Study on tsunami-resistance of a reinforced soil wall based on water tank experiment

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Research

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Abstract

Background：

The 2011 off the pacific coast of Tohoku earthquake (Mw=9.0) caused great damage of geotechnical structures in the vicinity of the eastern coasts. In contrast, many of reinforced soil walls constructed along the coast were less damaged by the tsunami. In this study, a model test using water tank is conducted to evaluate the behavior of a reinforced soil wall under strong water flow and water pressure like tsunami as an experimental prototype. The scale of model is 1/40, the height of wall is 25cm and the water level is 20cm, supposing that a tsunami hit the wall whose height is 10m in a full-scale without overflowing. Water flow hit the wall keeping its velocity and level. When the water penetrates into the backfill soil until ground water level is same as the level of water flow, the water was stopped and drained out of the tank.

In this study, 2 test cases were conducted. One is a sound wall, and the other is a wall with some opening of the front panels which simulates the gap of the wall due to residual settlement after an earthquake.

Results：

The sound wall has no deformation during and after the tsunami action. In the wall with some opening, around 30 minutes after the start of the tsunami action, the wall panel showed gradual deviations such as slippage. In all cases, the pore water pressure in the backfill soil rises with seepage of the water, but the soil was not completely saturated.

Conclusions：

It was found that a reinforced soil wall does not have large deformation unless there are some opening of the front panels and the backfill soil flow out of the wall. This result shows that reinforced soil wall does not collapse by seepage to the backfill soil or wave force of tsunami, but collapses by backfill soil flowing out from wall surface. Our results support that a reinforced soil wall has high tsunami-resistance. Given this information, it is necessary to prevent the wall from making some opening and prevent the backfill soil from flowing out.

Introduction

The tsunami caused by the 2011 off the pacific coast of Tohoku earthquake on March 11, 2011, having hit the Pacific Ocean brought enormous damage to the coastal plains. This event has resulted in the strong demand of necessary complex facilities development for earthquake-resistance and tsunami-resistance in coastal zones with the expected damage caused by the Nankai Trough earthquake, relocation of disaster prevention base and dwelling houses to the higher hills, and an emergency evacuation routes development (MILIT, 2013).

In particular, the development of an emergency evacuation route to the hills in coastal areas requires that in many cases, the roads need to be laid in existing urban areas. For embankment developments in such narrow grounds, the use of reinforced soil walls using reinforcement materials such as geotextiles, having few constraints on site. Earthquake resistance of the reinforced wall has been confirmed by previous model tests (Tsuji et al, 2011) and even in the Tohoku earthquake, about 98% of the 1,919 reinforced wall measurements under the conducted damages survey shows either no damage or just minor damages according to the report (Ichikawa et al, 2011 ; Kuwano et al, 2012).

The stability of the bank body and effective tsunami countermeasures has been verified using the water tank experiment simulating the tsunami effect. But the verification of the performance against tsunami of the retaining wall structure, has been stemming from the focused tide embankment with the maximum wave pressure mainly caused by the tsunami in many cases. Yamaguchi et al have demonstrated that the stability of the tide embankment against the overflow tsunami by tsunami model experiments on various types of tide embankments and reinforced embankment with multilayered horizontal reinforcement so that the rate of embankment erosion due to the tsunami decreased. Furthermore, it showed that the stability of tsunami is dramatically improved by integrating the covering work and the horizontal reinforcing material (Yamaguchi et al, 2012). Matsushima et al have demonstrated that as a model of a new type embankment, reinforcing the surface of the bank body with geotextiles integrated with cement modified soil and the covering work are effective against the overflow tsunami and the shock wave force of non- overflow (Matsushima et al, 2014).

However, the existing tsunami countermeasure tidal embankment is based on the premise that water does not permeate into the bank body. The road retaining wall structures including reinforced soil walls commonly provide drainage ditches to promptly drain water having permeated the embankment. These structures allow water to permeate more easily from the wall surface.

In the current design of the reinforced soil wall, stationary load and seismic load are assumed, and stability of wall and extraction yield strength of the horizontal reinforcement against the pressure of backfill soil are checked. But concrete design method is not established about the stability of the reinforced soil wall for the action of the tsunami.

Following three were considered as the effect that tsunami action causes to reinforced soil wall, which is wave force of tsunami, decreasing in backfill soil by seepage, and hydro static pressure from the backfill to the wall panels after lowering of tsunami level. The tsunami wave pressure pushing the wall surface effects to the passive direction of the backfill, but in the past damage example, the cracks by the passive breaking are not found in a crown of the backfill soil. Therefore, the passive resistance of the backfill soil is large enough against tsunami wave pressure. Besides, it is demonstrated that well compacted soil are not completely saturated even though the water permeated into soil(Tanimoto et al, 2013). In the design of reinforced soil wall, the strength of backfill soil to use for design is in the state that soil was saturated. In consequence, actual strength of the backfill soil when water penetrated is higher than strength assumed in design. However, there are few examples verified about the osmotic effect to backfill by the

stream action that streaming velocity is rapid like tsunami and about the behavior of the reinforced soil wall by the action of the water which penetrated in backfill right after tsunami receded.

Returning to the damage investigation result of the reinforced soil wall, there are many cases that soils at the back side is flowing out due to coming off from the front panel mainly due to the backwash of the tsunami (Kuwano et al, 2012). There was hardly any damage observed on the reinforced soil wall without overflow reportedly.

In this paper, a water flow device in a water tank which simulate the strong water flow of tsunami was developed to analyze about behavior and a factor to collapse of the reinforced soil wall when tsunami effected.

Methods

Past experiments and focused points in this experiment

Past method of tsunami effect given in the water tank experiment, include a method of generating wave force by horizontally sliding the wave plate from the hydrostatic state (Suzuki et al, 2014) and a method of generating a wave force by releasing a certain amount of water by using a water head difference (Nakagawa et al, 1969). These methods are effective for perceiving the tsunami as external forces and evaluating the strength of the structure. In another water tank experiments focusing on the embankment structure, they have verified the damage mechanism of the embankment and the factors of the disaster by providing a stream flowing over the embankment. Tokida et al have suggested that embankment damages are mainly erosion at back slope and scouring at toe of slope by overflow of embankment from results of water tank experiments and damage investigations. And they also suggested that only some erosion at front slope does not cause collapse of embankment (Tokida et al, 2013). Even in the method of reinforcing the embankment structure, there are many proposals focused on the prevention of erosion at its back side and verification by experiments (Kudo et al, 2014 ; Kuragami et al, 2013). This is believed to be due to the fact that the slope of the embankment receives the tsunami wave force acting on the front of the embankment and the permeation of overflowing water into the embankment is also limited. However, since the reinforced soil wall is an upright wall surface and its structure allows easy penetration to the back surface, it may be different from the general embankment behavior.

Based on the background, our experiment is to grasp the state of the reinforced soil wall by water flow simulating the tsunami, for a certain period without overflowing, having constant continuous water level and flow velocity. The reinforced soil wall type was subject to reinforced soil walls using geotextiles. Reinforced soil walls using geotextiles have been confirmed to have high earthquake resistance based on past experiences of damage and experiments(Ichikawa et al, 2011 ; Kuwano et al, 2012), and hydraulic experiments on tenacious structure tidal banks against the overflow of the tsunami were carried out; the concept of design has been compiled in a manual.

Outline of experiment equipment

A schematic diagram of the experiment device is shown in Fig. 1. The experimental device overviews are shown in Fig. 2. In general, the retaining wall popular height domestically is 3 m to 18 m (JRA, 2012), the height of retaining wall was supposed 10 m in out experiment. The experiment device scale was 1/40. Table 1 shows the comparison between real scale and model scale. The scale of the model was determined according to the similarity law under the 1G field, and the velocity of the water flow was determined according to the Froude similarity rule. Installing a partition made of an acrylic plate in the center of the experiment device, a model of reinforced soil wall was built. A clearance of 5 cm was set between the bottom surface of the reinforced soil wall model and the bottom surface of the water tank. A water flow pump was installed in front of and in the rear side of the reinforced soil wall so that the water flow at a constant speed could continue to act from the front face to the back face of the reinforced soil wall.

A cross section of reinforced soil wall model is shown in Fig. 3, and overviews of soil wall model are shown in Fig. 4. For the wall panel, aluminum plates with a width of 98 mm and a height of 24 mm were adopted, which was one piece having a proven track record in the previous experiment (Tsuji et al, 2011) on a reinforced soil wall having the same structure. It was supposed that the wall surface panel did not transform and adjusted only weight of the panel in consideration of model scale. Considering the scale of the model from the actual weight of the wall panel (3.05 kN/m^2), the plate thickness of the model panel was adjusted so that the weight of the wall panel was equivalent to the value at 1/40 scale (0.78 g/cm^2). Based on the results, the wall thickness of the wall panel was 3 mm. On the back of the wall panel, crushed stone layer was set with 1 cm wide simulating the drainage layer on the wall, and backfill soil was set behind the crushed stone layer. The soil test results of the backfill soil are shown in Table 2, and the grain size distribution of backfill soil is shown in Fig. 5. About 95% of the backfill soil consisted of fine sand and medium sand. The shear strength of backfill soil was estimated only in angle of shear resistance, the grain size of the backfill soil did not consider model scale. The compaction of the backfill soil was carried out so that the relative density had reached Dr = 90% according to the result of the test for maximum and minimum densities. This relative density is one of the standard value of compaction degree of road embankment in Japan (JRA, 2010). For the crushed stones layer, gravel with a maximum particle size of 3 mm was sieved with 2 mm sieve and an equalized material with a particle size of 2 mm to 3 mm was used. The grain size of crushed stone was chosen to flow out from clearance of the wall surface panel which is intentionally made as one of the test cases. Moreover, a nonwoven fabric was laid between the backfill soil and the crushed stone layer for preventing backfill soil from flowing out.

Conditions of the geotextile as the horizontal reinforcing, which were laying interval, laying length, and tensile rigidity were obtained from the structural calculation for the reinforced soil wall with the retaining wall height of 10 m (PWRC, 2016). As a result of the structural calculation, the tensile rigidity required for the geotextile was 20 kN/m to 115 kN/m on the model scale. Materials used for modeling geotextiles need to have equivalent tensile rigidity to the calculated value. Therefore, four candidate materials (A to D) were selected, and a tensile test was conducted as shown in Fig. 6. The tensile test results of candidate materials A to D are shown in Table 3 and graphs of tensile test results of candidate materials

D are shown in Fig. 7. As a result of the tensile test, the material D (tensile rigidity 100 kN/m) was selected to use for the geotextile model.

On the wall panel, a grid belt was attached for preventing the panel from slipping out. The appearance of the grid belt is shown in Fig. 8. Four grid belts per a wall panel were set, whose size is a width of 8 mm and a length of 50 mm, considering the scale of the model based on the structural calculation resulting from the real scale. As a material of the grid belt, a sheet made of polypropylene was adopted. The tensile elastic modulus of polypropylene is 1.1×10^6 kN/m^2. Since the tensile rigidity of the grid belt in the actual structure is 880 kN/m, which is 22 kN/m converted to the model scale. Therefore, the thickness of the polypropylene sheet was adopted 0.02 mm, considering the model scale. Furthermore, in order to make the friction between the grid belt and the backfill soil, particles of the backfill soil was glued to both sides of the sheet.

Tsunami effect

The tsunami effect in this experiment consists of two key points characterized by 1) a constant flow velocity continues to act, and 2) not to overflow. In this experience, tsunami height in the actual scale was assumed to be 8 meters from the bottom of reinforced soil wall. The estimated water level was 20 cm in model scale, and the stream was controlled during an experiment so that this water level could keep constant. According to the 2011 off the pacific coast of Tohoku earthquake tsunami simulation analysis by Kato et al, the maximum flow velocity at the 8 m tsunami height point was 1.4 m/s (Kato et al, 2011). Converted to 1/40 scale by the Froude similarity rule, the flow velocity in the water tank experiment device was about 22 cm/s. To keep this flow rate, the pump output was adjusted at the inflow side and outflow side. On the inflow side, four submersible pumps with 360 kW output were used to simulate the uphill of the tsunami by running pumps one by one. On the outflow side, one submersible pump with 5.5 kW output was used and they were operated at the timing when the water level had reached nearly the estimated water level.

Regarding the flow rate, since the flowmeter itself may interfere the water flow on the wall surface, the experimental flow velocity was measured when only the water flow was generated with the acrylic plate fixed to the wall surface before the model of the reinforced earth wall was prepared. The flow velocity was measured with an electromagnetic flow velocity meter AEM 1-D manufactured by JFE Advantech Co., Ltd. Figure 9 shows the flow rate measurement situation and measurement results. The flow rate of about 50 cm/s was continuously measured at a position of 20 cm from the bottom of the tank (15 cm from the base of the reinforced earth wall), and 5 cm from the wall. This velocity was faster than our target flow velocity (22 cm/s), but it was difficult to control the velocity in the model and it was more important to keep the elevation of the water flow. Therefore, we judged the flow condition was satisfied with our target.

The tsunami effect was kept continuously with a constant flow velocity to the wall for about 1 hour. It was the required time that the backfill soil on the back of the reinforced soil wall reached a sufficient

saturation condition. Immediately after the backfill soil on the back of the reinforced soil wall saturated, the water in the tank was drained to observe the deformation of the wall. Figure 10 shows a schematic diagram of time history of water flow.

Experimental Case

Experimental cases are shown in Table.4, considering the examples of damage of the reinforced soil wall which are found in the 2011 off the pacific coast of Tohoku earthquake etc.

First case was a reinforced soil wall in a sound state. Second case was the wall in whose panel some openings were intentionally provided. These openings were supposed a situation where the crushed stone of the back-filling material flows out. The height of an opening was 5 mm, and the openings were made on center two wall panels regularly.

Results And Discussion

Time history of states of reinforced soil wall

Table 5 shows the state of the reinforced soil wall at each representative time step and the situation of the reinforced soil wall after the experiment for each experimental case. It is evident from the Table 5 that it is difficult to prevent flooding in the embankment due to the arrival of the tsunami, and it is important to prevent erosion and flowing out of the embankment.

Figure 11 shows time history of penetration distance at the center of the wall. The penetration speed into the backfill soil was found generally constant regardless of the condition of the wall panels. Figure 12 shows time history of jutting front panel. In the CASE-2, it had the largest amount of draw-out of the wall panel, and the grid belt slipped out of the backfill soil. Almost no change was observed in CASE-1. However, in all cases, the deformation amount hardly changed in 30 minutes after the tsunami effect, and it was found that the deformation became larger at the time when a certain time passed. This phenomenon is conceivably caused by the wall surface being pushed in the passive direction by the action of the tsunami. The wall panel gradually could flow out due to the outflow of the back-filling material only in CASE-2.

Figure 13 shows the time history of pore water pressure in backfill soil. The pore water pressure was measured every 1 second, and the value of the figure shows the average of 60 seconds. The pore water pressure of CASE-1 was about 1.5 times higher than CASE-2. This may show the difference by the compaction conditions of backfill soil around measuring instrument. The notable point is that the pore water pressure is smaller than water pressure assumed in saturated soil with both cases. If backfill soil is completely saturated, the calculated water pressure at the measurement point is about 1.6kPa(=9.8kN/m3 × 0.16m). The measured maximum pore water pressure is about 1.3 kPa that means the pore water pressure rise only to approximately 80% of the calculated value. Accordingly, the backfill

soil in not saturated completely by seepage like the experiment by Tanimoto（Tanimoto et al, 2013）even if stream such as tsunami effected reinforced soil wall.

Results on sound reinforced soil wall (CASE-1)

In the event of tsunami there was no significant change in the reinforced earth wall after it. Moreover, to grasp the limit state of reinforced soil wall at the time of sound, by raising the water level as the second re-action and letting the tsunami overflow and drained again.

Nevertheless, there was no noticeable change in the reinforced earth wall itself, no settlement of the top edge occurred. The condition of front panel after finishing experiment is shown in Fig. 14.

Results on reinforced soil wall with openings in wall panel (CASE-2)

Around 30 minutes after the start of the tsunami action, the wall panel showed gradual deviations such as slippage. Figure 15 shows the condition of front panel after the first tsunami action. At the end of the tsunami, almost all the crushed stone at the backside flowed out and pulling out panels were confirmed until the third stage from the top. Although the maximum amount of settlement at the top end of the reinforced soil wall was seen to be 2 cm at the center (80 cm at the actual scale), since it is supported by the nonwoven fabric laid as prevention material of the back-filling material draw-out; in fact, the significant collapse could have occurred.

Conclusions

To ascertain the behavior of the reinforced soil wall during the tsunami action, an experiment was conducted to keep the water flow at a constant water level and flow rate acting on the reinforced soil wall model. Based on a series of experimental results, the conclusions are as follows:

1. In a sound state where no gap was provided in the wall panel of the reinforced soil wall, no noticeable change was observed in the reinforced earth wall due to the action of water flow;
2. If gaps occurred in the wall panel of the reinforced soil wall, the backfill soil flowed out due to the action of the water flow, and accordingly the wall panel slowly slipped out, and settlement also occurred at the top end of the reinforced soil wall;

These results indicate that reinforced soil walls requiring earthquake resistance and tsunami resistance are essential for ensuring the soundness of the facility for suppression of flow out of back filling soil. It was found that there was the possibility of preventing damage such as the top end being greatly settled or the shape of the embankment being greatly changed.

However, when deformation or gap occurs in the wall panel, there is a high possibility that deformation of the embankment top end and the reinforcing material by it are occurred. Further verification is necessary

for the tsunami resistance when the entire reinforced earth wall is deformed by an earthquake or the like and the safety of the reinforced earth wall against the tsunami effect.

Declarations

List of Abbreviations

Not applicable.

Availability of data and material

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Competing Interest

Not applicable.

Funding

Not applicable.

Authors' contribution

KK carried out the experiment and organized data and wrote the manuscript. TH advised the policy of the experiment and performed instruction of the manuscript. HH provided the water tank experiment device and advised about the way of the experiment. ST conducted the tensile test of the geotextile model and advised how to produce the reinforced soil wall model. SK produced the reinforced soil wall and advised how to organize the results. All authors read and approved the final manuscript.

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Tables

Table.1 Similarity low and model scale (Lr=40)

	Similarity	Real Scale	Model Scale
Height of wall	1/Lr	10m	25cm
Weight of panel	1/Lr	3.05t/m^2	0.778g/cm^2
Tensile stiffness of geogrid	1/Lr	800kN/m[illegible]4600kN/m	20kN/m[illegible]115kN/m
Tensile stiffness of gridbelt	1/Lr	880kN/m	22kN/m
Verocity of water flow	1/√Lr	1.4m/sec	22cm/sec

Table.2 Physical property of backfill soil

Backfill Soil	Fine content(Fc)	%	20.5
	Mean particle size(D50)	mm	0.075
	Maximum dry density (ρdmax)	g/cm^3	1.4
	Minimum dry density (ρdmin)	g/cm^3	1.09
Crushed Stone	Maximum particle size(Dmax)	mm	3

Table.3 Tensile stiffness of test sheet

Sample		Tensile stiffness (kN/m)
A	1st test	9.0
	2nd test	14.4
B	1st test	7.2
	2nd test	8.5
C	1st test	40.6
	2nd test	37.6
D	1st test	98.0
	2nd test	105.0

Table.4 Test cases

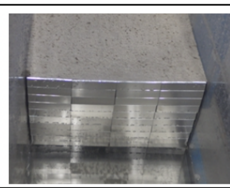
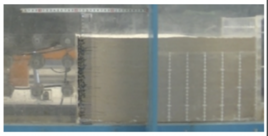
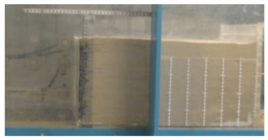
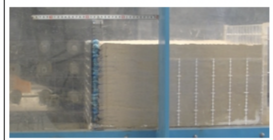
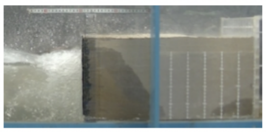
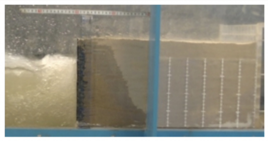
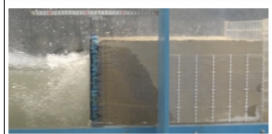
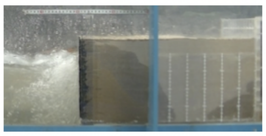
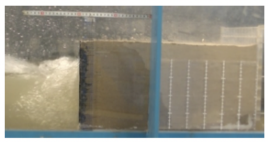
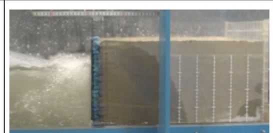
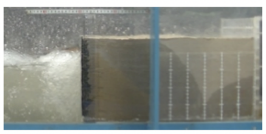
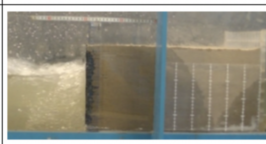
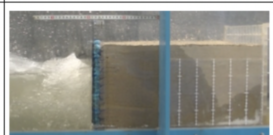
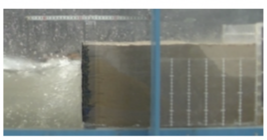
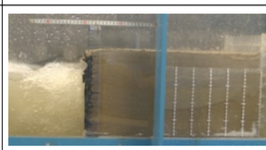
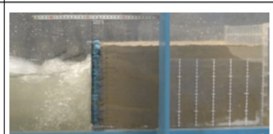
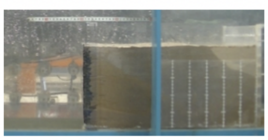
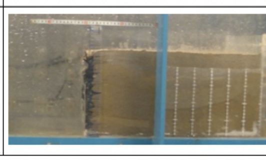
CASE		Gap of front panel	Backfill soil	Photo
1	Sound wall	–	Sandy soil (Dr=90%) Crushed stone	
2	Wall with some opening	○ (5mm)	Sandy soil (Dr=90%) Crushed stone	

Table.5 Condition of reinforced soil wall model during experiment

	CASE-1 Non-damaged wall	CASE-2 Damaged wall	CASE-3 Improved wall
Before starting			
5min later			
10min later			
30min later			
60min later			
After draining			

Figures

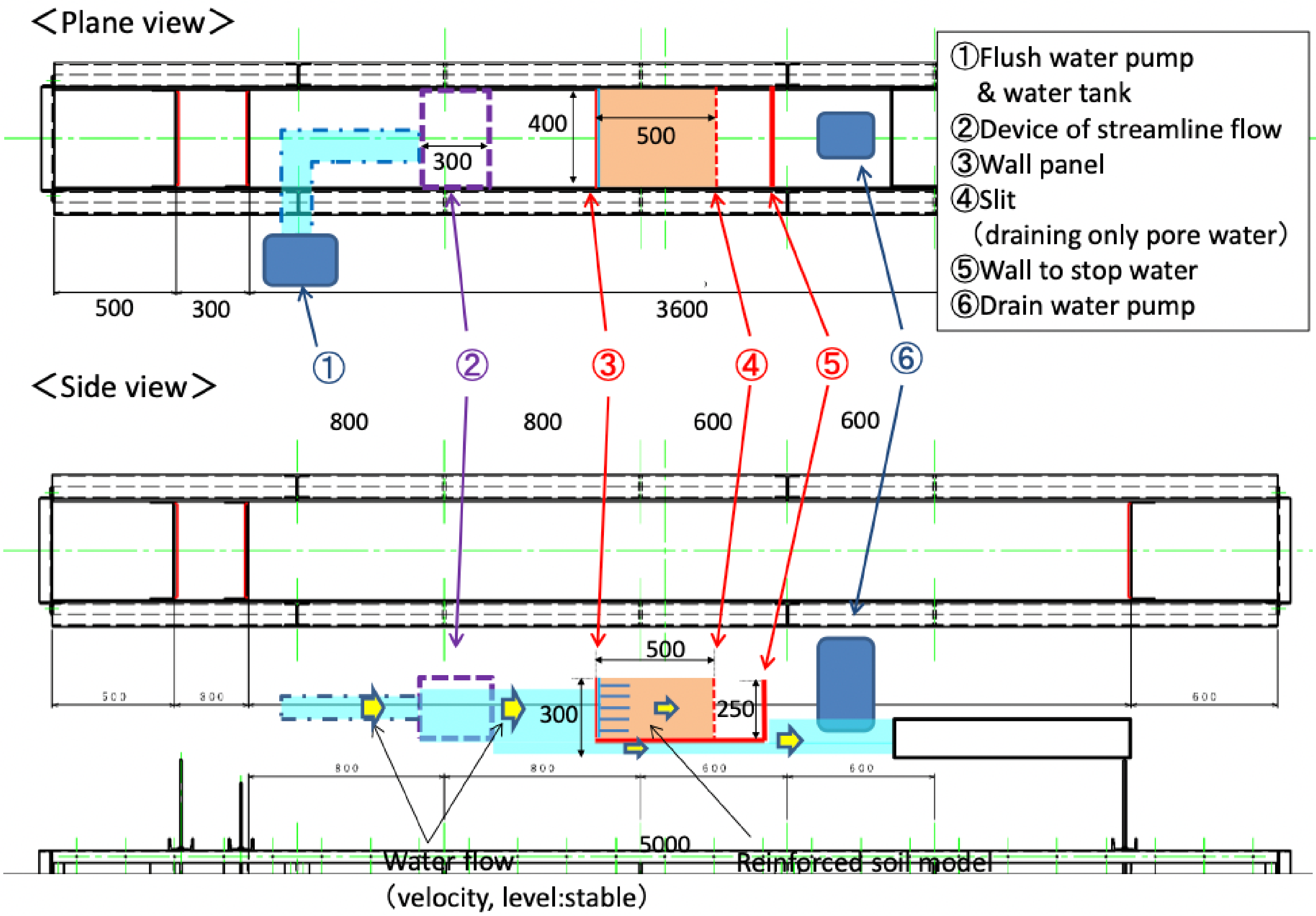


Figure 1

Schematic drawing of water tank experiment device

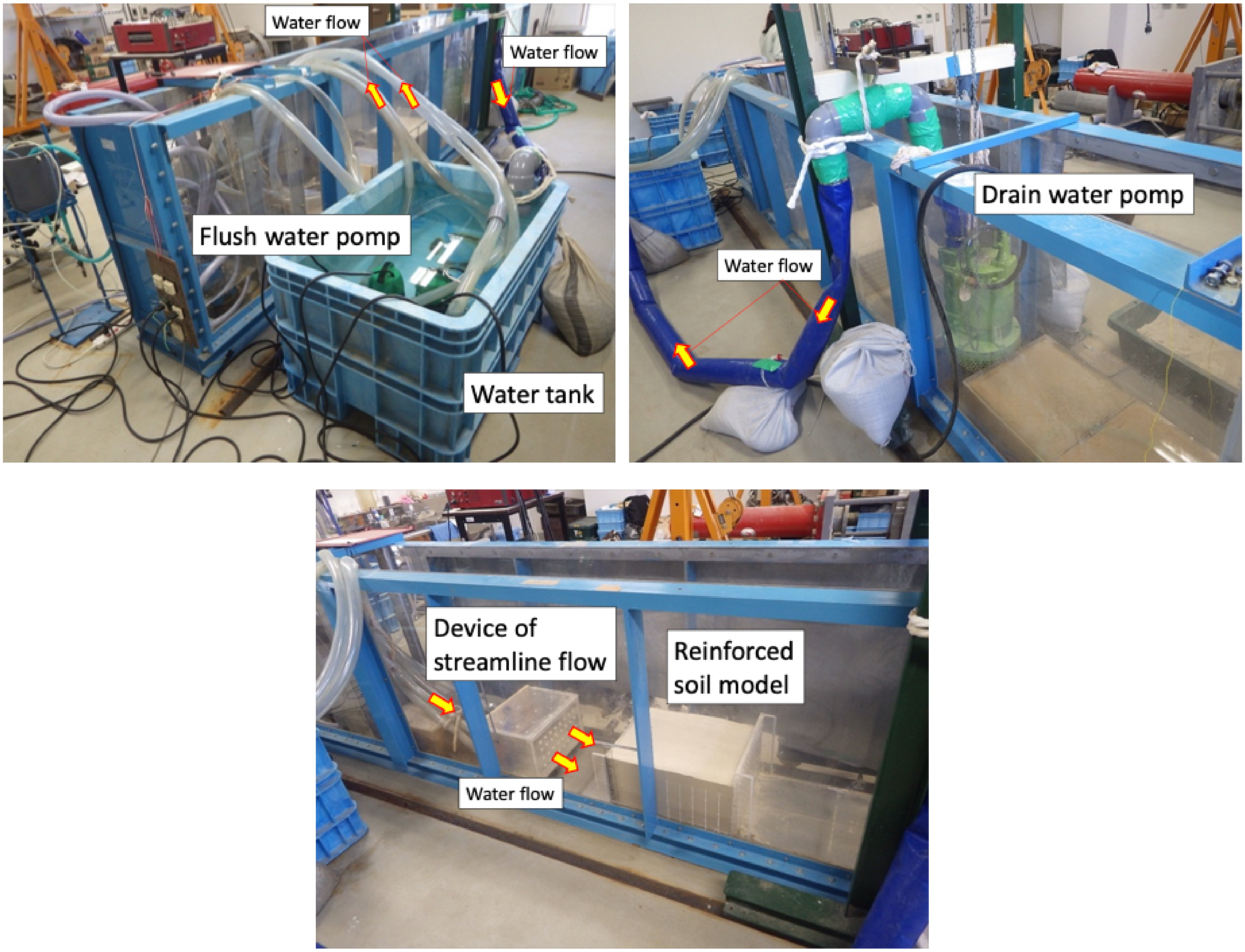


Figure 2

Overview of water tank experiment device (Left, Flush water pump; Right, Drain water pump; Bottom, Reinforced soil model)

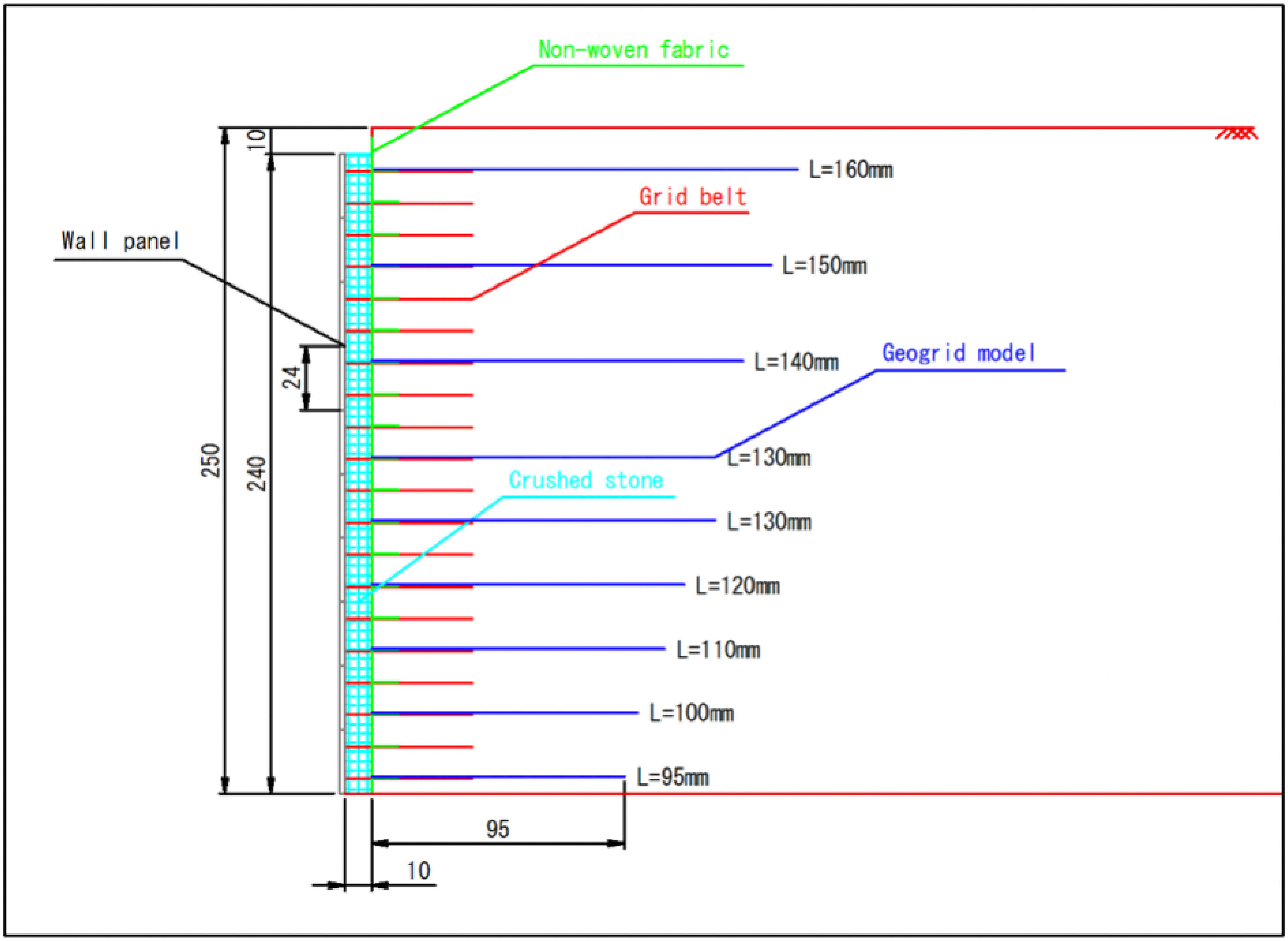


Figure 3

Cross section of reinforced soil wall model

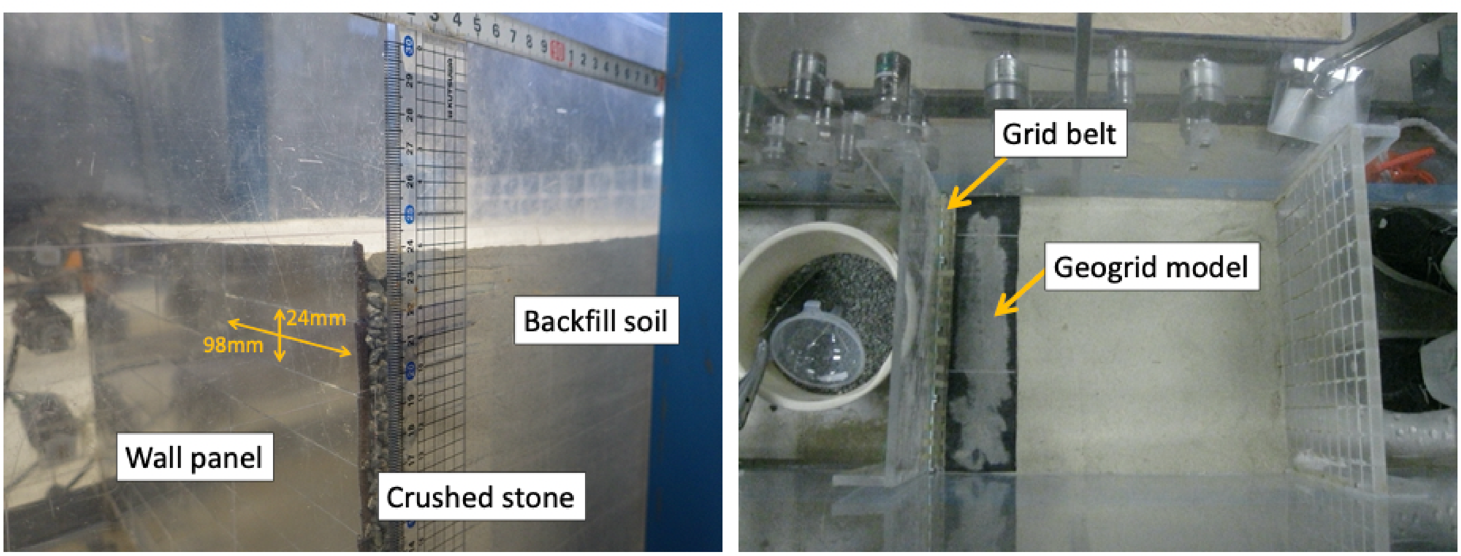


Figure 4

Overview of reinforced soil wall model (Left, Wall panel and backfill soil; Right, Grid belt and Geogrid model)

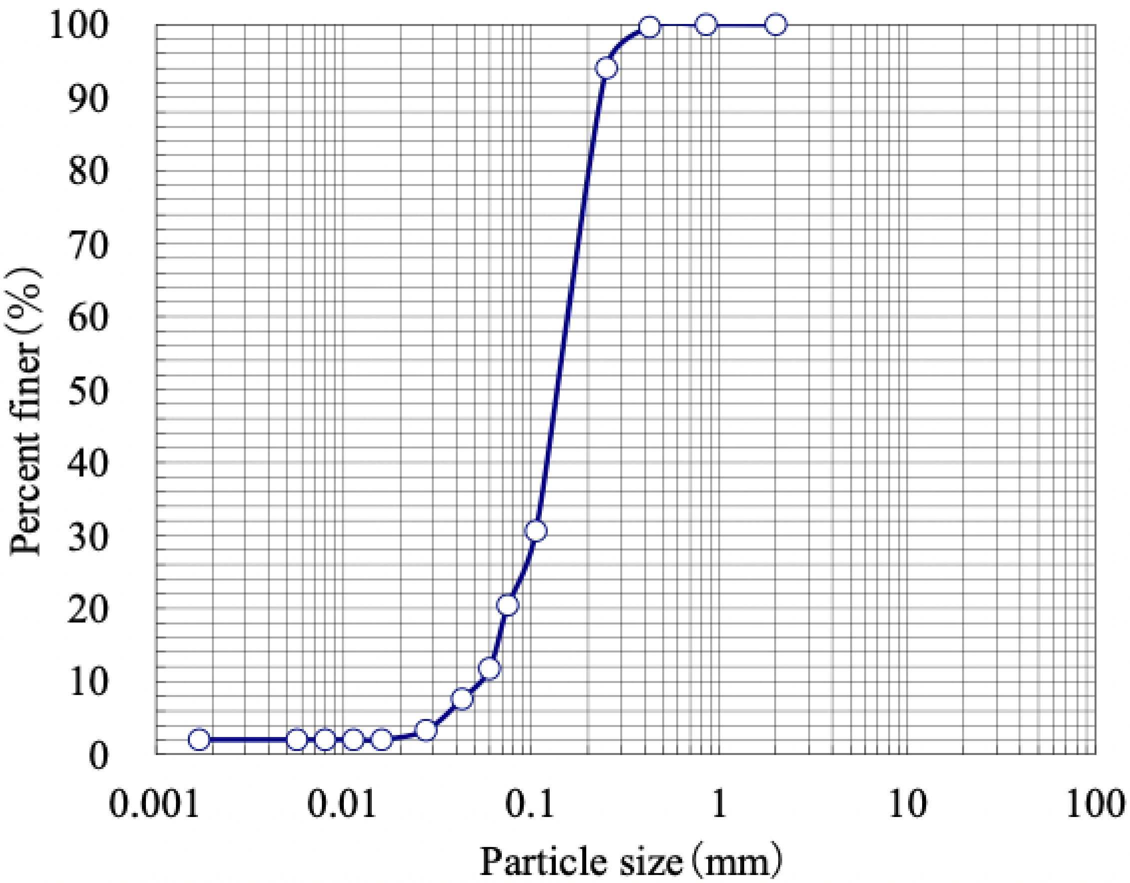


Figure 5

Particle size distribution curve of backfill soil

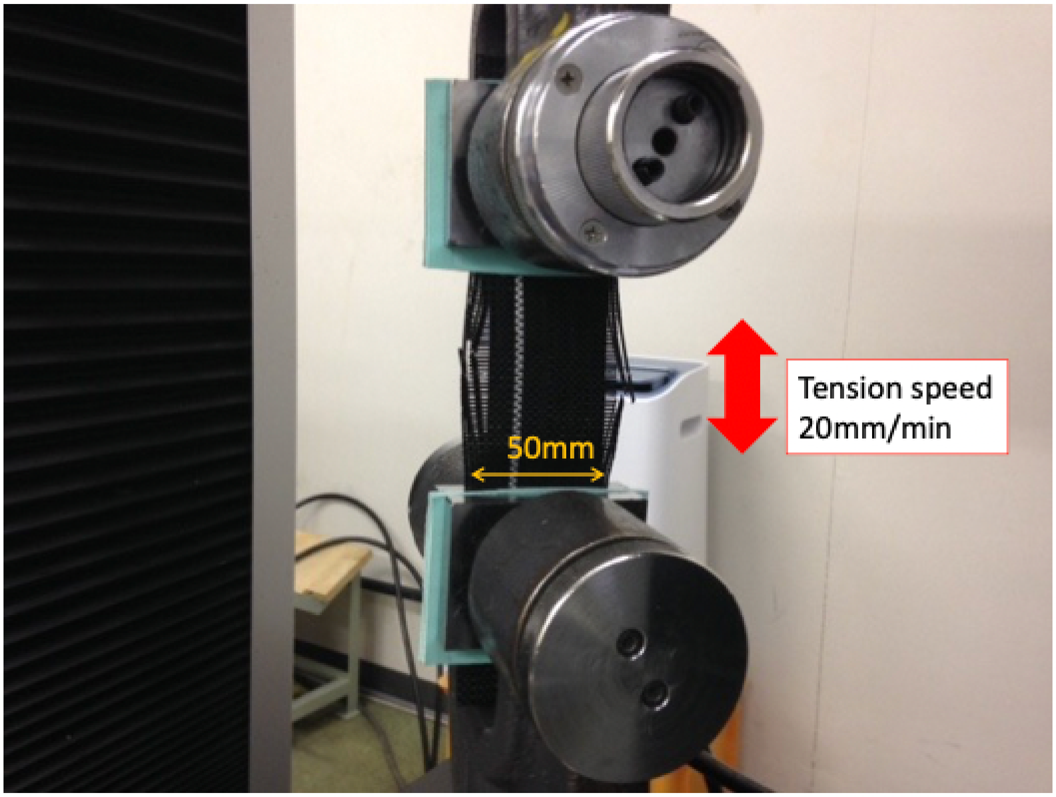


Figure 6

Tension test of geogrid model sheet

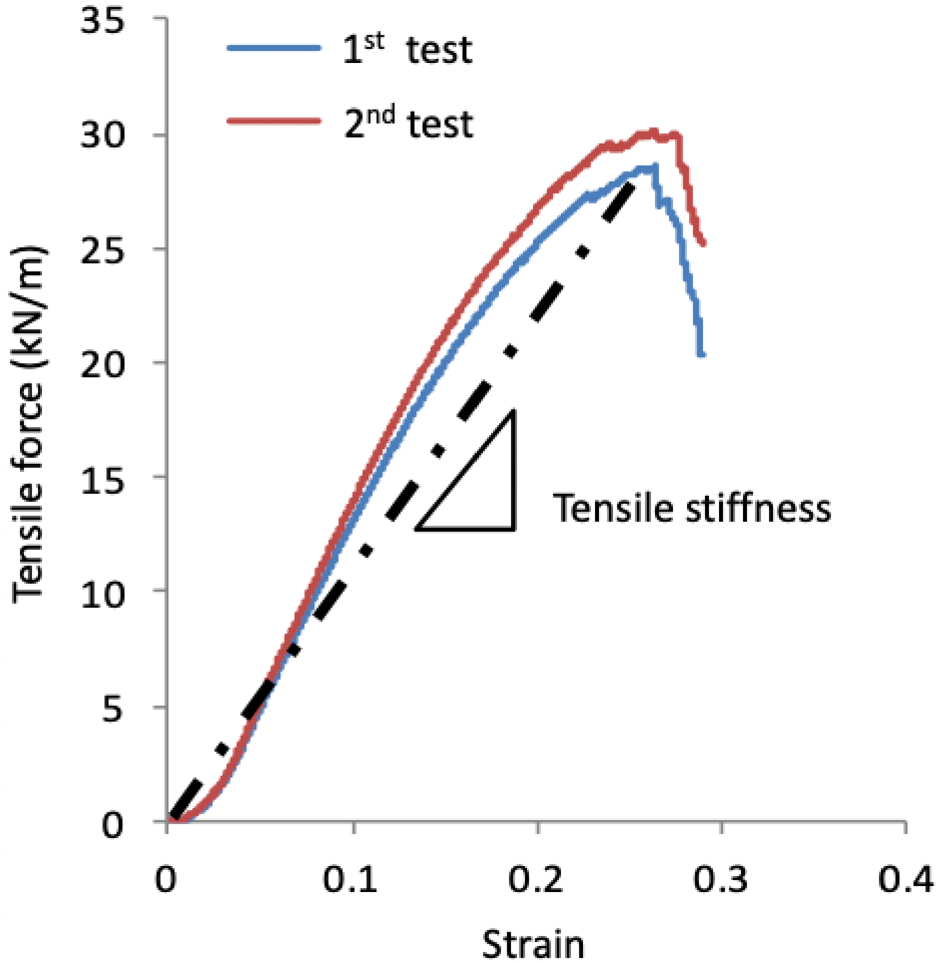


Figure 7

Tensile force-Strain curve (Sample D)

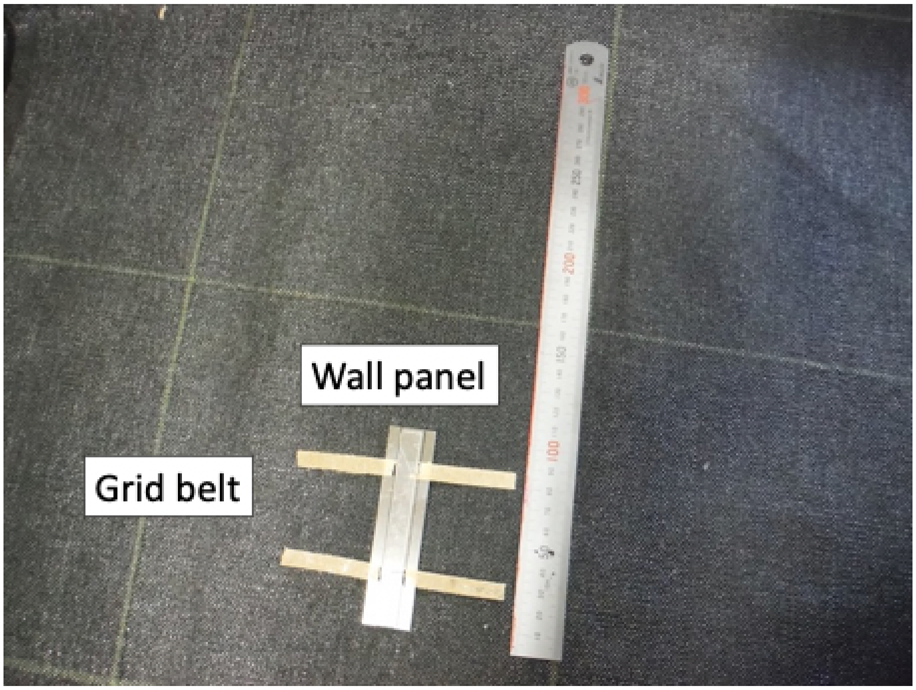


Figure 8

A wall panel and grid belt

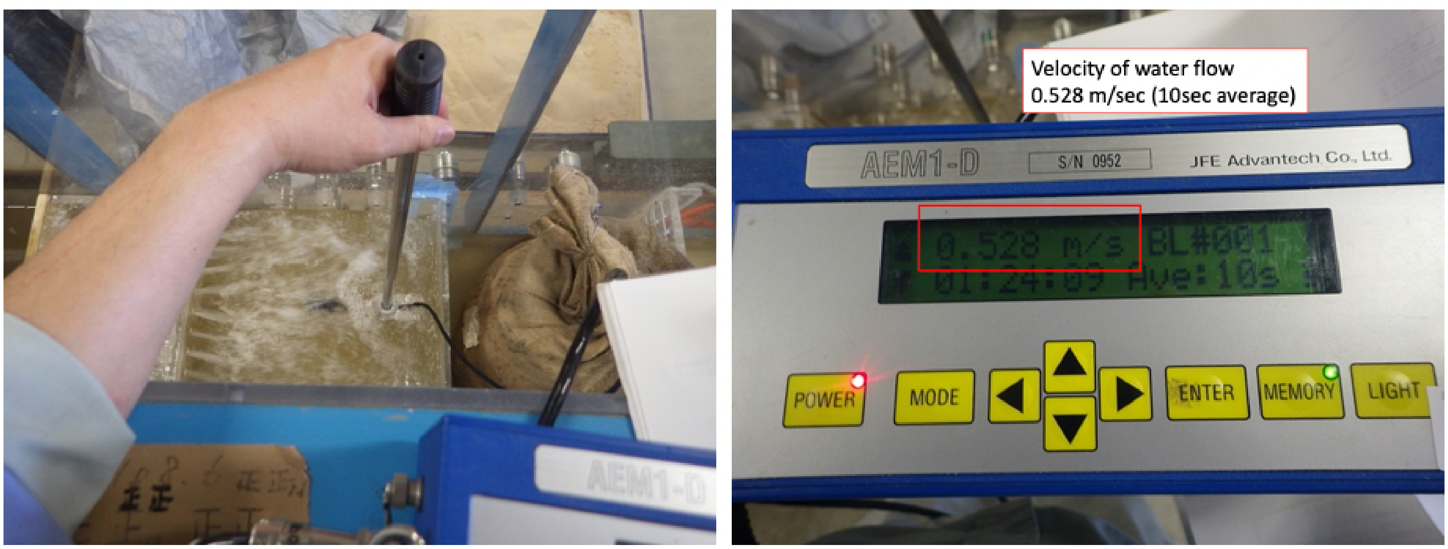


Figure 9

Left, Measuring velocity of water flow ; Right, Velocity of water flow

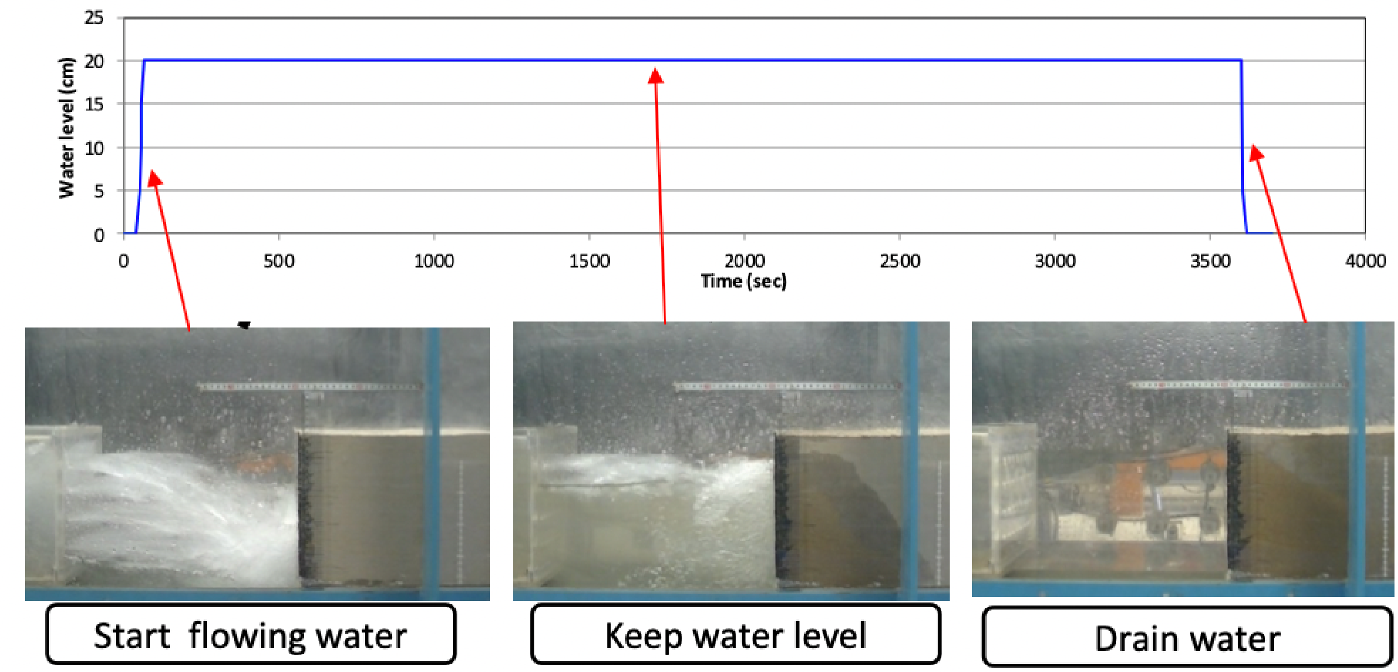


Figure 10

Time history of water flow in the experience

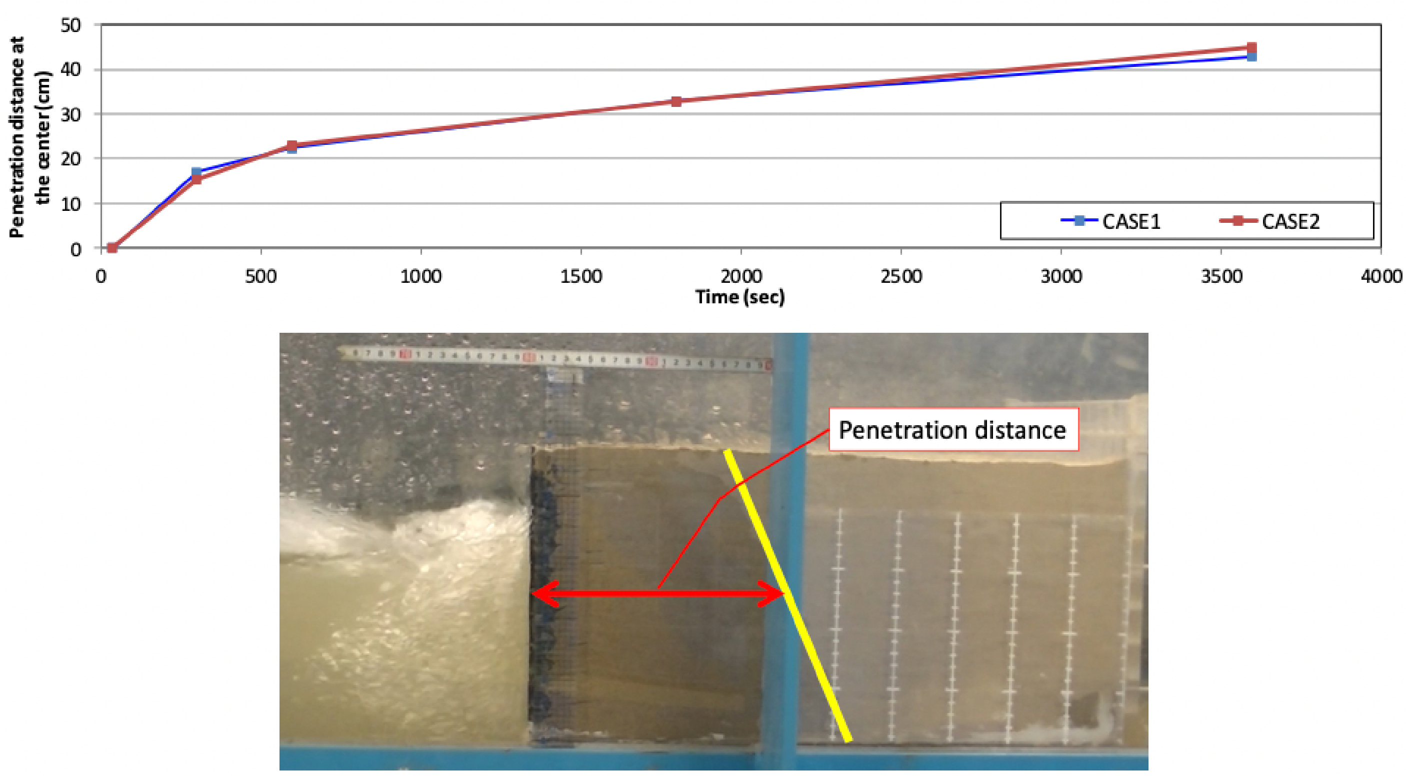


Figure 11

Time history of penetration distance at the center of the wall

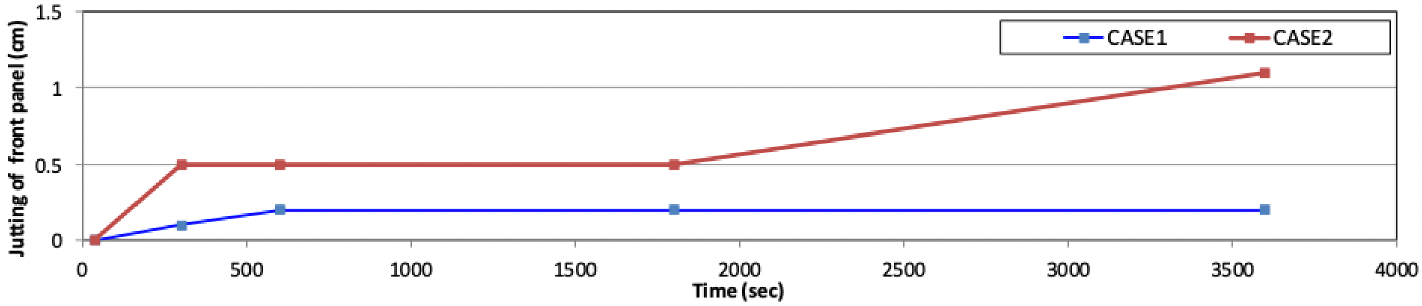
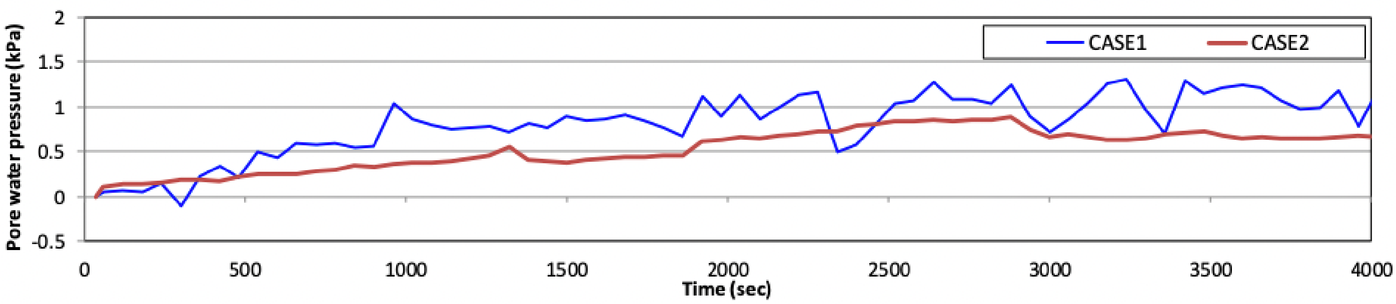


Figure 12

Time history of jutting of front panel



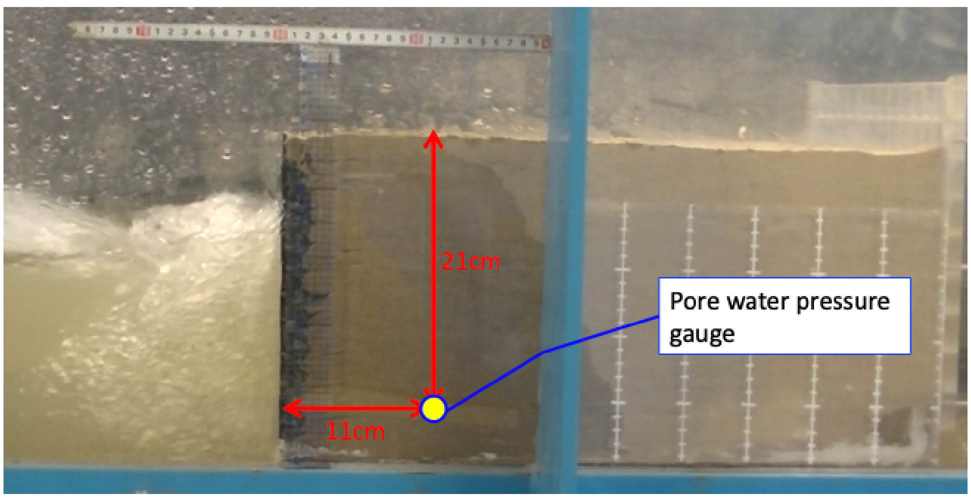


Figure 13

Time history of pore water pressure in backfill soil

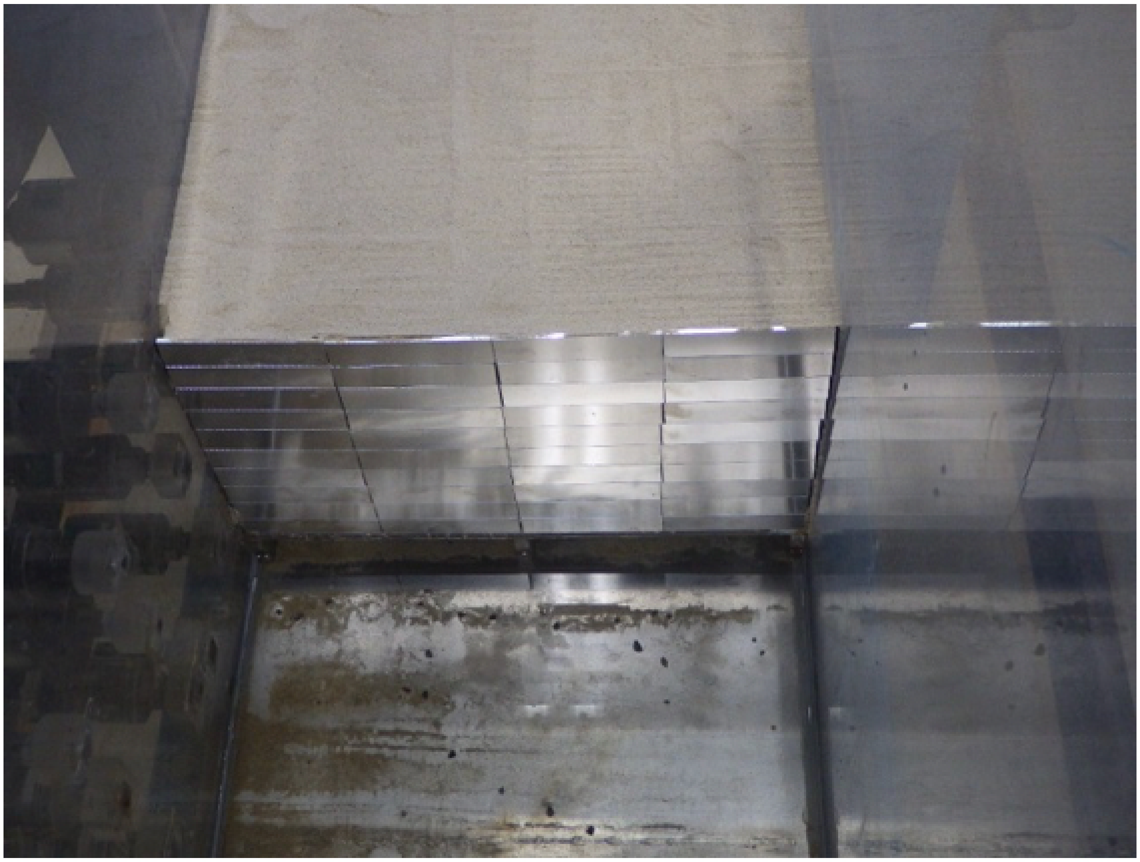


Figure 14

Condition of front panel after finishing experiment (CASE-1)

Figure 15

Condition of front panel after draining (CASE-2)