REPEATABILITY OBSERVATIONS FROM A 2D TIME-LAPSE SEISMIC SURVEY

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Abstract

Time-lapse seismic surveys are particularly useful for detecting changes in material characteristics. Distinguishing changes in subsurface conditions from noise, source and receiver coupling variability, source wavelet change, and other sources of error related to the dynamics of surface conditions in time-lapse seismic images is challenging, at best. The objective of this study is to identify factors that affect repeatability of high-resolution near surface time-lapse seismic data when using a projectile source in unconsolidated sediments and investigate minimizing the effects of these factors. Data for this study were acquired as part of a 2D time-lapse seismic reflection survey in the floodplain of the Rio Grande near Las Cruces, New Mexico. The source was a 30.06 fired into pre-drilled holes in sandy soil; the holes were used for the baseline and eight monitor surveys. Changes in wavelet characteristics clearly indicate that the source signature varied non-linearly as a function of the number of shots fired downhole. Results indicate that changes in the wavelet become increasingly non-linear at increasing distance from the source and spectrally degrade with continuous use despite attempts to maintain the same firing conditions. This change through use is caused in part by change in source signature due to degradation of the holes during initial shots. It appears necessary to fire multiple shots downhole prior to acquisition to compact unconsolidated sediments and condition holes to increase repeatability of the data. The number of conditioning shots is likely related to soil conditions (saturation, compaction, clay to sand content, etc.).

Introduction

Time-lapse seismic reflection surveys are predominantly used for reservoir management (de Waal and Calvert, 2003). This technique has also been used for environmental purposes, including the monitor of seasonal water table fluctuations (Baker et al., 2000). To confidently extract the physical meaning of time-lapse data, surveys must be highly repeatable (Huang et al., 1998). Repeatability is affected by a number of factors, including processing techniques (Porter-Hirsche and Hirsch, 1998), the ability of the source to deliver the same signal into the subsurface, and ambient noise conditions (Aritman, 2001).

The US Section of the International Boundary and Water Commission (US IBWC), the Army Corps of Engineers, Engineer Research and Development Center (ERDC), and Kansas Geological Survey have been studying seismic methods for interrogating earthen levees with the most recent focus being the earthen levee along the Rio Grande near Las Cruces, New Mexico. To simulate flood conditions, a dam was constructed against the levee in the floodplain using the unconsolidated floodplain sediments, and the pond filled with water pumped from the Rio Grande at a rate consistent with model flood conditions. As a part of this study a 2D seismic line was deployed in the floodplain parallel to the levee, dam and river. The objective of the profile was to monitor possible change in the shallow water table coincident with changes in seismic reflectivity due to changes in density or velocity with increasing sediment saturation. Since the line was shot multiple times, it was of interest to determine what effect, if any, the changing source coupling had on the results. Specifically, change in source signature could be the dominant variation from one survey to the next, which must be accounted for during data processing to compare the stacked sections from one survey to another.

Geologic Setting

The present landscape in Las Cruces, New Mexico was formed in the late Tertiary and Quaternary periods during which time the Rio Grande rift was active. Extensional forces caused faulting that pushed mountain ranges upward while adjacent sedimentary basins were depressed. Roughly four million years ago, the ancestral Rio Grande formed, connecting many of these basins and terminating at a lake near what is now El Paso, Texas (Mack, 1997). Today, the climate near Las Cruces is semiarid with hot and dry summer days and cool nights. During this study period (September 14 to 15, 2005), the temperature dropped from approximately 33°C during the day to 7°C at night.

Borehole data from a geotechnical engineering study at the site prior to our survey indicates that the near surface is comprised mostly of unconsolidated silt, sand, gravel, and some clayey layers down to at least 14 m where borings were terminated. The water table is 1.5 to 3 m beneath ground surface.

Data Acquisition

Data for this study were acquired at a site just south of Las Cruces, NM within 30 m of the Rio Grande. The 2D seismic line ran parallel to the levee in the floodplain between the river and the dam approximately 7 m from the base of the dam, extending nearly its entire length. Seismic receivers were two Mark Products 40 Hz geophones with 30 cm spacing. The data were recorded with 2000 samples per trace at a 0.25 ms sample interval. The source was a 30.06 projectile source fired downhole; source spacing was 2.5 m. Prior to firing the source, PVC piped was placed in and water poured down holes pre-drilled in the sediment to condition the holes. A baseline survey was recorded at 1:00 PM on September 14, 2005, after which time water was pumped continuously into the pond for four hours. The pump was temporarily switched off, and the first monitor survey data were acquired. Water was again poured downhole prior to acquiring data for the next survey. This was repeated for a total of eight monitor surveys spanning thirty-six hours.

Methodology

Data were processed consistent with near surface, high-resolution seismic reflection data to produce a final stacked section for each survey. Data were then reprocessed using the same sequence of steps except those that would affect amplitude. Immediately apparent during processing was the high amplitude nature of the air-coupled wave. Qualitatively, its strength appeared to decrease from the baseline to the first monitor survey, then increase throughout the remaining monitor. To analyze the air-coupled wave's amplitude as it changed with time, everything except the air-coupled wave was muted from the shot gathers after application of a 100 to 500 Hz bandpass filter was applied. The amplitude spectra were calculated for every shot gather in all nine surveys. There were several different peak frequencies evident in the air-coupled wave packet. Peak frequencies and their true amplitudes were recorded. The average amplitude of each peak frequency was calculated for each survey and plotted as a function of the number of times the source was fired downhole. The mean air-coupled wave amplitude was calculated by averaging the mean amplitude of each frequency for each survey and

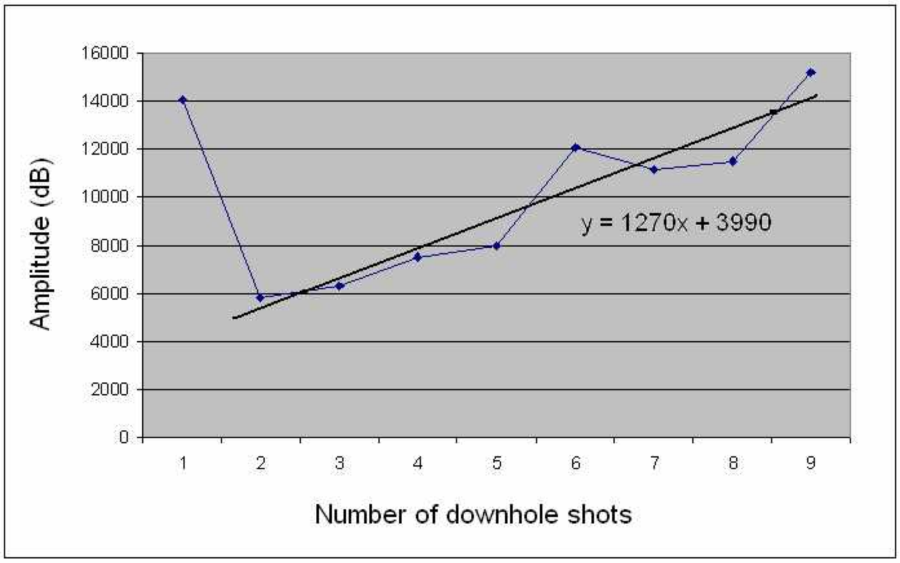


Figure 1 – Average change in air-coupled wave amplitude. There is a 59% amplitude decrease between one and two downhole shots, followed by a nearly linear amplitude increase for the remaining shots.

plotted as a function of time (Figure 1). The signal and noise remaining after surgically muting undesired energy was then analyzed in a fashion consistent with the air-coupled wave.

To understand how reflection strength was affected by repeated use of the same source hole, the same trace in the same shot gather from a particular station was analyzed for each survey. Everything except the desired reflection was surgically muted from the first four shot gathers, and an amplitude spectrum was generated for each of these shot gathers. The peak frequency and its associated amplitude were recorded, and two plots generated for each shot gather: the reflection frequency and amplitude versus number of shots fired downhole. Reflection wavelet frequency characteristics did not change significantly. Reflection amplitudes versus number of shots fired downhole for the 55.0 ms reflection appears to support a complex relationship (Figure 2).

To determine how significantly the source signature changed with repeated shots, a single representative trace was selected from the shot gather recording at the same source station for each

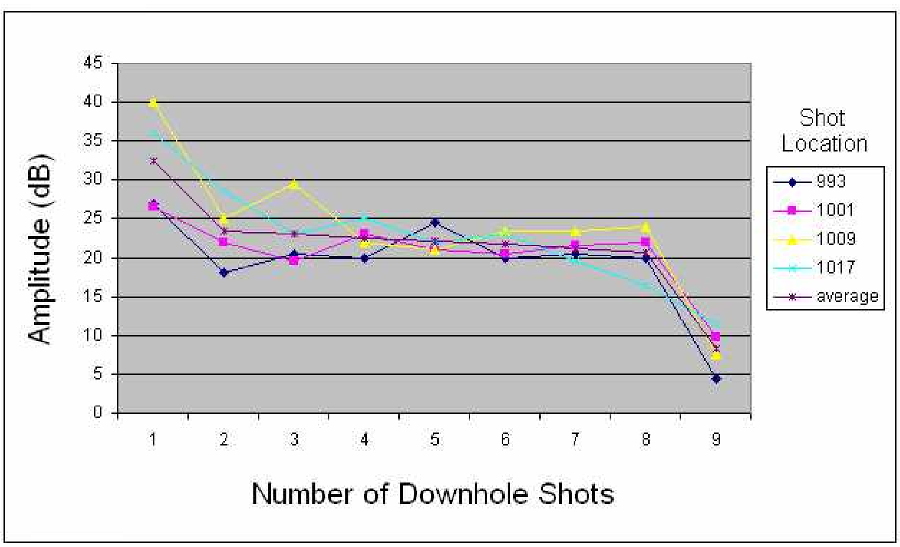
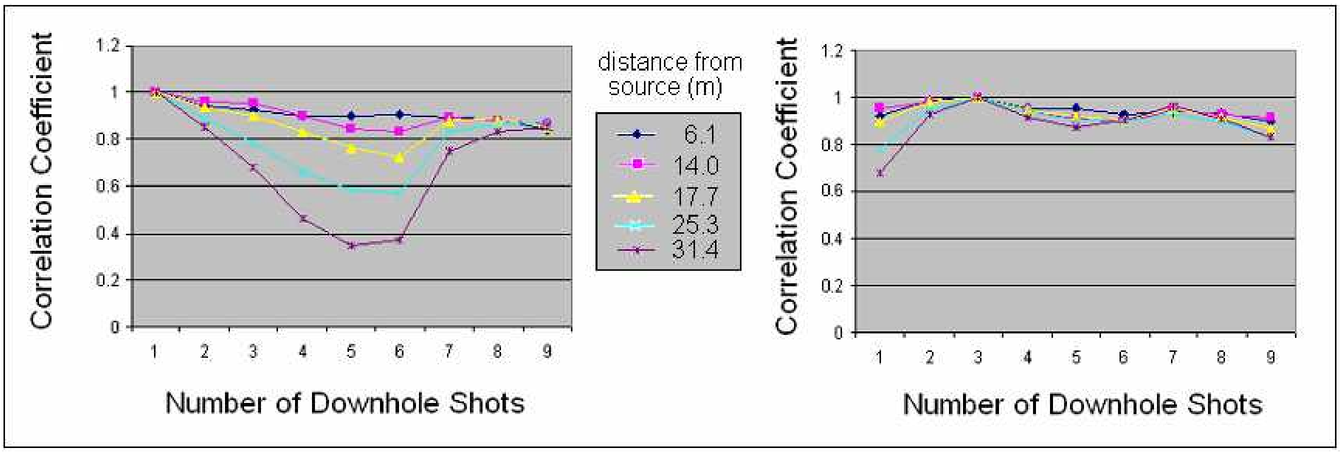


Figure 2 – Change in absolute reflection amplitude as a function of number of downhole shots fired for the 55 ms reflection in four shot gathers.

survey. Correlation coefficients were determined for all nine traces with respect to each trace. This was repeated for traces from five different receivers, both near and far relative to the source. Plots of correlation coefficient versus number of shots fired downhole were generated for each (Figures 3a and 3b).

To determine if there is any relationship between frequency and amplitude relative to progressively increasing occupations of the shot hole, a plot of frequency versus amplitude was generated using the average values of both the air-coupled wave and the remaining unmuted data for each survey. There was no apparent connection between amplitude and frequency of the air-coupled wave. For unmuted data, both a linear and an exponential fit were applied (Figure 4).



(a) **(b)**

Figure 3 – (a) Correlation coefficient for equivalent traces correlated with that of the baseline for each survey. These wavelets were taken from a shot gather recorded at the same shot station (1017). (b) Same as (a), except correlated with the trace from the second monitor survey, as opposed to the baseline.

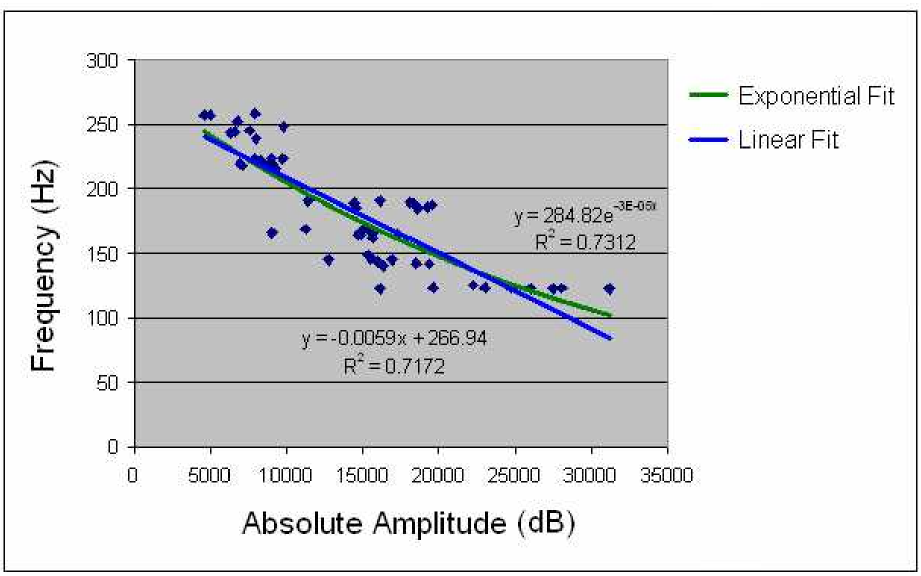


Figure 4 – The average frequency versus amplitude of unmuted data.

Discussion

The distinctive 59% decrease in absolute air-coupled wave amplitude from 14,000 dB to 5800 dB between the baseline and first monitor survey is the most noteworthy change that adversely affects the repeatability of the surveys (Figure 1). After the second shot the average air-coupled wave amplitude increases nearly linearly at a rate of approximately 1270 dB per survey throughout the remaining set of monitor surveys. The decrease in air-coupled wave amplitude between the first two surveys is very significant. This suggests improved seal between the gun and hole after the hole was conditioned by a single firing of the source downhole. Subsequent increasing air-couple wave amplitude indicates decreasing seal quality throughout the remaining eight shots. This suggests that, to optimize data acquisition in this setting using a 30.06 or similar source, the hole requires at least one downhole shot before acquiring any data to condition the hole and maximize the seal. On the ninth shot downhole, the seal has deteriorated to near that observed on the first shot, as indicated by air-coupled wave amplitude.

Absolute reflection amplitude was largest in wavelets from the baseline survey (Figure 2). Subsequent to the first shot fired downhole, reflection amplitudes remained approximately 30% below the reflection amplitude from baseline survey data until the ninth downhole shot. On the ninth downhole shot, reflection amplitude decreases by 60%. This suggests that the greatest level of source coupling occurred with the first downhole shot fired, after which source coupling remains fairly consistent for seven consecutive shots before another significant decrease occurs with the ninth shot. Consistency is vital for high-quality time-lapse seismic data. Therefore, though the first shot produces reflections with the highest amplitudes, the second through eighth shots are more repeatable.

Both air-coupled wave amplitude and reflection amplitude decrease with the second downhole shot. The air-coupled wave amplitude is indicative of the seal between the gun barrel and hole. Reflection amplitude on the other hand is indicative of energy transmitted from explosive to seismic at the borehole walls. Seal and source coupling are related in a complex, non-linear fashion.

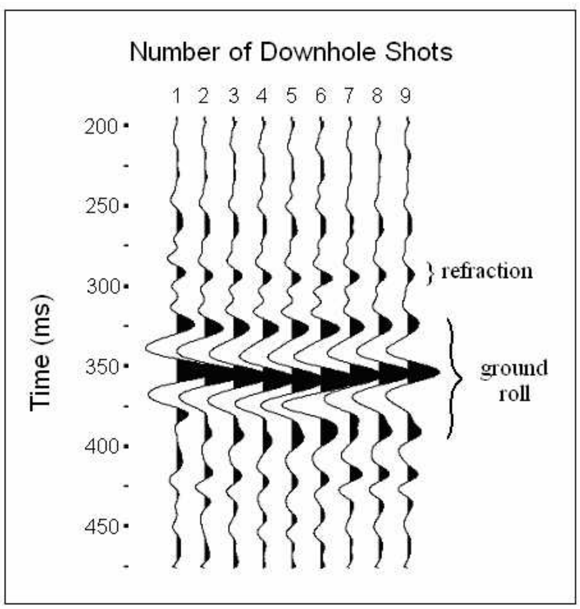


Figure 6 – Nine traces corresponding to the same shot (1017) and receiver (1120) station for each survey. The refracted energy arrives at approximately the same time. Ground roll traveltime appears to change as shots are fired downhole.

Representative traces selected from shot gathers recorded at the same source station for each repeat survey correlate best with the traces from the second monitor survey (Figure 3*b*) rather than the baseline (Figure 3*a*). The fact that traces from the third shot correlate better with successive shots down the same hole is suggestive of a significant change in source signature after the second firing downhole of the source. Source signature continues to change, but is most consistent for all surveys with the third shot.

Inspection of representative traces selected from the shot gather from the same source station for each survey reveals an apparent increase of 1 to 5 ms in ground roll traveltime, depending on source-to-receiver distance and the number of shots fired downhole (Figure 5). Ground roll traveltime consistently increased for each of the first five shots, then consistently decreased for the last 4 shots. An apparent increase in the ground roll traveltime can be caused by one of two things: an actual traveltime increase resulting from a change in phase velocity, or a phase shift in ground roll that appears as an apparent shift in traveltime. Dispersion curves generated for each survey indicate that the ground roll phase velocity was consistent for all nine surveys. The traveltime increase must be apparent rather than actual and results from a phase shift in the ground roll dependent on the hole conditions.

Conclusions

Repeatability must be optimized for near surface time-lapse seismic surveys to be practical. This study characterized changes in amplitude and frequency content for repeat shots by analyzing the amplitude and frequency content of the air-coupled wave, reflections, and ground roll. Air-coupled wave amplitude decreases significantly after the first downhole shot, indicating improvement in energy seal. Reflection amplitude decreases significantly after the first downhole shot, indicating decrease in source coupling. Reflection amplitude remained approximately the same for the seven subsequent shots, indicating consistent source coupling, a characteristic that is important for maximizing repeatability of time-lapse seismic data. An apparent traveltime shift was observed in the ground roll while phase velocity remained constant is likely indicative of a ground roll phase shift associated with downhole shots. Correlation coefficients of equivalent traces from different shots are a maximum when correlated with the third shot, suggesting the source signature is most repeatable after the second downhole shot. Therefore, to optimize repeatability, the source should be fired twice in each hole before acquiring data to adequately condition the hole.

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