208084324
37202991	2.42	10-Jul-15	0:49:43	0.490334917
37212959	2.91	24-Jul-15	20:42:36	8.863763555
37218903	1.73	2-Aug-15	19:15:33	1.637036882
37225911	1.78	12-Aug-15	14:37:29	0.754460602
37236391	1.92	1-Sep-15	1:20:11	0.625330467
37246151	1.68	21-Sep-15	5:53:40	0.169329072
37250999	1.85	29-Sep-15	14:27:22	0.318403396
37255455	2.13	8-Oct-15	22:08:46	1.203176601
37261751	1.57	21-Oct-15	3:21:40	0.338284823
37266383	1.2	31-Oct-15	14:36:27	0.194702691
37279191	1.05	30-Nov-15	3:44:34	0.141605568
37303528	1.67	8-Jan-15	21:00:01	0.355970655
37307792	1.33	22-Jan-15	3:39:54	0.140552219
37311176	1.59	31-Jan-15	16:13:55	0.201373919
37313864	1.49	7-Feb-15	14:12:27	0.313669769
37340792	1.74	17-Mar-15	11:43:24	0.240782218
37354952	3.49	2-Apr-15	18:50:17	0.277629906
37360480	2.26	10-Apr-15	3:36:43	1.283506117
37379496	2.77	13-May-15	6:02:16	2.702938057
37390288	2.47	30-May-15	8:37:37	2.602086871
37396760	1.78	10-Jun-15	13:17:09	0.501267125
37404456	1.25	20-Jun-15	7:58:34	0.584678839
37501584	2.24	14-Dec-15	6:07:25	0.96582308
37505920	2.3	25-Dec-15	17:24:17	1.584601829
37312311	3.03	27-Feb-16	18:45:25	0.658267913
37315759	1.56	9-Mar-16	7:55:33	0.46264238
37324375	1.62	30-Mar-16	6:53:18	0.679171982
37335119	3.39	21-Apr-16	18:14:16	2.950058933
37338543	1.55	2-May-16	10:14:53	0.554451834
37369485	5.2	10-Jun-16	8:04:42	10.5480116
37509776	1.38	2-Jan-16	22:50:30	0.282088546
37525200	1.49	17-Feb-16	12:41:45	0.124580132
37537600	1.54	20-Mar-16	6:29:53	0.113406973

37547256	1.44	9-Apr-16	6:54:50	0.174940105
37564120	2.93	11-May-16	13:55:58	1.037305485

List of events for GVDA

Event ID	Magnitude	Date	Time	PGA (cm/s/s)
10099601	2.85	14-May-05	16:21:00	1.42543346
10106402	1.74	14-Jan-09	13:45:24	0.723084066
10146673	2.61	10-Oct-05	18:39:23	0.918847715
10166945	2.1	29-Jan-06	15:51:56	1.823228609
10169049	2.81	10-Feb-06	1:16:53	6.014405217
10182341	1.93	9-May-06	7:50:44	1.834243527
10184429	2.74	22-May-06	20:56:48	2.474397832
10187993	2.49	9-Jun-06	1:27:53	1.745134243
10206813	3.12	7-Sep-06	14:44:44	1.451818145
10215273	2.19	1-Nov-06	16:24:10	1.266541558
10217437	2.28	14-Nov-06	13:45:02	1.767763974
10222349	2.44	12-Dec-06	17:36:55	1.038247477
10225585	2.78	8-Jan-07	3:05:26	10.82169471
10228393	2.1	26-Jan-07	2:05:46	1.966702927
10231941	2.7	15-Feb-07	11:32:31	1.60903888
10248973	2.73	22-May-07	18:13:23	1.376109067
10258309	2.8	28-Jun-07	6:35:43	5.745039542
10263721	2.32	19-Jul-07	23:26:11	0.981476105
10275733	4.73	2-Sep-07	17:29:15	4.686456889
10280445	1.76	14-Sep-07	11:57:59	0.822132285
10283201	2.11	30-Sep-07	1:03:25	3.625102064
10285397	2.79	15-Oct-07	21:29:54	4.07550112
10287821	2.42	31-Oct-07	1:20:44	1.489577296
10295849	4.06	19-Dec-07	12:14:08	3.333000575
10298489	2.48	7-Jan-08	18:11:13	1.418229427
10314041	1.76	24-Mar-08	4:44:58	0.67418348
10321561	4.19	1-May-08	3:55:29	11.4056943
10326021	2.36	21-May-08	10:20:33	1.97914214
10347025	3.29	4-Sep-08	8:42:01	1.271585975
10348453	1.93	12-Sep-08	23:02:08	2.011244501
10353485	3	11-Oct-08	19:33:50	11.76110027
10357093	3.16	30-Oct-08	17:09:31	7.704293769
10370141	4.45	9-Jan-09	3:49:47	8.617751967
10379489	1.53	3-Mar-09	0:57:48	0.665503401
10437793	1.59	13-Jul-09	7:12:55	0.545340844
10481781	3.44	16-Oct-09	10:03:35	2.391768584

10488581	1.96	1-Nov-09	22:55:23	0.823548194
10497213	3.29	15-Nov-09	7:54:18	1.136534915
10530013	4.28	16-Jan-10	12:03:21	27.75500762
10533765	1.94	23-Jan-10	18:53:44	2.070593958
10546925	1.73	24-Feb-10	5:37:27	0.578796795
10624077	1.82	19-Apr-10	18:33:28	2.291192339
10715365	3.41	18-Jun-10	15:14:34	2.402817638
10736069	5.43	7-Jul-10	23:53:27	120.9974801
10751997	2.61	14-Jul-10	20:14:45	2.803438764
10766421	1.96	31-Jul-10	2:54:28	1.470740647
10775845	3.38	11-Aug-10	20:47:15	1.406516464
10783581	3.59	21-Aug-10	13:59:38	4.22785106
10791757	1.88	3-Sep-10	12:34:39	1.254699946
10837325	1.42	11-Nov-10	18:05:10	0.473483271
10860669	2.26	21-Dec-10	18:08:52	3.281750837
10861101	3.17	23-Dec-10	3:39:30	1.660679323
10866637	3.3	3-Jan-11	11:38:06	3.178943727
10877701	1.46	21-Jan-11	14:40:10	1.069400995
10910725	2.15	19-Mar-11	2:44:37	0.97894942
10913493	2.79	23-Mar-11	13:49:19	3.101328349
10982077	3.09	26-Jul-11	17:42:06	1.769889533
10999389	1.95	28-Aug-11	6:50:51	0.641928916
11006189	4.14	14-Sep-11	14:44:47	4.650096147
11035389	3.08	22-Nov-11	14:39:35	1.547432031
11047469	2.39	29-Dec-11	1:11:55	3.832703537
11056933	1.75	21-Jan-12	17:10:21	0.970877151
11064837	2.3	9-Feb-12	9:22:53	5.377022782
11069573	2.93	20-Feb-12	14:10:46	1.272504516
11086258	3.26	30-Mar-12	6:09:23	3.257616791
11086290	2.79	30-Mar-12	7:38:55	1.113467038
11092194	3.52	12-Apr-12	18:52:54	1.764388843
11125626	2.83	22-Jun-12	15:11:40	2.400414613
11129106	2.75	30-Jun-12	3:21:16	2.617558219
11208242	2.92	25-Nov-12	2:07:18	3.528868747
11248906	1.37	25-Feb-13	4:21:34	0.403725057
11273762	2.18	27-Mar-13	18:52:36	1.153889623
11284506	2.74	13-Apr-13	22:16:44	1.059380092
11319362	2.91	16-Jun-13	3:56:11	2.012703288
11327386	3.41	28-Jun-13	17:45:38	23.54887613
11331378	2.65	7-Jul-13	8:19:09	0.972766493
11337786	3.19	22-Jul-13	1:59:42	2.553748262
11346906	2.65	8-Aug-13	18:32:41	1.802319675
11366218	2.68	18-Sep-13	16:44:48	1.54298906

11373346	2.5	5-Oct-13	20:35:17	3.958267407
11373386	2.47	5-Oct-13	22:09:50	4.347555237
11379194	2.91	16-Oct-13	13:43:33	11.33373094
11396858	2.1	29-Nov-13	18:20:19	2.30871375
11412418	2.64	10-Jan-14	3:39:43	5.481369955
11418122	3.19	27-Jan-14	12:42:29	6.079749722
12365851	2.03	30-Dec-08	3:01:38	0.896079845
14151344	5.2	12-Jun-05	15:41:45	167.1904328
14155260	4.88	16-Jun-05	20:53:23	37.2762123
14167764	2.82	1-Aug-05	7:53:52	1.235959977
14181016	2.93	3-Sep-05	5:08:02	2.499710596
14184260	1.64	12-Sep-05	22:20:41	0.465165496
14197132	3.36	8-Nov-05	22:03:37	33.96288449
14200940	1.85	29-Nov-05	8:45:06	0.687722114
14202012	1.75	4-Dec-05	17:05:08	0.535222549
14214132	1.67	23-Feb-06	21:32:19	0.955340002
14215616	1.52	5-Mar-06	8:29:18	0.95803021
14218504	3.66	24-Mar-06	5:54:09	2.525012553
14220900	2	9-Apr-06	6:36:05	1.914209759
14235084	1.65	24-Jun-06	13:57:17	0.885386972
14239184	3.9	10-Jul-06	2:54:39	2.317375782
14242104	2.73	22-Jul-06	8:52:05	2.863854901
14247380	1.81	21-Aug-06	1:41:58	0.919907431
14254944	3.18	5-Oct-06	19:54:02	2.819167968
14277496	2.8	2-Mar-07	4:26:59	2.084030142
14289668	2.04	9-May-07	5:29:07	1.190256446
14295640	4.26	2-Jun-07	5:11:22	9.6111433
14311328	1.93	4-Aug-07	10:57:25	0.680628213
14313896	2.47	17-Aug-07	6:27:52	1.641197889
14333124	2.25	14-Nov-07	16:06:57	1.345596197
14333648	3.29	17-Nov-07	21:15:32	3.838516235
14335828	2.04	2-Dec-07	0:50:21	0.878803269
14345272	2.85	29-Jan-08	16:38:30	4.09302168
14354228	2.72	4-Mar-08	16:44:18	3.261426219
14372428	1.55	2-Jun-08	23:04:40	1.293098152
14375728	1.89	18-Jun-08	4:23:15	1.331098254
14376816	2.96	24-Jun-08	15:06:03	0.950566819
14382172	2.22	20-Jul-08	2:21:40	1.198887357
14388184	3.16	19-Aug-08	1:55:05	3.295609461
14396336	4.14	2-Oct-08	9:41:46	3.448866484
14403732	4.11	17-Nov-08	12:35:35	23.74185366
14419200	1.73	3-Feb-09	12:41:41	1.224024888
14421880	2.37	16-Feb-09	23:10:14	1.226793329

14430024	2.31	15-Mar-09	8:55:38	1.530266411
14433456	4.77	24-Mar-09	11:55:48	4.731941738
14444832	3.86	16-Apr-09	17:55:28	1.734077255
14476736	3.2	19-Jun-09	15:30:32	1.477444255
14480288	1.88	27-Jun-09	4:56:23	0.573217495
14491232	3.53	26-Jul-09	4:53:54	42.13010753
14495088	2.84	3-Aug-09	10:42:42	2.21506605
14501168	1.49	17-Aug-09	9:52:43	0.681140011
14505780	1.97	2-Sep-09	20:13:43	0.657756514
14510164	1.66	13-Sep-09	19:06:12	0.962107969
14549396	1.32	24-Nov-09	20:26:56	0.671359032
14571732	3.12	11-Jan-10	23:23:55	1.620782204
14587508	2.84	10-Feb-10	11:27:36	2.109280005
14600292	4.23	13-Mar-10	16:32:34	1.078149374
14607748	3.89	4-Apr-10	22:56:39	2.515252767
14694996	2.47	5-May-10	16:53:28	2.162809775
14733020	3.18	3-Jun-10	8:44:06	2.712313695
14854812	3.94	6-Oct-10	17:58:05	1.50893926
14883716	3.75	19-Nov-10	0:56:50	2.306678719
14927556	2.86	2-Feb-11	17:15:17	3.075782446
14929836	2.96	5-Feb-11	1:25:21	3.332974971
14937812	2.74	20-Feb-11	2:30:22	0.961528062
14981788	2.62	9-May-11	8:27:40	0.8707101
14994308	1.64	1-Jun-11	9:08:14	1.342089507
14995172	3.11	3-Jun-11	5:45:14	14.30040396
15001524	2.01	14-Jun-11	8:35:03	1.033890121
15013004	1.94	7-Jul-11	5:03:46	1.2020714
15059660	2.93	5-Oct-11	18:20:01	1.385301186
15071396	2.97	1-Nov-11	23:25:19	0.997196798
15085356	1.7	12-Dec-11	8:31:25	4.540480377
15141409	2.39	28-Apr-12	5:36:19	1.60092679
15152625	3.38	21-May-12	6:19:52	9.621515809
15179393	2.02	17-Jul-12	7:44:17	1.035527774
15184937	1.71	30-Jul-12	14:25:40	0.715277498
15191145	2.07	12-Aug-12	1:04:01	1.579383417
15210065	2.56	3-Sep-12	6:22:08	7.968858893
15217865	3.02	18-Sep-12	21:09:31	9.813445354
15226761	2.15	8-Oct-12	22:33:54	0.751543518
15237073	3.87	28-Oct-12	7:46:55	10.74163904
15242161	1.94	7-Nov-12	7:08:19	1.110486086
15266297	2.53	20-Dec-12	17:34:35	1.995342968
15272577	2.11	12-Jan-13	22:17:16	2.346882179
15276649	2.75	23-Jan-13	8:45:41	3.31632066

15293905	3.47	4-Mar-13	23:17:40	4.519862821
15296281	4.7	11-Mar-13	16:55:59	45.81187446
15303793	2.49	13-Mar-13	22:47:16	0.893531642
15332633	3.08	25-Apr-13	18:59:35	9.461880264
15343017	3.12	15-May-13	16:20:00	1.284637788
15394337	1.83	20-Aug-13	6:34:19	0.801406231
15470961	1.45	28-Feb-14	8:29:50	0.868328089
15482849	2.54	29-Mar-14	17:17:08	1.970098306
15503377	3.84	19-May-14	20:08:51	1.0445323
15508753	2.53	4-Jun-14	14:45:37	3.585019551
15526321	2.82	13-Jul-14	21:47:18	2.002716431
15532705	2.89	30-Jul-14	8:54:21	2.011607625
37042383	2.49	19-Sep-14	8:38:02	1.377076789
37066415	3.56	4-Dec-14	16:53:15	2.41905888
37103367	3.67	26-Feb-15	1:18:37	1.378532225
37114583	2.23	9-Mar-15	19:49:50	1.463647871
37148847	2.57	20-Apr-15	19:25:52	1.358864775
37193439	2.45	29-Jun-15	9:31:15	3.306797786
37211696	2.8	14-Apr-14	14:37:01	9.099549495
37211999	2.98	23-Jul-15	15:17:45	2.376529858
37219223	1.94	3-Aug-15	9:22:11	0.847301442
37220584	2.32	6-May-14	23:24:49	1.264051315
37227175	1.65	14-Aug-15	7:56:40	1.232417693
37235727	2.67	30-Aug-15	2:59:07	1.809100293
37236592	2.05	26-Jun-14	21:10:33	1.349527892
37243591	4	16-Sep-15	16:10:44	2.334438236
37251775	2.17	1-Oct-15	1:15:06	4.718293571
37258872	1.49	17-Aug-14	7:13:45	1.559249726
37264048	2.86	3-Sep-14	3:30:53	1.695585262
37278088	2.86	11-Oct-14	18:53:38	1.166780736
37284704	3.29	3-Nov-14	8:53:34	1.300892516
37286351	3.05	19-Dec-15	1:45:42	1.064151897
37298432	3.14	23-Dec-14	7:59:00	1.298833892
37298607	1.54	22-Jan-16	3:16:24	0.685314838
37305144	2	14-Jan-15	7:56:44	1.426678567
37311088	1.55	31-Jan-15	10:40:12	1.076803574
37312423	2.13	28-Feb-16	3:50:05	2.115910818
37316744	1.76	15-Feb-15	3:08:05	1.730080776
37346360	1.8	23-Mar-15	10:05:12	1.199965051
37358992	2.35	8-Apr-15	10:49:01	1.442865594
37369485	5.2	10-Jun-16	8:04:32	81.66190673
37375696	2.66	6-May-15	9:19:25	1.087954535
37390968	3.59	31-May-15	13:02:53	5.393130051

37475560	3.47	14-Oct-15	13:55:28	2.048743611
37476536	3.19	16-Oct-15	5:29:47	1.017049874
37486464	1.81	6-Nov-15	15:13:36	1.225467753
37511280	3.3	9-Jan-16	11:43:01	20.29364057
37523696	3.43	14-Feb-16	9:01:06	2.897138989
37551176	2.33	19-Apr-16	7:57:54	2.440305294
37560392	2.76	6-May-16	6:19:24	3.09546233
37566752	1.96	13-May-16	17:14:06	1.444164921
37578280	1.89	30-May-16	0:19:24	0.465102754

List of events for DPK

Event ID	Magnitude	Date	Time	PGA (cm/s/s)
10021373	3.73	21-Jan-10	5:22:49	1.085574694
10097460	4.6	7-Apr-10	16:19:12	3.634922915
10253296	2.96	10-Sep-10	13:13:56	0.74177161
10319490	4.9	15-Nov-10	18:24:42	2.487753761
10341381	3.81	7-Dec-10	8:26:20	1.85844175
11035450	4.5	4-Feb-11	5:33:22	2.159700749
11065361	3.61	6-Mar-11	5:17:32	1.299179605
11117336	3.36	27-Apr-11	7:45:30	0.561731471
11193311	3.11	12-Jul-11	12:06:05	0.74521973
11239319	3.19	27-Aug-11	10:55:19	0.848194104
11274361	3.61	1-Oct-11	6:59:39	1.240283674
11357325	3.25	23-Dec-11	3:44:22	1.265613866
12015328	3.28	15-Jan-12	2:58:39	0.605342844
12082388	3.88	22-Mar-12	19:42:11	2.530899663
12113306	3.06	22-Apr-12	21:55:01	1.42781211
12137460	4.6	16-May-12	15:02:48	17.02313447
12151347	3.47	30-May-12	1:49:28	0.852532098
12294003	3.1	20-Oct-12	3:25:06	0.760600149
13068023	4.2	9-Mar-13	17:32:47	1.082449183
13170405	4.05	19-Jun-13	7:19:40	7.517184859
13178003	3.7	27-Jun-13	5:10:35	2.470157088
13178007	4.4	27-Jun-13	11:40:41	4.606044898
13216006	4	4-Aug-13	7:57:43	2.039986882
14068034	4	9-Mar-14	16:11:22	0.918929163
14125009	4.5	5-May-14	4:59:43	3.833089326
14314049	3.3	10-Nov-14	19:22:28	0.989428496
15013009	2.5	13-Jan-15	4:43:27	0.276747803
15049024	3.3	18-Feb-15	8:47:19	1.523704062
15275009	2.5	2-Oct-15	4:08:04	0.393666414

16059028	4.5	28-Feb-16	13:48:52	1.368484975
16099007	4	8-Apr-16	3:24:13	3.753266692
16129023	3.7	8-May-16	7:40:29	0.569659646
5047474	4.74	16-Feb-05	18:35:17	10.22049981
5155334	3.34	4-Jun-05	17:56:24	1.735443855
5208375	3.75	27-Jul-05	7:00:16	2.525083851
5235400	4	23-Aug-05	3:58:06	5.482544326
5272293	2.93	29-Sep-05	18:54:52	1.105837067
5304241	2.41	31-Oct-05	5:50:46	0.896294712
5332407	4.07	28-Nov-05	20:15:33	2.000709009
6141409	4.09	21-May-06	9:28:39	1.225579771
6172355	3.55	21-Jun-06	17:02:50	2.881917574
6208470	4.7	27-Jul-06	13:17:55	13.85767452
6349384	3.84	15-Dec-06	2:15:13	1.289563704
7037342	3.42	6-Feb-07	9:55:16	1.067027432
7137340	3.4	17-May-07	6:20:54	1.239500443
7248294	2.94	5-Sep-07	20:00:14	0.763814781
7279301	3.01	6-Oct-07	1:12:35	1.658089307
8027262	2.62	27-Jan-08	4:44:39	0.272750792
8124235	2.35	3-May-08	3:51:15	0.701942356
8169148	1.48	17-Jun-08	5:02:02	2.308465957
8207218	2.18	25-Jul-08	2:17:50	2.37044149
8348460	4.6	13-Dec-08	19:55:44	0.940972214
9003288	2.88	3-Jan-09	5:57:33	0.413910815
9089306	3.06	30-Mar-09	2:09:34	1.306234331
9116390	3.9	26-Apr-09	13:50:46	4.18473584
9151348	3.48	31-May-09	2:54:25	2.533486485
9231510	5.1	19-Aug-09	18:19:27	4.206385399
9263360	3.6	20-Sep-09	1:14:38	1.439295943
9286109	1.09	13-Oct-09	2:46:59	2.454080108

List of events for BVDA

Event ID	Magnitude	Date	Time	PGA (cm/s/s)
10659909	2.22	10-May-10	7:02:17	4.834973123
10671989	4.53	19-May-10	0:39:03	3.611575684
10701405	4.9	13-Jun-10	3:08:47	75.55982686
10701413	4.23	13-Jun-10	3:09:10	21.00999411
10715365	3.41	18-Jun-10	15:14:30	17.57489927
10736069	5.43	7-Jul-10	23:53:25	125.3735992
10746293	2.81	10-Jul-10	14:37:19	2.688223153
10775845	3.38	11-Aug-10	20:47:10	10.35606453

10858485	1.96	16-Dec-10	19:17:26	2.817418394
10864749	3.8	30-Dec-10	17:37:15	5.17850974
11422138	1.98	8-Feb-14	7:41:01	0.815783002
14724892	2.7	27-May-10	3:02:17	5.709224009
14849604	2.85	29-Sep-10	11:11:49	7.334977387
14883716	3.75	19-Nov-10	0:56:45	20.43279682
14895084	3.91	10-Dec-10	18:44:30	15.31670742
15486137	2.94	6-Apr-14	0:00:31	4.470616649
15525537	1.99	11-Jul-14	22:29:42	1.323254942
15527617	3.37	17-Jul-14	14:24:25	6.578016977
15535825	3.25	7-Aug-14	21:45:46	1.342175397
37191408	2.38	25-Feb-14	7:50:03	3.71287817
37262127	2.51	21-Oct-15	20:02:54	1.04012484
37271343	2.31	11-Nov-15	11:39:35	1.039838785
37277783	2.98	25-Nov-15	21:14:26	1.76187604
37296376	2.85	15-Dec-14	10:20:25	4.678795596
37306536	3.68	18-Jan-15	13:23:33	14.45708453
37306976	2.49	19-Jan-15	16:36:35	0.853882179
37313832	3.28	7-Feb-15	14:05:49	9.124067825
37336783	2.22	27-Apr-16	4:09:34	2.144191826
37369485	5.2	10-Jun-16	8:04:29	111.6822447
37374687	5.17	10-Jun-16	8:04:29	111.6822447
37374711	3.75	10-Jun-16	8:05:26	2.950626571
37375143	3.17	10-Jun-16	8:33:48	1.64407316
37375391	3.1	10-Jun-16	8:46:37	1.121014457
37377079	3.46	10-Jun-16	11:14:03	4.31730457
37380543	2.95	10-Jun-16	23:42:49	2.301894432
37380967	3.04	11-Jun-16	1:40:22	5.635503704
37384655	2.9	12-Jun-16	23:19:19	1.036368536
37390968	3.59	31-May-15	13:02:47	10.23849543