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EXPERIMENTAL AND ANALYTICAL STUDY ON COLLAPSES OF RETAINING WALLS DURING THE 2016 KUMAMOTO EARTHQUAKE

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Abstract

Many retaining walls for residential houses were damaged during the 2016 Kumamoto earthquake. There is always a risk that collapsed wall blocks and stones would create damage to structures as well as people and block the road for evacuation or restoration work. Therefore, we need to clarify the collapse mechanism and then construct a method how to design more ductile retaining walls.

In this study, we first carried out the survey on the collapsed retaining walls in Mashiki Town, Kumamoto prefecture, Japan. From the results of the damage survey, we found that Fixed Block Walls were most severely damaged, and it seems that the degree of their damage was affected by the height and the direction of them.

Second, in order to understand the dynamic behavior and find out the collapse mechanism of retaining walls, we conducted the shaking table tests with small-scale retaining walls and tried to reproduce the dynamic behavior through their simulations. As a result of the first experiment using the shaking table in DPRI, Kyoto University, the wall was not collapsed because of the stronger wall than the design based on the regulations. One reason is that the strength of the backfill mortar inside the wall did not follow the scaling low. The other reason is that the steel container supported the wall with the frictional force between the wall and the container.

Therefore, we conducted a second experiment with a re-designed model. In the second experiment, even though the friction problem was solved, the wall was not collapsed either, because of the smaller maximum input acceleration due to the capacity of the shaking table in KIT. However, since the frictional force was eliminated, we could simulate the results of the second experiment with the dynamic DDA (Discontinuous Deformation Analysis) quite nicely.

Finally, we analyzed the nonlinear behavior of the retaining walls to find key factors leading to the collapse by the dynamic DDA of the real-scale retaining walls. In our parametric study, we made two types of models that have different heights and different strengths of the backfill mortar. As a result, we found that the degree of the damage is affected by several factors such as height, direction of walls, and the strength of the backfill mortar. Furthermore, it is inferred that the overburden pressure from structures too close to the wall, which are not allowed in the current standards, affects the dynamic behavior of the walls.

Since the actual blocks were found to be completely separated whenever the walls were collapsed or severely damaged, it is suggested that whether blocks of walls were firmly connected with the backfill mortar or not is much more important than the strength of mortar in order to prevent severe damages in Fixed Block Walls. Therefore, we strongly recommend that the construction practice for and the immediate inspection of “the quality of the backfill mortar” must be implemented as soon as possible, which will ensure the inside integrity of the retaining walls and prevent their severe damages.

Keywords: 2016 Kumamoto Earthquake; Residential Retaining Wall; Shaking Table Test; DDA

1. Introduction

Many retaining walls for residential houses were damaged by the 2016 Kumamoto earthquake. There is always a risk that collapsed wall blocks would create damage to structures as well as people and block the road for evacuation or restoration work. In particular, it has been pointed out that the damage rate of the Fixed Block Wall was relatively high during the widespread use as the retaining wall for residential land [1]. Recently, there are some studies on collapses of retaining walls using shaking table test with small-scale retaining wall [2], however, few studies have been conducted to deal with actual earthquake damage.

Therefore, we first carried out the survey on the collapsed retaining walls in Mashiki Town, Kumamoto prefecture, where severe damages occurred by the 2016 Kumamoto earthquake, to understand the local damage situation. Furthermore, we analyze the causes of the earthquake damages in Mashiki Town by the shaking table tests with the small-scale retaining wall and dynamic analysis using the Discontinuous Deformation Analysis based on the results of the damage survey.

2. Damage Survey

All of the collapse surveys were visual inspections. We conducted a field survey in July 2016 and a survey with Google Street View on the Internet. The data were classified and organized by retaining wall type, height, direction, and damage level. Fig.1 shows the survey area. In the survey, damage level was defined as below.

- Slightly damaged: Small damages such as cracks on the wall
- Moderately damaged: Swellings or inclinations of the wall
- Collapsed: Collapsed state including falling and upper half-destruction

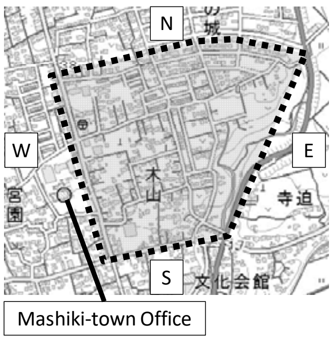


Fig.1 – Damage survey area in Mashiki Town

Retaining walls are broadly divided into two types: stone walls and concrete walls. In recent years, in Japan, the number of concrete retaining walls tends to be large due to their lower cost, better workability and stability than stone ones, and Mashiki Town is no exception. Fig.2 shows the survey results of the concrete retaining walls. The number of each retaining wall type is shown in parentheses on the right side of the construction method name in the figure.

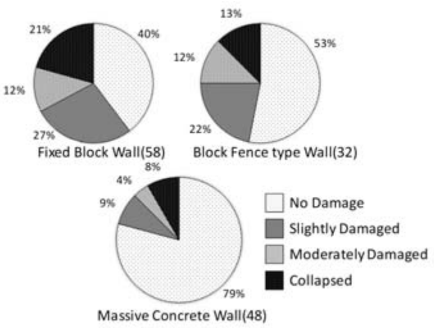
The construction methods are divided into three types. The Block Fence type Wall is made of a commercially available rectangular concrete blocks and is not recognized as a retaining wall in the relevant laws and regulations. However, since the number of construction and damages of Block Fence type Wall was large in the survey area, it was classified as a kind of retaining wall in this study. Note that no detailed classification was made, such as the presence of internal rebars since the survey was visual inspection.

The Fixed Block Wall is made by square pyramid shape blocks and concrete poured into their gaps and backside. In this classification, the existence of Unfixed Block Wall cannot be denied. Nevertheless, since the obligation to use backfill concrete has been written in related laws and guidelines, and backfill concrete was found in the many collapsed retaining wall cross-section during the field survey.

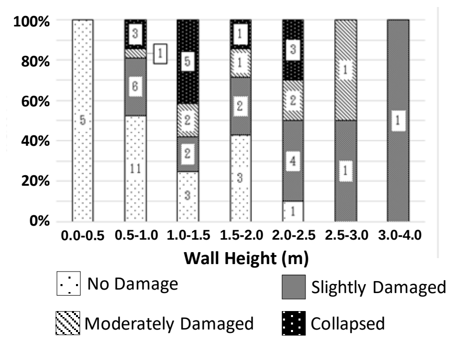
In addition, the Massive Concrete Wall includes various types of retaining walls, such as gravity type and L-type, plain concrete and reinforced one, and it is thought that there is a certain difference in the structural performance between each type of them. However, it is difficult to visually judge the internal structure, and the results of the survey which shows few damages of the Massive Concrete Wall were not sufficient to analyze the structural performance difference. In addition, the internal discontinuous surfaces are unlikely to be formed compared to the other two types of walls. Therefore, we classified them all of them as the Massive Concrete Wall.

Fig.2 (a) shows the damage rate of each construction method. The damage rate of the Massive Concrete Wall is the lowest, and the damage rate of the Fixed Block Wall is higher than the other types. In addition, Fig.2 (b) shows the damage rate of the Fixed Block Wall sorted by height, and the damages tends to increase as the retaining wall height increases. Although it is not shown in the figure, focusing on the constructed direction, it was confirmed that more damage occurred in the EW direction than in the NS direction. This tendency corresponds to the main damage direction of the structure (Kawase et al. [3]).

These characteristics indicated by the survey results imply that one of the causes of these tendencies found in the damage could be the presence of the discontinuous surface inside the walls.



(a) Damage rate by each construction method



(b) Damage rate by each wall's height (Fixed Block Wall)

Fig.2 – Damage survey results of concrete retaining wall

Fig.3 shows the survey results of the stone retaining wall. As well as the concrete retaining walls, the construction methods are divided into three types. The walls made by square pyramid shape stone blocks were judged to be basically fixed each other for the same reason as the Fixed Block Wall. In addition, we distinguished between Fixed Natural Stone Wall and Unfixed Natural Stone Wall based on whether concrete was filled in their stone's gaps.

The one of the characteristics of the survey results is that the damage-free rate of all type of stone retaining walls are lower than that of the Fixed Block Wall. As a reason for these damages, we can assume that most of the stone retaining walls were old and likely to be existing non-qualified retaining walls and that the components may have deteriorated over time.

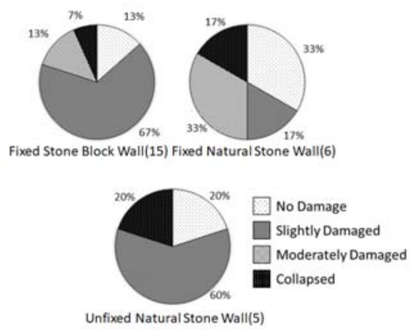


Fig.3 – Damage rate by each construction method (Stone retaining wall)

3. Shaking Table Test

Based on the damage survey, the shaking table test with small-scale retaining wall was performed to understand the behavior of the Fixed Block Wall with a large number of construction and a high damage rate during an earthquake. The height of the retaining wall is assumed to be 2m in actual size, and the size of the small-scale wall is reduced to 35% to match the steel container. The design of the retaining wall was based on the Act on Regulation of Residential Land Development [4] and the guidelines of Kumamoto Prefecture [5].

Fig.4 shows the designed sectional plan of the small-scale retaining wall.

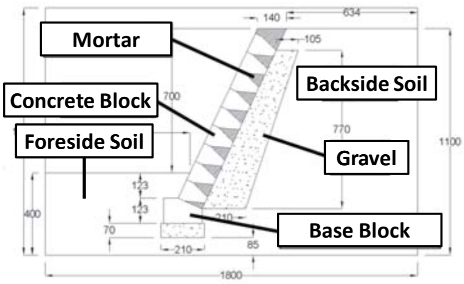


Fig.4 – Sectional plan of the small-scale retaining wall

The first shaking table test was performed with a hydraulic shaking table at the Disaster Prevention Research Institute, Kyoto University. The input wave used in the experiment is the observed wave in 2016 Kumamoto earthquake at KiK-net KMMH16. Note that the time of the wave is shortened based on Kagawa's scaling low [6]. In addition, accelerometers were installed on the wall surface and inside soil, and displacement gauges and motion captures were installed on the wall surface.

In the experiment, the acceleration amplitude of the input wave and the overhead load were controlled as the parameters. Table 1 shows the parameters of each material used for the first experiment. Although it is not shown in Table 1, according to the soil test, the water content was 8.2%, the soil particle density was 2.659 (g/cm^3), the gravel fraction was 5.7%, the sand fraction was 46.5%, and a fine fraction was 47.8%. Therefore, it is classified as "Sand of fine fraction nature with gravel". In addition, since the size of the gravel behind the wall is 0 to 40 mm in real scale, it should be 0 to 15 mm according to the scale of the model, and its density is 1.443(g/cm^3) calculated from the filled amount.

As a result of the experiment, although the loading load was increased to 5 times the standard, the deformation of the model was small, such as small inclination of the wall and subsidence of the backside soil as shown in Photo 1, and no damage was observed on the wall.

Table 1 – Parameters of each material used for shaking table test

(a) Concrete block and Mortar

Test Case		Density (kg/m³)	Elastic Modulus (kN/mm²)	Compressive Strength (N/mm²)	Splitting Tensile Strength (N/mm²)
1st shaking table test	Concrete Block	2170	18.0	24.1	–
	Mortar	2150	19.0	30.6	3.03
2nd shaking table test	Concrete Block	2244	23.3	22.3	–
	Mortar	2050	9.72	5.62	0.708

(b) Soil

Test Case	Density (g/cm³)	Cohesion (kN/m²)	Φ (deg)	Vs (m/s)	Vp (m/s)
1st shaking table test	1.566	18.0	24.1	152	394
2nd shaking table test	1.950	12.2	21.9	114	200

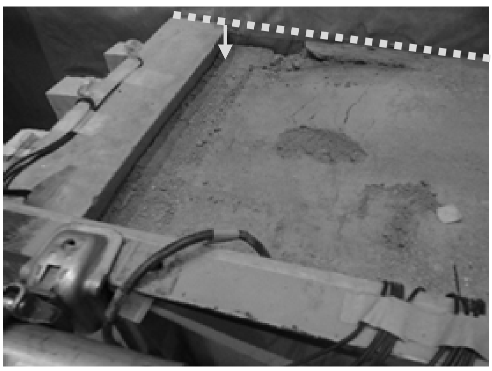


Photo 1 – Upper surface after the 1st shaking table test

It is assumed that there are some factors that made the wall stronger than the design based on the regulations and caused no damage on the wall as the result of the first experiment. One reason is that the strength of the backfill mortar did not follow the scaling low. The other reason is that the model wall was supported by the steel container due to the frictional force and the lack of sufficient soil density management. Therefore, we conducted a second experiment with an improved model.

The second experiment was performed using an electromagnetic shaking table owned by Gotou Laboratory of Kanazawa Institute of Technology.

In the second experiment, the compressive strength of backfill mortar was reduced to satisfy the scaling low (about 35% of 18(N/mm^2), minimum strength indicated in the design guideline[18)]) by adjusting the ratio of water-to-cement based on some advanced trials. In addition, the gap was created between the model wall and the steel container to prevent friction from occurring, and the density management of soil was performed in the same way as during the real construction with proper water content adjustment. In case that any damage is not observed on the model wall, it is allowed that the seismic wave without shortening the time for the scaling factor is applied to increase the vibration energy.

The sectional plan of the model and the measuring equipments were the same as those in the first experiment (ex. model size reduced to 35% of real-scale). Table 1 also shows the parameters of each material used for the second experiment. Although it is not shown in Table 1, according to the soil test, the water content was 14.0%, the soil particle density was 2.700(g/cm^3), the gravel fraction was 22.9%, the sand fraction was 59.2%, and a fine fraction was 17.9%. Therefore, it is classified as “Gravelly sand of fine fraction nature”. Despite the above improvements, as a result of the second experiment, the applied load was increased to 8.35 times the standard and real-scale seismic waves were input, no clear damage occurred to the model wall.

4. DDA Analysis of the shaking table test

In order to consider the shaking table test results and to verify the validity of the analytical model, we carried out the numerical simulation of the experiments with Discontinuous Deformation Analysis (DDA).

DDA is a technique for dynamically analyzing the behavior of an aggregate of arbitrarily shaped elastic blocks with large deformation based on the principle of potential energy minimization. In the case that contact between blocks occurs, the Mohr-Coulomb's failure criterion is applied to the boundary, in addition, in the case that penetration occurs, the penalty spring is inserted to allow no penetration. Therefore, DDA enables dynamic analysis with large deformation. [7,8,9] In addition to these analytical characteristics, since there are some studies on collapses of Fixed Block Wall with DDA [2,10], we adopted DDA as an analytical method in this study. Note that the calculation program used in this study was created by Prof. Guangqi Chen at Kyushu University.

The analysis model is created based on the sectional plan of the model wall, and the parameters of blocks and boundaries are set based on the results of material tests shown in Table 1. Tables 2 (a) and (b) show the physical properties for the simulation of the first experiment, and Tables 3 (a) and (b) show the ones for the simulation of the second experiment. In addition, parameters cannot be obtained directly from the material test were set as follows.

First, the elastic modulus and Poisson's ratio of soil were calculated from the Vs and Vp measured in the steel container shown in Table 1 (b). Second, the tensile strength of soil and gravel are generally considered to be sufficiently small to ignore, however, in this study, the tensile strength of the back soil is set to 10(kN/m^2) based on the previous studies on them [11,12] and for the gravel, the value was set to 1/10 of soil. Third, the shear strength of mortar is based on the experimental results by Sato [13] and the shear strength and tensile strength between mortar and blocks are set based on the previous studies on concrete joints [14,15] taking into account the compressive strength of the mortar specimens made by each experiment. At last, the internal friction angle is assumed to be 45(deg) as an average value in consideration of the variation, referring to previous reports [16,17].

As for the analytical parameters, the time interval was set based on the sampling time interval during the each experiment, and the spring constant of the penalty spring, which affects the collision behavior between the blocks, was set to the maximum value at which the model wall does not collapse in the sufficiently large input case (upper load was increased to 5 times the standard, input wave was KiK-net KMM16 EW 60% which has real-scale time). This spring constant was also applied for the simulation of the first experiment. Table 2 (c) and Table 3 (c) show the analytical parameters.

Fig.5 shows the analytical model for the simulation of the experiments. In the analysis, the acceleration wave measured on the bottom of the steel container during the experiments were input to the container in the analytical model. In addition, a 5 seconds waveform of amplitude 0 was added before each original input wave so that vibration and subsidence by the own weight be settled and the initial stress be loaded.

Table 2 – Parameters of each material and boundary for the simulation of 1st shaking table test

(a) Material parameters

Material	Density (ton/㎥)	Elastic Modulus (kN/㎡)	Poisson Ratio
Soil	1.566	1.02E+05	0.41
Gravel	1.443	1.00E+07	0.20
Concrete Block	2.170	1.80E+07	0.20
Mortar	2.150	1.90E+07	0.20

(b) Strength parameters of boundary

Boundary	Cohesion (kN/㎡)	Φ (deg)	Tensile Strength (kN/㎡)
Inside Soil	13.8	37.3	10.00
Inside Gravel	0.0	30.0	1.00
Inside Mortar	5372.7	45.0	3030.00
Block – Mortar	519.0	45.0	1291.74

(c) Analysis parameters

DDA Parameter	
Time Interval (s)	1.953E−03
Spring Constant (kN/m)	3.000E+03

Table 3 – Parameters of each material and boundary for the simulation of 2nd shaking table test

(a) Material parameters

Material	Density (ton/㎥)	Elastic Modulus (kN/㎡)	Poisson Ratio
Soil	1.950	6.38E+04	0.26
Gravel	1.572	1.00E+07	0.20
Concrete Block	2.244	2.33E+07	0.20
Mortar	2.050	9.72E+06	0.20

(b) Strength parameters of boundary

Boundary	Cohesion (kN/㎡)	Φ (deg)	Tensile Strength (kN/㎡)
Inside Soil	12.2	21.9	10.00
Inside Gravel	0.0	30.0	1.00
Inside Mortar	1800.9	45.0	708.00
Block – Mortar	174.0	45.0	301.83

(c) Analysis parameters

DDA Parameter	
Time Interval (s)	5.000E−03
Spring Constant (kN/m)	3.000E+03

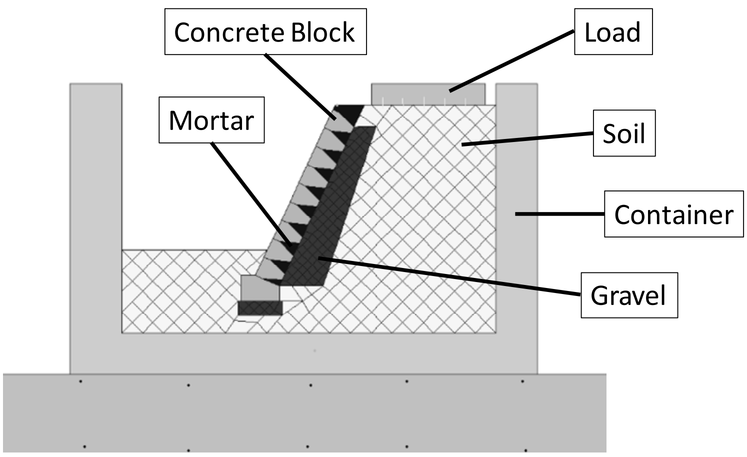
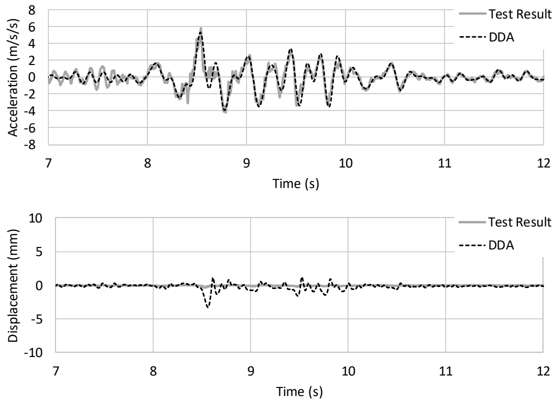


Fig.5 – Model of the small-scale retaining wall for the DDA

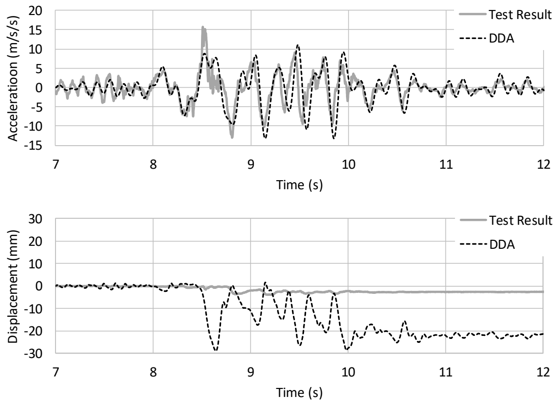
Fig.6 shows the simulation results of the first experiment, and Fig.7 shows the simulation results of the second experiment. All the graphs show the acceleration and displacement response at the top of the model wall, comparing the analytical values with the experimental values. Regarding the simulation of the first experiment, the experimental values can be reproduced relatively well in the case of low load and small input wave as shown in Fig.6 (a). However, in the case of high load and large input wave, the simulation result becomes larger than the experimental one as shown in Fig.6 (b). For example, the analytical value of an acceleration was 800(gal) larger, and the one of displacement was 20(mm) larger than the experiment result. In addition, it is confirmed that there is a gap of a phase between two waves.

On the other hand, as for the simulation of the second experiment, although a slight amplitude difference was confirmed in the acceleration responses, the experiment results were reproduced well in both of the small and large input cases as shown in Fig.7 (a) and Fig.7 (b).

From these results, it was confirmed that the model wall behaviors were reduced due to the effect of friction between the wall and the steel container in the first experiment and also that the friction was canceled in the second experiment. Moreover, the results of the simulation of the first experiment show that even if the wall strength is sufficiently high, it is presumed that damage will be able to occur in the case that the upper load is twice as large or more.

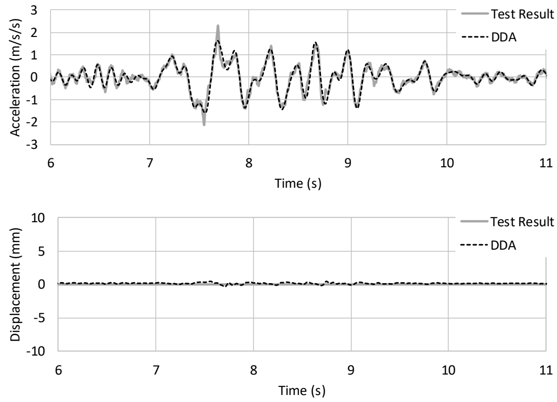


(a)Normal load, Reduced input wave (40%, EW)
(Time of input wave is shortened according to Scaling low)

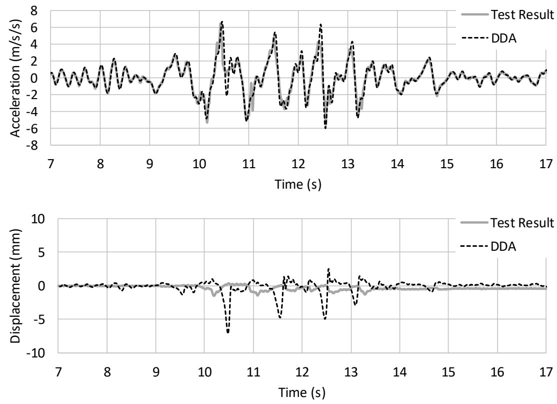


(b) Increased load (x2) load, Increased input wave (110%, EW)
(Time of input wave is shortened according to Scaling low)

Fig.6 – Simulation results of the 1st shaking table test



(a) Normal load, Reduced input wave (20%, EW)
(Time of input wave is shortened according to Scaling low)



(b) Increased load (x5) load, Reduced input wave (60%, EW)
(Time of input wave is real scale)

Fig.7 – Simulation results of the 2nd shaking table test

5. DDA Analysis of the real-scale retaining wall

Since the validity of the DDA as the method of dynamic analysis and an analytical model was confirmed through the simulations in Chapter4, we carried out the simulation expanded to the real-scale for reproducing and analyzing the actual damages.

For the real-scale simulation, two types of models of the wall, one with a height of 1 m and one with a height of 2 m, were created. In addition, the surrounding ground with a depth of 3 m and a width of 30 m was adopted to the retaining wall. The physical properties of the surrounding ground for the simulation were set according to the survey report in Mashiki Town [18,19], and the blocks, mortar and their tensile and shear properties were set referring to the previous studies [13,14,15,16,17], and taking into account the compressive strength of the backfill concrete. Table 4 (a) and Table 4 (b) show the parameters set in the simulation.

Additionally, as for the analytical parameters, the time step was set to 1/10 of the observed seismic wave, and the penalty spring constant was set to the maximum value at which the wall does not collapse at same level as the larger case in the simulation of the second experiment (input wave was KiK-net KMM16 EW 60%) based on the same concept as in Chapter 4. Table 4 (c) shows the analytical parameters set in the simulation.

In the simulation, the acceleration wave is input to the rigid container in the model. Hence, in order to reproduce the observed wave at the ground surface, the input waves are needed to be calculated from the original observed wave with the transfer function. For the reason as above, we analyzed the model without the retaining wall in order to take into account the effects of amplification of the ground under the structure and the effects of constraints around the model by the rigid container. In addition to the wall height and input wave, in this parametric study, the strength of backfill mortar was varied as below. The initial value of the compressive strength is the minimum value indicated in the design guideline [20], and the strength varied in the range of the strength ratio from 0.25 to 1.75.

Regarding the strength of mortar, it is considered that the variation of the strength and the adhesion performance due to construction failure or deterioration exist unevenly inside the wall, but in this study, it is assumed that the mortar strength and the adhesion performance are constant in the wall.

The analysis model is shown in Fig.8, and the list of simulation results are shown in Table 5.

Table 4 – Parameters of each material and boundary
for the simulation of real-scale retaining wall and ground

(a) Material parameters

Material	Density (ton/m³)	Elastic Modulus (kN/m²)	Poisson Ratio
Natural Soil	1.60	5.29E+04	0.37
Banking Soil	1.55	5.13E+04	0.37
Gravel	1.60	1.00E+07	0.20
Concrete Block	2.24	2.33E+07	0.20
Mortar	2.15	2.21E+07	0.20

(b) Strength parameters of boundary

Boundary	Cohesion (kN/m²)	Φ (deg)	Tensile Strength (kN/m²)
Inside Natural Soil	36.8	21.0	10.00
Inside Banking Soil	5.0	30.0	10.00
Inside Gravel	0.0	30.0	1.00
Inside Mortar	3512.0	45	1860.06
Block − Mortar	339.3	45	792.98

(c) Analysis parameters

DDA Parameter	
Time Interval (s)	1.000E−03
Spring Constant (kN/m)	1.000E+04

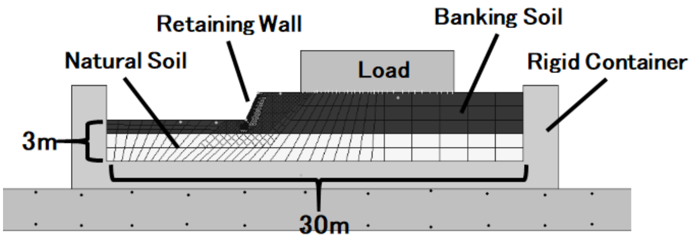


Fig.8 – Model of the real-scale retaining wall for the DDA

Table 5 – Simulation results of the real-scale retaining wall

Wall Height	Input Wave (KMMH16)	Strength Ratio of Mortar (Analysis/Regulation)	
		≦1.0	≧1.25
2m	NS, 100% (652gal)	No Damaged	No Damaged
	EW, 60% (693gal)	No Damaged	No Damaged
	EW, 100% (1156gal)	Moderately Damaged	No Damaged
1m	NS, 100% (652gal)	No Damaged	No Damaged
	EW, 100% (1156gal)	No Damaged	No Damaged

As a result of the analysis, moderate damage occurred only in the case that the strength of the backfill mortar was at or below the reference value (initial value) for the wall with a height of 2m constructed in the EW direction. On the other hand, in other cases, no damage was observed regardless of the mortar strength. However, in practice, all cases assumed here were moderately or more severely damaged (shown in Fig.2), while even in the case where the moderate damage was found as a result of analysis, the blocks did not spread out as the observed damage did.

Since the collapse state shown in Photo 2 was not simulated, the analysis was performed for the case that the adhesive and tensile strength between the mortar and the block were set to 0. Fig.9 shows the simulation results (residual deformation after vibration).

In consequence of the modification, in the case that the integrity of the wall was lost, the retaining wall with a height of 2m collapsed and spread out in both cases NS and EW wave input as observed in practice. On the other hand, none of the 1m retaining walls collapsed. As for the collapse process, although the deformation diagram during the collapse is not shown, intermediate state in the collapse process is that the center of retaining wall swelled similar to the residual deformation diagram of the retaining wall with a height of 1 m in the case EW wave input shown in Fig.9 (lower left). Furthermore, it inclined and could not support the soil pressure from the behind, and at last, collapsed to the front.

Photo 2 – An example of the collapsed retaining wall

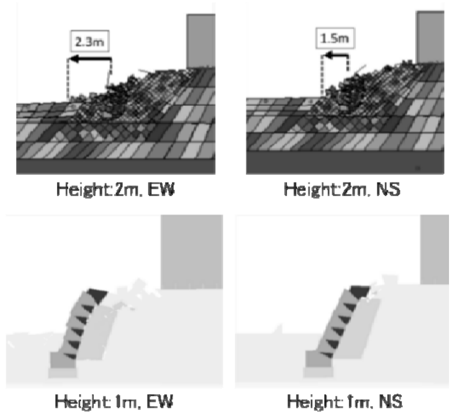


Fig.9 – Simulation results of the collapsed walls

These results suggest that the retaining wall that collapsed significantly during the earthquake had a problem with the quality of the backfill mortar and that the integrity of the inside of the wall was lost. Specifically, there is the possibility that sufficient compaction was not performed during construction and that the cold joints were made. In any case, it was found that there was a problem in the construction management rather than a problem in the design standards for the seismic safety of the Fixed Block Wall.

It is also possible that factors not considered in the simulation may have affected the degree of damages. For example, as a result of the reinvestigation with the Google Street view, there are block fences that were added just above the retaining wall and structures which were built near the cliff as shown in Photo 3. These factors were basically not taken into account in the seismic design and they may have interfered with the retaining wall as unexpected loads and vibrators, possibly causing damage during the earthquake. Since the model wall inclined in the simulation of the first experience in the case that the upper load was doubled from the standard value despite the sufficiently high strength of mortar, it is also assumed that the damages increased due to the additional factors above. In addition, it is considered that the strength inside the retaining wall was distributed unevenly unlike the assumption in the simulation.

Therefore, in order to explain whole damages of the retaining wall, more realistic simulation is needed based on more detailed investigations of the surrounding conditions and the internal structure of the wall.

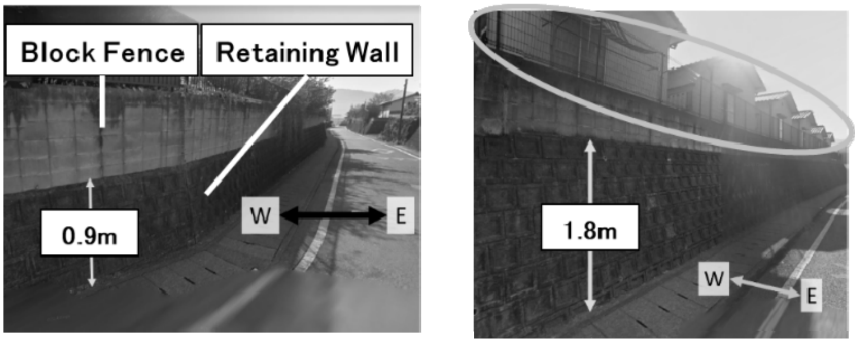


Photo 3 – Unexpected structures around retaining walls

6. Conclusion

In this study, we first conducted the damage survey on the collapsed residential retaining walls in Mashiki Town, which suffered heavy damage by the 2016 Kumamoto earthquake, and organized the relationship between the construction method, the height of the retaining wall, and the damage level. According to the results of the survey, since the Fixed Blocks Walls were most severely damaged, we carried out the shaking table tests and their simulation with DDA. Furthermore, based on them, real-scale simulation with the model including surrounding ground was conducted.

As a result, as observed in the damage survey, it was confirmed that the height and the constructed direction of the Fixed Block Wall affected the damage level and that the internal mortar strength and its integrity had a crucial effect on the seismic performance.

In addition to the fragility of the wall, various complex factors such as deterioration of the surrounding ground and excessive load can be considered as the cause of the damage of the retaining walls. However, in this study, since the integrity was lost in almost all the collapsed Fixed Block Wall observed, and from the perspective of contributing to the establishment of specific measures for design or construction, we conducted the experiments and the simulation especially focused on the vulnerability of the wall.

Although future problems remain in the analysis of unexpected factors such as the surrounding conditions that could lead to damage to the retaining wall, experiments and analysis under the conditions indicated in the current design standard show that even if the backfill mortar strength is low, the retaining wall with integrity between blocks and mortar is difficult to be damaged severely such as collapsed ones.

Therefore, as a countermeasure against the collapse of the retaining wall in the future, it is necessary to establish a construction and a reinforcement method to ensure the integrity of the wall.

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8. References

[1] Okimura T, Futaki M, Okamoto A, Nambu M (1999): Characteristics and Cause for Damage of Retaining Walls on Housing Lots by the Hyogoken-Nambu Earthquake. *Journal of Japan Society of Civil Engineers*, No637/VI-45, 63-77. (in Japanese)

[2] Hashimoto T, Miyajima M, Ikemoto T, Sakai H (2014): Study on Analysis and Experiment of Earthquake Resistance of Masonry Retaining Wall. *Journal of Japan Society of Civil Engineers*, Vol.70, No.4, I_991-I_1003. (in Japanese)

[3] Kawase H, Matsushima S, Nagashima F, Baovintu, Nakano K (2017): The cause of heavy damage concentration in downtown Mashiki inferred from observed data and field survey of the 2016 Kumamoto earthquake. *Earth, Planets and Space*, 69:3.

[4] *Act on Regulation of Residential Land Development*. (1961) (in Japanese)

[5] Kumamoto prefectural government office (2014): *Guide of development permission system and development permission application by City Planning Law*. (in Japanese)

[6] Kagawa T (1978): On the Similitude in Model Vibration Tests of Earth-Structures, *Journal of Japan Society of Civil Engineers*, No275, 69-77. (in Japanese)

[7] Shi G H (1989):Block system modeling by Discontinuous Deformation Analysis. Univ. of California. Barkeley. Dept. of Civil Eng.

[8] Onishi Y, Sasaki T, Shi G H (2005): *Discontinuous Deformation Analysis (DDA)*. Maruzen Publishing Co., Ltd. (in Japanese)

[9] Chen G, Zen K, Onishi Y (2004): Study on Analysis of Large Deformation for Discontinuous Media in Civil Engineering. *Journal of applied mechanics*, Vol.7, 797-804. (in Japanese)

[10] Sakai H, Yamaji T, Kumuji A (2009): Collapse Simulation of Stone Masonry Walls during the 2001 Geiyo Earthquake using Discontinuous Deformation Analysis. *Journal of Japan Society of Civil Engineers*, Vol.65, No.1, 575-580. (in Japanese)

[11] Tamrakar S B, Toyosawa Y, Itoh K (2004): A newly developed tensile strength measuring apparatus for soils (Comparison of tensile strength and unconfined compression strength for Kanto loam). *Proceedings of the 39th Annual Meeting of Japanese Geotechnical Society*, 251-252. (in Japanese)

[12] Ito M, Hirano F, Sugiura K (1974): A tensile strength measuring method for soil. *Proceedings of the 29th Annual Meeting of Japan Society of Civil Engineers*, Vol.3, 210-212. (in Japanese)

[13] Sato T (2008): Experimental study of shear strength of concrete. *Proceedings of the Japan Concrete Institute*, Vol.30, No.1. (in Japanese)

[14] Tamaki K, Takenoi I, Sada T (2006): Comparative Study on Treated Construction Joints. *Reports of Technical Research Institute of Sumitomo Mitsui Construction Co., Ltd.*, Vol.4, 69-75. (in Japanese)

[15] Watanabe N, Yoshida N (2001): Surface preparation and bond effect on concrete construction joint. *Proceedings of KAIHATSU KOEI Co., Ltd.*, Vol.8, 13-19. (in Japanese)

[16] Fujita Y, Ishimaru R, Hanai S, Suenaga Y (1997): Study on internal friction angle and tensile strength of plain concrete. *Journal of Structural and Construction Engineering (Transactions of AIJ)*, No.494, 7-14. (in Japanese)

[17] Yoshida Y, Mizuno E, Hatanaka S (2004): Uniaxial compression FEM analysis of cylindrical concrete specimens with different shape ratios. *Proceedings of the Japan Concrete Institute*, Vol.26, No.2, 19-24. (in Japanese)

[18] Mori T, Matsushita K, Kawasaki A (2017): Buildings and residential lands damage survey in Mashiki-machi, Kumamoto prefecture on The 2016 Kumamoto Earthquake. *Japanese Geotechnical Journal*, Vol.12. No.4, 439-455. (in Japanese)

[19] Kashiwa H, Arai H, Nakagawa H (2017): Earthquake Response and Soil-Structure Interaction Effects at Mashiki Town Office during the 2016 Kumamoto Earthquakes. *Proceedings of the Annual Meeting of Japan Association for Earthquake Engineering*, P3-15 (Poster session). (in Japanese)

[20] Japan Road Association (1977): *Design Guidelines for Retaining wall, Calvert and Temporary Structure*. Maruzen Publishing Co., Ltd. (in Japanese)

