

Description

This invention relates to marine seismic surveying and, more particularly, to a seismic reflection method of geophysical prospecting.

5 Generally speaking, marine seismic surveys are conducted by towing an energy source and seismic detectors behind a vessel. The source imparts an acoustic wave to the water, creating a wavefield which travels coherently into the underlying earth. As the wavefield strikes interfaces between earth formations, or strata, it is reflected back through the earth and water to the detectors, where it is converted to electrical signals and recorded. Through analysis of these signals, it is possible to determine the shape, position and lithology of the
10 sub-bottom formations.

A problem encountered in marine surveying as well as in inverse vertical seismic profiling, or "VSP", is that of water column reverberation. The problem, which arises as a result of the inherent reflectivity of the water surface and bottom, may be explained as follows.

15 A seismic wave generated in (or reflected off) earth strata passes into the water in a generally upward direction. This wave, termed the "primary", travels through the water and past the seismic detector which records its presence. The wavefield continues upward to the water's surface, where it is reflected back downwards. This reflected, or "ghost", wavefield also travels through the water and past the detector, where it is again recorded. Depending upon the nature of the earth material at the water's bottom, the ghost wavefield may itself be reflected upwards through the water, giving rise to a series of one or more subsequent ghost reflections.
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This reverberation of the seismic wavefield in the water obscures seismic data, amplifying certain frequencies and attenuating others, thereby making it difficult to analyze the underlying earth formations.

In instances where the earth material at the water bottom is particularly hard, excess acoustic energy or noise generated by the seismic source can also become trapped in the water column, reverberating in the same
25 manner as the reflected seismic waves themselves. This noise is often high in amplitude and, as a result, tends to cover the weaker seismic reflection signals sought for study.

In the art, Ruehle, United States Patent No. 4,486,865, discloses a technique for reducing ghosting wherein a pressure detector and a particle velocity detector are positioned in close proximity to one another in the water. The output of at least one of the detectors is gain-adjusted and filtered, using a deconvolution operation having
30 a predetermined amount of white noise to the zero lag of the autocorrelation function. The patent suggests that, by adding this deconvolved/gain-adjusted signal to the output of the other detector, ghost reflections may be cancelled.

Haggerty, United States Patent No. 2,757,356, discloses a marine seismic reflection surveying system in which two seismometer spreads are disposed at two distinct depths in the water such that water column reverberations received by them are 180 degrees out of phase. By combining the output of the detectors, the patent suggests that the reverberations will cancel.
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Berni, United States Patent No. 4,345,473, suggests the use of a vertical component accelerometer in combination with a hydrophone for cancelling surface-reflected noise in marine seismic operations.

Gal'perin, "Vertical Seismic Profiling", Special Publication No. 12 of the Society of Exploration Geophysicists, suggests the use of a seismic detector which combines the output of a pressure and velocity sensor for
40 use in VSP surveying.

EP-A-0089700 refers to a marine seismic method (and system) which reduces the effect of surface reflection, employing a sensing of both the pressure waves and the motion of the water particles.

45 US-A-4752916 describes a method (and system) for removing the effect of the source wavelet from seismic data measuring both the pressure field and the particle velocity.

While the aforementioned prior art techniques may be effective under certain circumstances, none is considered adequate for use in water-bottom cable surveying in deep water operations, i.e., surveys in depths greater than 15.2 to 30.5 m (50 - 100 feet). Moreover, techniques of the type proposed in the Ruehle patent suffer losses in signal quality inherent to the filtering process, for example, amplification of noise in certain
50 frequencies.

Accordingly, an object of this invention is to provide an improved system for marine seismic reflection prospecting, especially (but not exclusively) for marine seismic prospecting capable of attenuating coherent noise resulting, for example, from water column reverberation.

55 According to the present invention, there is provided a method of geophysical prospecting in water covered areas, comprising the steps of:

- A. generating a seismic wave for reflection from earth strata;
- B. detecting water pressure at a first position in the water resulting from said seismic wave and generating a signal representative thereof;

C. detecting water velocity at a position substantially near said first position resulting from said seismic wave and generating a signal representative thereof; and characterised by

D. generating an enhanced seismic reflection signal by multiplying at least one of said water pressure-representative signal and the water velocity-representative signal by a scale factor dependent upon an acoustical impedance of a substance through which said seismic wave travels, and by summing said scaled water velocity-representative and water pressure-representative signals, said enhanced seismic reflection signal being substantially free of at least downwardly-propagating components of reverberation of said seismic wave within the water.

In the method of the invention, the coherent noise is reduced by applying a scale factor to the output of a pressure transducer and a particle velocity transducer positioned substantially adjacent one another in the water. The transducers can be positioned at a point in the water above the bottom and, thereby, eliminate downgoing components of reverberation, or they can be positioned at the bottom of the water and thereby eliminate both upgoing and downgoing components of the reverberation.

The scale factor, which derives from the acoustical impedance of the water or water-bottom material, can be determined both deterministically and statistically. The former involves measuring and comparing the responses of the pressure and velocity transducers to a pressure wave induced in the water. The latter involves comparing the magnitude of the pressure signal autocorrelation to the pressure and velocity signal crosscorrelation at selected lag values or, alternatively, comparing the magnitude of the pressure signal autocorrelation to the velocity signal autocorrelation at selected lag values.

The water velocity-representative and water pressure-representative signals can be scaled by multiplying at least a selected one of them by a scale factor dependent upon an acoustical impedance of the water. The scaled signals are then summed to produce the so-called enhanced seismic reflection signal.

According to one aspect of the invention, this scale factor can be expressed as $(\rho' \alpha' / \text{Dir}_{\text{corr}}) * (G_p / G_v)$, where ρ' is a density of the water; α' is a velocity of propagation of the seismic wave in the water; G_p is a transduction constant associated with the water pressure detecting step (e.g. a transduction constant of the transducer with which the water pressure is recorded); G_v is a transduction constant associated with the water velocity detecting step (e.g. a transduction constant of the transducer with which the particle velocity is detected); and Dir_{corr} is a directivity correction factor associated with an angle of propagation of the seismic wave in the water.

According to another aspect of the invention, the directivity correction factor, Dir_{corr} , is expressed as a function of γ_p' , the angle of propagation from vertical of the seismic wave in the water. Here, Dir_{corr} is equal to $\cos(\gamma_p')$ for γ_p' less than a selected critical angle and, otherwise, is equal to 1. The critical angle is a function of the propagation velocity of the seismic wave and is substantially equal to $\arcsin(\alpha' / \alpha)$; where (α') is the velocity of propagation of the seismic wave in the water and (α) is a velocity of propagation of the seismic wave in an earth material at said water's bottom.

In another aspect, the invention provides a method for seismic reflection prospecting in water covered areas in which the water pressure and particle velocity signals are generated by detectors placed on, or substantially near, the water's bottom. As above, the pressure and velocity measured by those detectors can be scaled and summed to produce an enhanced seismic reflection signal. Here, however, the scale factor depends upon an acoustical impedance of a solid earth material at the water's bottom and is defined by the term $(\rho \alpha / \text{Dir}_{\text{corr}}) * (G_p / G_v)$, where (ρ) is the density of the earth material at the water's bottom; (α) is the propagation velocity of the seismic wave in that earth material; and Dir_{corr} , G_p and G_v are defined as above.

The aforementioned scale factor can be determined statistically or deterministically. The former involves determining the ratio of a selected lag of the autocorrelation of the water pressure to a selected lag of crosscorrelation of the water pressure and water velocity at selected lag values or, preferably, determining the ratio of a selected lag of the autocorrelation of the water pressure to a selected lag of the water velocity. The selected lags can correspond, for example, to a time of two-way travel of seismic wave through said water between the position at which the pressure and velocity detectors reside and the water's surface. Preferably, however, the selected lag is zero.

Derivation of the scale factor deterministically involves generating a pressure wave from a position above the sensor point (i.e. the point at which the pressure and particle velocity readings are taken during seismic data collection). The scale factor can then be derived from the ratio of the absolute values of the pressure and particle velocity magnitudes at the sensor point during selected arrivals, e.g. the first arrival of that pressure wave.

In order that the invention may be more fully understood, reference is made to the accompanying drawings, wherein:

Figure 1 depicts a preferred embodiment of marine seismic reflection prospecting system constructed in accord with the invention;

Figure 2 outlines a preferred operating sequence for a marine seismic reflection system of the type shown

in Figure 1;

Figure 3 depicts a cube of matter through which a pressure wave travels;

Figure 4 depicts a simplified physical model of an environment in which the invention operates;

Figure 5 depicts pressure and velocity waveforms arriving at a detector shown in Figure 4;

5 Figure 6 depicts the waveforms of Figure 5 modified for detectors placed at the bottom of the water (e.g. at the sea-bed);

Figure 7 depicts a preferred operating sequence for determining a scale factor in a system constructed in accord with a preferred practice of the invention;

Figures 8 - 10 depict further simplified physical models of an environment in which the invention operates;

10 Figure 11 depicts pressure and velocity waveforms arriving at a detector shown in Figures 8 - 10;

Figure 12 depicts the waveforms of Figure 11 modified for detectors placed at the bottom of the water (e.g. at the sea-bed);

Figure 13 is a table of physical constants; and

15 Figures 14 - 15 depict preferred configurations of elements used in an apparatus constructed in accord with the invention.

Figure 1 depicts a preferred marine seismic reflection prospecting system constructed in accord with the invention and having a hydrophone/geophone sensor pair disposed above the water bottom. In the illustration, a marine craft 14 tows a seismic source 16 and streamer 18 through a body of water 10, e.g., a lake or ocean, overlying a portion of the earth's surface 12 to be studied. The source 16 is preferably an acoustic energy source, e.g., an explosive device or compressed air gun, constructed and operated in a manner conventional to the art.

20 Illustrated streamer 18 includes sensor 22, including a hydrophone for detecting water pressure and a geophone for detecting water particle velocity. The streamer 18 and its accompanying hydrophone/geophone pair 22 are constructed and operated in a manner conventional to the art. In this regard, it will be appreciated, for example, that whereas only one sensor 22 is shown, in practice the streamer 18 could include a plurality of such units.

According to a preferred practice, the streamer 18 and hydrophone/geophone pair 22 are positioned on the water's bottom. Such an arrangement is ideal for use in three dimensional "bottom-cable" operations, where a long cable with sensors is deployed on the bottom 12, and a set of parallel lines, or swath, is shot with an airgun source 16. When the swath of shot lines is completed, the bottom cable 18 is retrieved and redeployed in a line displaced from, but parallel to, the previous location. There, another swath of shot lines is shot.

30 More particularly, a cable 18 with identical spatial arrays of hydrophones and geophones, with each individual hydrophone having a gimbaled geophone positioned next to it, is deployed on the water bottom. A separate electrical signal is sent to the recording system for each hydrophone and each geophone spatial array. The marine vessel 14 fires source 16 at predetermined locations while the signals from the hydrophone and geophone arrays are recorded. These data are referred to as reflection data.

35 Preferably, before the water-bottom cable is retrieved and redeployed, the shooting vessel 14 makes one traverse directly over the cable 18, shooting the marine seismic source 16 directly over each spatial array of hydrophones and geophones, e.g., pair 22, or as close thereto as practical. The resulting signals from the two arrays directly below the source are recorded. These data are referred to as calibration data.

40 In accord with this preferred practice, the recorded hydrophone and geophone reflection data are demultiplexed, gain-removed and amplitude recovered using identical amplitude recovery curves. Here, the gain-removal process properly uses the K-gain settings of the recording instruments.

45 The calibration data are also demultiplexed and gain-removed. Here, again, the gain-removal process properly uses the K-gain settings of the recording instruments. The particle velocity component of the geophone reflection and calibration data are then multiplicatively scaled by a factor

$$(G_p/G_v)(\rho')(\alpha')$$

where

50 G_p = hydrophone array transduction constant in units, for example, of volts/Newton/square meter
 G_v = geophone array transduction constant (volts/meter/second)
 ρ' = density of water (kilograms/cubic meter)
 α' = sound velocity of water (meters/second)

55 The illustrated system uses a filter designed in accord with the theoretical or measured impulse responses of the hydrophones and geophones to convert the phase spectrum and normalized amplitude spectrum of the geophone to match that of the hydrophone, or vice versa. This filter is applied to every trace of the reflection and calibration geophone data or the hydrophone data subsequent to scaling.

In further accord with a preferred practice, a scale factor K is determined from the calibration data for each

receiver station (I) by dividing the hydrophone first-arrival peak amplitude by the geophone first-arrival peak amplitude and taking the absolute value of the resultant value. Then, for each pair of traces recorded at receiver location (I), the geophone trace is multiplied by a factor K (not to be confused with the "K-gain" of the transducers) and added to the hydrophone trace.

5 The resulting data are then processed in the manner conventional to the art for water-bottom cable data.

According to another preferred practice, the factor K is calculated as the absolute value of the geophone first-arrival peak divided by the hydrophone first-arrival peak. Here, K is multiplied by the hydrophone trace prior to adding it to the geophone trace.

10 In another preferred practice, the factor K applied to the geophone traces is determined statistically, i.e., from the hydrophone and geophone reflection data. Using portions of traces where clean, vertical reflections are evident or, using stacked traces, K is estimated by way of any of the following expressions:

$$\begin{aligned} K &= \Phi_{pp}(0)/\Phi_{vv}(0) \\ K &= (-\Phi_{pp}(2d/\alpha')/\Phi_{vv}(2d/\alpha'))^{1/2} \\ K &= -\Phi_{pp}(2d/\alpha')/\Phi_{pv}(2d/\alpha') \end{aligned}$$

15 where

Φ_{pp} = autocorrelation function of a hydrophone trace

Φ_{vv} = autocorrelation function of a geophone trace

Φ_{pv} = crosscorrelation function of a hydrophone and geophone trace

d = water depth (meters)

20 α' = sound velocity in water (meters/second)

According to yet another preferred practice, if the calibration data were not shot and the signal-to-noise ratio of the data is too poor for the above method using autocorrelation and crosscorrelation functions to yield stable values of K, the factor K is determined as follows. Geophone traces are multiplied by a range of potential, or candidate, factors, K, and added to their respective hydrophone traces. The resulting data is then stacked. 25 Autocorrelation functions and amplitude spectra of the stacked data sets are computed and displayed. By iteratively performing these steps, an optimal value of K can be determined which minimizes the effects of the water-column reverberations.

Referring again to Figure 1, during data collection, seismic waves generated by seismic source 16 travel downward, as indicated by rays 30 and are reflected off earth strata 26, 28 or, more particularly, off the inter- 30 face 36 between those strata. The upwardly reflected waves 32 travel past the area occupied by the streamer 18 to the water's surface 38. During their first, or primary, passing the waves 32 are detected by the sensor 22 which generates electrical signals representative of pressure and particle velocity changes inherent to the wavefield and transmit those signals back to the vessel 14 for recording and processing.

35 Upon striking the water/air interface 38, most of the energy in the wavefield 32 is reflected back toward the water bottom 12, as indicated by rays 34, resulting in a second, downwardly travelling set of reflection data, or ghosts. These ghost reflections once again pass through the area occupied by the streamer 18, causing the hydrophone/geophone pair 22 to generate a further set of electrical signals. Depending upon the nature of the earth material at the water's bottom 12, a significant portion of the energy in the ghost reflections striking the water's bottom may once again be reflected back upward, creating a further ghost wavefield (not shown). 40 In addition, the water 10 often carries reverberant wavefields of trapped coherent energy, e.g., excess energy or noise generated by source 16 and by marine craft 14. This energy, which is not shown in the illustration, also reverberates in the manner discussed above between water surface 38 and bottom 12.

Because the ghost reflections and trapped coherent energy tend to overlap, or interfere with, the primary reflections, raw marine seismic reflection data is difficult to interpret. Whereas prior art schemes such as those 45 disclosed in the Ruehle patent have focused on the use of filtering schemes to eliminate ghost reflection data, the inventor named herein has discovered that coherent noise (both trapped and ghost) can be reduced by applying a selected scale factor to the outputs of a pressure transducer and a particle velocity transducer positioned substantially adjacent one another and, preferably, on the water's bottom. The scale factor, which can be derived from the acoustical impedance of the water or water-bottom material, may be determined either 50 deterministically and statistically, as discussed more fully below.

Figure 2 outlines a preferred operating sequence for a marine seismic reflection system of the type shown in Figure 1. In step 40, seismic source 16 generates an acoustic wave for transmission through the water and reflection from earth strata 26, 28. Wavefields representing primary and ghost reflections, as well as those coherent noise, travel through the water and past the streamers, where they are detected by hydrophone/ge- 55 ophone pair 22, step 42. The pair generates a water pressure-representative signal and a particle velocity-representative signal for recording and processing according to the teachings provided herein. The hydrophone/geophone pair 22 may be positioned anywhere in the water and, preferably, on or near the water's bot-

tom 12.

In steps 44 and 46, the system generates an enhanced seismic reflection signal representing a selected linear combination of the water pressure and the water velocity. In embodiments where the pressure and particle velocity detectors are positioned at a point above the water's bottom, this enhanced seismic reflection signal is characterized as being substantially free of at least downwardly-propagating components of reverberation of said seismic wave within the water. In preferred embodiments, where those detectors are positioned at the water's bottom, the enhanced seismic reflection signal is characterized as being substantially free of both upwardly and downwardly propagating components of reverberation.

More particularly, in step 44, the system scales the water pressure-representative signal and the particle velocity-representative signal by multiplying at least one of them by a scale factor dependent on

a) the acoustical impedance of the water, if the hydrophone/geophone pair is positioned at a point in the water 10 above the bottom 12; and

b) the acoustical impedance of the earth material 26 at the water's bottom, if the hydrophone/geophone pair is positioned on the bottom 12.

Preferably, the system executes step 44 by multiplying the recorded particle velocity function by a scale factor as derived below and by multiplying the measured pressure function by one.

A scale factor, determined in step 48, for use in conjunction with a hydrophone/geophone pair positioned at a point in the water above the bottom is

$$(\rho' \alpha' / \text{Dir}_{\text{corr}}) * (G_p / G_v)$$

where ρ' is a density of the water; α' is a velocity of propagation of the seismic wave in the water; G_p is a transduction constant associated with the water pressure detecting step (e.g., a transduction constant of the transducer with which the water pressure is recorded); G_v is a transduction constant associated with the water velocity detecting step (e.g., a transduction constant of the transducer with which the particle velocity is detected); and Dir_{corr} is a directivity correction factor associated with an angle of propagation of the seismic wave in the water.

A preferred sequence for computing the scale factor is described below in conjunction with Figure 7.

The aforementioned directivity correction factor, Dir_{corr} , is expressed as a function of γ_p' , the angle of propagation from vertical of the seismic wave in the water. Here, Dir_{corr} is equal to $\cos(\gamma_p')$ for γ_p' less than a selected critical angle and, otherwise, is equal to 1. The critical angle is a function of the propagation velocity of the seismic wave and can be substantially equal to $\arcsin(\alpha' / \alpha)$, where (α') is the velocity of propagation of the seismic wave in the water and (α) is a velocity of propagation of the seismic wave in an earth material at said water's bottom.

A preferred sequence for calculating the aforementioned directivity correction factor is shown in steps 50 - 54 of Figure 2. Particularly, in step 50, the system determines the critical angle. As indicated above, this angle is determined by computing $\arcsin(\alpha' / \alpha)$.

A preferred scale factor for use in conjunction with a hydrophone/geophone pair positioned at the water bottom is

$$(\rho \alpha / \text{Dir}_{\text{corr}}) * (G_p / G_v)$$

where (ρ) is the density of the earth material at the water's bottom; (α) is the propagation velocity of the seismic wave in that earth material; and Dir_{corr} , G_p and G_v are defined as above.

Figure 14 depicts a preferred configuration of elements in a system constructed in accord with the invention and operating with the method shown in Figure 2. The system 88 includes stores 90 and 92 for retaining pressure-representative and particle velocity-representative signals generated by hydrophone/geophone pair 22. Element 94 scales the pressure and/or velocity signal as described above in conjunction with step 44 (Figure 2). Element 96 sums the scaled pressure and velocity signal as discussed above in conjunction with step 46 (Figure 2). The system 88 further includes element 98 for determining a directivity correction factor as discussed above in conjunction with steps 50 and 52. That correction factor is multiplied, in accord with the teachings provided herein, as indicated over the data flow path indicator connecting elements 98 and 94. System 88 further includes element 100 for determining a scale factor in the manner discussed above in conjunction with step 48, above.

An apparatus constructed in accord with Figure 14 and operating according to the method of Figure 2 can be implemented in special purpose hardware using implementation techniques conventional to the art. Preferably, however, such apparatus is implemented on a general purpose digital data processor having conventional seismic data processing software tools. One preferred package of software tools is commercially available from the assignee hereof under the mark "TIPEX."

A further understanding of the invention and, more particularly, the aforementioned scale factor, may be attained by reference to the discussion which follows.

Relationship Between Upward and Downward Travelling Pressure and Particle Velocity Waves

In order to understand the relationship between upward and downward traveling pressure and particle velocity fields, it is helpful to focus on a very small cube of matter 60, as shown in Figure 3.

5 In this figure, the ray marked p_{zz} indicates the stress (pressure) acting in the outward direction from the cube 60 and in the direction of the z-axis 62. As shown, the net force operating on the cube in the +z direction may be expressed as follows

$$F_z = (p_{zz} + (\partial p_{zz}/\partial z)\Delta z)\Delta x\Delta y - p_{zz}\Delta x\Delta y$$

$$F_z = (\partial p_{zz}/\partial z)\Delta x\Delta y\Delta z$$

10 The mass of the cube 60 may be expressed as

$$m = \rho\Delta x\Delta y\Delta z$$

where ρ is the density of the cube

While, the acceleration of the cube in the +z direction may be expressed as

$$a_z = \partial v_z/\partial t$$

15

Since

$$F_z = ma_z$$

then

$$\partial p_{zz}/\partial z = \rho(\partial v_z/\partial t)$$

20

As used herein, compression is expressed as a positive pressure pulse, accordingly

$$p = -p_{zz}$$

since p_{zz} causes a rarefaction; where p is a scalar value.

25 Likewise, with respect to a geophone sitting upright on the xy plane of Figure 3, as used herein a positive velocity pulse will be expressed as a "bump" in the -z direction. Accordingly,

$$v = -v_z$$

Substituting this into the above,

$$\partial p/\partial z = \rho(\partial v/\partial t) \quad [\text{Eq. 1-1}]$$

30

Figure 4 depicts a simplified physical model of the environment in which the invention is practiced. More particularly, the illustration shows the air 66, water 10 and solid earth material 26 below the water bottom 12. Hydrophone/geophone pair 22 is shown in the water at a point above the water bottom 12. For purposes of the immediate discussion, it is assumed that plane waves vary in the direction of the x-axis 64 and the z-axis 62, but not in the direction of the y-axis.

35

For convenience, in the illustration $z=0$ is shown to be at water bottom 12. The water 10 depth is equal to (d) and the detector 22 is z_d meters above the water bottom.

A plane pressure wave traveling in the -z direction in the solid can be expressed as

$$p_u = \delta(t + (z/\alpha))$$

where $\delta(t)$ represents the Dirac delta function.

40

Likewise, a pressure wave traveling in the +z direction in the solid may be expressed as

$$p_d = \delta(t - (z/\alpha))$$

Using [Eq. 1-1] to determine the corresponding particle velocity plane waves

$$\partial v_u/\partial t = (1/\rho)(\partial p_u/\partial z) = (1/\rho\alpha)\delta'(t + (z/\alpha))$$

$$v_u = (1/\rho\alpha)\delta(t + (z/\alpha))$$

45

Likewise,

$$v_d = -(1/\rho\alpha)\delta(t - (z/\alpha))$$

So, from the foregoing, the relationships necessary to develop the responses of detectors 22 (i.e., a hydrophone/geophone pair) to vertically propagating waves are:

50

For the solid material 26 at the water's bottom:

55

$$p_u = \delta(t + (z/\alpha))$$

$$v_u = (1/\rho\alpha)\delta(t + (z/\alpha))$$

[Eq. 1-2]

$$p_d = \delta(t - (z/\alpha))$$

$$v_d = -(1/\rho\alpha)\delta(t - (z/\alpha))$$

For the water 10:

$$p_u' = \delta(t + (z/\alpha'))$$

$$v_u' = (1/\rho'\alpha')\delta(t + (z/\alpha'))$$

[Eq. 1-3]

$$p_d' = \delta(t - (z/\alpha'))$$

$$v_d' = -(1/\rho'\alpha')\delta(t - (z/\alpha'))$$

Detector Responses to Reflections at Arbitrary Height Above Water Bottom

A vertically traveling reflection wavefield in the solid 26 of Figure 4 can be represented as

$$p_u = \delta(t + (z/\alpha))$$

This implies that $t=0$ corresponds to the instant the wave arrives at the water-bottom 12, i.e., at $z=0$.

Of course, a portion of the pressure wave will be reflected back in the $-z$ direction. Therefore,

$$p_d = R'\delta(t - (z/\alpha))$$

where $R' = (\rho'\alpha' - \rho\alpha)/(\rho'\alpha' + \rho\alpha)$

and is defined as the normal incidence reflection coefficient

At the instant an incident wave strikes the water-bottom 12, the pressure field on the solid side of the solid/water interface is

$$p = p_u + p_d = (1 + R')\delta(t)$$

To avoid infinite acceleration of molecules at the solid/water interface, the pressure field on the water side of the interface must equal that on the solid side, at that instant of time. Accordingly, the amplitude of the transmitted pressure wave in the water is equal to $1+R'$.

Therefore,

$$p_u' = (1 + R')\delta(t + (z/\alpha'))$$

$$p_u' = T\delta(t + (z/\alpha'))$$

where T is the normal incidence transmission coefficient and equals $1+R'$

From [Eq. 1-3], the corresponding particle velocity wave is

$$v_u' = (1/\rho'\alpha')T\delta(t + (z/\alpha'))$$

Since the detectors 22 are located at an arbitrary distance z_d meters above the water-bottom, these waves will arrive at the detectors 22 at $t = (z_d/\alpha')$ seconds. The outputs of the pressure and velocity detectors can, accordingly, be expressed as

$$p(t) = T\delta(t - (z_d/\alpha'))$$

[Eq. 2-1]

$$v(t) = (T/\rho'\alpha')\delta(t - (z_d/\alpha'))$$

Note that [Eq. 2-1] does not take into account the transduction constants of the pressure and velocity detectors, nor any differences in their response characteristics to their respective fields. The use of these transduction constants is discussed below.

Referring to [Eq. 2-1], it will be appreciated that for a vertically arriving reflection pulse, the pressure and velocity signals are in phase; their relative amplitudes are related only by the acoustic impedance of the water ($\rho'\alpha'$); and, with some qualification, these two observations are true independent of the value of z .

Returning to Figure 4, an upward traveling pressure wave will continue until it encounters the air/water interface (i.e., the interface between the water 10 and the air 66). This interface has a reflection coefficient equal to -1. Accordingly, the pressure wave is reflected downward, in its entirety, and its sign is changed, i.e. from a compression pulse to a rarefaction pulse.

Therefore, the initial downwardly travelling component of the pressure wave can be represented by the equation

$$p_d' = -T\delta(t - ((2d - z)/\alpha'))$$

and, from [Eq. 1-3], the downwardly travelling component of the velocity wave can be represented by the equation

$$v_d' = (T/\rho'\alpha')\delta(t - ((2d - z)/\alpha'))$$

These waves will strike detectors 22 at

$$t = (2d - z_d)/\alpha'$$

Accordingly, these signals can be added to [Eq. 2-1] to produce the outputs:

$$p(t) = T\delta(t - (z_d/\alpha')) - T\delta(t - ((2d - z_d)/\alpha'))$$

[Eq. 2-2]

$$v(t) = (T/\rho'\alpha')\delta(t - (z_d/\alpha')) + (T/\rho'\alpha')\delta(t - ((2d - z_d)/\alpha'))$$

where, [Eq. 2-2] represents responses to the initial upwardly-travelling and downwardly-travelling components of the pressure and particle velocity waves.

The downward-traveling pressure and velocity waves continue until they again encounter the water-bottom interface 12, which is represented by the reflection coefficient

$$R = (\rho\alpha - \rho'\alpha')/(\rho\alpha + \rho'\alpha')$$

Accordingly, the reflected pressure wave becomes

$$p_u' = -RT\delta(t + ((2d + z)/\alpha'))$$

and from [Eq. 1-3]

$$v_u' = -(RT/\rho'\alpha')\delta(t + ((2d + z)/\alpha'))$$

These waves encounter detectors 22 at time

$$t = (2d + z_d)/\alpha'$$

[Eq. 2-2] can be updated to include these new signals, i.e., to represent the initial upwardly-travelling and downwardly-travelling components as well as the subsequent upwardly-travelling wave, as follows:

$$\begin{aligned} p(t) &= T\delta(t - (z_d/\alpha')) - T\delta(t - ((2d - z_d)/\alpha')) \\ &\quad - RT\delta(t - ((2d + z_d)/\alpha')) \\ v(t) &= (T/\rho'\alpha')\delta(t - (z_d/\alpha')) \\ &\quad + (T/\rho'\alpha')\delta(t - ((2d - z_d)/\alpha')) \\ &\quad - (RT/\rho'\alpha')\delta(t - ((2d + z_d)/\alpha')) \end{aligned}$$

The above process continues ad infinitum, and the signals $p(t)$ and $v(t)$ can be illustrated in Figure 5.

Referring to Figure 5, it is evident that if the detectors 22 are disposed at a position above the water bottom, i.e., $z_d < d$, $v(t)$ can be scaled by $\rho'\alpha'$ and added to $p(t)$ to yield the sum signal, $s(t)$ as follows

$$\begin{aligned} s(t) &= p(t) + \rho'\alpha'v(t) \\ s(t) &= 2T\delta(t - (z_d/\alpha')) - 2RT\delta(t - ((2d - z_d)/\alpha')) \\ &\quad + 2R^2T\delta(t - ((4d - z_d)/\alpha')) - \dots \end{aligned}$$

Comparing this to $p(t)$, it is evident that all downwardly propagating components of the reverberations have been eliminated. While, the upward propagating components remain.

It is, accordingly, seen that a marine prospecting system of the type depicted in Figure 1 and constructed in accord with one preferred practice of the invention, where the detectors 22 are positioned above the water's bottom, can eliminate downwardly travelling components of coherent reverberations if the pressure function is added to the velocity function, where the latter is scaled by $\rho'\alpha'$.

Detector Responses to Reflection at the Water Bottom

If the detectors 22 are disposed at the water bottom 12, i.e., at $z_d=0$, the pressure and particle velocity waves are modified, as shown in Figure 6. Upon substitution of the corresponding values into the prior sum equation yields

$$s(t) = p(t) + \rho'\alpha'((1+R)/(1-R))v(t)$$

and

$$s(t) = T\{1 + ((1+R)/(1-R))\}\delta(t)$$

Here, it is seen that all the reverberations due to the reflection wavelet, both upgoing and downgoing, are eliminated. However, the scale factor for $v(t)$, K , must be expressed as follows

$$K = \rho'\alpha'((1+R)/(1-R))$$

$$K = \rho'\alpha'(\rho\alpha + \rho'\alpha' + \rho\alpha - \rho'\alpha')/(\rho\alpha + \rho'\alpha' - \rho\alpha + \rho'\alpha')$$

$$K = \rho\alpha$$

Since K depends on the acoustic impedance of the water-bottom material, a system constructed in accord with the invention must consider K to be a variable from survey area to survey area, and probably for each received group within a survey area.

If, instead, $(\rho'\alpha')$ were used to scale $v(t)$, then

$$s(t) = 2T\delta(t) - 2RT\delta(t - (2d/\alpha'))$$

$$+ 2R^2T\delta(t - (4d/\alpha')) - \dots$$

which is identical to [Eq. 2-3] with $z_d=0$.

Calibration Methods

Figure 7 depicts a preferred processing sequence for determining the aforementioned scale factor deterministically and statistically. In the illustration, steps 70, 72 and 74 indicate a decision to determine the scale factor by one or both methods. While the deterministic method, which requires the sounding and measurement of transducer responsiveness, is preferred, the statistical method based on ratios of the pressure and particle velocity autocorrelations and crosscorrelations can also be used. Those skilled in the art will appreciate, of course, that both methods can be used in combination.

According to the statistical method 72, a marine seismic reflection system constructed in accord with the invention computes the autocorrelation of the pressure at a selected lag; see step 76. The system also computes the autocorrelation of the velocity at a selected lag; see step 77. Alternatively, the system computes the crosscorrelation of the pressure and particle velocity at a selected lag to wit, the two-way travel time of the seismic wave in the water column; see step 78. Preferably, the lags for the computations of steps 76 and 77 are zero. However, the lags for this combination can also be equal to the two-way travel time of the seismic wave between the sensor 22 and the water surface. In step 80, the system preferably divides the pressure autocorrelation by the velocity autocorrelation or, alternatively, the system divides the pressure autocorrelation by the pressure-velocity crosscorrelation.

In the discussion which follows, it is assumed that the velocity signal has been multiplied by the factor $(G_p/G_v)(\rho'\alpha')$

Mathematically, the autocorrelation/crosscorrelation ratio is expressed as follow.

$$\Phi_{pp}(\pm 2d/\alpha') = T^2\{-(1+R) - R(1+R)^2 - R^3(1+R)^2 - \dots\}$$

$$\Phi_{pv}(2d/\alpha') = T^2\{(1-R) + R(1-R^2) + R^3(1-R^2) + \dots\}$$

Therefore

$$\frac{-\Phi_{pp}(\pm 2d/\alpha')}{\Phi_{pv}(2d/\alpha')} = \frac{(1+R) + R(1+R)^2 + R^3(1+R)^2 + \dots}{(1-R) + R(1-R^2) + R^3(1-R^2) + \dots}$$

$$= \frac{1 + 2R + 2R^2 + 2R^3 + 2R^4 + \dots}{1 - R + R - R^3 + R^3 \dots}$$

$$= \frac{1 + 2R + 2R^2 \dots}{1}$$

$$= \frac{1+R}{1-R}$$

which is equal to the required scale factor for $v(t)$.

Mathematically, the ratio of the pressure and velocity autocorrelations at zero lag is expressed as follows.

$$\Phi_{pp}(0) = T^2\{1 + (1+R)^2 + R^2(1+R)^2 + R^4(1+R)^2 + \dots\}$$

$$\Phi_{vv}(0) = T^2\{1 + (1-R)^2 + R^2(1-R)^2 + R^4(1-R)^2 + \dots\}$$

Forming the ratio of these two values yields

$$\begin{aligned} \frac{\Phi_{pp}(0)}{\Phi_{vv}(0)} &= \frac{1 + (1+R)^2 + R^2(1+R)^2 + R^4(1+R)^2 + \dots}{1 + (1-R)^2 + R^2(1-R)^2 + R^4(1-R)^2 + \dots} \\ &= \frac{1+R+R^2+R^3+R^4+R^5+R^6+\dots}{1-R+R^2-R^3+R^4-R^5+R^6-\dots} \\ \frac{\Phi_{pp}(0)}{\Phi_{vv}(0)} &= \frac{1+R}{1-R} \end{aligned}$$

Accordingly, K is obtained as follows:

$$K = (\Phi_{pp}(0)/\Phi_{vv}(0))$$

Further, the ratio of the pressure wave autocorrelation to the velocity wave autocorrelation at a lag equal to the two-way travel time of the seismic wave in the water column may be expressed mathematically as follows.

$$\Phi_{pp}(\pm 2d/\alpha') = T^2\{-(1+R) - R(1+R)^2 - R^3(1+R)^2 - \dots\}$$

$$\Phi_{vv}(\pm 2d/\alpha') = T^2\{(1-R) - R(1-R)^2 - R^3(1-R)^2 - \dots\}$$

Forming the following ratio:

$$\begin{aligned} \frac{-\Phi_{pp}(\pm 2d/\alpha')}{\Phi_{vv}(\pm 2d/\alpha')} &= \frac{(1+R) + R(1+R)^2 + R^3(1+R)^2 + \dots}{(1-R) - R(1-R)^2 - R^3(1-R)^2 - \dots} \\ &= \frac{1+2R+2R^2+2R^3+2R^4+\dots}{1-2R+2R^2-2R^3+2R^4-\dots} \\ \frac{-\Phi_{pp}(\pm 2d/\alpha')}{\Phi_{vv}(\pm 2d/\alpha')} &= [(1+R)/(1-R)]^2 \end{aligned}$$

Therefore

$$K = [-\Phi_{pp}(\pm 2d/\alpha')/\Phi_{vv}(\pm 2d/\alpha')]^{1/2}$$

According to the deterministic method 74, a seismic energy source 16 is used to generate a pressure wave at a point disposed directly above the location of the sensor 22 in the water; see step 82. The output of the pressure and particle velocity detectors of the sensor 22 are then measured at a selected arrival of the resulting pressure wave; see step 84. A ratio of this measured pressure signal to the particle velocity signal is then used as the aforementioned scale factor; see step 86.

Figure 15 depicts a preferred configuration of elements 102 used for determining a scale factor in a system constructed and operated in accord with the invention.

In the configuration, statistical determinations are handled by elements 104-112 which are implemented to carry out the processes described above in conjunction with 72 and 76-80 (Figure 7). More particularly, the illustrated configuration 102 includes element 102 for routing data and controlling the other scale factor-determining elements, e.g., elements 104-120. Illustrated element 104 selectively determines an autocorrelation of the particle velocity signal. Element 106 selectively determines a crosscorrelation of the pressure and particle velocity signals, while element 108 selectively determines an autocorrelation of the pressure signal. The output of the autocorrelation and crosscorrelation elements 104-108 is routed through multiplexor 110 which selectively routes the appropriate values to element 112 for ratio calculations.

In the configuration, deterministic determinations are handled by elements 114-120 which are implemented to carry out the processes described above in conjunction with steps 74 and 82-86 (Figure 7). More particularly, the illustrated apparatus 102 includes elements 114 and 116 for identifying a selected arrival of the pressure wave, as described above in conjunction with step 84 (Figure 7). The apparatus also includes element 120 for determining a ratio of the arrival-representative signal, as described above in conjunction with step 86 (Figure 7).

An apparatus constructed in accord with Figure 15 and operating according to the method of Figure 7 can be implemented in special purpose hardware using implementation techniques conventional to the art. Preferably, however, such apparatus is implemented on a general purpose digital data processor having conventional seismic data processing software tools. One preferred package of software tools is commercially available from the assignee hereof under the mark "TIPEX."

General Angle-of-Incidence Analysis

Figure 8 depicts the environment of Figure 4 in a manner required to permit analysis of the more complicated case of a p-wave reflection A_1 arriving at the water-bottom at angle-of-incidence γ_p from vertical. In this and subsequent figures, rays marked with the letter A (or A' , etc.) denote p-waves, while those marked with the letter B denote s-waves.

In the discussion which follows, three types of water-bottom materials will be referred to as Normal, Hard and Soft. The physical properties for these three materials (and water) are contained in Figure 13.

For the Normal water-bottom, the following velocity relationships apply:

$$\alpha > \alpha' > \beta$$

Since the phase velocity of the arriving wave-front along the x-axis can be expressed as

$$C = (\alpha/\sin\gamma_p) = (\beta/\sin\gamma_s) = (\alpha'/\sin\gamma_p')$$

then

$$\begin{aligned} |c| &> \alpha > \alpha' > \beta \\ (\alpha/\sin\gamma_p) &> \alpha \\ \sin\gamma_p &< 1 \\ \gamma_p &< 90^\circ \end{aligned}$$

In like manner, the ranges of values for the angles γ_s and γ_p' can be determined, resulting in

$$\begin{aligned} 0 &< \gamma_p < 90^\circ \\ 0 &< \gamma_s < \sin^{-1}(\beta/\alpha) = 20.7^\circ \\ 0 &< \gamma_p' < \sin^{-1}(\alpha'/\alpha) = 61.9^\circ \end{aligned}$$

Using the method described by White in the text Seismic Waves - Radiation, Transmission, and Attenuation (McGraw-Hill, 1965), to which reference may be made for further details, scalar and vector displacement potential functions can be derived as solutions to the elastic wave equation, subject to the boundary conditions imposed by the model of Figure 8. From these potential functions, the pressure and particle velocity waves which will strike detectors 22 can be determined.

Using Whites' method, the following expressions are obtained for the pressure waves and particle velocity waves (in the-z direction) in the water:

$$p' = \rho' \omega^2 A_1' (e^{im'z}) (e^{-ilx}) (e^{i\omega t}) \quad [\text{Eq. 3-1}]$$

$$v' = \omega^2 ((1/\alpha'^2) - (1/c^2))^{1/2} A_1' (e^{im'z}) (e^{-ilx}) (e^{i\omega t})$$

where A_1' = displacement potential amplitude

$$\begin{aligned} m' &= \omega((1/\alpha'^2) - (1/c^2))^{1/2} \\ 1 &= \omega/c \\ c &= \alpha'/\sin\gamma_p' \end{aligned}$$

Substituting the location of the detectors 22 ($x=0, z=-z_d$) into the above expressions,

$$\begin{aligned} p' &= \rho' \omega^2 A_1' e^{i(\omega t - m'z_d)} \\ v' &= \omega^2 ((1/\alpha'^2) - (1/c^2))^{1/2} A_1' e^{i(\omega t - m'z_d)} \end{aligned}$$

Recalling that

$$m' = \omega((1/\alpha'^2) - (1/c^2))^{1/2}$$

Substituting

$$c = \alpha'/\sin\gamma_p'$$

into the above expression, the following are obtained

$$p' = \rho' \omega^2 A_1' e^{i\omega(t - (z_d/\alpha') \cos \gamma_p')}$$

[Eq. 3-2]

$$v' = (\omega^2/\alpha') \cos \gamma_p' A_1' e^{i\omega(t - (z_d/\alpha') \cos \gamma_p')}$$

The scalar potential function yielding these expressions for p' and v' indicates that they are frequency-domain representations of Dirac delta functions occurring at time

$$t = (z_d/\alpha') \cos \gamma_p'$$

They therefore correspond to the first arrivals of $p(t)$ and $v(t)$ of Figure 5.

It will be appreciated that the ratio of v' and p' is

$$v'/p' = \cos \gamma_p' / \rho' \alpha' \quad [\text{Eq. 3-3}]$$

which corresponds to the ratio of the amplitudes of the first arrivals in Figure 5. The additional cosine factor accounts for the directivity of the velocity detector.

The expression relating p' in the water to the incident pressure wave p is

$$p'/p = K_T$$

[Eq. 3-4]

$$K_T = (2(\rho' c^4)/\rho \beta^4) ((c^2/\alpha^2) - 1)^{1/2} / (A+B+C)$$

where

$$A = (\rho' c^4/\rho \beta^4) ((c^2/\alpha^2) - 1)^{1/2}$$

$$B = ((c^2/\alpha^2) - 1)^{1/2} ((c^2/\beta^2) - 2)^2$$

$$C = 4((c^2/\alpha^2) - 1)^{1/2} ((c^2/\alpha^2) - 1)^{1/2} ((c^2/\beta^2) - 1)^{1/2}$$

For normal incidence ($c \rightarrow \infty$), this expression reduces to the transmission coefficient T described above.

For the Hard water-bottom, the following velocity relationships apply:

$$\alpha > \beta > \alpha'$$

For

$$|c| > \alpha > \beta > \alpha'$$

the ranges of angles for the various reflected and refracted waves can be calculated. The results are

$$0 \leq \gamma_p \leq 90^\circ$$

$$0 \leq \gamma_s \leq \sin^{-1}(\beta/\alpha) = 33.8^\circ$$

$$0 \leq \gamma_p' \leq \sin^{-1}(\alpha'/\alpha) = 19.5^\circ$$

and the expressions of [Eq. 3-1]-[Eq. 3-4] also apply to the Hard water-bottom case.

The velocity relationships for the Soft water-bottom case are

$$\alpha' > \alpha > \beta$$

and for

$$|c| > \alpha' > \alpha > \beta$$

all the preceding expressions also apply.

The ranges of the angles for this condition are:

$$0 \leq \gamma_p \leq \sin^{-1}(\alpha/\alpha') = 53.1^\circ$$

$$0 \leq \gamma_s \leq \sin^{-1}(\beta/\alpha') = 13.9^\circ$$

$$0 \leq \gamma_p' \leq \sin^{-1}(\alpha'/\alpha') = 90^\circ$$

At this point, expressions for $p(t)$ and $v(t)$ corresponding to those of [Eq. 2-1] can be written as follows.

$$p(t) = K_T \delta(t - (z_d/\alpha') \cos \gamma_p') \quad [\text{Eq. 3-5}]$$

$$v(t) = (K_T \cos \gamma_p' / \rho' \alpha') \delta(t - (z_d/\alpha') \cos \gamma_p')$$

where K_T is given in [Eq. 3-4]

In the model, an upward-propagating reflection wave has encountered the detectors 22 at $z = -z_d$ and is preparing to strike the air/water interface. This is depicted in Figure 9 where, it will be noted, the origin of the coordinate system has been shifted to the surface of the water.

Solving the elastic wave equation subject to the boundary conditions imposed by this model, it is found that

$$A_2' = -A_1'$$

and

$$\begin{aligned} p' &= \rho' \omega^2 (A_1' e^{im'\zeta} - A_1' e^{-im'\zeta}) e^{-ilx_p' i \omega t} \\ v' &= \omega^2 ((1/\alpha'^2) - (1/c^2)) (A_1' e^{im'\zeta} + A_1' e^{-im'\zeta}) e^{-ilx_p' i \omega t} \\ m' &= \omega ((1/\alpha'^2) - (1/c^2))^{1/2} \\ 1 &= \omega/c \\ c &= \alpha' / \sin \gamma_p' \end{aligned}$$

Substituting the position of our detectors ($0, \zeta_d$), and $c = \alpha' / \sin \gamma_p'$ into the above expressions,

$$\begin{aligned} p' &= \rho' \omega^2 A_1' e^{i\omega(t + (\zeta_d/\alpha') \cos \gamma_p')} \\ &\quad - \rho' \omega^2 A_1' e^{i\omega(t - (\zeta_d/\alpha') \cos \gamma_p')} \end{aligned} \quad [\text{Eq. 3-6}]$$

$$\begin{aligned} v' &= (\cos \gamma_p' / \alpha') \omega^2 A_1' e^{i\omega(t + (\zeta_d/\alpha') \cos \gamma_p')} \\ &\quad + (\cos \gamma_p' / \alpha') \omega^2 A_1' e^{i\omega(t - (\zeta_d/\alpha') \cos \gamma_p')} \end{aligned}$$

It will be noted that the first term of p' and v' each represent a wave traveling in the $-\zeta$ direction (upward) and the second term a wave traveling in the $+\zeta$ direction (downward). It will also be noted that they are again frequency domain representations of Dirac delta functions.

The total time delay between the arrival of the above waves at our detectors is

$$\Delta t = (2\zeta_d/\alpha') \cos \gamma_p'$$

To relate this to the coordinate system of Figure 8, note that

$$\zeta = z + d$$

Therefore

$$\zeta_d = -z_d + d$$

and substituting above,

$$\Delta t = (2d - 2z_d/\alpha') \cos \gamma_p'$$

This represents the delay time between the arrival of the reflection of [Eq. 3-5] and the water surface ghost. Therefore, adding the time-domain representation of the downward-propagating components of [Eq. 3-6] to [Eq. 3-5] we obtain

$$p(t) = K_T \delta(t - (z_d/\alpha') \cos \gamma_p') - K_T \delta(t - ((2d - z_d)/\alpha') \cos \gamma_p') \quad [\text{Eq. 3-7}]$$

$$v(t) = (K_T \cos \gamma_p' / \rho' \alpha') \delta(t - (z_d/\alpha') \cos \gamma_p') + (K_T \cos \gamma_p' / \rho' \alpha') \delta(t - ((2d - z_d)/\alpha') \cos \gamma_p')$$

The downward-propagating wave is now ready to strike the water-bottom and to be partially reflected back toward our detectors. This model is shown in Figure 10.

Once again, solving the elastic wave equation,

$$p' = \rho' \omega^2 (-A_2' e^{im'z} - A_1' e^{-im'z}) e^{-ilx} e^{i\omega t}$$

$$v' = \omega^2 ((1/\alpha'^2) - (1/c^2))$$

$$(-A_2' e^{im'z} + A_1' e^{-im'z}) e^{-ilx} e^{i\omega t}$$

Substituting for the position of the detectors 22

$$p' = -\rho' \omega^2 A_2' e^{i\omega(t - (z_d/\alpha') \cos \gamma_p')} - \rho' \omega^2 A_1' e^{i\omega(t + (z_d/\alpha') \cos \gamma_p')} \quad [\text{Eq. 3-8}]$$

$$v' = (-\cos \gamma_p' / \alpha') \omega^2 A_2' e^{i\omega(t - (z_d/\alpha') \cos \gamma_p')} + (\cos \gamma_p' / \alpha') \omega^2 A_1' e^{i\omega(t + (z_d/\alpha') \cos \gamma_p')}$$

Here, the first term of p' and v' each represents the upward-propagating wave and the second term the downward. The time delay between the arrival of the two waves at our detectors is

$$\Delta t = (2z_d/\alpha') \cos \gamma_p'$$

Updating $p(t)$ and $v(t)$ in [Eq. 3-7] yields

$$p(t) = K_T \delta(t - (z_d/\alpha') \cos \gamma_p') - K_T \delta(t - ((2d - z_d)/\alpha') \cos \gamma_p') - K_R K_T \delta(t - ((2d + z_d)/\alpha') \cos \gamma_p') + \dots \quad [\text{Eq. 3-9}]$$

$$v(t) = (K_T \cos \gamma_p' / \rho' \alpha') \delta(t - (z_d/\alpha') \cos \gamma_p') + (K_T \cos \gamma_p' / \rho' \alpha') \delta(t - ((2d - z_d)/\alpha') \cos \gamma_p') - (K_R K_T \cos \gamma_p' / \rho' \alpha') \delta(t - ((2d + z_d)/\alpha') \cos \gamma_p') + \dots$$

where

$$K_R = A_2'/A_1'$$

The value of K_R depends upon the water-bottom material and the angle of incidence as follows:

Normal Water-Bottom

For the condition

$$|c| \geq \alpha \geq \alpha' \geq \beta$$

5 where

$$c = (\alpha/\sin\gamma_p) = (\alpha'/\sin\gamma_p') = (\beta/\sin\gamma_s)$$

$$10 \quad 0 \leq \gamma_p' \leq \sin^{-1}(\alpha'/\alpha) = 61.9^\circ$$

[Eq. 3-10]

$$15 \quad K_R = (-A+B+C)/(A+B+C)$$

where

$$A = (p'c^4/p\beta^4)((c^2/\alpha^2) - 1)^{1/2}$$

$$B = ((c^2/\alpha'^2) - 1)^{1/2}((c^2/\beta^2) - 2)^2$$

$$20 \quad C = 4((c^2/\alpha'^2) - 1)^{1/2}((c^2/\alpha^2) - 1)^{1/2}((c^2/\beta^2) - 1)^{1/2}$$

For

$$\alpha \geq |c| \geq \alpha' \geq \beta$$

25

$$61.9^\circ \leq \alpha_p' \leq 90^\circ$$

[Eq. 3-11]

30

$$K_R = (-A+B)\operatorname{sgn}\omega + iC/(A+B)\operatorname{sgn}\omega + iC$$

where

35

$$A = (p'c^4/p\beta^4)(1 - (c^2/\alpha^2))^{1/2}$$

$$B = 4((c^2/\alpha'^2) - 1)^{1/2}(1 - (c^2/\alpha^2))^{1/2}((c^2/\beta^2) - 1)^{1/2}$$

$$C = ((c^2/\alpha'^2) - 1)^{1/2}((c^2/\beta^2) - 2)^2$$

Hard Water-Bottom

40

For the condition

$$|c| \geq \alpha \geq \beta \geq \alpha'$$

$$0 \leq \gamma_p' \leq \sin^{-1}(\alpha'/\alpha) = 19.5^\circ$$

 K_R is given by [Eq. 3-10]

45 For

$$\alpha \geq |c| \geq \beta \geq \alpha'$$

$$19.5^\circ \leq \gamma_p' \leq \sin^{-1}(\alpha'/\beta) = 36.9^\circ$$

 K_R is given by [Eq. 3-11]

For

50

55

$$\alpha \geq \beta \geq |c| \geq \alpha'$$

$$36.9^\circ \leq \gamma_p' \leq 90^\circ$$

[Eq. 3-12]

$$K_R = A + i(-B+C) / -A + i(-B+C)$$

where

$$A = (p'c^4/p\beta^4)(1 - (c^2/\alpha^2))^{1/2} \operatorname{sgn} \omega$$

$$B = ((c^2/\alpha'^2) - 1)^{1/2} ((c^2/\beta^2) - 2)^2$$

$$C = 4((c^2/\alpha'^2) - 1)^{1/2} (1 - (c^2/\alpha^2))^{1/2} (1 - (c^2/\beta^2))^{1/2}$$

Soft Water-Bottom

For the condition

$$|c| \geq \alpha' \geq \alpha \geq \beta$$

$$0 \leq \gamma_p' \leq 90^\circ$$

 K_R is given by [Eq. 3-10]

Referring back to the expressions for $p(t)$ and $v(t)$ in [Eq. 3-9] and comparing them to Figure 5, those skilled in the art will readily appreciate how to modify the signals of Figure 5 to account for non-vertical incidence. An illustration so modified is shown in Figure 11. In that figure, it can be seen that to cancel all downward-propagating waves, $v(t)$ must be scaled by $(p'\alpha'/\cos\gamma_p')$ and added to $p(t)$.

$$s(t) = p(t) + (p'\alpha'/\cos\gamma_p')v(t)$$

[Eq. 3-13]

$$s(t) = 2K_T\delta(t - (z_d/\alpha')\cos\gamma_p')$$

$$- 2K_RK_T\delta(t - ((2d+z_d)/\alpha')\cos\gamma_p')$$

$$+ 2K_R^2K_T\delta(t - ((4d+z_d)/\alpha')\cos\gamma_p') - \dots$$

Assuming, once again, that the detectors 22 are placed at the water-bottom ($z_d=0$), the signals of Figure 11 are modified as shown in Figure 12. Here, it is also seen that all water-column reverberations may be eliminated through proper choice of a scale factor. More particularly, this can be accomplished if $v(t)$ is scaled as shown below and add it to $p(t)$.

$$s(t) = p(t) + (p'\alpha'/\cos\gamma_p')((1+K_R)/(1-K_R))v(t)$$

[Eq. 3-14]

$$s(t) = K_T\{1 + ((1+K_R)/(1-K_R))\}\delta(t)$$

As above, the scale factor required for $v(t)$ involves the reflection coefficient of the water-bottom, and,



therefore, its acoustic impedance. Methods for determining that scale factor are discussed in detail above.

Claims

1. A seismic reflection method of geophysical prospecting in water covered areas, comprising the steps of:
 - A. generating a seismic wave for reflection from earth strata;
 - B. detecting water pressure at a first position in the water resulting from said seismic wave and generating a signal representative thereof;
 - C. detecting water velocity at a position substantially near said first position resulting from said seismic wave and generating a signal representative thereof; characterized by
 - D. generating an enhanced seismic reflection signal by multiplying at least one of said water pressure-representative signal and the water velocity-representative signal by a scale factor dependent upon an acoustical impedance of a substance through which said seismic wave travels, and by summing said scaled water velocity-representative and water pressure-representative signals, said enhanced seismic reflection signal being substantially free of at least downwardly-propagating components of reverberation of said seismic wave within the water.
2. A method according to claim 1, wherein a pressure detector and a velocity detector are positioned substantially near the bottom of the water for detecting said water pressure and said water velocity and for generating signals representative thereof.
3. A method according to claim 2, wherein in step D the substance is solid earth material at the bottom of the water.
4. A method according to claim 3, wherein said scaling step (i) includes the further step of multiplying said at least one selected signal by a value dependent upon

$$\rho\alpha/\text{Dir}_{\text{corr}}$$
 where ρ is a density of said solid earth material, α is a velocity of propagation of the seismic wave in said solid earth material, and Dir_{corr} is a directivity correction factor.
5. A method according to claim 4, wherein said scaling step (i) includes the step of multiplying said at least one selected signal by a value dependent upon

$$(\rho\alpha/\text{Dir}_{\text{corr}}) * (G_p/G_v)$$
 where G_p is a transduction constant associated with the water pressure detecting step, and G_v is a transduction constant associated with the water velocity detecting step.
6. A method according to claim 4 or 5, wherein said scaling step (i) includes the step of generating said directivity correction factor, Dir_{corr} , to be equal to $\cos(\gamma_p')$ for γ_p' less than a selected critical angle, and to otherwise be equal to 1, where γ_p' is an angle of propagation from vertical of the seismic wave in the water.
7. A method according to claim 6, wherein said scaling step (i) includes the step of determining said critical angle to be substantially equal to $\arcsin(\alpha'/\alpha)$, where α' is the velocity of propagation of the seismic wave in the water and α is a velocity of propagation of the seismic wave in said solid earth material at the bottom of the water.
8. A method according to claim 3, including the step of determining said scale factor deterministically.
9. A method according to claim 8, where said scale factor determining step includes:
 - (a) generating a pressure wave from a position above the position of said pressure and velocity detectors,
 - (b) detecting, with said water pressure detector, water pressure during a selected arrival of said pressure wave and generating a signal representative thereof,
 - (c) detecting, with said velocity detector, a signal representative of the water velocity during a selected arrival of said pressure wave and generating a signal representative thereof, and
 - (d) determining said scale factor as dependent on a ratio of the absolute values of the magnitudes of the pressure wave velocity-representative signal and the pressure wave pressure-representative signal.



10. A method according to claim 9, wherein said pressure wave-generating step includes the step of generating said pressure wave from a position directly over said pressure and velocity detectors, and wherein preferably said pressure wave pressure detecting step includes the step of detecting water pressure during a first arrival of said pressure wave, and preferably said pressure wave velocity detecting step includes the step of detecting water velocity during a first arrival of said pressure wave.

Patentansprüche

1. Seismisches Reflektionsverfahren zum geophysikalischen Prospektieren in wasserbedeckten Gebieten, enthaltend die Schritte:
 - A. Erzeugen einer seismischen Welle zur Reflektion von Erdschichten;
 - B. Erfassen des aus der seismischen Welle entstehenden Wasserdrucks an einer ersten Stelle im Wasser und Erzeugen eines diesen darstellenden Signals;
 - C. Erfassen der aus der seismischen Welle entstehenden Wassergeschwindigkeit an einer Stelle, die im wesentlichen nahe der ersten Stelle liegt, und Erzeugen eines diese darstellenden Signals;

gekennzeichnet durch

 - D. Erzeugen eines verstärkten seismischen Reflektionssignals durch Multiplikation von wenigstens einem der Signale, die den Wasserdruck und die Wassergeschwindigkeit darstellen, mit einem Normierungsfaktor, der von einer akustischen Impedanz einer Substanz abhängig ist, durch welche die seismische Welle wandert, und durch Summierung der normierten Signale, die den Wasserdruck und die Wassergeschwindigkeit darstellen, wobei das verstärkte seismische Reflektionssignal im wesentlichen frei wenigstens von abwärts laufenden Komponenten der Rückstrahlung der seismischen Welle innerhalb des Wassers ist.
2. Verfahren nach Anspruch 1, dadurch gekennzeichnet, daß ein Druckaufnehmer und ein Geschwindigkeitsaufnehmer im wesentlichen nahe dem Grunde des Wassers angeordnet werden, um den Wasserdruck und die Wassergeschwindigkeit zu erfassen und diese darstellende Signale zu erzeugen.
3. Verfahren nach Anspruch 2, dadurch gekennzeichnet, daß im schritt D. die Substanz festes Erdmaterial am Grunde des Wassers ist.
4. Verfahren nach Anspruch 3, dadurch gekennzeichnet, daß der Normierungsschritt (i) den weiteren Schritt einschließt, daß das wenigstens eine ausgewählte Signal mit einem Wert multipliziert wird, der von

$$\rho\alpha/\text{Dir}_{\text{corr}}$$
 abhängig ist, worin ρ die Dichte des festen Erdmaterials, α Fortpflanzungsgeschwindigkeit der seismischen Welle in dem festen Erdmaterial und Dir_{corr} ein Richtkorrekturfaktor ist.
5. Verfahren nach Anspruch 4, dadurch gekennzeichnet, daß der Normierungsschritt (i) den Schritt einschließt, daß das wenigstens eine ausgewählte Signal mit einem Wert multipliziert wird, der von

$$(\rho\alpha/\text{Dir}_{\text{corr}}) * (G_p/G_v)$$
 abhängig ist, worin G_p eine Übertragungskonstante ist, die mit dem den Wasserdruck erfassenden schritt verbunden ist, und G_v eine Übertragungskonstante ist, die mit dem die Wassergeschwindigkeit erfassenden Schritt verbunden ist.
6. Verfahren nach Anspruch 4 oder 5, dadurch gekennzeichnet, daß der Normierungsschritt (i) den Schritt einschließt, daß der Richtkorrekturfaktor Dir_{corr} so erzeugt wird, daß er für γ_p' unterhalb eines ausgewählten kritischen Winkels gleich $\cos \gamma_p'$ und sonst gleich 1 ist, worin γ_p' ein Propagationswinkel der seismischen Welle in Wasser zur Vertikalen ist.
7. Verfahren nach Anspruch 6, dadurch gekennzeichnet, daß der Normierungsschritt (i) den Schritt einschließt, daß der kritische Winkel im wesentlichen als gleich $\arcsin(\alpha'/\alpha)$ bestimmt wird, worin α' die Fortpflanzungsgeschwindigkeit der seismischen Welle in Wasser und α die Fortpflanzungsgeschwindigkeit der seismischen Welle in dem festen Erdmaterial am Grunde des Wassers ist.
8. Verfahren nach Anspruch 3, dadurch gekennzeichnet, daß der Schritt der Bestimmung des Normierungsfaktors direkt erfolgt.



9. Verfahren nach Anspruch 8, dadurch gekennzeichnet, daß der Schritt der Bestimmung des Normierungsfaktors einschließt:
- (a) Erzeugen einer Druckwelle aus einer Stellung oberhalb der Stellung Druck- und Geschwindigkeitsaufnehmer,
 - (b) Erfassen des Wasserdrucks mit dem Wasserdruckaufnehmer während einer ausgewählten Ankunft der Druckwelle und Erzeugen eines diesen darstellenden Signals,
 - (c) Erfassen eines die Wassergeschwindigkeit darstellenden Signals mit dem Geschwindigkeitsaufnehmer während einer ausgewählten Ankunft der Druckwelle und Erzeugen eines diese darstellenden Signals, und
 - (d) Bestimmen des Normierungsfaktors in Abhängigkeit von einem Verhältnis der Absolutwerte der Größe des Signals, das die Druckwellenschwindigkeit darstellt, und des Signals, das den Druck der Druckwelle darstellt.
10. Verfahren nach Anspruch 9, dadurch gekennzeichnet, daß der Schritt der Erzeugung der Druckwelle den Schritt einschließt, daß die Druckwelle aus einer Stellung direkt über den Druck- und Geschwindigkeitsaufnehmern erzeugt wird und daß vorzugsweise der Schritt der Erfassung des Drucks der Druckwelle den Schritt einschließt, daß der Wasserdruck während einer Erstankunft der Druckwelle erfaßt wird, und daß der Schritt der Erfassung der Geschwindigkeit der Druckwelle vorzugsweise den Schritt einschließt, daß die Wassergeschwindigkeit während einer Erstankunft der Druckwelle erfaßt wird.

Revendications

1. Une méthode sismique par réflexion de prospection géophysique dans des zones recouvertes d'eau, comprenant les étapes suivantes:
- A. production d'une onde sismique devant se réfléchir des couches terrestres;
 - B. détection de la pression de l'eau à la première position dans l'eau, résultant de ladite onde sismique et production d'un signal représentatif de la même;
 - C. détection de la vitesse de l'eau à une position essentiellement proche de ladite première position, résultant de ladite onde sismique et production d'un signal représentatif de la même; caractérisée par
 - D. la production d'un signal sismique par réflexion amélioré en multipliant au moins l'un dudit signal représentatif de la pression d'eau et dudit signal représentatif de la vitesse de l'eau, par un facteur d'échelle qui dépend d'une impédance acoustique d'une substance à travers laquelle ladite onde sismique se propage, et en additionnant lesdits signaux mis à l'échelle représentatifs de la vitesse de l'eau et de la pression de l'eau, ledit signal sismique par réflexion amélioré ne contenant essentiellement et pour le moins aucune composante de réverbération à propagation descendante de ladite onde sismique dans l'eau.
2. Une méthode conformément à la première revendication, dans laquelle un détecteur de pression et un détecteur de vitesse sont positionnés essentiellement près du fond marin pour détecter ladite pression de l'eau et ladite vitesse de l'eau et pour produire des signaux représentatifs des mêmes.
3. Une méthode conformément à la deuxième revendication, dans laquelle dans le cadre de l'étape D, la substance est une matière terrestre solide au fond de l'eau.
4. Une méthode conformément à la troisième revendication, dans laquelle ladite étape de mise à l'échelle (I) comprend l'étape ultérieure de multiplier au moins un signal sélectionné par une valeur établie en fonction de
- $$p\alpha/Dir_{corr}$$
- où p est une densité de ladite matière terrestre solide, α est une vitesse de propagation de l'onde sismique dans ladite matière terrestre solide, et Dir_{corr} est un facteur de correction de directivité.
5. Une méthode conformément à la quatrième revendication, dans laquelle ladite étape de mise à l'échelle (I) comprend l'étape de multiplier au moins un signal sélectionné par une valeur établie en fonction de
- $$(p\alpha/Dir_{corr}) * ((G_p/G_v))$$
- où G_p est une constante de transduction associée à l'étape de détection de la pression d'eau, et G_v est une constante de transduction associée à l'étape de détection de la vitesse d'eau.
6. Une méthode conformément à la 4ème ou à la 5ème revendication, dans laquelle ladite étape de mise à



l'échelle (i) comprend l'étape de production dudit facteur de correction de directivité, Dir_{corr} devant être égal à $\cos(\gamma_p')$, pour γ_p' de moins qu'un angle critique sélectionné, et être autrement égal à 1, lorsque γ_p' est un angle de propagation de l'onde sismique dans l'eau à partir de la verticale.

- 5 7. Une méthode conformément à la sixième revendication, dans laquelle ladite étape de mise à l'échelle (i) comprend l'étape de détermination dudit angle critique devant être essentiellement égal au sinus de l'arc (α'/α) , où α' est la vitesse de propagation de l'onde sismique dans l'eau et α est la vitesse de propagation de l'onde sismique dans ladite matière terrestre solide au fond de l'eau.
- 10 8. Une méthode conformément à la troisième revendication, englobant l'étape de détermination dudit facteur d'échelle selon une méthode déterministe.
- 15 9. Une méthode conformément à la huitième revendication, dans laquelle ladite étape de détermination du facteur d'échelle comprend:
- 20 (a) production d'une onde de pression à partir d'une position au-dessus de la position desdits détecteurs de pression et de vitesse,
- (b) détection, avec ledit détecteur de pression d'eau, de la pression de l'eau pendant une arrivée sélectionnée de ladite onde de pression et production d'un signal représentatif de la même,
- (c) détection, avec ledit détecteur de vitesse, d'un signal représentatif de la vitesse de l'eau pendant une arrivée sélectionnée de ladite onde de pression et production d'un signal représentatif de la même, et
- 25 (d) détermination dudit facteur d'échelle qui dépend d'un rapport des valeurs absolues des grandeurs du signal représentatif de la vitesse de l'onde de pression et du signal représentatif de la pression de l'onde de pression.
- 30 10. Une méthode conformément à la neuvième revendication, dans laquelle ladite étape de production d'onde de pression comprend l'étape de production de ladite onde de pression à partir d'une position directement au-dessus desdits détecteurs de pression et de vitesse et dans laquelle l'étape de détection de pression de ladite onde de pression comprend de préférence l'étape de détection de la pression de l'eau pendant une première arrivée de ladite onde de pression et ladite étape de détection de vitesse de l'onde de pression comprend de préférence l'étape de détection de la vitesse de l'eau pendant une première arrivée de ladite onde de pression.
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