

**HIGH FIDELITY VIBRATORY SOURCE SEISMIC METHOD FOR USE IN
VERTICAL SEISMIC PROFILE DATA GATHERING WITH A PLURALITY OF
VIBRATORY SEISMIC ENERGY SOURCES**

The present invention pertains to vertical seismic profile data acquisition and processing and more particularly to a pre-processing vertical seismic profile data method in which data generated by multiple vibrating sources is received and prepared for high resolution or high fidelity data processing.

In vertical seismic profile data, it is conventional practice to use a single seismic source to apply a force to the ground in the proximity of a wellbore. The subsequent motion caused by the application of this force is measured at various locations within the wellbore. This is done by energizing the seismic source and detecting the downgoing wave and upcoming or reflected wave at a first receiver location in the wellbore. The receiver is then moved several feet along the length of the wellbore and the source is energized again. The downgoing and upcoming seismic waves are again measured. This procedure is repeated periodically through selected lengths of the well that constitute zones of interest. By controlling the duration and frequency of the force, a broad band signal with sufficient energy is achieved. By using the receiver motions and segregating the downgoing and reflected waves a seismogram is constructed, usually by correlation, or inversion in the frequency domain, with the signal representing the downgoing wave. From this procedure properties of the impedance function of the earth can be calculated.

The present invention provides a method for generating, recording and preprocessing high resolution vibratory source data for use in vertical seismic profile technology. The method of the present invention includes measuring the motion or motions of the vibrators. These motions are related to the actual vibrator applied force by a transfer function of a minimum phase, causal, linear

system and are used to separate received signals. These signals are used in an inversion operation to process the received data. The system of the present invention relates the actual vibrator output with the measured vibrator motion or motions. The vibrators are energized with a predetermined pattern. This pattern is used to separate the received data according to the source used to generate the detector motion or motions. The received data may then be processed to isolate the downgoing waves for each vibratory source. The separated data may then be processed by conventional correlation using the downgoing wave data to produce a seismogram. In the alternative, a ratio may be determined by dividing the vibratory seismic data by the measured motion or motions of each of the vibrators to remove the unknown applied force leaving the earth reflectivity times a time derivative, divided by a minimum phase function. Minimum phase deconvolution is performed to remove the time derivative divided by the transfer function of minimum phase.

Figure 1 is a drawing of a typical vertical seismic profile data gathering technique.

Figure 2 is a plan view of an alternate arrangement of vibratory sources in the use of the present invention.

Figure 3 is a plan view of a second alternate arrangement of vibratory sources in the use of the present invention.

Figure 4 is a block diagram of a flow chart illustrating a preprocessing method for vertical seismic profile data generated by multiple vibratory sources.

In the present invention, multiple seismic sources are used. Each of these sources is a vibratory source in which a signal directly related to the actual signal that the vibrator is sending into the ground is used in preprocessing. These signals are reflected by interfaces separating formations having different impedances. The reflected signals produce motion or motions detected by a

seismic receiver, such as a geophone, located within a wellbore. This seismic receiver is positioned at one point in the wellbore, vibratory motions are generated by sources and detected by the receiver. The receiver is moved a
5 predetermined distance to a different location in the well and the process is repeated.

In order to construct a seismogram, a determination of which source was responsible for the detected motions of the receiver must be made. Each source has unique
10 characteristics that aids in isolating the source that generated the force which caused the receiver motions, since the data received will vary for each source. Processing with the estimate of one source on data generated by another source will produce an inaccurate
15 seismogram. In order to increase the accuracy in producing a seismogram, the data must be separated according to its generating source for further processing with the force from its corresponding source.

In a first embodiment of the present invention, the
20 data is separated according to the source which generated it. From this point, the downgoing wave may be isolated and the data may be further processed as typical data by any one of the well known methods for processing vertical seismic profile data.

In a second embodiment of the present invention, the
25 vibrator motion or motions are measured to provide a signal that is used to process the data by eliminating an unknown. The data is divided by a minimum phase relative of the actual transmitted signal in the frequency domain, which
30 removes the actual transmitted signal from the determination. When solving for the earth reflectivity, detected data, which is the time derivative of the transmitted vibrator ground force multiplied by the earth's reflectivity, is divided by a quantity equal to the
35 vibrator ground force multiplied by a transfer function of minimum phase. By doing this, the vibrator force is

removed from the data. This leaves the earth reflectivity multiplied by a time derivative divided by a minimum phase transfer function, which ratio is then removed by minimum phase deconvolution.

5 In gathering seismic data using seismic acoustic energy, ground vibrations from a vibratory source may be used by placing a large mass in contact with the ground. A simple vibrator may be used in the present invention. Typically a force is applied by reversing hydraulic flow in
10 a chamber in a reaction mass that is suspended by a piston and rod assembly attached to a stilt structure at a cross member.

Typically, the reaction mass motion is measured by mounting accelerometers on the reaction mass itself. The
15 motion of a baseplate, which is actually coupled to the ground, is measured by accelerometers mounted on the stilt structure cross member. In the present invention, pairs of accelerometers are used in each position so that the outputs may be compared and a determination may be made
20 whether the signal generated is suitable for use in further processing.

Figure 1 is a system diagram illustrating the data gathering process of the present invention. A wellbore 16
25 is illustrated as located a distance from vibrators 18, 20, 22 and 24 with two pairs of accelerometers 26, 28, 30 and 32, as described above, located on trucks 34, 36, 38 and 40, respectively. The signals are transmitted via radio link 42 to master vibrator memory 44 where they are checked to determine their reliability and are stored for
30 comparison at a later time.

The signals that are generated into the earth by vibrators 18, 20, 22 and 24 are reflected off the interface between subsurface impedance Im_1 and Im_2 at various points, I_1 , I_2 , ... etc. along the interface. These reflected
35 signals are detected by a seismic receiver D positioned in wellbore 16. After detection of signals, seismic receiver

D is moved a predetermined distance uphole, as illustrated in phantom, and vibrators 18, 20, 22 and 24 are re-energized. The generated signals are reflected off the interface between subsurface impedance Im_1 and Im_2 at various points, I_1 , I_2 , ... etc. along the interface a second time. This procedure is repeated several times to produce the effect of having a vertical string of geophones instead of the traditional horizontal line.

In Figure 1, the vibratory sources on trucks 34, 36, 38 and 40 are illustrated as being positioned radially in a straight line from borehole 16. Figures 2 and 3 illustrate possible alternate arrangements for trucks 34, 36, 38 and 40.

In Figure 2, the vibratory sources are spaced equally along a circumference defined by a predetermined radius. This radius may be of any practical distance. The spacing of trucks 34, 36, 38 and 40 along the circumference need not be of equal distance but may be spaced so that all the trucks are in the top half of the circle, in one quadrant, etc.

In Figure 3, trucks 34, 36, 38 and 40 are spaced randomly around borehole 16, at different radii. Trucks 34, 36, 38 and 40 are illustrated as having three in the top half of a circle with borehole 16 as its center. However, any random arrangement is possible as long as the separation of the signals from the vibratory sources is not impaired.

When the signals generated by vibrators 18, 20, 22 and 24 on trucks 34, 36, 38 and 40 are transmitted to mass memory 44, they are conveyed to recorder 46 for transfer to tape 48 for combination with raw seismic data received from seismic receiver D. The received data signals and the raw seismic data stored on a tape 48 can be transferred to computers at other locations.

The measured signals are representative of the actual signals that are generated into the surface of the earth

through vibratory source technique. These measured signals are minimum phase relatives of the actual signals that are generated into the earth by this technique. In the present invention, a signal which is minimum phase related to the
5 actual force generated into the earth is measured and taken from the vibrator source directly. Thus, a relative of the actual signal is used in the process.

The present invention takes a different approach than conventional processing for vertical seismic profile data.
10 First, the present invention uses multiple sources and recognizes that the motions measured on the vibrator are related to the actual output force or signal that is put into the ground by a minimum phase transfer function in the frequency domain. Both the minimum phase transfer function and the actual output force are unknown. Second, this
15 embodiment of the present invention performs an inversion operation instead of the correlation process of conventional vertical seismic profile processing.

The detected seismic data is represented in the
20 frequency domain by the product of the time derivative of the actual force with the reflectivity of the earth.

By using inverse filtering through a minimum phase band pass filter, the ratio of the measured seismic motion to the measured motion of the vibrator can be computed.
25 This ratio eliminates the unknown actual output force. A scaling factor is also required to preserve total energy through this inverse filtering process.

The resulting seismogram is represented by the ratio of the measured seismic motion to the measured motion of
30 the vibrator and is the desired answer, the earth reflectivity, convolved with a minimum phase function. A property of minimum phase functions is that their derivative and their reciprocal are also minimum phase. Thus the seismogram can be further processed with minimum
35 phase deconvolution to obtain the impulse response of the earth in the frequency domain. In essence, the ratio of

the measured seismic motion to the measured motion of the vibrator seismogram is the band limited impulse seismogram. It is causal and minimum phase related to the earth response.

- 5 This method for multiple sources is always correct since the actual and unknown vibratory motion has been eliminated.

Two methods of simultaneous separation are as follows:

10 **METHOD 1**

	SWEEP #	1	2	3	4
	VIBRATOR A (phase)	0	0	0	0
15	VIBRATOR B (phase)	0	180	0	180
	VIBRATOR C (phase)	0	0	180	180
	VIBRATOR D (phase)	0	180	180	0

- 20 This method avoids a 90 degree problem and only requires that a sweep done at 0 degrees be the mirror image of one done at 180 degrees. However, for effective separation, the system should guarantee that Vibrator A's motions are repeatable in real time.

25 **METHOD 2**

	SWEEP #	1	2	3	4
	VIBRATOR A	OFF	0	0	0
30	VIBRATOR B	0	OFF	0	0
	VIBRATOR C	0	0	OFF	0
	VIBRATOR D	0	0	0	OFF

- 35 As in the first method confirmation of the separation assumption needs to be made in real-time.

This method produces slightly less signal, three instead of four, but uses the least demanding requirement for separation, namely that the sweeps repeat.

5 For both of these methods the necessary processing signals can be encoded in a similar fashion and the individual vibrator motions can be extracted. This means that only one signal needs to be telemetered to the recorder for each sweep sequence.

10 Referring now to Figure 4 a flow chart of the method of present invention is illustrated in block form. This method may be performed on any digital computer or work station currently in use in the art.

15 Initially, at block 50 data stored on tape 48 is received. Data received may be of any type of multiple source seismic data generated using vibratory source techniques.

20 At block 52 the received data is separated. This process begins when the seismic energy responsible for the data is first generated. There are several methods for generating seismic data to permit separation of the detected data which have been discussed previously. Any of the previous methods along with any methods currently in use in the art may be used to separate the received data, however, the preferred embodiment with
25 the phase separation previously described.

30 At block 54, the inversion process is performed on the received data with the measured signals. This represents a significant difference between the present invention and conventional processing. In conventional processing, the received data is convolved with the downgoing wave signals that are generated into the earth's surface. In the present invention, an inversion process is used which eliminates certain
35 assumptions which have been described previously. The detected data is divided in the frequency domain by the

measured signals, which leaves the earth's reflectivity multiplied by a time derivative divided by a minimum phase transfer function.

At block 56 a minimum phase band pass filter is
5 used to band limit the impulse seismogram. The
resulting seismogram at this point, or processed
detected data after this step, is now represented by
the earth's reflectivity convolved with a minimum phase
function. It is a property of minimum phase functions
10 that their derivative and their reciprocal are also
minimum phase.

In block 58 the seismogram is further processed
with minimum phase deconvolution to obtain the impulse
response of the earth in the frequency domain. In
15 essence the seismogram resulting after the inversion
process and minimum phase band pass filtering is the
band limited impulse seismogram. It is causal and
minimum phase related to the earth response.

In block 60 the resulting seismogram is displayed.
20 This display may be of any type in use in the art, such
as a computer generated sheet, a CRT display etc., as
long as impedance changes can be determined.

The method of the present invention for
generating, recording and pre-processing high
25 resolution vibratory source vertical seismic profile
data has been described which includes the steps of
data separation, division of the separated data with
measured signals and minimum phase deconvolution. As
stated previously, an actual vibrator signal related to
30 what the vibrator is sending into the ground is used in
pre-processing. The vibrator motion is measured to
provide a signal that is used to process the data. The
data is divided by the actual transmitted signal in the
frequency domain.

CLAIMS

1. A method for processing high resolution vibratory source vertical seismic profile data wherein electrical signals representing seismic information generated by multiple vibrators are received by a receiver positioned
5 at one location in a wellbore, characterized by:
 - receiving measured signals representing transmitted seismic waves from each of said multiple vibrators;
 - separating said electrical signals
10 corresponding to each of said multiple vibrators;
 - dividing said electrical signals with said measured signals to obtain earth reflectivity multiplied by a time derivative divided by a minimum phase transfer function to obtain a minimum phase
15 data set;
 - filtering said minimum phase data set with a minimum phase band pass filter; and
 - performing minimum phase deconvolution on said minimum phase data set to obtain earth reflectivity.
2. The method according to claim 1 in which the separating step includes the step of:
 - varying the generation sequence of each of said multiple vibrators.
3. The method according to claims 1 or 2 in which the receiving measured signals step includes the steps of:
 - measuring the seismic signal actually transmitted into the earth's surface; and
 - converting said measured seismic signals into a measured electrical signal.



4. The method according to any of claims 1, 2 or 3 in which the separating step includes the step of:

varying the generation sequence of each of said multiple vibrators.

5. The method according to any of claims 1 to 4 in which the separating step includes the steps of:

estimating the motion of each of the vibratory sources which is related to the vibrator applied force times a transfer function of minimum phase, causal, linear system; and

relating actual vibrator output with said estimated vibrator motion.

6. An apparatus for recording high resolution vibratory source vertical seismic profile data where electrical signals representing seismic information produced by a force generated into the ground are received by a device for receiving electrical signals placed at one position in a wellbore, characterized by:

means for receiving measured signals representing said force generated into the ground by each of a plurality of vibratory sources;

separating means for separating said electrical signals according to each of said plurality of vibratory sources;

means for dividing said electrical signals with said measured signals to obtain earth reflectivity multiplied by a time derivative divided by a minimum phase transfer function signals;

means for deconvolving said earth reflectivity multiplied by a time derivative divided by a minimum phase transfer function signals;

recording means for said summed earth reflectivity multiplied by a time derivative divided by a minimum phase transfer function signals; and



display means for displaying said recorded summed earth reflectivity multiplied by a time derivative divided by a minimum phase transfer function signals.

7. The apparatus according to claim 6 in which the separating means includes:

means for varying the generation sequence of each of said multiple vibrators.

8. The apparatus according to claim 6 or 7 in which the means for receiving measured signals includes:

means for measuring the seismic signal actually transmitted into the earth's surface; and

means for converting said measured seismic signals into a measured electrical signal.

9. The apparatus according to any of claims 6 to 8 in which the means for separating includes:

means for varying the generation sequence of each of said multiple vibrators.

10. The apparatus according to any of claims 6 to 9 in which the separating means includes:

means for isolating downgoing waves in said separated electrical signals; and

means for correlating said separated electrical signals with said downgoing waves to obtain earth reflectivity.