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NUMERICAL ANALYSIS OF TSUNAMI FLOW AROUND COASTAL DYKE

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ABSTRACT: Japan has a long stretch of coastal dykes along its shoreline to protect against storm surges, tsunamis and high wind waves. The 2011 Tohoku Earthquake and Tsunami caused serious damage to these coastal dykes. To improve the coastal dykes along the damaged coast and also to reconsider tsunami risks in other parts of the Japanese coast, it is important to understand the effect that a tsunami can have on a coastal dyke. The present paper thus aims to analyze a tsunami flow around a coastal dyke using a LES numerical model. To simulate both an impact phase and an overtopping phase of a tsunami flow, which were observed in the 2011 tsunami, a dam break flow and a pump flow were used to generate a tsunami-like flow in the numerical model. Based on the numerical results, the pressure and the velocity field around a coastal dyke were ascertained. These effects were considered to have a big influence on the dike failure in the 2011 tsunami, and thus it is recommended that the design of countermeasures should include a calculation of both of these parameters.

Keywords: Tsunami, coastal dyke, overtopping, numerical analysis, LES model.

INTRODUCTION

Japan has a long stretch of coastal dykes along its shoreline to protect against storm surges, tsunamis and high wind waves. The 2011 Tohoku Earthquake and Tsunami caused serious damage to these coastal dykes along the Pacific coast of northeastern part of Japan (Fig. 1). According to the Ministry of Land, Infrastructure, Transport and Tourism (2011), 190 km out of total 300 km of coastal dykes in three most affected prefectures (Iwate, Miyagi and Fukushima) were completely or partially destroyed.

Many field surveys were conducted after the 2011 Tohoku Earthquake and Tsunami to clarify the actual damage to structures. Mikami et al. (2012) indicated that the causes of destruction could be found in the large wave pressures acting on dykes for a long period of time and the scouring induced by the tsunami wave as it overtopped the dykes. Yeh et al. (2012) indicated that flow-induced suction pressure near the dyke crown could have caused the failure of concrete panels that covered the infill. Suppasri et al. (2012) indicated that scouring around the foundations caused by strong current and poor connection with the foundations and with neighboring blocks caused failure.

Fig. 1 Damaged coastal dyke in Tohoku after the 2011 Tohoku Earthquake and Tsunami

To improve coastal dykes along the damaged coast due to the 2011 Tohoku Earthquake and Tsunami and also to reconsider tsunami risks in other parts of the Japanese coast, it is important to develop a deeper understanding of how tsunamis affect coastal dykes. There are many factors that affect the level of damage to such structures by tsunamis, but the tsunami flow characteristics are considered to be one of the most important factors. The present paper thus aims to analyze the tsunami flow around a coastal dyke using a numerical model.

PREVIOUS STUDIES ABOUT TSUNAMI AND COASTAL DYKE

Before the 2011 Tohoku Earthquake and Tsunami, the effect that tsunamis had on a coastal dyke was investigated by the means of both laboratory and numerical experiments.

Kato et al. (2006) conducted a series of large-scale experiments with solitary waves to measure the distribution of wave pressure acting on coastal dykes. The study found how impulsive pressure acting on the

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seaward slope of a coastal dyke due to the wave breaking in front of the dyke could be produced by these phenomena.

Nishimura et al. (1978) conducted a series of two-dimensional experiments with solitary waves to clarify the scoring at the seaward toe of coastal dykes. As a result of this study, two parameters, the rate of return flow and water layer thickness, were found to be important for the quantitative prediction of the total amount of scouring and the scouring patterns.

Numerical analyses were also performed by a number of other authors. For example, Hamzah et al. (2000) investigated tsunami run-up and pressure on a vertical wall using a numerical model based on Navier-Stokes equations coupled with VOF method. Gotoh et al. (2002) investigated the characteristics of tsunami flow behind the vertical wall using the MPS method, which is one of the gridless Lagrangian model.

However, although solitary waves were used to generate tsunamis in many of the previous studies, the prolonged overtopping flow has not yet been fully investigated.

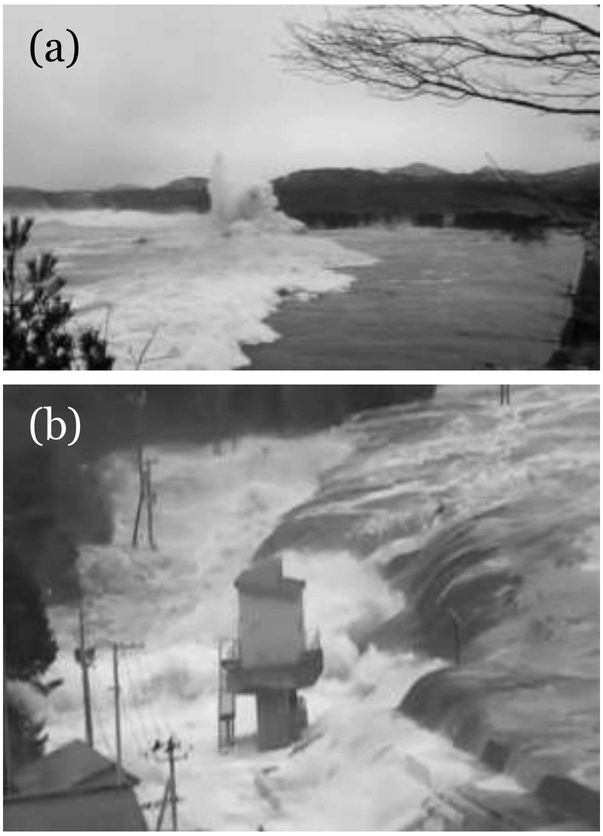


Fig. 2 Snapshots of tsunami flow around coastal dykes in the 2011 Tohoku Earthquake and Tsunami

Fig. 2 shows snapshots of tsunami flows around coastal dykes during the 2011 Tohoku Earthquake and Tsunami. Fig. 2 (a) indicates how the tsunami collided with the seaward slope of a coastal dyke and (b) shows the tsunami overtopping a coastal dyke and flowing into inland area. Hence, it appears that the leading tsunami flow against a coastal dyke has two phases: an impact phase and an overtopping phase. Both phases have a potential to cause failure in the structure, and thus it is necessary for practicing engineers to have a method to reproduce the flows generated by high-order events such as the 2011 Tohoku Earthquake and Tsunami.

TSUNAMI GENERATION

Generally speaking, to generate a tsunami-like flow in a wave flume or a numerical model, three types of methods exist, namely using a solitary wave, a dam break flow or a pump flow (Fig. 3). Before the 2011 Tohoku Earthquake and Tsunami a pump flow was not widely used to simulate a tsunami; however after the 2011 tsunami this type of flow came into use (e.g. Kato et al. 2012) as it is easy to create a prolonged overtopping flow. In the present study, a dam break flow and a pump flow were used to analyze an overtopping flow.

NUMERICAL MODEL

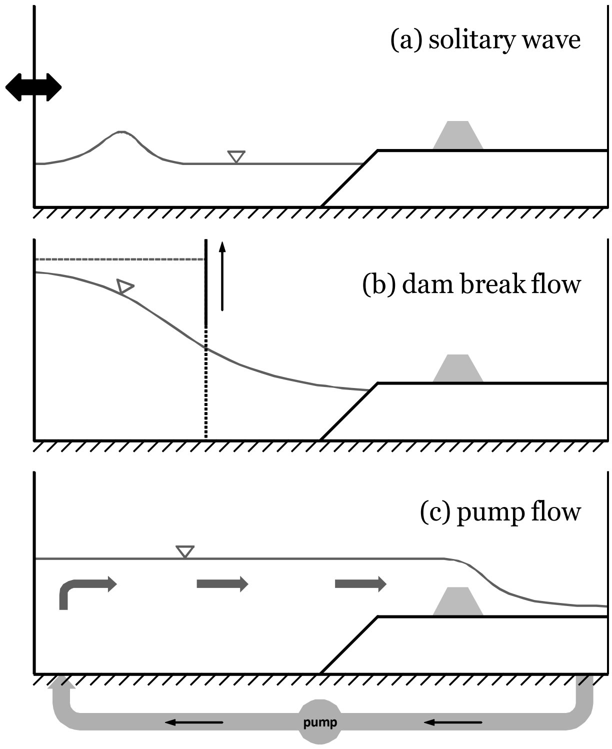


Fig. 3 Three types of methods to generate a tsunami-like flow in a wave flume or a numerical model

Governing Equations and Numerical Scheme

In this study, the flow field is solved by a one-phase (liquid-phase) Large Eddy Simulation (LES) model which is applied to a laboratory scale. The governing equations are the spatial filtered Navier-Stokes equations along with the continuity equation,

$$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial^2 \overline{u_i}}{\partial x_j x_j} - \frac{\partial}{\partial x_j}\left(\tau_{ij}\right) + g_i \quad (1)$$

$$\frac{\partial \overline{u_j}}{\partial x_j} = 0 \quad (2)$$

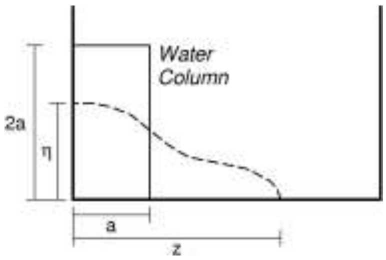
where u_i is the velocity component, t is time, x_i is coordinate spacing, ρ is the density of fluid, p is the pressure, v is the kinematic viscosity, g_i is the gravitational acceleration, τ_{ij} is the sub-grid-scale (SGS) stress. The Smagorinsky model (Smagorinsky 1963) is used to estimate the SGS stress.

The Cubic Interpolated Pseudo-particle (CIP) method (Yabe et al. 1990) is employed to solve the governing equations and the Successive Over-Relaxation (SOR) method is employed to solve the pressure equation.

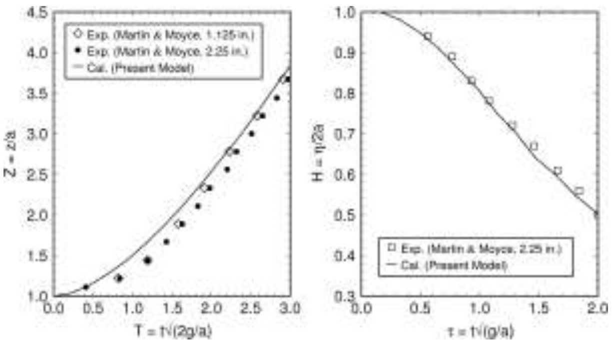
The free surface position is calculated using the density function method. If a grid cell is filled with water, the density function f takes 1, and f takes 0 with no water in a grid cell. The free surface is located in a grid where the density function is 0.5. The density function is described by the equation below, which is calculated using the CIP method.

$$\frac{Df}{Dt} = 0 \quad (3)$$

The grid size applied in the calculation is 1 cm in all directions, with non-slip conditions applied to the bed and lateral boundaries.



(a) Settings of a water column



(b) Comparisons of the results

Fig. 4 Model verification with the experimental data of the collapse of a water column (Martin and Moyce 1952)

Model Verification

The numerical model has been validated with the experimental data of the collapse of a water column (Martin and Moyce 1952). Fig. 4 shows the time series of the position of the leading edge of the collapsed water column (z) and the height of the residual water column (η) with the experimental results. The numerical results are in good agreements with the experimental results.

NUMERICAL RESULTS AND DISCUSSION

The dam break flow and the pump flow used to analyze an overtopping flow in the numerical model and each computational domain is shown in Fig. 5. A coastal dyke model was placed on the horizontal bottom after a 1/10 slope. The offshore water depth was 20 cm. A pool was created behind the dyke to avoid accumulating the overtopping water.

Dam Break Flow Tests

In the case of the dam break flow tests, the flow characteristics of both the impact and overtopping phases can be analyzed.

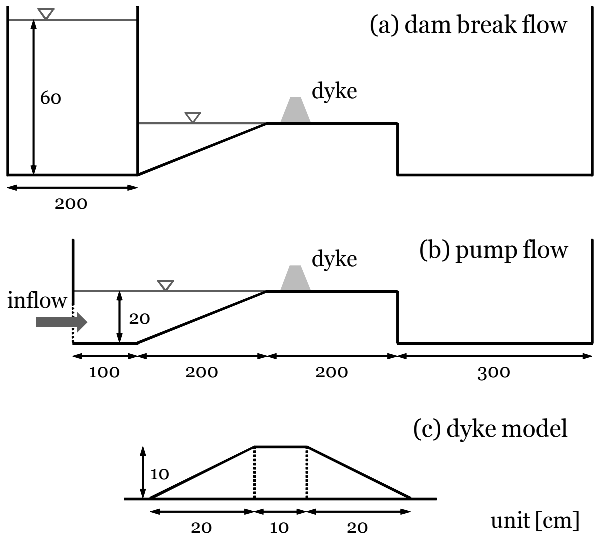


Fig. 5 Computational domain

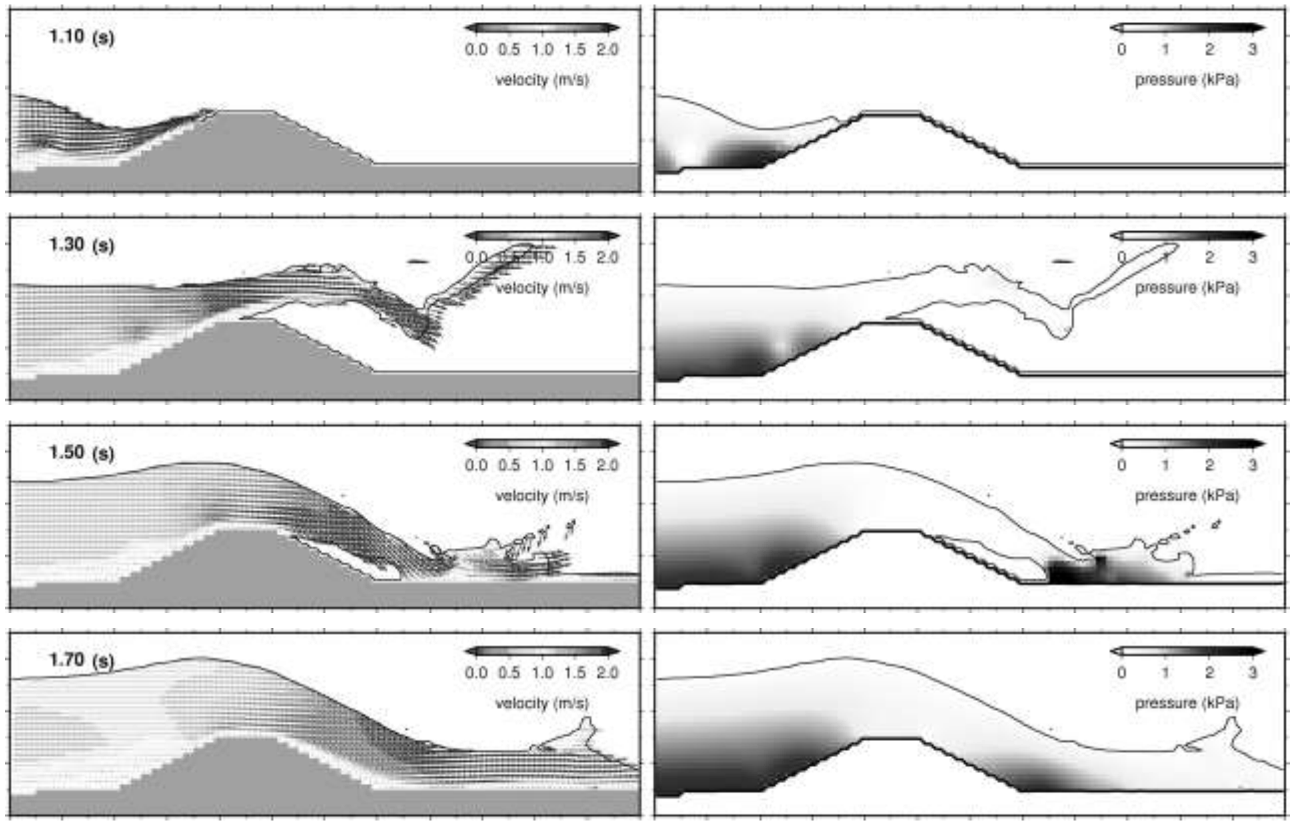


Fig. 6 Calculated results of the velocity and pressure fields around a dyke

Fig. 6 shows the calculated results of the velocity and pressure fields around a dyke. A bore type flow runs up the seaward slope and a dropping jet is formed behind the dyke.

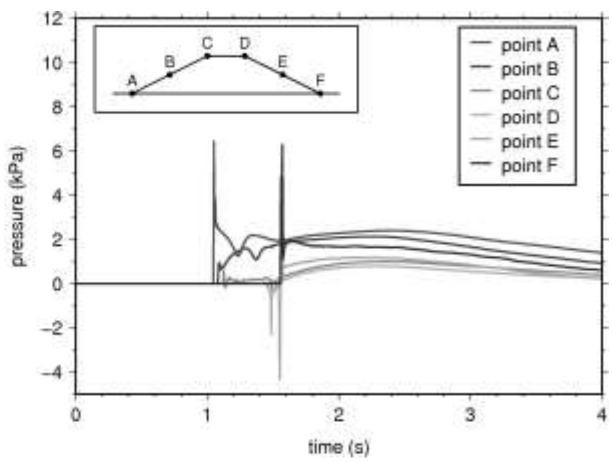


Fig. 7 Time series of the pressure acting on a dyke

Fig. 7 shows the time series of the pressure acting on a coastal dyke. Impulsive pressure occurs at the toe of the seaward slope of the coastal dyke and high pressure is found also at the toe of the landward slope. As mentioned in Yeh et al. (2012) and Kato et al. (2012), negative pressure occurs on the landward slope.

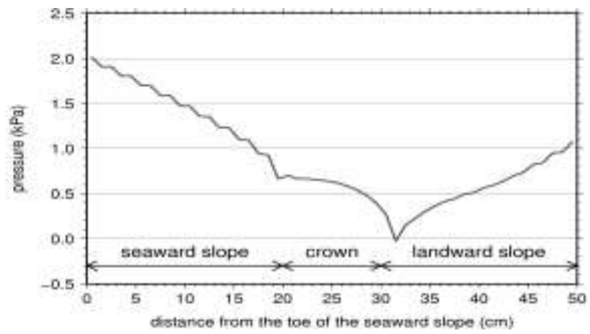


Fig. 8 Distribution of the pressure acting on a dyke

Pump Flow Tests

To focus on the flow characteristics of the overtopping phase of a high order tsunami event pump flow tests were also performed.

By creating a continued inflow at the offshore boundary a flow can reach an almost steady state. Fig. 8 shows the distribution of the pressure acting on the dyke at that moment. On the seaward slope the pressure is almost equivalent to hydrostatic pressure. On the other hand, on the landward slope the pressure takes a negative value at the top which gradually increases in value as it goes towards the toe.

In addition, to compare different geographical conditions, tests with a slope behind a dyke instead of a pool were also performed. The affected area due to the 2011 Tohoku Earthquake and Tsunami can be divided into two areas (northern and southern parts) from a geographical point of view. While there is a hill just behind a dyke and a residential area in the northern part, a flat plain extends behind a dyke in the southern part. In the northern part, it is easy for water to accumulate behind a dyke (see Fig. 2 (b)) and thus a slope was set behind a dyke to reproduce this condition.

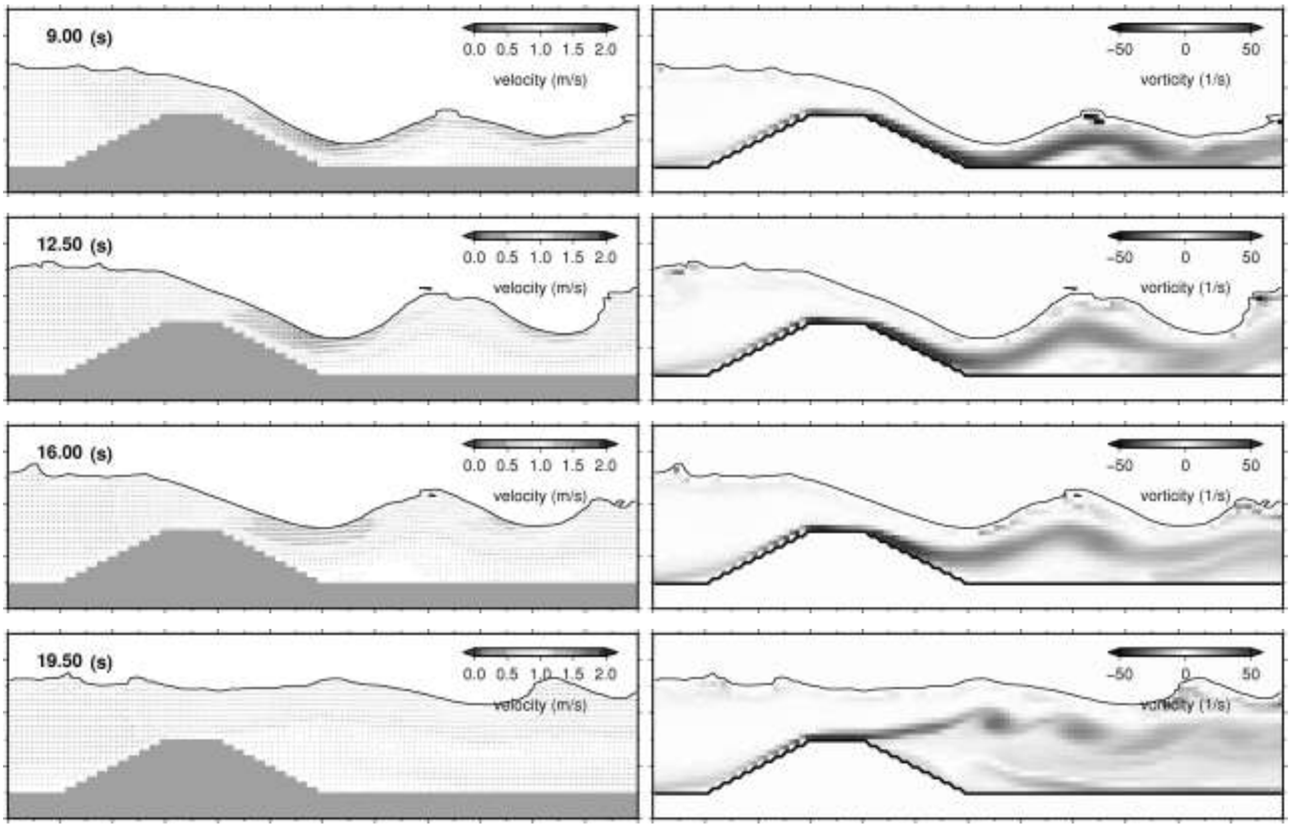


Fig. 9 Calculated results of the velocity and vorticity fields around a dyke

Fig. 9 shows the calculated results of the velocity and vorticity fields around a dyke. At the beginning a high velocity stream overtops and reaches the landward toe of the dyke. However, as the water depth behind the dyke becomes larger, the main streamline gradually flow higher than the dyke and the velocity becomes smaller. These results indicate that the geographical conditions around a dyke can have an important effect on the flow patterns of water around it.

CONCLUSIONS

In this study numerical analyses were performed to understand the characteristics of tsunami flows around coastal dykes during the 2011 Tohoku Earthquake and Tsunami. A dam break flow and a pump flow were used to simulate a prolonged overtopping flow in the numerical model. Based on the results, the pressure acting on a coastal dyke and the velocity field around it show that two distinctive phases can be identified, namely an impact and an overtopping phase. However, to describe the cause of dyke failure more clearly, it would be necessary in the future to compare the numerical results and the actual damage found in dykes in the damaged areas of Tohoku after the 2011 event.

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REFERENCES

Gotoh, H., Hayashi, M. and Sakai, T. (2002). Simulation of tsunami-induced flood in hinterland of seawall by using particle method. Proc. 28th Int. Conf. Coast. Eng. 1155-1167.

Hamzah, M. A., Mase, H. and Takayama, T. (2000). Simulation and experiment of hydrodynamic pressure on a tsunami barrier. Proc. 27th Int. Conf. Coast. Eng. 1501-1507.

Kato, F., Inagaki, S. and Fukuhama, M. (2006). Wave force on coastal dike due to tsunami. Proc. 30th Int. Conf. Coast. Eng. 5150-5161.

Kato, F., Suwa, Y., Watanabe, K. and Hatogai, S. (2012). Mechanisms of coastal dike failure induced by the Great East Japan Earthquake Tsunami, Proc. 33rd Int. Conf. Coast. Eng. in press.

Martin, J. C. and Moyce, W. J. (1952). An experimental study of the collapse of liquid columns on a rigid horizontal plane, Philosophical Transactions of the Royal Society of London, Series A, 244:312-324.

Mikami, T., Shibayama, T., Esteban, M. and Matsumaru, R. (2012). Field survey of the 2011 Tohoku earthquake and tsunami in Miyagi and Fukushima prefectures, Coast. Eng. J. 54(1):1250011.

Nishimura, H., Watanabe, A. and Horikawa, K. (1978). Scouring at the toe of a seawall due to tsunamis. Proc. 16th Int. Conf. Coast. Eng. 2540-2548.

Smagorinsky, J. (1963). General circulation experiments with the primitive equations. Monthly Weather Review. 91(3):99-164.

Suppasri, A., Shuto, N., Imamura, F., Koshimura, S., Mas, E. and Yalciner, A. C. (2012). Lessons learned from the 2011 Great East Japan Tsunami: Performance of tsunami countermeasures, coastal buildings, and tsunami evacuation in Japan. Pure Appl. Geophys. in press. (doi:10.1007/s00024-012-0511-7)

The Ministry of Land, Infrastructure, Transport and Tourism (2011). White Paper on Land, Infrastructure, Transport and Tourism in Japan, 2010, http://www.mlit.go.jp/english/white-paper/mlit-index.html.

Wessel, P. and Smith, W. H. F. (1998). New, improved version of generic mapping tools released. Eos Trans., AGU. 79(47):579.

Yabe, T., Ishikawa, T., Kadota, Y. and Ikeda, F. (1990). A multidimensional cubicinterpolated pseudoparticle (CIP) method without time splitting technique for hyperbolic equations. J. Phys. Soc. Japan. 59(7):2301-2304.

Yeh, H., Sato, S. and Tajima, Y. (2012). The 11 March 2011 East Japan Earthquake and Tsunami: Tsunami effects on coastal infrastructure and buildings. Pure Appl. Geophys. in press. (doi:10.1007/s00024-012-0489-1)