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Tsunami Safety Evaluation of Public Buildings in Shizuoka Prefecture, Japan

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Abstract

On March 11th, 2011, the Great East Japan Earthquake (Tohoku Earthquake) with a magnitude of 9.0 triggered massive tsunamis and caused the catastrophic disaster in the Tohoku region and other areas along the Pacific coast in Japan. Consequently, a numerous number of buildings and structures collapsed, tumbled or slid, which took away over 15,000 lives as well as communities in a moment.

Following the event, post-earthquake national efforts have been made for upgrading the technical standards and design guidelines for the safety evaluation of tsunami evacuation buildings (structures for evacuation from tsunami attacks). Also, from the year 2012 to 2014, Shizuoka Prefecture conducted the tsunami safety evaluation of 43 coastal public buildings against tsunamis caused by a major earthquake that is expected to occur along the Nankai Trough in the future. Based on the results of this evaluation, it was found that the safety capacity would deteriorate rapidly if the estimated water height increases even by a little, even for buildings judged to be safe for the estimated water height of tsunami.

Considering the importance of the facilities as places to protect many lives after the occurrence of a large-scale earthquake, it is necessary that sufficient allowance is ensured for tsunami evacuation buildings compared to the estimated tsunami force, and it is extremely important to thoroughly notify the residents in the area (evacuees), people in charge in administration, supervisors of the buildings the allowance for the estimated water height by indicating the limit water height that the building is capable of enduring.

This report shows the results of tsunami resistance safety evaluation of 43 public buildings in Shizuoka prefecture, a proposal on retrofitting in case the performance against tsunami is insufficient, and a suggestion of calculation of limit water height of the buildings.

Keywords: Tsunamis, tsunami evacuation buildings, safety evaluation, limit water height

1. Introduction

In Japan, the importance of ground measures against tsunamis including tsunami evacuation buildings was pointed in outline of measures against Tokai earthquakes in May 2003, and outline of measures against Tonankai/Nankai earthquakes in December of the same year, and the Building Center of Japan conducted a basis study on its tsunami guidelines based on the results. In Indonesia on December 2004, damages were caused by a tsunami after an earthquake occurring off Sumatra Island. Such series of events led to the issuance of "Guidelines regarding tsunami evacuation buildings, etc."[1] by cabinet office in June 2005, which showed the basic concept for structural requirements against the tsunami forces when building a tsunami evacuation facility based on the Tsunami guidelines of the Building Center of Japan.

Furthermore, "Act on establishment of tsunami disaster prevention areas" was enforced on December in order to mitigate the disasters caused by tsunamis after the Tohoku Earthquake on March 11th, 2011, and the standards on tsunami resistance safety evaluation for tsunami evacuation facilities was legislated.

Based on these, this Prefecture prepared "Shizuoka Prefecture tsunami resistance diagnosis manual for existing buildings (RC and S buildings)"[2] summarizing the tsunami resistance diagnosis for existing buildings in easily understood manners in March 2015, and structural design architects have implemented safety evaluation on tsunami resistance of private buildings with reference to this manual.

2. Maximum water level (estimated) of tsunami caused by a major earthquake in the Nankai Trough

Shizuoka Prefecture (population approx. 3.7 million) is located near the center of Japan (Fig. 1), facing the Pacific Ocean and extending 155km east to west and 118km north to south with area approximately 7,782km^2. It also has a coastline of total extension as long as 500km on the southern end of the prefecture, as well as a mountain range comprising of 3,000m-elevation mountains represented by Mt. Fuji in the north. The climate is mild oceanic type in general.

Under the ground in Shizuoka Prefecture, four plates (Pacific Plate, Philippine Sea Plate, Eurasia Plate and North American Plate) come in contact in a complex manner, making it an area where large and small earthquakes have repeatedly occurred since the old times. Especially in Nankai Trough in the ocean off the prefectural coast, it is predicted that an M8 to 9 earthquake will occur with the probability of about 70% within the next 30 years, and "The 4th Earthquake Damage Estimation for Shizuoka Prefecture"[3] which was prepared by Shizuoka Prefecture in 2013 also assumes occurrence of a large tsunami with height exceeding 20m if an earthquake of the largest class occur (Fig. 2).

Fig. 1 – Location of Shizuoka Prefecture in Japan

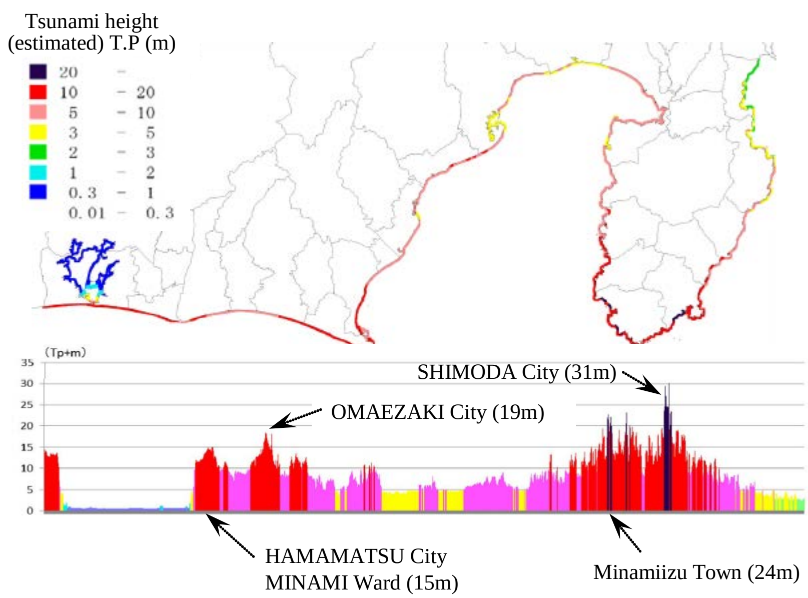


Fig. 2 – Maximum tsunami height (estimated) at major cities in Shizuoka Prefecture

3. Method of tsunami resistance safety evaluation

3.1 Tsunami resistance safety evaluation

In tsunami resistance safety evaluation of buildings against the estimated water depth, the relationship between collapsing, sliding, and overturning against the tsunami forces is supposed as shown in Fig.3.

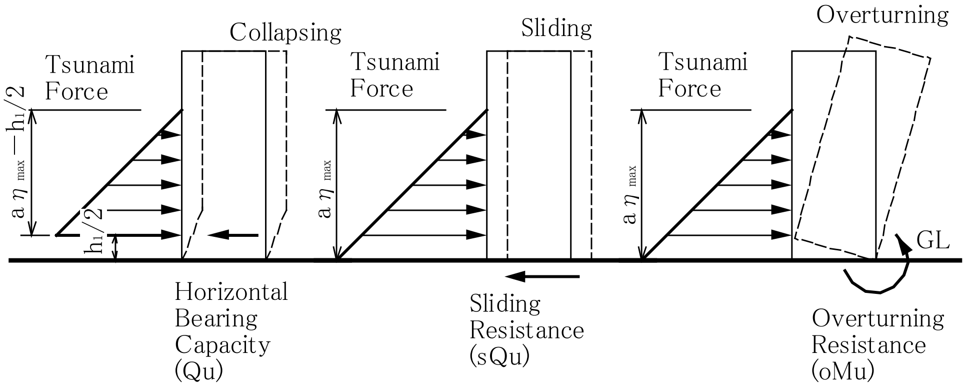


Fig. 3 – Relationship between collapsing, sliding, and overturning against tsunami

3.1.1 Water pressure and tsunami force

The tsunami water pressure applied on the building was calculated using Eq.(1) based on the water depth and water depth coefficient assuming the water pressure indicated in Fig. 4. Here, the value 1.5, 2.0 or 3.0 was adopted as water depth coefficient “a” depending on the geographical conditions based on the finding of tsunami damage investigation after The Tohoku Earthquake. The tsunami force was calculated using Eq.(2). In addition, the total tsunami force for either half of the floor heights of upper and lower floors was applied on the position of the floor in application in actual work to simplify the calculations, and the tsunami force was reduced by multiplying the rate of the total opening area to the total area of outer wall and if there were openings on the outer wall which is the surface subjected to pressure (however, 70% of tsunami force before reduction was consider the lower limit).

$$q_z = \rho g (ah - z) \tag{1}$$

$$Q_z = \rho g \int_{Z1}^{Z2} (ah - z) B dz \tag{2}$$

Here, q_z: Tsunami pressure assumption in the direction of tsunami (kN/m^2)
ρ: fluid density of water (t/m^3)
g: Gravitational acceleration (m/s^2)
a: Water depth coefficient (according to Table 1)
h: water height for design (m)
z: Height of the corresponding part ($0 \leqq z \leqq a\,h$) (m)
Q_z: Tsunami force in the direction of tsunami advance used in structural calculation (kN)
B: Width of surface subjected to pressure in the corresponding section (m)
z_1: Minimum height for the surface subjected to pressure ($0 \leqq z_1 \leqq z_2$) (m)
z_2: Maximum height for the surface subjected to pressure ($z_1 \leqq z_2 \leqq a\,h$) (m)

Table 1 – Setting of water depth coefficient "*a*"

Barrier for tsunami		No barrier
Distance from seashore, river, etc.		*a*=3.0
500m or larger	500m or smaller	
a=1.5	*a*=2.0	

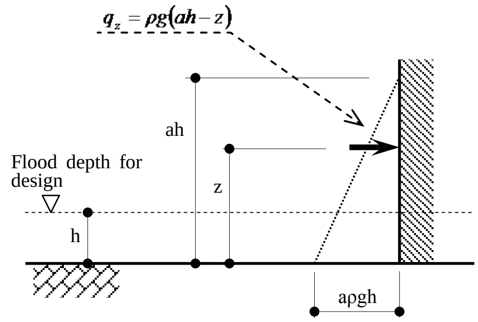


Fig. 4 – Tsunami wave pressure

3.1.2 Buoyant force

The buoyant force applied on a building was taken into consideration when water flowed into the building and when it did not in calculation of each of sliding and overturning. In this case, the buoyant force when water flowed in was calculated using the body volume equal to or larger than the water depth and the volume of air accumulations under each floor slab. The buoyant force when water did not flow in was calculated using the total volume of the building equal to or larger than the water depth. Each buoyant force was applied in upward vertical direction on the uppermost floor (Fig. 5).

3.1.3 Horizontal bearing capacity

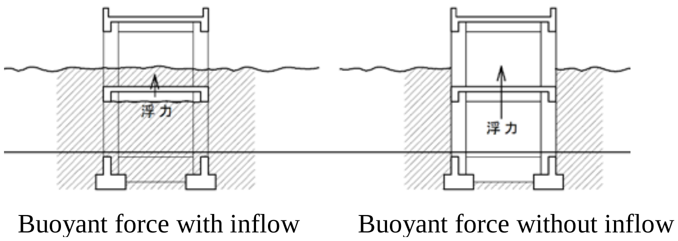
The horizontal bearing capacity of a building was calculated through nonlinear incremental loading (push-over) analysis using the hydrostatic force distribution with the product of water depth coefficient "*a*" and water height "*h*" as the vertex (Fig. 4), and the retained horizontal bearing capacity at story deformation angle (such as at a point of time about 1/300 to 1/150) at which no large rigidity deterioration had occurred depending on the building structure type was adopted. Furthermore, the buoyant force was neglected in horizontal bearing capacity, considering that the effect of buoyant force generated by inundation depth on the resistance of the component was small.

3.1.4 Sliding

The sliding resistance of a building was to be calculated depending on the basic style, and it was considered the sum of the frictional resistance between the foundation bottom surface and the ground (friction coefficient of 0.5 approximately) and the passive soil pressure resistance for the foundation embedding part for spread foundation. In addition, the friction force and resistance of piles were not added for pile foundation, even though it was also possible to use the ultimate lateral resistance of piles with the presumption that the piles and foundation are bound (Fig. 6).

3.1.5 Overturning

The overturning moment of a building was calculated by multiplying the distance from the fulcrum on the collapsing side to the center of gravity with the total building weight subtracted with the buoyant force. The tensile strength of the piles shall be added if it can be confirmed that the piles and the foundation are bound in pile foundation (Fig. 6).



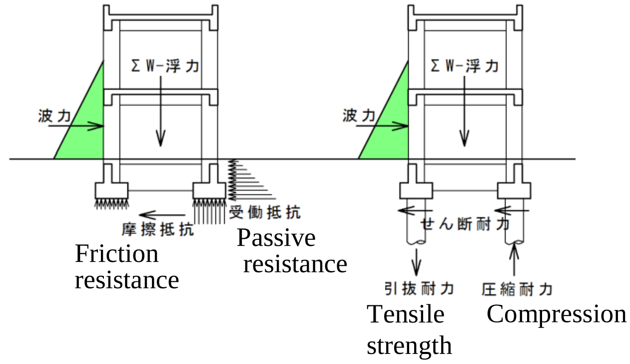


Fig. 5 – Buoyant force caused by seawater inflow/no inflow

Fig. 6 – Sliding resistance and overturning

4. Limit water height

It has been found in tsunami resistance safety evaluation of buildings that the safety capacity deteriorates dramatically when the flood depth increases even by a little, even for a building which has been judged safe against the estimated inundation depth.[4]

Since tsunami evacuation buildings are important facilities where many people evacuate from tsunamis after the occurrence of a large-scale earthquake, it is necessary to specify them carefully by selecting buildings with sufficient allowance against the estimated water level. However, we must be able to instinctively understand up to what height the building is capable of enduring and how much allowance its height has compared to the estimated water level in addition to the judgment of safety against the estimated water height in order to do so.

Therefore, we propose a method which sets the water height at the point of time when collapsing, sliding or overturningof the building aginst tsunami and the tsunami force balance each other in calculation as the limit water height, and which calculates the value based on tsunami resistance safety evaluation results instead of complex a convergence calculation.

4.1 Calculation of limit water height

If we define the tsunami resistance performance (rate of collapsing, sliding and overturnig against the tsunami force) as the index-value for limit water height as α, the ratio of limit water height against the estimated water height (h_{max}/h: allowance) can be expressed by Eq.(3) to Eq.(5) based on the balance between tsunami force in Eq.(2) and resistance in Fig. 4, and the relationship between the index-value and allowance can be expressed as shown in Fig. 7.

$$\text{For collapsing: } h_{max} ⁄ h = \alpha^{0.5} - [h_1 ⁄ (2ah)](\alpha^{0.5} - 1) \quad (3)$$

$$\text{For sliding: } h_{max} ⁄ h = \alpha^{0.5} \quad (4)$$

$$\text{For overturning: } h_{max} ⁄ h = \alpha^{(1/3)} \quad (5)$$

Here,
h: estimated water height (m)
h_{max}: limit water height (m)
α : tsunami resistance index-value
h_1: 1st floor height (m)
a : water height coefficient (Table 1)

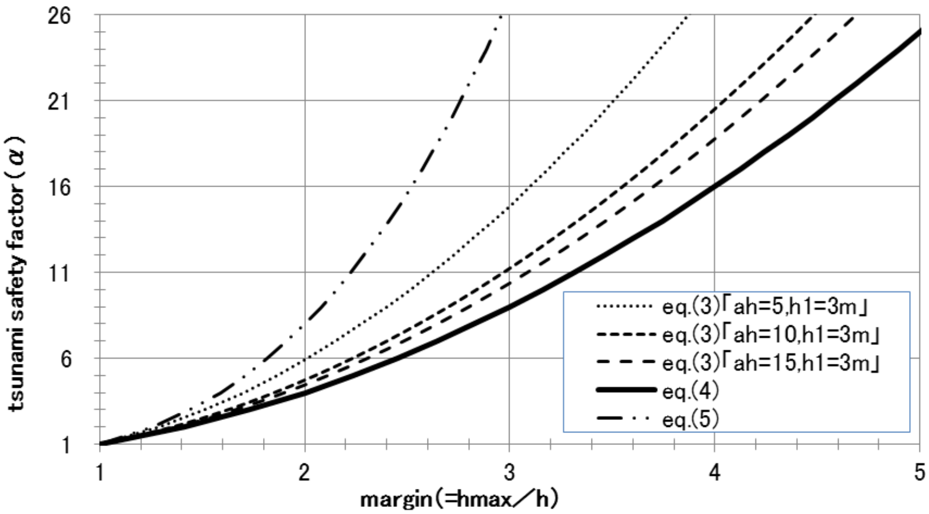


Fig. 7 – Relationship between limit flood depth for tsunami resistance safety factor (each index-value)

5. Tsunami resistance safety evaluation for public buildings in Shizuoka Prefecture and limit water height

5.1 Results of tsunami resistance safety evaluation on 43 public buildings

From the year 2012 to 2014, Shizuoka Prefecture conducted a tsunami resistance safety evaluation on the 43 existing buildings which are located near the coastline (and had no tsunami resistance design) as a part of the measures against tsunami caused by a major earthquake in the Nankai Trough which are expected to occur in the future (Table 2).

Based on the evaluation results, 53% (23 buildings) were judged as safe against the estimated water level. Since many of the 20 buildings judged as at risk are relatively small in scale, we are currently examining measures with relocation to areas which will not be affected by tsunamis as the basic measure.

Considering that that the limit flood depth is not so large even if the tsunami resistance safety is larger than 1.0 and that sliding and overturning occurred even in 4-story RC buildings in The Tohoku Earthquake, it is necessary to take due caution in tsunami resistance safety evaluation.

Table 2 Tsunami resistance safety evaluation results on 43 public buildings in Shizuoka Prefecture

Building No.	Application	Year built	Number of floors	Structure	Maximum Building height (m)	Total area (m^2)	Water height coefficient "a"	Estimated water height h (m)	$a \cdot h$ (m)	Determined case	Judgment	Limit water height h_{max} (m)
1	Multiple-dwelling house	2001	4	RC	15.15	1,572	2.0	2m or smaller	4m or smaller	Slide	Safe	3.4
2	Multiple-dwelling house	1978	5	RC	14.15	1,291	2.0	2m or smaller	4m or smaller	Slide	Safe	3.5
3	Multiple-dwelling house	2010	8	RC	25.00	2,915	1.5	2m or smaller	4m or smaller	Slide	Safe	9.2
4	Office	1986	7	SRC	30.60	12,220	1.5	3.87	5.81	Collapse	Safe	9.2
5	Office	1979	2	RC	8.10	787	2.0	4.26	8.52	Slide	At risk	4.1
6	Office	1990	2	RC	8.50	357	3.0	5.91	17.73	Slide	At risk	3.0

7	Office	1970	2	RC	8.05	589	3.0	6.90	20.70	Slide	At risk	3.2
8	Office	1972	2	RC	7.70	559	3.0	2.15	6.45	Slide	Safe	2.2
9	School (school building)	1997	5	SRC	26.50	4,929	1.5	2.07	3.11	Slide	Safe	6.8
10	School (school building)	1974	3	RC	12.79	1,293	1.5	2.24	3.36	Slide	Safe	5.3
11	School (gymnasium)	1958	2	RC+S	9.10	767	1.5	2.04	3.06	Slide	At risk	1.6
12	School (school building)	1964	4	RC	16.14	4,069	1.5	2.43	3.65	Slide	Safe	6.8
13	School (school building)	1970	3	RC	12.78	2,931	1.5	2.46	3.69	Slide	Safe	5.2
14	School (library)	1970	1	RC	4.85	411	1.5	2.28	3.42	Slide	Safe	2.9
15	School (gymnasium)	1967	2	S	13.20	1,371	1.5	2.45	3.68	Slide	Safe	2.5
16	School (school building)	1972	2	RC	8.44	540	1.5	2.31	3.47	Slide	Safe	4.4
17	School (school building)	1972	2	RC	7.78	400	1.5	2.35	3.53	Slide	Safe	4.1
18	School (gymnasium)	1978	2	S+SRC	15.03	1,134	1.5	2.34	3.51	Slide	Safe	4.8
19	School (annex building)	1985	3	RC	13.29	497	1.5	2.34	3.51	Slide	Safe	5.3
20	School (annex building)	2012	1	S	3.99	77	1.5	2.38	3.57	Slide	At risk	1.4
21	School (school building)	1985	2	S	9.90	291	1.5	2.45	3.68	Slide	At risk	2.2
22	School (school building)	1988	2	RC	8.79	228	1.5	2.26	3.39	Slide	Safe	3.1
23	School (annex building)	2010	1	S	3.50	81	1.5	2.42	3.63	Slide	Safe	1.1
24	School (annex building)	2010	1	S	3.50	81	1.5	2.42	3.63	Slide	Safe	1.1
25	School (school building)	2010	1	S	5.93	333	1.5	2.45	3.68	Slide	Safe	2.8
26	School (cafeteria)	1978	1	RC	6.90	277	3.0	2.20	6.60	Slide	At risk	1.8
27	School (annex building)	2011	1	S	3.68	147	3.0	2.64	8.07	Slide	At risk	0.5
28	Police station	1967	2	RC	7.90	655	2.0	5.27	10.54	Slide	At risk	2.4
29	Police station	1981	2	S	6.15	67	2.0	5.27	10.54	Slide	At risk	1.1
30	Police station (police box)	1993	2	WRC	7.75	79	2.0	5.46	10.92	Slide	At risk	2.2
31	Police station (police box)	1982	2	WRC	7.14	127	2.0	5.25	10.50	Slide	At risk	2.3
32	Police station (police box)	1995	2	RC	8.17	149	3.0	3.56	10.68	Slide	At risk	1.9
33	Police station (police box)	1974	2	WRC	6.40	86	2.0	2.06	4.12	Slide	At risk	2.0

34	Police station (police box)	1998	2	WRC	7.25	161	3.0	2.31	6.93	Slide	Safe	2.7
35	Police station (police box)	1980	2	WRC	6.10	99	2.0	2.07	4.14	Slide	Safe	1.5
36	Police station (police box)	2005	2	S	7.70	104	3.0	2.34	7.02	Collapse	At risk	1.3
37	Police station (police box)	1995	2	RC	9.45	125	2.0	3.52	7.04	Collapse	At risk	2.4
38	Police station (police box)	1968	1	WRC	4.15	109	3.0	5.18	15.54	Slide	At risk	1.7
39	Police station (police box)	1991	2	WRC	8.37	149	3.0	5.87	17.61	Slide	At risk	2.5
40	Warehouse	1983	2	RC	7.40	137	3.0	3.90	11.70	Slide	At risk	2.3
41	Office	1986	7	SRC	37.59	7,199	3.0	2.26	6.78	Collapse	Safe	3.7
42	Office	2003	1	RC	4.45	271	3.0	3.20	9.60	Slide	At risk	3.2
43	Office (machinery room)	2003	2	RC	11.8	359	3.0	3.00	9.00	Slide	Safe	3.1

5.2 Proposal on retrofitting for consideration (ex. Building No.1)

While tsunami resistance safety evaluation determined that Building No.1 was safe against the estimated water height, the methods of retrofitting to endure the maximum water height 5.6m (height of 3rd floor slab) were examined so that the top floor (4th) can be used as safe floor for evacuation with a purpose to develop a tsunami resistance retrofitting methods for future consideration.[5]

Since it was confirmed in tsunami resistance safety evaluation results that it was effective to increase the resistance against sliding and overturning, it is considered effective to adopt a retrofitting method using additional piles (14, added horizontal bearing capacity approximately 13,000kN) to compensate the insufficient resistance to the tsunami force (Fig. 8, Fig. 9).

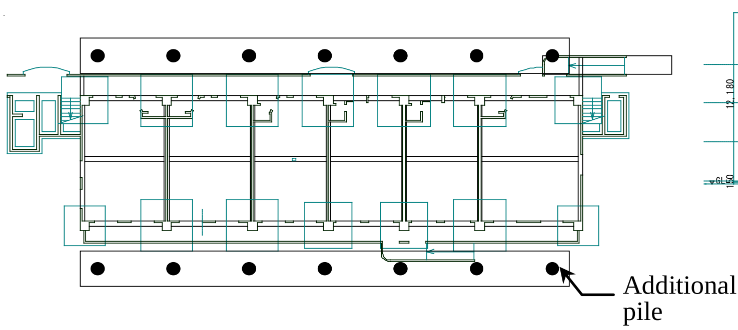


Fig. 8 Foundation plan (pile retrofitting proposal)

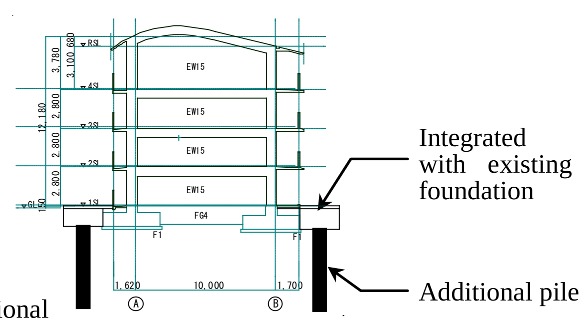


Fig. 9 Elevation (pile retrofitting proposal)

6. Conclusion

This report presented the results of tsunami resistance safety evaluation on 43 public buildings inShizuoka Prefecture and proposed a method to calculate the limit water height.

Considering the importance as facilities to protect many human lives after the occurrence of a large earthquake, it is necessary that sufficient alloance is ensured for tsunami evacuation facilities against the estimated water level, and it is considered extremely important to thoroughly notify the local residents (evacuees), the persons in charge in administration, facility supervisor about the allowance against estimated water height by indicating the limit water height for the corresponding building in oder to address this.

Lastly, Shizuoka Prefecture estimates that there will be approximately 96,000 victims in a tsunami caused by a major earthquake in the Nankai Trough which is expected to occur in the future, and is taking comprehensive measures against earthquakes and tsunamis with a goal to reduce the number of victims to approximately 80% (approx. 80,000 people) by the end of March 2023. To address this goal, establishment of tsunami evacuation facilities is an urgent matter, and the prefecture is instructing the cities and towns to promptly implement tsunami resistance safety evaluation on existing buildings.

7. Acknowledgements

This report has been prepared based on the outcomes of Prefectural building tsunami resistance performance evaluation commitee, special committee on tsunami resistance performance evaluation at Shizuoka Association of Architectural Firms, and tsunami resistance performance evaluation manual preparation committee on existing buildings (especially the chairperson: Professor Yoshiaki Nakano of Institute of Industrial Science, the Univ. of Tokyo). We hereby express our gratitude to all the parties involved.

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