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A Versatile Shotgun Source for Engineering and Groundwater Seismic Surveys

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Short Note

A versatile shotgun source for engineering and groundwater seismic surveys

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INTRODUCTION

We describe an electrical seismic gun that is capable of firing 8-gauge blank black powder shells in a water-filled borehole under relatively high hydrostatic pressures. The new seismic gun is a modified version of the electrical shotgun source for engineering seismic surveys introduced by Pullan and MacAulay (1987). Our modifications seal the firing circuit and 8-gauge shell against water entry so underwater detonation will occur reliably at depths to at least 80 m (0.9 MPa atmospheric pressure). Source energy is controlled by varying the size of the black powder load in the shell from 50 grains to 500 grains (10 kJ to 100 kJ). Although our seismic gun may be used in any seismic application suitable for modest explosive charges, it was initially developed as a versatile source for use in seismic investigations of the shallow subsurface (primarily engineering and groundwater studies). As of this writing, the gun has been used for optimum offset and CMP high-resolution seismic reflection profiling, engineering refraction surveys, fixed-source and variable-source noise tests, and vertical traveltime measurements in water wells. Other potential uses include VSP and borehole-to-surface or borehole-to-borehole seismic tomography .

DESIGN AND ASSEMBLY

Design of the new gun is based on several requirements: (1) the gun must be functional in water at depths encountered in shallow boreholes (e.g., water wells up to 100-m depth); (2) the gun must be capable of using a variety of g-gauge source energies; (3) the gun must be easy and safe to use with standard precautions. Early tests using mechanical and electromechanical designs suggested that an electrical gun (no moving parts) using an explosives blaster to detonate electrical 8-gauge shells best met the above requirements. The current design is described below in terms of four subassemblies (chamber, breech, pipe, and hanger). Straight threads are used throughout so that mating parts can be compressed rather than locked together. Pipe threads (such as those used in domestic steel plumbing) are not acceptable because they are locking threads and are rated for pressures less than the pressures encountered in water-filled boreholes. In the construction details that follow, part numbers are given in parentheses for comparison with Figure 1 which is a schematic plan for the fully assembled gun.

Chamber

The basic source is an 8-gauge (21 mm) industrial blank shotgun shell (Part 4) with an electrical primer and standard hull. A standard hull for an 8-gauge shell holds a maximum of 300 grains of black powder or a comparable amount of Pyrodex powder. To prepare a load over 300 grains, the hull is removed and a sleeve is placed over the brass rim of the shell. The resulting oversized 8-gauge shell can be made to hold any size load by simply adjusting the length of the sleeve. An alternate method of constructing 8-gauge shells to hold more than 300 grains is to insert a piece of l/2-inch diameter thin-walled polyvinylchloride (PVC) tubing into the shell hull. The PVC tubing is glued inside the hull and the size of load determines the tubing length. Both methods of preparing 8-gauge loads greater than 300 grains were developed by a commercial supplier and are available up to a maximum load of 500 grains. The standard chamber (Part 3) is used with standard g-gauge shells (loads up to 300 grains). Overall length of the standard chamber is the same as the untrimmed standard 8-gauge hull so that the chamber can be placed in mud with no barrel to plug. A second chamber is used with oversized 8-gauge shells loaded with more than

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300 grains. Both chambers are constructed from a high strength steel alloy and employ a rupture seal and rupture seal holder. The rupture seal holder (Part 1) is made from cold-rolled steel and is threaded onto the chamber with l-3/4 x 8 thread. The seal-holder holds a piece of l/16-inch to l/4-inch thick rubber or neoprene seal material (Part 2) against the chamber end; the seal ruptures when the shell is detonated. A rupture seal is needed for water depths greater than approximately 8 m to prevent water from entering the 8-gauge shell before firing (wet powder is difficult to ignite).

Breech

The breech (Part 8) holds the commercially available electrode assembly (Part 7) and is made from cold-rolled round steel cut down to the same diameter as 2-inch schedule-160 pipe and fitted with two O-ring seals. The first O-ring seal (Part 13), between the breech and pipe (Part 18), is designed to prevent water from entering the gun and shorting the firing circuit. A second O-ring seal (Part 5) is placed on top of a threaded boss used to attach the chamber to the breech. This O-ring prevents water from covering the back of the shell that could also short the firing circuit. Proper contact between the primer on the 8-gauge shell and the stainless steel electrode firing pin (Part 12) is assured by hand tightening the chamber so that the O-ring is compressed. Thread designs are l-7/8 x 8 (between the breech and pipe) and l-1/8 x 12 (on the boss between the breech and chamber). The electrode assembly is attached to the gun's internal wiring through a neoprene boot (Part 10) and is fitted with an O-ring seal (rated at 140 MPa) at its contact with the breech. Shrink tubing (Part 11) and nylon bushings (Parts 6 and 9) are used to insulate the firing pin from the breech. The lower nylon bushing (Part 6) is also needed to insulate the breech from an area as large as the primer on the shell. To prevent recoil from driving the lower nylon bushing into the breech, the breech is machined with a shoulder stop. Although the grounding screw (Part 16) can attach the electrical ground wire (Part 17) anywhere along the gun, attachment to the breech is convenient. To add to the gun's versatility, the boss thread design was chosen to allow use of an expendable polystyrene capsule which is threaded onto the breech in place of the chamber. These commercially available capsules hold 8-gauge shells with black powder loads up to 500 grains and are destroyed upon detonation.

Pipe

The pipe (Part 18) protects the internal wiring, gives the gun weight to reduce recoil, and allows straight threads to be used in the construction of the gun. The material chosen is 2-inch schedule-160 black pipe of length 1.5 m. This pipe has extra thick walls (approximately 3/8 inch) which allow l-7/8 x 8 threads to be used. One end of the pipe is chamfered (the hanger end) to allow an end plug (Part 19) to be welded to the pipe. The end plug, formed from 2-l/2-inch cold-rolled round steel, is cut down to match the diameter of the pipe. The end plug has l-7/8 x 8 external threads to allow the hanger (Part 23) to be attached to the gun. Welding the end plug to the pipe is accomplished with a deep V-bead. A commercially available bulkhead connector (Part 21) is threaded into the end plug. The mating cable with cable connector (Part 22) and O-ring seal (between the bulkhead connector and the end plug) are rated at 140 MPa. Wires soldered to pigtails of the bulkhead connector complete the circuit to the breech end of the gun. The soldered junction (not shown in Figure 1) is covered with shrink tubing for protection. It is necessary to prewind the internal wires to prevent unnecessary tangling during final assembly.

Hanger

The hanger (constructed of a 20-cm length of 2-inch schedule- 160 black pipe) encloses the bulkhead connector and provides a secure connection for the hoist cable (Part 26). As mentioned above, the hanger screws to the external threads on the end plug. To prevent this connection

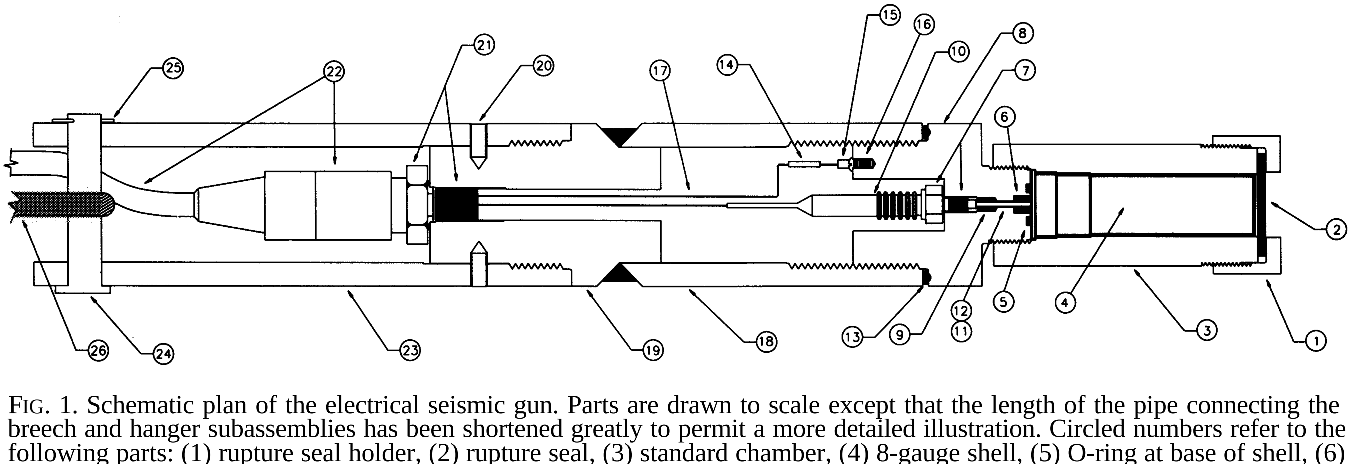

FIG. 1. Schematic plan of the electrical seismic gun. Parts are drawn to scale except that the length of the pipe connecting the breech and hanger subassemblies has been shortened greatly to permit a more detailed illustration. Circled numbers refer to the following parts: (1) rupture seal holder, (2) rupture seal, (3) standard chamber, (4) 8-gauge shell, (5) O-ring at base of shell, (6) lower nylon bushing, (7) electrode assembly, (8) breech, (9) upper nylon bushing, (10) neoprene electrode boot, (11) shrink tubing with silicone grease covering electrode firing pin, (12) electrode firing pin, (13) O-ring between pipe and breech, (14) bullet connector, (15) spade connector, (16) grounding screw, (17) electrical ground wire, (18) pipe (shortened for this illustration), (19) end plug, (20) set screw, (21) bulkhead connector, (22) cable (to blaster) with cable connector, (23) hanger, (24) clevis pin, (25) locking pin, (26) aircraft (hoist) cable. The overall length and total weight of the gun depends on the pipe length (a pipe of 1.5-m length results in a 1.9-m overall length and 25-kg total weight).

from separating in downhole applications, it is locked to the end plug with set screws (Part 20). At the top of the hanger, a clevis pin (Part 24) is used to attach a 1/4-inch diameter aircraft steel hoist cable with tensile strength of 6200 N (1400 lbs).

BANDWIDTH AND REPEATABILITY

Characteristics of the seismic energy produced by the new gun in a steel-cased borehole were measured at Quarry View Park in Boise, Idaho. The shallow subsurface at this site is composed of 170 m of fluvial and lacustrine sediments underlain primarily by basaltic and rhyolitic rocks. Near-surface sediments at the time of the test were unsaturated and the water table was at 9.9-m depth. An 8-gauge shot record (Figure 2a) was generated by the new gun with a 500-grain black powder load under 2.3 m of water at the bottom of a steel-cased borehole (12.2-m total depth). To provide a comparison with a different explosive source, another shot record (Figure 3a) was acquired under identical experimental conditions using 9.2 g of detonating cord fixed by a small weight at the bottom of the borehole and detonated with a seismic-quality electrical blasting cap. Receivers were 100-Hz geophones (0.6 critical damping) planted at 2-m intervals over a flat profile at 52-146 m in length. An electrical blaster was used to detonate the sources and to simultaneously trigger the seismograph.

Examination of both records (Figures 2a and 3a) shows ringing (possibly from casing vibration) for approximately 40 ms following the first arrival, with the earliest probable reflections interpreted at times greater than 100 ms. The reflection between 170-200 ms likely represents a geologic sequence at 170-212 m depth consisting of basaltic material of 24-m thickness underlain by 18 m of medium to coarse sandstone, and a relatively thick layer of silicic volcanic rocks (W. Burnham, personal communication, 1990). Surface waves are not well developed on either record, and an

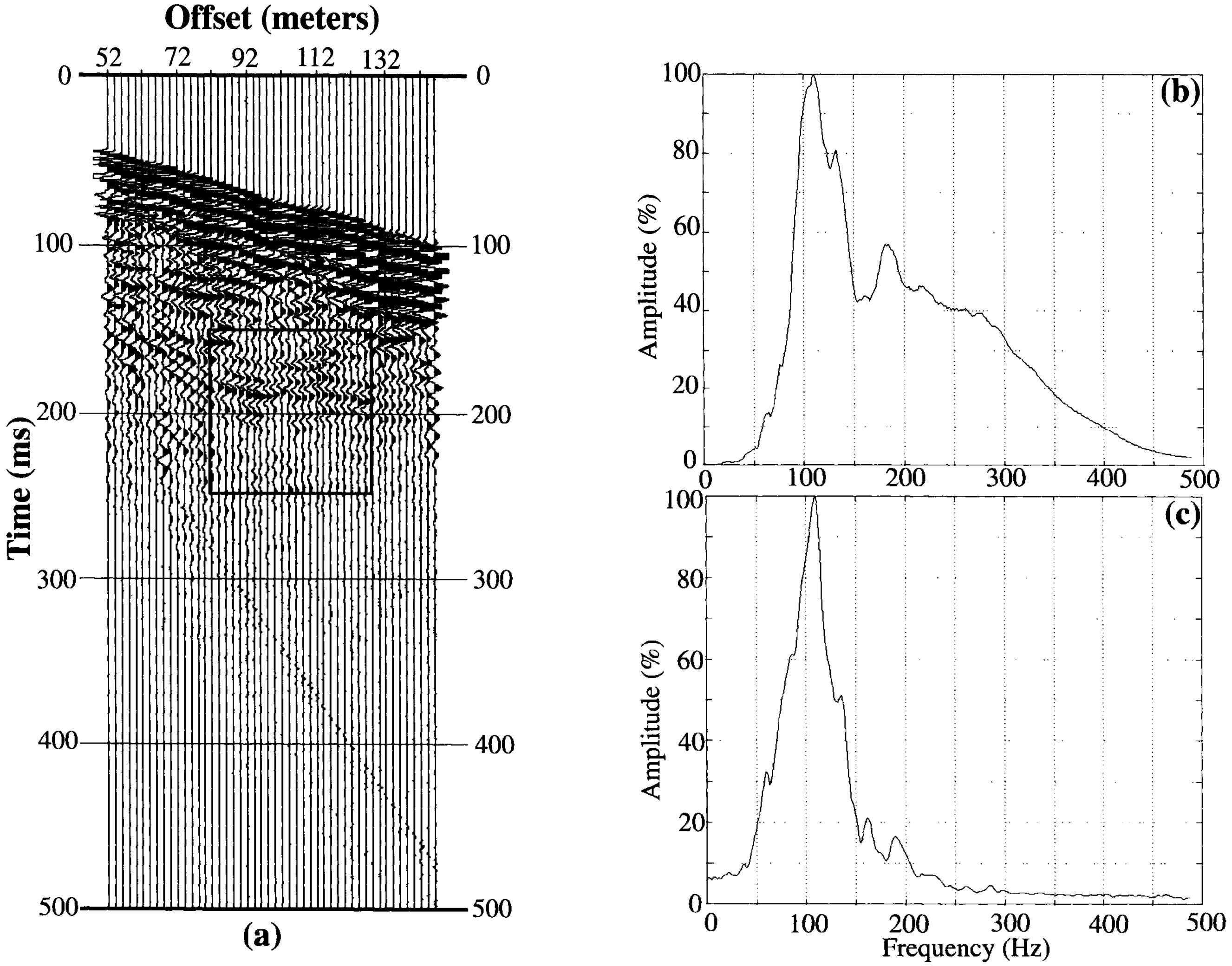

FIG. 2. Quarry View Park source test for 8-gauge 500-grain black powder load fired by new seismic gun in steel-cased borehole: (a) unprocessed 48-channel field record (each trace has been multiplied by the same scalar to preserve relative amplitudes within the record); (b) average amplitude spectrum for all 48 traces (duration 0-500 ms); (c) average amplitude spectrum for 100-ms reflection window shown in (a). Acquisition parameters: shot depth 12.2 m (water depth 2.3 m), analog band-pass filter 100-2000 Hz, sampling rate 0.1 ms, minimum offset 52 m, maximum offset 146 m, station spacing 2 m, single vertical 100-Hz geophones (Mark L-40 A-2) damped at 0.6 critical, digital instantaneous floating point seismograph (Bison 9048), seismograph trigger taken from electrical blaster.

air wave (somewhat stronger for the detonating cord source) traverses the records at 330 m/s apparent velocity.

The average whole-trace amplitude spectrum for the Quarry View Park 8-gauge data is peaked near 110 Hz, with a secondary peak near 185 Hz, and significant frequency content to 400 Hz (Figure 2b). Computation of spectra within different windows (not shown) suggests that the 185-Hz energy is most prominent in the early ringy part of the record, and the persistence of significant frequency content to 400 Hz results from high-frequency energy in the near-offset traces. The average amplitude spectrum of the 170-200 ms reflection (included within a 100-ms window) shows a peak frequency of 110 Hz with significant energy between 40-200 Hz (Figure 2c). Rapid falloff of the spectra below 100 Hz is caused by the combined effect of l00-Hz geophones and a 100-Hz low-cut acquisition filter. Similar properties are observed in the spectra computed for the detonating cord source (Figures 3b and 3c).

Repeatability of the new gun was examined as part of the Quarry View Park test by comparing seismograms generated by two different 8-gauge (500 grain) shots with all acquisition parameters held constant. Raw unnormalized traces recorded at a given offset were superposed to provide a qualitative impression of repeatability (Figure 4). The superposition of traces indicates good consistency of both waveform shape and amplitude, and also indicates that the largest discrepancies in trace amplitude typically occur at early arrival times where absolute amplitudes are also largest (i.e., the first 25-50 ms after the first break). An estimate of the average size of the amplitude discrepancy was made by subtracting traces after aligning the first breaks and then computing the root-mean-square (rms) residual. In the Quarry View Park test, the rms residual is typically 15-20 percent of the rms amplitude of the original two traces under comparison.

Another aspect of repeatability is the consistency between time zero at the seismograph and the actual detonation of the 8-gauge shell. Precise timing of the first peaks in Figure 4 data indicates a uniform static shift of 0.3 ms between traces, suggesting that there is a reasonably consistent time relationship between the seismograph trigger from the blaster and detonation of the 8-gauge shell, at least for the two repeated

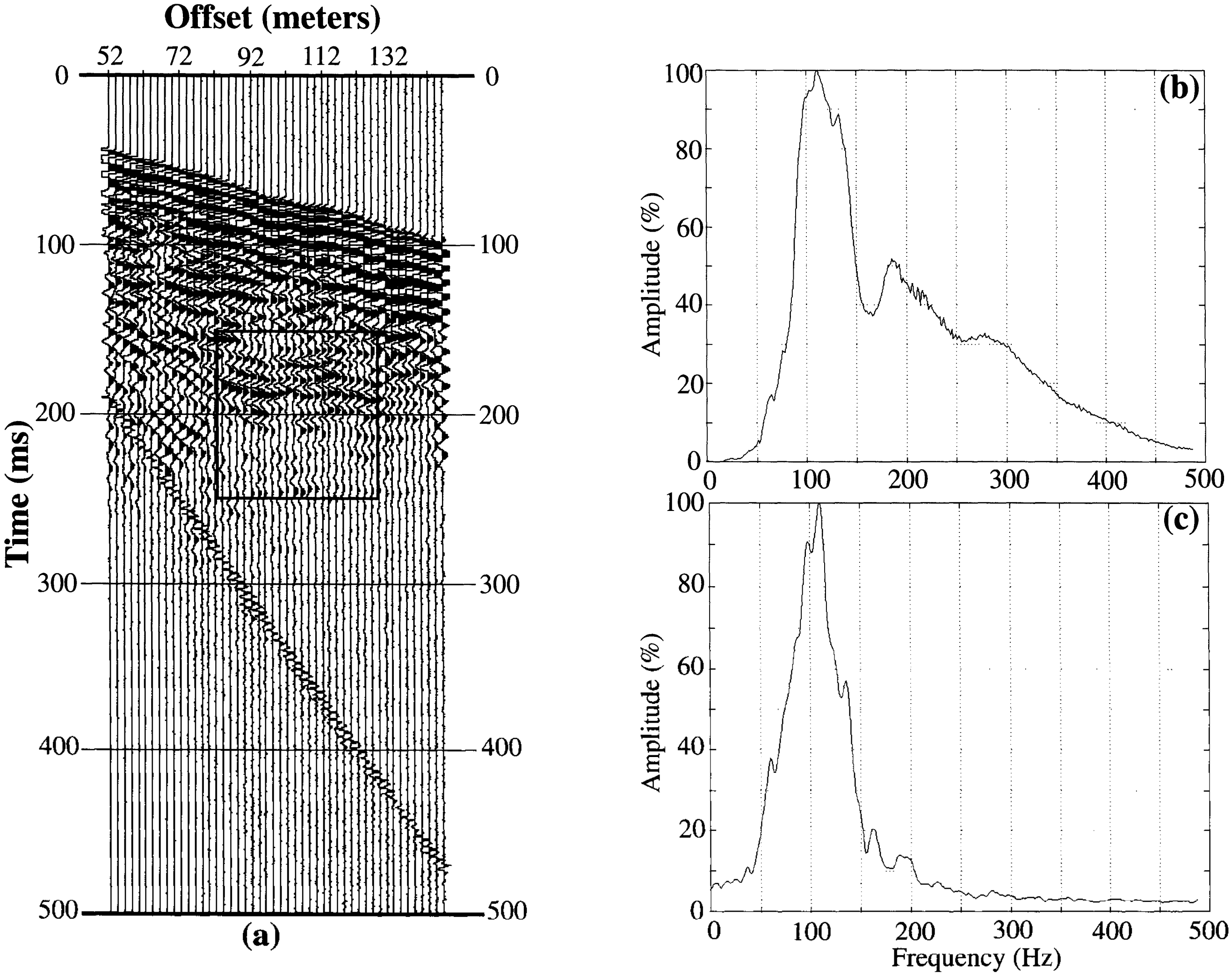

FIG. 3. Quarry View Park source test for 9.2 g detonating cord plus seismic-quality blasting cap detonated in steel-cased borehole: (a) unprocessed 48-channel field record (each trace has been multiplied by the same scalar to preserve relative amplitudes within the record); (b) average amplitude spectrum for all 48 traces (duration O-500 ms); (c) average amplitude spectrum for l00-ms reflection window shown in (a). Acquisition parameters same as in Figure 2.

shots in the Quarry View Park test. However, we have noticed static shifts of several ms between repeated shots in other experiments where acquisition parameters were tightly controlled, and suspect (but have not proven) occasional variability in the detonation delay of the electrical primer used in 8-gauge shells. Therefore, it may be advisable to use a mechanical impulse trigger for the seismograph in some applications involving electrically detonated 8-gauge shells (e.g., an application where automatic vertical stacking of high-frequency seismograms is done in the field).

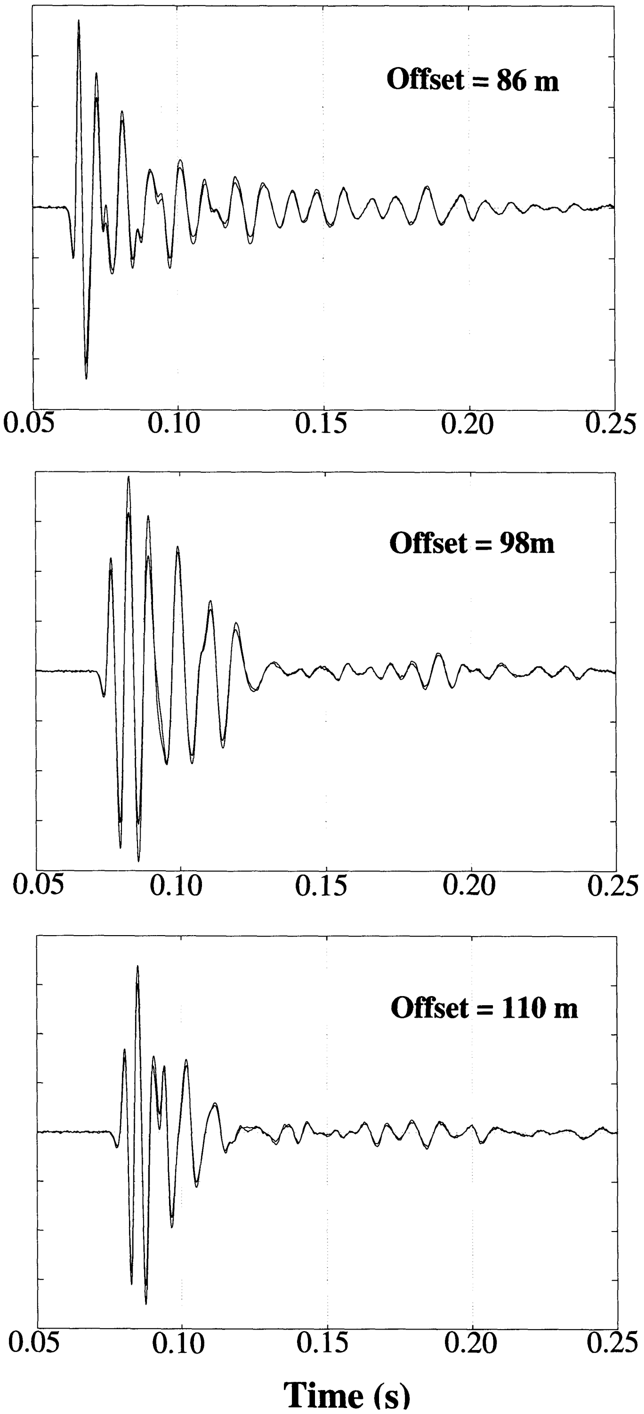

FIG. 4. Comparison of traces from Quarry View Park repeatability test for &gauge, 500-grain black powder loads fired by new seismic gun. Gun was fired twice with all acquisition parameters held constant (acquisition parameters same as in Figure 2). Raw unnormalized trace pairs at three different offsets have been plotted after alignment on first breaks.

The SEG Engineering and Groundwater Committee sponsored comparison tests of shallow seismic sources at field sites in New Jersey (1985) and in California (1988) which were summarized by Miller et al. (1986; 1992). The seismic gun described here was not included in the SEG source tests because it was developed after their conclusion. However, it is reasonable to expect that the performance characteristics (i.e., energy output and spectral content) of our source at the SEG sites would have been similar to those reported by Miller et al. (1986; 1992) for 8-gauge downhole seismic guns firing blanks. It is also important to note that because of differences in site properties and experimental procedure, the results of the Quarry View Park test cannot be strictly compared with the SEG source studies.

DISCUSSION AND CONCLUSIONS

Approximately 300 test firings of the new seismic gun confirm that the seals function properly and detonation is reliable at different depths in water-filled boreholes. At present, the maximum water depth at which we have successfully test-fired the gun is 80 m in an aquifer test well (0.9 MPa including atmospheric pressure). An absolute maximum depth for reliable operation of the new gun has not been established, but the lowest rated seal is the rupture seal which is anticipated to work properly at a water depth of at least 100 m (1.1 MPa). The gun requires that the shell and rupture seal (if water pressure is great enough to require a rupture seal) be changed after each shot. During the shell change, it may be necessary to wipe debris from the electrode if it appears to be fouled. The breech does not need to be disassembled and dried between shots which can be a serious problem with some electrically detonated seismic guns. Different source energy requirements can be met by different 8-gauge loads, and electrically detonated 8-gauge shells can be shipped and stored without special licenses or magazines. The source may be suspended in a borehole at various depths or may easily be seated in the mud at the bottom of a shallow well. There is no need for a drop-rod because an explosives blaster is used for detonation. Operation is simple but requires the usual safety precautions for working with seismic guns and electrically detonated explosives.

The new seismic gun provides a relatively inexpensive ($250 for materials, cables extra) solution to the problem of impulsive source generation in a wide variety of surface or borehole seismic experiments designed to image shallow targets. Reliable operation is assured in water-saturated environments, the energy output is easily adjustable, transportation and storage of the source material is simplified relative to many explosives, and seismic crews require training on only one source device. However, experiments which require many repeated shots in a deep borehole may be impractical because of the need to raise the gun to the surface between shots for reloading. This disadvantage may be overcome in the future through the use of a gas feed line and the detonation of an explosive gas mixture in the chamber. We also note that no experiments have been carried out to investigate the gun's potential to inflict damage to a permanent borehole.

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