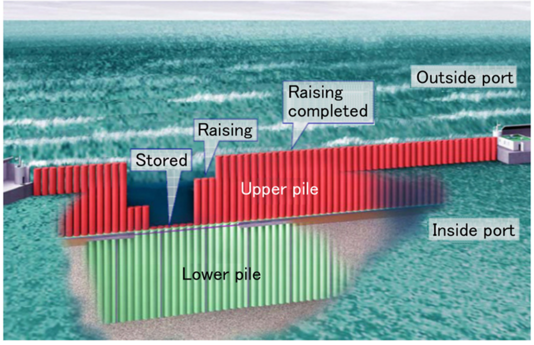
Development of Vertical Telescopic Breakwater that Rises from Seabed in Emergencies



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The mouths of ports and harbors are open to allow vessel passage. There is apprehension about the serious damage that can be caused by tsunamis or high tides entering through the mouth and running up not only rivers, but also on land. This report introduces the "Vertical Telescopic Breakwater (VTB)" developed for the solution of these problems. The VTB is a line of cylindrical structures, each of which consists of an upper steel pile and a lower steel pile, and they are stored in the seabed in normal times. The upper piles are raised during emergencies such as tsunamis and high tides. The VTB allows the prompt opening of port channels by lowering the upper piles after the disaster has been averted.

1. Introduction

In our country, population and city functions are concentrated along coastal areas. The risk of disasters such as tsunamis and high tides has been increasing year by year, especially since the March 11 Great East Japan Earthquake and due to the imminence of To-kai, Tonan-kai and Nan-kai (eastern, south-eastern and southern seas) earthquakes, as well as rising sea levels and typhoons growing in size brought about by global warming.

Breakwaters of ports and harbors in Japan have been upgraded to protect lives and property from disasters such as tsunamis and high tides. At the same time, ports and harbors must provide a passage for vessels through an opening. As a result, it is inevitable that ports and harbors are vulnerable to tsunamis and high tides entering through the mouth.

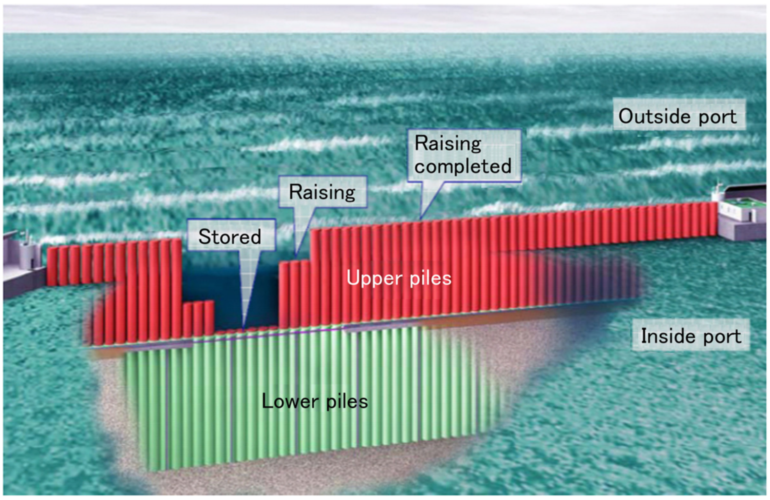

Figure 1 Features of Vertical Telescopic Breakwater (VTB)

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The VTB is a movable breakwater that can solve these problems. The VTB can be stored under the seabed to allow the free passage of vessels in normal times, and is raised above the sea surface in a tsunami or high tide emergency to shut the mouth and shield the port against surging water, as shown in **Figure 1**.

This VTB has been developed as a joint effort of the public and private sectors by organizing a coordinated study group consisting of four private companies; Obayashi Corporation, TOA Corporation, Nippon Steel and Sumikin Engineering and Mitsubishi Heavy Industries, Ltd., and the Port and Airport Research Institute, which is an Independent Administrative Institution under MLITT.

2. Structure and Features

2.1 Outline of structure

The VTB has a telescopic structure consisting of lower steel piles installed in the seabed and upper steel piles (movable pipes), which can be raised and lowered, inserted in the lower pile (**Figure 2**). The upper piles are arranged in line to form a tide barrier. Gaps of several centimeters between the upper piles remain for the installation of lower piles with a larger diameter. As a result, a series of small openings is provided along the whole length of the breakwater.

The gaps can partially reduce their opening rate with gap-clogging auxiliary pipes against upcoming waves (**Figure 3**).

The lower piles installed in the seabed are connected to air pipes from an air supplying facility on land.

Air is supplied to the inside of the upper piles installed in the seabed. The upper piles start to rise when the internal air pressure in the piles exceeds the effective weight of the piles. The piles protrude above the sea surface and stop at the height of stoppers installed in the lower piles. The lowering of the piles is carried out by venting the air from the upper piles through the exhaust valve installed at the top of the piles. The raising and lowering speeds are controllable by adjusting the air supply rate and air venting rate.

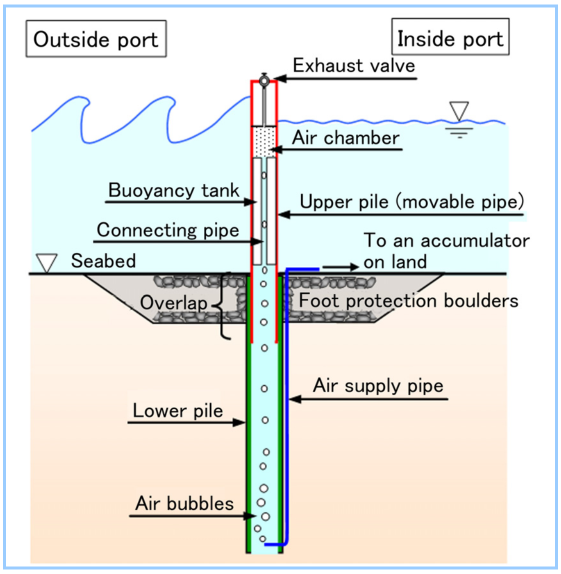


Figure 2 Sectional View of Vertical Telescopic Breakwater (VTB)

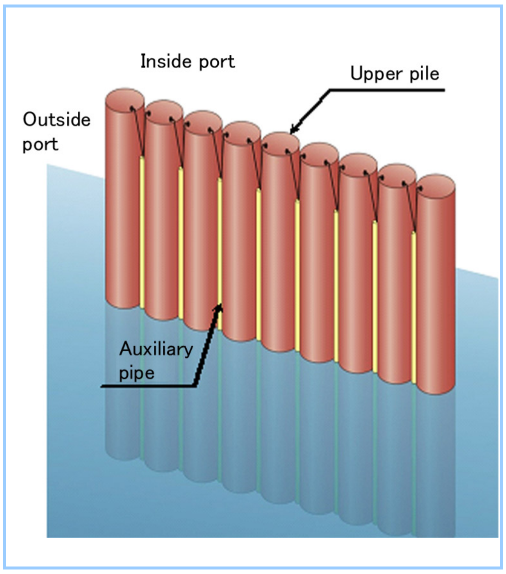


Figure 3 Improvement of shielding rate by installing auxiliary pipes

2.2 Features

The raising and lowering of the breakwater can be controlled by operating the supply and venting of air to the upper piles as explained above.

(1) The breakwater is normally installed in the seabed to allow the free passage of vessels. In addition, the breakwater does not affect the sea tides or ocean currents, and the exchange of sea water in the harbor is also no t impeded.

(2) The raising and lowering of the upper piles do not require a large scale driving facility, rather a simplified mechanism that is easily maintained that supplies and vents highly pressurized air.

(3) The breakwater is installed in the seabed, which ensures a high level of safety against earthquakes.

(4) The materials used are widely used steel pipes, ensuring high reliability and safety.

These features of this breakwater installed at the mouths of ports and harbors (ship route) enable both protection against disasters caused by tsunamis and high tides, and improve operational rates of cargo handling by ensuring calmness in the harbor. Possible applications of the utility of this breakwater are shown in **Figure 4**.

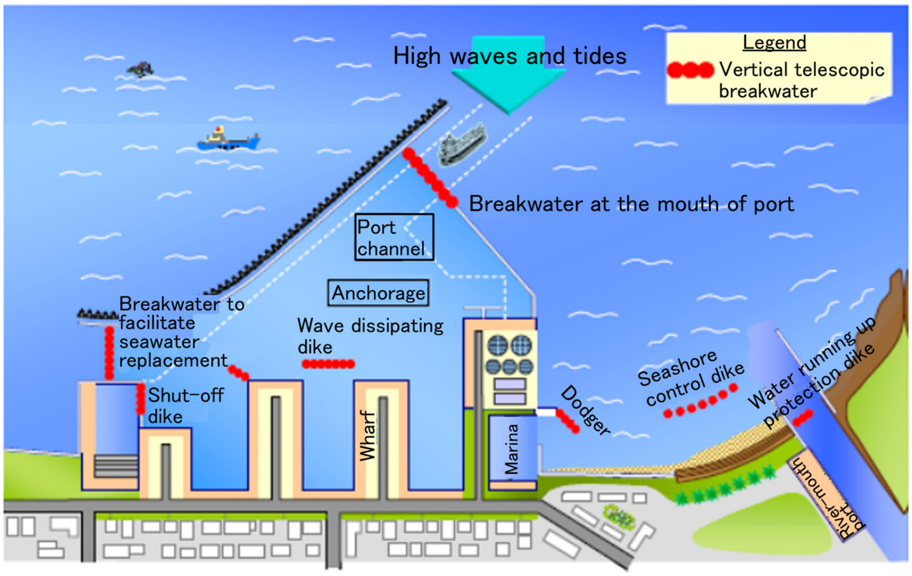


Figure 4 Examples of VTB Installation

3. Structure and Features

The technical problems below caused by structural characteristics must be solved for the development of this breakwater. Both hydraulic model experiment[1,2] and field tests[3] in Numazu Port were conducted to solve the problems. An intensive investigation was also made on the reinforcement structure at the upper-lower overlap position.

(1) The gap between the upper piles is inevitable because of VTB installation restrictions, making the verification of the shielding effectiveness as a breakwater necessary.

(2) The transition mechanism of horizontal stress caused by incident waves, which the upper pile receives, must be clarified, and the stress at the overlap of upper and lower piles must be understood.

(3) The adhering condition of marine growth on the upper piles during lengthy periods of storage in the lower piles, as well as the anti-corrosion durability of the construction materials, must also be verified.

3.1 Hydraulic model experiment

A hydraulic model experiment was conducted to clarify the wave protection effect using a Large Hydro Geo Flume (length: 184 m, depth: 12m, width: 3.5m) at the Port and Airport Research Institute. Experiments were conducted under the conditions of a 1/5 scale model and the opening rates were 0.05, 0.1 and 0.15 for wind waves and tsunamis. The opening ratio (α) is defined as; $\alpha = b/(B+b)$ (b: gap width between the pipes, B: pipe diameter). A picture of the experiment is shown in **Figure 5**.

Figure 6 shows the relationship between the upper pile opening rate(α) and the transmission coefficient of the waves. The figure shows a larger opening rate results in a larger transmission coefficient (passed wave height after breakwater/incident wave height). The transmission coefficient differs with the wave period. In the case of an opening rate 0.05, the transmission coefficient can be reduced to 0.35 to 0.40 for wind waves, and 0.25 to 0.30 for tsunamis. In addition, the transmitting flow rate to the back of the breakwater (inside the port) can be roughly calculated by deriving the relationship between the opening rate and flow velocity at the opening from the results of the experiments (Figure 6).

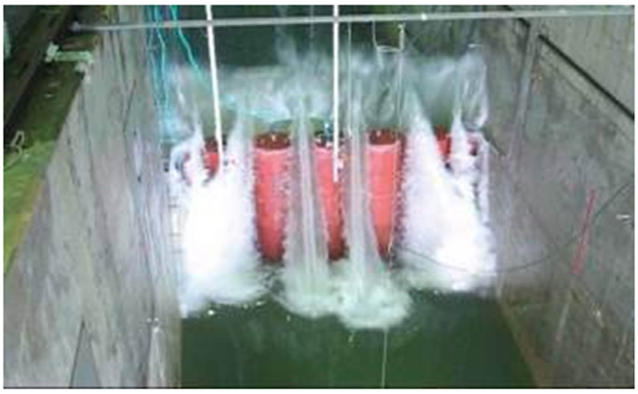


Figure 5　Hydraulic model experiment (against tsunami wave)

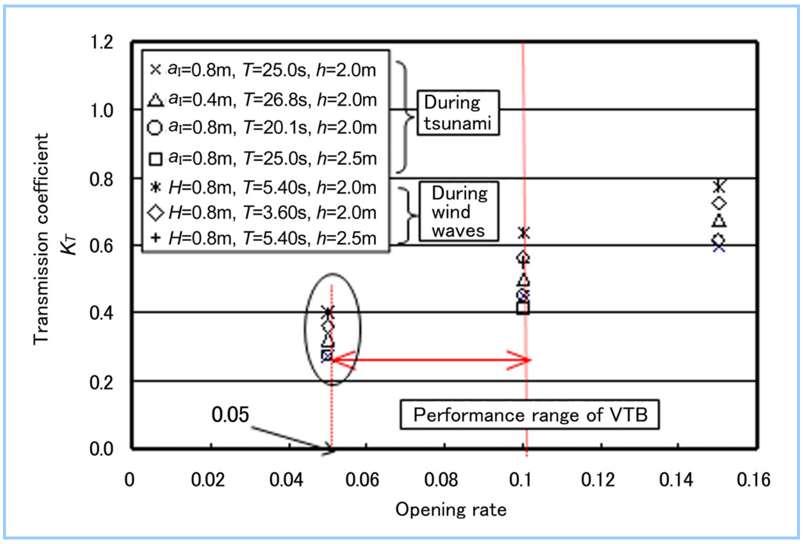
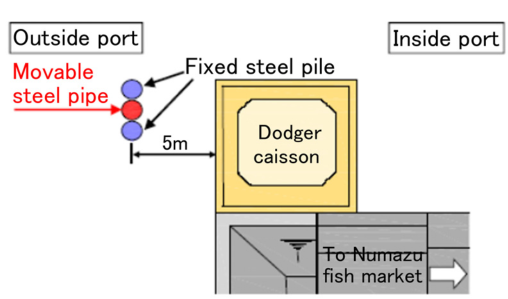


Figure 6　Relation between the upper pile opening rate and transmission coefficient

3.2　Verification test in real sea area

A test facility was installed in front of a caisson of Numazu Port in Shizuoka prefecture in September, 2006 for the verification test in a real sea area, and the test was conducted for about three years. (**Figure 7**).



Upper steel pile (movable pipe)	φ1422mm　L=14.75m
Lower steel pile	φ1600mm　L=16.75m
Fixed pile	φ1422mm×2 pcs (installed by Shizuoka prefecture)
Water depth	7.5 m
Top of upper pile	3.25 m above sea surface
Floating equipment	Compressor and air pipes

Figure 7　Horizontal layout of verification test facilities

(1)　Outline of test facility

The first year in the three-year verification test, fundamental performances such as mobility, hydraulic and dynamic characteristics were verified. In the second year, the upper piles were raised for the investigation of marine growth and steel material degradation after one year of being submerged. Also in May of 2009, two and a half years after installation, an investigation of the dissolved oxygen concentration in the lower pile, verification of the system equipment for the opening/closing of the exhaust valves and other verification tests were conducted in addition to the second year tests[4].

(2) Test results

[1] Manufacturing of steel pipe and processing accuracy

The upper pile was made by welding four kinds of steel pipes of different thicknesses. The concentricity of pipes, which was the most important factor, was 0 mm, and good circularity was ensured.

The lower pile was driven into the seabed with a vibrohammer, and very good vertical accuracy for placement was attained with the help of the installation of guide members.

[2] Raising and lowering test

The mobility verification was mainly conducted in 2006, mainly focusing on lowering tests. After leaving the breakwater for three years, the remote air supply/venting equipment was installed, and an investigation on the raising time was conducted. The system reliability was verified to be free from problems during more than one hundred raising/lowering tests. **Figure 8** shows the situation of a raising test in the field.

Figure 8 Situation of raising test in the field

[3] Hydraulic and dynamic characteristic test (response test in ocean waves)

Impact forces expected to be applied to the contacting points between the upper and lower piles, and fatigue problems caused by repeated load due to the shaking of the upper piles were a concern. The acceleration of the piles, wave pressure applied to the front/back faces of the upper piles and strain around the overlap between the upper/lower piles were measured continuously for approximately two weeks. **Figure 9** shows the field conditions.

Figure 10 shows the concept of the numerical model of upper pile floating body movement in ocean waves. Analyses were conducted for the impact response of the upper piles. **Figure 11** shows a sample of the simulation results, and good reproduction of upper pile movement can be seen. A schematic illustration of the force balance along the upper pile is shown in **Figure 12**.[4,5]

[4] Marine growth

The upper pile was raised after approximately one year from the last lowering of the breakwater, and an investigation of marine growth was conducted. Acorn shells of 1 to 2 mm thick were observed on the top cap, but close to nothing was observed on the side face of the pile. This is believed to be due to the low dissolved oxygen (2 ppm measured) concentration in the lower pile.

Figure 9 Response test in ocean waves

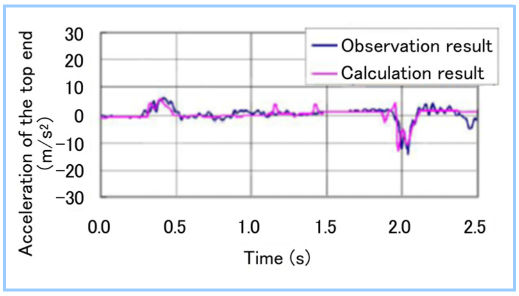


Figure 11 Acceleration of upper pile in ocean waves

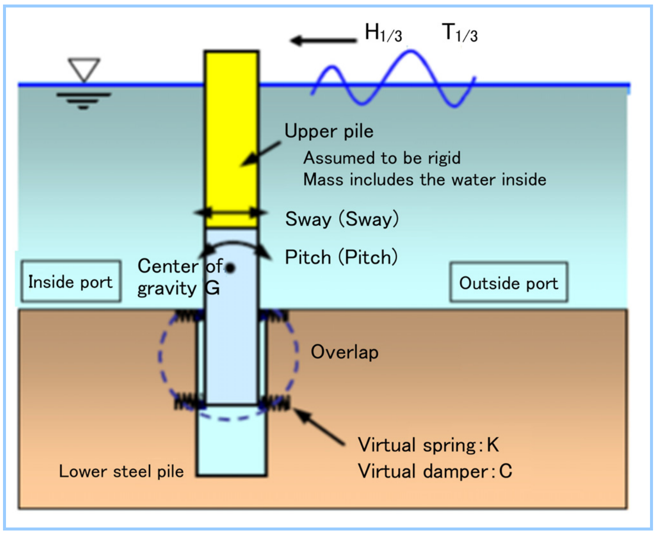


Figure 10 Concept of numerical model of upper pile floating body movement in ocean waves

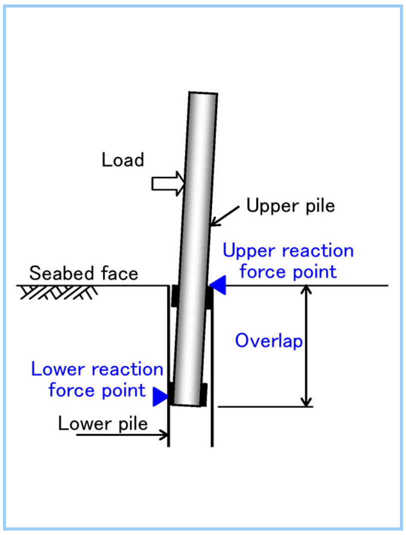


Figure 12 Outline of load applied

3.3 Structural reinforcement at overlap

The overlap transfers the load acting from the upper pile to the lower pile as shown in Figure 12. The upper and lower ends are the points where stress is concentrated (reaction force point), and reinforcement in the pile sectional direction is required in addition to an increase in the wall thickness of the pile base metal. An investigation using 3-dimensional elastoplasticity FEM analysis (ABAQUS solid model), which can consider large deformations and points of contact, was conducted.[6]

Figure 13 shows the results of the analysis at the overlap where tsunami power is applied as design load under the conditions of a lower pile diameter of 3,000 mm (thickness 60 to 45 mm) and an upper pile diameter of 2,800 mm (wall thickness 28 to 32 mm). The reinforcement was verified to be appropriate as the steel pile and reinforcement are within the yield stress, and the maximum stress is generated at a general position above the overlap. In addition, further analysis by increasing the load from the conditions in Figure 13 was conducted for the verification of bearing capacity.

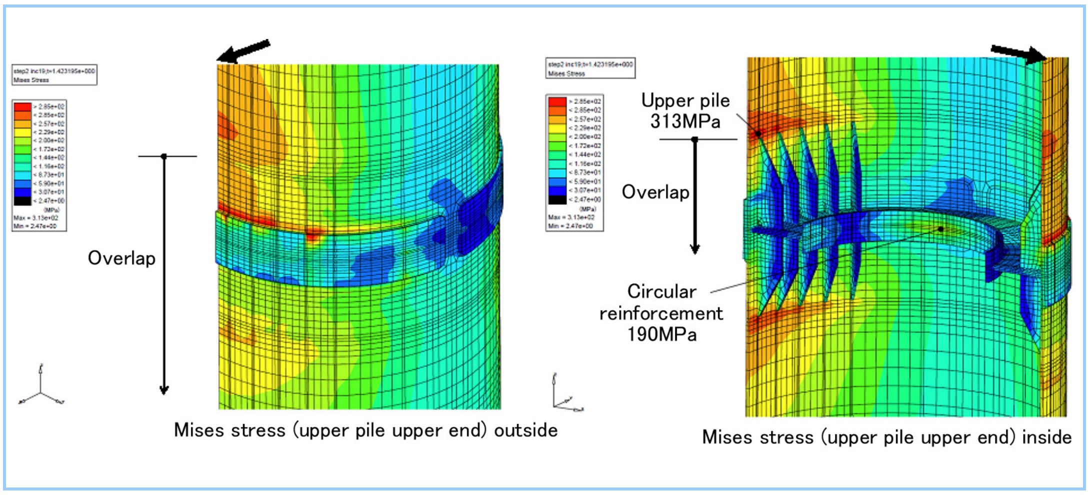


Figure 13 Result of FEM analysis

Figure 14 shows the load to deformation relationship, and **Figure 15** shows the fractured deformation condition after reaching the maximum bearing capacity. With an increased load, the yield area is expanded. However, the load could be increased to the point of 2.6 times of the supposed design value without a sudden fall of bearing capacity. The final deformation shape was the buckling at the position above the overlap. This indicates further reinforcement can be attained by extending the thick-wall area upward.

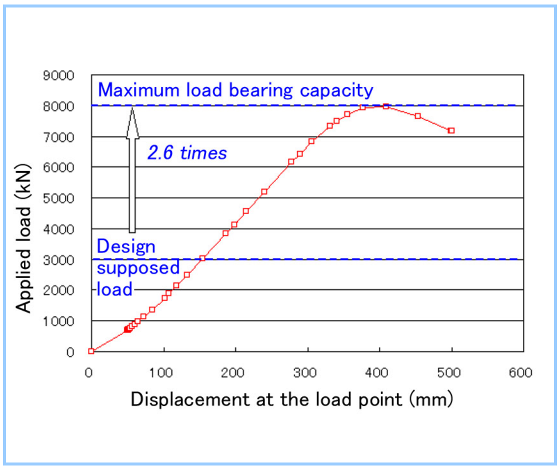


Figure 14 Load-deformation relationship

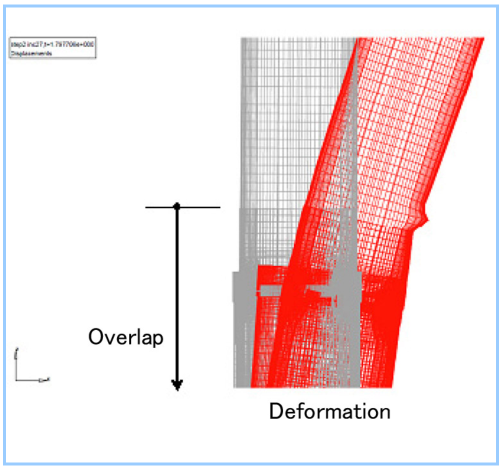


Figure 15 Deformation conditions when the maximum load is applied

4. Approach to simplification of air supply and shorter raising time

With the results of the tests, labor saving efforts on operation were conducted for practical application. In addition, in the tsunami re-prediction results of the Central Disaster Prevention Council after the East Japan Earthquake on March 11, 2011, the predicted arrival times of tsunamis will become shorter than current predictions. So, a new simulation program, which allows parametric study, was developed for the improvements such as a shorter raising time.[7]

4.1 Miniaturization of air supply facility

We found a water-tight tank (buoyancy tank) installed in the upper pile can reduce the amount of air supply required to raise the upper pile. It also shortens the raising time and downsizes the capacity of accumulator to preserve supply air.

In addition, for the reduction of equipment such as the number of air supply pipes, three upper piles are connected at the top as a single set. Simply supplying air to just the center pile can raise the three piles simultaneously as shown in **Figure 16**.

With the application of the measures noted above, the simplification of construction and the reduction of potential problems with air pipes have become possible.

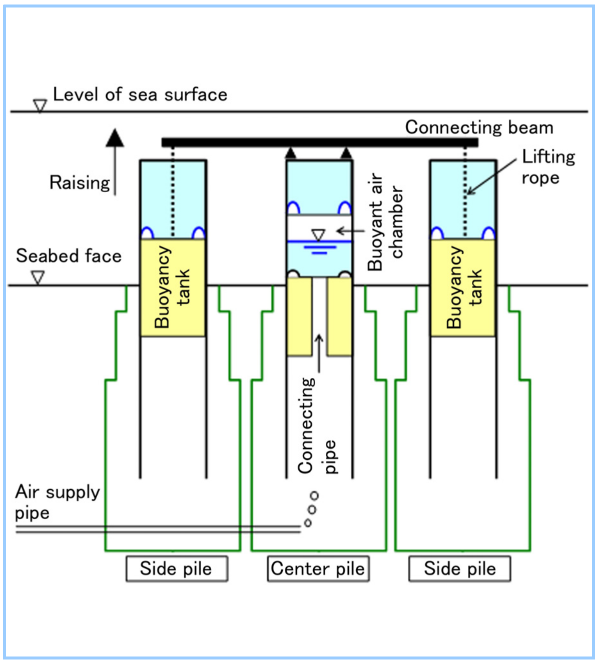


Figure 16 Outline of connected three-pile structure

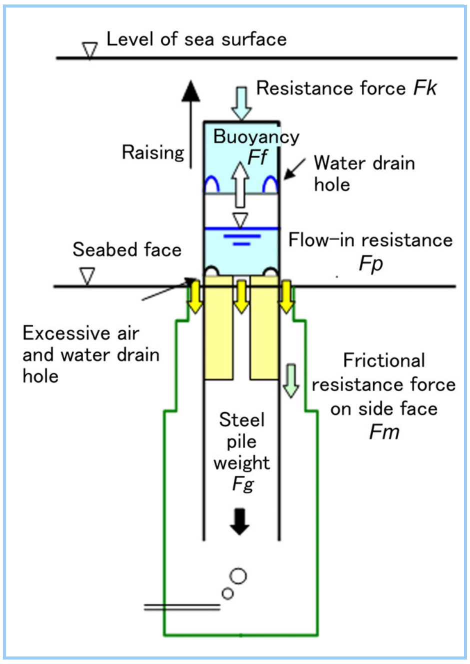


Figure 17 External forces applied to raising steel pile

4.2 Air supply and raising simulation

(1) Air supply simulation

In the study of raising time estimation, the estimation of the air discharge speed of the compressed air (supplied air amount) at the bottom of the lower piles is required. The discharge air speed is mainly determined by the energy loss resulting from pipe friction through the air pipe from the land facility to the lower pile bottom end. Using the fundamental formulas of air flow (equation of continuity, energy conservation law and momentum conservation law), and composing the discharge system by sequential computation of minute segments along the supply pipe, we developed the “Air Supply Simulation Program” to calculate the discharge speed

(2) Raising simulation

The forces acting on the upper pile during raising are as noted below (**Figure 17**):

F_f : Buoyancy
F_g : Pipe weight
F_k : Resistance acting on the upper pile end
F_m : Frictional resistance on the pile side face
F_p : Pressure loss resistance in the double pipe flow (flow-in resistance)

F_g, F_k, F_m and F_p are the resistances against the buoyancy F_f

With the sequential calculations of the minimal distances of these forces, considering the upper pile relative positions as shown in **Figure 18** using the movement formula below, the “Raising simulation Program,” which can estimate the time history response (changes of upper pile position, flow-in resistance, etc.) and the time between the starting of raising and the completion of raising (raising time). Computational Fluid Dynamics (CFD) analysis was used for the flow-in resistance, flow resistance was finely investigated by reviewing the pressure loss and the estimate accuracy of raising time was improved by reflecting the results in the raising simulation program.

[Movement formula of upper pile (raising)]

$$M_{uka}\frac{d^2H_{uk}}{dt^2}=F_f-F_g-F_k-F_m-F_p$$

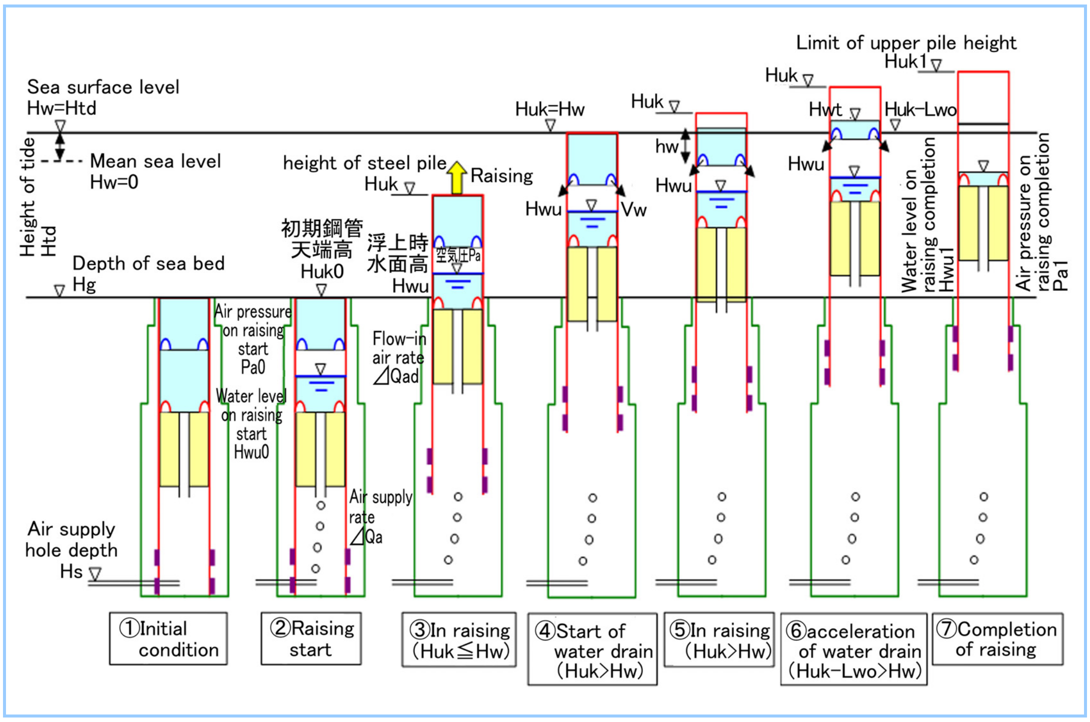


Figure 18 Relative positions in VTB raising

(3) Verification of raising simulation

In the verification of the raising simulation program, a comparison was made to the VTB hydraulic model experiment conducted at the Port and Airport Research Institute described in section 3. The verification test in the field was conducted from 2006 to 2009. The program was well verified as following the test results to a high degree of accuracy. (**Figure 19**)

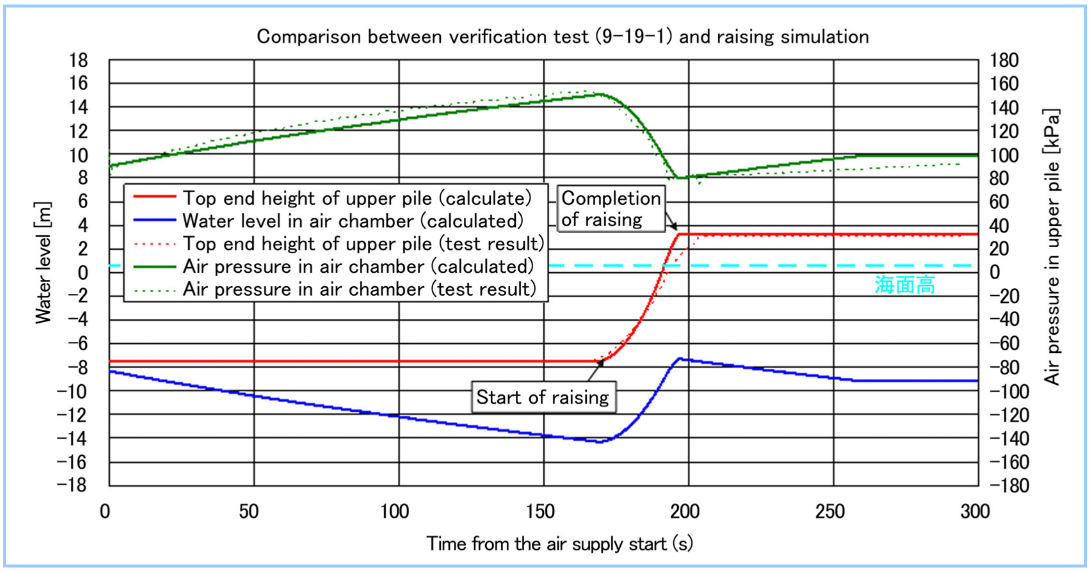


Figure 19 Comparison between verification test in ocean waves and raising simulation

4.3 Method to reduce raising time

An investigation to reduce the raising time of the three-pile combined VTB shown in Figure 16 was conducted by utilizing the developed raising simulation program. The investigation focused on the Fp (pressure loss resistance – flow-in resistance of double pipe inside flow) which is a structural feature of VTB.

The sea water pushed aside needs to flow into the upper and lower piles when the upper pile is being raised. The sea water flowing into the lower pile (Figure 17) flows both through the clearance between the lower piles and upper piles, and flows through the connecting pipe installed at the center pile. The reduction of raising time by applying improvements to each flow route below was investigated.

(1) Expansion of clearance between upper and lower piles

A stabilizer is installed at the top of each lower pile to adjust the clearance with the upper pile. The clearance must be increased to lower the flow-in resistance. However, the larger clearance adversely affects the pile collision in high wave. Accordingly, the clearance was limited to 20 mm or less, and the shortening of raising time was investigated in relation to the change of clearance.

(2) Expansion of connecting pipe diameter and installation of connecting pipe to each pile

An increase of flow-in in the amount of sea water through the connecting pipe is thought to be effective in reducing the flow-in resistance. Accordingly, the expansion of connecting pipe diameter and the installation of connecting pipes in side piles as additional new sea-water flow-in routes were verified for the shortening of raising time.

Under the conditions of a lower pile diameter of 3,000 mm and an upper pile diameter of 2,800 mm, the clearance was increased from 15 mm to 20 mm as a countermeasure (1), and the shortening of raising time was calculated. The result showed a significant reduction of raising time from approximately nine minutes before the improvement to five and half minutes. Countermeasures (1) and (2) above were verified to be effective in reducing the raising time by using the raising time simulation program.

5. Tsunami Countermeasures Project in Kainan-Area, Shimotsu Port Coast in Wakayama Prefecture

The Kainan area near the Shimotsu Port coast in Wakayama prefecture is located at the bay end of a deeply-indented coast line, and has suffered from floods from tsunami due to its geographical characteristics in past years. In addition, a tsunami significantly exceeding the current breakwater height is expected to come in the predicted of Tonan-kai and Nan-kai earthquakes, which have a high probability of occurrence in the next 30 years. Important administrative institutions, disaster prevention agencies and main transportation networks, in addition to residential areas and businesses, are located in the predicted tsunami immersion area on the coast. Countermeasures against tsunami are greatly desired.

Raising the bank of the current seawall will cause significant problems for the cargo handling of vessels. Accordingly, the tsunami protection project through the installation of VTB at the mouth of the port, forming a line of defense in front of the predicted immersion area is under way.

6. Conclusions

Parts of the outline and technical development of VTB developed from 2004 are introduced in this report.

The East Japan Earthquake occurred on March 11, 2011, recording 9.0 on the Richter scale, the worst in Japan's history. A huge tsunami was generated by this earthquake, and coastal areas facing the Pacific Ocean in Tohoku and Kanto suffered from the catastrophic disaster. The invasion of a huge tsunami of more than 30 m in height is predicted in Kouchi and Shizuoka Prefectures according to the tsunami predictions announced by the Central Disaster Prevention Council.

As described above, the susceptibility of coastal areas against tsunami has been pointed out. We would like to continue the study to utilize the VTB technology and evaluate it as a reliable breakwater in the future.

We would like to extend our acknowledgment to those people who provided support and cooperation in the development of the Vertical Telescopic Breakwater (VTB).

Special acknowledgments:

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