

## DESCRIPTION

### SUBSURFACE EXPLORATION METHOD

#### TECHNICAL FIELD

[0001]

5           This application claims the benefit of Japanese patent application No. 2009-25292, filed on November 12, 2009, the contents of which are hereby incorporated by reference herein in its entirety.

[0002]

10           The present invention relates to a subsurface exploration method for nondestructively visualizing and exploring the ground using elastic waves (including acoustic waves), and in particular, to a method for extensively, at a time, visualizing structures under the ground including concrete  
15 structures and base rock, and the presence of local looseness, cavities or gravels contained therein.

#### BACKGROUND ART

[0003]

          As a method for nondestructively visualizing and  
20 exploring the ground using elastic waves (for example, acoustic waves), a method called "elastic (seismic) wave tomography" is available. Methods of the elastic wave tomography are classified depending upon means of generating elastic waves and layout for propagating elastic waves. When  
25 roughly classified from the viewpoint of means of generating

elastic waves, the elastic wave tomography is classified into  
a transmitter for generating elastic waves by blasting or  
mechanically, and a transmitter for generating elastic waves  
by use of piezoelectric ceramics or magnetostrictive material  
5 employing a piezoelectric effect or a magnetostrictive effect.  
Next, when roughly classified from the viewpoint of layout,  
the elastic wave tomography is classified into a reflection  
method and a refraction method using blasting from the surface  
of the ground, and a cross hole (borehole-to-borehole)  
10 tomography method using boreholes.

[0004]

The cross hole tomography has a method as shown in Patent  
Literature 1. This method is applicable to subsurface  
exploration in the design of a foundation structure,  
15 exploration of underground obstructions and the like by making  
an exploration using intrinsic attenuation (referred to as  
"viscous attenuation") under the ground as well as elastic  
wave velocity.

#### CITATION LIST

20 PATENT DOCUMENT

[0005]

Patent Document 1            Japanese Patent Application Laid-Open  
No. Hei. 10-68779

#### SUMMARY OF THE INVENTION

25 PROBLEMS TO BE SOLVED BY THE INVENTION

[0006]

However, the viscous attenuation handled in Patent Literature 1 is based on Biot theory and is intended for only attenuation generated by the friction between soil particles and water in the vicinity thereto during propagation of elastic waves in the ground under a state saturated with water (refer to Fig. 4A). On the contrary, in the actual ground, attenuation occurs under a state including reflection or transmission as well as viscous attenuation. More specifically, there is a difference between attenuation in the actual ground and viscous attenuation and it is difficult to take a concern by removing only viscous attenuation from the attenuation in the actual ground. Accordingly, a state of the ground may be impossible to determine with high precision and thus misinterpretation may occur.

[0007]

In view of the foregoing problems, it is an object of the present invention to provide a subsurface exploration method capable of avoiding misinterpretation of the ground by determining a state of the ground with high precision.

MEANS FOR SOLVING THE PROBLEMS

[0008]

According to a first aspect of the present invention, there is provided a subsurface exploration method for nondestructively visualizing the ground using an elastic wave,

the method including: installing a receiver and a transmitter that transmits the elastic wave at known positions of the ground; causing the transmitter to transmit the elastic wave; causing the receiver to receive the elastic wave having  
5 propagated through a path under the ground from the transmitter toward the receiver; obtaining a damping factor and a velocity of the elastic wave having propagated; and setting one or more damping factor threshold values and one or more velocity threshold values for the damping factor and the  
10 velocity, respectively, and comparing the damping factor and the velocity to the damping threshold value and the velocity threshold value, thereby determining a state of the ground.  
[0009]

According to a second aspect of the present invention,  
15 the state of the ground is determined mainly on a difference between granularities of primary components of the ground including sand, silt or clay by comparing the velocity threshold value to the velocity, and the state of the ground is determined mainly on a difference between saturated state  
20 of the ground from a state containing bubbles or gravels to a hard state of the ground by comparing the damping factor threshold value to the damping factor.  
[0010]

According to a third aspect of the present invention, the  
25 state of the ground is determined as a state of sand, loose

sand or sand with gravel; a state of hard clay or dense sand;  
a state of clay containing bubbles or sand containing bubbles;  
or a state of loose clay or clay.

[0011]

5           According to a fourth aspect of the present invention,  
the ground is concrete or base rock, and the presence of a  
crack in the ground is determined by the velocity threshold  
value and a ground formation medium existing in the crack is  
determined by the damping factor threshold value.

10   [0012]

          According to a fifth aspect of the present invention, the  
elastic wave is based on a single carrier frequency modulated  
by a pseudo-random signal.

[0013]

15           According to a sixth aspect of the present invention, the  
damping factor and the velocity are obtained by correlation  
operation between the pseudo-random signal and the received  
elastic wave.

[0014]

20           According to a seventh aspect of the present invention,  
all the transmitter and the receiver are installed under the  
ground.

ADVANTAGEOUS EFFECTS OF THE INVENTION

[0015]

25           The present invention provides highly precise

determination for a state of the ground and avoidance of misinterpretation of the ground. More specifically, the following items become available.

[0016]

5           Since attenuation of an elastic wave in the actual ground is determined and the determination result is used to determine a state of the ground, the state of the ground can be exactly determined by a combination with a velocity of an elastic wave under the ground.

10   [0017]

          If a pseudo-random signal is used, even when a high frequency is used as a carrier frequency, an elastic wave can be propagated a long distance and thus highly precise measurement and measurement having little adverse effect of  
15   background noise are available.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0018]

          Fig. 1 is a schematic view showing a subsurface exploration system according to a first embodiment of the  
20   present invention;

          Fig. 2 is a schematic view showing a layout relationship of the ground, transmitters and receivers;

          Fig. 3 is a schematic view showing that a velocity and damping factor are obtained for each block of the ground by  
25   the tomography method;

Fig. 4 is a schematic view for describing major attenuations of an elastic wave;

Fig. 5 is a flowchart for determining a state of the ground from a velocity and a damping factor of an elastic wave according to the first embodiment of the present invention;

Fig. 6 is a schematic view schematically showing a state of the ground relative to a velocity and a damping factor of an elastic wave in the same embodiment;

Fig. 7 is a schematic view showing a state of the ground capable of being determined from a velocity and a damping factor of an elastic wave according to a second embodiment of the present invention;

Fig. 8 is a cross-sectional view of the ground obtained from a velocity distribution chart and a damping factor distribution chart obtained by actual measurement in the second embodiment of the present invention;

Fig. 9 is a schematic view showing a state of the ground capable of being determined from a graph plotting velocities and damping factors obtained in FIG. 8; and

Fig. 10 is a schematic view schematically showing a relationship between a velocity and a damping factor of an elastic wave according to a third embodiment of the present invention.

MODE FOR CARRYING OUT THE INVENTION

[0019]

Embodiments of the present invention will be described below with reference to the accompanying drawings.

[0020]

Referring first to Fig. 1, the overall configuration of a subsurface exploration system according to a first embodiment will be described below. Hereinafter, even when embodiments are different, the components will be denoted by the same reference numerals (including the conventional art).

[0021]

10       A subsurface exploration system 100, as shown in Fig. 1, includes: a transmitter (SOR) 120 that transmits an elastic wave 102; a receiver (REC) 124 that receives the elastic waves 102 propagating through a path 104A under the ground 104; and an analyzer (ANE) 132 that determines a state of the ground  
15   104 existing therebetween on the basis of the received elastic wave 102 (a received wave). Additionally, the subsurface exploration system 100 includes a frequency generator (FNG) 112 that determines a single frequency signal (a carrier frequency) to be output, and a phase converter (PHC) 114 that  
20   phase-converts a single frequency signal output from the frequency generator 112 to be used as a PRBS signal (described later) of one pseudo-random signal. The analyzer 132 can obtain cross-sectional images of the ground 104 between the receiver 124 and the transmitter 120, from the elastic waves  
25   102 received by the plurality of receivers 124. (A method for

obtaining cross-sectional images is publicly known as the tomography method.)

[0022]

Accordingly, the subsurface exploration system 100 can  
5 nondestructively visualizes and explores the ground 104 using elastic waves, as an elastic wave tomography apparatus.

[0023]

Respective components will be described in detail below.

[0024]

10 In the ground 104, as shown in FIG. 2, boreholes 106 (two in Fig. 2) extending in the vertical direction of a paper face are spaced at a predetermined interval. One borehole 106 (left side in Fig. 2) is defined so that one transmitter 120 is allowed to transmit while moving in the vertical direction at  
15 predetermined intervals. In the other borehole 106 (right side in Fig. 2), a plurality of receivers 124 are spaced at predetermined intervals in the vertical direction. (More specifically, the transmitters 120 and the receivers 124 are installed at known positions of the ground.) In the boreholes  
20 106, all the transmitters 120 and the receivers 124 are installed (installed under the ground 104). Accordingly, the receivers 124 can receive internal information of the ground 104 more stably than when either or both of the transmitter and the receiver is placed on a surface of the ground 104. The  
25 transmitters 120 and the receivers 124 will be described again

later.

[0025]

The frequency generator (FNG) 112 can digitally output a carrier signal that is a continuous sinusoidal signal of any frequency (a single frequency) as a single frequency signal (a carrier frequency). Also, it may be said that the frequency generator 112 is provided with frequency determination means that selects and determines a single frequency of an elastic wave 102. The frequency determination means may be configured from, for example, a circuit including a CPU.

[0026]

A phase converter (PHC) 114 is connected to the frequency generator 112. The phase converter 114 phase-converts a single-frequency digital signal (a single frequency signal) output from the frequency generator 112 with a PRBS code. A PRBS signal that is one of pseudo-random signals is output to a D-A converter 116. (More specifically, a carrier frequency of the PRBS signal is a single frequency.) The output is made to an analyzer 132 as well. The PRBS code is a pseudo-random binary sequence code. The PRBS code uses, for example, an M sequence (maximal-length sequences) the cycle of which is longest, of code sequences generated by a feedback among shift registers in the phase converter 114. Thus, the PRBS symbol is  $(2^n - 1)$  and, for example, the wave number is 4095 at  $n = 12$  and exclusiveness is very strong. Accordingly, when an auto-

correlation is calculated, a peak of the correlation value is high and an S/N ratio becomes very high in combination with the advantageous effects of a pulse compression technology. In this way, the phase converter 114 phase-converts a single  
5 frequency signal of a frequency input from the frequency generator 112 with a PRBS code generated in an own interior. The PRBS code may be introduced from the outside.

[0027]

The D-A converter (DAC) 116, connected to the phase  
10 converter 114, converts a signal output from the phase converter 114 from a digital value to an analog value and output the analog signal.

[0028]

A transmission amplifier (AMP) 118, connected to the D-A  
15 converter 116, amplifies and outputs a signal output from the D-A converter 116 in an analog manner.

[0029]

The transmitter (SOR) 120, connected to the transmission  
amplifier 118, converts an electric signal output from the  
20 transmission amplifier 118 into mechanical vibration, and transmits and outputs elastic waves 102 as transmitted waves. The elastic wave 102 is based on a single carrier frequency modulated into a PRBS signal. In the present embodiment piezoelectric ceramics for the transmitter 120 are used.  
25 Accordingly, the transmitter 120 can stably generate

mechanical vibration even a small type. Such an advantageous effect can be similarly obtained by using a magnetostrictive material as well.

[0030]

5           The Receiver (REC) 124 receives, as a received wave, an elastic wave 102 that is mechanical vibration propagating through the path 104A under the ground 104 from the transmitter 120 and converts the wave into an electric signal. As the receiver 124, for example, an underwater microphone  
10   called a hydrophone is available.

[0031]

          The receive filter (RCF) 126, connected to the receiver 124, removes, for example, traffic noise or construction noise generated above the ground 104, from signals received by the  
15   receiver 124. Accordingly, by selecting an appropriate noise filter, the receive filter 126 can significantly suppress an adverse effect of such noise. The receive filter 126 may include a variable amplifier as needed.

[0032]

20          An A-D converter (ADC) 128, connected to the receive filter 126, converts a signal passing through the receive filter 126 from an analog value into a digital value.

[0033]

          A data recorder (DTR) 130, connected to the A-D converter  
25   128, records a signal output from the A-D converter 128.

[0034]

The analyzer (ANE) 132, connected to the phase converter 114 and the data recorder 130, calculates a correlation value between a PRBS signal (a pseudo-random signal) involved in a transmitted wave output from the phase converter 114 and a  
5 signal by the received wave recorded on the data recorder 130. The (own) correlation operation provides exact measurement of a reach time of an elastic wave 102 to the receiver 124. By determining the reach time, a velocity V (P-wave velocity  
10 taken herein) can be determined. At the same time, a damping factor D can be exactly determined from a ratio of an amplitude of a received wave to an amplitude of an elastic wave 102 at initial transmission using a correlation value. More specifically, a sound pressure (an amplitude) of a  
15 transmitted wave is taken as  $A_{Wi}$  (dB), a sound pressure of a received wave as  $A_{Wo}$  (dB), a distance between the transmitter 120 and the receiver 124 as  $L$  (m), and a carrier frequency of the elastic wave 102 is taken as  $f$  (kHz). Thus, an attenuation  $AT$  (dB) and a damping factor  $D$  (dB/kHz/m) can be expressed in  
20 the following equations (1) and (2):

$$AT \text{ (dB)} = A_{Wi} \text{ (dB)} - A_{Wo} \text{ (dB)} \quad (1)$$

$$D \text{ (dB/m)} = AT \text{ (dB)} / f \text{ (kHz)} / L \text{ (m)} \quad (2)$$

[0035]

The analyzer 132 stores a velocity threshold value  $V_{sh}$   
25 and a damping factor threshold value  $D_{sh}$  provided for the

obtained velocity  $V$  and damping factor  $D$ , respectively.

Additionally, the analyzer 132 can compare between a velocity threshold value  $V_{sh}$  and a damping factor threshold value  $D_{sh}$ , and a velocity  $V$  (including a velocity  $V_{ij}$  to be described

5 later) and a damping factor  $D$  (including a damping factor  $D_{ij}$  to be described later) and make a specific determination

(described later) of a state of the ground 104. The

determination result is plotted on a graph of cross-sectional images and velocity-damping factors with a monitor or a

10 printer (not illustrated) associated with the analyzer 132.

Otherwise, the determination result is stored in the analyzer 132 as electronic data.

[0036]

The analyzer 132 can determine a cross-sectional image

15 (tomogram) of the ground between the boreholes 106, 106 by

using data (the above velocity  $V$  and damping factor  $D$ )

determined at predetermined positions of the respective

receivers 124 corresponding to the respective predetermined

positions of the transmitters 120 in the boreholes 106. More

20 specifically, a velocity  $V_{ij}$  and a damping factor  $D_{ij}$  can be determined for each block  $A_{ij}$  ( $i, j = 0, 1, 2, \dots$ )

partitioned in a mesh shape between the boreholes 106, 106

shown in FIG. 3 according to the tomography method (publicly known).

25 [0037]

In this way, the analyzer 132 can determine a state of a path 104A formed from a block Aij under the ground 104 at a high S/N ratio using a pulse compression technology by correlation operation.

5 [0038]

An attenuation AT will be described below.

[0039]

The attenuation AT under the ground is expressed as a sum of distance attenuation, viscous attenuation, transmission  
10 attenuation, and a scattering attenuation, as shown in equation (3).

Attenuation AT = Distance attenuation + Viscous  
attenuation + Transmission attenuation + Scattering  
attenuation (3)

15 [0040]

The distance attenuation illustrates an attenuation state increasing with the distance. The viscous attenuation is an attenuation state generated by friction between soil particles SP and water W, resulting from vibrations between the soil  
20 particles SP and water W not agreeing with each other while elastic waves are passing (Fig. 4A). The viscous attenuation can be calculated by the kinematic wave theory Biot 1955 in porous medium or the like. When a carrier frequency of 1 kHz to 20 kHz is used, for example, the viscous attenuation  
25 becomes larger as grain size is larger in the completely

saturated ground 104, namely, the viscous attenuation becomes larger in the case of sand and the viscous attenuation becomes smaller in the case of clay. According to the kinematic wave theory in the porous medium, the viscous attenuation has  
5 little influence of looseness of the ground. The transmission attenuation is an attenuation state caused by converting an elastic wave into thermal energy when an elastic wave is emitting into and penetrating through a substance with different density (penetrating through a density D1 to D2)  
10 (Fig. 4B). The transmission attenuation occurs at a layer boundary or the like and becomes larger after passing through an area with low density, such as air bubbles (may include various gases, hereinafter) under the ground. The scattering attenuation is an attenuation state caused by reflection or  
15 scattering while elastic waves are emitting into a substance with different density (Fig. 4C). The scattering attenuation occurs when an object over a size  $1/4$  to  $1/2$  times as large as the wavelength of an elastic wave, such as gravel, exists and in the case of the ground containing a large amount of gravel  
20 layer or bounding stones, the scattering attenuation becomes larger.

[0041]

Referring next to Fig. 5, a determination method for a state of the ground 104 using a velocity V and a damping  
25 factor D of an elastic wave 102 will be described below. Fig.

6 shows the determination result.

[0042]

First, the receiver 124 and the transmitter 120 that  
transmits an elastic wave 102 are installed at known positions  
5 of the ground 104.

[0043]

Next, an elastic wave 102 by a PRBS signal is transmitted  
from the transmitter 120 and the elastic wave 102 propagating  
through a path 104A under the ground 104 from the transmitter  
10 120 toward the receiver 124 is received by the receiver 124.

[0044]

Next, by calculating a correlation value between a PRBS  
signal and the received elastic wave 102, a velocity  $V$  and a  
damping factor  $D$  of the propagating elastic wave 102 are  
15 determined.

[0045]

Next, from the velocity  $V$  and the damping factor  $D$ , a  
velocity  $V_{ij}$  and a damping factor  $D_{ij}$  are determined for each  
block  $A_{ij}$  according to the known tomography method (step S8).  
20 Then, a velocity distribution chart and a damping factor  
distribution chart are determined.

[0046]

Next, a value of the velocity  $V_{ij}$  and a value of the  
damping factor  $D_{ij}$  are compared to the velocity threshold  
25 value  $V_{sh}$  and the damping factor threshold value  $D_{ij}$  for case

classification, respectively.

[0047]

Generally, a velocity has a good correlation to the hardness and porosity of the ground. In the case that the ground is sand, the velocity becomes high, while in the case that the ground is clay, the velocity becomes low. In the case that the ground contains bubbles or gases (simply, referred to bubbles), the velocity becomes low.

[0048]

10        Attenuation of an elastic wave is generated by a sum of viscous attenuation, transmission attenuation and scattering attenuation, as described above. The viscous attenuation becomes larger as grain size is large in the ground completely saturated with water. In other words, in the case of sand, 15 viscous attenuation becomes larger and, in the case of clay, viscous attenuation becomes smaller. The transmission attenuation occurs while penetrating through a substance with different density, and becomes larger after passing through an area with low density, such as air bubbles (may include 20 various gases, hereinafter) under the ground. The scattering attenuation is an attenuation caused by reflection or scattering when an object over a size  $1/4$  to  $1/2$  times as large as the wavelength of an elastic wave 102, such as a gravel, exists and in the case of the ground containing a 25 large amount of gravel layer or bounding stones, the

scattering attenuation becomes larger.

[0049]

Accordingly, case classification is performed in combination with a damping factor  $D_{ij}$  and a velocity  $V_{ij}$ . More specifically, a damping factor threshold value  $D_{sh}$  and a velocity threshold value  $V_{sh}$  are provided for the damping factor  $D_{ij}$  and the velocity  $V_{ij}$ , respectively. By comparing the damping factor  $D_{ij}$  and the velocity  $V_{ij}$  to the damping factor threshold value  $D_{sh}$  and the velocity threshold value  $V_{sh}$ , respectively, a state of the ground 104 is determined.

[0050]

First, in the case that the velocity  $V_{ij}$  is larger than the velocity threshold value  $V_{sh}$  and the damping factor  $D_{ij}$  is larger than the damping factor threshold value  $D_{sh}$  (Yes in step S10, S12), it is determined that a state of the ground 104 is a sand layer not containing bubbles but containing gravels (CONDITION 1 that is a state of sand SA, loose sand LS, sand with gravel (including only gravels) SC) (step S14).

[0051]

In the case that the velocity  $V_{ij}$  is larger than the velocity threshold value  $V_{sh}$  and the damping factor  $D_{ij}$  is smaller than the damping factor threshold value (Yes in step S10, No in step S12), a state of the ground 104 is a sand layer not containing bubbles, gases or gravels. When the damping factor  $D_{ij}$  is further smaller, it is determined that a

state of the ground 104 may be hard clay (CONDITION 2 that is a state of hard clay TC or dense sand TS) (step S16).

[0052]

In the case that the velocity  $V_{ij}$  is smaller than the velocity threshold value  $V_{sh}$  and the damping factor  $D_{ij}$  is larger than the damping factor threshold value  $D_{sh}$  (No in step S10, Yes in S18), it is determined that a state of the ground 104 is clay containing bubbles or gases, or clay containing gravels (CONDITION 3 that is a state of clay FC containing bubbles F or sand FS containing bubbles) (step S20).

[0053]

In the case that the velocity  $V_{ij}$  is smaller than the velocity threshold value  $V_{sh}$  and the damping factor  $D_{ij}$  is smaller than the damping factor threshold value  $D_{sh}$  (No in step S10, S18), it is determined that a state of the ground 104 is clay not containing bubbles or gases (CONDITION 4 that is a state of loose clay LC or clay CR) (step S22).

[0054]

More specifically, it is difficult to distinguish gravels SC, sand SA, dense sand TS, loose sand LS, hard clay TC, clay FC containing bubbles F, sand FS containing bubbles F, and clay CR in Fig. 6 by using only velocity. However, it is possible to distinguish them by using the damping factor threshold value  $D_{sh}$ .

[0055]

By using the velocity threshold value  $V_{sh}$  and the damping factor threshold value  $D_{sh}$ , the analyzer 132 can uniquely determine the state of the ground 104 with high promptness from a relationship between velocity and damping factor.

5 Determination of a state of the ground 104 and comparison for each location can be achieved with ease just by preparing Fig. 6 without need for showing a state of the ground 104 as a cross-sectional image.

[0056]

10 In the present embodiment, the velocity threshold value  $V_{sh}$  and the damping factor threshold value  $D_{sh}$  are set to 1.6 km/s and 0.3 dB/kHz/m, respectively. The velocity and the damping factor in a common sedimentary layer are approx. 1.5 to 1.7 km/s and approx. 0.1 to 0.3 dB/kHz/m, respectively.

15 However, they depend upon a state of the ground 104. The velocity threshold value  $V_{sh}$  and the damping factor threshold value  $D_{sh}$  may be set out of the ranges described above. Such threshold values may be corrected by making a comparison to boring information.

20 [0057]

In the present embodiment, a state of the ground 104 is determined from the damping factor  $D$  based on the attenuation  $AT$  including viscous attenuation in this way. Accordingly, a state of the ground 104 can be determined more exactly than in  
25 a conventional manner (such as a method using viscous

attenuation alone or a method without use of damping factor).

[0058]

When the ground is locally loose, fine bubbles that do not affect the change in velocity exist in many cases, and no velocity changes but only a damping factor may become larger. By utilizing such a relationship, the analyzer 132 can determine even looseness in the ground 104.

[0059]

In the present embodiment, only each one of the velocity threshold value Vsh and the damping factor threshold value Dsh is set. A state of the ground 104 is determined as a state of sand, loose sand or sand with gravel; a state of hard clay or dense sand; a state of clay containing bubbles or sand containing bubbles; or a state of loose clay or clay. However, the present invention is not limited thereto.

[0060]

For example, in the second embodiment, a plurality of at least either one of the velocity threshold value Vsh and the damping factor threshold value Dsh are provided, achieving finer determination. In such a case, all state illustrated in Fig. 6 can be distinguished. For example, the velocity threshold value Vsh is set between 1.5 km/s and 1.6 km/s of the velocity V (hereinafter,  $V_{ij}$  shown as V) of the elastic wave 102 and between 1.6 km/s and 1.7 km/s, respectively (total: two). A damping factor threshold value Dsh is set

between 0.05 dB/kHz/m and 0.1 dB/kHz/m, between 0.1 dB/kHz/m and 0.2 dB/kHz/m, between 0.2 dB/kHz/m and 0.3 dB/kHz/m, and between 0.3 dB/kHz/m and 0.5 dB/kHz/m of a damping factor  $D$  (hereinafter,  $D_{ij}$  also expressed as  $D$ ) of the elastic wave 102, respectively (total: four).

[0061]

In a conventional technique, by highly precisely measuring a velocity  $V$ , it is conceivable that the velocity  $V$  is determined in the following three cases: 1.5 km/s, 1.6 km/s, and 1.7 km/s. In that case, in Fig. 7, a loose clay layer  $G1$  can be determined from a velocity of 1.5 km/s. However, boulder stone  $S$  contained therein cannot be determined. Also, a loose sand layer  $G2$  or a hard clay layer  $G3$  can be determined from a velocity of 1.6 km/s. However, identification thereof cannot be made. In addition, the presence of bubbles (subsurface gas)  $F$  in a hard clay layer  $G3$  cannot be determined. Additionally, a dense sand layer  $G4$ , gravels  $G5$  or a hard clay layer  $G6$  can be determined from a velocity of 1.7 km/s. However, identification thereof cannot be made.

[0062]

On the other hand, a second embodiment provides more highly precise determination of a state of the ground 104 as illustrated in FIG. 7 in combination with four damping factor threshold values  $D_{sh}$  with the velocity threshold value  $V_{sh}$ . In

the case of a loose clay layer G1, the damping factor D is 0.05 dB/kHz/m. But a damping factor of boulder stone S is high (0.2 dB/kHz/m) even at the same velocity V as a velocity in a loose clay layer, the presence of boulder stone S can be identified. In the case of a loose sand layer G2 and hard clay layer G3, the loose sand layer G2 has a higher damping factor D (0.3 dB/kHz/m against 0.05 dB/kHz/m) even at the same velocity V. Thus, the hard clay layer G3 can be identified against the loose sand layer G2. Also, a damping factor D of a bubble F in the hard clay layer G3 is much higher than that of the loose sand layer G2 (0.5 dB), the presence of any bubble F can be identified. Additionally, in the dense sand layer G4, gravel layer G5 and hard clay layer G6, a damping factor D of the gravel layer G5 is higher (0.5 dB) than a damping factor D (0.1 dB) of the dense sand layer G4 even at the same velocity V and a damping factor D of the hard clay layer G6 is small (0.05 dB). Thus, the dense sand layer G4, the gravel layer G5 and hard clay layer G6 can be easily identified from each other.

[0063]

Figs. 8A and 8B show a state of the ground 104 in the present embodiment, using a velocity distribution chart and a damping factor distribution chart from measurement results of an actual landfill along Tokyo Bay. The measurement conditions were as follows: distances between boreholes 106 were 66 m and

55 m and the measurement depth was 65 m. Fig. 8A is a velocity distribution chart and Fig. 8B is a damping factor distribution chart. Each of Figs. 8A and 8B shows the determined state of the ground 104 with G10 to G19. G10 is a loose sand layer (Loose sand; alluvial sand layer), G11 is a loose clay layer (Clay; alluvial clay layer), G12 is a loose silt layer (Silt; alluvial silt layer) composed of medium particles of clay and sand, G13 is an alternate layer of sand and silt, G14 is a dense sand layer (Dense sand; alluvial sand layer), G15 is a hard clay layer (Hard Clay; alluvial clay layer), and G16 is a bubble in the clay layer (Soil gas; organic gas).

[0064]

Such configuration data, when graphed with velocity versus damping factor, is as shown by empty circles in Fig. 9. Herein, a broken-line arrow shows a difference between sand and clay. Also, a solid-line arrow shows mainly a difference between a saturated layer and an unsaturated layer. An area H1 surrounded by round broken lines is deviated from the solid-line arrow as compared to an area H2. Accordingly, by defining an appropriate damping factor threshold value Dsh between the area H1 and the area H2, the presence of bubbles (organic gas) can be clearly determined. More specifically, by a comparison between the velocity V and the velocity threshold value Vsh, a state of the ground 104 is determined mainly from differences

in granularity of primary components of the ground 104 of sand, silt or clay. In addition, by a comparison between the damping factor  $D$  and the damping factor threshold value  $D_{sh}$ , a state of the ground 104 can be more accurately determined mainly by the determination of differences in saturated state of the ground 104 from a state containing bubbles or gravels to a dense state of the ground 104.

[0065]

By determining a state of the ground 104 in this way, for example, a shield tunnel can be constructed while avoiding gravels (boulder) under the ground 104. (For example, presence of such gravels (boulder) may stop a shield machine.)

[0066]

In the present embodiments, the ground 104 contains gravels, sand or clay. However, the present invention is not limited thereto. The present invention may apply to, for example, artificial floor surfaces and base structures made of concrete as well as base rock. Referring now to Fig. 10, a case where the ground 104 is concrete or base rock will be described below as a third embodiment.

[0067]

When an obtained velocity  $V$  is larger than the velocity threshold value  $V_{sh}$  (for example, 1.6 km/s), a state of the ground 104 is determined as base rock R2 without a crack

(CONDITION 2). On the other hand, when the obtained velocity  $V$

is smaller than the velocity threshold value  $V_{sh}$ , a state of the ground 104 is determined to have a crack. When the obtained damping factor  $D$  is larger than the damping factor threshold value  $D_{sh}$  (for example, 0.3 dB/kHz/m), an object existing in the crack CR1 is determined to be a bubble (including gas) (CONDITION 3). When the obtained damping factor  $D$  is smaller than the damping factor threshold value  $D_{sh}$ , an object existing in the crack CR2 can be determined to be water or other substance (CONDITION 4). At this time, by additionally setting the damping factor threshold value  $D_{sh}$  to a smaller value, for example, water or concrete can be identified. More specifically, when the ground 104 is concrete or base rock, the presence of cracks in the ground 104 may be determined from the velocity threshold value  $V_{sh}$ , and a ground formation medium such as bubbles, water or concrete existing in a crack may be determined from the damping factor threshold value  $D_{sh}$ . For example, in excavation of base rock to construct a shield tunnel or investigating a concrete base structure of a dam, if a crack is found therein and water exists inside the crack, it is necessary to drain the water and to fill the inside with concrete. At that time, by appropriately setting two damping factor threshold values  $D_{sh}$  as described above, it can be determined whether a crack exists and whether an object existing in the crack is air, water or concrete. Accordingly, since the construction work of

a shield tunnel or evaluation of a concrete base structure is implemented and then repair work and the like are promptly investigated, such civil engineering work can be performed with higher efficiency than in a conventional technique.

5 [0068]

In determining a state of the ground 104, a frequency to be used is single and a correlation between a PRBS signal that is a pseudo-random signal and the received elastic wave 102 is taken, and therefore, a state of the ground 104 can be  
10 analyzed at a high S/N ratio. As illustrated in FIG. 2, since many receivers 124 receive elastic waves 102 at a time, widespread visibility of the ground 104A in cross section becomes easy. Also, the path 104A is between the transmitter 120 and the receiver 124 and determination of a state of the  
15 ground 104 basically uses a transmitted wave, and therefore, a higher S/N ratio can be ensured.

[0069]

Additionally, by using a PRBS signal modulation-controlled by a pseudo-random code against a single frequency,  
20 transmission and reception can be performed at a higher frequency than a conventional one (to approx. 200 Hz). In the above-mentioned embodiment, measurement at 20 kHz is available. Thus, the ground 104 can be investigated with measurement resolution more than ten times as many as in a conventional  
25 way. For example, when a velocity of the elastic wave 102

under the ground 104 is taken as 2 km/s, the resolution is approx. 5 m in a conventional technique. However, in the present embodiment, a resolution of approx. 0.2 m can be achieved. Since a frequency band of background noise (such as traffic noise and construction noise above the ground 104) is low, little effect of background noise can be achieved.

[0070]

As a frequency is higher, the elastic wave 102 tends to exponentially attenuate more, and hence it is difficult to propagate an elastic wave with a high frequency a long distance. However, use of a PRBS signal enables to scatter energy of the elastic wave 102 on a time axis, and therefore, an elastic wave 102 with a high frequency can be propagated to some hundreds of meters against a conventional one (order of several meters). In the above-mentioned embodiment, propagation of the elastic wave has been verified as follows: more than 400 m at 1 kHz and more than 20 m at 30 kHz.

[0071]

More specifically, by use of a PRBS signal and correlation operation, the elastic wave 102 can be propagated a long distance while using a high frequency, and a state of the ground 104 can be determined by performing measurement with high precision without much adverse effect of noise (including vibration) above the ground 104.

[0072]

More specifically, according to the above-mentioned embodiment, an internal structure, local looseness, cavities, presence of gravels under the ground 104 can be visualized in a wide sphere at a time, and a state of the ground 104 can be  
5 determined with high precision while avoiding misinterpretation of the ground 104. More specifically, the following advantages become available. By determining attenuation of an elastic wave 102 in the actual ground 104, the result is used to determine a state of the ground 104.  
10 Accordingly, the velocity  $V$  and the damping factor  $D$  of the elastic wave 102 under the ground 104 can be combined to exactly determine a state of the ground 104.

[0073]

Since a pseudo-random signal is used, the elastic wave  
15 102 can be propagated a long distance even a high frequency is used as a carrier frequency. Thus, measurement with high precision and measurement without much adverse effect of background noise (such as traffic noise or construction noise above the ground 104) are available.

20 [0074]

It is also conceivable to use electromagnetic waves in place of the elastic waves 102. However, an electromagnetic wave tends to be absorbed in water, if any and is susceptible to electrical noise. More specifically, in an area where a  
25 steel tower or the like exists or in an urban region, or below

the surface of groundwater or sea water, a method using electromagnetic waves is difficult to apply. (Because of this, the tomography method using electromagnetic waves tends to be limited to applications where such electromagnetic waves are used above the surface of groundwater in a mountain area or the like.) On the other hand, the above-mentioned embodiment uses elastic waves 102, and therefore, has no limits described above and has wider applicability than a method using electromagnetic waves. More specifically, the above-mentioned embodiment provides investigation without limitations on locations, such as petroleum or natural gas deposit, or areas for corrupt smell gas (organic gas) including methane gas. During pile driving for structure construction, for example, in bay areas (such as Tokyo Bay or Osaka Bay), the above-mentioned embodiment is an effective method in preventing accidents such as jetting of corrupt smell gas.

[0075]

Having described the present invention as related to the embodiments, it is to be understood that the present invention is not limited to the embodiments. More specifically, it is further understood that various modifications and design changes may be made in the present invention without departing from the spirit and scope thereof.

[0076]

For example, the present embodiment uses piezoelectric

ceramics or magnetostrictive material for the transmitter 120. However, the present invention is not limited thereto and may use other one.

[0077]

5           Moreover, in the present embodiment, the elastic wave 102 is based on a single carrier frequency modulated by a pseudo-random signal. Although the inventor has demonstrated that by use of the pseudo-random signal a velocity  $V$  and a damping factor  $D$  can be obtained with a significantly excellent S/N ratio, the pseudo-random signal is not always required to be used. Moreover, the pseudo-random signal is a PRBS signal using M sequence. However, the present invention is not limited thereto, and the pseudo-random signal may use a signal of Gold sequence, Barker sequence or the like.

15   [0078]

          In addition, the present embodiment uses correlation operation between a pseudo-random signal and a received elastic wave 102. However, the present invention is not limited thereto.

20   [0079]

          In the present embodiment, the transmitters 120 and the receivers 124 are installed in the boreholes 106 to minimize ground information of extreme surfaces of the ground 104 and noise transmitted from surfaces, thus grasping a state of the ground 104 with high precision. More specifically, in the

present embodiment, the receivers 124 that have conventionally been installed on the surface of the ground 104 to prevent degradation of a broken-line density may be omitted. However, the present invention is not limited thereto. For example, either or both of the receivers 120 and the receivers 124 may be installed on the surface of the ground 104. At that time, simple layout of the transmitters 120 and the receivers 124 is available.

[0080]

Additionally, in the present embodiment, the velocity  $V$  and the damping factor  $D$  of the elastic wave 102 are obtained by correlating the pseudo-random signal to the elastic wave 102. However, the means of obtaining the velocity  $V$  and the damping factor  $D$  of the elastic wave 102 in the present invention is not limited thereto. In addition, in the present embodiment, a velocity  $V_{ij}$  and a damping factor  $D_{ij}$  for each block  $A_{ij}$  are obtained by the tomography method from a velocity  $V$  and a damping factor  $D$  of the elastic wave 102, and the state of the ground 104 is determined for each block  $A_{ij}$ . However, the present invention is not limited thereto. Rough determination of the state of the ground 104 may be made from the velocity  $V$  and the damping factor  $D$  of the elastic wave 102 at the previous step of the tomography method.

INDUSTRIAL APPLICABILITY

[0081]

The present invention can apply to a method for extensively visualizing and exploring structures under the ground including concrete structures and base rock, and the presence of local looseness, cavities or gravels in a  
5 nondestructive way at a time using elastic waves (including acoustic waves).

#### REFERENCE SIGNS LIST

[0082]

- 100 subsurface exploration system
- 10 102 elastic wave
- 104 ground
- 104A path
- 106 borehole
- 112 frequency generator
- 15 114 phase converter
- 116 D-A converter
- 118 transmission amplifier
- 120 transmitter
- 124 receiver
- 20 126 receive filter
- 128 A-D converter
- 130 data recorder
- 132 analyzer

## CLAIMS

1. A subsurface exploration method for nondestructively visualizing the ground using an elastic wave, the method including:

installing a receiver and a transmitter that transmits the elastic wave at known positions of the ground;

causing the transmitter to transmit the elastic wave;

causing the receiver to receive the elastic wave having propagated through a path under the ground from the transmitter toward the receiver;

obtaining a damping factor and a velocity of the elastic wave having propagated; and

setting one or more damping factor threshold values and one or more velocity threshold values for the damping factor and the velocity, respectively, and comparing the damping factor and the velocity to the damping threshold value and the velocity threshold value, thereby determining a state of the ground.

2. The subsurface exploration method according to claim 1, wherein

the state of the ground is determined mainly on a difference between granularities of primary components of the ground including sand, silt or clay by comparing the velocity

threshold value to the velocity, and

the state of the ground is determined mainly on a difference between saturated state of the ground from a state containing bubbles or gravels to a hard state of the ground by comparing the damping factor threshold value to the damping factor.

3. The subsurface exploration method according to claim 2, wherein the state of the ground is determined as a state of sand, loose sand or sand with gravel; a state of hard clay or dense sand; a state of clay containing bubbles or sand containing bubbles; or a state of loose clay or clay.

4. The subsurface exploration method according to claim 1, wherein the ground is concrete or base rock, and the presence of a crack in the ground is determined by the velocity threshold value and a ground formation medium existing in the crack is determined by the damping factor threshold value.

5. The subsurface exploration method according to any of claims 1 to 4, wherein the elastic wave is based on a single carrier frequency modulated by a pseudo-random signal.

6. The subsurface exploration method according to claim 1, wherein the damping factor and the velocity are obtained by

correlation operation between the pseudo-random signal and the received elastic wave.

7. The subsurface exploration method according to any of  
5 claims 1 to 6, wherein all the transmitter and the receiver are installed under the ground.