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COLLAPSE MECHANISM OF SEAWALLS BY IMPULSIVE LOAD DUE TO THE MARCH 11 TSUNAMI

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Abstract *On March 11,2011 the huge tsunami caused by the magnitude 9.0 earthquake devastated the Tohoku Pacific Ocean coastal regions of Japan. The impulsive fluid load of the tsunami caused devastating damage to the seawalls in the Tohoku region of Japan. On April 13-15, we investigated one of the disaster area, the town of Taro which had been very famous for having a 10m high seawall.*
This special lecture focuses on the collapse mechanism of the seawall by the impulsive fluid load due to the March 11 tsunami.

1 INTORODUCTION

The huge tsunami caused by the magnitude 9.0 earthquake hit the north-eastern offshore regions of Japan on March11,2011. The town of Taro is located in north-eastern Japan as shown in Fig.1 and the seawall had been constructed in double lines as shown in Fig.2 [1]. This was very famous for having a 10 m high seawall, the highest seawall in the world which was called as “a great wall”. The dignified appearance of the seawall was like the wall of a jail as shown in Fig.3 [2]. However, the tsunami

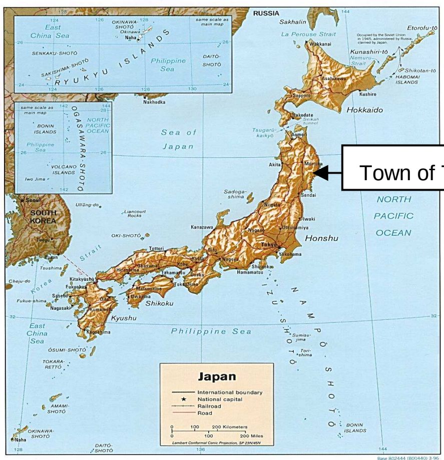

Figure 1: Where is the town of Taro?

Figure 2: Town of Taro before tsunami

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overflowed and destroyed the seawall in the town of Taro, as shown in Fig.4, which is a picture taken by Mr.Masahiko Hatakeyama[3].

Figure 5 is also a picture of the town of Taro taken by Mr.Tetsuo Oshita [4] which was almost completely destroyed by the tsunami, with the exception of the Taro hotel (right) and the fishermen's association (left).

Figure 3: Seawall before tsunami

Figure 4: Tsunami overflowed the seawall taken by Masahiko Hatakeyama [3].

The town of Taro has a history of typical tsunami protection [5],[6],[7] as it had been attacked by huge tsunami twice before.

One of major tsunami hit on June 15, 1896, claimed the lives of 1859 people in the town of Taro (total 21953 dead in Japan) and had a tsunami height of 14.6m.

The other one, hit on March 3, 1933, claimed the lives of 911 people in the town of Taro (total 3064 dead in Japan) and had a tsunami height of more than 10m. Since then, people had wanted to construct a seawall (dike) and part of a seawall was built at last in 1958.

On May 24,1960, the Chile tsunami hit the town of Taro, but there was no damage (0 dead in Taro, but 142 dead in Japan) as it was protected by this seawall.

Figure 5 : Tsunami struck the town of Taro taken by Tetsuo Oshita [4].

In 1979, all seawalls were completed with the total length of 2433m and the height of 10m (sea level). On February 27, 2010, the Chile tsunami again struck the town of Taro which was protected by these seawalls. Therefore, people felt sure that the seawall would protect the town of Taro from tsunami.

On March 11, 2011, however, the huge tsunami hit the town of Taro, collapsing seawalls and 210 people (total 20891 people in Japan, as of July 10) were killed or missing. Between April 13-15, we investigated the collapse mechanism of the seawall by the March 11 tsunami from the viewpoint of impulsive fluid load [8],[9].

To this end, this lecture presents as follows:

(1) the site disaster investigation
(2) the scale of the March 11 tsunami by numerical simulation
(3) the tsunami behavior for the seawall by the particle method (MPS method)
(4) the presumption of collapse mechanism of the seawall
(5) the future protection proposal for a huge tsunami

2 SITE DISASTER INVESTIGATION OF THE SEAWALL

We investigated the collapsed seawall in the town of Taro between April13-15,2011 one month after the tsunami.

The object of the investigation was to collect the traces of the tsunami disaster focusing on the causes of collapse mechanism of the seawall. The places of investigation were the shooting points 1,2,3 after the tsunami as shown in Fig. 6 [10].

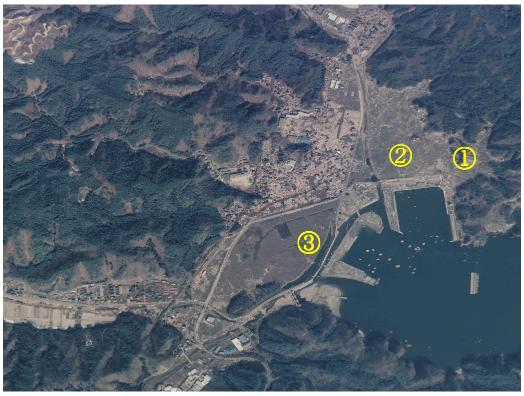

Figure 6 : Town of Taro after tsunami
（Figures show shooting points）

2.1 The structure of the seawall

Figure 7 shows the standard section of the seawall which compacts the filling soil in the covered concretes of a sea-side slope, seawall crown and face of a back slope. The foot protection is worked in the back slope. The covered concrete is composed of blocks of 4 steps in the front surface and 2 steps in the back surface in which the joints were connected by the elastomer adhesive.

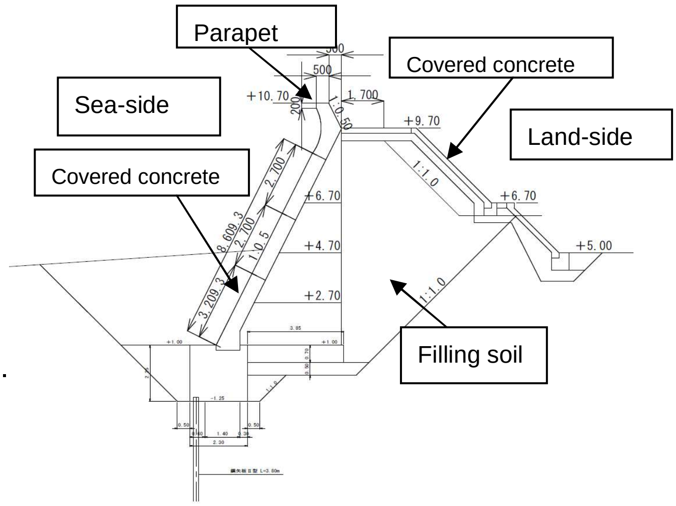

Figure 7: Standard seawall section

2.2 Site investigation results

Generally, the seawalls of the shooting point of 1 and 2 were almost completely washed away, but the seawall of the shooting point 3 remained as it was, although the covered concrete in the face of back slope was stripped by the erosion of the tsunami.

Figure 8 shows comparison views at point 1 in Fig.6 before and after the tsunami. Here, you can see the seawall before the tsunami (a), but the seawall disappeared after tsunami in a mess of concrete blocks (b).

Figure 9 is the picture of the land-side at point 1 in Fig 6, which is compared to before and after tsunami. You can see that many houses before the tsunami have disappeared and the concrete blocks of seawall were washed away after the tsunami.

(a) before tsunami（see seawall）　(b) after tsunami（seawall was disappeared）

Figure 8: Sea-side at shooting point 1

(a) before tsunami

(b) after tsunami

Figure 9: Land-side at shooting point 1

Figure 10: Concrete block was fallen down to the sea-side at point 1.

Figure 11: Back slope protection was collapsed at point 2.

Figure 10 shows the picture of a concrete block turned over toward the sea-side, although it is generally considered that the concrete fragments have fallen down toward the land-side due to a front wave pressure. This phenomenon may be due to the effect of return flow (receding water or backwash).

Figure 11 is the picture of the collapse of the back slope at point 2 in Fig.6. It was found that the covered concrete of the back slope was completely consumed and part of the filling soil was washed away. This may have been caused by the effects of overflow and return flow. Only buttress remained in the seawall after the tsunami.

Figure 12: Collapsed seawall toward the sea-side at point 2.

Figure 13: Back slope protection was stripped at point 3.

Figure 12 is the picture of concrete blocks turned over toward the sea-side at point 2 in Fig.6. This may be also due to the effect of return flow. The joint between covered concrete blocks was cut off like shear failure horizontally.

Figure 13 shows the filling soil in the back slope in which the covered concrete was stripped by the tsunami at point 3 in Fig.6. The covered concrete disappeared and only the filling soil was left in the seawall. This may have been caused by erosion and infiltration of overflow and return flow, or the foot protection may have been destroyed by the overflow tsunami.

3 TSUNAMI RUN UP CALCULATION [11]

Figure 14 shows the places of sea level and flow velocity computed by the tsunami run up numerical calculation in the town of Taro in order to examine the overflow time of the seawall by the tsunami.

3.1 Up-flow tsunami

Figure 15 illustrates the relationship between the sea level, flow velocity and distance of seawall at 15:22:53(36min.30sec after the earthquake occurrence at 14:46:23). It was found that the tsunami did not overflow the seawall. The flow velocity was about 1m/sec in front of the seawall.

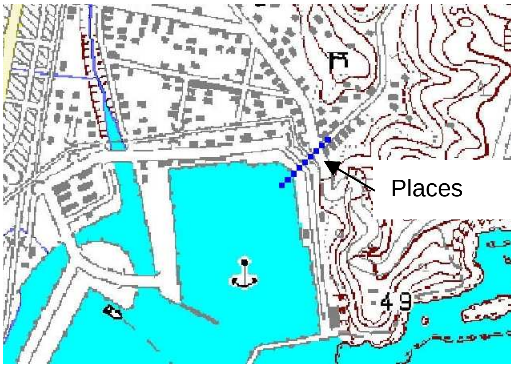

Figure 14: Places of tsunami run up calculation in the town of Taro

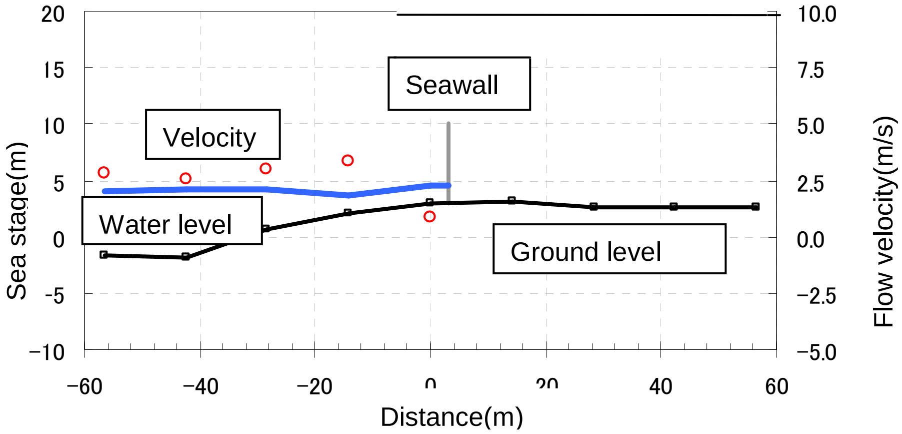

Figure 15: Water level (m) and flow velocity (m/s) at 15:22:30
(36.5min.after the earthquake occurrence) Notice: Seawall was not overflowed.

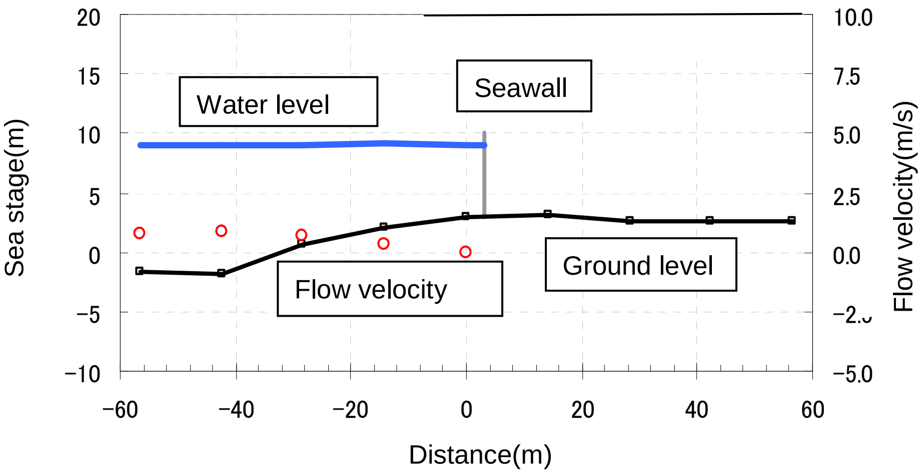

Figure 16: Water level (m) and flow velocity (m/s) at 15:23:23
(37min. after the earthquake occurrence) Notice: Seawall was not overflowed.

Figure 16 also shows the relationship between the sea level, flow velocity and distance of seawall at 15:23:23 (37min.after the earthquake occurrence). The sea level just reached to the seawall, but the seawall was not overflowed by the tsunami.

Figure 17, however, demonstrates the sea level of 15m which overflowed the seawall of 10m at the time of 15:24:03 (37min.40sec after the earthquake occurrence).

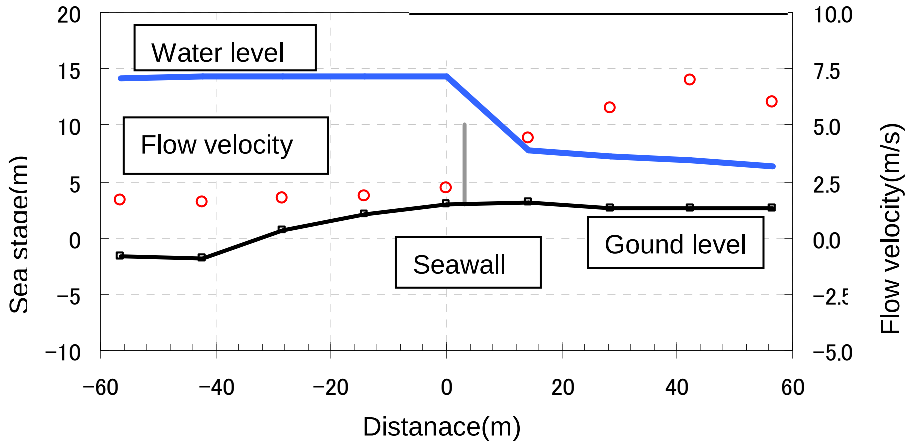

Figure 17: Water level(m) and flow velocity(m/s) at 15:24 (37.7min.after the earthquake occurrence) Notice: Seawall was overflowed by the tsunami.

It is interesting that the flow velocity with 2.5m/sec in front of the seawall increased up to the maximum velocity of 7.5m/sec at the distance of 40m. Herein, the wave velocity is expressed by c= $\sqrt{gh}$ (g: gravity acceleration, h: sea depth). It was found that the sea depth of h=2.0m was measured at the distance of 40m in land-side, and, as such, the wave velocity was found as c=4.4m/sec, and the Froude Number F_r =v/c =1.7 >1 was found as the supercritical flow [12].

Figure 18 is a picture of the clock found at the site. Notice the time stopped at 15:23-24, the time the tsunami struck and, therefore, the tsunami run up calculation was verified.

Figure 19 shows the flooded area in the town of Taro at 15:30:23 (44min.after the earthquake occurrence). The town of Taro was flooded in a sea depth of more than 6.0m.

Figure 18: Clock found at the site. Notice: the time stopped at 15:23-24, the time the tsunami struck.

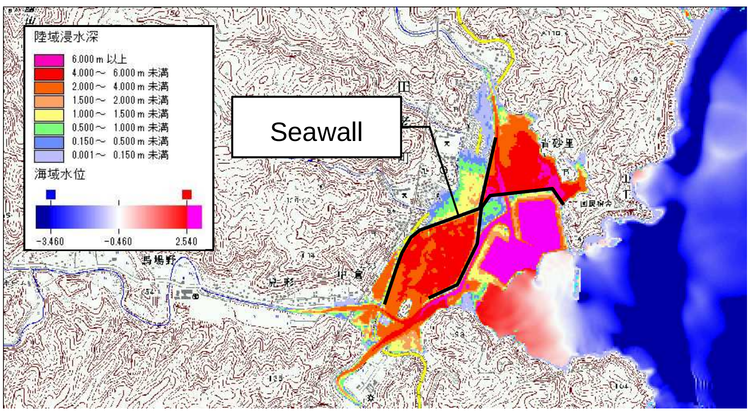

Figure 19: Flooded area at 15:30:23 on March 11,2011 (44 min.after the earthquake occurrence)

3.2 Effect of return flow

Figure 20 shows the relationship between the sea stage (water level), flow velocity and time due to the up-flow and return tsunami at the distance of 5m in front of seawall after the seawall collapsed. It was found that the maxumum flow velocities were about 6.0m/s due to the up-flow at the time of 37min. and 4.0m/s (negative value) due to the return flow at the time of 40min after the earthquake occurrence.
It was alos noted that the water level has decreased to the 0m at the time of 47min. from 9m at the time of 38min..

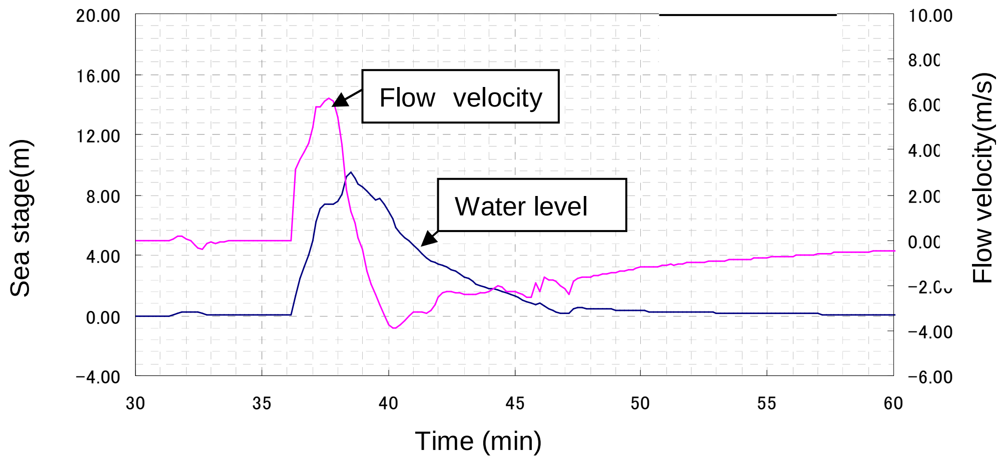

Figure 20: Water level(m) and flow velocity (m/s)due to up-flow and return flow at the distance 5m in front of seawall after the seawall collapsed

4 DYNAMIC BEHAVIOR OF TSUNAMI FOR THE SEAWALL BY MPS METHOD

Figure 21 represents the dynamic behavior of the tsunami which overflowed the seawall by using the MPS (Moving Particle Semi-implicit) method [8], [13] which was modified by considering the effect of successive wave.

At t=0sec, it is assumed that the tsunami model with height of 15m and initial flow velocity of 2.5m/sec starts toward the seawall with a rigid body. At t=0.5sec, the up-flow tsunami collided with the seawall and the wave vibration propagated in the tsunami. Between t=1.0-3.0sec, the tsunami overflowed the seawall and touched down in the land-side with a splash. Between t=3.5-4.5 sec, it was found that the tsunami split into two directions, one headed toward the land-side with a high velocity which is said to be a super-critical flow and the other tsunami toward the sea-side after landing which is said to be a breaking wave. This will cause an erosion of filling soil by rolling up the face of the back slope. Actually, it is considered that the up-flow tsunami hit the seawall many times and the return flow struck the seawall from the land-side each time, although these phenomena may be investigated by the further calculations.

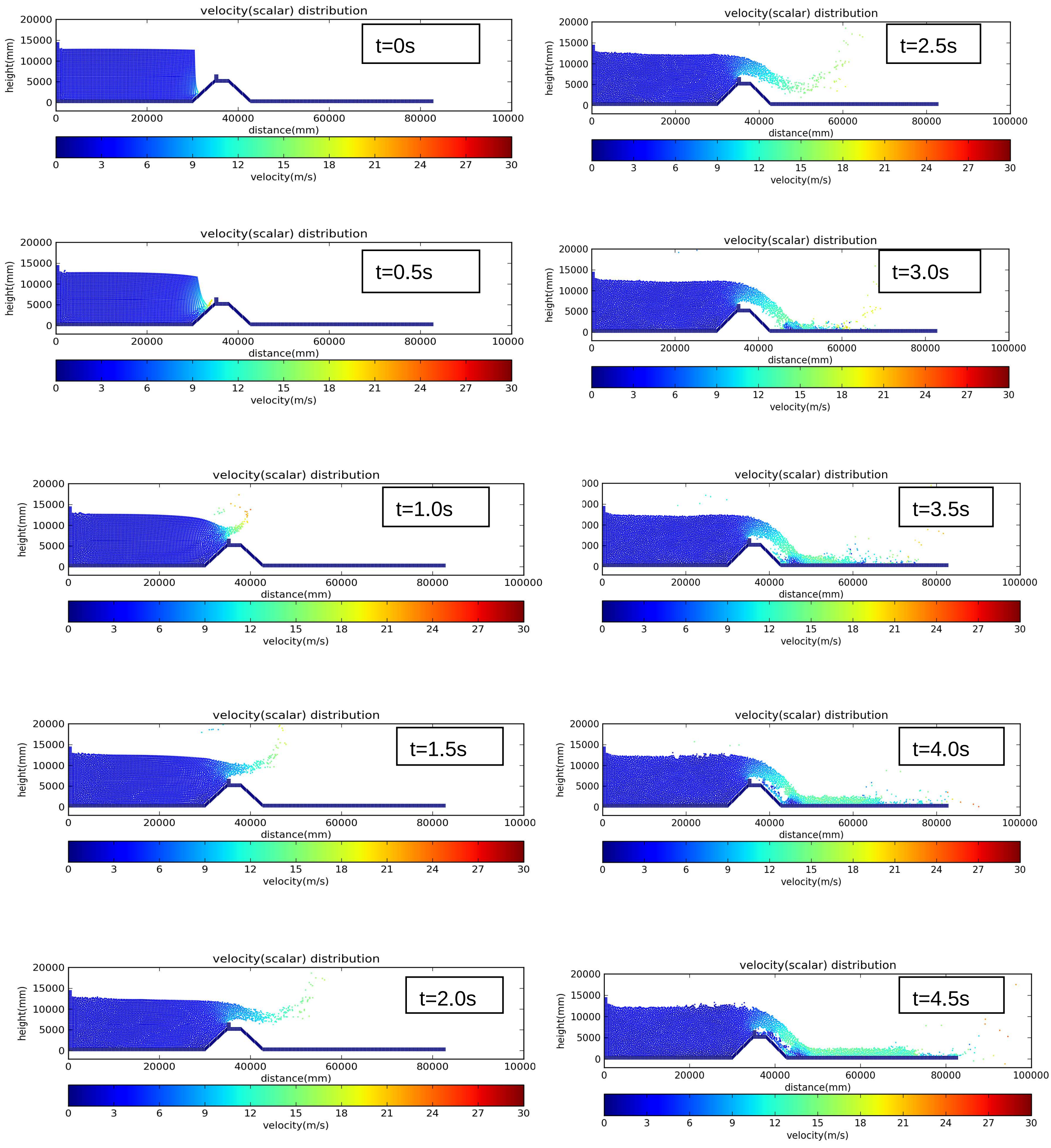

Figure 21: Tsunami hit the seawall by MPS method
(Tsunami height: 15m and initial flow velocity: 2.5m/s)

5 COLLPAPSE MECHANISM OF SEAWALL

Figure 22 shows a presumption of collapse mechanism of the seawall from the viewpoints of the site investigation, the tsunami run up calculation and the tsunami behavior by using the MPS method.

(1) It was considered that the parapet was striped by the impulsive fluid load of the up-flow tsunami.
(2) It was suggested that the tsunami overflowed the seawall dropped down the back slope and collapsing the covered concrete and foot protection in the back slope by the dropping down of sea mass.
(3) After the tsunami touched down in the land-side, part of the tsunami changed into a breaking wave which will erode the filling soil in the seawall.
(4) After inundating the hinterland, the tsunami came back to the sea as the return flow which collapsed the filling soil of the seawall by erosion, infiltration and buoyancy and, as such, the covered concrete of the front slope turned down toward the sea-side.
The detailed collapse mechanism will be examined by the future study.

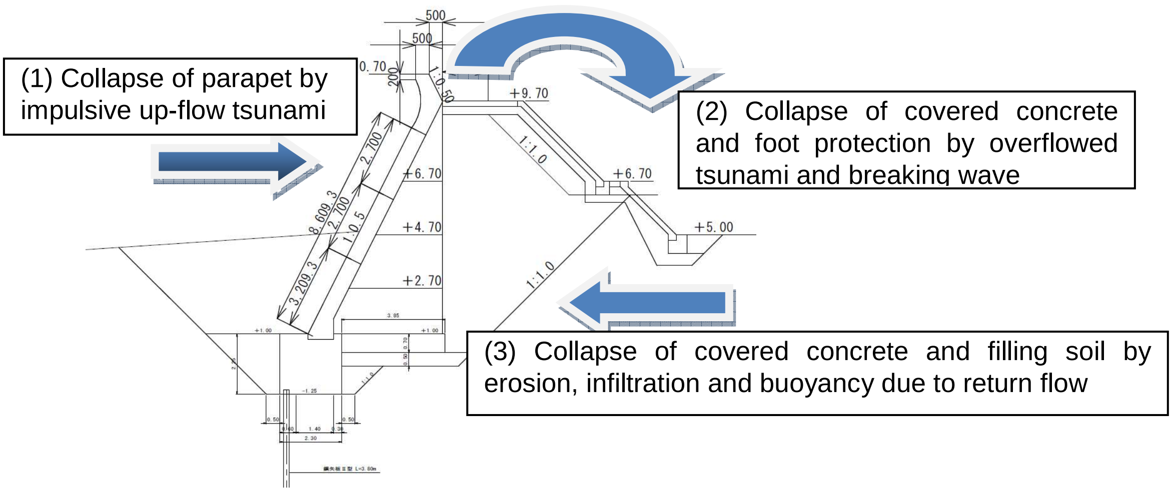

Figure 22: Presumption of collapse mechanism of seawall

6 COUNTER-MEASURE AGAINST HUGE TSUNAMI

Recently, the tsunami research committee in Japan has decided that a tsunami is divided into two categories. One is level 1: a small or medium tsunami which can be protected by the seawall, the other is level 2: a huge tsunami which cannot be protected by only the seawall and people have to evacuate to higher ground.

6.1 Counter-measure by seawall

Therefore, the ideas for counter-measure by the seawall against the level 2 tsunami are considered as follows:
(1) The seawall in the town of Taro was the gravity concrete type which was not covered by the sheet to cut off the sea water. This overflowed and the return flow tsunami eroded the filling soil in the seawall. Therefore, the seawall should be covered with a rubber sheet to cut off the sea water between the covered concrete and filling soil as an example of armor levee method in the river as shown in Fig. 23 [14] and the seawall should be also fixed to the ground by using piles.

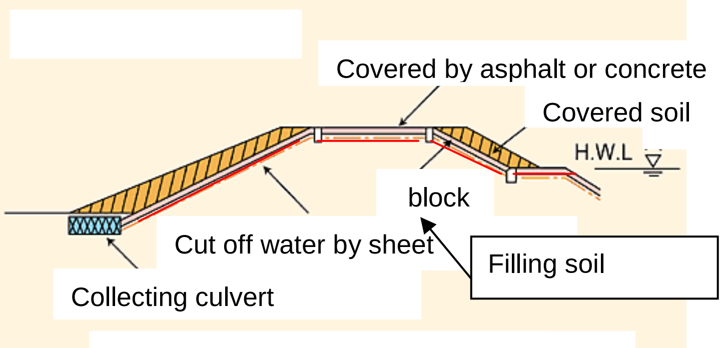

Figure 23: Armor levee method[14]

(2) In order to mitigate the impulsive fluid force of a huge tsunami, we propose plane and space type grid seawalls as shown in Fig.24 [15]. The enormous energy of a huge tsunami may be decreased by these structures which have been used as check dams for debris flow.

(a)Plane type grid seawall (b) Space type grid seawall

Figure 24: Examples of steel type grid seawall [15]

(3) In order to increase the strength and deformability of the seawall, the steel-concrete composite type seawall is considered as shown in Fig.25 [16] which was already constructed as a counter-measure against the storm surges in the seashore of Oita prefecture, Japan. This type of structure is said to be "a flare-shaped seawall" which may be useful for a huge tsunami, if the height of seawall can be increased.

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(a) Construction of flare seawall （b） After completion

Figure 25: Example of steel-concrete composite seawall [16]

6.2 Counter-measure by using tsunami hazard map

People have to evacuate higher ground or higher sturdy building by vigilance against the level 2 tsunami using the prepared tsunami hazard map as shown in Fig.26 which shows an example in the part of Fukuoka city, Japan.

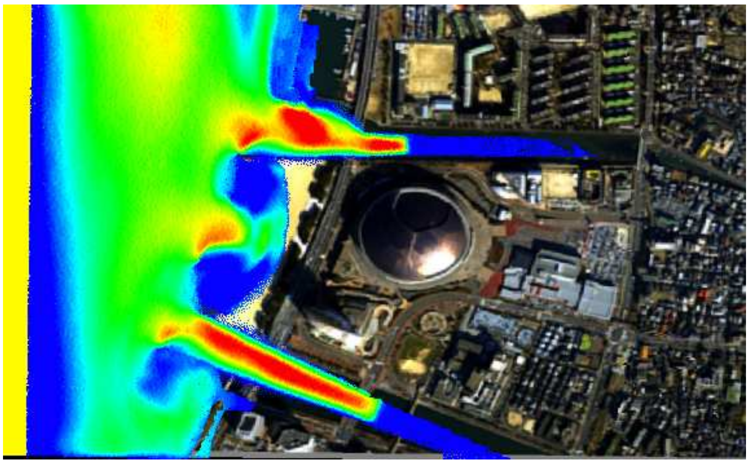

Figure 26: Tsunami hazard map in the part of Fukuoka city, Japan

7 CONCLUSION

The following conclusions are drawn from this study.

(1) The March 11 tsunami with enormous force destroyed and devastated the town of Taro which had a 10m high seawall, the highest seawall in the world.
(2) In the site disaster investigation, the concrete blocks were turned down toward the sea-side which may have been caused by the return flow and the filling soil of the back slope was washed away by dropping down of sea mass and a breaking wave after the tsunami overflowed.
(3) The time of the tsunami overflow could be estimated by the tsunami run up calculation which was verified by the clock found at the site.
(4) It was confirmed that the particle method could estimate the dynamic behavior of the tsunami to the seawall. This method will be useful tool as a counter-measure against a huge tsunami by changing the size of seawall and the scale of tsunami.
(5) In conclusion, there were three causes for the collapse mechanism of the seawall:
The collapse of parapet by impulsive up-flow tsunami, the collapse of covered concrete and foot protection by overflowed tsunami and the collapse of covered concrete and filling soil by erosion, infiltration and buoyancy due to return flow.
(6) The future protection for a huge tsunami is proposed as in the examples of the armor levee method, the grid type seawalls and the steel-concrete composite type. At the same time, people have to practice to evacuate higher ground by using the prepared tsunami hazard map against the level 2 tsunami,.

Finally, authors wish that the disaster area struck by the March 11 tsunami may be recovered as soon as possible.

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