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SEQUENTIAL TIME-HISTORY ANALYSIS OF BUILDING STRUCTURES UNDER EARTHQUAKE AND TSUNAMI LOADS

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ABSTRACT

To develop the sophisticated evaluation method of tsunami-resistant performance for building structures, sequential non-linear time-history response analysis under earthquake and following tsunami loads was performed and the fundamental behavior of building structures was discussed. Then a time-history model for vertical profile of tsunami wave was developed based on the results of fluid analysis using smoothed-particle hydro-dynamics (SPH) method. Applying the proposed time-history model for vertical profile of tsunami wave as the input load after an earthquake load in the sequential non-linear time-history response analysis, the following results were revealed.

(1) Froude number affects the vertical distribution of the maximum tsunami pressure to building structure. And Froude number affects also the vertical distribution of inter-story drift ratio of building structure. The proposed time-history model for vertical profile of tsunami wave shows the results of an approximate vertical distribution of inter-story drift ratio of building structure obtained from the results of SPH fluid analysis.

(2) According to the sequential non-linear time-history response analysis under earthquake load and following tsunami load with the proposed time-history model for vertical profile of tsunami pressure, it is revealed that structural damage by earthquake affects the maximum displacement of building structure by tsunami. It is important to detect the deterioration of fundamental period caused by the seismic damage for detailed tsunami-resistant performance evaluation.

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Sequential Time-history Analysis of Building Structures under Earthquake and Tsunami Loads

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ABSTRACT

To develop the sophisticated evaluation method of tsunami-resistant performance for building structures, sequential non-linear time-history response analysis under earthquake and tsunami loads was performed. Then a time-history model for vertical profile of tsunami wave was developed based on the results of fluid analysis using smoothed-particle hydrodynamics (SPH) method. Applying the proposed time-history model for vertical profile of tsunami wave as the input load after an earthquake load in the sequential non-linear time-history response analysis, the following results were revealed. (1) Froude number affects the vertical distribution of the maximum tsunami pressure to building structure. And Froude number affects also the vertical distribution of inter-story drift ratio of building structure. The proposed time-history model for vertical profile of tsunami wave shows the results of an approximate vertical distribution of inter-story drift ratio of building structure obtained from the results of SPH fluid analysis. (2) According to the sequential non-linear time-history response analysis under the earthquake load and the following tsunami load with the proposed time-history model for vertical profile, it is revealed that structural damage by earthquake load before tsunami load affects the maximum displacement of building structure. It is important to detect the deterioration of fundamental period caused by the seismic damage for detailed tsunami-resistant performance evaluation.

Introduction

A large tsunami was occurred in the 2011 off the Pacific coast of Tohoku earthquake, and a lot of buildings were damaged. After that, the tsunami design load and anti-tsunami design code have been developed in Japan. The Ministry of Land, Infrastructure and Transport (MLIT) revised the structural design requirements of the anti-tsunami buildings as the guideline [1]. According to this guideline, there is a tendency that the required shear force of anti-tsunami design becomes larger than that of seismic design. Therefore, more-detailed and accurate method for anti-tsunami design is required.

In general, tsunami wave force can roughly be divided into an impact wave pressure and a continuous wave pressure. It is necessary to calculate an appropriate tsunami load against the building due to each kind of tsunami wave pressure comprehensively. However recent researches [2], [3] focused on the modelling of the time-history of tsunami load for buildings, an

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appropriate model have not been established for the vertical distribution of the wave pressure acting on the building structure. Therefore, this study tries to propose the modelling of the time-history of tsunami load for buildings with an appropriate vertical distribution of the wave pressure acting on the building structure.

Vertical profile of tsunami wave pressure based on fluid analysis

Outline of fluid analysis method in this study

For the calculation of the tsunami wave pressure, a fluid analysis program (open source smoothed particle hydro-dynamics solver: SPHysics [4]) was employed. It is called as SPH method in this study. In the SPH method, each particle (calculation point) is spatially distributed in the shaped-space defined by the kernel function. And SPH method makes the physical value on the particle within the influence radius smooth. Assuming that an arbitrary particle i with neighboring micro area dx, the particle mass m_i and the density ρ_i, the physical value $f(x)$ is approximated by the Eq. 1. Using Eq.1 and the spatial distribution approximated by Eq. 2, the Navier-Stokes equation is described as Eq. 3.

$$\nabla f(x) \cong \sum_{i=1}^{N} \frac{m_i}{\rho_i} f(x_i) \nabla W(x - x_i, h) \tag{1}$$

$$\begin{aligned} \nabla f(x) &\cong -\int f(x') \nabla W(x - x', h)\, dx' \\ &\cong -\sum_{i=1}^{N} \frac{m_i}{\rho_i} f(x_i) \nabla W(x - x_i, h) \end{aligned} \tag{2}$$

$$\frac{1}{\rho_i} \cdot \frac{\partial \sigma^{\alpha\beta}}{\partial x^{\beta}} = \sum_{i=1}^{N} m_i \frac{\sigma_i^{\alpha\beta} + \sigma_j^{\alpha\beta}}{\rho_i \rho_j} \left(\frac{\partial W_{ij}}{\partial x^{\beta}} \right) + b_j \tag{3}$$

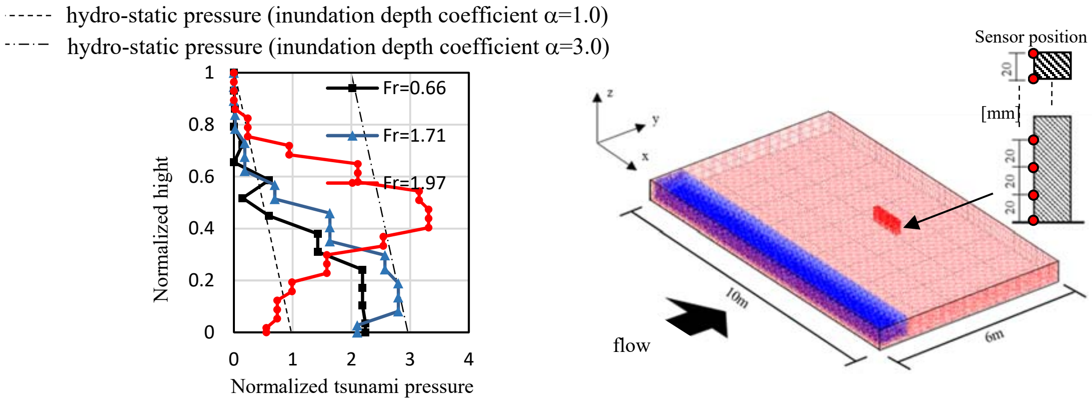
where, W: weight function, h: smoothing length, σ: stress tensor, α, β: direction component of position vector, i, j: particle number, b: interaction term.

Sample results of fluid analysis

Through a fluid analysis simulating a dam break test, a vertical distribution profile of tsunami pressure was obtained. Fig. 1 shows the relationship between the pressure height normalied by the maximum inundation depth and the pressure normalied by the hydro-static pressure at the lowest layer with the same inundation depth. Froude number Fr is also defined by Eq. 4.

$$F_r = u_i / \sqrt{g h_i} \tag{4}$$

where, u_i: flow velocity (m/s) at time i, g: gravitational acceleration(m/s^2), h_i: inundation depth (m) at time i. As the Froude number Fr is larger, the height of maximum wave pressure observed at the upper story of buildings. On the other hand, as the Froude number Fr is smaller or after the impact wave pressure, the height of maximum wave pressure observed at the lower story of buildings.



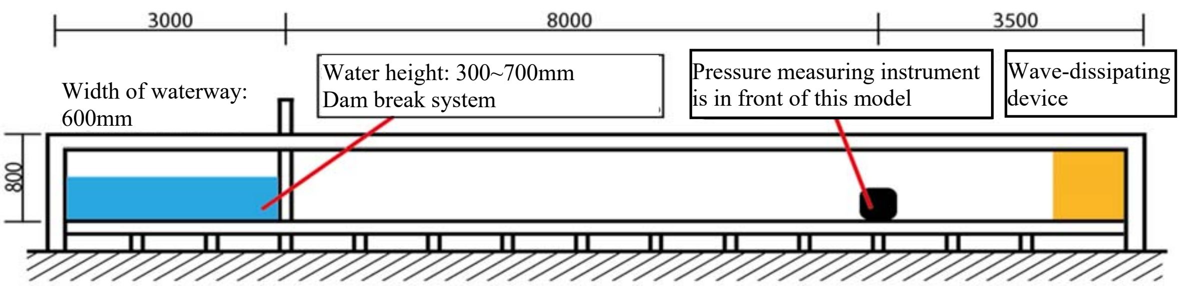
(a) at the maximum pressure (b) outline of dam break test

Figure 1. Sample of vertical distribution profile of the tsunami wave pressure [3]

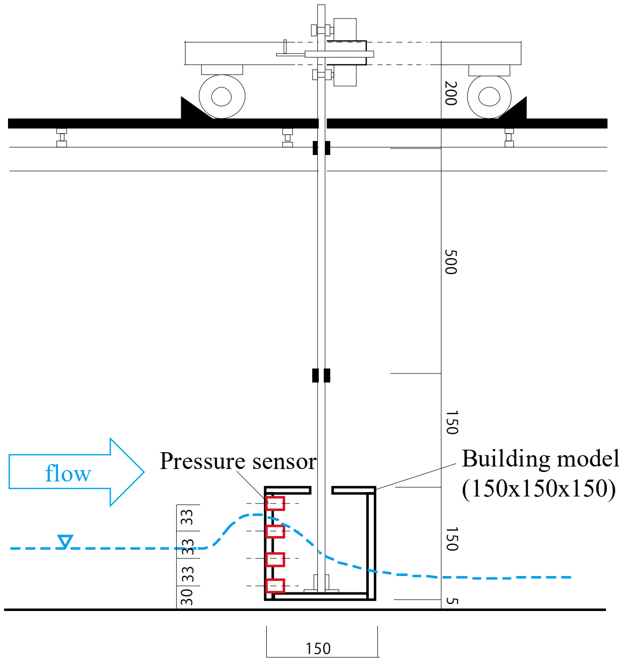
For the verification of fluid analysis, some case of the fluid analysis which simlates the simple hydraulic experiment [5] are duscussed.. In the investigated case shown in Table 1, the water storage height was changed from 0.3(m) to 0.7(m) (maximum flow depth from 1.2(m) to 1.8(m)) as a parameter. The experimental outline is shown in Fig. 2. The maximum wave pressure and maximum fluid velocity were almost equal between analytical results and experimental results. As shown in Fig. 3, the time-history by fluid analysis results roughly approximate the experimental results without the influence of ignoring the devices such as propeller anemometer.

Table 1. Comparison between fluid analysis results and experimental results

CASE	Water storage height (m)	Max. wave pressure (kN/m^2)		Max. fluid velocity (m/s)	
		Analysis	Exp.	Analysis	Exp.
CASE1	0.3	2.12	2.16	1.81	1.65
CASE2	0.4	3.27	3.30	2.18	2.04
CASE3	0.5	4.83	4.06	2.63	2.73
CASE4	0.6	4.96	4.68	2.84	2.86
CASE5	0.7	5.99	6.32	3.24	3.47

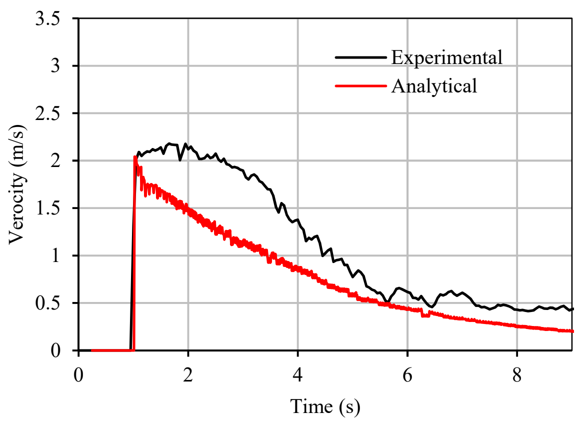


(a) Overview of hydraulic experimental system [5]

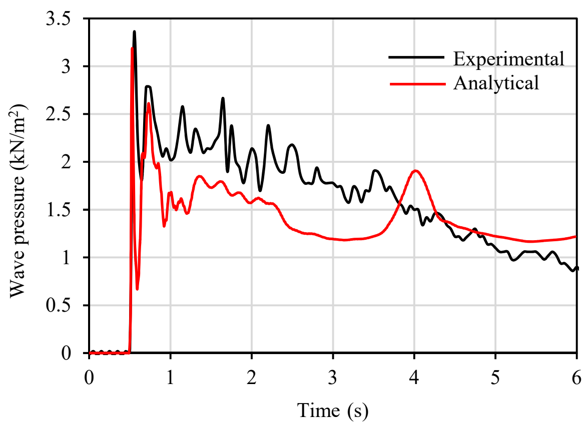


(b) Elevation of building model and pressure sensor in the experiment [5]

Figure 2. Outline of Hydraulic experiment [5]



(a)fluid velocity



(b)wave pressure

Figure 3. Time-history of fluid velocity and wave pressure obtained from analytical and experimental results

Modeling of the time-history of tsunami load for buildings

A previous model of the time-history of tsunami load for buildings [3]

Suzuki et. al. [3] proposed a model of time-history of tsunami load as shown in Fig. 4. It is assumed that the surge wave acts as an impact wave pressure. And the wave pressure Q_1 and Q_2 are calculated using Eq. 5 and 6 respectively.

$$Q_1 = \rho g(\alpha h - z) \tag{5}$$

$$Q_2 = \frac{1}{2}\rho \cdot C_D \cdot u^2 \tag{6}$$

where, Q_1 is the surge wave pressure (kN/m^2), ρ is the unit mass of sea water (tf/m^3), g is the gravitational acceleration (m/s^2), α is the inundation depth coefficient, h is the inundation depth (m), z is the height from the ground surface, Q_2 is the wave pressure after an impact pressure (kN/m^2), C_D is the drag coefficient, u is the tsunami velocity(m/s).

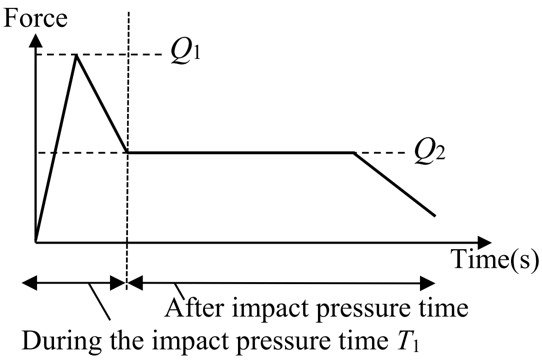


Figure 4. A model of time-history of tsunami load for buildings [3]

In this model, the vertical distribution profile of the wave pressure is assumed to be a triangular distribution during the impact pressure time and to be an uniform distribution after the impact pressure time. It cannot reflect the vertical distribution profile such as fluid analysis result which is depend on the Froude number Fr.

A new proposed time-history model for vertical profile of tsunami wave pressure

The time-history of vertical distribution profile as shown in Fig. 5 is proposed in this study. Based on the preliminary study, tsunami force distribution formula can be expressed by Eq. 7 when the Froude number Fr is over 1. The relationship between Fr and the peak wave pressure in the vertical distribution $p_{max}(t)$ is expressed by Eq. 8. The relationship between Fr and the peak wave pressure location $\mu(t)$ is expressed by Eq. 9. The variable $\sigma(t)$ that defines the shape of the vertical distribution profile based on the Froude number Fr is expressed by Eq. 10. During t=0 to T_1, $\mu(t)$ increases to a normalized height 1 constantly. The maximum wave pressure p'_{max} occurs when $t = T_1/2$. When t=0 and t=T_1, $p_{max}(t)$ is the same as $p'_{max}/2$. The tsunami wave pressure at $t \leq T_1/2$ is expressed by the Eq. 11, and that at $T_1/2 \leq t \leq T_1$ is expressed by Eq. 12. When $t \geq T_1$, the tsunami wave pressure was calculated by Eq. 13.

In the case where the Froude number Fr is smaller than 1, the wave pressure is expressed by Eq. 5 during the $t \leq T_1/2$, and the wave pressure is expressed by Eq.12 during the $T_1/2 \leq t \leq T_1$. When $t > T_1$, the tsunami wave pressure was calculated by Eq. 6.

Table 2 shows the tsunami wave pressure distribution formula in each time categorie and Froude number Fr.

$$p'(h',t) = p_{\max}(t)\times\exp\left(-\frac{\{h'-\mu(t)\}^2}{2\sigma(t)^2}\right) \qquad (h'\le 0.5)$$

$$= p_{\max}(t)\times\exp\left(-\frac{\{h'-\mu(t)\}^2}{2\sigma(t)^2}\right)\times 2(1-h') \qquad (h'>0.5) \tag{7}$$

$$p_{\max}(t) = -\frac{4\times 0.913\exp(0.655F_r)}{T_1^2}\times\left(t-\frac{T_1}{2}\right)^2 + 0.913\exp(0.655F_r) \tag{8}$$

$$\mu(t) = \frac{2\{1-8.0\times10^{-5}\exp(4.4F_r)\}}{T_1}t + \{2\times8.0\times10^{-5}\exp(4.4F_r)-1\} \tag{9}$$

$$\sigma(t) = \frac{1}{\sqrt{2\pi}p_{\max}}\times\frac{4}{F_r} \tag{10}$$

$$Q_1 = p'(h',t)\rho g h_{\max} \tag{11}$$

$$Q_m = (1-\beta)\times Q_1 + \beta\times Q_2 \quad (\text{where, } \beta\text{=0~1}) \tag{12}$$

$$Q_2 = \frac{1}{2}\rho\cdot C_D\cdot u^2 \tag{13}$$

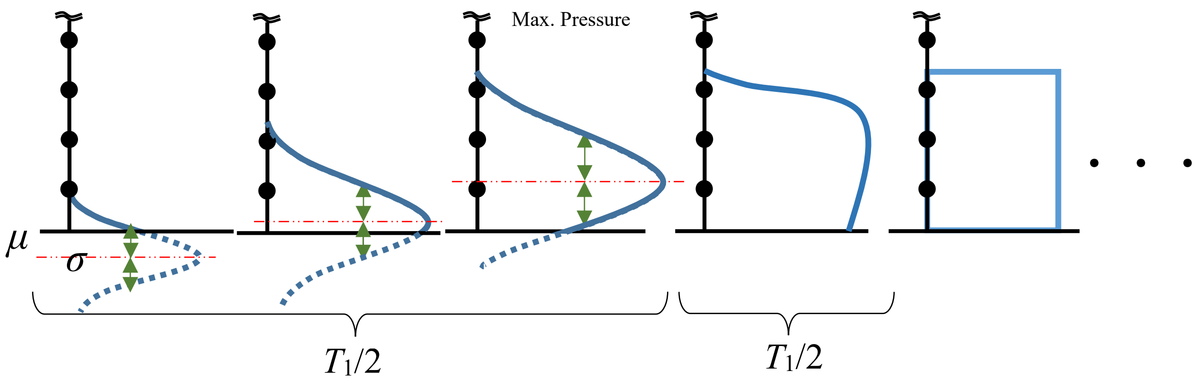


Figure 5. Time-history model of vertical profile of tsunami wave pressure

Table 2. Tsunami wave pressure distribution formula in each time categories and *Fr*

	Surge pressure period $0\le t\le T_1/2$	**Transition period** $T_1/2\le t\le T_1$	**After impact pressure period** $T_1<t$
$Fr>1$	$Q_1 = p'(h',t)\cdot\rho g h'_{\max}$	$Q_m=(1-\beta)\times Q_1+\beta\times Q_2$ where, $\left(\beta=\frac{t-T_1/2}{T_1/2}\right)$	$Q_2=\frac{1}{2}\rho\cdot C_D\cdot u^2$
$Fr\le 1$	$Q_1=\rho g(h'_{\max}-h')$		

Verification of a proposed model by non-linear time-history response analysis

Outline of analysis model of building

Reinforced concrete (RC) building is considered to verify the proposed model. The building has seven story that each height is 3(m) and each weight is 500(tf). The floor plan is rectangle, and the area is 20(m)×20(m). It is assumed that this building has a pile foundation structure and the sliding or over-turning against the tsunami wave does not occur. And the opening ratio at the building surface is assumed to be 0.

In the non-linear time-history response analysis, the structure is modeled as a muiti degree of freedom spring-mass system (MDOF). The skeleton curve is a trilinear type, and the cracking point strength Q_c is set to 1/3 times of the yield strength Q_y. The yield displacsement δ_y of each story assumed to be 1/200 (rad.) in terms of inter story drift ratio. The crack displacement δ_c is set to 1/10 times of the yield displacement δ_y. The stiffness reduction rate at yield point is 0.3, and the stiffness after yield is 1/1000 of the initial stiffness. Takeda model is employed for the hysteresis model. The damping is proportional to the tangent stiffness, and the viscous damping constant is 0.05. The shear force of each story is calculated by Eq. 14.

$$Q_i = C_i \cdot \sum W_i \tag{14}$$

where, Q_i is the shear force (kN) at the i story, C_i is the shear force coefficient, and ΣW_i is the total building mass (kN) above the i story. The shear force coefficient of each story is proportional to the A_i distribution of the Building Standard Law of Japan and the base shear force coefficient C_0 is set to 0.55.

Comparison of response of MDOF system applying the previous model, proposed model, and the fluid analysis results as input loads

In the case of affecting the tsunami load without earthquake

In this study, Suzuki's time-history model for tsunami load [3] as a previous model, a new proposed time-history model for tsunami load with vertical distribution profile equation, and a time-history obtained from fluid analysis as tsunami load are performed in MDOF system. Froude's scaling law is employed to the results of fluid analysis of scaled model, and full-scaled load is applied to the MDOF system. The calculation time step is 0.001(s), and the calculation time starts at the t=0(s) as the time of reaching the tsunami to the building. Table 3 shows the cases of tsunami wave in this study.

Table 3. Analytical cases in this study

Case	Froude number F_r	Max. inundation height h(m)	Impact pressure time T_1(s)
Case1	0.66	0.22	0.31
Case2	1.71	0.26	0.25
Case3	1.90	0.32	0.23

Figure 6(i) shows the comparison of the maximum response of MDOF under only the tsunami load obtained from the above-mentioned models' analysis. From Fig. 6(i), the results of a new proposed model approximate the results of inputting the time-history obtained from fluid analysis to MDOF as tsunami load. In particular to case 1, a new model's results fairly approximate the results of inputting the time-history obtained from fluid analysis to MDOF as tsunami load more than a previous model's results, however vertical distribution profile of tsunami pressure is almost the same between a new proposed model and a previous model (Suzuki's model) in the case of the Froude number is less than 1 ($Fr < 1$). It indicates that the interpolation formula during the transition period $T_1/2 \leq t \leq T_1$ affects the results.

In addition, case 3 shows that the results of a new proposed model quite approximate the results of inputting the time-history obtained from fluid analysis to MDOF as tsunami load. In the case of the Froude number is more than 1 ($1 \leq Fr$), vertical distribution profile of tsunami pressure is quite different between a new model and a previous model (Suzuki's model). It indicates that the tsunami load obtained from fluid analysis can be represented by the new model in terms of not only interpolation formula but also vertical distribution profile of tsunami pressure.

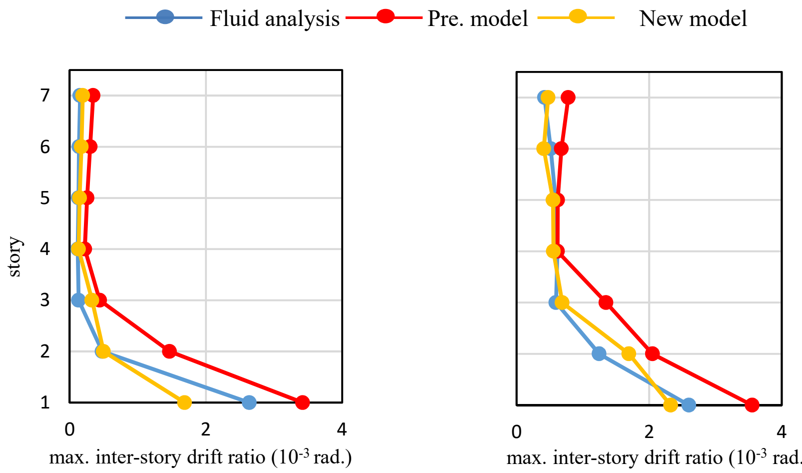
In the case of affecting the tsunami load after the earthquake

Typically, the building suffered the strong earthquake before tsunami load. Therefore, the earthquake record is applied to the MDOF system before applying the tsunami load. Assuming that the building is damaged by earthquake, the fundamental characteristic of structure would be changed before applying the tusnami load. In this study Tohoku 1978 (NS) is employed as the earthquake record in order to compare the result of the reference [4].

Figure 6(ii) shows the comparison of the maximum response for MDOF system under the earthquake and following tsunami load in each case. From Fig. 6(ii), the response of a new proposed model approximates the response of inputting the time-history obtained from fluid analysis to MDOF as tsunami load after an earthquake more than a previous model. But it seems to be not so much approximated than the case of only the tsunami load.

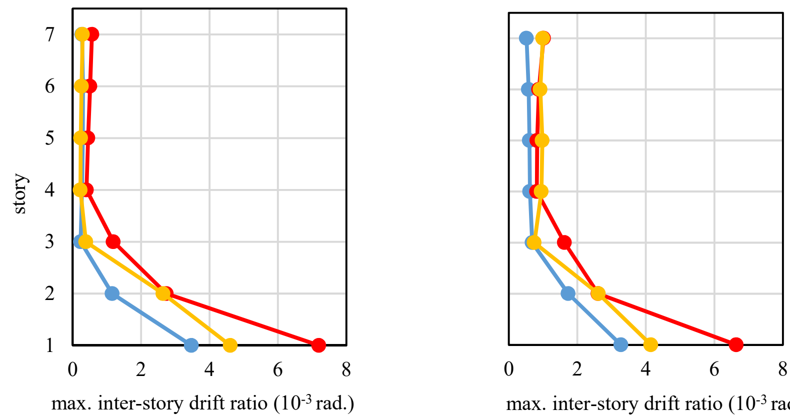
Therefore, in order to investigate the influence of the damage caused by earthquake to the tsunami response, the relationship between the natural period of the structure (or damaged structure) and the impact pressure duration T_1 is examined. Figure 7 shows the relationship between the ratio Rc/Rs. Rc is the maximum inter-drift ratio at the 1st story due to the tsunami load after the earthquake load. Rs is the maximum inter-drift ratio at the 1st story due to only the tsunami load. Note that the impact pressure duration T_1 is varied from 0.1(s) to 1.0(s) in a parametric study, however the impact pressure duration T_1 is 0.23(s) in Case 3 shown in Table 3.

The natural period of the structure which is not damaged by the earthquake is 0.370(s). And the natural period of the strucutre damaged by the earthquake is 0.614(s) in this study. The ratio of Rc/Rs in Fig. 7 indicates that the response due to tsunami load increases when impact pressure duration T_1 is getting closer to the natural period of building (or natural period of damaged building). It is important to detect the deterioration of fundamental period caused by the seismic damage before tsunami response anlysis.



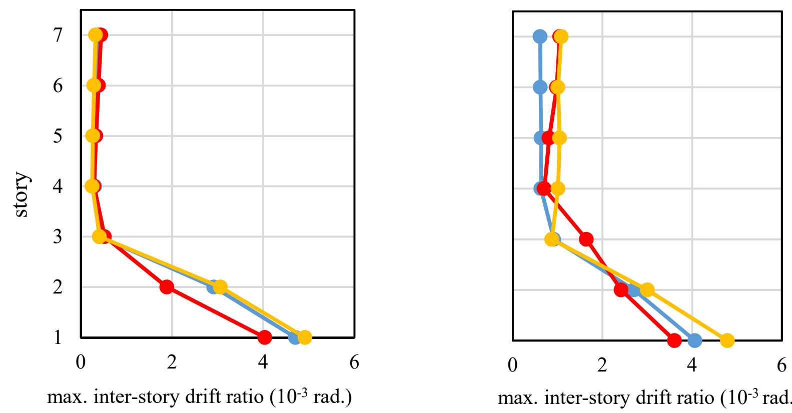
(i) under tsunami load (ii) under tsunami load after earthquake

(a) Case 1



(i) under tsunami load (ii) under tsunami load after earthquake

(b) Case 2



(i) under tsunami load (ii) under tsunami load after earthquake

(c) Case 3

Figure 6. The comparison of the maximum response for MDOF (i) under each tsunami load model and (ii) under each tsunami load model after earthquake

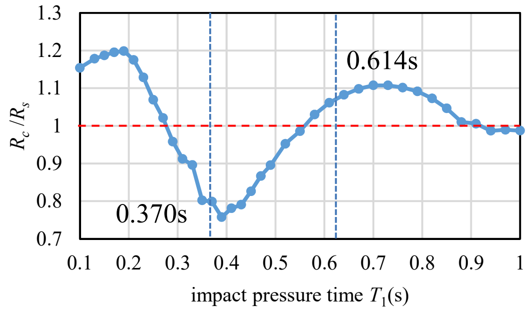


Figure 7. The ratio of *Rc*/*Rs* vs. impact pressure duration T_1

Conclusions

A new proposed time-history model for vertical profile of tsunami load is verified to compare to a previous time-history model for tsunami load [3] and the SPH fluid analysis result as tsunami load. The main conclusions obtained in this research are summarized below.

(1) The results of a new proposed model approximate the results of inputting the time-history obtained from fluid analysis to MDOF as tsunami load.

(2) According to the sequential non-linear time-history response analysis under the earthquake load and the following tsunami load, it is revealed that structural damage by earthquake affects the maximum displacement of building structure caused by the following tsunami load.

(3) The response due to tsunami load increases when impact pressure duration T_1 is getting closer to the natural period of building (or natural period of damaged building). It is important to detect the deterioration of fundamental period caused by the seismic damage before tsunami response anlysis.

A new proposed time-history model for vertical profile of tsunami load is determined to model the specific results obtained from fluid analysis. In the future, it is necessary to reveal the mechanism of changing the vertical profile of tsunami load due to the Froude number.

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