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An Identification Method of Geological Boundary Using Elastic Waves

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Abstract—This paper focuses on a technique for identifying the geological boundary of the ground strata in front of a tunnel excavation site using the first order adjoint method based on the optimal control theory. The geological boundary is defined as the boundary which is different layers of elastic modulus. At tunnel excavations, it is important to presume the ground situation ahead of the cutting face beforehand. Excavating into weak strata or fault fracture zones may cause extension of the construction work and human suffering. A theory for determining the geological boundary of the ground in a numerical manner is investigated, employing excavating blasts and its vibration waves as the observation references. According to the optimal control theory, the performance function described by the square sum of the residuals between computed and observed velocities is minimized. The boundary layer is determined by minimizing the performance function. The elastic analysis governed by the Navier equation is carried out, assuming the ground as an elastic body with linear viscous damping. To identify the boundary, the gradient of the performance function with respect to the geological boundary can be calculated using the adjoint equation. The weighed gradient method is effectively applied to the minimization algorithm. To solve the governing and adjoint equations, the Galerkin finite element method and the average acceleration method are employed for the spatial and temporal discretizations, respectively. Based on the method presented in this paper, the different boundary of three strata can be identified. For the numerical studies, the Suemune tunnel excavation site is employed. At first, the blasting force is identified in order to perform the accuracy improvement of analysis. We identify the geological boundary after the estimation of blasting force. With this identification procedure, the numerical analysis results which almost correspond with the observation data were provided.

Keywords—Parameter identification, finite element method, average acceleration method, first order adjoint equation method, weighted gradient method, geological boundary, navier equation, optimal control theory.

I. Introduction

IT is highly important to understand in advance behavior and characteristics of the ground in the civil engineering works such as tunnels, traffic roads, dams, etc. To know what kind of behavior the externally forced ground shows is directly related to safety managements, cost reduction measures and environmental assessments, etc., in the constructions. Until now, the property investigations of the ground such as geological reconnaissance of a drilling survey, geophysical exploration, paling of investigation and rock test have been used as the generalized method in designing the civil engineering works. However, the conventional investigative approaches require a lot of time and cost for investigation, and sometimes it leads that the construction must be prolonged for the investigation. Thus, a number of improvements should be developed for these reasons. Consequently, the forecast technique with a numerical simulation, by which the constructions can be carried out more safer and less expensive, is considerably developed by the progress of a computer and the related analytical technology recently. In this research, the identification that forecasts the boundary strata of the geological condition by the three-dimensional numerical analysis technique is developed.
At the tunnel constructions, the problem that excavating into weak strata or fault fracture zones without careful preparation sometimes may cause prolongation of the construction works and human damages. Thus, in this research, an identification technique is presented to examine in a numerical manner the boundary layer of geological property. On the assumption that a tunnel is excavated, the value of the ground coefficients are identified using ground vibration caused by blasts with dynamite and the first order adjoint equation method. It is possible that useful information can be obtained beforehand for going into the weak ground strata and fault fracture zones in the excavating works by identifying the geological boundary. Because data on position of boundary layer in the geological strata can be explored beforehand, safer and less expensive excavation works are possible. Moreover, this technique can be performed without stopping the excavation works at the cutting face consuming less expensive search costs. In order to perform the minimization procedure, we introduce the index of the magnitude of discrepancy. It is referred as the performance function. According to inverse analytical technique which is introduced in this research, the state quantity is actually observed and the performance function is defined as the square sum of the residuals between calculated velocity and this observed velocity. An unknown coefficient is established by identifying the purpose coefficient that minimize this function. The assumption for initial values of parameters to be identified is one of the key concept of the present computational procedure, because the first order adjoint equation yields neither a necessary nor a sufficient condition of the global minimum. The fact that the variation of the extended performance function is zero implies that the necessary and sufficient condition of the stationary state. Therefore, the assumption of initial values of parameters is important and depends on the practical problem to be identified. For the minimization procedure, we utilize a weighted gradient method. Although this is simplest and most primitive method, it is possible to obtain a convergence of the computations starting from wide initial assumptions.
Identification of the geological boundary of the ground in three dimension becomes possible by applying the present technique. The results of this research leads to a plenty of contribution to the engineering works because the position of

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geological boundary can be determined by numerical analysis with this technique. It is possible to know in advance not only rock properties but also natural geological boundary between rock strata. A number of methods for parameter identification have been presented in the fields of meteorology e.g. [2] and hydraulic mechanics e.g. [8] or [17]. Methods for identification of parameters such as seepage and temperature of the ground have been discussed by Asai and Kawahara [13], Kojima et al. [6], Kawahara et al. [7]. To estimate the geological structure in the ground, an identification method of rock parameters have been presented by Chaparro et al. [1], Swoboda et al. [4], Koizumi and Kawahara [10], Ohkami and Swoboda [14], Huang and Liu [16], Xiang et al. [18]. This research set a precedent for the future various identification problems.
In order to show effectiveness of the present method, the verification is performed using computational model in three dimension. We can confirm the answer corresponding to the theory from results of the numerical analysis. The effectiveness of this technique was shown.

II. Identification Method of Geological Boundaries

Using the indicial notation and summation convention, an identification method of position of geological boundaries can be determined. The procedure is to find out the coordinate of the position $x_{\beta j}$ at β-th node in the j-direction so as to minimize the following extended performance function J^*;

$$J^* \quad = \quad J + \Lambda + \Xi, \tag{1}$$

In equation (1), J is referred to the performance function and expressed in the following form;

$$J \quad = \quad \frac{1}{2}\int_{t_0}^{t_f} (\dot{u}_{\alpha i} - \eta_{\alpha i}) Q_{\alpha i \beta j} (\dot{u}_{\beta j} - \eta_{\beta j}) dt, \tag{2}$$

where $\dot{u}_{\alpha i}$ and $\eta_{\alpha i}$ mean the computed and the observed velocities at observed point α in the i-direction, respectively. $Q_{\alpha i \beta j}$ represents the weights adjusting the measurements dimension, t_0 and t_f are the initial and the final times.

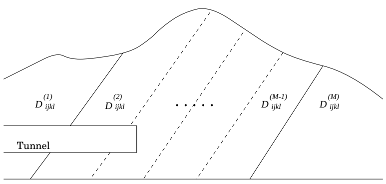

Fig. 1. Sectional view of tunnel excavation

The natural ground is composed of some strata as shown in Figure 1. The Navier equation which shown by the displacements is applied to a dynamic analysis of the ground as a governing equation. In this research, the ground is assumed as a linear elastic body. The governing equation can be expressed as follows;

$$D_{ijkl} u_{k,lj} + \rho b_i - \rho \ddot{u}_i \quad = \quad 0, \tag{3}$$

where u_i, b_i and ρ denote displacement, body force and density of the ground, respectively. Here, over dot denotes time differentiation. Based on the elastic modulus and the Poisson ratio of each stratum, D_{ijkl} can be derived as follows;

$$D_{ijkl} \quad = \quad \sum_{m=1}^{M} D_{ijkl}^{(m)}, \tag{4}$$

where M is the maximum number of strata and $D_{ijkl}^{(m)}$ is elastic coefficient matrix at stratum (m). The constraint equations are the dynamic elastic equation discretized by the finite element method;

$$\Lambda = \frac{1}{2}\int_{t_0}^{t_f} \lambda_{\alpha i} (\hat{\Omega}_{\alpha i} - M_{\alpha i \beta j} \ddot{u}_{\beta j} - C_{\alpha i \beta j} \dot{u}_{\beta j} - K_{\alpha i \beta j} u_{\beta j}) dt, \tag{5}$$

In equation (5), $\lambda_{\alpha i}$ is the Lagrange multiplier. $M_{\alpha i \beta j}$, $C_{\alpha i \beta j}$, $K_{\alpha i \beta j}$ denote mass, damping, stiffness coefficients, and $\hat{\Omega}_{\alpha i}$ is the surface force term, respectively, For the damping matrix $C_{\alpha i \beta k}$, Rayleigh damping defined by the sum of the damping proportional to the mass and proportional to the stiffness is introduced. Where boundary conditions are as follows. The boundaries Γ_1 and Γ_2 are known boundary of displacement $u_{\beta j}$ and surface force $\Omega_{\beta j}$, respectively;

$$u_{\beta j} \quad = \quad \hat{u}_{\beta j} \qquad \text{on} \quad \Gamma_1, \tag{6}$$

$$\Omega_{\beta j} \quad = \quad \hat{\Omega}_{\beta j} \qquad \text{on} \quad \Gamma_2, \tag{7}$$

where $\hat{u}_{\beta j}$ and $\hat{\Omega}_{\beta j}$ mean the known displacement and surface force. The precise formulation is found in equation (13).
The stabilization term Ξ is represented as follows;

$$\Xi = \frac{1}{2}\int_{t_0}^{t_f} (x_{\alpha i}^{(l+1)} - x_{\alpha i}^{(l)}) W_{\alpha i \beta j} (x_{\beta j}^{(l+1)} - x_{\beta j}^{(l)}) dt, \tag{8}$$

where $x_{\alpha i}^{(l)}$ means reference value of the position of the geological boundaries at l-iteration and $W_{\alpha i \beta j}$ is the stabilization weights to secure the stability of the computation. The last term Ξ will be zero at the final iteration stage.

III. Discretization

A. Finite Element Method

As for the spatial discretization, the finite element method is applied. A computational domain is divided into tetrahedron elements, and approximated by the linear polynomial of coordinates x, y and z. The finite element equation can be expressed as follows;

$$M_{\alpha i\beta j}\ddot{u}_{\beta j} + C_{\alpha i\beta j}\dot{u}_{\beta j} + K_{\alpha i\beta j}u_{\beta j} = \hat{\Omega}_{\alpha i}, \quad (9)$$

where damping and the other coefficient matrices are written as follows;

$$M_{\alpha i\beta j} = \int_V \rho\delta_{ij}N_\alpha N_\beta dV, \quad (10)$$

$$K_{\alpha i\beta j} = \int_V N_{\alpha,j}D_{ijkl}N_{\beta,l}dV, \quad (11)$$

$$C_{\alpha i\beta j} = \alpha_0 M_{\alpha i\beta j} + \alpha_1 K_{\alpha i\beta j}, \quad (12)$$

$$\hat{\Omega}_{\alpha i} = \int_{\Gamma_2} N_\alpha \hat{t}_i d\Gamma + \int_V \rho N_\alpha \hat{b}_i dV, \quad (13)$$

in which N_α is called as the shape function, which expresses the approximate geometry of displacement distribution. For the damping matrix $C_{\alpha i\beta j}$, Rayleigh damping defined by the sum of the damping proportional to the mass and proportional to the stiffness is introduced. Two coefficients α_0 and α_1 in eq.(12) are parameters obtained by the characteristic frequency of elastic body and the damping constant.

B. Average Acceleration Method

As for the temporal discretization, the average acceleration method is applied to the finite element equation. The average acceleration method is a numerical technique to solve the second order differential equation. It is assumed that the acceleration at $t^{(n)} \leq t \leq t^{(n+1)}$ is equal to the mean value of the acceleration of $t^{(n)}$ and $t^{(n+1)}$, and constant. In the average acceleration method, the displacement and the velocity at $(n+1)$ time are assumed as follows;

$$u^{(n+1)}_{\beta j} = u^{(n)}_{\beta j} + \Delta t\dot{u}^{(n)}_{\beta j} + \frac{\Delta t^2}{4}(\ddot{u}^{(n+1)}_{\beta j} + \ddot{u}^{(n)}_{\beta j}), \quad (14)$$

$$\dot{u}^{(n+1)}_{\beta j} = \dot{u}^{(n)}_{\beta j} + \frac{\Delta t}{2}(\ddot{u}^{(n+1)}_{\beta j} + \ddot{u}^{(n)}_{\beta j}), \quad (15)$$

where Δt is time increment, $u^{(n+1)}_{\beta j}$ and $\dot{u}^{(n+1)}_{\beta j}$ denote the displacement and the velocity at $(n+1)$ time, respectively. These equations are identical to the Newmark β method with γ=1/2 and β=1/4. The equation (16) can be obtain by discretizing the finite element equation and denoting quantities in the present time as (n);

$$G_{\alpha i\beta j}\ddot{u}^{(n+1)}_{\beta j} = \hat{\Omega}_{\alpha i} - H_{\alpha i\beta j}\ddot{u}^{(n)}_{\beta j} - I_{\alpha i\beta j}\dot{u}^{(n)}_{\beta j} - K_{\alpha i\beta j}u^{(n)}_{\beta j}, \quad (16)$$

where each matrices are written as follows;

$$G_{\alpha i\beta j} = M_{\alpha i\beta j} + \frac{\Delta t}{2}C_{\alpha i\beta j} + \frac{\Delta t^2}{4}K_{\alpha i\beta j}, \quad (17)$$

$$H_{\alpha i\beta j} = \frac{\Delta t}{2}C_{\alpha i\beta j} + \frac{\Delta t^2}{4}K_{\alpha i\beta j}, \quad (18)$$

$$I_{\alpha i\beta j} = C_{\alpha i\beta j} + \Delta t K_{\alpha i\beta j}, \quad (19)$$

Calculating acceleration $\ddot{u}^{(n+1)}_{\beta j}$ using eq.(16) and substituting these into eqs.(14) and (15), displacement $u^{(n+1)}_{\beta j}$ and velocity $\dot{u}^{(n+1)}_{\beta j}$ can be obtained.

IV. Derivation of Gradient and Adjoint Equation

The extended performance functional J^* should be stationary, thus,

$$\delta J^* = 0, \quad (20)$$

From the necessary condition of eq. (20), the adjoint equation (21) and the terminal conditions (22) and (23) can be derived as follows;

$$-\ddot{\lambda}_{\alpha i}M_{\alpha i\beta j} + \dot{\lambda}_{\alpha i}C_{\alpha i\beta j} - \lambda_{\alpha i}K_{\alpha i\beta j} - (\ddot{u}_{\alpha i} - \dot{\eta}_{\alpha i})W_{\alpha i\beta j} = 0, \quad (21)$$

$$\lambda_{\alpha i}(t_f) = 0, \quad (22)$$

$$\dot{\lambda}_{\alpha i}(t_f)M_{\alpha i\beta j} + \big(\dot{u}_{\alpha i}(t_f) - \eta_{\alpha i}(t_f)\big)W_{\alpha i\beta j} = 0, \quad (23)$$

The precise derivation is written in the reference [10]. Using eqs.(21) and (22), (23), eq.(20) can be transformed as follows;

$$\delta J^* = \int_{t_0}^{t_f} \lambda_{\alpha i}B_{\alpha i\beta j}\delta x_{\beta j}dt, \quad (24)$$

where;

$$B_{\alpha i\beta j} = \int_{\Gamma^{(s)}} (N_\alpha D^{(m)}_{ijkl}N_{\beta,l})n_j d\Gamma. \quad (25)$$

Thus, the update equation can be written as follows taking $x^{(0)}_{\beta j} = x^{(l)}_{\beta j}$ at l the iteration cycle;

$$W^{(l)}_{\alpha i\beta j}x^{(l+1)}_{\beta j} = W^{(l)}_{\alpha i\beta j}x^{(l)}_{\beta j} - \mathrm{grad}(J^{(l)})_{\alpha i}, \quad (26)$$

where;

$$\mathrm{grad}(J^{(l)})_{\beta j} = \lambda_{\alpha i}B_{\alpha i\beta j}, \quad (27)$$

V. Identification Method to Determine the Geological Boundaries

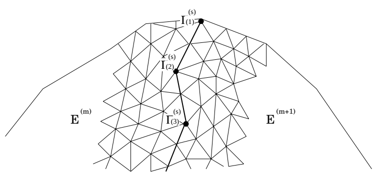

Fig. 2. Target and initial geological boundaries

Geological boundary between the strata of which elastic modulus are $E^{(m)}$ and $E^{(m+1)}$ is denoted by $\Gamma^{(s)}$. The boundary line $\Gamma^{(s)}$ is not always straight line. Thus, the line $\Gamma^{(s)}$ is divided to be the sum of the pieces of the sub-boundary lines $\Gamma^{(s)}_{(n)}$, which are expressed in Figure 2. The integral over the line $\Gamma^{(s)}$ can be transformed into the sum of the integral over $\Gamma^{(s)}_{(n)}$, i.e.,

$$\int_{\Gamma^{(s)}} (N_\alpha D^{(m)}_{ijkl} N_{\beta,l}) n_j d\Gamma = \sum_{n=1}^{N} \int_{\Gamma^{(s)}_n} (N_\alpha D^{(m)}_{ijkl} N_{\beta,l}) n_j d\Gamma; \quad (28)$$

If the exact boundary line $\Gamma^{(s)}$ is known in advance, the term $B_{\alpha i \beta j}$ is;

$$B_{\alpha i \beta j} = 0, \quad (29)$$

Unfortunately, the exact boundary line is not known when we start the computation. Thus, the boundary line is assumed as the initial condition, which is expressed as $\Gamma^{(s)}_{(n)}$. The initial boundary and the boundary at the intermediate iterations are referred to the false boundary and denoted by $\Gamma^{(s)}_{(n)}$. On the boundary $\Gamma^{(s)}_{(n)}$, $B_{\alpha i \beta j}$ is not zero. Thus, the $grad(J^{(l)})_{\beta j}$ in eq.(27) can be obtained. Using the update equation (26) the new position of the boundary can be computed.

VI. Numerical Example

By numerical study, the identification technique is verified by using the adjoint equation method which is derived in the preceding sections. To prove the availability of the method which is the identification of the geological boundary, the simplified model is applied. The analytical model is set to not complex shape but shape which can be easily calculated as the reasons of verification of the identification technique. The finite element mesh which had been shown in Figure 3 developed from geological data near the Suemune tunnel.

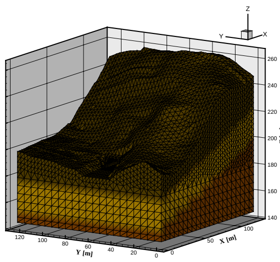

Fig. 3. Finite element mesh

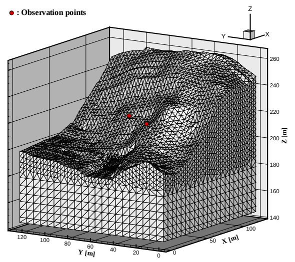

Fig. 4. Computational condition

TABLE I
Geological properties of the model

	Properties of each Stratum		
	Elastic modulus $[kN/m^2]$	Density $[kg/m^3]$	Poisson ratio
Stratum 1	1.0×10^6	2.40×10^3	0.32
Stratum 2	1.0×10^5	2.32×10^3	0.32
Stratum 3	1.0×10^6	2.40×10^3	0.32

The finite element mesh in 3D is shown in Figure 3. The total number of nodes and elements are $25,135$ and $139,578$, respectively. There are three geological strata in this computational domain. These are called as stratum 1, 2 and 3. The geological condition of layer 1 and 3 are consist of hard rocks, on the other hand, strata 2 is formed of soft rock. The elastic modulus, density of the ground and Poisson ratio are presupposed as the table I. The time increment used for the computation was $\Delta t = 1.0 \times 10^{-2}[sec]$. The total time of computation was $1.0[sec]$. The damping coefficients were given $\alpha_0 = 2.5 \times 10^{-1}$ and $\alpha_1 = 1.6 \times 10^{-3}$. The two observation points are set so as to cross the geological boundary. The measured velocities at No.1 : $(X_1, Y_1, Z_1) = (70.0, 62.6, 220.0)$ and No.2 : $(X_2, Y_2, Z_2) = (57.5, 41.3, 221.5)$ are used for computation. We assumed the following boundary conditions; the three components of the displacement were assumed to be zero for the bottom surface. The horizontal direction displacement of the side surface of the computational domain were assumed to be zero and all the other surface were considered to be stress free. Because computational domain is extracted the limited range around the tunnel from the semi-infinite and continuous natural ground, we must define boundary condition so that a continuity with the domain of it beyond is almost satisfied in the edge face of the computational domain. Because the tunnel face and observation points are included in the central part of the computational domain, the boundary effects may be small if we consider the first part of the first wave group formed by the blast.

We now consider the assumption of blasting force. The Borehole pressure which was introduced by U. S. Army Corps of Engineers [15] is given from the left-hand side at the side surface. The external force to occur by a actual blast has the following characteristics: (1) It shows a sharp increase at short times. (2) It shows a gradual decline after the rise. (3) It diffuses to the ground slowly. Therefore Borehole pressure which is proposed by U.S. Army Corps of Engineers is applies to be able to describe a history of the pressure in this research.

$$F_0 = 6.06 \times 10^{-3} \left(\frac{\rho_e V_d^2}{1 + 0.8 \rho_e} \right), \quad (30)$$

Eq.(30) shows the highest point of pressure of the explosion. where F_0, V_d^2 and ρ_e are highest value of pressure, detonating velocity and specific gravitational acceleration. We can describe a blasting phenomenon by introducing this Borehole pressure. It is given two exponential functions in order to consider the time variable influence. So that we can easily calculate development of formula, eq.(30) is transformed into following form.

$$f(t) = A(e^{-\xi t} - e^{-\eta t}), \quad (31)$$

where A means maximum amplitude of pressure which occurs by a blast. ξ and η are coefficients that are defined to be able to express time history of blasting force $f(t)$ arbitrarily. In this research, ξ and η are set 1000 and 5000, respectively.

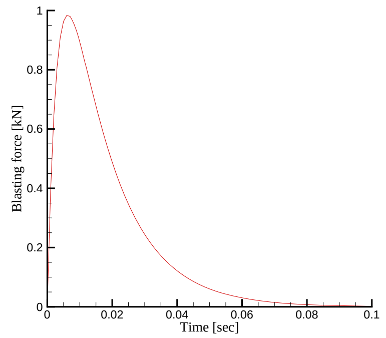

Fig. 5. Time history of external force

The time when pressure by the blasting force reaches the highest value is shown by using two coefficients as follows;

$$t_{peak} = \frac{\ln(\eta/\xi)}{\eta - \xi}, \tag{32}$$

Eqs.(30), (31), (32) are shown by G. Wu [13]. The external force which is defined as explained above is plotted in Figure 5. In this research, initial value of external force is set as $2.0 \times 10^5 [kN]$. In this paper, the actual geological boundary, that is the boundary of two strata with different elastic moduli, is identified assuming initial boundary, of which positions are different from the actual boundary. Boundary positions can be expressed by the coordinates, X, Y and Z. The actual boundary, which is the target boundary of the computation, is placed in advance. This is not known at the starting position. Thus, the initial boundary is assumed one. It is important what value is assumed at the initial boundary. To verify the general versatility, three cases which are different initial conditions are analyzed. In numerical study, it is assumed that the geological boundary is located in a inclined direction on the computational model. The initial and target geological boundaries are shown in Figures 6.

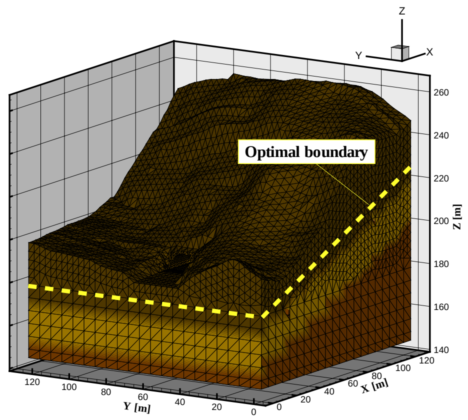

Fig. 6. Initial assumed and target boundaries

This inclined boundary surface is described by plane equation. When a calculation is performed, there is a matter that we have to consider. It is a definition method of the performance function. As previously mentioned, the performance function consists of square sum of the residuals between computed and observed velocities. Under ordinary circumstances, observed data at the construction site are employed as observed velocity. However the observation velocity of this study is the calculation arbitrarily beforehand. The verification of the algorithm for the identification technique is performed easily and simply, because we used this method. If this identification method is effective, because observed velocity is not actual data, observed velocity corresponds with computed velocity.

VII. Numerical Result

Red points plotted in Figure 7 show the variation of the performance function. It is shown in Figure 7 that the performance function to be converged to zero. This result means that the calculated velocities are coincident with the observation velocities. Like figure (Fig.$9-14$), the discrepancy between computed and observed velocity become zero. Blue points represented in Figure 8 show that the movements of the geological boundaries from an initial to a target values. The value of the coordinates in the Z direction at the $X = 126.0$ and $Y = 0.0$ are described in Figure 8. Figure 15 shows the identified boundary. The identified boundary (Fig. 15) is coincident with the target boundary (Fig. 6). Thus, the identification method when it is supposed that natural ground is consists of several stratum was verified. The identification to be based on optimal control theory was performed. The effective of present algorithm is verified from all these results.

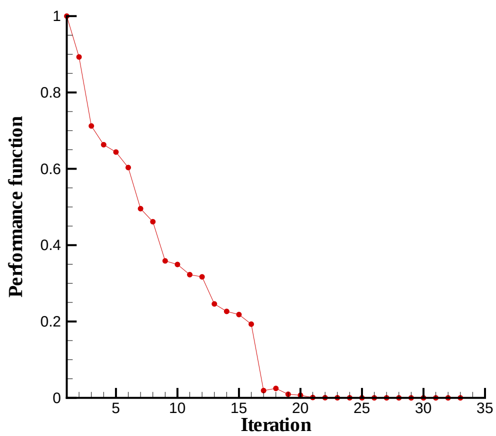

Fig. 7. Variation of performance function

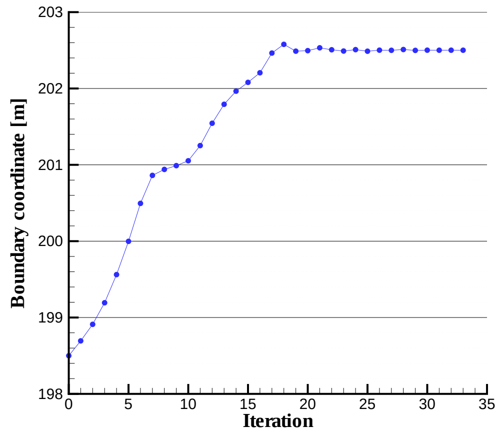

Fig. 8. Variation of boundary coordinate

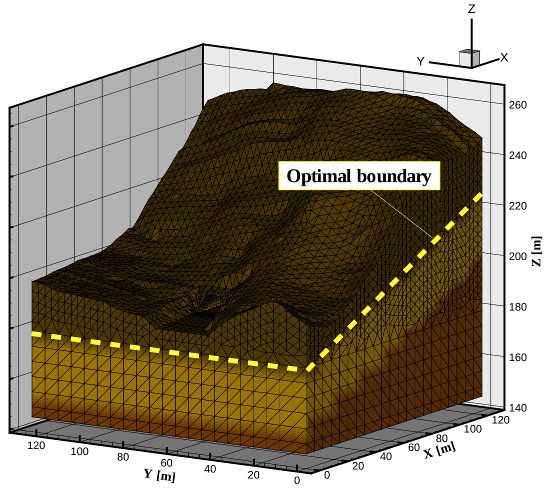

Fig. 15. Identified boundary

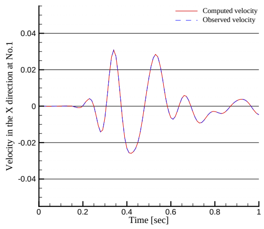

Fig. 9. Velocity (X-axis at No.1)

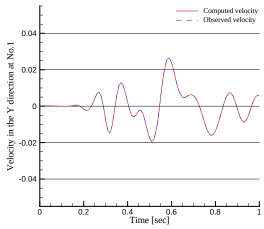

Fig. 10. Velocity (Y-axis at No.1)

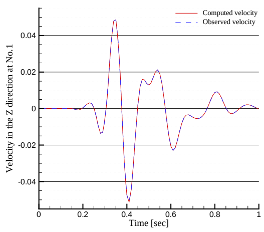

Fig. 11. Velocity (Z-axis at No.1)

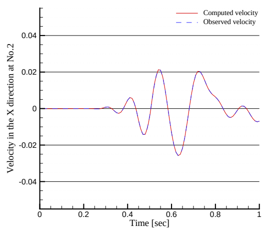

Fig. 12. Velocity (X-axis at No.2)

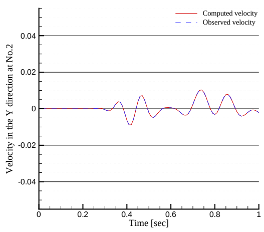

Fig. 13. Velocity (Y-axis at No.2)

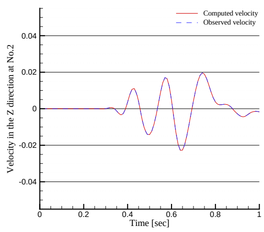

Fig. 14. Velocity (Z-axis at No.2)

VIII. Conclusion

In this paper, an identification technique to determine the position of geological boundary has been presented. The first order adjoint equation method of the optimal control theory was usefully used to identify the boundary stratum. Minimizing the performance function, which is the square sum of the discrepancies between the computed and observed velocities, the geological stratum were identified. The weighted gradient method which uses the gradient derived by the adjoint equation method was applied as a minimization technique. Effectiveness of this technique has been shown as results of verification. Safety and less expensive excavating works will become possible by the establishment of the technique for the identification of geological boundary.

As future research, this technique will be improved to do more accurate analysis. For example, the numerical assumption of actual blasting force at the excavation site and the exact expression for the actual phenomenon will be discussed. The other identification problem can be mentioned as almost same analytical technique because a part in search of the gradient with respect to control variable of performance function is expressed as unified derivation. Then based on this study, the three-dimensional issue of the identification of geological boundary strata using actual blasting waves will be preformed.

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