





## 1. Introduction

Serious damage by the 2011 off the Pacific coast of Tohoku Earthquake Tsunami in Japan reminded us how important it is to maintain tsunami evacuation buildings in predicted inundation areas. The things to do for tsunami countermeasures is not only to construct new tsunami evacuation buildings but also to designate some existing buildings as tsunami evacuation buildings. In Japan, *Practical Guideline on Requirement for Structural Design of Tsunami Evacuation Buildings* [1] by National Institute for Land and Infrastructure Management (NILIM) is assumed to be used for evaluating the anti-tsunami performance of tsunami evacuation buildings. On the other hand, Shizuoka Prefecture in Japan has an original manual of evaluation method [2]. However, due to the lack of manpower and budget, the local government may not be able to apply the above-mentioned guidelines. Thus, the multiple grade levels in evaluation method for anti-tsunami performance from simple-way to detailed-way must be needed according to the situation of each stakeholder. From the view point of design load, *Recommendations for Loads on Buildings* [3] by Architecture Institute of Japan (AIJ) suggested three routes of calculating the wave force; (A) time-history of inundation depth and flow velocity, (B) the maximum inundation depth and the maximum flow velocity, and (C) the maximum inundation depth. Above-mentioned guidelines basically use the wave force formula of the route (C) and don't consider the routes (A) and (B). This paper proposes the multiple grade levels in the anti-tsunami performance evaluation method that considers also the routes (B) and (C) by organizing previous studies and examines the difference in the judgment results.

## 2. Wave Force Formula by AIJ

*AIJ Recommendations for Loads on Buildings* proposes routes (A), (B), and (C) of calculating the surge force and the drag force respectively. This paper describes the wave force formulas of the routes (B) and (C) considering the maximum inundation depth and the maximum flow velocity to investigate an anti-tsunami evaluation method based on the wave force formulas of that.

The route (B) is a wave force calculation method when the maximum inundation depth and the maximum flow velocity are available. The surge force is expressed as Eq. (1), and the drag force is expressed as Eq. (2).

$$F = \frac{C_{D3}}{2} \rho \eta v^2 B, \quad C_{D3} = 1.3 + 6.3 \frac{\eta}{D} \quad (0.01 < \frac{\eta}{D} < 0.17) \quad (1)$$

$$F = \frac{C_D}{2} \rho \eta v^2 B \quad (2)$$

where,  $C_{D3}$ : coefficient for calculating the wave force,  $\rho$ : density of seawater,  $\eta$ : maximum inundation depth,  $v$ : maximum flow velocity,  $B$ : width of the building,  $D$ : distance between the coastline and the building,  $C_D$ : drag coefficient. The difference between the surge force and the drag force depends on the difference between  $C_{D3}$  and  $C_D$ . These formulas could result in a large external force when the maximum inundation depth and the maximum flow velocity are not measured simultaneously.

The route (C) is a wave force calculation method when the maximum inundation depth is available. The surge force is expressed as Eq. (3), and the drag force is expressed as Eq. (4).



$$F = \frac{a^2}{2} \eta^2 \rho g B \quad (3)$$

$$v = Fr \sqrt{g \eta} \quad (4)$$

where,  $a$ : water depth coefficient,  $g$ : gravitational acceleration,  $Fr$ : Froude number.

Additionally, the fluid analysis is performed, and the results are compared with the solutions of the formulas to consider the difference in the wave force by the routes (B) and (C). In this study, the wave force formulas are discussed using *DualSPHysics*, which is a fluid analysis program based on the smoothed particle hydrodynamics (SPH) method and has been validated in the literature [4].

Fig. 1 shows the analytical model. The width of the waterway is 50m and that of the building is 10m.  $\Delta h$  is set so that the Froude number is 0.7 to 2.0 referring to the literature [5]. The analysis is performed on a 1/10 scale based on the Froude similarity law so that the calculation time is not too long. The calculation time interval is set to 0.01 second, and the output wave force is smoothed by averaging every 0.05 second. Fig. 2 shows the wave force by the formulas and the analysis.

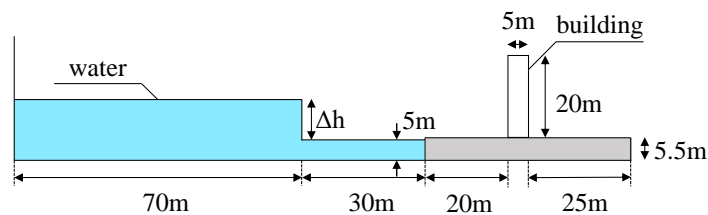


Fig. 1 – Analytical model

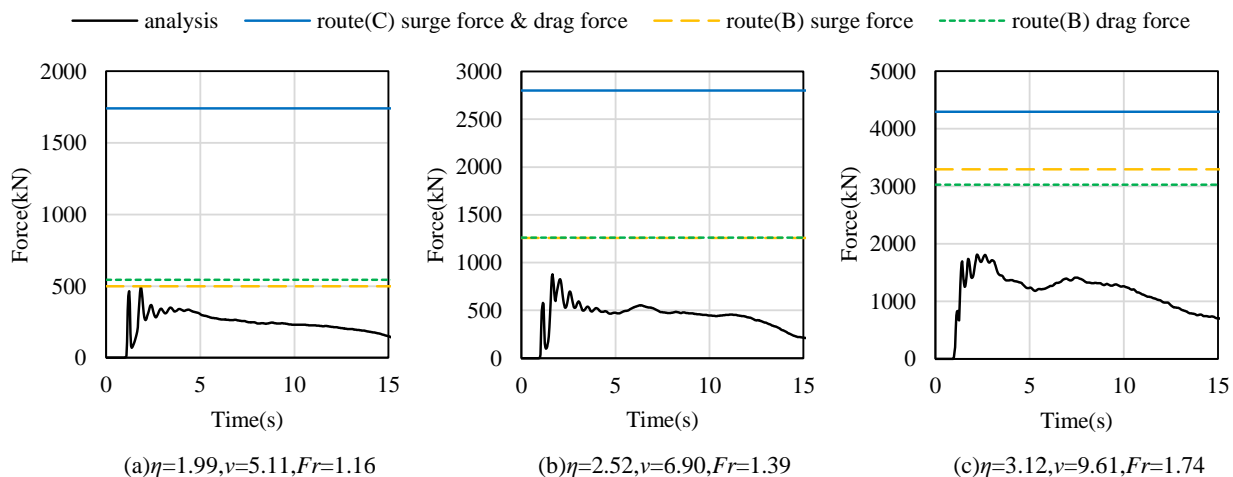


Fig. 2 – Wave force by formulas in guideline and fluid analysis

The wave force by the route (B) is closer to the fluid analysis value than that by the route (C). However, a larger value was calculated in some cases where the Froude number was large, because the maximum inundation depth and the maximum flow velocity were not measured simultaneously.



### 3. Evaluation Method for Anti-Tsunami Performance

Fig. 3 shows the flowchart of the evaluation method for anti-tsunami performance. The evaluation method based on the route (C) is defined as the primary diagnosis and that based on the route (B) is defined as the secondary diagnosis in this research. Additionally, other evaluations (collision, scouring, and evacuation performance) are performed regardless of the diagnostic levels. The method specified in the Shizuoka Prefecture's manual [2] is used to evaluate of collision and scouring.

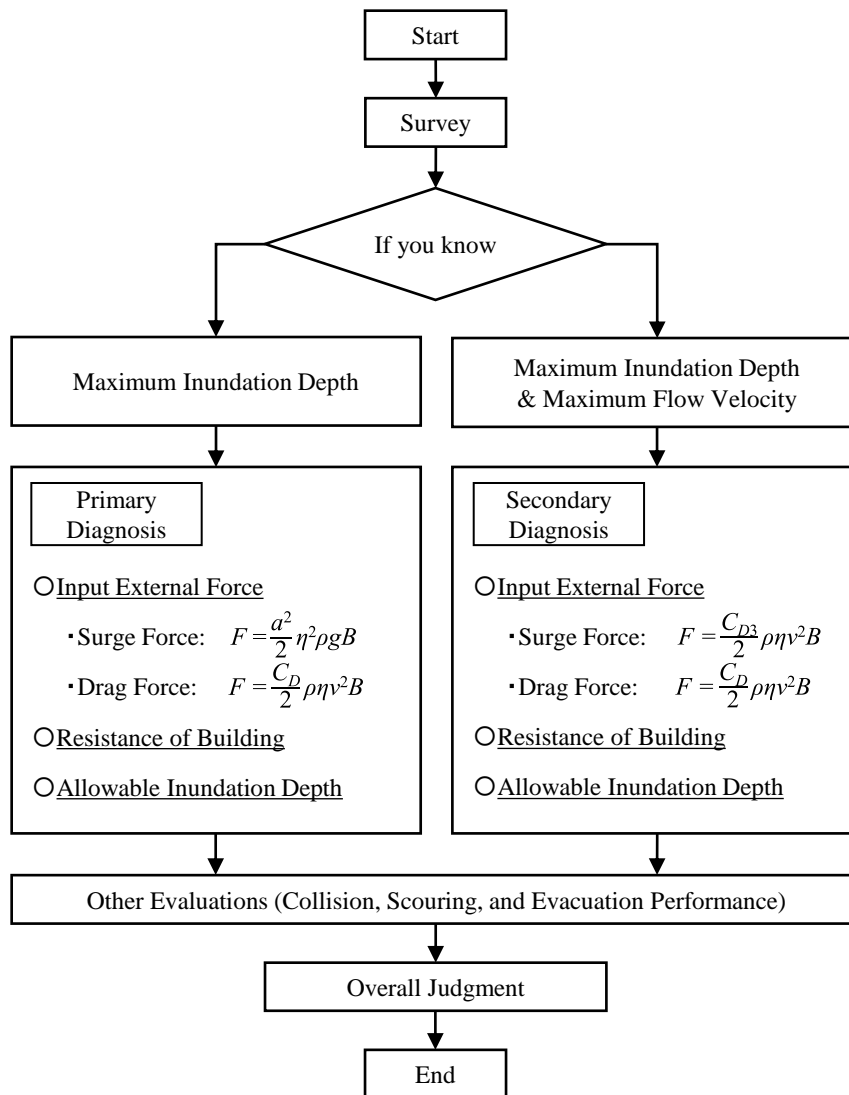


Fig. 3 – Flowchart of evaluation method for anti-tsunami performance

#### 3.1 Input External Force

The previous study based on the field survey of the 2011 off the Pacific coast of Tohoku Earthquake Tsunami [6] classified the damage to buildings by tsunami into three types: “collapse”, “sliding”, and “overturning”. Fig. 4 shows the models of the forces for each failure mechanism. The input external forces by the surge forces are expressed as Eq. (5) to (7).

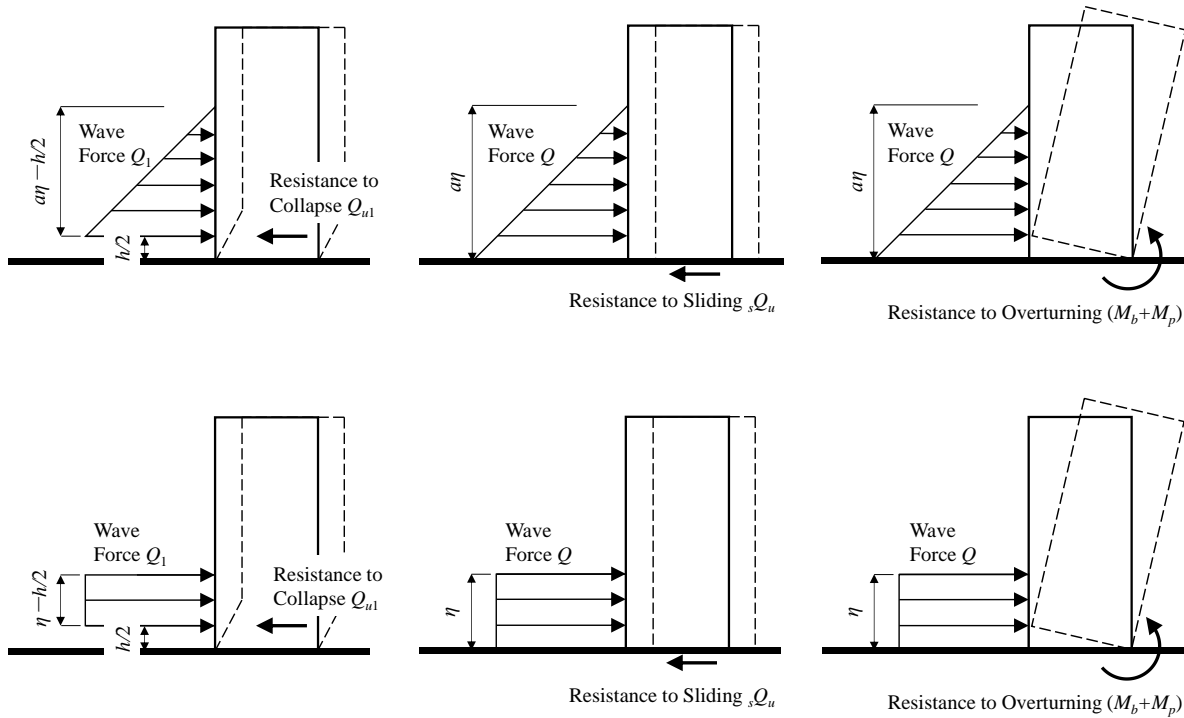


Fig. 4 – Force model for each failure mechanism (upper: surge force, lower: drag force)

$$Q_1 = \frac{\gamma}{2} \left( a\eta - \frac{h}{2} \right)^2 \rho g B \quad (5)$$

$$Q = \frac{\gamma}{2} a^2 \eta^2 \rho g B \quad (6)$$

$$M_w = \frac{\gamma}{6} a^3 \eta^3 \rho g B \quad (7)$$

where,  $Q_1$ : wave force on the 1<sup>st</sup> floor,  $Q$ : wave force on the entire structure,  $M_w$ : overturning moment,  $\gamma$ : reduction coefficient. The input external forces by the drag forces are expressed as Eq. (8) to (10).

$$Q_1 = \frac{\gamma C_D}{2} \rho B \left( \eta - \frac{h}{2} \right) v^2 \quad (8)$$

$$Q = \frac{\gamma C_D}{2} \rho B \eta v^2 \quad (9)$$

$$M_w = \frac{\gamma C_D}{4} \rho B \eta^2 v^2 \quad (10)$$



When the wave height  $a\eta$  exceeds the building height, the calculation is performed excluding the vertical external force portion exceeding the building. In primary diagnosis, the flow velocity is calculated by Eq. (11) since only the maximum inundation depth is handled.

$$v = a \sqrt{\frac{g\eta}{2}} \quad (11)$$

In secondary diagnosis, the equivalent water depth coefficient  $a_q$  is used instead of the water depth coefficient  $a$ . The equivalent water coefficient  $a_q$  is obtained from Eq. (12).

$$a_q = \sqrt{\frac{C_{D3}v^2}{\eta g}} = \sqrt{C_{D3}} \cdot Fr \quad (12)$$

### 3.2 Anti-tsunami Strengths of Building Structure

The resistant strengths of the building structure for each failure mechanism are expressed as Eq. (13) to (16).

$$Q_{u1} = W_b' C_B \quad (13)$$

$${}_sQ_u = \begin{cases} \mu(W_b - Q_z) & \text{(Spread Foundation)} \\ n_p \cdot \min(Q_{su}, Q_{mu}) & \text{(Pile Foundation)} \end{cases} \quad (14)$$

$$M_b = \frac{1}{2} L(W_b - Q_z) \quad (15)$$

$$M_p = n_{pt} P_t d_e \quad (16)$$

where,  $Q_{u1}$ : horizontal bearing capacity,  $Q_1$ : resistance to sliding,  $M_b$ : moment of resistance by weight of the building,  $M_p$ : moment of resistance by pull-out force of piles,  $W_b$ : weight of the building,  $W_b'$ : weight of the building (excluding foundation),  $C_B$ : base shear coefficient,  $\mu$ : friction coefficient,  $Q_z$ : buoyancy,  $Q_{su}$ : shear strength of the pile,  $Q_{mu}$ : shear force at ultimate bending moment of the pile,  $n_p$ : total number of piles,  $L$ : depth of the building,  $n_{pt}$ : total number of tension side piles,  $P_t$ : pull-out strength of the pile,  $d_e$ : distance between the fulcrum of the building and the center of gravity of tension side piles. If detailed information such as structural drawings is not available, the resistant strengths of the building structure are calculated by assuming that the building has a spread foundation and that the tsunami doesn't flow into the building.

### 3.3 Allowable Inundation Depth

If all the ratios of the resistant strength of the building in each failure mechanism to the external forces (these are expressed as  $Q_{u1}/Q_1$ ,  ${}_sQ_u/Q$ ,  $(M_b+M_p)/M_w$ , respectively and called the index values) are 1.0 or more, the building can be evaluated as having the necessary performance for the predicted tsunami. In the primary diagnosis, the wave force is evaluated by the hydrostatic pressure multiplied by the water depth coefficient.



However, the wave force on the entire structure is a quadratic function of  $\eta$  (the inundation depth) from Eq. (6), and the overturning moment is a cubic function of  $\eta$  from Eq. (7). Thus, when the input external forces are expressed as functions having different orders (variable:  $\eta$ ), the force-based index values have difficulties to compare the anti-tsunami performance against to each failure mechanism. In this study, by converting the index values to the allowable inundation depths, the margin for each failure mechanism can be uniformly compared based on the inundation depth.

The index values for the surge force are converted to the allowable inundation depths using formulas suggested by Sakuta [7]. When the index values for collapse, sliding, and overturning are  $\beta_1$ ,  $\beta_2$ , and  $\beta_3$  respectively, the allowable inundation depths  $\eta_{max1}$ ,  $\eta_{max2}$ , and  $\eta_{max3}$  for the surge force are given by Eq. (17) to (19).

$$\frac{\eta_{max1}}{\eta} = \sqrt{\beta_1} - \frac{h}{2a\eta} (\sqrt{\beta_1} - 1) \quad (17)$$

$$\frac{\eta_{max2}}{\eta} = \sqrt{\beta_2} \quad (18)$$

$$\frac{\eta_{max3}}{\eta} = \sqrt[3]{\beta_3} \quad (19)$$

The index values for the drag force are converted to the allowable inundation depths based on the Froude number which is calculated from the estimated inundation depth and flow velocity. With reference to the formulas of Sakuta [7], the allowable inundation depth for collapse is given by Eq. (20), and the allowable inundation depths for sliding and overturning are given by Eq. (18) and (19).

$$\frac{\eta_{max1}}{\eta} = \frac{h}{4\eta} + \frac{1}{2} \sqrt{\frac{h^2}{4\eta^2} + 4\beta_1 \left(1 - \frac{h}{2\eta}\right)} \quad (20)$$

### 3.4 Evacuation Performance

The evacuation performance of the building is simply determined using Eq. (21) referring to the literature [8]. Here, the larger the  $D_e$ , the higher the evacuation performance of the building.

$$D_e = v_w \times (t_{sp} - t_{ini}) / d \quad (21)$$

where,  $D_e$ : radius of the range to be able to evacuate to the building,  $v_w$ : walking velocity,  $t_{sp}$ : time between occurrence of earthquake and arrival of tsunami,  $t_{ini}$ : time between occurrence of earthquake and start of evacuation,  $d$ : detour ratio.



### 3.5 Overall Judgment

Anti-tsunami Index of Structure ( $I_T$ ) is a new index that uniformly displays anti-tsunami performance using the margin converted into the inundation depth and is defined as Eq. (22).

$$I_T = \frac{\min[\eta_{max1}, \eta_{max2}, \eta_{max3}]}{\eta} \quad (23)$$

If this value is 1.0 or more, it is determined that the anti-tsunami performance of the building is adequate.

## 4. Application

The proposed evaluation method is applied to an existing building, and the effect of different diagnostic levels is discussed.

### 4.1 Description of the Building

The target building is a three-story RC school building whose height is 11.3m and 1<sup>st</sup> floor height is 4.1m, located in Japanese coastal municipality. It has a foundation with 101 high-strength concrete piles (100 piles + 1 test pile) of 500mm diameter and 30m length (15m + 15m, welded joint). It is assumed that it has rectangular plane of 60m × 8m ignoring the protrusion and XX' is the axis of overturning rotation because the tsunami acts from the bottom of this paper in the floor plan shown in Fig. 5. According to the literature [1], the water depth coefficient  $a$  is 2.0 because the building is located within 500m from the coastline (Fig. 6), and there are some greenhouses (not shielding objects) and buildings (shielding objects) between the building and the coastline. The base shear coefficient  $C_B$  is 0.3, and the reduction coefficient depending on the aperture ratio  $\gamma$  is 0.7. The pull-out strength of the pile  $P_i$  is the value based on the strength of the rebar of the pile because it was lower than the ultimate pile capacity (pull-out direction) based on *Notification No.1113 of the Ministry of Land, Infrastructure, Transport and Tourism* of Japan. The assumed tsunami has a maximum inundation depth of 4.69m and a maximum flow velocity of 5.25m/s according to the prediction of inundation by the local government. The time between the occurrence of the earthquake and the arrival of the tsunami  $t_{sp}$  is 19 minutes, and the detour ratio  $d$  is 1.4. It is assumed that there is no collision or scouring. In this paper, the case where detailed information can't be obtained (simple case) is also examined in the primary diagnosis to consider the effect of the difference in the amount of available information on the diagnosis result. Table 1 shows the pile foundation data.

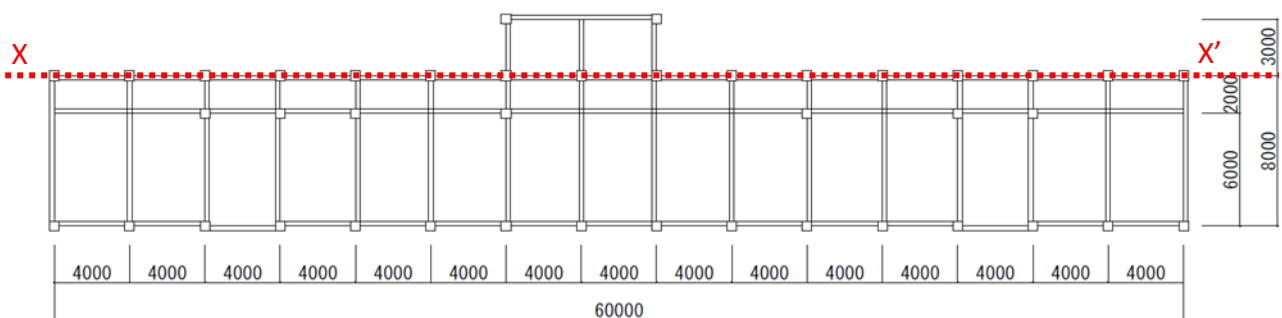


Fig. 5 – Plan of objective building





Fig. 6 – Aerial photograph

Table 1 – Pile foundation data

$Q_{mu}$ : shear force at ultimate bending moment of the pile (kN)	124.6
$Q_{su}$ : shear strength of the pile (kN)	102.6
$P_t$ : pull-out strength of the pile (kN)	349.8
$n_{pi}$ : total number of tension side piles	66
$d_c$ : distance between the fulcrum of the building and the center of gravity of tension side piles (m)	5.8

#### 4.2 Diagnostic Result

Table 2 shows the index values for the surge force and the drag force and the ratio of the allowable inundation depth to the estimated inundation depth calculated by Eq. (17) to (20).

Table 2 – Index value and ratio of allowable inundation depth to estimated inundation depth

	Surge Force						Drag Force					
	$\beta_1$	$\beta_2$	$\beta_3$	$\eta_{max1}/\eta$	$\eta_{max2}/\eta$	$\eta_{max3}/\eta$	$\beta_1$	$\beta_2$	$\beta_3$	$\eta_{max1}/\eta$	$\eta_{max2}/\eta$	$\eta_{max3}/\eta$
Primary Diagnosis (Simple)	0.47			0.75			0.51			0.80		
Primary Diagnosis	0.47	0.57	3.34	0.75	0.76	1.49	0.51	0.57	4.45	0.80	0.76	1.64
Secondary Diagnosis	5.25	2.80	36.12	1.67	1.67	3.31	1.70	1.91	14.84	1.22	1.38	2.46



In the primary diagnosis, the magnitudes of the surge force and the drag force are equal, but the index values for collapse and overturning are larger during the drag force action due to the difference in wave pressure distribution. On the other hand, in the secondary diagnosis, the index values for all failure mechanism are larger during the surge force action because the drag force is larger than the surge force. The index values for sliding and overturning couldn't be calculated in the simple case of the primary diagnosis. The reason is that the buoyancy  $Q_z$  exceeded the weight of the building  $W_b$ , and the building was judged to be lifted by assuming that the building had a spread foundation.

Fig. 7 shows the allowable inundation depth for each failure mechanism. In the primary diagnosis,  $\eta_{max1}$  is the smallest and less than the assumed inundation depth (4.69m), and it is judged that the building collapses. However, in the secondary diagnosis,  $\eta_{max1}$ ,  $\eta_{max2}$ , and  $\eta_{max3}$  all exceed the assumed inundation depth. From Table 2, the index value varies widely for each failure mechanism, but the variation of the ratio of the allowable inundation depth to the assumed inundation depth is smaller.

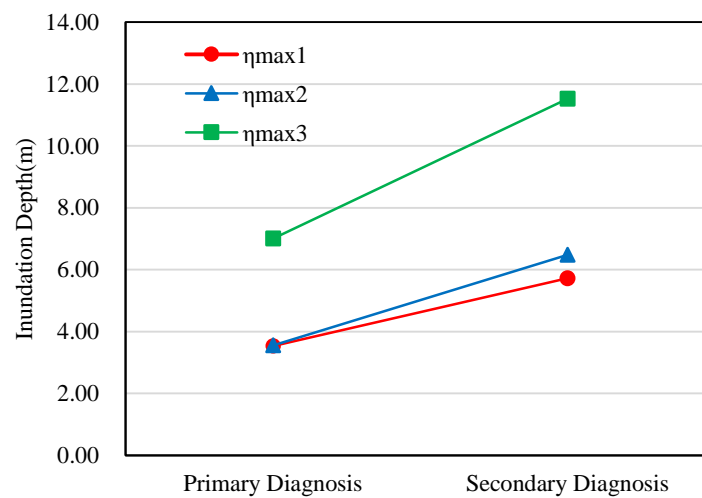


Fig. 7 – Allowable inundation depth for each failure mechanism

Table 3 shows the results of the evaluation of the evacuation performance. In the literature [8], it is assumed that the walking velocity  $v_w$  is 1.0m/s under good damage situations and 0.5m/s under bad damage situations due to the precursory earthquake during the day and multiplied by the correction coefficient 0.8 during the night. Also, the time between the occurrence of an earthquake and the start of evacuation  $t_{ini}$  is assumed to be 10 minutes at night and 5 minutes at daytime. Therefore, cases I to IV are set as shown in Table 3. In case I, it is possible to evacuate to the building within a radius of 154m, but in case 4, people at a distance of 600m from the building can also reach it.

Table 3 – Evacuation performance

Case	I	II	III	IV
Earthquake Damage Situation	Bad	Good	Bad	Good
Occurrence Time of Disaster	Night	Night	Day	Day
$v_w$ (m/s)	0.4	0.8	0.5	1.0
$t_{ini}$ (min)	10	10	5	5
$D_e$ (m)	154	309	300	600



Finally, Table 4 summarizes  $I_T$  and diagnostic results. The anti-tsunami performance of the building was determined to be “failure” in the primary diagnosis, but “acceptable” in the secondary diagnosis.

Table 4 – Diagnostic results

	Allowable Inundation Depth (m)			Lifted / Not Lifted	$I_T$	Result
	$\eta_{max1}$	$\eta_{max2}$	$\eta_{max3}$			
Primary Diagnosis (Simple)	3.53			Lifted		FAILURE
Primary Diagnosis	3.53	3.55	7.01	Not Lifted	0.75	FAILURE
Secondary Diagnosis	5.72	6.48	11.52	Not Lifted	1.22	ACCETABLE

## 5. Concluding Remarks

In this paper, a flowchart for evaluating the anti-tsunami performance according to the available data due to the manpower and budget was proposed, and the effect of difference in diagnostic levels on diagnostic results was considered. The following findings were obtained.

- (1) The formulas of the route (B) in AIJ guideline can evaluate the wave force closer to the actual condition than the formulas of the route (C). However, the wave force obtained by the route (B) tends to be large when the Froude number is large because it is greatly affected by the Froude number. On the contrary, it is noted that the wave force obtained by the route (C) tends to be overestimated when the Froude number is small. When evaluating the wave force using these formulas.
- (2) Proposed anti-tsunami index value is possible to compare margins for each failure mechanism by considering the allowable inundation depths as the dimension of the index.
- (3) By calculating the radius of the range to be able to evacuate to the building, the evacuation performance of the building was verified.
- (4) Displaying the margin as  $I_T$  makes it easier to understand the evaluation results of anti-tsunami performance of existing RC buildings.
- (5) Considering the pile foundation, more accurate buoyancy, and the assumed flow velocity, the allowable inundation depth which was underestimated is more appropriately evaluated, and the anti-tsunami performance of the building which was determined to be “failure” may be “acceptable”.

## 6. References

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