The effective material properties of rock mass inversed from dynamic test data

Rui Huang
School of Regional Development and Creativity, Utsunomiya University, Utsunomiya, Japan
School of Architecture and Civil Engineering, Xihua University, Chengdu, China

Takafumi Seiki
School of Regional Development and Creativity, Utsunomiya University, Utsunomiya, Japan

Qinxi Dong
School of Civil Engineering and Architecture, Hainan University, Haikou, China

Hui Wang
School of Civil Engineering and Architecture, Hainan University, Haikou, China

Ömer Aydan
University of the Ryukyus, Okinawa, Japan

ABSTRACT: In order to understand characteristics of wave propagation on rock mass, as well as to solve the difficulty of experiment result reproducibility at high frequency, it is essential to obtain the effective material property parameters of rock mass inversed from dynamic test data. In this study, the authors propose an inversing method based on dynamic finite element analysis (FEM) to obtain the elastic modulus and Rayleigh damping coefficients. This method is applied to in-situ experiments in an active Oya tuff underground quarry, Utsunomiya City, Tochigi Prefecture, Japan, and all material property parameters are determined using the displacement-time historical data integrated from the acceleration curves recorded at the sensor locations with impact loading. A good agreement of the dynamic numerical results using inversed material parameters compared with the measured acceleration data is obtained.

Keywords: inversion, dynamic finite element analysis, elastic modulus, Rayleigh damping coefficients, in-situ experiment.

1 INTRODUCTION

The Oya tuff underground quarry located in Utsunomiya City, Tochigi Prefecture, is the largest tuff production area in Japan, and it is also a tourist attraction as a material cultural heritage of Japan. According to the predictions of the Institute of Disaster Prevention Science and Technology, and the Earthquake Research Promotion Headquarters, Utsunomiya city is likely to be hit by the offshore plate in Ibaraki Prefecture and a strong downward type earthquake in Tokyo, and the Oya tuff underground quarry is also likely to be affected by a strong downward earthquake.

At present, there have been a lot of researches on dynamic vibration characteristics of underground structures and voids (Dintwe, Seiki, Aydan, & Tokashiki, 2019; Ömer Aydan, Takashi Ito, Takafumi Seiki, Katsumi Kamemura, & Iwata, 2019; Seiki, Ishii, Takahashi, Noguchi, & Ohmura, 2016; Seiki et al., 2019), which are related to the seismic response of rock mass and the propagation of elastic waves. However, there is little research on the effective inversion of material property parameters of Oya rock mass using dynamic responses measured in the field. Previously, heavy hammer impact tests were conducted in the basement of Oya tuff underground quarry, the impact-load and acceleration at the five observation points were recorded along the measurement line (Hiroaki Takamura, Seiji Ebisu, & Takafumi Seiki, 2022). Subsequently, the dynamic response analysis of the vibrational shock wave propagation characteristics observed in the experiment was analyzed by numerical simulation, but the high frequency part was not in good agreement(Takafumi Seiki, Seiji Ebisu, Hiroaki Takamura, & Yuki Kusunoki, 2022).

Based on the previous research results, the material property values of Oya tuff underground quarry, which include the elastic modulus E and Rayleigh damping coefficients α and β, are inversed using the displacement-time historical data integrated twice from the acceleration of the monitoring point. This study can reproduce the propagation characteristics under the impact-loads, which is of great issue for the safety evaluation of Oya tuff underground quarry.

2 IN-SITU EXCITATION EXPERIMENT

The experimental site was set at the bottom of the Oya tuff underground quarry, the surface of Oya rock mass after stone excavation is flat and homogeneous, which is conducive to the impact-load test data as little interference as possible. Five accelerometers with a diameter of 24 mm are used in this work, fixed with M6 screw on a 30mm square 100mm long prism, as described in the previous paper (Hiroaki Takamura et al., 2022). In the experiment, a hammer of 5.5kg was used to impact the excitation point, the radius of the impact hammer excitation was 0.038m, and the five measuring points (A, B, C, D, E) were placed on the same line with a double distance of 0.3m (T. Seiki, 2022). The impact-load of time history is shown in Figure 2.

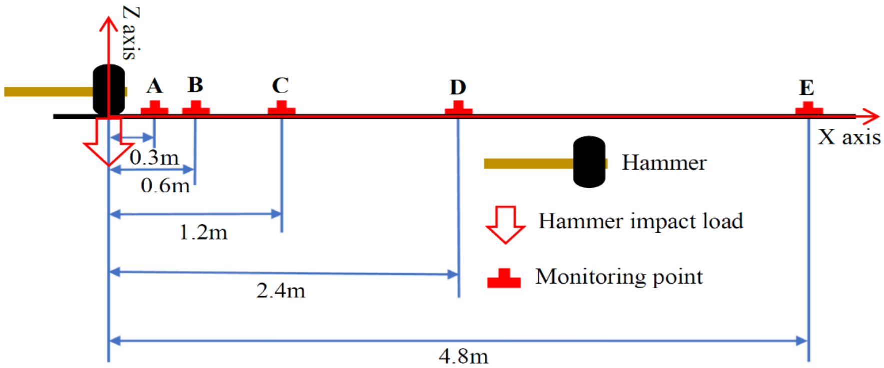

Figure 1. Conceptual diagram of shock vibration experiment.

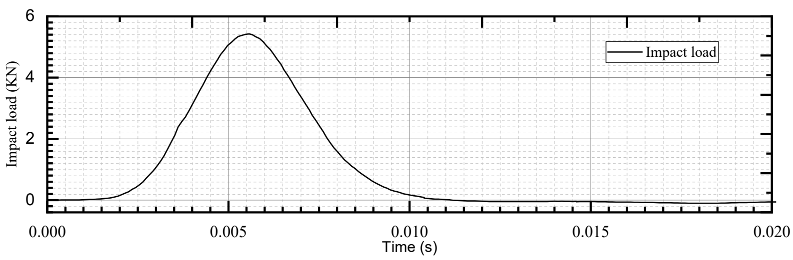

Figure 2. Time series of Impact-load.

According the analysis of experimental measurement data, it can be seen that the peak values of measured acceleration all appear along the Z direction, but there are values even in the X axis direction orthogonal to the vibration propagation direction. Moreover, displacement-time history in three directions were analyzed in the previous studies, and the attenuation of the measured data performance may be affected by the physical properties of the Oya tuff underground quarry. Based on the experimental results, it is clarified that in addition to geometric distance attenuation, the wave propagation should also consider the physical attenuation of the media. On the basis of theory, we study how to obtain the physical parameters of the propagation medium through inversion, and then reproduce the shock vibrating wave.

3 DYNAMIC INVERSION OF ELASTIC MODULUS AND RAYLEIGH DAMPING COEFFICIENTS

3.1. Dynamic response analysis

Using the 3D finite element discretization of Oya tuff structure, the matrix equation of motion can be expressed as

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) = \mathbf{f}(t) \tag{1}$$

with initial condition

$$\mathbf{u}(\mathbf{0}) = \mathbf{0}, \qquad \dot{\mathbf{u}}(\mathbf{0}) = \mathbf{0} \tag{2}$$

In which, $\mathbf{M}$ is the mass matrix; $\mathbf{C}$ is the damping matrix; and $\mathbf{K}$ is the stiffness matrix; $\boldsymbol{f}(t)$ is finite element load vector. $\ddot{\mathbf{u}}(t)$, $\dot{\mathbf{u}}(t)$, $\mathbf{u}(t)$ are the vectors of nodal acceleration, velocity and displacement, respectively.
For Rayleigh damped Oya tuff structure, the damping matrix $\mathbf{C}$ used in this study, can be expressed as

$$\mathbf{C} = \boldsymbol{\alpha}\mathbf{M} + \boldsymbol{\beta}\mathbf{K} \tag{3}$$

where, α, β are the mass-proportional and stiffness-proportional damping coefficients, respectively.
If the damping ratio ξ is constant throughout the Oya tuff structure, scalar values α, β can be computed using two significant natural modes i and j using the following equation:

$$\boldsymbol{\alpha} = \frac{2\boldsymbol{\xi}\boldsymbol{\omega}_i\boldsymbol{\omega}_j}{\boldsymbol{\omega}_i + \boldsymbol{\omega}_j}, \qquad \boldsymbol{\beta} = \frac{2\boldsymbol{\xi}}{\boldsymbol{\omega}_i + \boldsymbol{\omega}_j} \tag{4}$$

3.2. Estimating parameter algorithm in time domain

Generally, algorithms take experimental values of unknown parameters as input data and refine them iteratively until the system model response is sufficiently close to the displacement-time history integrated from the measured acceleration value. The output error is defined in the non-linear least squares sense in the time domain.

$$\boldsymbol{J}(\boldsymbol{P}) = \frac{\mathbf{1}}{\mathbf{2}}\int_{t_0}^{t_f}\sum_{i=1}^{n}(\boldsymbol{u}_i^*(\boldsymbol{t}) - \boldsymbol{u}_i(\boldsymbol{P},\boldsymbol{t}))^2\boldsymbol{dt} \tag{5}$$

where, n is the number of measured displacements at the surface of the Oya tuff slab; and $u_i(\mathbf{P}, t)$ and $u_i^*(t)$ are calculated and measured displacement-time histories at the location of accelerometer i, respectively. The vector P represents unknown material parameters that contain $\mathbf{P} = (\boldsymbol{E_1}, \boldsymbol{E_2}, \dots, \boldsymbol{E_m}, \alpha, \beta)^{\boldsymbol{T}}$. t_0 , t_f are the lower and upper time limitation to match calculated and measured responses of the Oya tuff structure in the time domain.
In order to obtain the optimal unknown parameter value, Gauss-Newton algorithm is adopted to minimize equation (5) without calculating Hessian matrix (Dong & Matsui, 2006). For an unconstrained minimization problem, the algorithm generates the following sequence of parameters.

$$\boldsymbol{AdP} = \boldsymbol{b} \tag{6}$$

In which, A is an (m+2)×(m+2) matrix that can be represented by the sensitivity coefficients.

$$A = \int_{t_0}^{t_f} \left(\sum_{i=1}^{n} \frac{\partial u_i}{\partial p_k} \frac{\partial u_i}{p_j} \right) dt,$$

$$b = \int_{t_0}^{t_f} \left(\sum_{i=1}^{n} (u_i^*(t) - u_i(p,t)) \frac{\partial u_i}{p_j} \right) dt, \quad j, k = 1, 2, \dots, m+2 \tag{7}$$

3.3. Dynamic inversion of material parameters

The finite element mesh, consisting 44574 8-node solid elements and 48755 nodes, is shown in Figure 3. The lateral remote boundaries were truncated at a distance of 20 m away from the center of the hammer impact loading, and the depth of Oya tuff structure was taken as 20 m. Owing to the symmetry of the geometry and loading, only a quarter of the region was considered in the 3D FE model. In order to discuss the effectiveness of inversion calculation for practical test problems, it is necessary to simplify the inversion parameters. In this study, the Oya rock mass is assumed to be an elastic homogeneous semi-infinite medium.

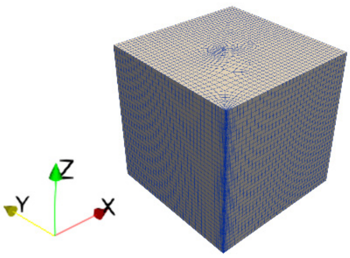

Figure 3. Finite element mesh.

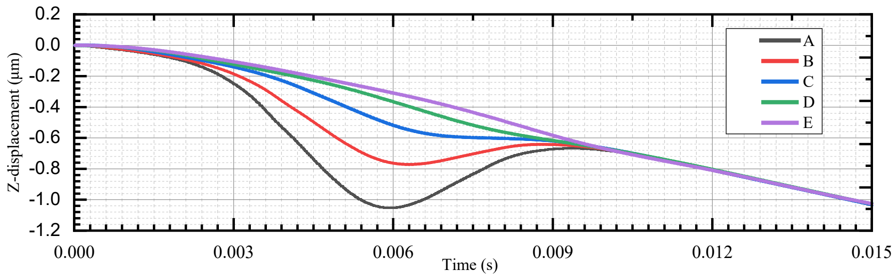

Figure 4. Z-displacements of points A to E with time histories integrated from recorded acceleration data.

As stated in the foregoing, the inversion of such Oya tuff mass involves determining elastic modulus E, and Rayleigh damping coefficients, α, β. There are total of 3 unknowns to be inverse in the time domain. The mass density and Poisson's ratio of Oya rock mass are known as, ρ=1770kg/m^3 and ν=0.23, respectively; the initial seed elastic modulus E takes 7GPa, and the damping ratio ξ is assumed as 3%. The initial seed values of Rayleigh damping coefficients α, β are calculated by equation (4) via eigenvalue analysis. Assuming the natural modes 1 and 30 are selected to compute α, β, and they take as α=8.896, β=4.830×10^{-5}. The loading is applied on the 3D FE model as a dynamic pulse data recorded from shock vibration test as shown in Figure 3. The analytical time takes 0.012s with time step 1.2×10^{-5}s for the transient finite element analysis with in-house code. The z displacement-time histories are obtained by integrating the acceleration-time histories at the five observation points (Ö. Aydan, 2007), as shown in Figure 4. Through analyzing the z displacements curves of A to E points, the displacement data between 0.0025s to 0.008s are selected as input data to inverse the material parameters, which have the highest credibility.

The inversed values of the elastic modulus and Rayleigh damping coefficients from 3D FE dynamic response analysis in the time domain for Oya rock mass are summarized in Table 1.

Table 1. The inversed material properties of Oya rock mass.

Parameters	Indices	Units	Values
Rayleigh damping coefficient	α	1/s	29.254
Rayleigh damping coefficient	β	s	3.576×10^{-4}
Elastic modulus	E	GPa	4.29776

4 COMPARISON BETWEEN MEASURED AND COMPUTED ACCELERATION

The acceleration-time histories between in-situ measured and computed with 3D FE analysis using the inversed values of elastic modulus and Rayleigh damping coefficients are also compared at the five accelerometer locations of A to E as shown in Figure 5. From Figure 5, it is found that the measured and computed acceleration-time histories are in basically agreement, besides fifth accelerometer location E. A large deviation takes place at accelerometer location E, which may be the influence of the reflect wave at computing model boundaries.

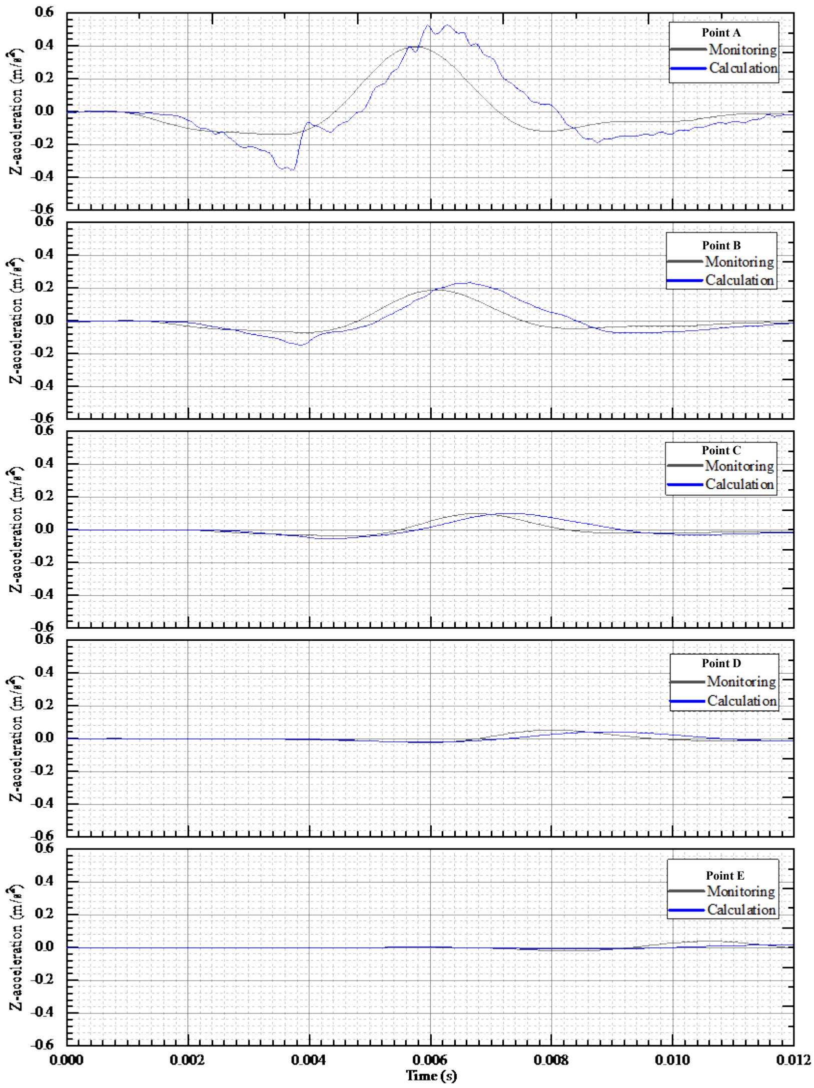

Figure 5. Comparison between measured and computed Z-acceleration time-histories at points A to E.

In general, the computed acceleration waveforms using the inversing results is in a good agreement with the measured curves, which indicates that the inversion results are reasonable and acceptable, and verifies the effectiveness and reliability of the inversion method for the elastic modulus and Rayleigh damping coefficients.

5 CONCLUSION

A theoretical method for the inversion of elastic modulus and Rayleigh damping coefficients of rock mass is proposed in this paper, and this method is used for inversion material property values of Oya tuff underground quarry. The calculation results show that the accelerations obtained by numerical simulation is in good agreement with the monitoring ones on the test site. This means that the shock vibration waveforms are reproduced, and also verifies that the inversion method can be used to evaluate underground structures. This method can also be applied to the inversion of elastic multilayered media, even heterogeneous media, which will be further discussed in the following paper.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. H. Takamura, Nishimatsu Construction Co. Ltd. and Dr. S. Ebisu, Murasaki construction Co. Ltd. for leading and conducting the field tests and their great help in experimental data processing. We would like to express our gratitude by describing that the field tests were carried out in a part of activity of Rock Dynamics Sub-Committee, Rock Mechanics Committee, Japan Society of Civil Engineers.

REFERENCES

Ö. Aydan, (2007). An integration technique for ground displacement from acceleration records and its application to actual earthquake records. *Journal of The School of Marine Science and Technology, Tokai University, Vol.5, No.2*, pp.1-12.

Dintwe, T. K. M., Seiki, T., Aydan, Ö., and Tokashiki, N. (2019). *The Behaviour of Oya Tuff Pillars Under Static and Shock Loading.* Paper presented at the ISRM Rock Dynamics Summit.

Dong, Q., & Matsui, K. (2006). *Structural evaluation of pavement using surface wave and portable FWD tests.* SPIE-The Nondestructive Evaulation for Health Monitoring & Diagnostics, San Diego, USA.

H. Takamura, S. Ebisu, and Seiki, T. (2022). Study of Wave Propagation by Vibration Excitation on Oya Tuff Slab and Its Dynamic Analysis (Part 1)-Characteristics of Emplical Wave Propagation of Vibration Excitation-(in Japanese). *48th Japan Rock Mechanics Symposium, JSCE, Tokyo,* 19-24.

Ö. Aydan, T. Ito, Seiki, T., K. Kamemura, and Iwata, N. (2019). *2019 Rock Dynamics Summit* (1st Edition ed.). London.

Seiki, T., Ishii, T., Takahashi, K., Noguchi, S., and Ohmura, T. (2016). *Seismic Response of Numerical Analysis and Field Measurement in Oya Tuff Underground Quarry.* ISRM International Symposium - EUROCK 2016.

Seiki, T., Takahashi, K., Dintwe, T. K. M., Noguchi, S., Ohmura, T., and Aydan, Ö. (2019). *Consideration of Structural Stability for Oya Underground Quarry With Dynamic Response.* ISRM Rock Dynamics Summit, Okinawa, Japan.

Seiki, T., S. Enisu, H. Takamura, and Y. Kusunoki (2022). Study of Wave Propagation by Vibration Excitation on Oya Tuff Slab and Its Dynamic Analysis (Part 2)-Reproducibility of Impact Excitation Experoment by Dynamic Analysis-(in Japanese). *48th Japan Rock Mechanics Symposium, JSCE, Tokyo*, 25-30.