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Seismic characteristics of field measurements and numerical analyses of an underground quarry in Oya

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ABSTRACT: Oya tuff, which is categorized as soft rock, has been excavated in Oya area of Utsunomiya City, Tochigi Prefecture, Japan, for building stone and retaining walls for several decades. It is one of the most commonly used rock materials in Japan. As a result, there are many abandoned underground quarries existing in this area. After the 2011 East Japan Great Earthquake, the consideration of the seismic responses of underground quarries has become very important. Almost all of Oya underground quarries have been excavated using room and pillar method except some, which are long wall type. In the study, the quarry under investigation is an active room and pillar type and this paper presents the field measurement techniques used to study the seismic response of the quarry. Using the field data, underground dominant frequencies were obtained through analytical solutions. A numerical model was then developed using a Finite Difference method (FDM) program FLAC3D to assess the dynamic stability of the quarry.

1 INTRODUCTION

Oya tuff is pumice volcanic gravel tuff and one of the most popular building soft rock. Many abandoned underground quarries exist in this area. After the 2011 East Japan Great Earthquake, the consideration of the seismic responses of quarries has become very important (Aydan 2014, Inoue et al. 2012). Almost all of the abandoned underground quarries in Oya were excavated using room and pillar technique while some of them are of long wall type. The authors consider the seismic response of a pillar in room and pillar type quarry through the numerical analyses and field measurement. Three seismometers were installed on a pillar along its vertical direction. The authors also carry out dynamic stability analyses for the underground space using an FDM software, FLAC3D. In this study, the authors discuss the dynamic characteristics of an Oya underground quarry through the results of field measurements and numerical analyses. Those results yielded the seismic characteristics and the natural period of the underground quarry. The authors also discuss the difference of the seismic response characteristics of a pillar in the underground quarry. Finally, the authors consider the structure stability of underground quarry with the instrumental and computational results.

2 FIELD MEASUREMENT OF DYNAMIC MOTION OF A PILLAR IN UNDERGROUND QUARRY

Based on surveys after huge collapse of underground quarry around 1990 and previous researches (Seiki et al. (2007, 2016), it became clear that the subsidence of underground quarries was caused by illegal excavation without regarding structural safety (Oyagi & Hungr 1989, Katayose & Seiki 2008). It is expected that the safety of undergrounds are checked continuously during exploitation.

There are several ways to get the dominant frequency of the rock mass and ground such as micro tremor observations, seismic observation and vibration test. The previous researchers surveyed dynamic characteristics at a certain underground quarry. However, there are only few researches which focuses on both field measurement and its structural safety. Thus, this study focuses on measurement of micro-tremors and seismic waves of pillars in the quarry. Based on the results, this study evaluates the dynamic characteristics of the ground. Specifically, the authors calculated the Fourier spectrum ratio of the horizontal and vertical components of the velocity, which is called H/V spectrum (Nakamura 2008), and compare those dominant frequencies and characteristic magnification. The authors consider the phase of wave propagation in the pillar from records. Additionally, magnitude and direction to epicentres and location of earthquake effects were considered.

The authors calculated the theoretical spectrum by multilayer geological structure which is estimated by s-waves and compare it with H/V spectrum. Finally, we summarize the valuable results and knowledge to understand dynamic responses of underground quarry. The authors consider that the knowledge is useful for safety consideration of present Oya underground quarry, which is primary purpose of the study.

3 SEISMIC MEASUREMENTS AND MICRO TREMOR SURVEY

3.1 *Introduction to underground quarry and observation points*

The authors measured a room and pillar type underground quarry for mining Oya tuff spreading 60 m from east to west, 160 m from north to south and 60 m in depth from the ground surface. Its pillar reached up to 30 m in height, which is the maximum allowable height in the regulations for mining Oya tuff. The side width of the pillars is around 10 m and aligned along N51E. Three seismicmeters were installed along the vertical direction of the pillar. Here, the upper one is PTP, the middle one is PMD, the bottom one is PBT, respectively (Figure 1, Photo1). H1 is parallel to N51E. With the use of seismograph, both seismic motion and microtremor could be measured.

3.2 *Seismic data for analysis*

The authors checked earthquakes, which were detected at Oya Observation Centre with the earthquake lists provided from Japan Metrological Agency (Figure 2). Also we collected basic information such as magnitude, coordinates of epicentre of those earthquakes. Twenty earthquakes were chosen around of Oya area, see (Table 1). A recent study by Seiki et al. (2016) on seismic responses of longwall type quarry 2 km away from the current study area, has shown that increase in wave velocities results in high strain levels in roofs.

3.3 *Methodology for measurement and analysis*

The authors carried out micro-tremor surveys and seismic observations at 3 points on a pillar by

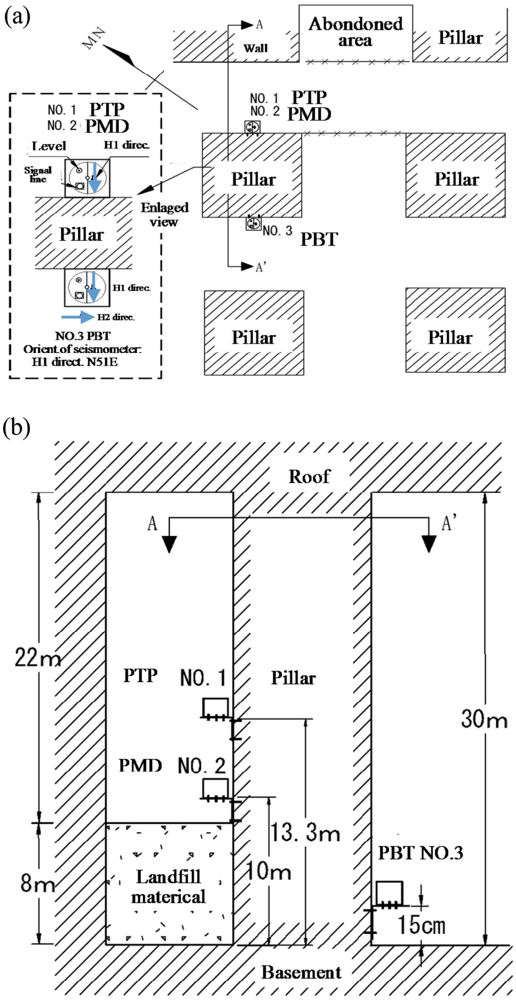

Figure 1. Layout of underground quarry and locations of instruments, (a) plane view, (b) elevation view.

Photo 1. Seismic meter and point for velocity measurement along the pillar.

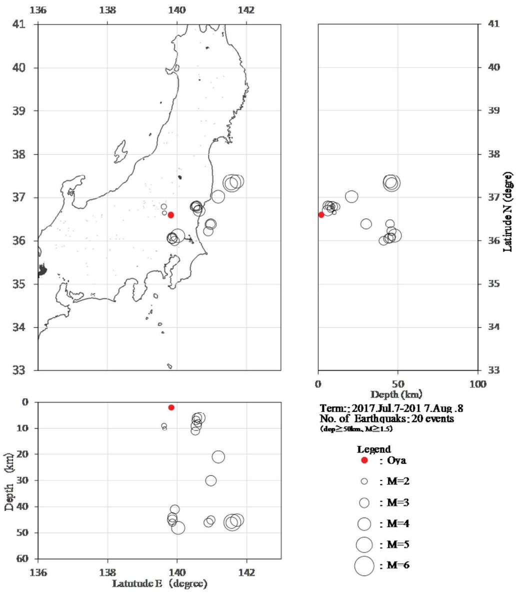

Figure 2. Epicentre and magnitude of selected earthquake in this study.

seismometers which are able to measure motions in 3 directions and their natural frequency is about 1 sec. The instruments can measure 9 components simultaneously and record in the system of Lennartz electronic GmbH. We analysed selected seismic data in 3 components, e.g. vertical direction, V, horizontal direction, H1 and the other horizontal direction and perpendicular to H1, H2, to understand characteristics of wave propagation and compared H/V spectrum and of micro-tremors with those of selected seismic data.

We selected s-wave domains from recorded data of tremors and seismic events to calculate H/V spectrum with Parzen Window function of 0.4 Hz in band width from smoothened records. In the case of calculating horizontal components, we carried out the square root of squared sum of two perpendicular horizontal records. On the other hand, we extract micro tremor part from apparent seismic datum in 20 sec. After the main seismic motion and calculate H/VB and H/V spectrum of it in the same way as seismic records. We also analysed wave records caused by Fukushima ken-Oki (FO, Offshore at Fukushima Pref.), M = 5.8 and extract 1 sec. of beginning part of s-wave. Figure 3 shows an example of seismic motion data which was measured in Oya. We calculate transfer function by transfer matrix method of free software, GRDAMP and get amplitude spectrum. Here, the transfer function is based on the bottom formation given by P-S wave velocity logs and borehole datum.

Table 1. Specification of earthquake data.

Date	Time	Lat	Long	Dep	Mag(1)	Region
8-Jul-17	09:21:19.8	36.733	140.602	8.0	2.7	Ibaraki ken Hokubu
8-Jul-17	20:48:50.9	37.378	141.723	45.0	4.5	Fukushima ken Oki
9-Jul-17	03:36:32.5	37.028	141.187	21.0	4.3	Fukushima ken Oki
12-Jul-17	02:36:41.3	36.067	139.858	45.0	3.5	Ibaraki ken Nanbu
12-Jul-17	09:13:22.0	36.050	139.860	44.0	3.3	Ibaraki ken Nanbu
13-Jul-17	09:30:18.5	36.225	140.900	46.0	3.2	Ibaraki ken Oki
17-Jul-17	15:53:28.2	36.395	140.970	45.0	3.0	Ibaraki ken Oki
19-Jul-17	16:25:57.7	36.090	139.862	46.0	2.7	Ibaraki ken Nanbu
20-Jul-17	09:11:24.2	37.340	141.587	46.0	5.8	Fukushima ken Oki
20-Jul-17	09:56:50.1	37.323	141.567	46.0	4.1	Fukushima ken Oki
20-Jul-17	10:15:03.4	36.703	140.638	6.0	3.9	Ibaraki ken Hokubu
25-Jul-17	09:52:02.8	36.393	140.973	30.0	3.7	Ibaraki ken Oki
26-Jul-17	01:07:06.9	36.000	139.932	41.0	3.2	Ibaraki ken Nanbu
26-Jul-17	02:31:36.6	36.650	139.638	10.0	1.5	Tochigi ken Hokubu
2-Aug-17	02:18:45.2	36.815	140.542	7.0	3.0	Ibaraki ken Hokubu
2-Aug-17	07:15:56.8	36.120	140.022	48.0	4.6	Ibaraki ken Nanbu
2-Aug-17	12:46:29.2	36.800	140.542	9.0	3.6	Ibaraki ken Hokubu
3-Aug-17	22:41:37.2	36.792	140.523	11.0	3.0	Ibaraki ken Hokubu
4-Aug-17	13:54:14.6	36.818	140.570	6.0	3.3	Ibaraki ken Hokubu
7-Aug-17	18:34:42.4	36.802	139.620	9.0	1.8	Tochigi ken Hokubu

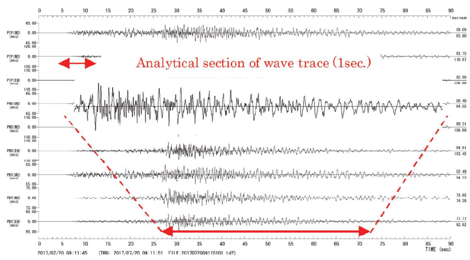

Figure 3. A seismic record measured at Oya.

4 ANALYTICAL RESULT

4.1 *Introduction to H/V spectrum*

With respect to the location of the epicentre 20, seismic records in 5 areas were selected and calculated the averaged spectrum as shown in Figure 4. From this results, the peak value of low frequency is predominant around 5 to 7 Hz. There is no significant difference among those areas. Amplitude spectrum decreased from Ibaraki ken-Oki (IO, Offshore at Ibaraki Pref.), Ibaraki ken-Hokubu (IH, North part in Ibaraki Pref.), Ibaraki ken-Nanbu (IN, South part in Ibaraki Pref.), Fukushima ken-Oki, Tochigi ken-Hokubu (TH, North part in Tochigi Pref.), subsequently. As there is no clear difference for 5 areas, we present the results in an averaged spectrum of individual measuring points as shown in Figure 5. Based on the results, the bottom point (bottom of the pillar, PBT) is predominant around 6 Hz. However, Middle point (middle of the pillar, PMD) and (top of the pillar, PTP) vibrate in slightly higher frequency than PBT. The dominant frequency reaches to around 10 Hz at upper point, PTP. Based on those results, there is no significant difference of dynamic characteristics of pillars from the viewpoint of seismic data used for analysis in individual area and there is no significant difference regarding the dominant frequency of dynamic characteristics of a pillar. Peak spectrum is prominent in around 6 Hz. Amplitude spectrum has slight difference in relation to the direction of epicentres. The spectra of the records from the earthquakes which has epicentre in south-east and north-east are slightly larger than that from the other epicentres. For earthquakes with epicentres in north-west area from Oya, their amplitudes are smaller than the other areas, it tends that amplitude of the peak spectrum are smaller than the others.

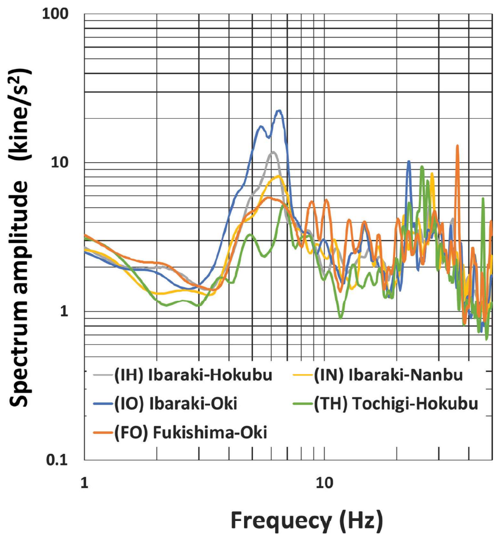

Figure 4. Fourier spectra of 5 events recorded at PNT in Oya.

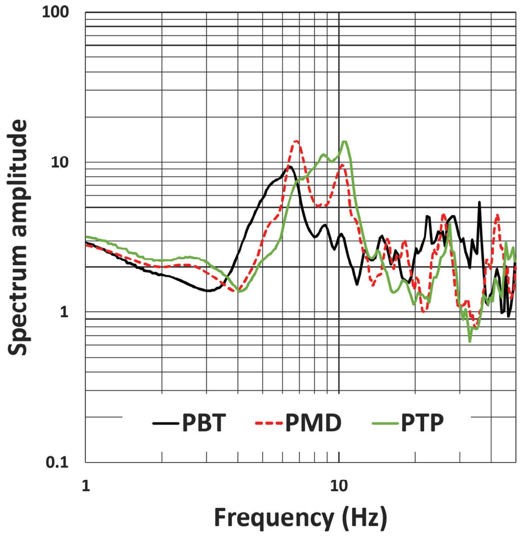

Figure 5. H/V Fourier spectrum of points in pillar.

4.2 *Characteristics of a micro tremor*

As the authors evaluate dynamic characteristics of a pillar, we compare H/V spectrum of earthquake and that of micro tremor. Figure 6 shows H/V spectrum of averaged seismic records and a micro tremor at upper and middle measuring point along the pillar. This figure shows that the spectra are almost same with a dominant frequency of 6 Hz at the bottom measuring point (PBT), 10 Hz in the upper measurement point (PTP).

4.3 *Dynamic characteristics of geological model*

We assumed the horizontal multilayer formation model in Oya area and calculate the characteristics of wave propagation through transfer matrix method. Then we compared the wave propagation of seismic data and microtremor with that of multilayer model formation. Since we use individual layer thickness of borehole data, S wave velocity of P-S wave velocity log and estimated density and damping ratio, we calculate theoretical spectrum ratio of the multilayer model. Here, the assumption is that oblique incident of SV wave from the base layer which is the upper surface of 6th layer. Table 2 shows the properties of the layers in the layer model. Figure 7 shows their theoretical spectrum and it shows that the second dominant frequency is 11.4 Hz. Even though the first dominant frequency is slightly smaller than the spectrum ratio of seismic waves and microtremors at the bottom measuring point, it was realised spectrum tendency of the model harmonizes with that of the seismic wave and microtremor approximately.

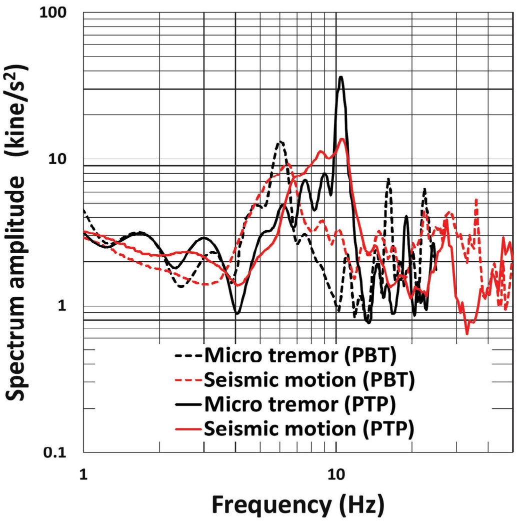

Figure 6. Fourier spectra of records using different monitoring techniques at different elevations.

Table 2. Characteristics of the multi-layer model.

Layer no.	Geology of formation	Thickness (m)	Density (kg/m^3)	S wave velocity (m/s)	Damping ratio
1	Surface soil	0.30	1.7	250	0.05
2	Silt	1.85	1.65	150	0.05
3	Gravel	2.50	1.9	450	0.05
4	Oya tuff (1)	20.0	1.95	700	0.05
5	Oya tuff (2)	25.35	2	940	0.05
6	Oya tuff (3)	–	2.1	1045	0.05

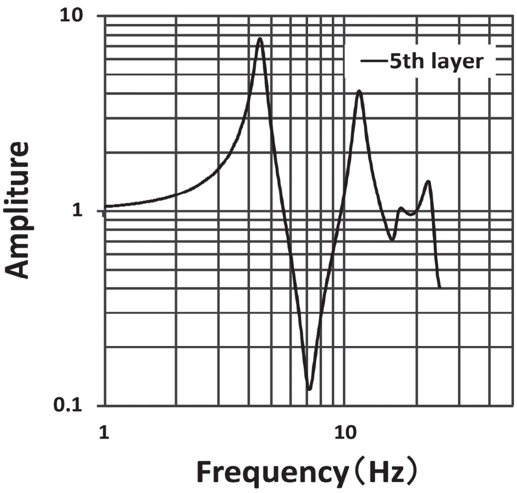

Figure 7. Amplification of the 5th layer.

5 SEISMIC STABILITY ANALYSES FOR OYA UNDERGROUND QUARRY

5.1 *Methodology for analysis*

This study numerically investigates the effect joints on the stability of Oya underground quarry using a 3D Finite Difference Method program FLAC3D. The stability was evaluated through the comparison of deformation with and without joint presence.

5.2 *Stability background*

Underground mines stability is of great concern in the geotechnical division mainly for a safe working environment in the mine (Mortazaria et al. 2009). Stability in the underground space is affected by couple of factors. However in this paper attentions will be on the discontinuity factor. The underground mine under investigation is of room and pillar type and thus it is inevitable not to focus on the pillar stability as major considerations. In the room and pillar mines, pillars are basically accountable for entire support of the overburden load from the roof top to the surface. Additionally they ought to be stable through the mining process and in some cases even for post mining activities (Zhaou et al. 2011, Mortazari et al. 2009, Hyuing-Sik et al. 2012). Discontinuities in general are zones of weakness, thus they reduce the strength of a rock mass or intact rock. Discontinuities cause different types of failures in rock mass depending on their position, orientation and joint properties. In most cases discontinuities pose great risks or overall failure of the underground. This paper aims to investigate the effects of discontinuity on Oya tuff underground quarry stability with a numerical code FLAC3D. For static scenarios, structures tend to be stable even with the presence of discontinuities. However in the dynamic conditions such as earthquakes, initiation of structure failure may occur and the investigation for dynamic states has to be taken into consideration.

5.3 *Modelling of Oya underground quarry*

The whole underground space was modelled using FLAC3D from the vertical shaft and all other horizontal spaces as seen Figure 8. The model has dimensions of 200 m × 105 m × 80 m (length × width × height). The rock property parameters used in the analyses were obtained from the laboratory tests and are given in Table 3. The simulation model adopted the perfect plastic constitutive model, which follows Mohr-Coulomb criterion, for the whole rock mass. Since mapped discontinuities at the field were generally near vertical, vertical interfaces were used to represent

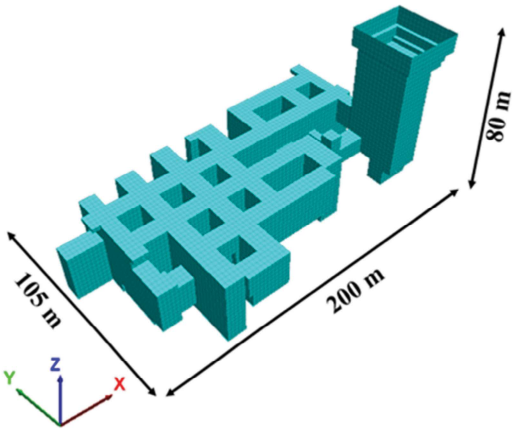

Figure 8. Model used in Numerical Analyses, 3D Model setup of Oya underground quarry.

Table 3. Material properties used in the numerical analyses.

Material property	Oya tuff	Joint
Bulk modulus (Pa)	1.38×10^9	–
Shear modulus (Pa)	0.91×10^9	–
Cohesion (Pa)	2.1×10^6	3.0×10^4
Friction angle (°)	30	20
Tension strength (Pa)	1.08×10^6	–
Density (kg/m^3)	1730	–

the joints according to their actual positions. The joint embedded is at 90 degrees, which means, no significant changes are expected in strength and displacement

5.4 *Results of numerical analysis*

The numerical analysis results, as shown in Figure 9 (a) after applying the vertical stress according to the quarry depth of 80 m. The maximum subsidence of about 3.7 cm was observed in the roof. If discontinuities are considered, the subsidence has a higher value and it is about 3.9 cm which takes place particularly around the pillar regions with the joint. The contours of the vertical displacement are shown in Figure 9. The distribution of the maximum displacement decreases down from the roof to the floor of the quarry, with a maximum and minimum displacement of 4 cm and 0.3 cm respectively for the jointed model. Figure 10 illustrates the situation under the dynamic state with which the simulation reveals the possibility of failure in the roof and top shaft walls and, whereas under static conditions yielding appeared on shaft walls only.

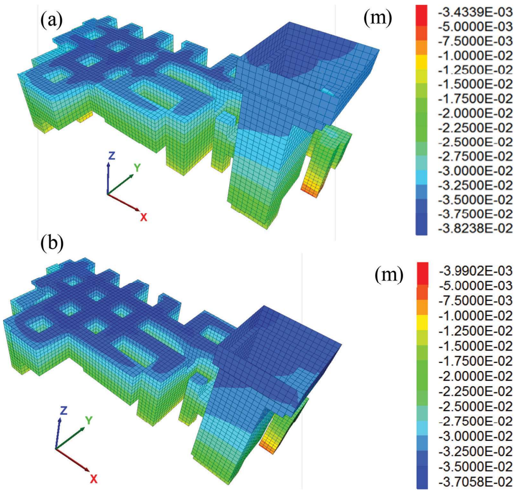

Figure 9. Computed displacement counters for models without (a) and with joints (b).

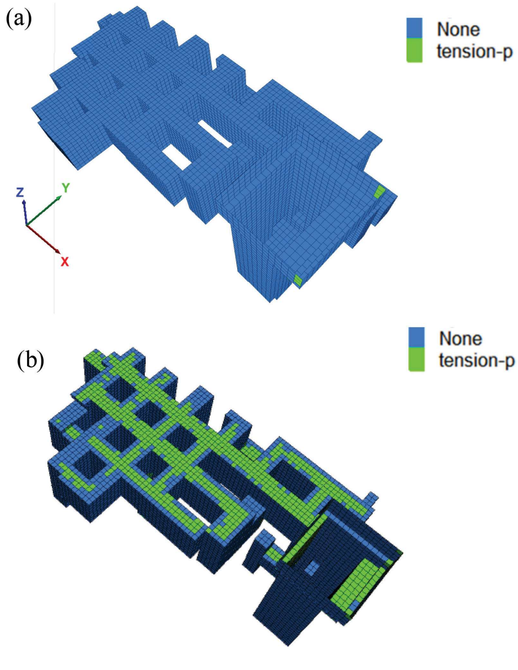

Figure 10. The excavated section showing yield zones. (a) static state and (b) dynamic state.

6 CONCLUSION

There is no significant difference in the H/V spectrums of seismic data recorded in 5 different areas around Oya. However, the magnification and direction of the epicentres from Oya slightly affect the spectrum. It is clear that the dominant frequency is about 6 Hz at the bottom point and it is close to 10 Hz according to the elevation of the measuring point from the bottom.

The dominant frequency of the seismic motions and micro tremors are almost same and it is 6 Hz at the bottom and 10 Hz at the top point.

The authors analysed a multilayer formation model for Oya and evaluated the characteristics of the seismic wave propagation by transfer matrix method. It shows that the first and second dominant frequencies are 4.4 Hz and 11.4 Hz, respectively. As the first dominant frequency approximately harmonises with spectrum ratio of the seismic waves and micro-tremors at the bottom point for the measurement, we estimate the dominant frequency of the underground quarry is 4.5 to 6 Hz.

The dynamic response of the underground quarry indicated that the dominant frequency is about 4.5 Hz to 6 Hz at the base of the quarry. The dominant frequency of the pillar is approximately 10 Hz. The H/V spectrum can reduce the influence of the epicentre and wave propagation and represent the site characteristics of the underground quarry. The H/V spectrum shows the dynamic characteristics of a pillar in the quarry.

The numerical analyses indicated that displacements are small, which implies that they are in stable condition for the static state. Therefore more comprehensive studies are necessary in order to take into account discontinuity orientations mapped from the underground quarry to validate the results and ensure stability.

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