

CHALLENGE FOR OYA UNDERGROUND QUARRY

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Abstract

Oya tuff which is mined at Oya area, Utsunomiya City Tochigi Prefecture, Japan is one of the most popular building stone. After mining those stone material many underground quarries has existed. Several decades ago, some of those underground spaces were officially and broadly utilized for various purposes, i.e., storage for vegetables and fruits, museum, research laboratory. However, some of them drastically collapsed around the beginning of 1990. Since then, the evaluating structural stability has been a serious issue not only for utilizing underground quarries but also safety for residents in Oya area. The authors will introduce our challenges at Oya area. Firstly as we evaluate the structural stability of those underground quarries, we carried out stability analysis for the structures in the static and dynamic state. Those analyses simulated the excavation and seismic state. Secondly, we considered utilizing ways for those underground quarries with some questionnaires and those analyses. Thirdly we have tried to understand material characteristics of Oya tuff, especially on weathering process empirically. We will introduce some of our challenges.

Keywords: Oya tuff, Underground quarry, structural stability, utilization

1. INTRODUCTION

1.1 Background

Oya tuff which is geologically classified into green tuff or pumice tuff is mined at Oya area, Utsunomiya City, Tochigi Prefecture, Japan as one of the most popular building stone in Japan. After mining the stone materials, large underground spaces are left behind. In this area, there are over 200 underground ruined quarries, and about 10 active underground quarries exist currently. Even though people have looked for utilizing way for those underground quarries for a long time, it has stopped due to of several huge collapse around 1990's. The authors have the challenge to find the ways of utilizing those underground spaces officially and broadly and let the area active. Our research group have carried out three approaches to Oya area. Research Unit 1 Utilization for Oya underground spaces (i.e. Saito, *et. al*, 2017). Research Unit 2: Structural assessment for the spaces (i.e. Seiki *et. al*, 2014), Research Unit 3 Understanding engineering characteristics of Oya tuff (i.e. Seiki, *et. al*, 2011). This paper will briefly introduce individual progress of Research unit 2 and 3. As Oya tuff mining is on private economic activity, it is difficult for the local government to support those developing activity officially. We should consider several scenarios for the redevelopment of Oya underground spaces and the area from the viewpoints of software and hardware.

1.2 Redevelopment Scenarios for Oya underground space

The authors progress the combinational approach for forwarding use of Oya underground quarries. For the first step, the area needs to call for entrepreneurs to start the business because of investing not only in the business budget but also for the safety assessment. After the process will be accepted by the entrepreneurs for business activity in Oya. Subsequently, we may guide the way for safety assessment and safety countermeasure there. From the research viewpoint, we need Research unit 2. As Oya tuff get easily weathered and deteriorate, there is need to understand the factor and weathering process of Oya tuff for long-term stability and utilization for the underground space. For the reason Research unit 3 is included. This paper will mainly introduce hardware research units, unit 2 and 3.

2. STABILITY ASSESSMENT FOR OYA UNDERGROUND QUARREY

2.1 Introduction

After the 2011 Great East Japan Earthquake, it is getting important to evaluate seismic stabilities of infrastructures (Aydan *et.al.* 2011). The authors tried to check the seismic response of some underground quarries through numerical analysis and field measurement. The authors selected some seismic velocity waves from thousands records to investigate site effect around the quarries. The authors analysed the frequency characteristics of those quarries using selected records by Flac3D. Additional numerical analyses were carried out using some selected strong motions from some strong earthquakes in order to check the response of quarries beneath the underground quarries.

2.2 Seismic response analysis on natural period of underground openings

2.2.1 Three-dimensional dynamic analysis subjected sinusoidal velocity waves

First, the excavation steps of the underground quarry were simulated under static condition and yielding of rock mass around the cavity was analysed using elastic perfectly-plastic behaviour. Then, the numerical model was subjected to seismic base shaking applied at the bottom of the model. The model area, which is 340 m in length, 340 m in width and 68 m in depth, and it consists in 953,700 elements (Fig. 1) with the material parameters (Table 1). The element is cubic with 2 m side length. The infinite boundary was set around the side of the model using Lysmer type boundary condition. Dyanamic analyses were carried out using recorded velocity wave data measured in Oya area induced by nearby

Table 1. Material parameter for Oya tuff and Kanto loam.

Parameter	Oya tuff	Kanto loam
Bulk modulus K (MPa)	1.38×10^3	1.6×10^3
Shear modulus G (MPa)	0.91×10^3	0.17×10^2
Cohesion c (MPa)	2.10	1.5×10^{-2}
Internal friction angle ϕ (degree)	30	40
Tensile strength σ_t (MPa)	1.08	1.6×10^{-2}
Moisture density ρ_t (kg/m ³)	1.77×10^3	1.35×10^3

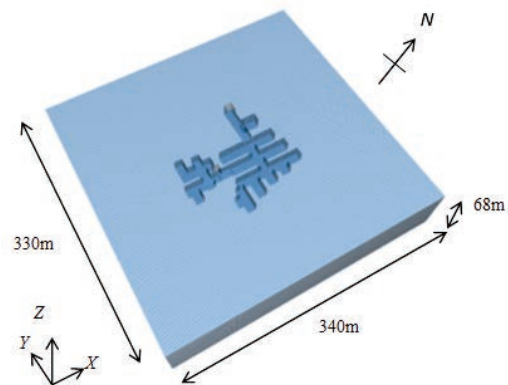


Figure 1. Geological model for numerical analysis and the boundary conditions of the Oya underground quarry (Dark zone indicates the underground quarry).

Table 2. Input wave cases for numerical analyses

Earthquake	Type	Observation Location	Case No
2011 Great East Japan Eq. (M9.0)	Inter-plate	Oya	1-A
		Tsukidate	1-a
2014 Fukushima - oki (M6.8)	Inter-plate	Oya	1-B
		Aizu-Wakamatsu	1-b
2014 Ibaraki Nanseibu (M5.6)	Intra-plate	Oya	2-C
		Kiryu	2-c

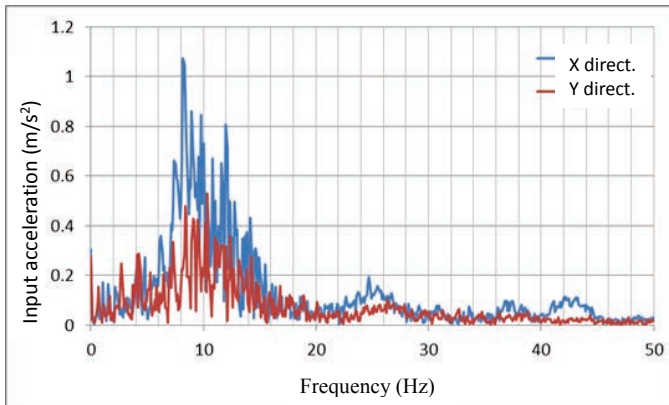


Figure 2. Fourier spectra of input acceleration from Kik-net, NIED (Case1-a), (X and Y directions are defined in Figure 1).

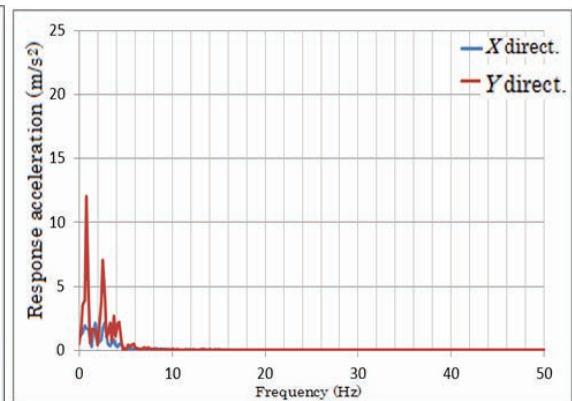


Figure 3. Fourier spectrum of response acceleration (Case1-a), (X and Y directions are defined in Figure 1).

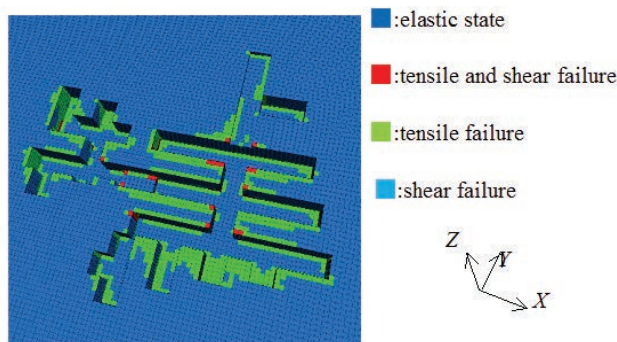


Figure 4 Plastic failure zone around underground quarry for Case1-a.

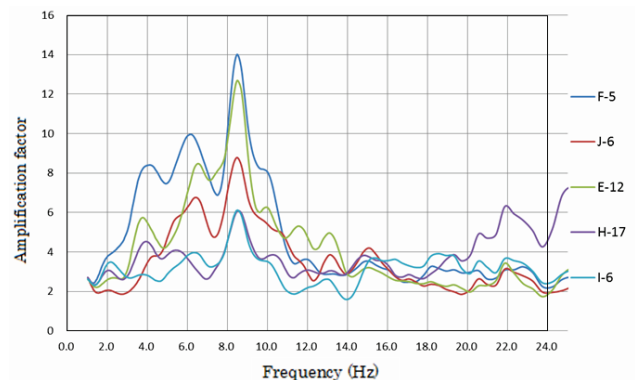


Figure 5 Fourier spectra of observation points in Oya region (F-5 to I-6 are selected observation points in Oya).

earthquakes (Table. 2). Even though the input velocity is generally converted from one measured at depth to the other depth for calculation, the authors input the recorded data on the bottom of the survey model because we consider worst case scenario against seismic stability of the underground quarry.

2.2.2 Analysis using velocity wave records recorded around Oya area

Fourier spectra of input accelerations of Case1-a is shown in Figure 2. and its response at rock mass among two parallel caverns is shown in Figure 3. Both response accelerations along the axes are larger than those of the observed accelerations. Response accelerations become about 10 times larger than input ones of the Case 1-a. This implies that large earthquakes may affect the stability of the underground quarries in Oya. The failure zone spreads in a broad area along sidewall and the upper surface (Fig. 4). Although the total failure of underground quarries may not occur, the result shows the possibility of roof falls and spalling at side-walls.

2.3 Observation system for abandoned oya tuff underground quarries and its seismological characteristics

2.3.1 Observation system for abandoned Oya tuff underground quarry

The Oya Region Improvement Office operates a continuous observation System for abandoned Oya tuff underground quarries, which mainly consists in 97 seismometers and additional instruments to record water levels installed in Oya area to measure micro vibration caused by cracking and falling of blocks from the roof, side walls and pillars. This monitoring system has been in operation to observe the structural stability of underground quarries since 1990's. Observed seismological data has been used to estimate the possibility of the underground collapse. Almost all seismometers measure vertical (up-down) direction of velocity and a few three-dimensional measurements are equipped to observe the

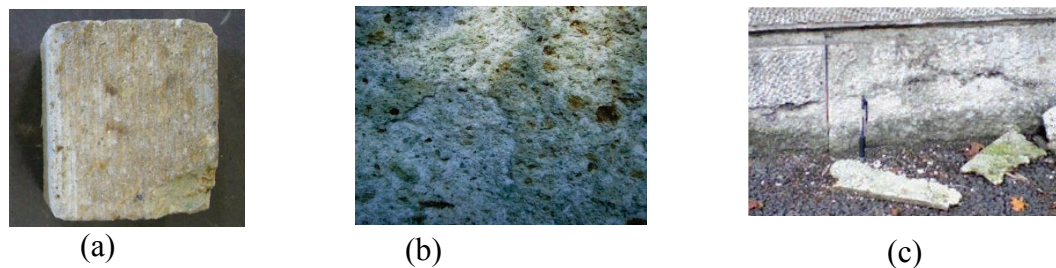


Figure 6 Weathering feature of Oya tuff brick. (a) Colour tone change, (b) Scale-shaped laminar ex-foliation with salt, (c) plate-shaped laminar ex-foliation.

stability especially. Moreover, those seismometers are installed at the bottom of borehole, which is about 20 m below the ground surface to eliminate ambient noise. Every measuring point has a solar-cell generated amplifier to observe vibrations. Observed analogue data is converted into digital optical data and transferred to Oya observation centre via transmission units.

2.3.2 Seismological characteristics of Oya tuff underground quarry

Recently, the efficient use of the observed data has begun at Oya observation centre except for some failure events of abandoned underground quarries. The authors have started to investigate seismological characteristics of Oya tuff rock masses and Oya underground quarries since 2015. Figure 5 shows FFT data of selected up-down seismic waves measured on Oya tuff and averaged 16 earthquake events. The data imply that the natural frequency of Oya underground quarries may be between 5 Hz to 10 Hz. It indicates that there are some frequency differences among natural frequency obtained from numerical analyses and measured observations. The sensitivity of seismometer causes a low response at an observed frequency less than 5 Hz. Additionally, we need to install more effective measurement devices to check the responses at the frequency around 10 Hz.

3. ENGINEERING CHARACTERISTICS FOR OYA TUFF

3.1 Weathering occurrence and Oya tuff

Fresh Oya tuff presents light green colour with brown clay mineral spots, which originally present dark green and changed its colour to dark brown after quarrying. Those are called 'Miso' or soya bean paste, and soft enough to manufacture stone bricks and statures. On the other hand, environment easily influences to change the strength of Oya tuff. In fact, the surface of stone bricks of Oya tuff generally and gradually turns greenish to brownish after constructing a wall around the house. Stone dealers of Oya tuff are concerned for weathering of Oya tuff because it is important for them to qualify long life against degrading and changing colour appearance on surface. This study focused on the progress of weathering of Oya tuff and we tried to clear the phenomena and relation with an environmental factor, moisture content. Weathering is a key important phenomenon of degradation of rock material. From geological viewpoint many studies are describing the phenomenon and the fact of weathering (i.e. Kimura *et al.* 2003). However, the factor of individual rock materials is not mentioned in detail. This study tried to reproduce weathering phenomenon of Oya tuff empirically and considered the mechanism and relation with humidity and temperature.

3.2 Weathering of Oya tuff

The authors categorize weathering of Oya tuff into followings three types (see Figure 6).

- (1) Colour tone change at surface
- (2) Scale-shaped plate exfoliation with crystalizing salt
- (3) Laminar-shaped plate exfoliation

We thought those types relate with chemical weathering and physical weathering including salt weathering. Field observation was identified that Oya tuff crystalized gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), thenardite (Na_2SO_4) and mirabilite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$) on the surface. Crystallisation of those minerals

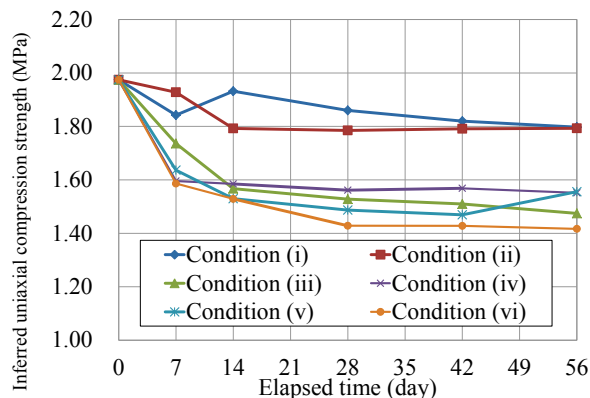


Figure 7 Inferred uniaxial compression strength and elapsed time at exposure test.

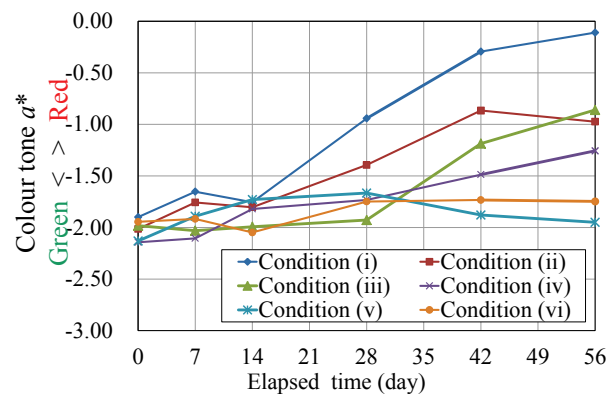


Figure 8 Colour tone a^* change and elapsed time in exposure test.

may cause salt weathering. This study focused on (1) colour tone change and strength fluctuation or hardening and softening at surface which includes the preliminary step of type (2) and (3)

3.3 Measurement of colour tone change and strength

3.3.1 Introduction

In this study, we carried out several kinds of measurements and observations to understand the process of weathering and mechanism at outdoor exposure test. Dry and humid cyclic test with needle penetration test, which can evaluate inferred uniaxial compression strength with converting from the NP value calculated by needle penetration force and needle penetration depth, powder X-ray diffraction (XRD) test. Colour tone analysis by spectrophotometer which decomposes surface colour of Oya tuff samples into $L^*a^*b^*$ colour system and energy dispersive X-ray spectroscopy (EDX) on scanning electron microscope (SEM). This paper mentioned only the results of outdoor exposure test as a selected results for the experiments.

3.3.2 Outdoor exposure test

An environment where Oya tuff products are placed, strongly influences the weathering progress. We set six conditions for outdoor exposure test. Condition (i) exposed samples without any covers, Condition (ii) is that samples soaked in water, Condition (iii) shaded samples from sunlight and covered moisture, Condition (iv) is that samples soaked in water and shaded them against sunlight, Condition (v) merely covered samples with vinyl Ziplock bag and Condition (vi) covered samples with vinyl Ziplock bag and shaded them against sunlight. Those conditions are selected to clear environmental factors which affect weathering progress. We prepared five prism-shaped samples which are 6 cm in width, 7 cm in height and 13 cm in length and had put them at roof floor of the department building in Utsunomiya University for about two months, from December 2009 to January 2010. Additionally some of them had been exposed until January 2011.

3.3.3 Results of outdoor exposure test

Starting outdoor exposure test, inferred uniaxial compression strength or the strength clearly rose and fell in comparison with amount of strength fluctuating after two weeks (see in Figure 7). As the strength of Oya tuff related with amount of water content, we checked moisture content or absolute humidity which was calculated on the value of temperature and humidity, rainfall frequency. XRD detected small amount of thenardite and gypsum from the samples. Especially, it detected thenardite even after 1st week. From the viewpoint from colour tone change, at exposure test, colour of sample surface turned greenish into brownish. a^* value, which was more useful to distinguish the colour tone change than L^* and b^* , clearly changed greenish to reddish at Condition (i), (ii) and (iii) shown in Figure 8. Especially, at Condition (i), the colour tone change significantly because samples are most likely to contact water such as rainfall, moisture in air and obtain effect of climate environment. Thus, a^* value easily presents daily influence on humid and dry condition of climate.

6. CONCLUSIONS

6.1 Summary

Over 200 underground quarries are located within in a narrow zone, 4 km in East-West width and 6 km in North-South length in Oya area, Utsunomiya City, Tochigi Prefecture, Japan. This paper introduced briefly introduce 2 of 3 research units of our challenge in Oya area.

6.2 Seismic response analysis on the natural period of underground quarries

The structural stability was checked by actual earthquake data in numerical models representing the simplified geometry of a typical Oya tuff underground quarry. The result shows that resonance phenomenon occurs. While large earthquakes may not cause severe damage leading to its collapse, limited roof-fall and spalling due to tensile stresses may occur in some parts of the underground quarry.

6.3 Monitoring of seismic response of abandoned Oya tuff underground quarries

The authors have started to utilize some seismic record measured by the system and to check natural frequency of the underground quarries by normalized FFT analyses. The results show that the natural frequency of underground quarries ranges between 5 Hz and 10 Hz. There is some difference between measured and computed natural frequencies. The sensitivity of current seismometers may not be capable of recording responses at frequencies lower than 5 Hz. Therefore, we need to improve monitoring system up to the frequency of 10 Hz.

6.4 Colour tone change of monitoring of seismic response of abandoned Oya tuff underground quarries

This paper introduced the results of outdoor exposure test, however, we conducted many kind of experiment for understanding mechanism of weathering of Oya tuff. At those experiments, we measured colour tone change and inferred uniaxial compression strength. On the empirical results, this study cleared that moisture content as an environment factor of weathering of Oya tuff. It may have a threshold changing strength and colour tone. Oscillation of moisture content is also a factor for them. Once Oya tuff absorbed moisture mineral components of calcium and Sodium may leach and crystalize salts such as gypsum and thenardite. When those salt mineral may break or cover voids and matrices the strength will be weaker or stronger at the sample surfaces. Goethite which was crystalized at exposed sample changed colour tone. For the next step, this study needs quantitative approaches to clarify the mechanisms.

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REFERENCES

- Aydan, Ö., Ohta, Y., Daido, M., Kumsar, H. Genis, M., Tokashiki, N., Ito, T., & Amini, M., 2011, Chapter 15: Earthquakes as a rock dynamic problem and their effects on rock engineering structures. *Advances in Rock Dynamics and Applications*, Editors Y. Zhou and J. Zhao, CRC Press, Taylor and Francis Group, 341-422.
- Kimura, T. & Matsukura, Y., 2003, The effect of environmental conditions on salt weathering: a laboratory experiment, *Bull. Terr. Env. Res. Center Univ. of Tsukuba*, 4: 149-155 (in Japanese).
- Saito A., Seiki, T & Sato, D. 2017, Consideration to space value evaluation of Oya underground quarry from view of structural safety, *Proc of Underground Space Symp. Vol.22*, pp.29-34, JSCE, (in Japanese).
- Seiki, T., Sato, A., Kikuchi, K. (2011): Weathering mechanisms and mechanical property changes of Oya tuff, *Proc. of 12th ISRM Int. Congress on Rock Mech. Harmonising Rock Engineering and the Environment*, Qian & Zhou (eds), Beijing, China, pp. 821-824, Nov.2011.
- Seiki, T., Takaba, H. and Hasegawa, N., 2014, Some Considerations on Seismic Stability of Oya Underground Quarry, *Proc. of 2014 ISRM Intl. Symp. 8th Asian Rock Mechanics Symposium Rock Mechanics for Global Issues – Natural Disasters, Environment and Energy -*, ERD4-4, Sapporo, Japan, 9ps.