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Design of the tsunami protection wall against mega earthquakes and huge tsunamis

Masaaki Wani
Chubu Electric Power Co., Inc., Nagoya, Japan
Graduate School of Engineering and Science, University of the Ryukyus, Japan

Yoshihito Sato
Chubu Electric Power Co., Inc., Nagoya, Japan

Koto Ito
Chubu Electric Power Co., Inc., Nagoya, Japan

ABSTRACT: Chubu Electric Power Company has been implementing countermeasures in Hamaoka Nuclear Power Station (NPS) against tsunami and severe accidents following the disaster at Tokyo Electric Power Company's Fukushima Daiichi NPS that was caused by the 2011 Tohoku Earthquake. For this purpose, the L-shaped Tsunami protection wall 22 m high above sea level was constructed along coastline around the site. The total length of the protection wall was approximately 1.6 km and it was fixed to reinforced concrete underground walls, which were embedded in rock mass. Foundation rock consists of intercalated mudstone and sandstone. The tsunami protection wall has to withstand anticipated huge tsunamis such as the Nankai Trough Giant Tsunami, furthermore it has to withstand against the strong ground shaking of anticipated mega earthquakes to occur before the tsunami. The design seismic force is evaluated by the dynamic response analysis that can consider an interaction between structure, ground and bedrock, whereas the design wave force is set as hydrostatic pressure. Therefore, the tsunami protection wall must be designed reasonably based on the difference of seismic force and tsunami wave force. In this paper, the authors describe the concept of structural design on the basis of the above conditions and consider support performance of the protection wall and bedrock against the anticipated mega earthquake and huge tsunami.

1 INTRODUCTION

1.1 *Overview of Hamaoka NPS*

Chubu Electric Power supplies electric power to the central part of the main island of Japan facing the Pacific Ocean. The Hamaoka NPS is located in Shizuoka prefecture, and along the Pacific coast (Figure 1).

The Hamaoka NPS is Chubu Electric Power's only nuclear power station which has five nuclear power plants. Unit 1 and 2 are under decommissioning since 2009, and other 3 units are now waiting to restart. The total output of the remaining Units, 3, 4, and 5, is 3,617 MW.

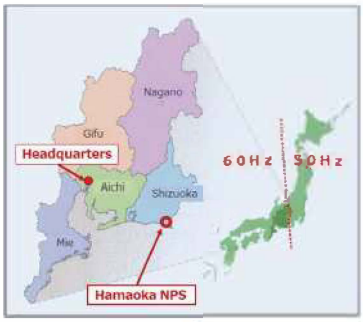

Figure 1. Location of Hamaoka NPS

1.2 *Tsunami countermeasures at Hamaoka NPS*

The 2011 off the Pacific coast of Tohoku Earthquake (hereinafter referred to as the 2011 Tohoku Earthquake), the most massive earthquake that Japan has received in the past, and a huge tsunami that followed caused extensive damage to the Pacific coastal area of eastern Japan. Furthermore the 2011 Tohoku Earthquake and subsequent tsunami had a major impact on nuclear power stations along the Pacific coast, and caused the accident at Tokyo Electric Power's Fukushima Daiichi NPS where radioactive materials were discharged.

When the 2011 Tohoku Earthquake occurred, the nuclear reactors of Fukushima Daiichi NPS sensed massive seismic ground motions and automatically shut down. However, after the earthquake, tsunami waves higher than the station site arrived, flooding the site and buildings. Key facilities were made unusable, including seawater intake pumps for cooling and emergency generators. When batteries ran out, the power station lost its "cooling function". Consequently this led to a severe incident escalating to a massive discharge of radioactive materials.

Fukushima Daiichi NPS was not fully prepared for the arrival of the tsunami nor the subsequent accident. To prevent a similar accident, we had promptly started safety improvement measures work, including tsunami countermeasures, after the accident.

We have applied a three phase strategy to tsunami countermeasures in the Hamaoka NPS (Table 1); "flooding prevention measures 1", "flooding prevention measures 2", and "enhanced emergency measures".

Firstly, "flooding prevention measures 1" are designed to prevent a tsunami flooding the station site. (Figure 2). We constructed "tsunami protection wall" measuring 22 m above sea level, stretching approximately 1.6 km along the front side of the station on the ocean side. In order to prevent a tsunami from entering the station site from the sides, "cement-mixed soil embankments" with a height of 22-24 m above sea level are also constructed on the eastern and western edges of the site (Figure 3-4).

Table 1. Three phase strategy to tsunami countermeasures

Flooding Prevention Measures 1	Prevention of tsunami inundation of the station site
Flooding Prevention Measures 2	Prevention of tsunami flooding of buildings on the site
Enhanced Emergency Measures	Adopting multiple alternative means of electric power supply, water injection, and heat sink

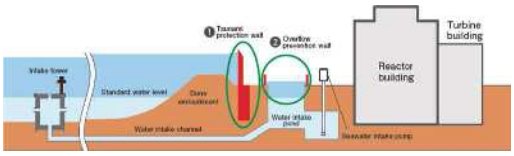

Figure 2. Flooding Prevention Measures 1

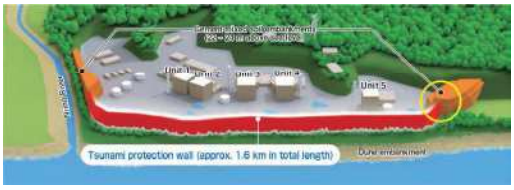

Figure 3. Perspective view of the tsunami protection wall and the cement-mixed soil embankments

Figure 4. Tsunami protection wall and cement-mixed soil embankment (eastern side)

In addition, we built "overflow prevention walls", approximately 4 m high, around water intake ponds that are linked to the sea via water intake tunnels.

Secondary, "flooding prevention measures 2" are designed to prevent buildings from flooding even if there is inundation in the station site (Figure 5). For preparedness against a tsunami higher than the tsunami protection wall, the pressure resilience and waterproof performance of exterior doors are reinforced by replacing reactor buildings' waterproof doors with watertight doors and combining them with new tsunami protection doors for dual protection (Figure 6). Watertight doors are also installed at rooms that contain important facilities.

Finally, "enhanced emergency measures" referring to ensure the cooling function will work even if there is a situation similar to that at the Fukushima Daiichi NPS, as there will be multiple alternative means of cooling the reactor such as electric power supplies (Figure 7), water injection, and heat sink.

In this paper, we explain the tsunami protection wall which is a major pillar of tsunami countermeasures of the Hamaoka NPS.

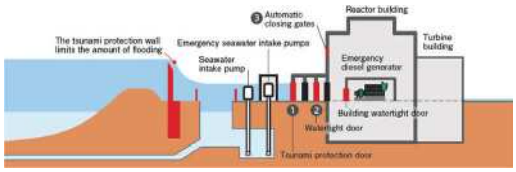

Figure 5. Flooding Prevention Measures 2

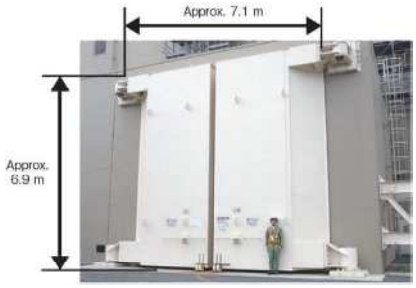

Figure 6. Reinforced protection door

Figure 7. Gas turbine generator Building

2 DESIGN OF TSUNAMI PROTECTION WALL

2.1 *Requirements for design*

There is a dune embankment with a height of 12-15 m above sea level on the ocean side of the Hamaoka NPS, and it had played a significant role as a natural protection against past-tsunamis until the Fukushima Daiichi accident occurred. However, we had promptly started safety improvement measures work, including the tsunami protection wall, after the accident.

When we started to design the tsunami protection wall, there were three requirements given below in consideration of the lessons in the disaster caused by the 2011 Tohoku Earthquake and the local conditions of the Hamaoka NPS.

- To withstand megaquakes and huge tsunamis, which may exceed paleo-quakes and paleo-tsunamis,
- To prevent large deformation against external forces far beyond the design force, and
- To be a slim structure that can be installed at the place with a limited width.

2.2 *Structural overview of the tsunami protection wall*

We had considered a structure satisfying above requirements and reached a conclusion that a combination of a wall, which had enough strength and resiliency, and a foundation, which supported the wall with high stability would be the most suitable.

As a result, we adopted a new structural system for seawalls. An L-shaped composite wall consisting of steel and steel-framed reinforced concrete was fixed to foundation of two underground walls of reinforced concrete that were embedded into solid bedrock (Figure 8). This structure provides an extra safety margin to seismic-resistant and tsunami-resistant design.

2.2.1 *L-shaped wall (upper structure)*

L-shaped wall consists of vertical wall and floor slab. To withstand huge tsunamis, it must have enough strength, but on the other hand, it is desirable to be lightweight to reduce the inertial force of megaquakes. As a result, the vertical wall was designed as steel structure which had high strength and resiliency and was lightweight. Moreover, to enhance seismic resistance, the structurally critical lower part of the vertical wall is filled with concrete.

The L-shaped wall stands 14-16 m high above the site, which is situated at an elevation of 6-8 m above sea level. A total of 109 blocks, each 12 m long, were constructed.

2.2.2 *Underground wall (foundation)*

The size of the underground wall is 7 m in width, 1.5 m thick, and approximately 10-30 m deep according to depth from ground level to bedrock surface.

To withstand megaquakes and huge tsunamis, Large-diameter reinforcing steel, such as D51 steel, is mainly used, and the underground wall is embedded into bedrock consisting of intercalated mudstone and sandstone (Figure 9).

218 underground walls in total were constructed at 6 m intervals and arranged so that they were perpendicular to the vertical wall. Special excavators were used to drill to the designated depth. After erecting reinforced frames assembled at the site, high-fluidity concrete was cast.

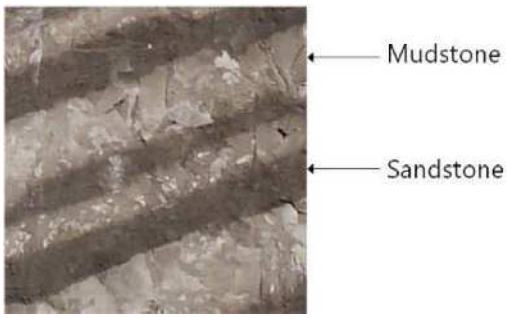

Figure 9. Bedrock (mudstone and sandstone)

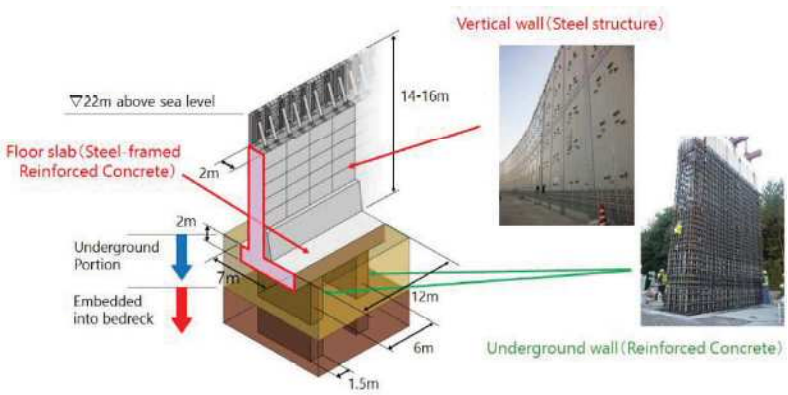

Figure 8. Structural overview of the tsunami protection wall

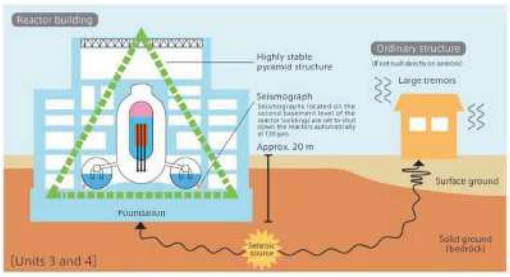

Figure 10. Basic seismic design of Hamaoka NPS

2.3 *Concept of seismic-resistant design*

As the Hamaoka NPS is within the hypocentral region of the anticipated Tokai Earthquake, the station has been built with a conservative seismic design from the very beginning of its construction (e.g. highly stable pyramid-like structure, built directly on bedrock) (Figure 10). Similarly, about the tsunami protection wall, seismic resistance was enhanced by embedding the foundation into bedrock.

The seismic structural design of the protection wall was based on a response analysis against the design earthquake ground motions for the Nankai Trough Megaquake that is expected to be even greater than the triple megaquake (the Tokai, Tonankai, and Nankai) that had been anticipated before the 2011 Tohoku Earthquake occurred.

2.4 *Concept of tsunami-resistant design*

When the 2011 Tohoku Earthquake occurred, many seawalls or other structures were destroyed by subsequent huge tsunamis. With respect to the damage, two failure mechanisms explained are regarded as the principal factors. One is sliding and falling the caisson by tsunami wave force, and the other is scouring the mound.

As mentioned above, the foundation of the tsunami protection wall is embedded into bedrock so that it has high resistance to sliding and scouring. Therefore, it is important to secure enough safety margin for wave force generated by anticipated huge tsunamis.

To calculate tsunami wave force, the appropriate assessment formula is used after taking into account the location where the structures to be assessed are located (undersea or on land).

The formula for assessing tsunami wave force acting on undersea structures is proposed by Tanimoto et al. (1984) and is mainly used in a working level.

On the other hand, regarding the wave force acting on land structures such as the tsunami protection wall, various assessment formulas are proposed (JSCE (2017)). Among these formulas, the major formulas such as Asakura et al. (2000) regard tsunami wave pressure as a hydrostatic pressure

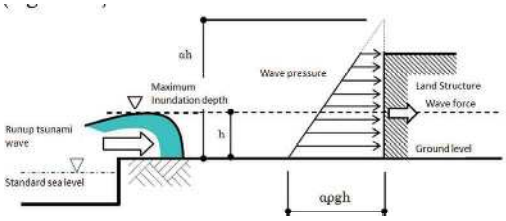

Figure 11. Assessment of wave force acting on a land structure

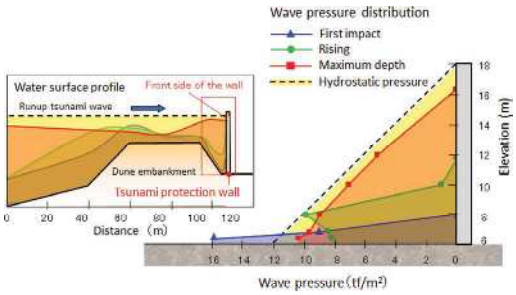

Figure 12. Wave pressures acting on the protection wall

equivalent to α times the maximum inundation depth of a runup tsunami wave in a state without a structure (Figure 11).

Based on the geographic characteristic of the site which has a dune embankment on the ocean side of the wall, hydraulic experiments were carried out to confirm applicability of the concept mentioned above. The nearshore topographical were set up in a 205m long 2-dimensional wave-generating channel to investigate tsunami wave force acting on the wall. The scale of models were 1/40. As a result, it was found that the maximum tsunami wave force acting on the wall was measured when tsunami overflew it, and the vertical distribution of pressures at the maximum tsunami wave force could be expressed by a linear relationship, which depend on the maximum water level at the wall as below Figure 12 (Matsuyama et al. (2012)).

Based on the result of experiment, the design wave force was set by integrating the vertical distribution of wave pressures acting on the wall equivalent to hydrostatic pressures of the wall height.

3 NUMERICAL ANALYSIS ABOUT THE STABILITY OF PROTECTION WALL AGAINST MEGAQUAKE AND HUGE TSUNAMI

The tsunami protection wall has to withstand huge tsunamis such as the Nankai Trough Giant Tsunami, furthermore it has to withstand against the strong ground shaking of anticipated mega earthquakes to occur before the tsunami. As mentioned above, seismic force acts on whole structure and ground dynamically. On the other hand, tsunami wave force

acts on mainly the vertical wall statically. Therefore, the wall must be designed reasonably based on the difference of seismic force and tsunami wave force.

Based on the above, numerical analyses were carried out to confirm the differences in the behavior of the protection wall and support performance of the bedrock against the anticipated mega earthquake and huge tsunami.

3.1 *Outline of analysis*

3.1.1 *Seismic response analysis*

Firstly, a seismic response analysis of the structure-ground coupled system was conducted using two-dimensional FEM. The analysis model is shown in Figure 13. Specifically, ground including bedrock and floor slab were modelled by plane strain element, and vertical wall and underground wall by beam element. In addition, ground reaction springs to consider sliding and separation were set between the structure and the ground. The depth of the model was set 6m for one underground wall.

Main properties of the structure model were unit weight and Young's modulus. Regarding the bedrock, unit weight, initial shear modulus and deformation characteristics obtained from tests were used. The nonlinearity of deformation characteristics of the ground model during shaking was considered by the modified General Hyperbolic Equation (GHE) model. As an example, the dynamic deformation property of the bedrock is shown in Figure 14.

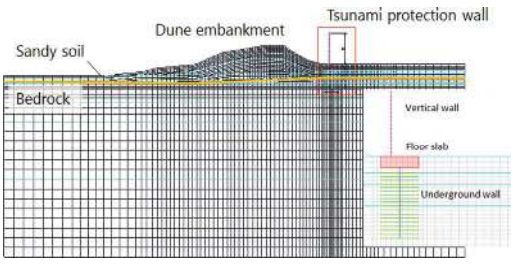

Figure 13. Analysis model (non-linear FEM)

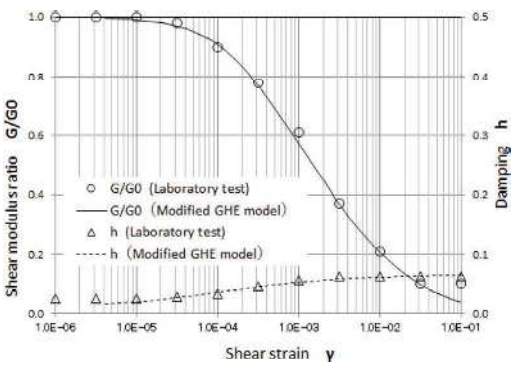

Figure 14. Dynamic deformation property of bedrock

The input acceleration on bedrock for the analysis is shown in Figure 15.

3.1.2 *Tsunami response analysis*

Secondary, a tsunami response analysis was conducted. The analysis model was the same one of the seismic analysis basically, however the ground model was linear because it is static analysis. The initial state of the analysis was just after the earthquake, so shear modulus of the ground model was set in consideration of the decrease caused by the earthquake. Specifically, it was set in reference to the G/G0 - γ relations of the modified GHE model according to the maximum shear strain of each element.

The tsunami wave force to act on the vertical wall was set as hydrostatic pressures equivalent to 16m height, from ground surface to the top of the wall, based on the above-mentioned information.

3.2 *Analysis result*

Firstly, responses of the protection wall in case of earthquake and tsunami are shown in Table 2. The deformation of the vertical wall due to the tsunami is small with approximately 5mm at the same level as the maximum deformation due to the earthquake. However, in regard to the bending moment and shear force acting on the underground wall, the responses due to the tsunami are both smaller than those due to the earthquake, especially the difference in shear forces is remarkable.

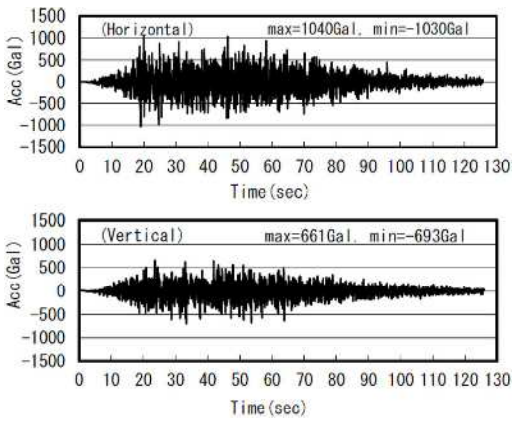

Figure 15. Input acceleration on bedrock

Table 2. Response of the structure (maximum value)

Event	Earthquake	Tsunami
Deformation of vertical wall	4.9mm	4.8mm
Bending moment of underground wall	93.2MNm	74.8MNm
Shear force of underground wall	13.4MN	7.6MN

The vertical distributions of shear force acting on the underground wall are shown in Figure 16. Though both direction and quantity of deformation of the vertical wall are mostly the same, positions of the peak of shear force distribution are different. Specifically, the maximum shear force due to tsunami occurs near the top of the underground wall, whereas the one due to earthquake occurs at lower elevation; near the border of sandy soil and bedrock. Behavior of the underground wall during earthquake is greatly affected by dynamic deformation of ground around the wall. Therefore, this is regarded as the main reason for the difference.

Secondary, with regard to responses of the bedrock, strain components ε_x, ε_y and γ_{xy} of the ground around the underground wall are shown in Figure 17. In the both case, locations of the peak of each strain distribution are mostly the same and they are either near the interface between of sandy soil and bedrock or near the bottom of the underground wall. However, a difference is noted in the distribution shape of the shear strain. Large shear strain is distributed mainly on the right side in case of tsunami, whereas it is distributed not only on the same side but on the other side in case of earthquake. In any way, the maximum values of these strains on the bedrock due to both earthquake and tsunami are less than the deformability limit of the bedrock, so that it indicates that the underground wall is safely supported by the bedrock.

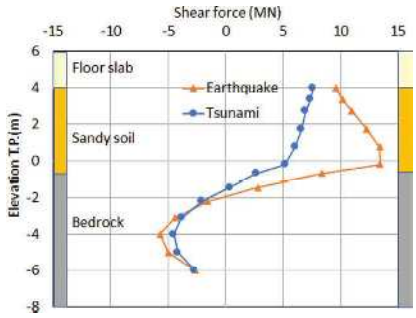

Figure 16. Distribution of shear force on the underground wall

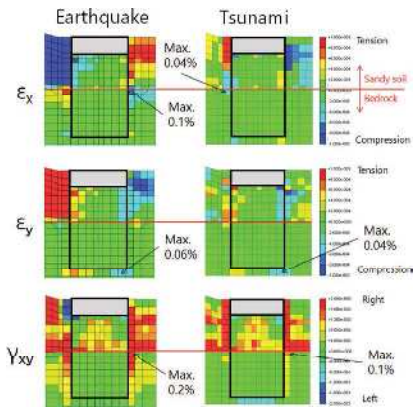

Figure 17. Normal and shear strain distribution in ground around the underground wall

4 CONCLUSION

In this paper, the fundamental concept of seismic and tsunami-resistant design of the tsunami protection wall at the Hamaoka Nuclear Power Station against mega-earthquakes and huge tsunamis was described.

The evaluation method of the design seismic force and the design tsunami wave force acting on the protection wall in consideration of the local conditions of the site was discussed, moreover, numerical analyses were carried out to confirm the behavior of the protection wall and support performance of the bedrock during anticipated mega-earthquake and associated tsunami. As a result, the following conclusions are drawn.

1. The deformation of the vertical wall of the tsunami protection wall due to the tsunami is as small as the maximum deformation due to the earthquake. However, the loads acting on the underground wall due to the tsunami are smaller than those due to the earthquake.
2. Though both direction and quantity of deformation of the vertical wall are mostly the same, positions of the peak of shear force on the underground wall are different.
3. Behavior of the underground wall during earthquake is greatly affected by dynamic deformation of ground around the wall.
4. The underground wall is safely supported by the bedrock on the basis of the difference of seismic force and tsunami wave force.

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