Iranian Journal of Geophysics, Vol 19 No 3, 2025, Page 137 – 151 (Research Article)
DOI: 10.30499/ijg.2024.481977.1642

Assessing the role of bathymetric data resolution and FD grid spacing in numerical tsunami simulation

Leila Etemadsaeed[1*], Hamid Zafarani[2] and Fatemeh Saber[3]

[1] *Assistant Professor, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran*
[2] *Professor, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran*
[3]*M.Sc. Graduate, Faculty of Engineering, Civil Engineering Group, Ale-Taha Institute of Higher Education, Tehran, Iran*

(Received: 06 October 2024, Accepted: 18 October 2024)

Abstract
Tsunami hazard analysis in tsunami-prone areas is crucial for disaster preparedness and mitigation. Tsunami hazard can be assessed using either empirical relationships or numerical simulations, with the latter offering greater accuracy. Numerical tsunami simulations involve transforming the governing differential equations into algebraic equations through numerical methods, which are then solved computationally. As for tsunami waves, the horizontal length scale (wavelength) is much greater than the vertical length scale (water depth), the shallow water equations can efficiently and sufficiently accurately describe the propagation and inundation phases of a tsunami. The finite difference method is a common numerical technique used to solve shallow water equations. This method approximates derivatives by using difference equations on a grid. Achieving accurate numerical solutions requires bathymetric data with sufficient resolution, which is not always available. Additionally, decreasing the finite difference grid spacing improves accuracy but also increases computational demand. This raises key questions: Can the lack of bathymetric data with sufficient resolution be compensated by reducing the size of the finite difference grid spacing? To what extent do the resolution of bathymetric data and the size of finite difference grid spacing play a role in the accuracy of tsunami numerical modeling? This study is an attempt to thoroughly investigate the impact of bathymetric data resolution and finite difference grid spacing on the accuracy of tsunami height estimations, focusing on Chabahar Bay in the Makran subduction zone as a real-world case study.

Keywords: Tsunami, numerical modeling, finite difference method, FD grid spacing, bathymetric data resolution, Chabahar bay

*Corresponding author: Etemadsaeed@iiees.ac.ir

1 Introduction

Tsunamis are long-wavelength, long-period water waves generated by massive disturbances on the sea floor, such as earthquakes, landslides, and underwater volcanic eruptions, or on the surface, such as meteorite impacts. Although tsunamis are relatively rare events, their highly destructive effects make them a significant hazard, necessitating investigations into their potential future occurrences.

In recent years, particularly following the devastating 2004 Indian Ocean tsunami, triggered by the Sumatra earthquake, and the 2011 Japan tsunami, caused by the Tohoku earthquake, there has been a marked increase in attention to this natural hazard. This heightened awareness has led to extensive studies on tsunami modeling and hazard assessment. Tsunami hazard assessment involves deriving quantitative estimates of tsunami parameters at a specific spot along the coast, which is critical for effective disaster preparedness. There are two main approaches for tsunami hazard assessment:

Deterministic Tsunami Hazard Assessment (DTHA): This conservative method calculates tsunami hazard based on the largest possible tsunami or the worst-case scenario.

Probabilistic Tsunami Hazard Assessment (PTHA): In contrast, PTHA evaluates tsunami hazard by considering various scenarios and the occurrence probabilities of each one, akin to the methodologies used in probabilistic earthquake hazard analysis.

Considering the worst-case scenario in the deterministic approach, while requiring fewer calculations, is only justified in special cases where extremely high safety standards must be met, such as for nuclear power plants. In most other cases, particularly when risk-based decision-making is necessary for estimating potential damages and losses in coastal areas, the deterministic approach is unsuitable due to the relatively low probability of the worst-case tsunami occurring. Additionally, it is often difficult to identify the worst-case scenario because the factors controlling the maximum size of these great earthquakes are still poorly understood. According to McCaffrey (2008), current evidence cannot rule out the possibility that any subduction zone may produce a magnitude (Mw) 9 or larger earthquake. Furthermore, assuming the worst-case scenario does not necessarily lead to the worst outcome in all locations. Given the numerous uncertainties associated with tsunami events—where thousands of different scenarios, each with varying probabilities, could potentially occur—considering all possible scenarios in hazard assessment is essential and the main weakness of the deterministic method lies in its focus on one or a few key scenarios without accounting for their likelihood of occurrence. Due to the limitations of DTHA and the more comprehensive and reliable nature of PTHA, the latter has become the preferred approach for tsunami hazard assessment (e.g., Zafarani et al. 2023).

To effectively assess tsunami hazard, numerical modeling of the tsunami phenomenon is usually essential. In DTHA, numerical modeling is limited to a selected number of scenarios, while PTHA involves extensive numerical modeling across numerous scenarios to account for uncertainties inherent in the phenomenon. Tsunami numerical modeling is a critical area of research that significantly contributes to disaster management and preparedness. Accurate tsunami models enable us to assess risks, predict wave behavior, and implement effective mitigation measures to protect lives and property.

Numerical tsunami modeling entails solving the fundamental equations governing tsunami propagation and inundation using computational methods. Over the years, various methodologies have been employed in tsunami numerical simulations. One widely recognized approach is the finite difference (FD) method, which discretizes the tsunami governing equations to solve for wave propagation and inundation. This technique has been integrated into several modeling frameworks, including COMCOT (Cornell Multi-grid Coupled Tsunami Model), which supports both linear and nonlinear shallow water equations (Liu et al., 1998) and has been used in some studies to model tsunamis (e.g., Heidarzadeh and Satake, 2014; Rashidi et al., 2020; Zafarani et al., 2023). COMCOT utilizes a nesting scheme that allows for flexible computational grid sizes and time steps, enabling researchers to capture intricate details of tsunami behavior across multiple layers of a simulation.

In addition to the FD method, other numerical approaches, such as the finite volume method, the boundary element method, and the finite element method, have also been developed. Each methodology has its strengths and limitations, with the choice of model often depending on the specific requirements of the simulation, including the scale of the area under study and the available computational resources. The importance of continued research in tsunami modeling cannot be overstated; by advancing our modeling capabilities, we can improve disaster preparedness for tsunamis, enhance public safety, and ultimately save lives. Accurate tsunami models enable us to assess risks, predict wave behavior, and implement effective mitigation measures to protect lives and property.

For accurate numerical tsunami simulation, high-resolution bathymetric data is essential, although such data is not always available. While reducing finite difference (FD) grid spacing can enhance solution accuracy in numerical modeling, it also increases computational costs. This raises the question: In the absence of high-resolution bathymetric data, to what extent can the accuracy of numerical modeling be improved by reducing the FD grid spacing? This study, in continuation of our previous research (Etemadsaeed et al., 2024), aims to examine the role of bathymetric data resolution and FD grid spacing in the accuracy of numerical tsunami modeling. Optimal numerical modeling should strike a balance between adequate accuracy and acceptable computational time.

In this study, Chabahar Bay, located within the central part of the Makran subduction zone, is selected as the focus area for tsunami numerical modeling due to the availability of both 3-sec and 15-sec resolution bathymetric data, offering a valuable opportunity to assess the effects of varying FD grid spacing and bathymetric resolution on tsunami modeling. The Makran subduction zone along the southern coasts of Iran and Pakistan represents a significant seismogenic area capable of generating tsunamigenic earthquakes (Zafarani et al., 2023).

2 Examining the Effect of Bathymetric Data Resolution and FD Grid Spacing on Numerical Tsunami Modeling

For numerical tsunami modeling, the three phases of the phenomenon—generation, propagation, and inundation—must be modeled numerically. To achieve this, the differential equations governing the propagation and inundation phases, along with initial conditions introduced by the generation phase, need to be solved using a proper numerical method.

Generation phase: For earthquake-induced tsunamis, which account for approximately 80% of all tsunamis, the initial water surface elevation caused by the earthquake on the sea floor during the generation phase is incorporated as an initial condition.

Since the total rupture time of an earthquake is significantly shorter than the period of the resulting tsunami wave, it is conventional to treat the displacement of the seabed as occurring instantaneously. This approach, commonly referred to as passive seismic generation (Dutykh et al., 2007; Kervella et al., 2007), assumes that static rather than dynamic displacement occurs at the seabed due to the earthquake. In this method, the initial water surface elevation is equated to the vertical displacement of the seabed. This is based on the assumption that the water mass above the fault zone, impacted by fault movement, cannot be drained during the short rupture time (Steketee, 1958). Therefore, the initial conditions for tsunami wave propagation are derived by transferring the final static vertical displacement of the seabed to the water surface. Okada's (1992) closed-form solution is applied to calculate the vertical displacement at the seabed.

Propagation and inundation phases: Shallow water equations adequately describe the propagation and inundation phases of tsunamis. Although more accurate equations exist to describe tsunami propagation and inundation (e.g., Navier-Stokes and Boussinesq equations), they are not typically optimal for tsunami hazard analysis due to their high computational cost.

A common approach for numerically solving shallow water equations is the FD method. This study utilizes the FD method and the COMCOT software (Liu et al., 1998) for tsunami modeling. COMCOT supports both linear and nonlinear shallow water equations for tsunami simulations, featuring a nesting scheme that allows for flexible FD grid sizes and time steps across multiple layers, as well as a moving boundary scheme for calculating coastal inundation areas and inundation depths.

In tsunami propagation modeling, for depths exceeding 50 meters, linear shallow water equations provide a reasonable approximation for the governing equation. However, in shallower waters, nonlinear equations—accounting for both nonlinear terms and bottom friction—must be used (Imamura et al., 1995).

For an optimal numerical solution, using a nested (non-uniform) grid is highly suitable. This approach allows for a denser FD grid in areas closer to the shore while using a coarser grid in more distant regions. A denser grid near the coast is essential because coastal areas experience more complex wave interactions due to variations in bathymetry, as well as the reflection, refraction, and diffraction of waves. These finer details require higher resolution to accurately capture tsunami wave behavior, particularly as they approach the shoreline and cause inundation. By refining the grid in these critical regions, the model can provide more accurate predictions of wave height, velocity, and potential coastal impact. Additionally, by using a nested grid, linear shallow water equations can replace nonlinear equations, where accuracy is not compromised. It is worth noting that solving linear equations is significantly faster than solving nonlinear equations, and as the FD grid spacing decreases, the computational time for the numerical solution increases.

Accurate numerical solutions depend on the availability of bathymetric data with sufficient resolution, which is not always accessible. In numerical modeling, reducing the mesh size can enhance solution accuracy, but it also increases computational costs. This research investigates how much reducing the FD grid spacing can improve the accuracy of numerical modeling in the absence of high-resolution bathymetric data. Additionally, it explores the impact of bathymetric data resolution and FD grid spacing on tsunami simulation accuracy, aiming to strike a balance between precision and computational efficiency.

In this study, the focus is on the Makran subduction zone and Chabahar Bay. Bathymetric data with a maximum resolution of 15 seconds is available for the entire Makran subduction zone, while higher-resolution local bathymetric data (3 seconds) is available for Chabahar Bay. By conducting numerical tsunami modeling in Chabahar Bay under various conditions, the effects of bathymetric data resolution and FD grid spacing on the accuracy of tsunami numerical simulations can be thoroughly assessed.

For this purpose, an ensemble of 38 critical scenarios for the Chabahar region has been selected from the 1776 scenarios studied by Zafarani et al. (2023). These 38 scenarios include earthquakes with varying magnitudes, occurring at different locations and depths within the Makran subduction zone. For each fault location, some non-uniform slip distribution scenarios are considered. Figure 1 shows the considered fault locations in this study. The Chabahar Bay is marked by a red star in this figure.

Numerical tsunami modeling for these 38 scenarios was conducted using the FD method and a nested grid with three layers (as shown in Figure 2). The first layer uses a grid spacing of 30 seconds, while the second layer uses 15 seconds, with both layers relying on bathymetric data at a 15-second resolution. The third layer incorporates four different FD grid spacing and bathymetric data resolution to evaluate their effects on numerical modeling accuracy. Details of the FD grid spacing, time step, and types of equations used for these three layers are provided in Table 1.

It is important to note that the bathymetric data with a 15-second resolution (2020 version) was obtained from the GEBCO database (GEBCO Compilation Group, 2020), while the 3-second resolution bathymetric data was derived from local surveys conducted in the Chabahar area. Additionally, a constant Manning's coefficient of 0.025 was applied to account for friction in layers 2 and 3. For comparison purposes, 82 modeling stations within Chabahar Bay, as shown in Figure 3, have been considered.

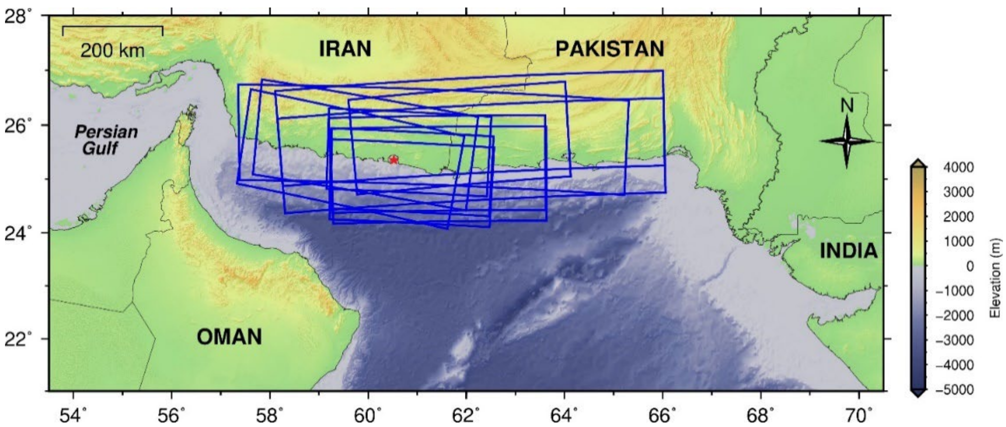

Figure 1. Considered fault locations in this study. Chabahar Bay is marked with a red star.

Table 1. Bathymetric data, FD grid spacing, time step, and type of equations used for the three layers of the nested grid.

Layer Number		Bathymetric Data Used	FD Grid Spacing (h)	Time Step (Δt)	Type of Equations Used
1		Gebco_15 sec_2020	30 seconds	1.97	Linear
2		Gebco_15 sec_2020	15 seconds	0.98	Nonlinear
3	Case 1	Local survey with 3 seconds resolution	5 seconds	0.98	Nonlinear
	Case 2	Gebco_15 sec_2020	5 seconds	0.98	Nonlinear
	Case 3	Local survey with 3 seconds resolution	15 seconds	0.98	Nonlinear
	Case 4	Gebco_15 sec_2020	15 seconds	0.98	Nonlinear

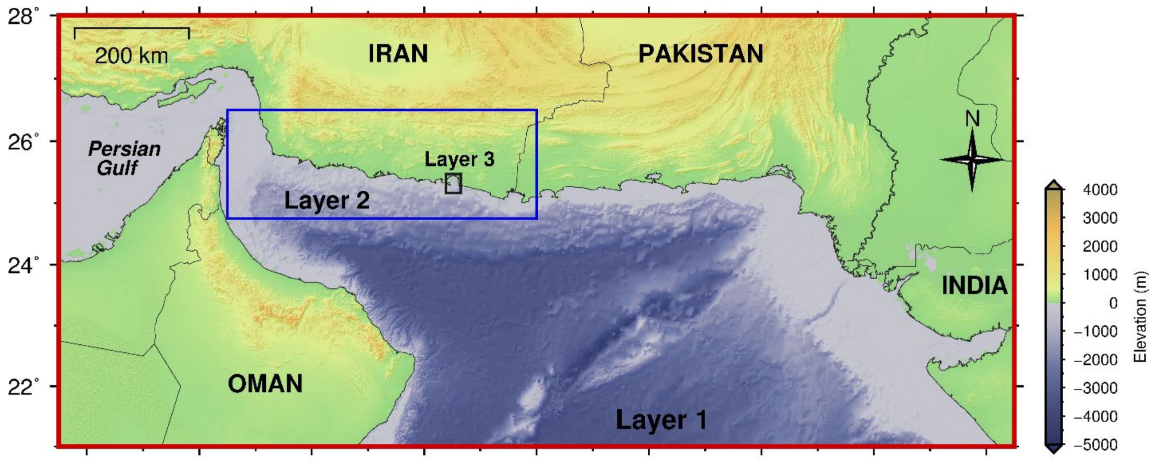

Figure 2. Nested grid with three layers employed in this study: the boundary of the first layer is shown in red, the second layer in blue, and the third layer in black.

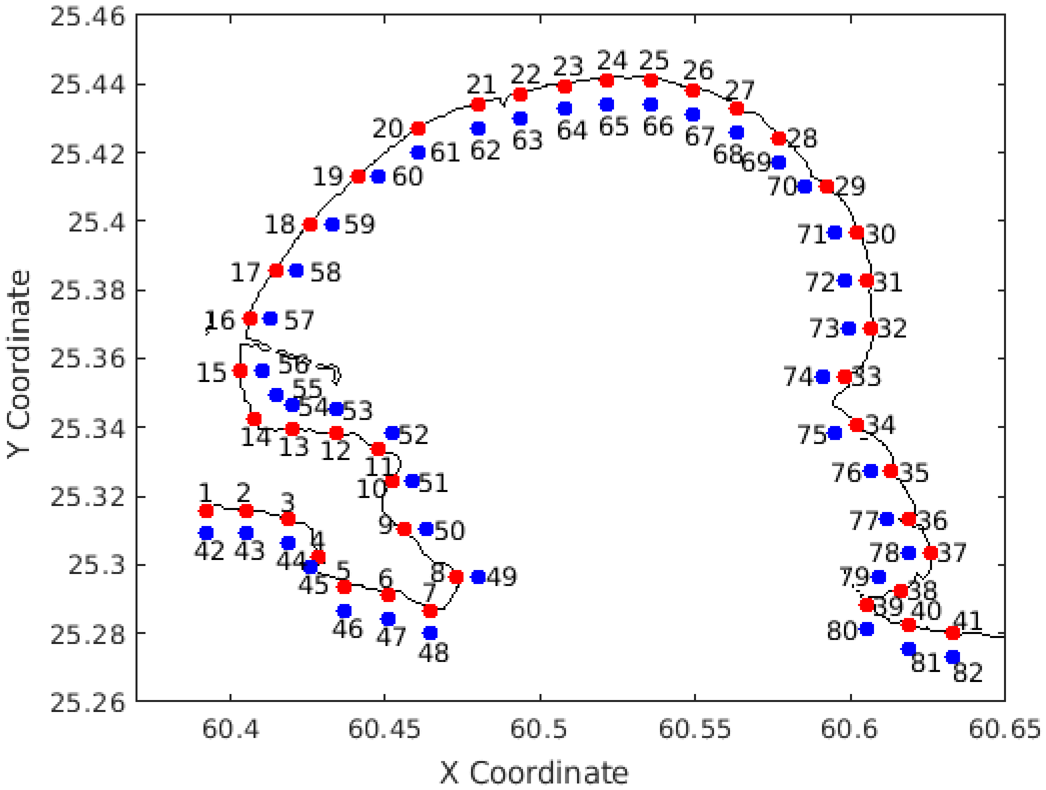

Figure 3. Modeling stations considered in Chabahar Bay: Stations 1 to 41 (red stars) are located closer to the shoreline compared to stations 42 to 82 (blue stars).

3 Numerical Modeling Results and Discussion

Figure 4 displays the contour of maximum tsunami height from the free surface (Z_{max}) for one of the scenarios of interest, across four cases representing the third layer (as shown in Table 1). In this figure, the top-left, top-right, bottom-left, and bottom-right panels correspond to cases 1 to 4 of layer 3, as outlined in Table 1. According to this figure, both the FD grid spacing and the resolution of the bathymetric data affect the accuracy of tsunami numerical modeling, but it appears that the latter has a greater impact.

Additionally, Figures 5 and 6 compare the overall Z_{max} values across all scenarios ($(Z_{max})_{\text{overall}} = \max(Z_{max})_i$, i=1:38, there are totally 38 scenarios) for the first set of 41 stations and the second set of 41 stations (according to Figure 3), respectively, for the four cases of the third layer. It is important to note that during the analysis, some stations initially selected based on the 3-second bathymetric resolution were later found to be located on land rather than in the water based on the 15-second bathymetric resolution. These stations were subsequently removed from the results of these two figures (see Figure 7).

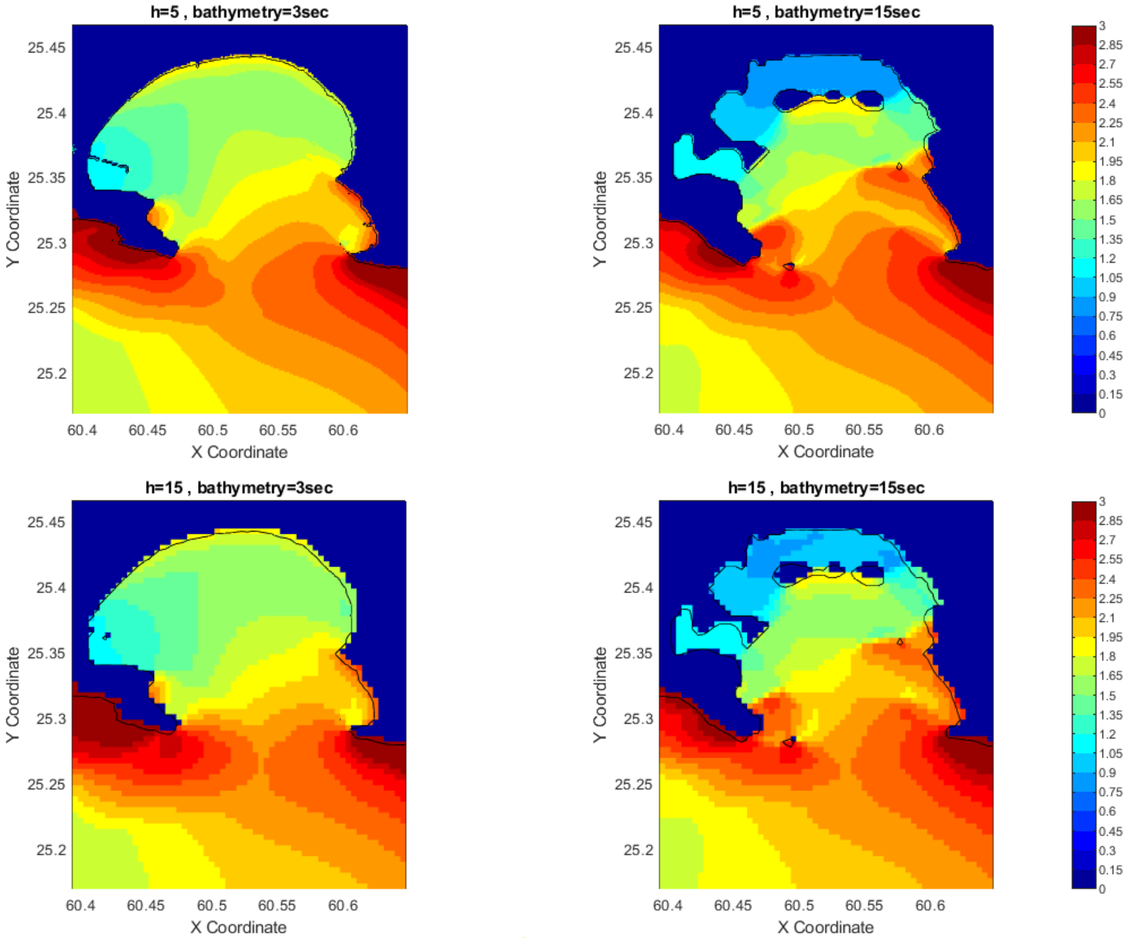

Figure 4. Contour of Z_{max} in four cases of layer 3 (according to Table 1), for one of the 38 scenarios as an example.

Given that case 1 provides the most accurate solution, Figure 5 demonstrates the impact of FD grid spacing and bathymetric data resolution on the accuracy of tsunami numerical modeling for stations 1 to 41. According to this figure, we cannot determine which factor is more important. In some stations, such as station 15, the FD grid spacing appears to have a greater effect on accuracy than the bathymetric data resolution, while in other stations, the bathymetric data resolution is more effective. Figure 6, which is related to the set of stations farther from the coastline, shows us that as we move slightly away from the coastline, the effect of bathymetric resolution on the accuracy of the solution is dominant over the effect of the FD grid spacing.

Now, it is useful to examine the time history of tsunami wave height at some stations, as indicated by their locations in Figure 8. Figures 9-14 show the time history of tsunami wave height from the free surface (Z) for one of the scenarios of interest, across four cases representing the third layer at these stations.

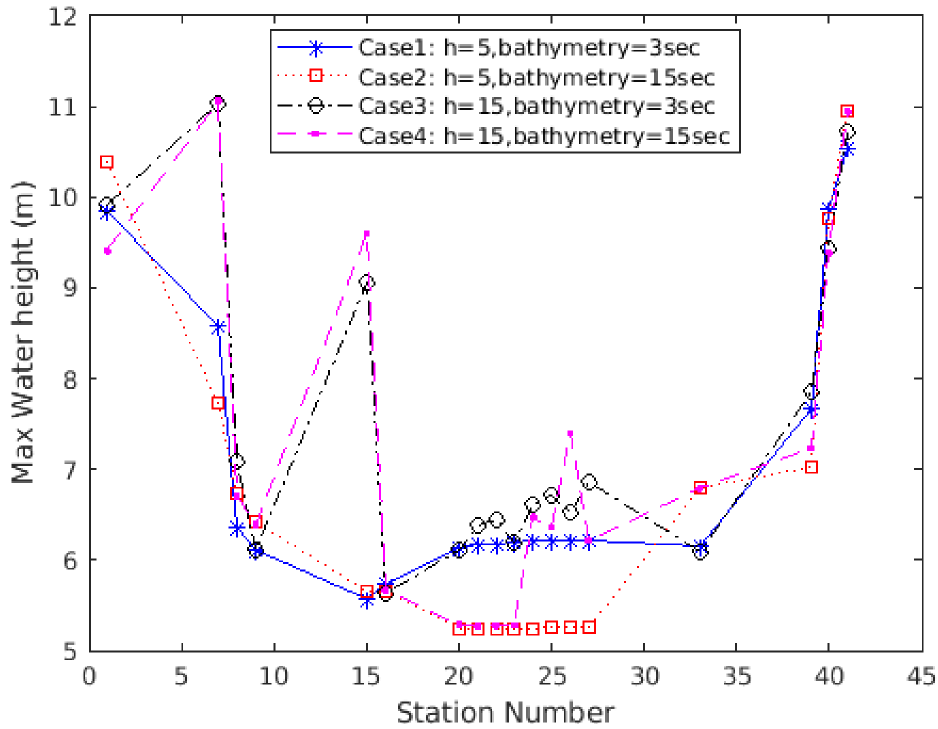

Figure 5. Overall Z_{max} values across all scenarios for the first set of 41 stations, in the four cases of layer 3.

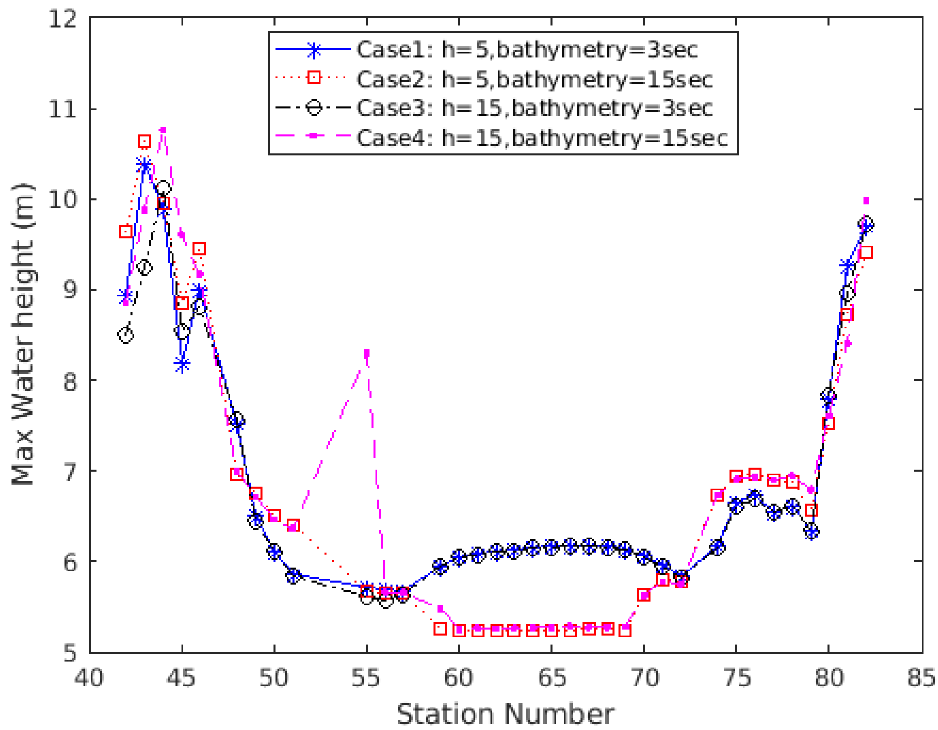

Figure 6. Overall Z_{max} values across all scenarios for the second set of 41 stations, in the four cases of layer 3.

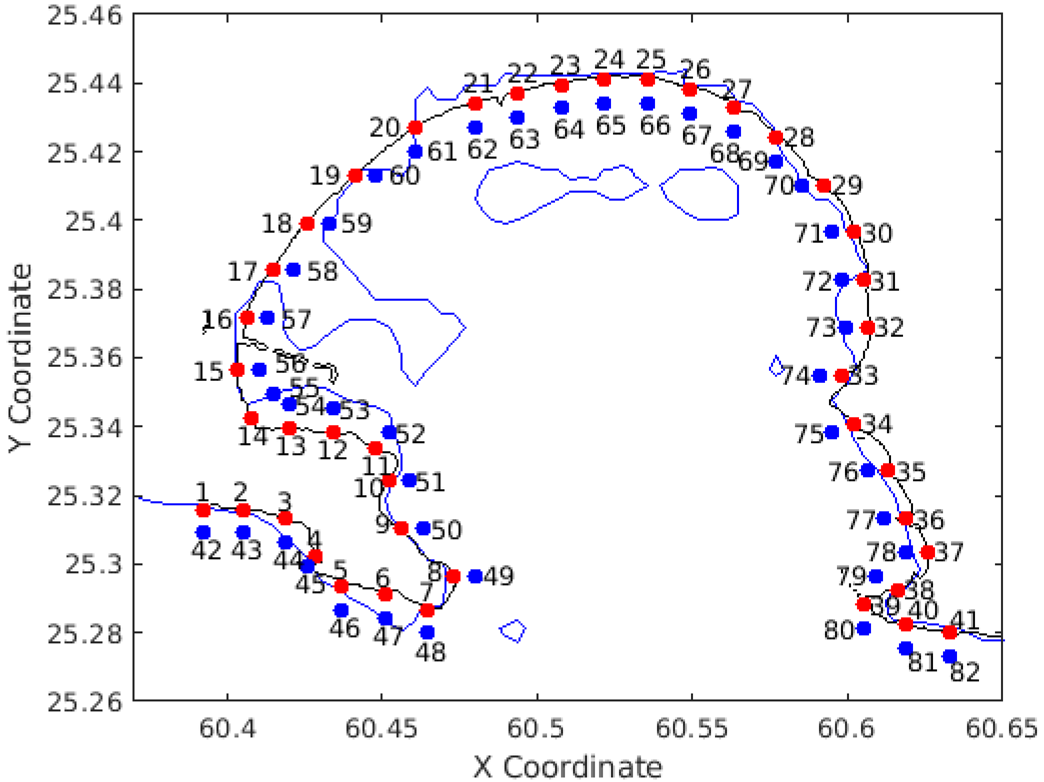

Figure 7. Location of stations relative to the coastline based on bathymetry with a resolution of 3 seconds (black line) and 15 seconds (blue line).

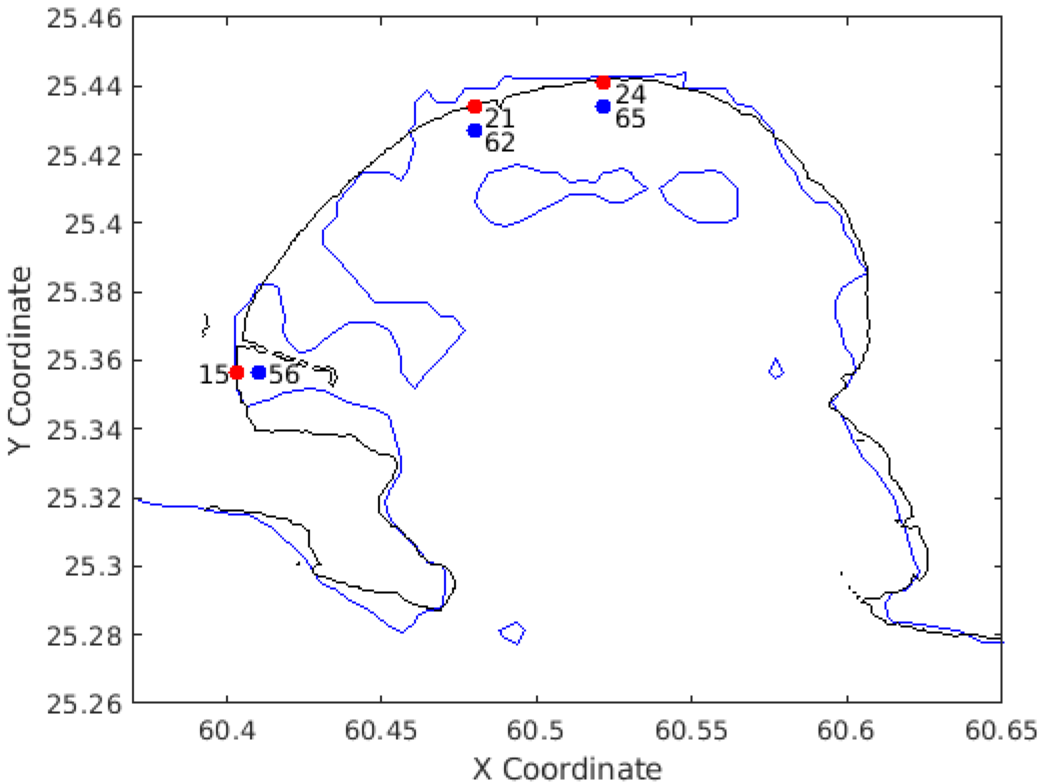

Figure 8. Locations of stations where the time history of tsunami wave height is presented.

Figure 9 shows the time history of the tsunami wave height at station 15. This figure demonstrates that reducing the size of the FD grid spacing and increasing the bathymetric resolution both improve the accuracy of tsunami numerical modeling results; however, at this station, the role of FD grid spacing is crucial. By comparing the records from this station with those from others, we can infer that these results are influenced by the fact that this station is very close to the coastline, as indicated by both bathymetric resolution datasets. The location of this station is selected on an FD grid point when using *h*=5 seconds. However, for *h*=15 seconds, it does not, and achieving the tsunami water height (*Z*) at this location requires interpolation, which may involve using points that are situated on land rather than in the water.

Moving farther from the coastline at station 15 leads us to station 56. Figure 10 shows the time history of the tsunami wave height at this station. Here we see that although both the FD grid spacing and bathymetric resolution affect the accuracy of the results, the effect of bathymetric resolution is significantly greater. This means that with higher resolution, even with a larger FD grid spacing, a relatively good solution can be achieved; however, the lack of accuracy from lower resolution cannot be compensated for by simply reducing the FD grid spacing. Figures 11-14 for some other stations indicate similar results.

By comparing Figures 11 and 12, we can conclude that the impact of the FD grid spacing size diminishes as we move farther from the coastline. However, the importance of bathymetric resolution remains. Comparing Figures 13 and 14 shows similar results.

According to all these figures, reducing the size of the FD grid spacing and increasing the bathymetric resolution both improve the accuracy of tsunami numerical modeling results. As we approach the coastline, the importance of FD grid spacing and bathymetric resolution increases. Consequently, the relative position of the station to the coastline at the desired resolution and specific FD grid spacing directly influences the accuracy of the modeling results. It is concluded that, when suitable bathymetric resolution is unavailable, and/or reducing the FD grid spacing is not feasible, it is better to obtain more reliable results by focusing on stations located farther from the coast. Water height values at these distant stations (e.g., at a depth of 10 meters) can be converted to values at the coastline using approximate methods such as Green's Law approximation (Kamigaichi, 2015).

Ultimately, while both reducing the FD grid spacing and increasing bathymetric resolution improve the accuracy of tsunami modeling results, the effect of bathymetric resolution is significantly greater. High-resolution bathymetry plays a more critical role than the size of the FD grid spacing. Additionally, when bathymetric resolution is insufficient, reducing the FD grid spacing below the bathymetric resolution does not significantly enhance accuracy unless the desired station is near the coast and not located on an FD grid point.

Theoretically, as FD grid spacing decreases, computational time increases, while the solution becomes more precise. However, this study shows that, with a bathymetric resolution of 15 seconds, reducing the FD grid spacing to one-third of its original size (from 15 to 5 seconds) does not substantially improve accuracy, especially for points that are not very close to the coastline. In contrast, when the bathymetric resolution is 3 seconds, the improvement from decreasing the FD grid spacing is clear, especially for stations that are very close to the coastline. Therefore, using an FD grid spacing smaller than the bathymetric data resolution does not substantially impact the accuracy of the numerical solution unless the desired station is near the coastline and not located on an FD grid point.

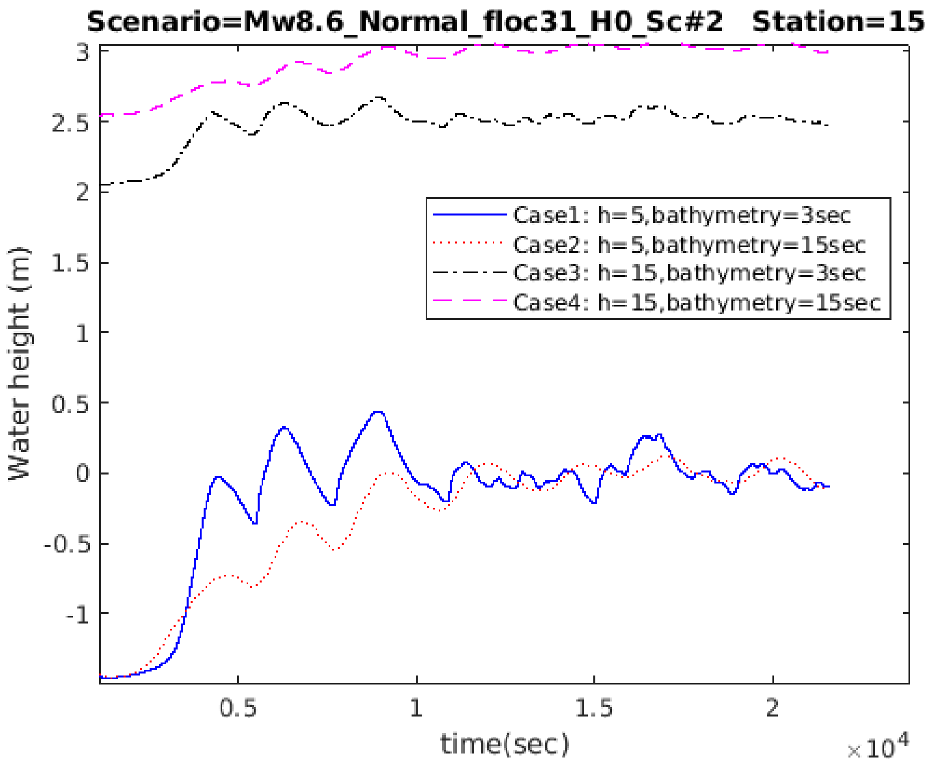

Figure 9. Time history of tsunami wave height at station 15 for one of the 38 scenarios, across the four cases of layer 3.

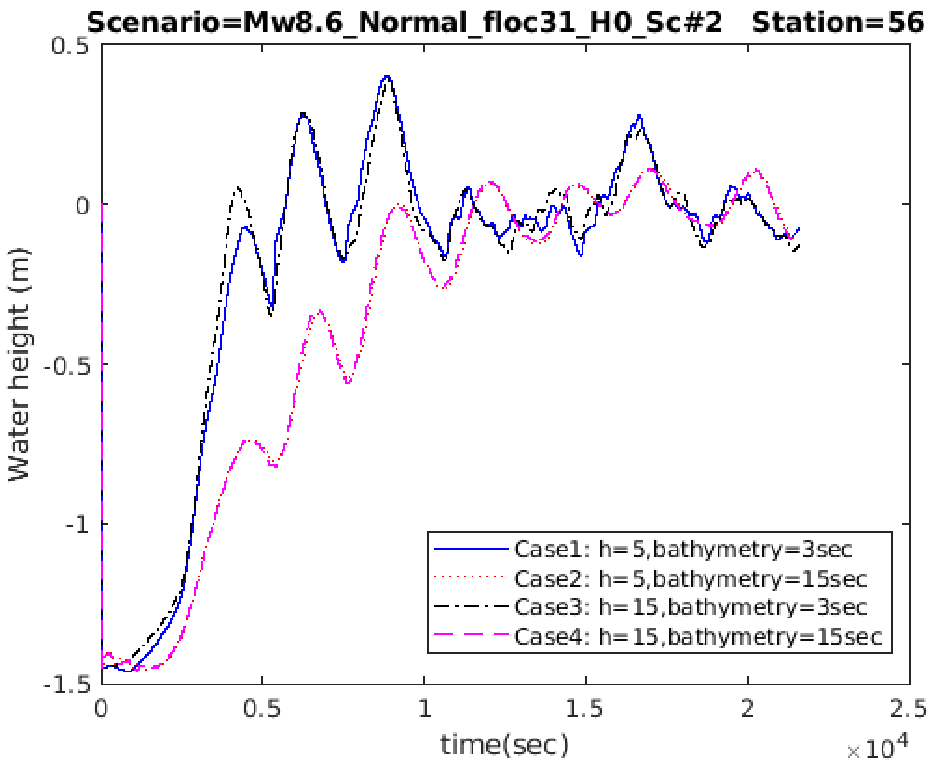

Figure 10. Time history of tsunami wave height at station 56 for one of the 38 scenarios, across the four cases of layer 3.

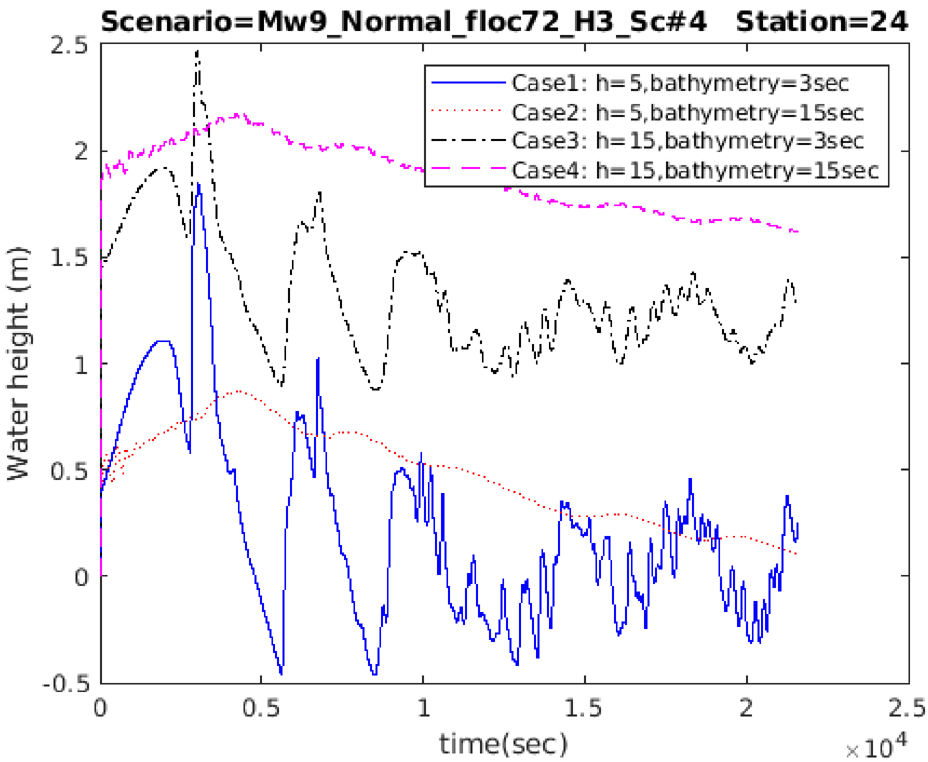

Figure 11. Time history of tsunami wave height at station 24 for one of the 38 scenarios, across the four cases of layer 3.

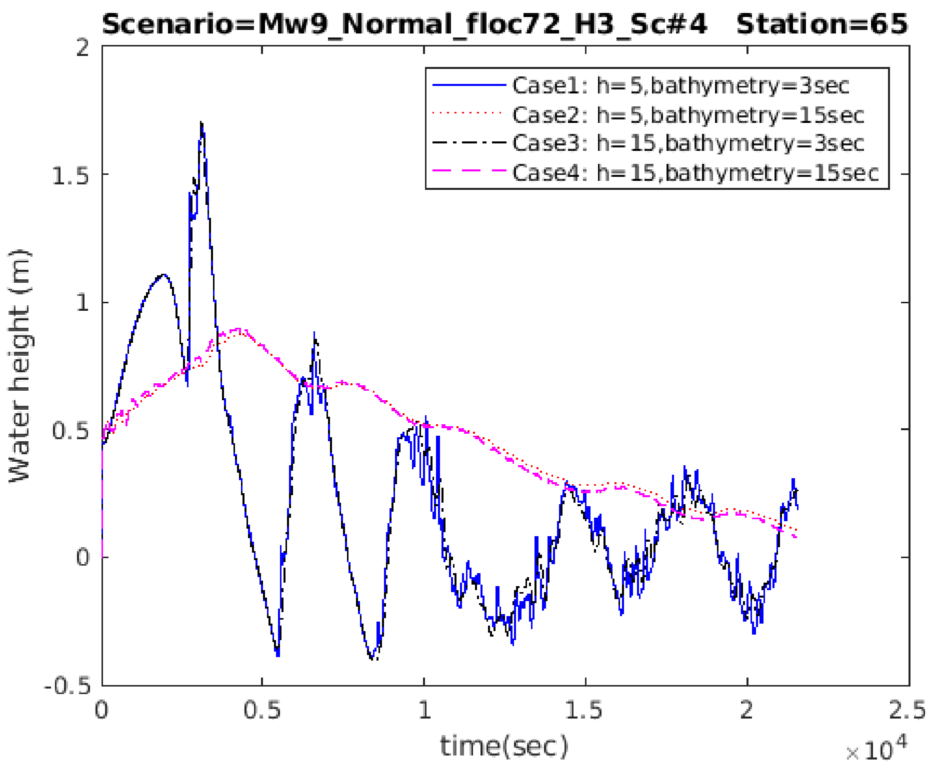

Figure 12. Time history of tsunami wave height at station 65 for one of the 48 scenarios, across the four cases of layer 3.

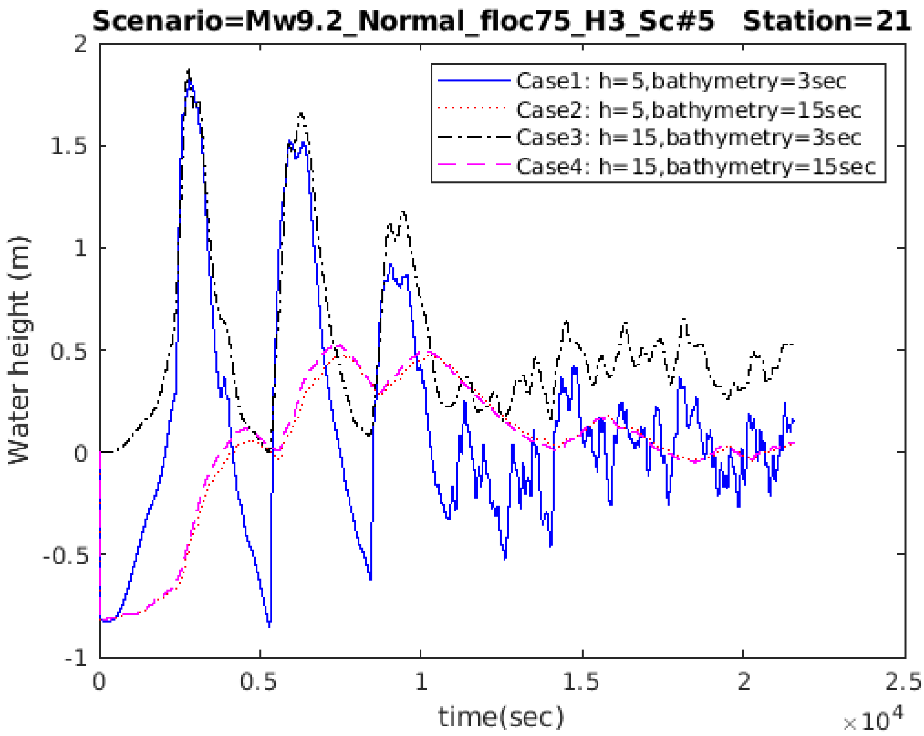

Figure 13. Time history of tsunami wave height at station 21 for one of the 38 scenarios, across the four cases of layer 3.

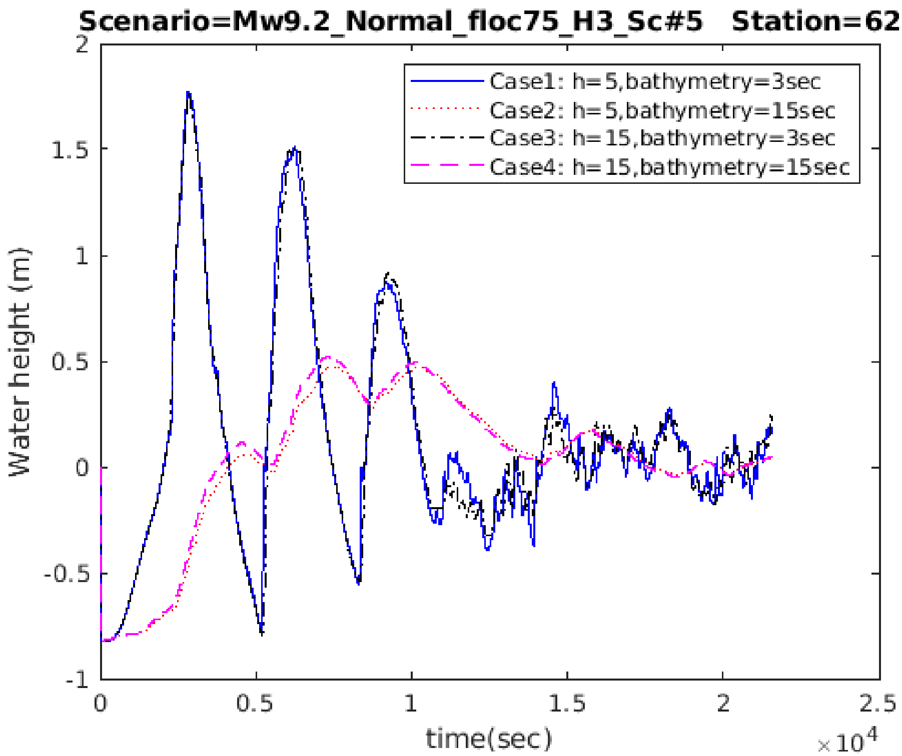

Figure 14. Time history of tsunami wave height at station 62 for one of the 38 scenarios, across the four cases of layer 3.

4 Conclusions

This study examined the impact of bathymetric data resolution and FD grid spacing on the accuracy of numerical tsunami modeling. For this purpose, we focused on Chabahar Bay, where bathymetric data with resolutions of 3 seconds and 15 seconds are available. We utilized 38 tsunami-generating earthquake scenarios in various locations of the Makran subduction zone, with different non-uniform slip distributions and fault depths of 0, 3, and 14 km, using the COMCOT tsunami model, which employs FD for numerical modeling. A nested grid with three layers was applied in this study, defining four ordered pairs of bathymetric resolution and FD grid spacing in layer 3, the smallest layer that circumscribes Chabahar Bay.

The results indicate that increasing the resolution of bathymetric data is significantly more effective at improving the accuracy of the numerical tsunami solution than reducing the FD grid spacing. Furthermore, the importance of bathymetric data resolution and especially the FD grid spacing size grows as one approaches the coast. Notably, when it is not practical to consider the FD grid spacing small enough, focusing on stations located farther from the coast can yield more reliable results, as these stations are less sensitive to FD grid spacing.

Additionally, placing stations directly on FD grid points is critical to improving the accuracy of wave height assessments, as interpolating values from grid points may introduce errors, particularly for coastal stations. While theoretically, reducing FD grid spacing enhances computational precision, this study shows that reducing FD grid spacing from 15 to 5 seconds does not substantially improve accuracy when using 15-sec bathymetric data, for stations that are not very close to the coastline. In contrast, a clear improvement in accuracy is observed with 3-sec bathymetric data. Therefore, these findings underscore the significance of high-resolution bathymetry in tsunami modeling and provide practical guidance on optimizing FD grid spacing relative to the available bathymetric resolution and the location of the station.

Acknowledgments
We gratefully acknowledge the support provided by the International Institute of Earthquake Engineering and Seismology (IIEES).

References

Dutykh, D., Dias, F., & Kervella, Y. (2006). Linear theory of wave generation by a moving bottom. Comptes Rendus Math., 343, 499-504. https://doi.org/10.1016/j.crma.2006.09.016

Etemadsaeed, L., Zafarani, H., Saber, F. (2024). Sensitivity analysis of tsunami numerical modeling to bathymetric data and finite difference grid spacing. 9th International Conference on Seismology and Earthquake Engineering, Tehran, Iran.

GEBCO Compilation Group (2020). GEBCO Gridded Bathymetry Data. https://doi.org/10.5285/e0f0bb80-ab44-2739-e053-6c86abc0289c

Heidarzadeh, M., & Satake, K. (2014). Possible sources of the tsunami observed in the northwestern Indian Ocean following the 2013 September 24 Mw 7.7 Pakistan inland earthquake. Geophys. J. Int., 199(2), 752-766. https://doi.org/10.1093/gji/ggu297

Imamura, F., Yalciner, A. C., & Ozyurt, G. (1995). Tsunami modelling manual, Technical Report, Disaster Control Research Center, Tohoku University, Sendai, Japan.

Kamigaichi, O. (2015). Tsunami Forecasting and Warning. Encycl Complex Syst Sci, 1–38. https://doi.org/10.1007/978-3-642-27737-5_568-3

Kervella, Y., Dutykh, D., & Dias, F. (2007). Comparison between three-dimensional linear and nonlinear tsunami generation models. Theor Comput Fluid Dyn, 21, 245-269. https://doi.org/10.1007/s00162-007-0047-0

Liu, P. L. F., Woo, S. B., & Cho, Y. S.

(1998). Computer Programs for Tsunami Propagation and Inundation. Technical Report, School of Civil and Environmental Engineering, Cornell University, p. 111.

McCaffrey, R. (2008). Global frequency of magnitude 9 earthquakes. Geology, 36, 263-266. https://doi.org/10.1130/G24402A.1

Okada, Y. (1992). Internal deformation due to shear and tensile faults in a half-space. Bulletin of the Seismological Society of America, 82, 1018–1040.

Rashidi, A., Shomali, Z. H., Dutykh, D., & Keshavarz Farajkhah, N. (2020). Tsunami hazard assessment in the Makran subduction zone. Natural Hazards, 100(2), 861-875. https://doi.org/10.1007/s11069-019-03848-1

Steketee, J. A. (1958). On Volterra's dislocations in a semi-infinite elastic medium. Can J Phys, 36, 192–205. https://doi.org/10.1139/p58-024

Zafarani, H., Etemadsaeed, L., Rahimi, M., Kheirdast, N., Rashidi, A., Ansari, A., Mokhtari, M., & Eskandari-Ghadi, M. (2023). Probabilistic tsunami hazard analysis for western Makran coasts, south-east Iran. Natural Hazards, 115(2), 1275-1311. https://doi.org/10.1007/s11069-022-05595-2