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Study on the stability of stone wall in earthquake by discontinuous deformation analysis

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ABSTRACT: Old-time stone walls are important cultural assets in Japan. There are many cases of large deformation or collapse of stone walls caused by earthquakes in the past. In order to maintain the seismic stability of stone wall, good repair of large deformed wall is an essential project. In the repair, it is a big issue whether the reinforcement of wall is employed or not. If reinforcement is not applied, a risk remains that the stone wall deforms largely again when encountering a big earthquake. If reinforcement is applied, it is required how to enhance the seismic resistance by the reinforcement. To examine these issues, we carry out a numerical analysis of stone wall by the discontinuous deformation analysis (DDA). In the analysis, a large deformed stone wall is reproduced, and the material parameters for analysis are determined. Based on the results, the seismic stability of the stone wall is examined for the case of employing reinforcement by soil improvement.

1 INTRODUCTION

In Japan, there are many classical stone walls that experienced hundreds of years after construction. In order to maintain and manage these traditional structures in the future, it is important to properly evaluate the stability of structure. Furthermore, in Japan where earthquakes occur frequently, there are many stone walls that cause large deformation and lead to collapse due to earthquake. In order to maintain the long-term stability of traditional structures, a method to accurately evaluate the stability on earthquake is required.

In recent years, many studies on the method for evaluating the stability of stone wall have been carried out. As the example of past research, an exit index which is an empirical index (Nishida, 1998), a method based on earth pressure theory (Ichioka, 1996) and a numerical analysis (Noma, 2013), have been reported. However, at the present stage it is difficult to establish a method for quantitatively evaluating the stability of stone wall based on the deformation of wall during earthquake which considers the waveform of seismic motion.

In this paper, we investigate the necessity of reinforcement when repairing or rebuilding a stone wall where collapse occurs due to past earthquakes and large deformation exudes due to soil pressure, and we examine the method for reinforcement for stone wall.

2 STRUCTURE OF STONE WALL

2.1 *Current status*

Figure 1 shows the current deformation of the stone wall. Point A in Fig. 1 (b) is sinking, and point B is staring. From this fact, it can be easily inferred that the ground between point A and B is loose, and a slip surface may exist between point A and B, the shape of which is unknown. For the stone wall shown in Figure 1, the rebuilt repair work was planned. It became an issue whether reinforcement should be carried out or not, when rebuilding. We perform a numerical analysis with consideration for this stone wall.

2.2 *Collapse due to earthquake*

On June 28, 1948, an earthquake of magnitude 7.1 with epicenter of Fukui Plain occurred. The earthquake ground motion was intense, and in the vicinity of the epicenter almost 90% of houses were destroyed. Due to this earthquake, collapse occurred in several stone walls adjacent to the stone wall shown in Fig. 1. Figure 2 shows an example of the collapse. By reproducing this collapse, we confirm the applicability of our numerical analysis later.

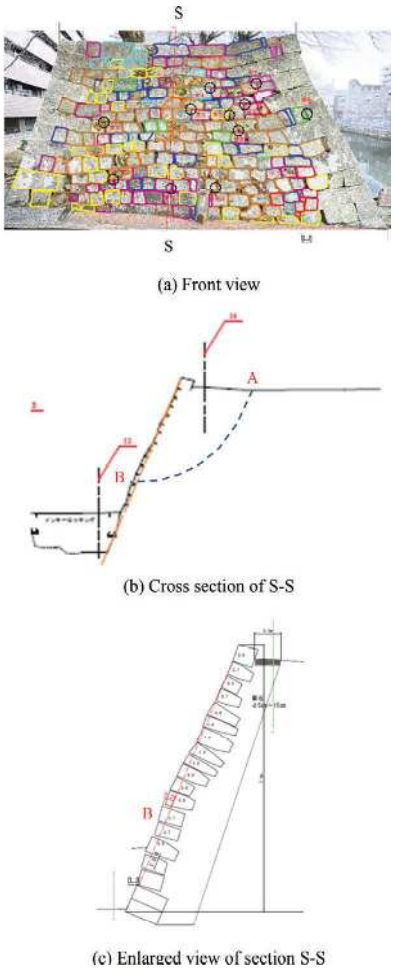

Figure 1. Deformation of stone wall.

Figure 2. Stone wall collapsed in Fukui earthquake, 1948.

3 METHOD OF ANALYSIS

3.1 *Method*

The analysis method is required to express the state of stone wall at all times, i.e., stability during earthquake or collapse at earthquake. The analysis is also required to represent the process from the stable state to the collapse of stone wall during earthquake. Since the discontinuous deformation analysis (DDA) is considered to satisfy these conditions (Monma, 1994), we reproduce the collapse of stone wall during earthquake, and examine the effect of reinforcement by soil improvement.

3.2 *Self-weight analysis and earthquake analysis*

We perform the analysis at three stages of self-weight static analysis, self-weight dynamic analysis and earthquake analysis.

Self-weight analysis is separated to static analysis and dynamic analysis. The self-weight static analysis is performed by stepwise analysis where the initial block velocity at each step reaches zero.

In the self-weight dynamic analysis, the initial block velocity at each step is inherited from the final speed at the preceding step.

Earthquake analysis inherits the stress and deformation of the self-weight dynamic analysis, and performs the analysis by applying the seismic force for each step.

3.3 *Dynamic analysis*

The external force in the seismic vibration analysis may be "own weight and seismic force". There are two kinds of method considering seismic force. One is the static seismic intensity method and the other is the dynamic seismic force method. In the static seismic intensity method, a constant inertia force is uniformly applied to all blocks in a horizontal or a vertical direction at a fixed time. In the dynamic seismic force method, the observed acceleration waveform of actual earthquake is applied to the box-shaped block outside the model. In this paper, the latter method is adopted in order to analyze the deformation of the stone wall during earthquake.

4 REPRODUCTION ANALYSIS

4.1 *Analysis model*

Figure 3 shows the analysis model used for the reproduction analysis. In Fig. 3, area A is a stone wall made of the shape shown in Fig. 1 (b), but the surface shape is restored to the shape before ingestion. Area B is a chestnut stone, and is assumed a discontinuous surface which coincides with the backfill ground and constitutes blocks. Since the chestnut stone part is finer than the stone wall part, the constituent block is divided into smaller parts than C. Area C is the backfill ground behind stone walls, and the block is divided with an arcuate discontinuity. Area D is the same ground as C, but it is set as a different category from C because the ground surface is a road. Area E is a box type that surrounds the ground of the model and that is a block simulating the ground around the model.

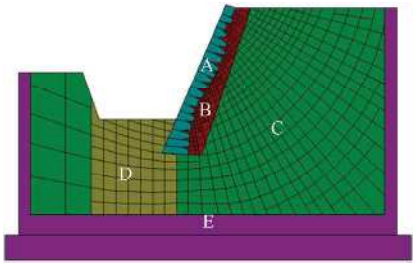

Figure 3. Division of stone wall area. A: stone wall, B: chestnut stone, C: backfill behind stone wall, D: same ground as C (ground surface is a road), E: box type that surrounds the ground of the model.

Table 1. Material property values used for reproduction analysis.

Category	Unit volume weight (kN/m³)	Elastic coefficient (MPa)	Poisson's ratio (-)	Friction angle (°)	Adhesive force (kN/m²)
A	26	1,000	0.25	35	0
B	26	100	0.25	35	25
C	19	100	0.3	30	25
D	19	100	0.3	30	50
E	19	10,000	0.3	30	0

During earthquake analysis, we apply seismic force to the center of these blocks as inertia force. The block indicated by E is a slide, and constitutes a horizontal roller.

4.2 *Material properties*

Table 1 shows the material property values used for analysis. Since the reproduction analysis is a basic study, the material property values are set by referring to the past literature.

4.3 *Seismic waveform*

In the analysis, inertia force is applied in the X direction of the box-shaped block from outside of the model. As the seismic waveform, we used the observed acceleration waveform (maximum value 500 gal) in the Kobe earthquake.

4.4 *Result of reproduction analysis*

Figure 4 shows the collapse process of the stone wall during the earthquake, which is obtained by the DDA. Figure 5 shows the time history of the maximum displacement rate obtained by the analysis.

As shown in Fig. 4, (a) starts to collapse, (b) shows large deformation, (c) - (e) shows collapse. In Fig. 4 (b), point A is settled and point B is impregnated, which is consistent with Fig. 1 (b). Fig. 4 (e) is consistent with the collapse mode shown in Fig. 2.

Figure 5 (a) shows the time history of the maximum displacement rate obtained by analysis, and (b) shows the input seismic waveform. In Fig. 5 (a), time 0 - 2.5 s is the self-weight static analysis, and time 2.5 - 2.8 s is the self-weight dynamic analysis, both of which are self-weight analysis. In self-weight analysis, the maximum displacement rate converged to 10^{-3} or less. After 2.8 s, the earthquake

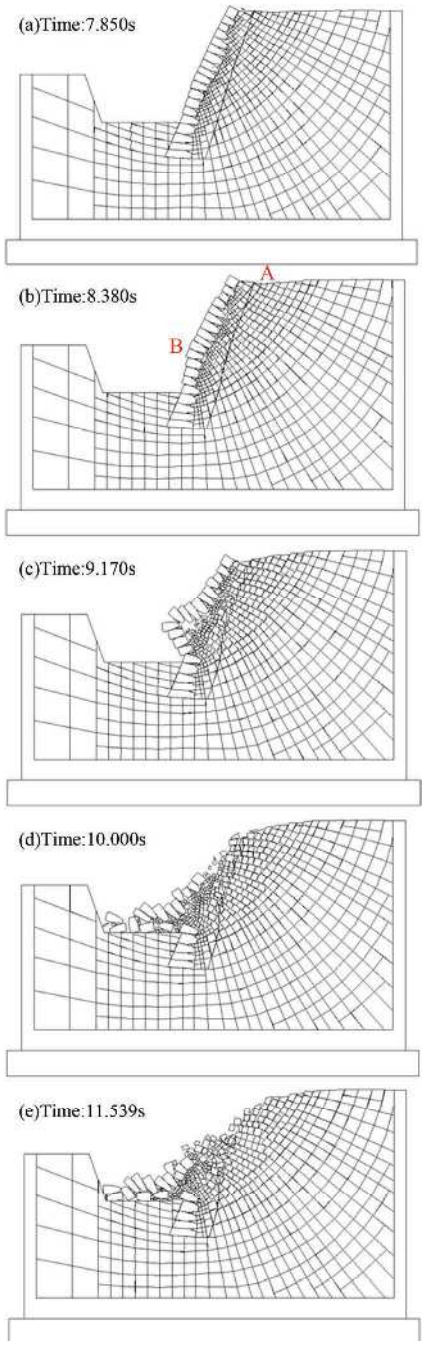

Figure 4. Collapse process of stone wall during earthquake obtained by DDA

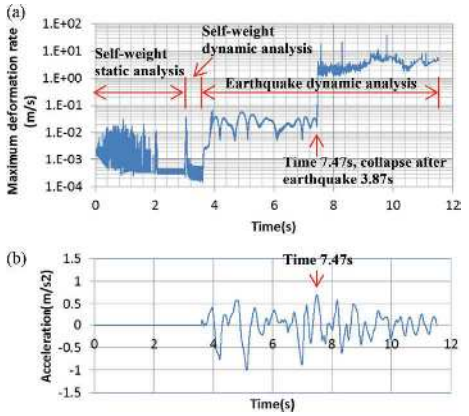

Figure 5. Time history of maximum displacement rate obtained by analysis. (a) time history, (b) input seismic waveform.

dynamic analysis is shown. At time 7.47 s (3.87 s after the start of earthquake) the maximum displacement rate increased sharply. This time may be considered the start time of collapse. This time matches the maximum value of the acceleration in the plus direction in the input seismic waveform shown in Fig. 5 (b).

Based on the above results, it seems that the analysis reproduces the constant stability of stone wall and the collapse due to earthquake.

5 REINFORCEMENT ANALYSIS

From the results of reproduction analysis, there is a possibility that the stone wall shown in Fig. 1 will collapse in the future due to earthquake, if the wall is rebuilt only by restoring the surface shape.

Referring to the collapse process shown in the reproduction analysis, the collapse of stone wall during earthquake is considered due to the failure of the backfill ground behind the stone wall. Then improvement of the ground behind the stone wall is required.

Figure 6 shows the analytical model of the ground improvement scheme. In Fig. 6, area A: stone wall, B: chestnut stone part, C-G: ground, H: a box type block that surrounds the ground of the model, and I: ground improvement part. Distribution and material property values of C - G are set from the results of the laboratory soil test of the boring core and the surface wave survey of the site. Table 2 shows the material property values of the block and discontinuous surface used for analysis.

According to the residential land disaster prevention manual (Residential disaster prevention study group, 2007.), if the ground surface acceleration of a large earthquake is assumed the order of 400 to 500 gal, the design horizontal seismic intensity is considered to be about 0.25. In the reinforcement analysis, considering

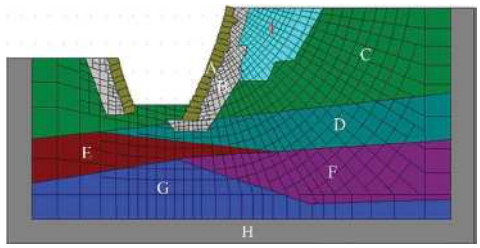

Figure 6. Analytical model of soil improvement plan. A: stone wall, B: chestnut stone, C-G: ground, backfill, H: box type block that surrounds the ground of the model, and I: soil improvement part.

Table 2. Material property values of block and discontinuous surface used for reinforcement analysis.

category	Unit volume weight (kN/m3)	Elastic coefficient (MPa)	Poisson's ratio (-)	Friction angle (°)	Adhesive force (kN/m2)
A	22	100	0.25	45	0
B	20	30.0	0.25	40	10
C	18	16.8	0.3	15	30
D	18	14.0	0.3	20	35
E	18	14.0	0.3	20	75
F	18	16.8	0.3	20	80
G	18	47.6	0.3	30	30
H	18	1,000	0.3	0	0
I	18	28.0	0.3	15	50

the safety side, the maximum acceleration of the input ground motion is set to 500 gal.

For the analysis, we use the observed acceleration waveform in the Kobe earthquake, which is shown in Fig. 7. In the analysis, horizontal waveform is NS and vertical is UD. As shown in the recorded waveform, the maximum acceleration in the vertical direction is 0.41 to 0.54 times smaller in the

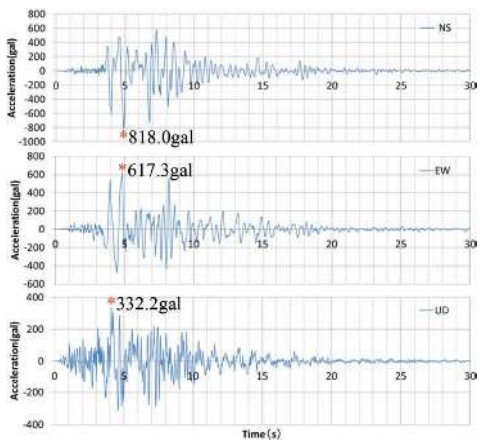

Figure 7. Observed acceleration waveform of Kobe earthquake.

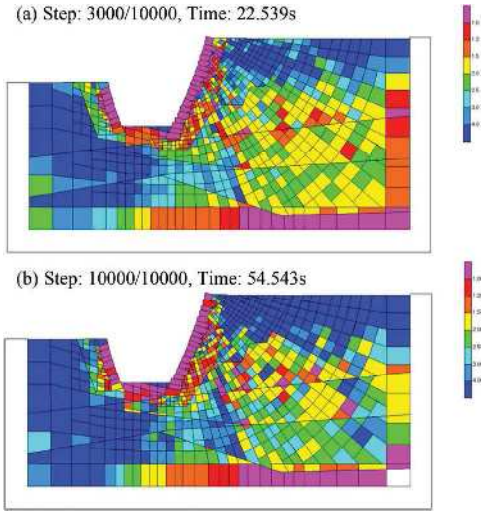

Figure 8. Distribution of real-time local safety factor obtained by reinforcement analysis. (a): After self-weight analysis, (b): After earthquake dynamic analysis.

horizontal direction. In the analysis, maximum value 300 gal in the vertical direction is used compared to 500 gal in the horizontal direction.

Reinforcement analysis was carried out in the same order as the reconstruction analysis, self-weight static analysis, self-weight dynamic analysis and earthquake dynamic analysis.

Figure 8 shows the distribution diagram of Real-time local safety factor obtained by reinforcement analysis. In Fig.8, (a): after self-weight analysis, and (b): after earthquake dynamic analysis.

After the earthquake, the safety factor of the lower part of soil improvement section decreases constantly (after self-weight analysis), but there is no continuous decrease. The stone wall and the backfill ground are stable during earthquake.

Figure 9 shows the distribution of cumulative displacement vector obtained by reinforcement analysis. In Fig.9, (a): after self-weight analysis, (b): after earthquake dynamic analysis. The cumulative displacement vector distributes in a direction similar to the bulge form observed in the actual stone wall. This result is consistent with the actual deformation of stone wall. The cumulative displacement vector distributes regularly, and there is no point where the vector becomes extremely large. As the result, it can be inferred that both the stone wall and ground are stable after the earthquake.

After the earthquake, the cumulative displacement and displacement rate in the lower part of stone wall are sorted out to confirm the cumulative amount of displacement of the stone wall. Figure 10 shows the cumulative displacement and displacement rate of block 21. In Fig.10, (a): the position of block 21, (b): cumulative displacement, (c): displacement rate. In Fig.10 (a), Ux is the cumulative displacement in

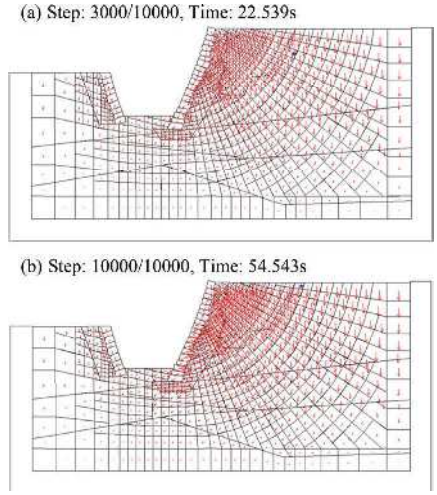

Figure 9. Distribution of cumulative displacement vector obtained by reinforcement analysis. (a): After self-weight analysis, (b): After earthquake dynamic analysis.

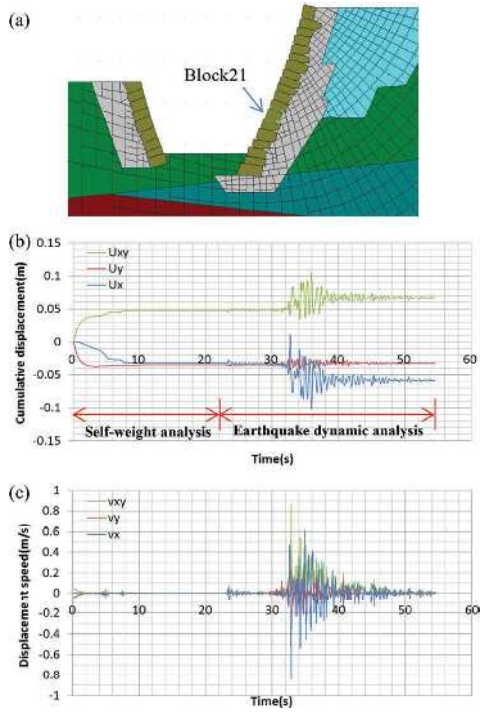

Figure 10. Cumulative displacement and displacement rate of block 21 obtained by reinforcement analysis. (a): The position of block 21, (b): Cumulative displacement, (c): Displacement rate.

horizontal direction, Uy is the cumulative displacement in vertical direction, and Uxy is the cumulative displacement vector. The cumulative displacement due to the earthquake increases by about 26.2 mm

in horizontal direction before the earthquake (after self-weight analysis). There is a decrease of about 2.3 mm in vertical direction. It is confirmed that the cumulative displacement after the earthquake clearly converges.

In Fig.10 (b), vx is the displacement rate in horizontal direction, vy is the displacement rate in vertical direction, and vxy is the displacement rate vector. As similar with the cumulative displacement, it is confirmed that the displacement rate after the earthquake converges clearly.

It is possible to confirm that the stone wall and ground are stable during the earthquake, from the distribution of local safety factor, the distribution of cumulative displacement vector, the cumulative displacement, and displacement rate of the lower part of stone wall. As the result, we confirm the effectiveness of soil improvement.

6 CONCLUSION

It is an important task of disaster prevention to evaluate the stability of ground structure during earthquake. Numerical analysis is a powerful method for the evaluation. It is necessary to grasp accurately ground condition, to construct an appropriate model and to select an appropriate numerical method.

In ground structures like stone wall, stone wall is discontinuous body, and ground is continuum. Numerical methods targeting continuum are difficult to apply to stone wall. It is difficult to apply numerical methods targeting discontinuous object to ground. In this paper, we employ DDA. It is important to divide the ground into discontinuous blocks when applying DDA. Therefore, the stress state obtained by FEM is grasped beforehand, and the ground block is divided by arc discontinuity line with the slip line considered possible as the potential crack.

By using DDA, we can reproduce the deformed state of stone wall and the collapse of stone wall during the earthquake. Reinforcement analysis also confirms the stability of stone wall by soil improvement during earthquake. As the result, it is confirmed that DDA is effective for the stability analysis of stone wall during earthquake, and it is shown how to apply DDA to stone wall structure.

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