

An East Sea/Japan Sea Tsunami Simulator

K.O. Kim[†], B.H. Choi[‡], E. Pelinovsky[∞], J.-H. Yuk[‡] and B.I. Min[‡]

[†] Korea Ocean Research & Development Institute, Ansan 426-744, Korea
kyeongok.kim@gmail.com

[‡] Dept. of Civil and Environmental Eng. Sungkyunkwan University, Suwon 440-746, Korea
bhchoi.skku@gmail.com

[∞] Institute of Applied Physics Russian Academy of Sciences, Nizhny Novgorod, 603950, Russia
pelinovsky@hydro.appl.sci-nnov.ru



ABSTRACT

Kim, K.O., Choi, B.H., Pelinovsky, E., Yuk, J.-H. and Min, B.I., 2011. An East Sea/Japan Sea tsunami simulator. Journal of Coastal Research, SI 64 (Proceedings of the 11th International Coastal Symposium), 1058 - 1062. Szczecin, Poland, ISSN 0749-0208

A study of historic and prognostic tsunamis was performed, focusing on estimates of the maximum wave height and run-up height along the Korean coast. A numerical model was created based on 2D shallow-water equations, and a run-up correction was calculated from the 1D analytical long-wave run-up theory. The tsunamis of 1983 and 1993 were reproduced to validate the numerical model. The computed maximum wave heights and run-up heights agree with the observations, especially for the well-documented 1993 tsunami. Three hypothetical earthquake-generated tsunamis were used to estimate the prognostic characteristics of tsunami waves in the East (Japan) Sea. The results indicate that our tsunami simulator can be used to accurately simulate historic and prognostic tsunami events.

ADDITIONAL INDEX WORDS: *Shallow-water theory, Numerical simulation, Run-up*

INTRODUCTION

Historically, tsunamis in the East (Japan) Sea have been fairly common events. They can cause significantly more damage to the Japanese coast than to the Russian and eastern Korean coasts. With the ability to predict potential tsunamis, we can help mitigate this kind of natural disaster. Usually, shallow-water theory is applied to simulate tsunami waves in the East (Japan) Sea. In particular, the regional multigrid coupled finite-difference model (FDM) is constructed to simulate the entire process of tsunami generation, propagation and run-up (Choi *et al.*, 2003). In this model, either a linear or nonlinear version of the shallow-water equation with a different type of coordinate system (i.e., Cartesian or spherical) can be assigned to a specific region. These subregions are dynamically connected, and any ratio of grid sizes can be used to connect two adjacent subregions. In contrast with the FDM, which focuses on specific regions (Choi *et al.*, 2003), the finite-element model (FEM) can accommodate bottom topography and coastal configurations in a more detailed manner. The advantage of the FEM-based tsunami simulation model is that the mesh system can be continuously updated, which is particularly important for complicated ports and coastal regions (Choi *et al.*, 2008). The numerical tsunami model can reproduce tsunami wave propagation from its source in the open sea to the coast using detailed topography and bathymetry that have close to real features. Model output characteristics (run-up height and inundation velocity) are necessary to evaluate the tsunami risk for coastal resident populations. Previous work analyzing tsunami characteristics was performed using the shallow-water model with "non-reflected" boundary conditions on the coast, which were modeled using the equivalent wall at the last sea point for depths of 5-10 m (Choi *et al.*, 2003). Run-up heights were then corrected using simplified formula from the 1D analytic theory of long sine wave runup - runup ratio (Shuto, 1972; Choi *et al.*, 2002a). Directly calculating tsunami wave propagation from its source to the coastal zone using the single numerical model and various

nested methods with different mesh resolutions in the open sea and the coastal zone is not very accurate (Choi *et al.*, 2003). Accurate tsunami computation near the coast requires small grid steps (10-100 m), which significantly increase the computation time. As a result, such numerical models are difficult to use in operational practice. For example, in the East (Japan) Sea, a tsunami usually arrives at the eastern Korean coast within 100 minutes of its corresponding earthquake, requiring that the run-up height in coastal zones be predicted very quickly. It is thus necessary to develop a fine-mesh model for the entire East (Japan) Sea or apply the concept of the run-up ratio based on empirical or theoretical data. The main purpose of this study was to develop an FEM model to enable the rapid forecast of run-up height on natural beaches. FEM-based tsunami simulations were conducted to reproduce how waves propagated during the 1983 and 1993 tsunamis and examine how three hypothetical tsunamis in the East (Japan) Sea were created.

NUMERICAL MODEL AND MESH SYSTEM

The digital bathymetric and topographic database was established in the form of grid point value (GPV) with an interval of one-minute horizontal space for the region including 117°-143°E longitude and 24°-52°N latitude and also with an interval of one arc-second west of 135°E longitude (Choi *et al.*, 2002b). To calculate tsunami propagation in the fine finite element system, we used ADCIRC (The Advanced CIRCulation model for shelves, coast and estuaries), developed by Luetich *et al.* (1992). ADCIRC solves equations that are formulated using the traditional hydrostatic pressure and Boussinesq approximations and discretized in space using the finite element (FE) method and discretized in time using the finite difference (FD) method. For this research, we used the 2DDI (2-dimensional depth-integrated) model. The elevation was obtained from the solution of the depth-integrated continuity equation in the form of the generalized wave

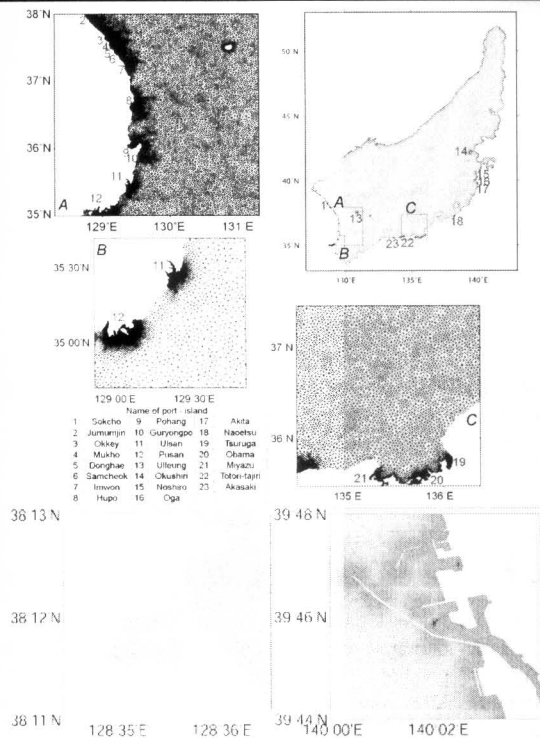


Figure 1. Model area and FEM mesh system. Lower-left: Sokcho Port; Lower-right: Akita Port.

continuity equation (GWCE), and the velocity was obtained from the solution of the 2DDI momentum equation.

The mesh system was recomposed using the conforming Delaunay triangulation (CDT) method and the boundary and topography information of the previous mesh system (upper-right panel in Figure 1; Choi *et al.*, 2008). The major ports and islands of Korea (13 areas) and Japan (10 areas) were included in the model. The size of mesh was limited to a maximum of 2 km in deep-sea areas that were within 500 m from the coast and 20 m from ports. Figure 1 shows the overall mesh system used for the tsunami simulation and the regionally refined elements of the major ports and islands. The wavelengths were also analyzed using long-wave theory, depending on the water depth. A long wave with a period of 600 seconds consists of at least 20 meshes. In addition, a realistic or flattened bathymetry caused by smoothing or sub-sampling topographic features can cause numerical models to overestimate the transmission of tsunami waves beyond these features. In these cases, fine mesh systems that can accommodate detailed topographic highs are necessary to estimate energy scattering.

Of the several fault parameters of the 1983 Central East Sea earthquake, the Aida Model-10 (Aida, 1984) is now considered to be the best estimate because it explains the total tsunami energy and distribution of tsunami energy most accurately. For the 1993 Hokkaido earthquake, the fault parameters suggested by Takahashi *et al.* (1994) are considered to be the most accurate. In addition to the tsunamis of 1983 and 1993, three hypothetical earthquake-generated tsunamis located in the gap zones of the seismic map are considered. According to the Headquarters for Earthquake Research Promotion (2004), it is possible that an earthquake with a magnitude greater than 7.5 will occur northwest of Hokkaido (magnitude 7.8, occurrence probability 0.006-0.1%), north of Sado Island (magnitude 7.8, occurrence probability 3-6%)

or in the front of Akita (magnitude 7.5, occurrence probability 3%) in the next 30 years. These three scenarios are considered in this study and are termed Hypoth1, Hypoth2 and Hypoth3, respectively. Figure 2 shows the initial sea-surface heights and the locations of the two historical and three hypothetical tsunamis. An initial surface profile was determined using methods of Mansinha and Smylie (1971), which assume that the initial surface profile is the same as the vertical dislocation of the seabed when the speed of vertical dislocation of the plate is faster than the celerity of propagation of the long wave. The mesh system was refined using the initial surface profile and a minimum grid space of 200 m.

The 2DDI equations in spherical coordinates for the simulation of the tsunami generation and propagation are

$$\frac{\partial \eta}{\partial t} + \frac{1}{R \cos \phi} \left[\frac{\partial P}{\partial \chi} + \frac{\partial}{\partial \phi} (Q \cos \phi) \right] = 0, \\ \frac{\partial P}{\partial t} + \frac{gh}{R \cos \phi} \frac{\partial \eta}{\partial \chi} - fQ = 0, \quad \frac{\partial Q}{\partial t} + \frac{gh}{R} \frac{\partial \eta}{\partial \phi} - fP = 0. \quad (1)$$

In these equations, ϕ and χ are the latitude and longitude, respectively, P and Q are the discharges per unit width in the directions of ϕ and χ , respectively, R is the radius of the earth, and f is the Coriolis parameter. These equations are solved in the closed domain with fully reflected boundary conditions in last sea points which are equivalent to the vertical wall on these depths. Output of model is the water oscillations around the “computed wall”.

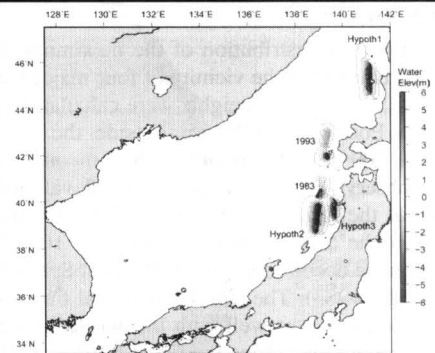


Figure 2. The location and initial water level of the 1983, 1993 and three hypothetical tsunamis.

ANALYTICAL APPROACH TO COMPUTE RUN-UP HEIGHT

In analytical theories of long-wave run-up, the rigorous solutions of the 1D nonlinear shallow-water equations are obtained for a plane beach using only the Carrier-Greenspan transformation (Carrier and Greenspan, 1958) for various shapes of the incident wave (Didenkulova, 2009). The important result here is that the linear and nonlinear theories predict the same maximum value for run-up height if the incident wave is far from the shore. Thus, linear theory can be applied to analyze the run-up process. In the framework of linear theory, rigorous solutions are found for various bottom profiles and not only a plane beach. The popular approximation of the bottom profile is a plane beach combined with a flat bottom (such a configuration is usually applied in laboratory modeling). In this case, the incident and reflected waves are easily separated on the flat bottom, and the run-up height of the monochromatic wave can be calculated (Shuto, 1972). Such runup ratio was used to estimate run-up height on the Korean coast during the 1993 tsunami (Choi *et al.*, 2002a). Another approach suggested by Kaistrenko *et al.* (1999) is more suitable for this application and allows the computation of

run-up heights through water oscillations at the last sea point where non-reflected boundary conditions are usually applied. The run-up correction in the framework of the analytical linear theory of long-wave run-up is determined by integral

$$\eta_{\text{coast}}(t) = \int_0^{t-T} \sqrt{(t-\tau)^2 - T^2} \cdot \frac{d^2 \eta_{\text{wall}}(\tau)}{d\tau^2} d\tau \quad (2)$$

where η_{coast} and η_{wall} are the water displacements on the coast and at the last sea points, respectively, and T is the estimated travel time of tsunami from the “wall” to the coast ($T=2L(gH)^{-1/2}$), L is the distance to the coast and H is the water depth at the last sea point. Thus, from the 2D computations, the water oscillations at the last sea points, $\eta_{\text{wall}}(t)$, the run-up height, and the maximum value of $[\eta_{\text{wall}}(t)]$ can be found through the simple integration of Eq. 2. Such an approach has been used to predict tsunami characteristics on the French coast of Mediterranean (Pelinovsky et al., 2002), but it has never been verified using real data.

MODELING OF HISTORIC AND PROGNOSTIC EVENTS

The model was used to simulate two historic (1983 and 1993) and three prognostic tsunamis. First, the 2DDI shallow-water model was used to calculate the water elevation for all five runs. Run-up heights were then computed using Eq. 2. The results of the numerical simulations are discussed below.

The 1983 Event

Figure 3 shows the distribution of the maximum wave height due to the 1983 tsunami in the vicinity of four major Korean ports. The tsunami maximum wave heights were calculated to be 20 cm in the Sokcho Port and 40–80 cm outside the port. Tsunami heights of over 200 cm were found in the Imwon Port. Figure 4 compares the observed and calculated water elevations during the 1983 tsunami at the Sokcho and Mukho ports. The first tsunami wave arrived at the Sokcho and Mukho ports 100–110 minutes after the earthquake occurred in the central East Sea (it occurred at 11:59 on May 26, 1983). The simulated arrival times at the other major ports generally agree well with the actual measured arrival times. The maximum elevations predicted by the model are close to the actual measurements. The observed shapes of the marigrams also agree well with the modeled results. Figure 5 shows a time series of tsunami wave heights computed using the fine mesh model and transformed using theoretical Eq. 2 for certain beaches on the eastern Korean coast that have actual measured data. The time series of tsunami wave heights computed using the fine mesh model reveals water displacement along the vertical wall (dashed line), and the time series of transformed tsunami wave height reveals onshore water displacement (solid line). The computations and observations for Gungchon Beach agree reasonably well but do not agree for the other beaches. The lack of agreement between

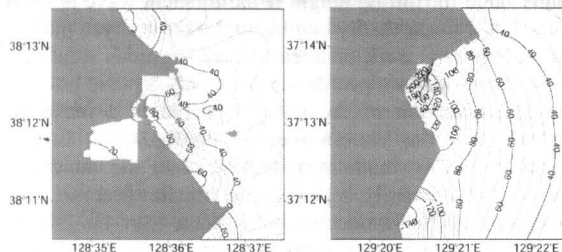


Figure 3. Maximum tsunami wave height (unit: cm) distribution in the Sokcho (left) and Imwon (right) ports for the 1983 tsunami.

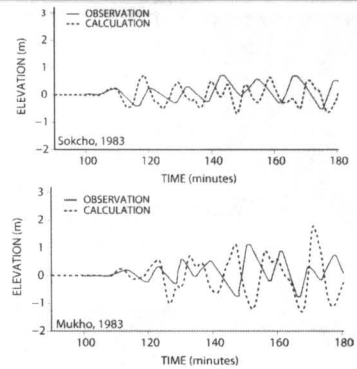


Figure 4. Observed and computed water elevations for the 1983 tsunami simulation.

the calculated and observed data for the other beaches may be a result of unreliable witness observations at those beaches.

The 1993 Event

The calculated maximum tsunami wave height for the 1993 tsunami was high (over 200 cm) in the Mukho and Imwon ports (Figure 6). The highest calculated tsunami wave height for the 1983 and 1993 tsunami events occurred at the Imwon Port in Korea. Figure 7 presents the calculated tide-gauge records of the 1993 tsunami. We also evaluated the model performance according to the mesh refinement by comparing the results of the three runs using three different mesh systems: a coarse mesh (45×10^3 meshes), a less coarse mesh (179×10^3 meshes), and a fine mesh (638×10^3 meshes; this study) (Figure 7).

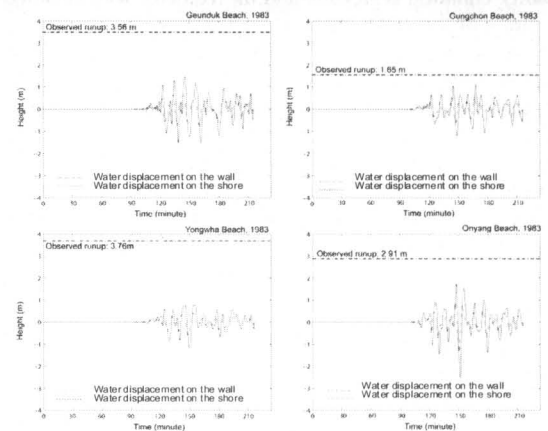


Figure 5. Computed time series of water displacement on the vertical wall (dashed line) and onshore (solid line) during the 1983 tsunami. Observed run-up heights are shown by dashed line.

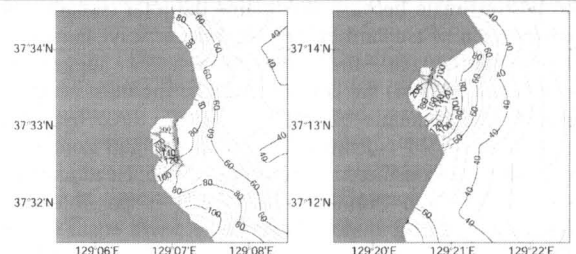


Figure 6. Maximum tsunami wave height (unit: cm) distribution in the Mukho (left) and Imwon (right) ports for the 1993 tsunami.

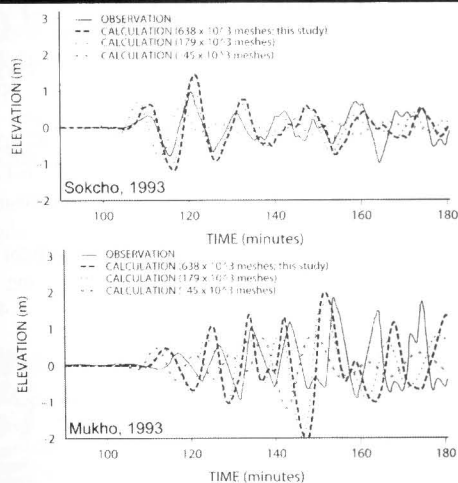


Figure 7. Maximum tsunami wave height (unit: cm) distribution in the major ports for the 1993 tsunami.

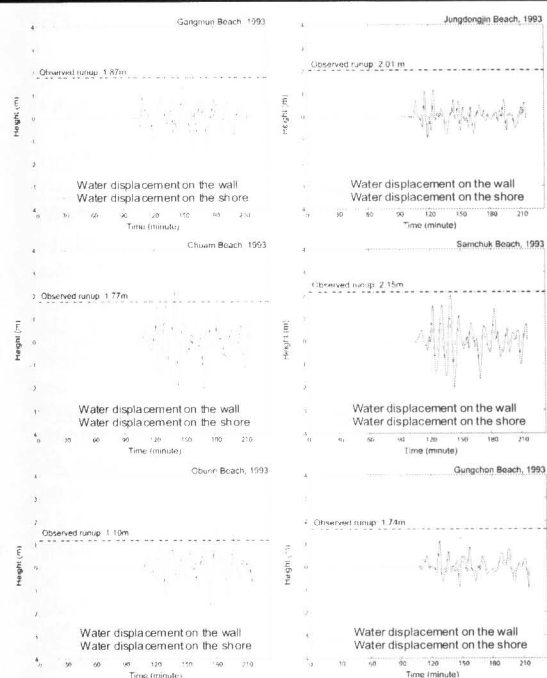


Figure 8. Computed time series of water displacement on the vertical wall (dashed line) and onshore (solid line) during the 1993 tsunami. Observed run-up heights are shown by dashed lines.

The computed maximum water elevation increased with mesh refinement. Additionally, the calculated maximum water elevation for the fine-mesh system (638×10^3 meshes) was close to the actual water elevation. This study indicates that the finer mesh has a better reproducibility with similarity to observations. Overall, the simulated time series of water elevation confirmed the observations. For the 1993 tsunami, the maximum transformed wave agrees well with the observed run-up height (Figure 8). The similarity between the computed and observed values for the well-documented 1993 tsunami suggests that the tsunami simulator developed in this study performed well.

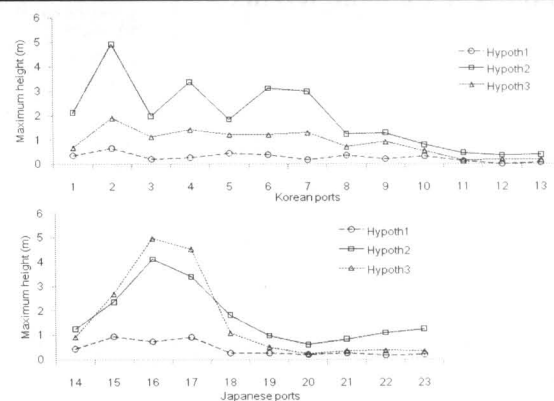


Figure 9. Maximum tsunami wave heights due to three hypothetical tsunamis in the Korean and Japanese ports listed in Figure 2.

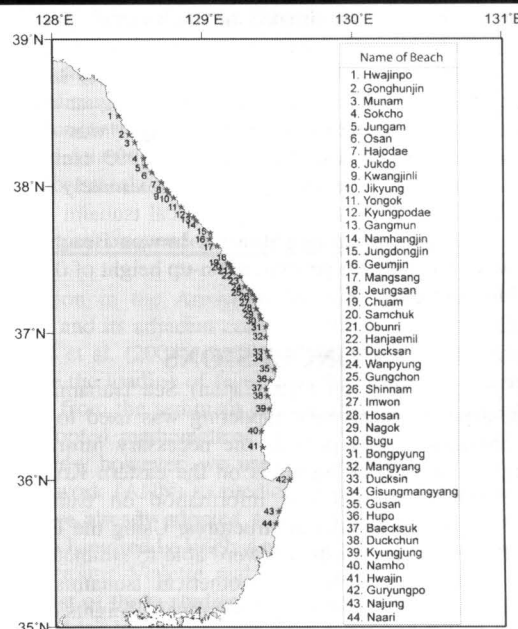


Figure 10. Beach locations along the east Korean coast.

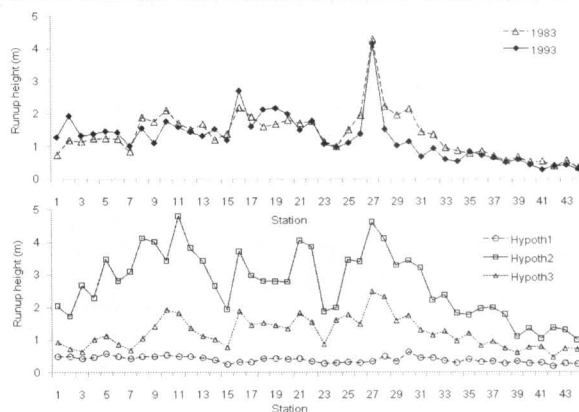


Figure 11. Run-up heights along the east Korean coast for the 1983, 1993 and hypothetical tsunami events, as estimated by the theoretical equation.

Hypothetical Tsunami Events

The maximum wave heights of hypothetical tsunamis were estimated to provide useful information for tsunami disaster prevention and allow the mapping of the tsunami inundation of coastal areas facing the East (Japan) Sea. Figure 9 shows the maximum wave heights for the hypothetical tsunami events calculated for the 23 ports in Figure 1. The maximum wave height due to the second hypothetical tsunami (Hypoth2) was highest in all 13 Korean ports. The largest maximum wave height (approximately 5 m) occurred in the Jumunjin Port. The maximum wave heights due to the second hypothetical tsunami (Hypoth2) were high in Japanese ports; however, the maximum wave heights were also high in port Nos. 15-17 due to the third hypothetical tsunami.

Overall, the wave heights were the largest for the second hypothetical tsunami (Hypoth2). Wave heights were low in port Nos. 8-13 (Korean ports) and 19-23 (Japanese ports). Using the time series of water elevation obtained from the model and the previously introduced conversion method for the time series of water elevation on the beach, run-up heights were estimated for almost all of the beaches situated on the eastern Korean coast (Figure 10). The ability to predict run-up height on the beaches of the east Korean coast is very important for tsunami hazard mitigation. The estimated tsunami run-up heights at 44 beaches are displayed in Figure 11. The run-up height was 4-4.5 m at Imwon Beach (No. 27) for the 1983 and 1993 tsunamis. The highest run-up height was calculated (approximately 5 m) near Yongok (No. 11) for the second hypothetical tsunami (Hypoth2). The large predicted run-up height at the Imwon Beach may be a result of wave focusing. In general, a run-up height of 0.5-5 m was predicted for the eastern Korean coast.

CONCLUSIONS

In the present study, an East (Japan) Sea tsunami simulator using fine-mesh finite element modeling was used to reproduce tsunami propagation and provide the necessary information for mitigating the impacts of tsunamis on the eastern Korean coast. This study provides important information on tsunami wave height for the design of coastal structures. Using the FEM-based model with a very fine mesh, we were able to simulate the 1983 and 1993 tsunamis and three hypothetical tsunamis. Through simulations, we calculated the maximum wave heights during five tsunamis. In particular, the maximum wave heights in the main ports of Korea and Japan were calculated and discussed. We also evaluated our model performance by comparing the measured and calculated data, and the results demonstrate that the simulator is capable of reproducing tsunami propagation. In addition, the maximum wave heights were calculated on the eastern Korean coast. Run-up height on natural beaches was estimated using a theoretical equation and a time series of wave heights calculated from the FEM-based model. This system can conveniently compose and decompose local ports and other areas of interest, while taking water depth and topography into account. We demonstrate that this simulator can be used for tsunami inundation mapping of the coastal areas facing the East (Japan) Sea. However, due to the complicated coastal conditions, more detailed topography and bathymetry information may be required. High-resolution micro-topography may be available in the near future and may allow for better simulations with a more-detailed FEM mesh system.

LITERATURE CITED

- Aida, I., 1984. A Source Models of the 1983 Nihonkai-earthquake Tsunami. *Proceeding of 3rd United States-Japan Cooperative Program in Natural Resources Tsunami Workshop*, pp. 57-76.
- Carrier, G.F. and Greenspan, H.P., 1958. Water waves of finite amplitude on a sloping beach. *J. Fluid Mech.*, 4, 97-109.
- Choi, B.H.; Pelinovsky, E.; Riabov, I., and Hong, S.J., 2002a. Distribution functions of tsunami wave heights. *Natural Hazards*, 25(1), 1-21.
- Choi, B.H.; Kim, K.O., and Eum, H.M., 2002b. Digital bathymetric and topographic data for neighboring seas of Korea. *J. Korean Soc. Coastal and Ocean Eng.*, 14, 41-50 (in Korean with English abstract and figure captions).
- Choi, B.H.; Pelinovsky, E.; Hong, S.J., and Woo, S.B., 2003. Computation of tsunami in the East (Japan) Sea using dynamically interfaced nested model. *Pure and Applied Geophysics.*, 160(8), 1383-1414.
- Choi, B.H.; Pelinovsky, E.; Jeon, C.K., and Kim, K.O., 2008. Effects of the Bottom Topography on Tsunami Propagation in the East (Japan) Sea. *China Ocean Engineering*, 22, 277-290.
- Didenkulova, I., 2009. New trends in the analytical theory of long sea wave runup. In: E. Quak and T. Soomere (ed.), *Applied Wave Mathematics: Selected Topics in Solids, Fluids, and Mathematical Methods*, Springer, pp. 265-296.
- Kaistrenko, V.; Go, C.N., and Chung, J.Y., 1999. A simple method for tsunami wave form recalculation through the shelf. *IOC-IUGG Joint International Workshop on Tsunami Warning Beyond 2000 Theory, Practice and Plans* (Seoul, Korea), pp. 15.
- Luettich, R.A.; Westerink, J.J., and Scheffner, N.W., 1992. *ADCIRC: An advanced three dimensional circulation model for shelves, coasts and estuaries, report 1: theory and methodology of ADCIRC-2DDI and ADCIRC-3DL*. Dredging Research Program Technical Report DRP-92-6, U.S. Army Engineers, Waterways Experiments Stations, Vicksburg, MS, 137(L09603), pp. 1-4.
- Manshinha, L. and Smylie, D.E., 1971. The Displacement Fields of Inclined Faults. *Bull. Am. Seismol. Soc.* 61(5), 1433-1440.
- Pelinovsky E.; Kharif C.; Riabov I., and Francius M., 2002. Modelling of tsunami propagation in the vicinity of the French coast of the Mediterranean. *Natural Hazards*, 25(2), 135-159.
- Shuto, N., 1972. Standing Waves in Front of a Sloping. Dike. *Coastal Engineering in Japan, JSCE*, 15, 13-23.
- Takahashi, T.; Shuto, N.; Imamura, F., and Ortiz, M., 1994. The best fault model for the 1993 Hokkaido Nansei-Oki' earthquake tsunami. *Proceedings of Coastal Engineering*, 41, pp. 251-255 (in Japanese).
- The Headquarters for Earthquake Research Promotion, Japan, 2004. *A Report on Long-Term Evaluation for Seismic Activity in the East of East Sea / Japan Sea*.

ACKNOWLEDGEMENT

The authors wish to thank the Ministry of Land, Transport & Maritime Affairs, Korea (PM55970) and the Korea Ocean Research & Development Institute (PE98533) for supporting this study. EP also had support from RFBR (08-05-00069, 09-05-91222) and State Contract 02.740.11.0732.