COMPARATIVE STUDY OF EXPERIMENTS AND ANALYSES ON TSUNAMI GENERATION BY HORIZONTAL CRUSTAL DEFORMATION

Y. Michiguchi[1], Y. Mitobe[2], H. Sugino[3] and H. Tanaka[4]

[1] *Researcher, Regulatory Standard and Research Division, Secretariat of Nuclear Regulation Authority (S/NRA/R) , yoko_michiguchi@nsr.go.jp*
[2] *Associate Professor, Department of Civil and Environmental Engineering, Tohoku Gakuin University, y_mitobe@mail.tohoku-gakuin.ac.jp*
[3] *Senior Researcher, Regulatory Standard and Research Division, Secretariat of Nuclear Regulation Authority (S/NRA/R) , hideharu_sugino@nsr.go.jp*
[4] *Professor, Department of Civil Engineering, Tohoku University, hitoshi.tanaka.b7@tohoku.ac.jp*

Abstract

To evaluate the effects of horizontal crustal displacements along a trench on the initial displacement distribution of water on a sea surface, we conducted hydraulic physical experiments by introducing a movable slope (gradient *1/10*) to simulate actual tsunami phenomena; then, we conducted numerical analyses using a tsunami simulation code and compared the numerical results with those observed from the hydraulic experiments. The water-level rise was measured using ultrasonic water-level meters during the horizontal movement of the slope under water. To gain a more thorough understanding, we varied the water depth and parameters of the slope's movement, such as the total horizontal displacement, velocity, and acceleration. The numerical analyses, based on nonlinear long-wave theory, were conducted using all the same conditions used during the hydraulic experiments. In the numerical analysis, the equation proposed by Tanioka and Satake (1996) was used for the calculation of the water-level rise due to the horizontal displacements of the slope. In both the hydraulic experiment and numerical analysis, the maximum tsunami height became greater with larger horizontal velocities of slope movement and with lower water depth. The location of the maximum tsunami height was almost at the center of the slope in the experimental and analytical results. To investigate the dominant parameters to explain the maximum tsunami height, we further conducted a non-dimensional analysis. Relative tsunami height (H_{max}/dy), which is defined as the tsunami height (H_{max}) normalized by the total height of the net rise of the seabed level due to the horizontal displacement of the slope (dy), was compared with the risetime (Tr: the time for the horizontal displacement of the slope) normalized by the time of long-wave propagation over the slope length ($T = L/c$, L: slope length, c: celerity of the long-wave). The relative tsunami height (H_{max}/dy) decreased with larger dimensionless risetimes (Tr/T) in the hydraulic experiments. As the water level rise due to the horizontal slope displacement directly occurs only on the slope itself, the generated waves started to propagate toward the outer areas of the slope during the rise of the water level. When the risetimes were too long relative to the time scale of the wave's propagation, the maximum water level was not able to reach the net rise of the seabed's elevation. This non-dimensional analysis suggested that the maximum tsunami height could be estimated using the dimensionless risetime parameter. Although this trend of maximum tsunami height versus dimensionless risetime also appeared in the numerical analysis, the relative tsunami height in the hydraulic experiment exceeded 1, which was not a possibility in the numerical analysis. Further, the delay in the water-level rise relative to the horizontal displacement was observed in the hydraulic experiment but not in the numerical results. Therefore, we need further experiments and discussions to understand the characteristics of the waves generated by underwater horizontal seabed displacements and refine our numerical simulations.

Keywords: tsunami earthquake, tsunami height, hydraulic experiment, tsunami propagation analysis

1. Introduction

Tsunamis due to inter-plate earthquakes are generated by vertical and horizontal deformations of the ocean bottom associated with crustal movement. In conventional tsunami evaluations, the initial displacement distribution of the water at the sea surface are configured using only vertical deformations because horizontal deformations are negligibly small (Tanioka and Sateke, 1996)[1]. However, Tanioka and Satake (1996) [1] indicated that the net vertical rise of the ocean bottom due to horizontal displacement affects the initial displacement distribution of the water at the surface. This conclusion was reached based on tsunami propagation analyses of observed waveforms at the coasts of previous tsunamis, such as "tsunami earthquakes" generated along oceanic trenches. The "Tsunami Recipe", which was published in 2017 by the Earthquake Research Committee in Headquarters for Earthquake Research Promotion[2], suggested that consideration should be given to the net vertical rise of the ocean bottom due to horizontal displacement in addition to vertical deformations when modelling the initial displacement distribution of water at the sea surface for tsunami propagation analyses.

However it is difficult to observe the initial displacement distribution of water at the sea surface due to crustal movement around a trench directly, and there are no current methods that allow for the direct estimation of the net vertical rise of the ocean bottom due to horizontal displacement. Therefore, to evaluate the effects of horizontal crustal deformation along a trench on the initial displacement distribution of the water at the sea surface, we conduct the hydraulic experiments by introducing a movable slope (gradient of *1/10*) to simulate actual tsunami phenomena. Then, we conduct numerical analyses using a tsunami simulation code, and compare the results with those observed from the hydraulic experiments.

2. Numerical analyses of one-dimensional horizontal tsunami propagation

2.1 Analysis method and initial conditions

In this study, we conduct numerical analyses of one-dimensional horizontal tsunami propagation under the same conditions as the hydraulic experiments conducted by Michiguchi et al. (2019) [3]. Fig. 1 shows the analysis model, which was generated in consideration of the hydraulic experiment system shown in Fig. 2.

The hydraulic experiment was designed at a scale of 1/28,900 to the assumed actual submarine geography based on submarine geography of several oceanic trenches around Japan, and consisted of a channel that was 400-cm long, 26.5-cm wide, and 49-cm deep, a slope of 17-cm height and a *1/10* gradient for mimicking submarine geography, and an actuator to control the slope. In the hydraulic experiments, the water level was measured using ultrasonic water-level meters during the horizontal movement of the slope under water. The ultrasonic water-level meters were installed at 12 measurement points. To gain a more understanding of the factor which makes water level high, we varied the water depth and several parameters

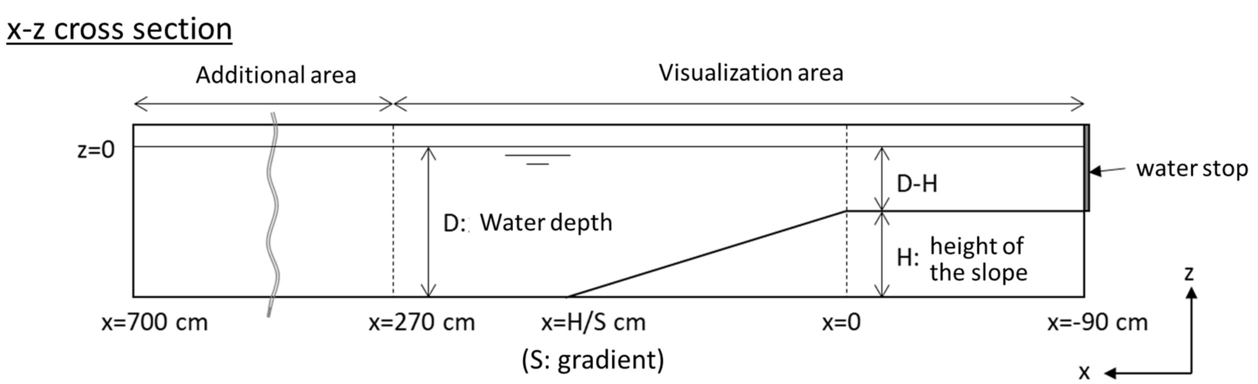


Fig. 1 - Analysis model

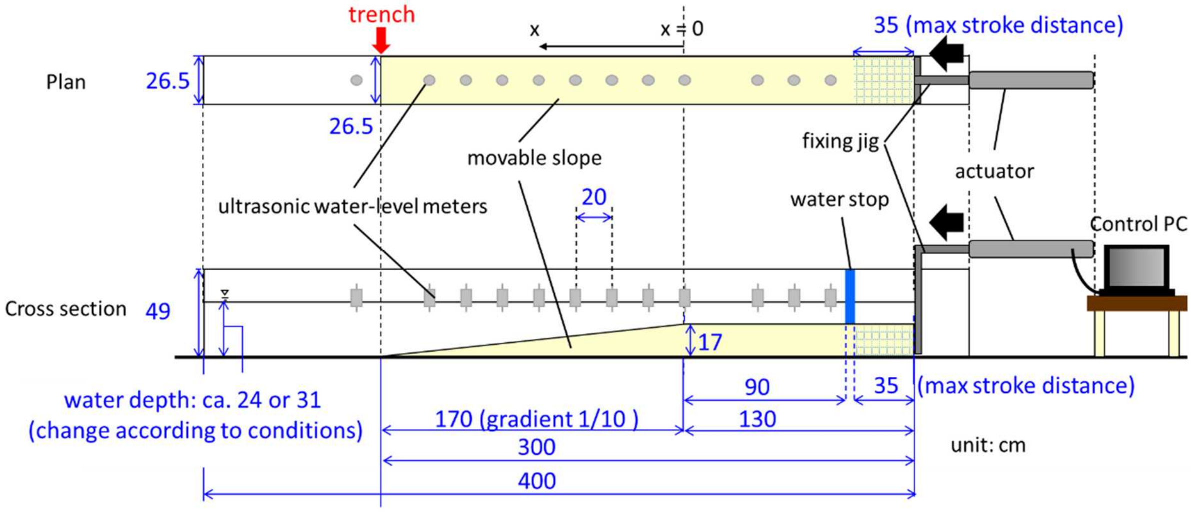


Fig. 2 - Schematic of the hydraulic experiment

Table 1 Conditions in the hydraulic experiment

Case No.	Acceleration (cm/s^2)	Velocity (cm/s)	Total horizontal displacement (cm)	Risetime(s)	Water depth (cm)
case1 (base case)	50	20	20	1.4	24
case2	50	15	20	1.63	
case3	50	25	20	1.3	
case4	30	20	20	1.53	
case5	100	20	20	1.3	
case6	50	20	10	0.9	
case7	50	20	30	1.9	
case8	50	20	20	1.4	31
case9	50	15	20	1.63	
case10	50	25	20	1.3	
case11	30	20	20	1.53	
case12	100	20	20	1.3	
case13	50	20	10	0.9	
case14	50	20	30	1.9	

of the slope's movement, such as the total horizontal displacement, velocity, and acceleration. Table 1 indicates the 14 conditions tested in the hydraulic experiments, and Fig. 3 shows the definition of each condition in the hydraulic experiments.

We conducted numerical analyses of one-dimensional horizontal tsunami propagation using non-linear wave theory. Eq. (1) and (2) are the equation of continuity and the equation of motion, respectively:

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} = 0 \tag{1}$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{gn^2}{D^{7/3}}M^2 = 0 \tag{2}$$

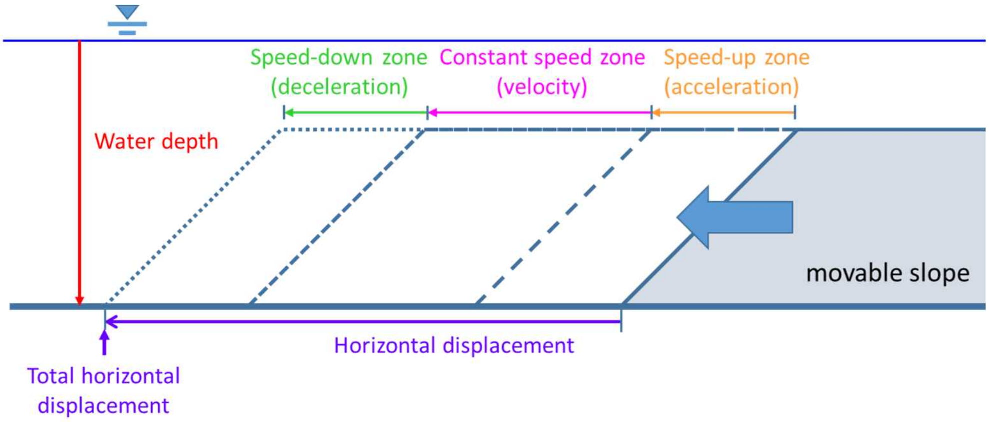


Fig. 3 - The hydraulic experimental conditions

where x is the horizontal axis, M is the discharge flux in the x-direction (m^2/s), D is the total water depth (m), η is the vertical displacement of water surface above the still water surface (m), g is gravitational acceleration (m/s^2), and n is Manning's roughness ($m^{-1/3}s$). In this study, n is 0.025 $m^{-1/3}s$.

The initial displacement data of the water at the sea surface due to horizontal displacement in the numerical analyses is given the net vertical rise of the bottom due to the horizontal displacement of the slope obtained in the hydraulic experiments reconstructed by time grid Δt=0.0005 s. The value of u_h in Eq. (3), i.e. the net vertical rise of the ocean bottom due to the horizontal displacement, was found following Tanioka and Satake (1996) [1] (their Eq. (4)):

$$u_v = u_z + u_h \tag{3}$$

$$u_h = u_x \frac{\partial H}{\partial x} \tag{4}$$

where u_v is the total vertical displacement caused by crustal movement (m), u_z and u_h are the vertical displacement and the horizontal displacement due to the crustal movement (m), respectively, and H is the water depth (m).

2.2 Results of numerical analyses

Fig. 4 shows the maximum water level determined via the numerical analyses versus the measurement points where the horizontal distance from the top of the slope. Fig. 5 is in case of the hydraulic experiment. The top of both figures indicate the conditions where we changed only the velocity of the slope, the middles indicate the conditions where we changed only the acceleration of the slope and the bottoms indicate the conditions where we changed only the displacement of the slope.

In the hydraulic experiment where we changed only the condition of velocity, it was found that the faster the velocity was, the higher the maximum water-level became. When only the condition of acceleration was changed, there was almost no difference in the maximum water level at each measurement point. When only the condition of displacement was changed, the larger the displacement was, gradually smaller the differences in the maximum water-level is. The location of the maximum water level was almost at the center of the slope (the horizontal distance from the top of the slope was around 80 cm), which was found both in the hydraulic experiments and the numerical analyses. When it was evaluated by only the difference in the water depth, the water level in the deep water depth is about 90 % on average of that in the shallow depth.

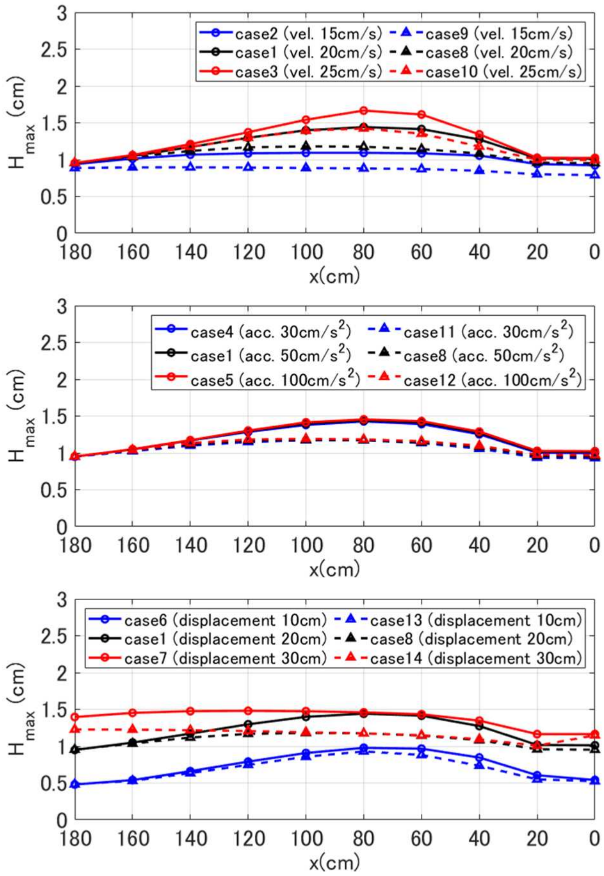


Fig. 4 - Maximumanalysis water-level at each measurement point. Upper panel: velocity changes only; middle panel: acceleration changes only; and lower panel: displacement changes only.

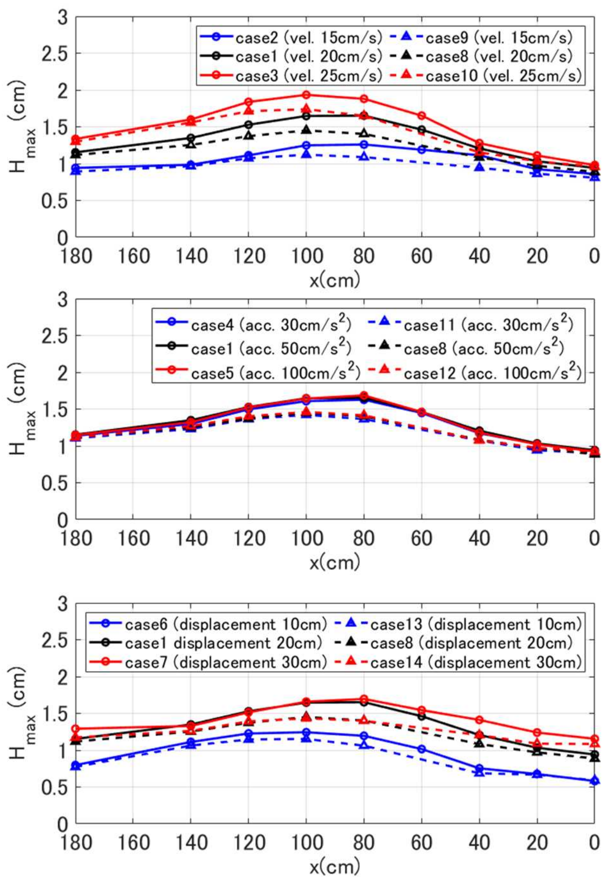


Fig. 5 - Maximum experiment water-level at each measurement point. Upper panel: velocity changes only; middle panel: acceleration changes only; and lower panel: displacement changes only.

However, the maximum water levels found from the numerical analyses were about 80 % of those found in the hydraulic experiments. Fig. 6 indicates the time history of the water level and the total net rise of the ocean bottom due to the horizontal displacement of the slope at measurement points x＝20, 60, 100 and 140 cm for Case 1. The waveforms and the relationship between the water level and total height according to analytical results were similar to thoses found from the experimental results. However, the experimental results showed that the time when the water level started to rise was delayed compared with the time when the slope begin to move as the water depth deepened toward the left side of the figure. In contrast, the analytical results indicated that the time when water level started to rise and the time when the slope began to move were the same. This time difference between the numerical analyses and the hydraulic experiments suggests that conventional tsunami analysis methods are not able to reproduce the time delay when the net rise of the ocean bottom level due to the horizontal displacement of the slope appears.

Fig. 7 indicates the time history of the water level and the total net rise of the ocean bottom due to the horizontal displacement of the slope at measurement points x＝100 cm for Cases 1, 3 and 6. The water level is 40‐100% of the total net rise of the ocean bottom due to the horizontal displacement of the slope. Only for

Case 6 in the hydraulic experiment was the water level higher than the total net rise of the ocean bottom due to the horizontal displacement of the slope. This result also suggests that conventional tsunami methods are unable to reproduce this phenomenon.

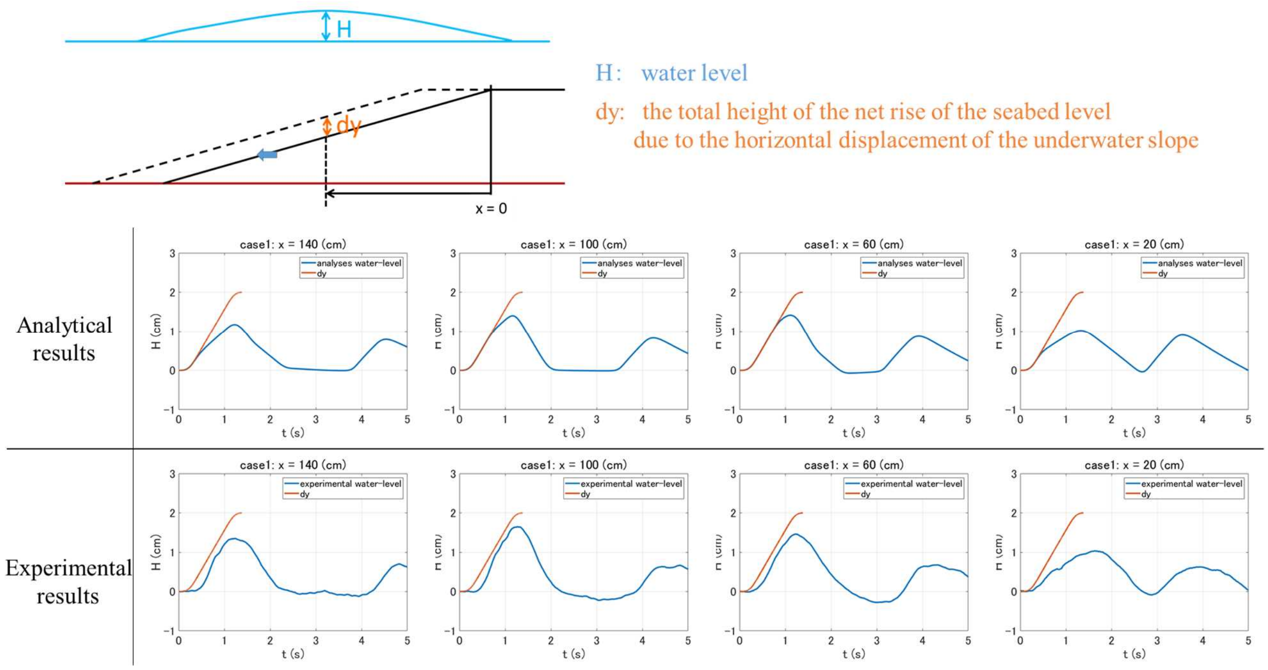


Fig. 6 - Water level and the total net rise of the ocean bottom level due to the horizontal displacement of the slope at measurement points x＝20, 60, 100 and 140 cm for Case 1. Upper panel: analytical results; lower panel: experimental results. The left-hand side in the figure shows the bottom of the slope, and the right-hand side shows the top of the slope.

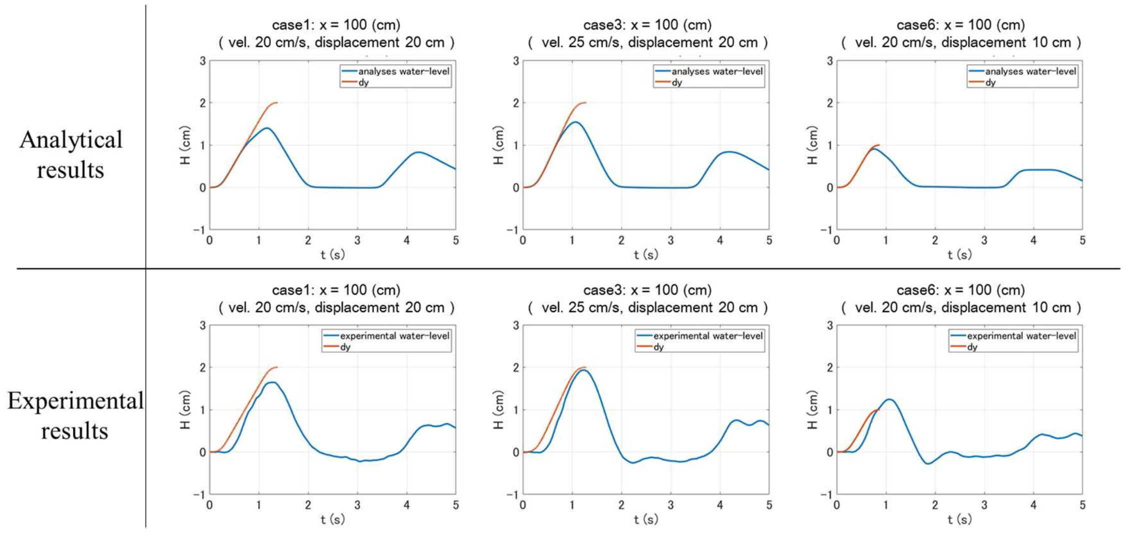


Fig. 7 - Water level and the total net rise of the ocean bottom level due to the horizontal displacement of the slope at measurement point x＝100 cm in Cases 1, 3 and 6. Upper panel: analytical results; lower panel: experimental results.

2.3 Non-dimensional analysis

To investigate the dominant parameters that explain the maximum tsunami height, we conducted a non-dimensional analysis of the analytical results, similar to that performed by Michiguchi et al. (2019) [3]. Fig. 8 indicates the relative tsunami height (H_{max}/dy), which is defined as the tsunami height (H_{max}) normalized by the total height of the net rise of the seabed due to the horizontal displacement of the slope (dy), versus the dimensionless risetime (Tr/T), which is defined as the risetime (Tr: the time for the horizontal displacement of the slope: see Table 1) normalized by the time of long-wave propagation over the slope length ($T = L/c$, L: slope length, c: celerity of the long-wave) (Kajiura, 1970) [4].

In the non-dimensional analysis we obtained two regression curves: $y = e^{(-x/2.69)}$ and $y = 2.37e^{(-x/1.03)}$, which correspond to the analytical and experimental results, respectively.

Overall, we found that the relative tsunami height (H_{max}/dy) decreased with larger dimensionless risetimes (Tr/T). However, the analytical value of H_{max}/dy was lower than its experimental equivalent for dimensionless risetimes. In particular, the difference of H_{max}/dy between the analytical and experimental curves was larger for smaller dimensionless risetimes. We note that the relative tsunami height in the hydraulic experiment exceeded 1, which represented conditions what were not possible to explore with the numerical analysis. This means that the analytical results are not able to reproduce all of the experimental results.

We also calculated the approximate dimensionless risetimes of past tsunamis and plotted them in Fig. 8. Most of the data are plotted between 0–1.1 for dimensionless risetimes, where it is seen that the difference between the analytical and experimental curves of H_{max}/dy is large.

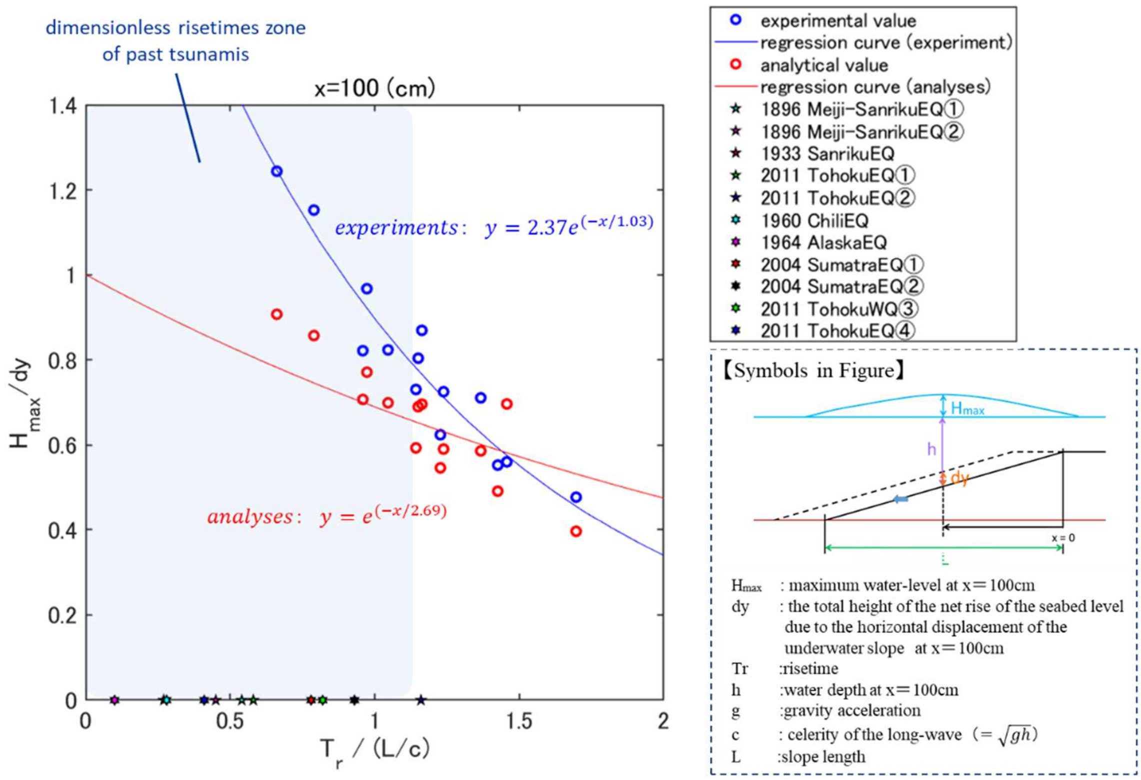


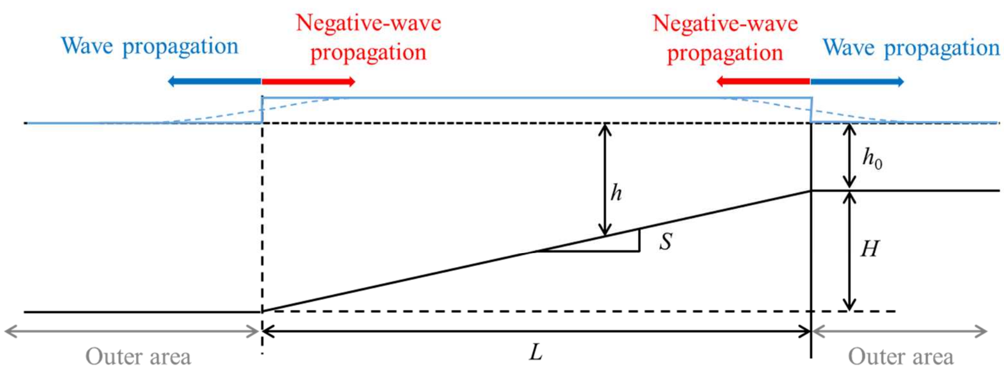
Fig. 8 - H_{max}/dy versus the dimensionless risetime ($Tr/(L/c)$)

3. Summary and Discussion

3.1 The dominant parameters that explain the maximum tsunami height

In both the numerical analyses and the hydraulic experiments, the maximum water level became greater with larger horizontal velocities of the slope and with lower water depths (Case 3). The location of the maximum water level was almost at the center of the slope in the hydraulic experiments and the numerical analyses. The non-dimensional analysis also suggested that the maximum tsunami height could be estimated using the dimensionless risetime parameter. The relative tsunami height (H_{max}/dy) decreased with larger dimensionless risetimes (Tr/T), meaning that the risetime of the slope and the time of long-wave propagation influenced the maximum tsunami height.

Fig. 9 shows the effect of wave propagation on the maximum water level. As the water level on the slope rose due to the horizontal displacement of the slope, the generated waves started to propagate toward the outer areas of the slope. Therefore it is considered that the water level on the slope are suppressed. When the risetimes were too long relative to the time scale of the wave propagation, the maximum water level was not able to reach the net rise of the seabed's elevation. The non-dimensional analysis suggested that the maximum tsunami height could be estimated using the dimensionless risetime parameter.



H:	height of the slope	Tr:	risetime
h:	water depth at the point	c:	celerity of the long-wave $(=\sqrt{gh})$
h_0:	water depth from surface to top of the slope	L:	slope length

Fig. 9 - Effect of wave propagation on the maximum water level

3.2 Difference between the analytical and experimental results

3.2.1 Water level

Although the condition that the maximum water level occurred was the same in the numerical analyses and the hydraulic experiments (Case 3), the maximum analytical water level was about 80% of that found experimentally at the center of the slope. However, we considered only the net vertical rise of the ocean bottom due to the horizontal displacement in the numerical analyses. Actually, the vertical momentum of water might also be generated by the horizontal movement of the slope. In the hydraulic experiments, as it is thought that momentum of water affects the water level, we plan to conduct further experiment which measures momentum of water.

3.2.2 Rising water level start time

Under all conditions, the time when the water level started to rise was faster in the numerical analyses than in the hydraulic experiments. In the numerical analyses, the net vertical rise of the ocean bottom was due to the horizontal displacement of the slope, where the initial displacement distribution of the water at the sea surface was simultaneously affected (shown in Fig. 10). However, as shown in Fig. 6, a delay in the water level rise relative to the horizontal displacement was observed in the hydraulic experiment. We suggest that the difference in the time (between the numerical analyses and the hydraulic experiments) that the water level reached a maximum was also affected by the difference of the start time of the rising water level.

In addition, the location where the water level rise was different between the numerical analyses and the hydraulic experiments (shown in Fig. 10). In the numerical analyses, the water level increase due to the horizontal slope displacement directly occurred only on the slope itself, whereas the water level increase occurred near the top of the slope in the hydraulic experiments. We also suggest that the location where the water level rise was affected by the momentum of water induced by the horizontal movement of the slope, as also surmised in Section 3.2.1.

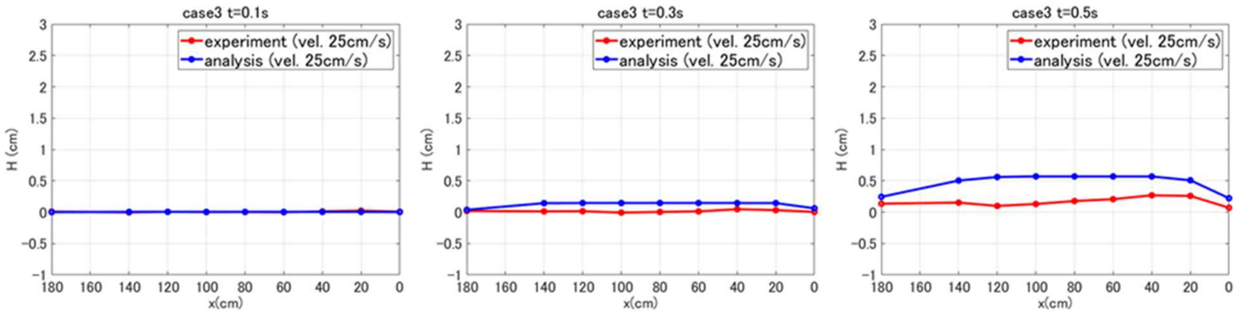


Fig. 10 - Comparison between the analyticaland the experimental water levels at the different time

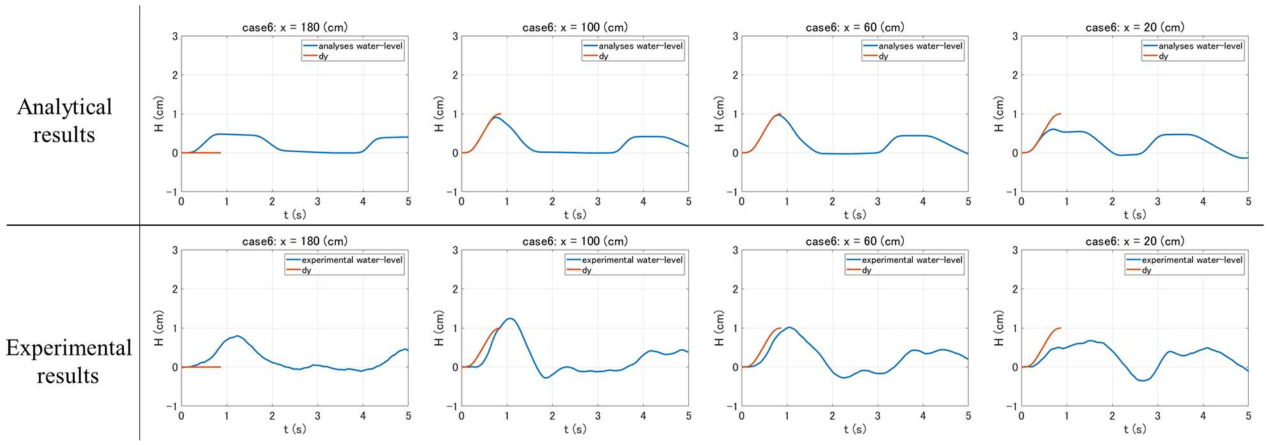


Fig. 11 - Water level and the total net rise of the ocean bottom level due to the horizontal displacement of the slope at measurement points x=20, 60, 100 and 180 cm for Case 6. Upper panel: analytical results; lower panel: experimental results.

3.2.3 Relationship between H_{max} and dy

The maximum water level relative to the total net rise of the ocean bottom due to the horizontal displacement of the slope was small in the numerical analyses. We suggest, as also described in Section 3.1, that this phenomena occurred due to the generated waves propagating toward the outer areas of the slope as the water level started to rise. However, the water level increase due to the horizontal slope displacement occurred only on the slope itself. When the risetimes were too long relative to the time scale of the wave propagation, the maximum water level was not able to reach the net rise of the seabed's elevation.

However, only for Case 6 in the hydraulic experiment did the maximum water level exceed the total net rise of the ocean bottom due to the horizontal displacement of the slope under water. Fig. 11 shows the time history of the water level and the total net rise of the ocean bottom due to the horizontal displacement of the slope at measurement points x＝20, 60, 100 and 180 cm for Case 6. At the center of the slope, the relative tsunami height in the hydraulic experiment exceeded 1. As mentioned before, we were unable to consider this value in the numerical analyses. Thus, conventional tsunami methods are not able to reproduce this phenomenon, and further discussions regarding the mechanism of this phenomenon are required.

4. Conclusions

We conducted numerical analyses and hydraulic experiments to evaluate the effects of horizontal crustal deformation along a trench on the initial displacement distribution of water at the sea surface. We found that the maximum water level became greater with larger horizontal velocities of the slope and with lower water depths (Case 3). In addition, the non-dimensional analysis suggested that the maximum tsunami height could be estimated using the dimensionless risetime.

However, we found the following diffrerences on the basis of comparing the numerical analyses results with the hydraulic experiment results: (1) water-level, (2) rising water-level start time and (3) condition which the relative tsunami height in the hydraulic experiment exceeded 1. We plan to clarify the mechanisms occurred the differences above.

5. References

[1] Tanioka Y, Satake, K (1996): Tsunami generation by horizontal displacement of ocean bottom. *Geophysical Research Letters*, **23** (8), 861-864.

[2] Earthquake Research Committee in Headquarters for Earthquake Research Promotion (2017): Tsunami prediction method for earthquakes with specified source faults (Tsunami Recipe), 38p.

[3] Michiguchi Y, Mitobe Y, Sugino H, Tanaka H (2019): Experimental study on tsunami generation due to horizontal crustal deformation. *Journal of Japan Society of Civil Engineers, Series B2 (Coastal Engineering)*, **75** (2), I_343 - 348, in Japanese.

[4] Kajiura K (1970): Tsunami source, energy and the directivity of wave radiation. *Bulletin of the Earthquake Research Institute*, **48**, 835-869.

