DOI: 10.24850/j-tyca-13-06-09

Articles

Assessment of the tsunami hazard on the Algerian coast: Scenario study of a tsunami generated by an earthquake on the Bay of Algiers

Evaluación del peligro de tsunami en la costa argelina: estudio de escenario de un tsunami generado por un terremoto en la bahía de Argel

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Abstract

The western Mediterranean coasts have been hit by tsunamis in the past and can be opposed to this risk at any time. The North African margin is the main area prone to destructive earthquakes that sometimes trigger tsunamis and potentially harm human life and coastal city property. The present study consists of numerical modeling of a wave of tsunami acting on the Algerian coasts for an earthquake of magnitude Mw 7.55 with length and width of the fault (73.3 x 29.9 km) and a vertical slip of 3.5 meters. This numerical modeling is based on a code of calculations developed based on the two-dimensional hydrodynamic model sources Telemac-2D, making it possible to map the heights of the waves and maximum speeds generated by the tsunami. The simulation indicates that the maximum values for the surface heights are about 1.2 meters and 30 to 50 m/s for the flow velocities. The results show that our study area is more exposed to the inundation hazard by a tsunami causing significant damage to basic infrastructure. The results obtained are exported to a GIS information platform allowing the development of an illustrative cartography of the hydraulic characteristics of the tsunami's wave generated and the arrival time and displacement of the inundation with the location of vulnerable areas to inundation. This constitutes a decision-making tool for land use planning decision-makers and a means of Risk

Tecnología y ciencias del agua, ISSN 2007-2422, 13(6), 408-452. DOI: 10.24850/j-tyca-13-06-09

mitigation in the event of potential earthquakes causing tsunamis in the region.

Keywords: Height, inundation, Numerical modeling, speed, Telemac.

Resumen

Las costas del Mediterráneo occidental han sido afectadas por tsunamis en el pasado y pueden oponerse a este riesgo en cualquier momento. El margen del norte de África es una zona principal propensa a terremotos destructivos que a veces desencadenan tsunamis y plantean un peligro potencial para la vida humana y los bienes de las ciudades costeras. El presente estudio consiste en un modelado numérico de una ola de tsunami que actúa sobre las costas argelinas para un terremoto de magnitud Mw 7.55 con longitud y anchura de la falla (73.3 x 29.9 km) y un deslizamiento vertical de 3.5 metros. Este modelado numérico basado en un código de cálculos desarrollado sobre la base de las fuentes de modelos hidrodinámicos bidimensionales Telemac-2D permite mapear las alturas de las ondas y las velocidades máximas generadas por el Tsunami. La simulación indica que los valores máximos para las alturas de superficie son de aproximadamente 1.2 metros y de 30 a 50 m/s para las velocidades de flujo. Los resultados obtenidos muestran que el área de estudio está más expuesta al riesgo de inundación por un tsunami que causa daños significativos a la infraestructura básica. Los resultados obtenidos se exportan a una plataforma de información SIG que permite el desarrollo de una cartografía ilustrativa de las características hidráulicas de la ola generada por el tsunami, y de la hora de llegada y desplazamiento de la inundación con la ubicación de zonas vulnerables a la inundación. Esto constituye una herramienta de toma de decisiones para los tomadores de decisiones de planificación del uso de la tierra y también un medio de mitigación del riesgo en el caso de los posibles terremotos que causan tsunamis en la región.

Palabras clave: altura, inundación, modelado numérico, velocidad, Telemac.

Received: 24/05/2021

Accepted: 30/08/2021

Introduction

Due to the collision between the African and Eurasian plates, the region of Algiers is under a regime of compression with a field of constraints directed to NNW-SSE (Domzig *et al*., 2006). This region has moderate seismicity and sometimes earthquakes greater than 6 (Amir, Cisternas, Dudley, McAdoo, & Pararas-Carayannis, 2013). These earthquakes are localized in the marine environment (Boumerdès in 2003) or nearby (El-Asnam in 1954 and 1980) (Heddar *et al*., 2012) and are therefore able to generate tsunamis by the simple transmission of the coseismic deformation to the mass of overlying water or neighbor (Domzig *et al*., 2006; Yelles-Chaouche, 1991). As was the case during the earthquake of Boumerdès of 2003 of magnitude Mw 6.8, registered in many places in the western Mediterranean, on the Algerian coast, and the Balearic Islands (Sahal *et al*., 2009). In this context, this study relates to the numerical modeling of the wave of a tsunami from the scenario of an earthquake of magnitude Mw 7.55 to the Algerian coast with length and width of the fault (73.3 x 29.9 km) and a vertical slip of 3.5 meters. The epicenter is here located at 2.98E, 36.98N. The numerical simulation of the tsunami is done by the resolution of equations of Saint Venant (continuity equation and the equation of conservation of the quantities of movement) according to the linear and non-linear approximations "shallow water" (Thual, 2003; Tan, 1992), it is considered that the fluid is incompressible, homogeneous and non-viscous (the density of the fluid is constant), this assumption allowed us to integrate the value (ρ = constant) in the continuity equation to simplify the equation of momentum (Allgeyer *et al*., 2012). We also assume that the acceleration of vertical motion is negligible compared to the acceleration due to gravity. This hypothesis allows us to translate the pressure in terms of depth of immersion (Hervouet, 2001; Thual, 2003). Solving the equations describing the propagation of the tsunami is carried out using a diagram digital finite element (Hervouet, 2003), in spherical or cartesian coordinates (Mader, 2004), in a system of nested grids. With the approach of the coasts, the period of the waves and the wavelength decreases strongly. The energy conservation led to an increase in the height of the waves. Modeling tsunamis near coastal areas require fine meshing to take into account the strong irregularities in the bathymetry and accurately assess the flood zones. On the other hand, modeling far from the coast does not require such precision. The mesh used is constructed by integrating bathymetric data and topographic data.

Materials and methods

To achieve the objectives of this study, an approach based on integrating the geographic information system Quantum-GIS (https://docs.qgis.org/3.16/en/docs/user_manual/), and the TELEMAC system was used; this approach is represented by the following flowchart (figure 1).

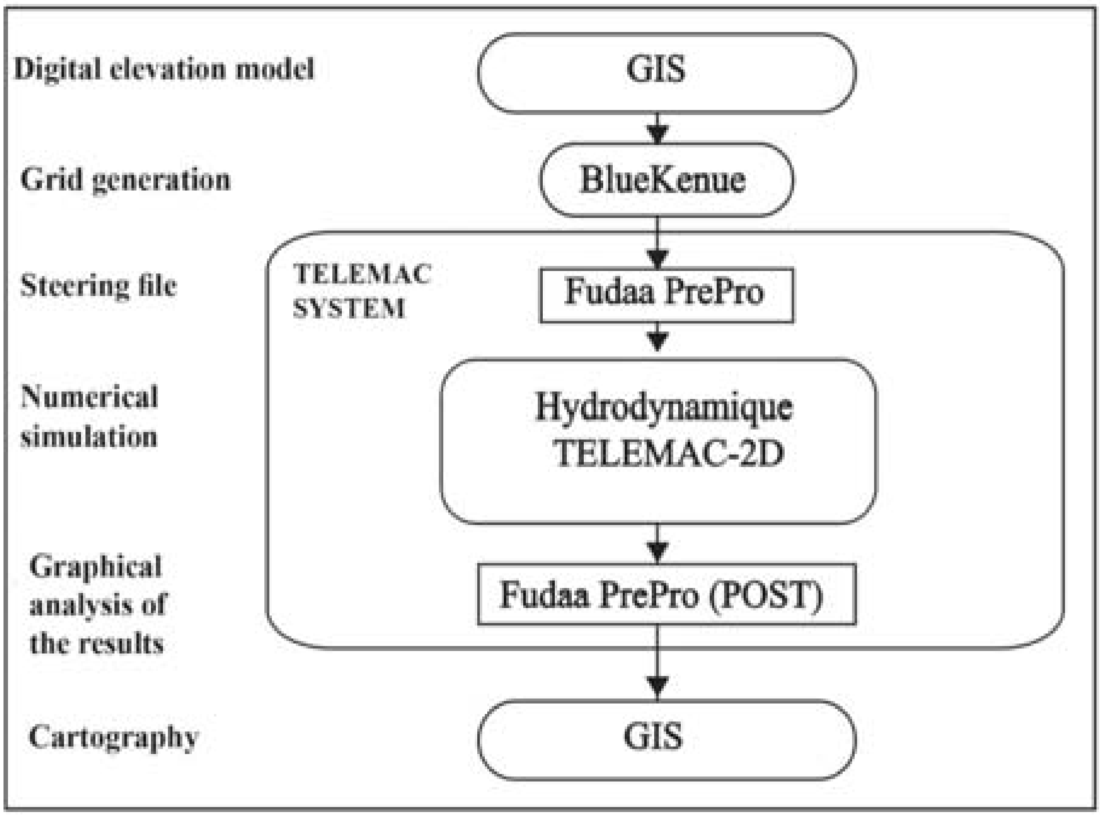

Figure 1. Flowchart showing the employed methodology.

Blue Kenue

Blue Kenue is an advanced data preparation, analysis, and visualization tool for hydraulic modeling. It allows to prepare and integrate of the geometric data (grid generation) with the input data and to visualize the results once the simulation is completed (Government of Canada, 2022); it provides visualization by dynamic 1D, polar, 2D, and 3D views. Indeed, one of the advantages of Bluekenue is that it is compatible with many data formats (.xyz, .shp, ...) Thus, we were able to import the isolines corresponding to the isobathymetry lines in the form of a GIS shape file. A mesh has been created, which is based on the isobathymetric lines. The grids obtained have meshes of 200 x 200 m for the bathymetry and 30m x 30 m for the topography.

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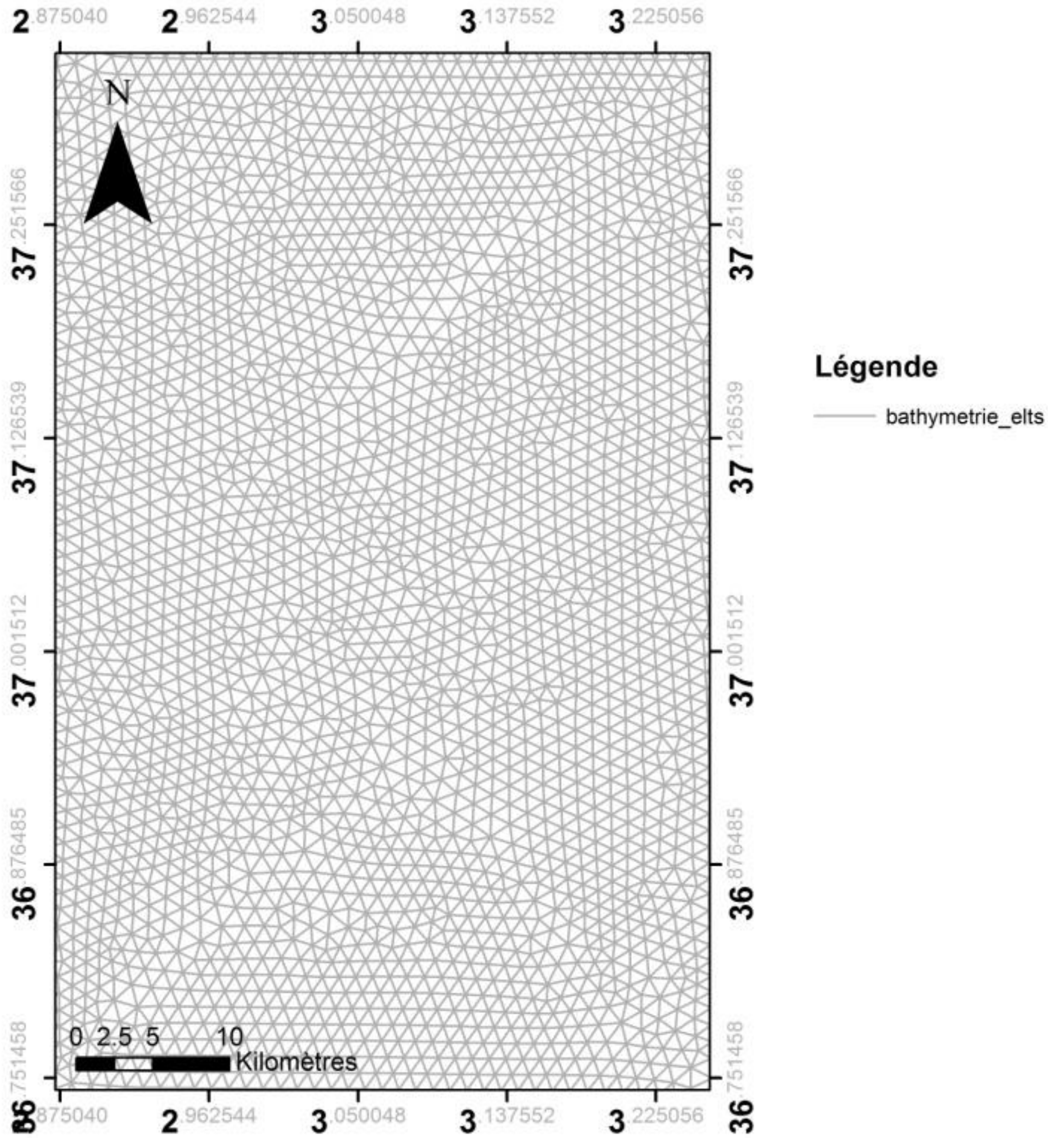

Figure 2. Triangular mesh of the study area with BlueKenue software.

Hydrodynamic modeling

Fudaa prepro

FUDAA PREPRO is a pre-processing and post-processing tool for many hydraulic models; it allows the users to define the parameters to introduce in the hydraulic model (*e.g.*, initial and boundary conditions) (Atlassian, n.d.).

Telemac-2d

The model used to simulate tsunami propagation is a code based on the open sources of the TELEMAC-2D code (Wiki, 2022).

The equations governing the dynamics of free surface flows are described by the equations of Saint-Venant, in the non-

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dispersive medium. Consequently, the temporal evolution of the wave height and the horizontal currents is calculated at any point in the study area. The calculation is based on solving the following hydrodynamic equations (Hervouet, 2007):

Continuity equation :

$$\frac{\partial h}{\partial t} + u.\nabla h + h\mathrm{div}(u) = S_h \tag{1}$$

Momentum along x :

$$\frac{\partial u}{\partial t} + u.\nabla u = -g\frac{\partial Z}{\partial x} + S_x + \frac{1}{h}\mathrm{div}(hv_t.\nabla u) \tag{2}$$

Momentum along y :

$$\frac{\partial v}{\partial t} + u.\nabla v = -g\frac{\partial Z}{\partial y} + S_y + \frac{1}{h}\mathrm{div}(hv_t.\nabla v) \tag{3}$$

Where:

h (m) is the height of the water.

u and *v* are components of the velocity (m/s).

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v_t diffusion coefficients of the velocity and the tracer (m^2/s).

Z is the coast of the free surface (m).

t is time (s).

x and y are horizontal space coordinates (m).

S_h is the source or fluid wells (m/s).

S_x and S_y (m/s^2) are source terms or wells of the dynamic equations.

h, u, and v are the unknown.

Initial conditions and limits

The initial conditions used in the simulation consist in initializing the free surface elevation to zero, in which Telemac-2D automatically calculates the initial depths of the water by the difference between the free surface and the bottom.

A Thompson boundary condition is applied at the coast level to allow outgoing waves to propagate freely across the domain, in which case Telemac-2D automatically calculates the boundary values. The Thompson method is to use the characteristics method to try to

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calculate the missing information. This technique is also useful when the model is over-constrained, meaning that too much information is provided at the limit. In this case, if the speed and level of information are inconsistent, there is a tendency to draw too much or not enough energy into the model. In this case, the Thompson method makes it possible to recalculate a speed and adjust the information imposed on the limit very slightly to make it consistent (EDF-DRD, 2010).

Further, a Manning coefficient has been set at 0.025 for depths below zero and 0.06 for dry land modeling.

Bathymetric data

The bathymetric data used for the study area come from the international database GEBCO 30 (British Oceanographic Data Centre & National Oceanography Centre, n.d.) is supported by the International Hydrographic Organization (IHO), by the United Nations (UNESCO) as well as by the Intergovernmental Oceanographic Commission (IOC). The bathymetric information is the result of a compilation at the scale of the globe of bathymetric surveys and data from satellite altimetry. They are issued free of charge (British Oceanographic Data Centre & National Oceanography Centre, n.d.).

An extraction was performed for the area covering the whole of the western Mediterranean basin (Figure 3).

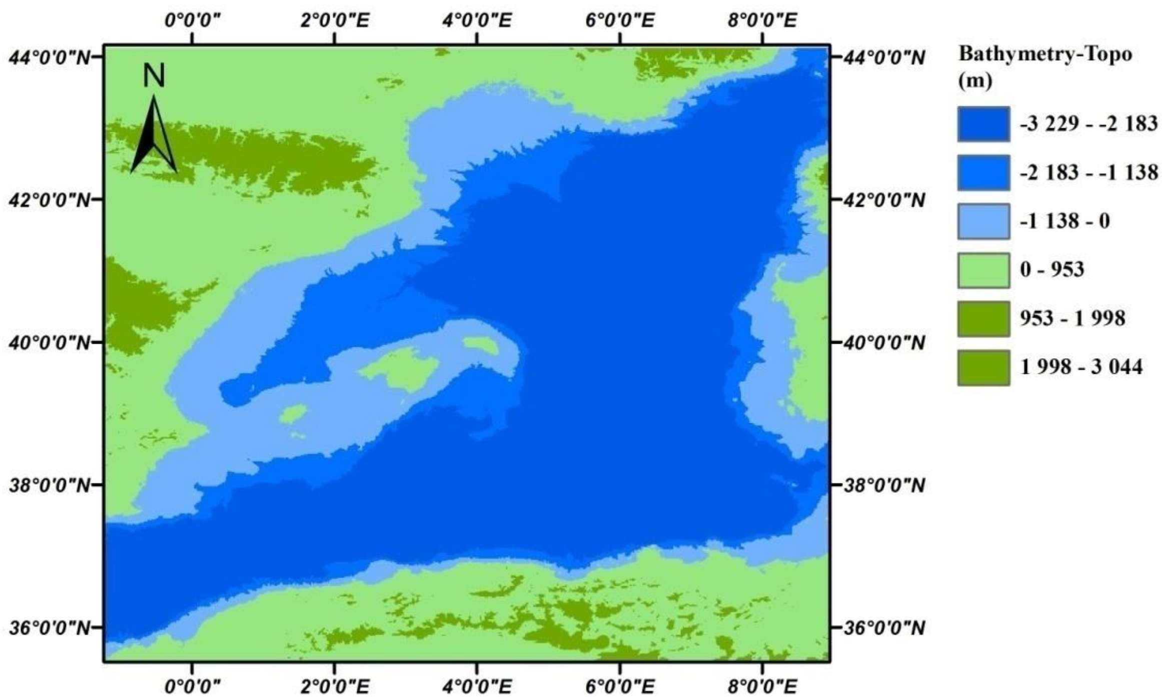

Figure 3. Extract the GEBCO30 file: bathymetry with an average mesh of 1'x1' (National Oceanography Centre & British Oceanographic Data Centre, 2022).

The study area extends from 2.85° E to 3.29° E to the latitude and 36.68° N to 37.38° N for the longitude.

Construction of digital elevation model grids

The various sources of topo-bathymetric data were used to construct the grids necessary for the calculations with meshes of 200 m x 200 m and 30 x 30 m for the finest. The DEM was produced using the Blue Kenue software using the linear interpolation triangulation method. This interpolation method is chosen because most of the data used already mesh and the large number of values considered. The quality of the data interpolated by this method was tested by cross-validation. This technique involves removing the measured data one by one and then predicting it from the interpolation of the neighboring data. Cross-validation errors are then obtained by subtracting the predicted values of the measured values. This procedure made it possible to locate significant punctual errors at the border of the SRTM (Shuttle Radar Topography Mission) and GEBCO data. This is due to the combination of data from multiple sources at very different scales and of several types: meshes and probes. Once located,

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these erroneous points were removed, and new interpolations were made. The final mesh of the compute domain has 90240 nodes.

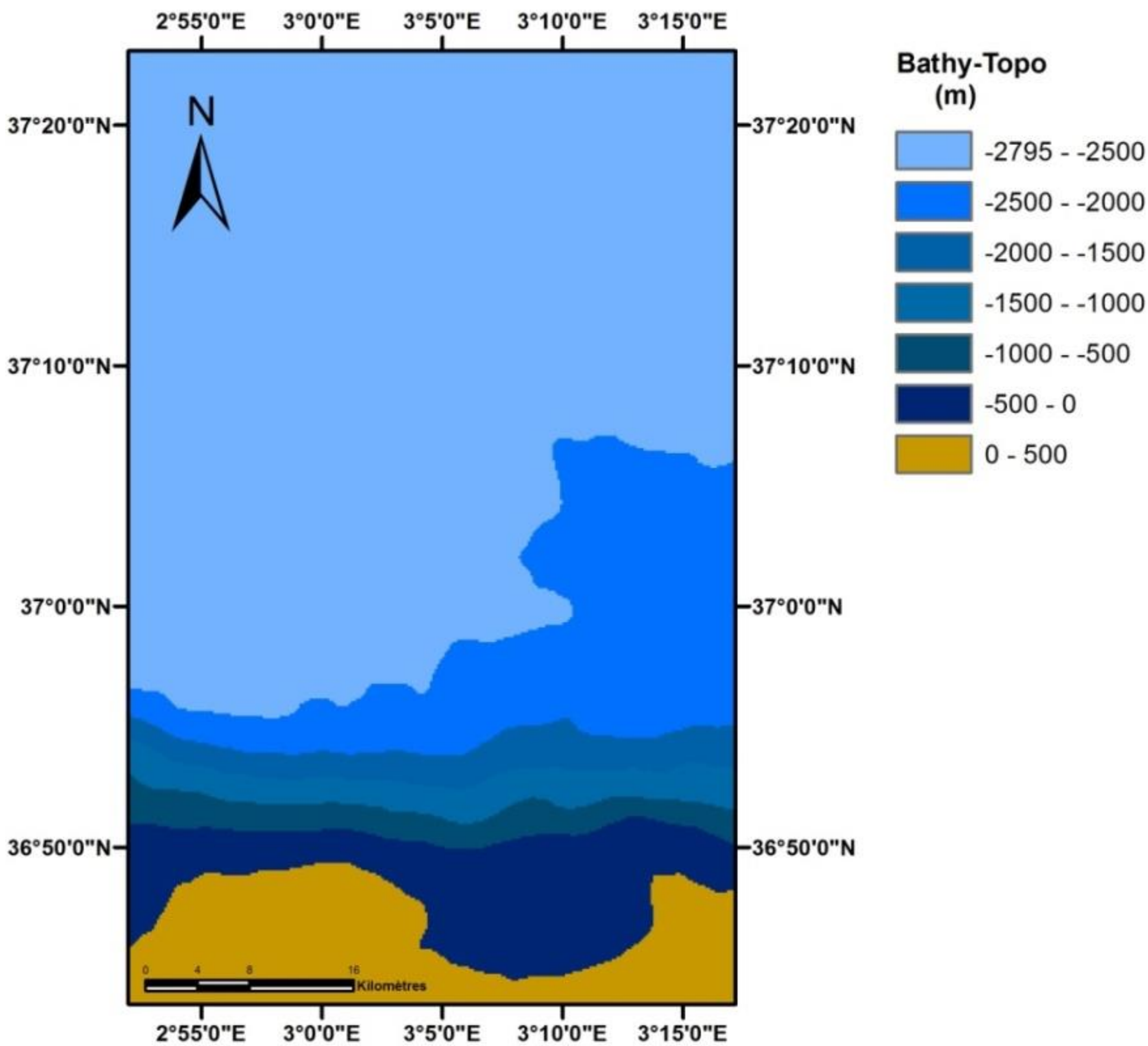

Figure 4. Mesh of the study area built from SRTM / GEBCO30 data.

The result of the modeling will depend strongly on the quality of bathymetric data.

Parameters of source-earthquakes

In this work, earthquake parameters and seismic zoning are based on previous studies (Terrier, 2007). In this context, a scenario of an earthquake of magnitude Mw 7.55 is chosen for modeling the tsunami. The epicenter of this earthquake is located at 2.98 E, 36.98N at 20 km north of the Algerian coast; the fault's length and width (73.3 x 29.9 km) with a vertical slip of 3.5 meters and the focal depth of seism are 07 km. The exact source of the earthquake is generated by the movement of a blind reverse fault-oriented NE-SW (Yelles *et al*., 2009). The scenario corresponds to the maximum credible event for return periods probably several hundred to several thousand years.

Results and discussion

Initial deformation

This model consists initially in calculating the initial deformation associated with a seismic failure using the TOMAWAC calculation code (Wiki, 2014) using the algorithms developed by (Okada, 1992), which correspond to the method commonly used by the various models based on the elastic half-space theory (Allgeyer *et al*., 2012; George & Leveque, 2006).

These algorithms allow us to calculate the deformation of the ocean floor from the characteristics of the flaw, which is the origin of the earthquake, to allow this deformation to propagate to the free surface (Figure 5).

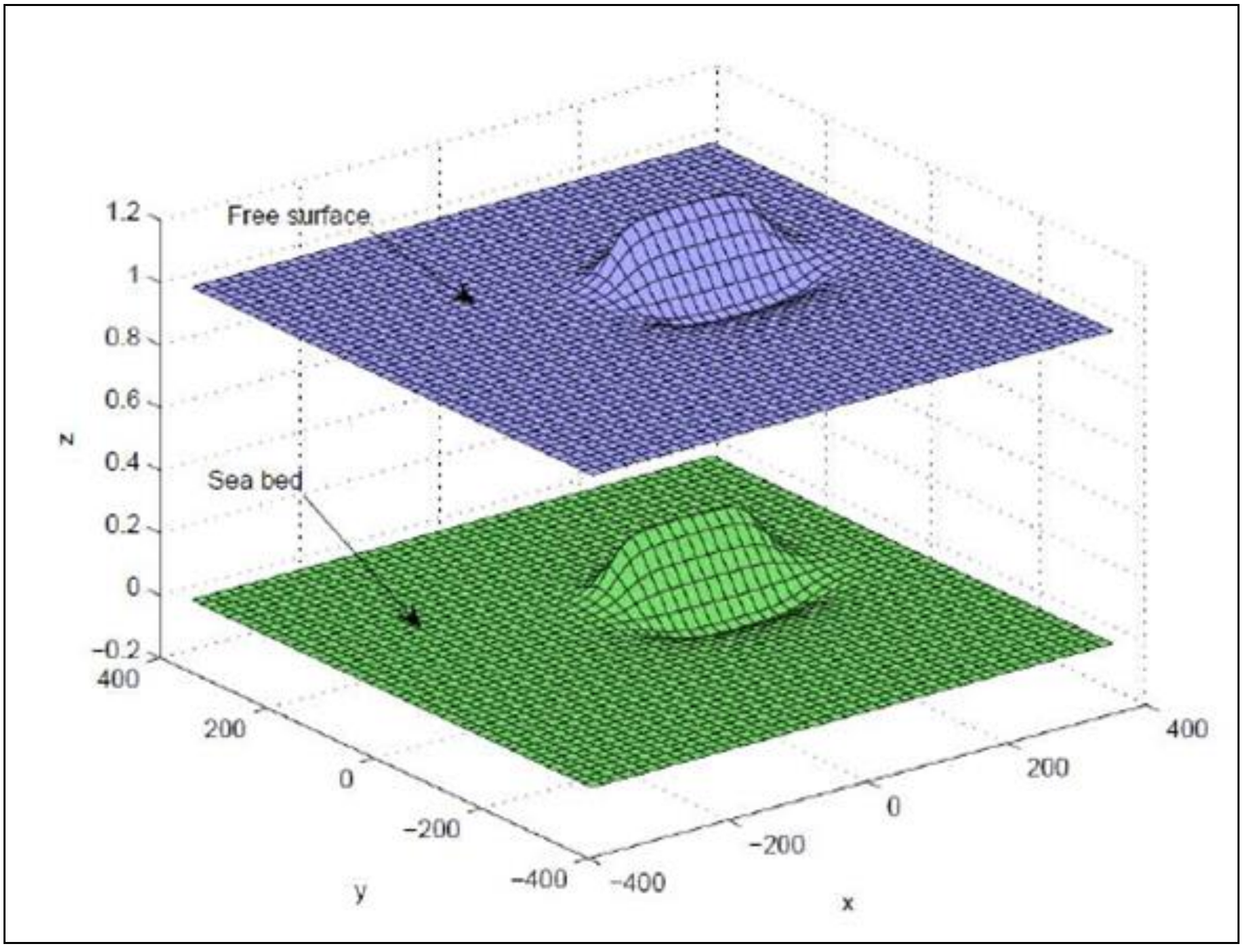

Figure 5. Calculation principle is the initial deformation associated with a seismic rupture.

The result shows a maximum deformation of 1.6 meters in the free surface (Figure 6).

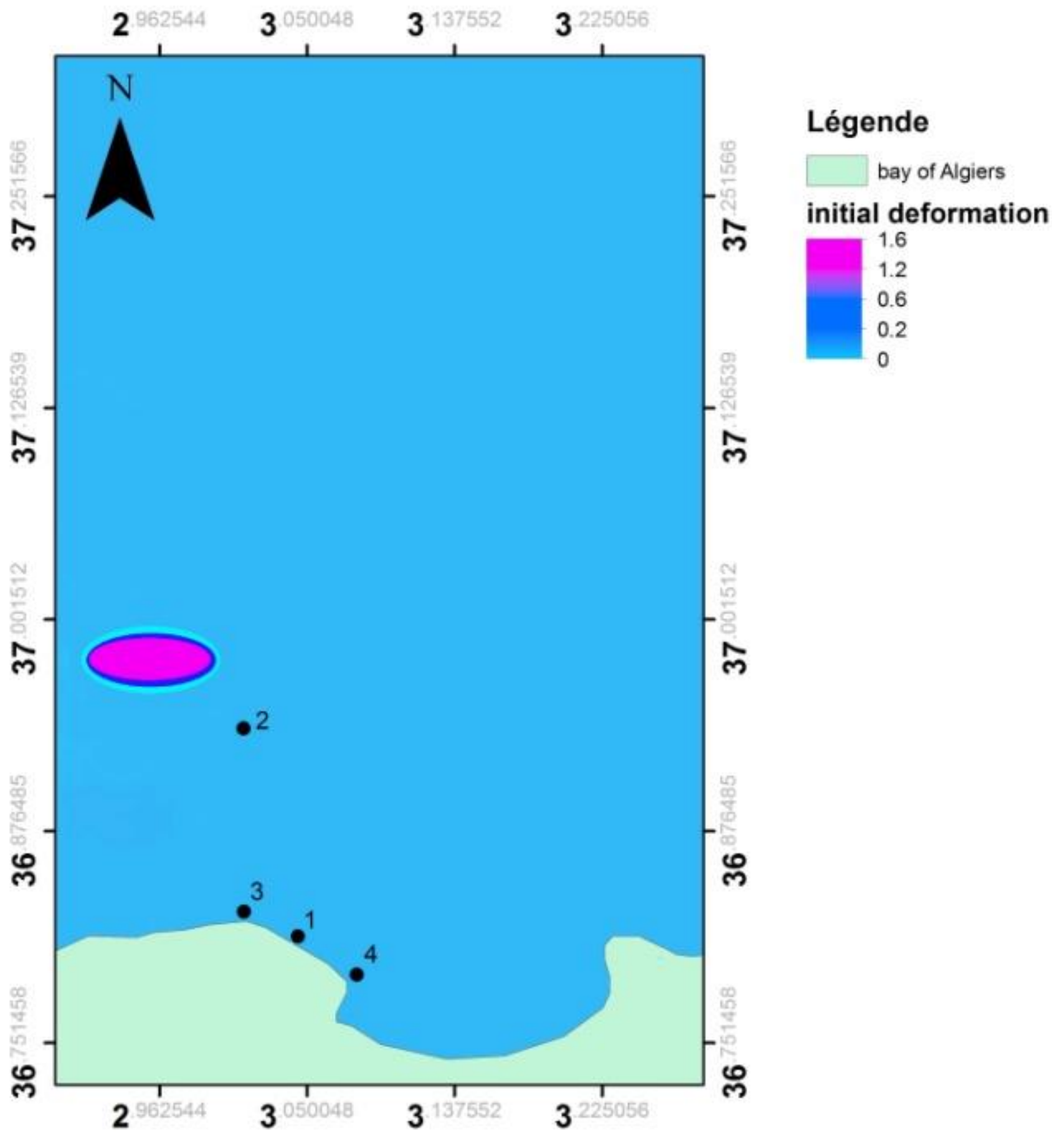

Figure 6. Initial deformation of the water surface simulated for an earthquake of Mw 7.55.

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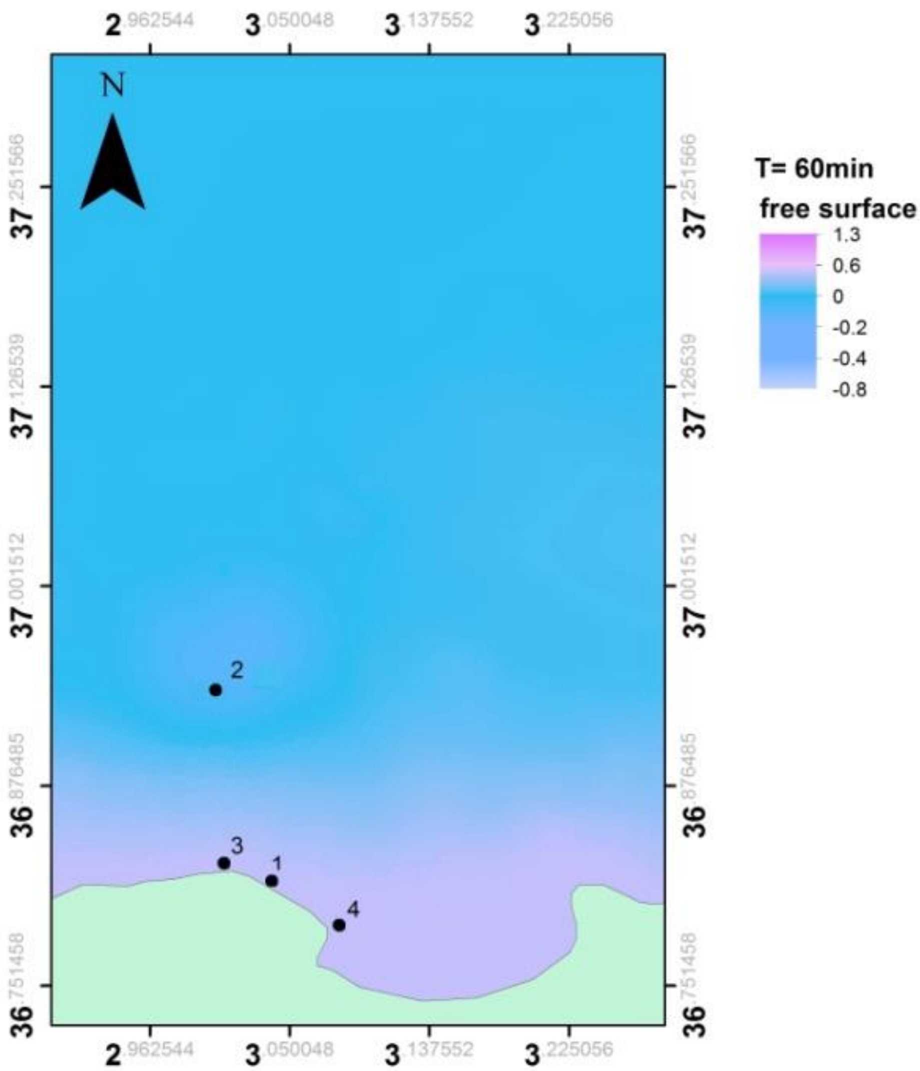

Figure 7. Illustration of the tsunami propagation generated by an earthquake of magnitude Mw 7.55 after 60 min in the North-West region of the Bay of Algiers.

In this study, we present the maximum height and horizontal velocity simulated for four different measurement points located along the coast of Algiers over one hour, summarized in Table 1. These four measurement points are established according to the morphometric properties of Algiers Bay.

Table 1. Location of the points chosen for the region of Algiers.

ID Point	Latitude (N°)	Longitude (E°)
1	3.0467	36.8144
2	3.0163	36.9232
3	3.0121	36.8292
4	3.0782	36.7935

The hydraulic results obtained by digital simulation show that the peak of the tsunami reaches the coasts of the Bay of Algiers after 10 minutes of the earthquake. Figure 8, Figure 9, Figure 10, and Figure 11 present the wave heights simulated for the four points.

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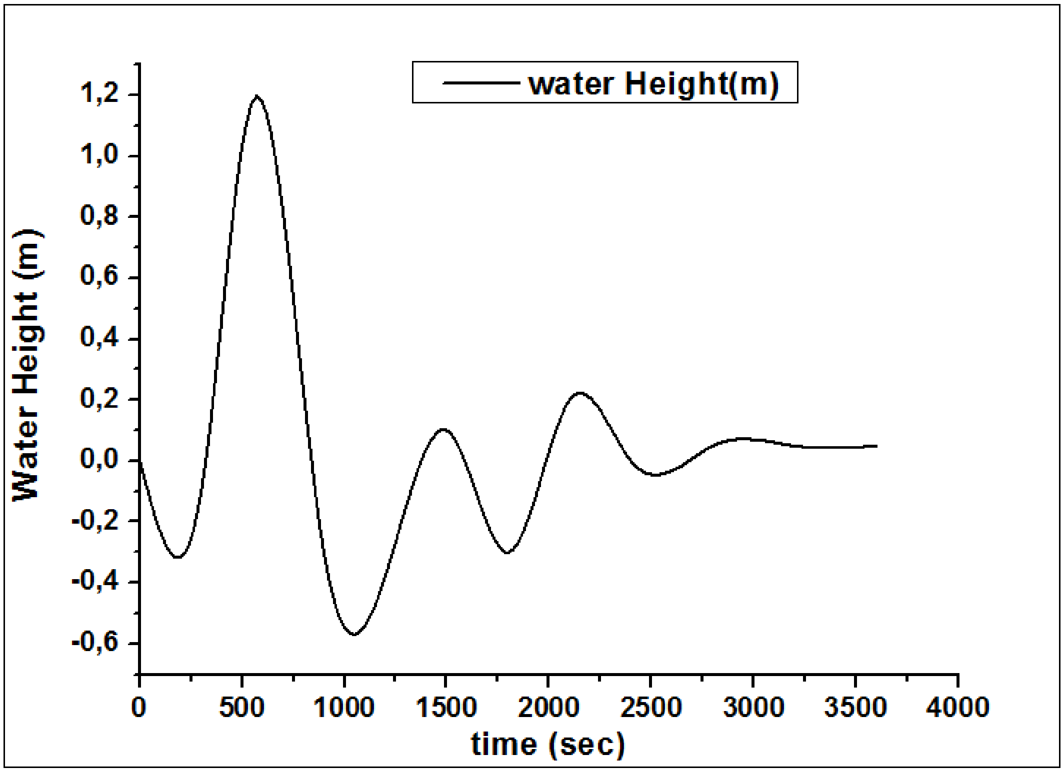

Figure 8. Wave heights simulated in Point 1.

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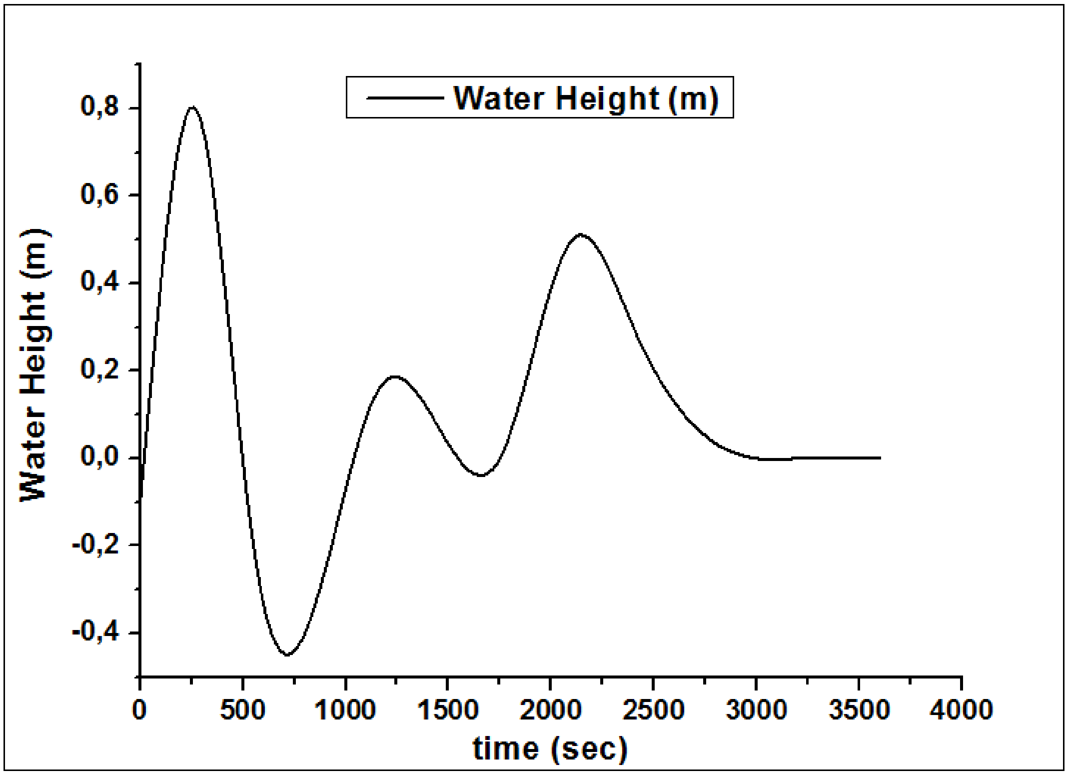

Figure 9. Wave heights simulated in Point 2.

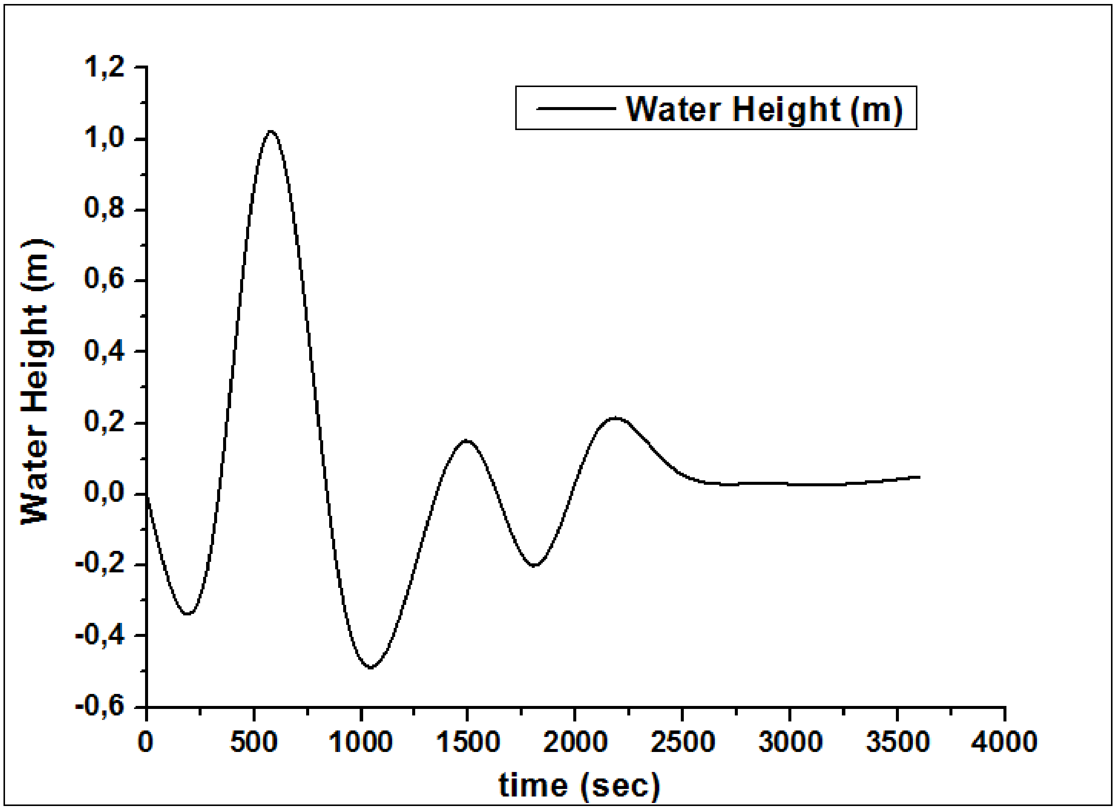

Figure 10. Wave heights simulated in Point 3.

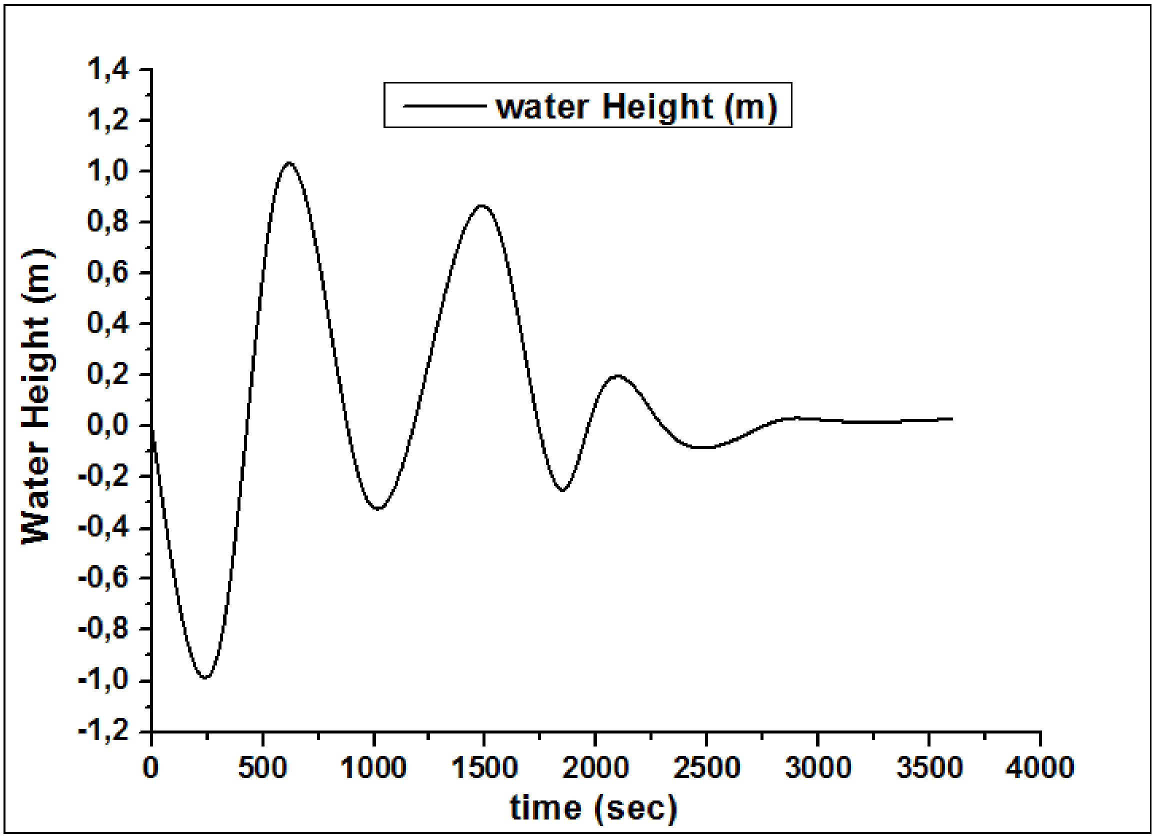

Figure 11. Wave heights simulated in Point 4.

Wave heights greater than one meter are obtained for points 1, 3, and 4. These three points are located precisely near the coast of the Bay of Algiers.

When approaching the coasts (points 1, 3, and 4), the speed of the tsunami and the wavelength decrease but its amplitude increases (shoaling effect) with the decrease in depth. There is then a transfer

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between the declining kinetic (velocity) energy and the increasing potential (wave height) energy (Lavigne *et al*., 2011).

The maximum wave height is obtained at point 1, equal to 1.2 meters.

At point 2, located near the epicenter, the height of the swell obtained is 0.8 meters. This is lower than what is observed closest to the coast of Algiers.

According to this simulation, the peak in points 1, 3, and 4 would be produced 8 minutes after the earthquake, against the peak in point2 would be 4 minutes after the earthquake. The maximum wave height reaches around 1.2 meters in the Bay of Algiers.

This bay is in the shape of a semicircle, with a maximum length of approximately 35 km and a maximum width of about 7.0 km, open to the north, and the bottom is in a gentle, uniform slope in the order of 1.1 % of the 0 m isobath to that of the 100 m. The morphology and orientation of the bay also contributed to the amplification of the tsunami.

Figures 12, 13, 14, 15, 16, 17, 18 , and 19 present the evolutions of horizontal and vertical velocities (u,v) calculated for the four points.

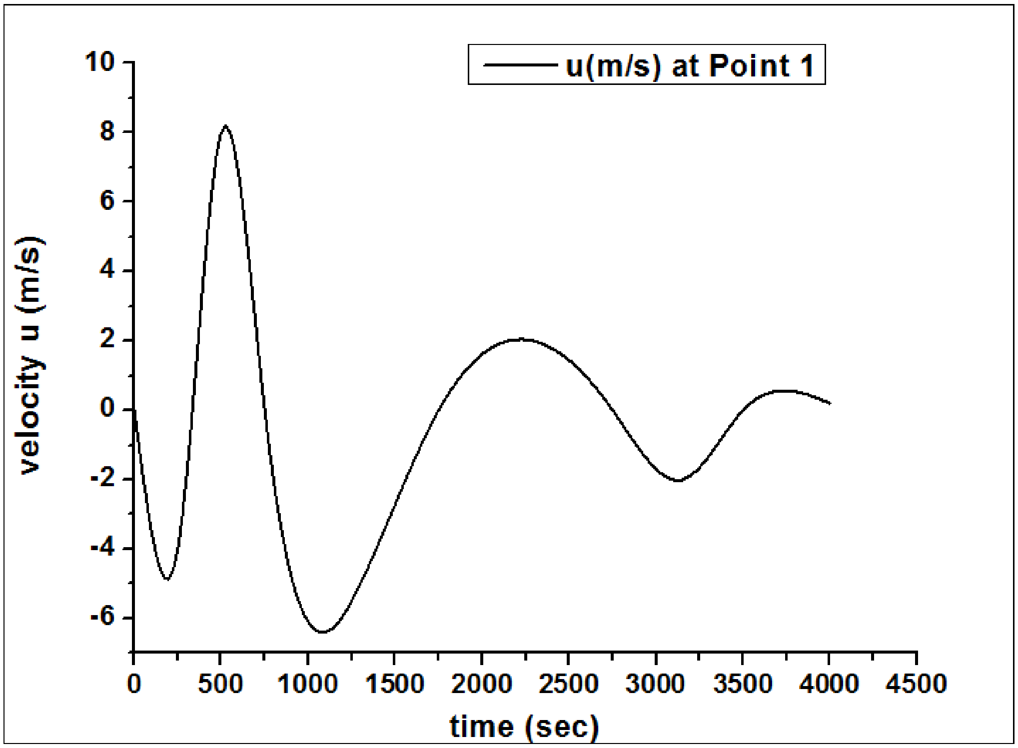

Figure 12. Evolution of Horizontal velocity *u* (m/s) for Point1.

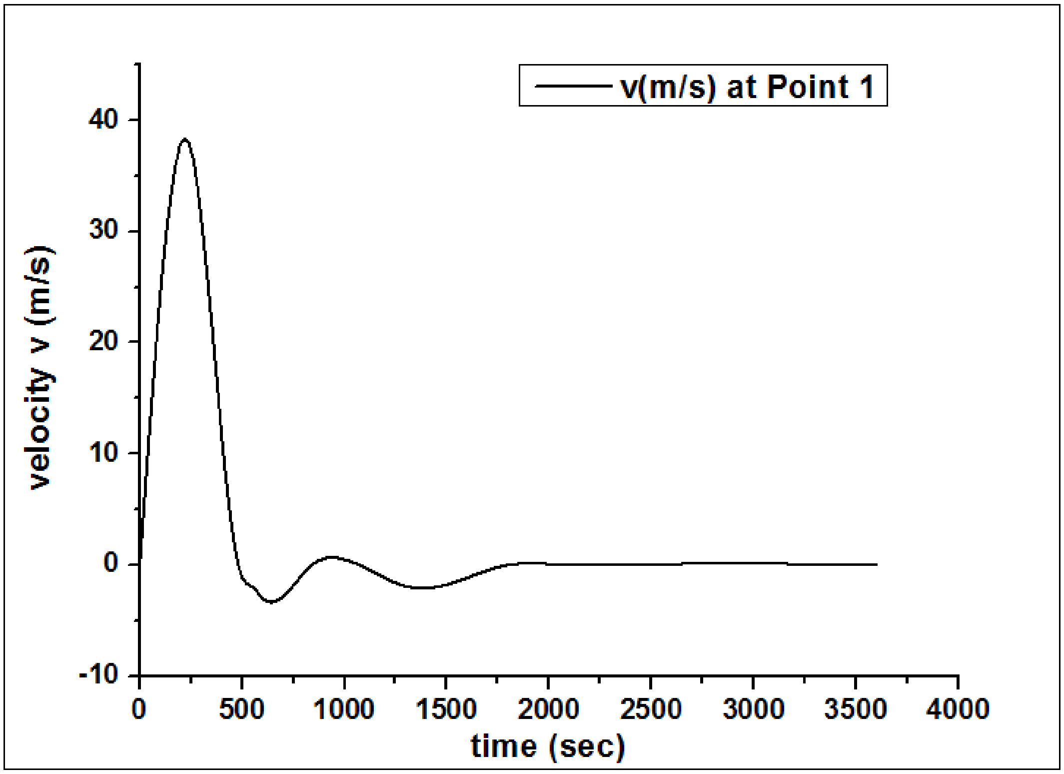

Figure 13. Evolution of Vertical velocity *v* (m/s) for Point1.

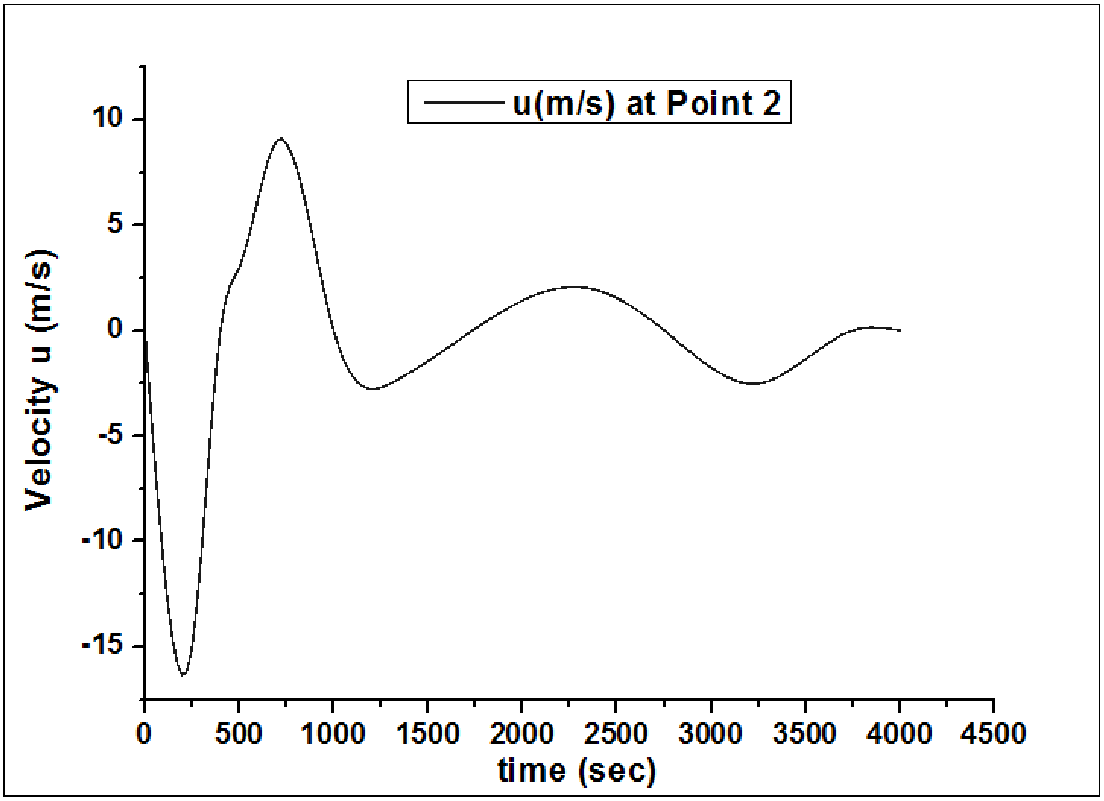

Figure 14. Evolution of Horizontal velocity *u* (m/s) for Point2.

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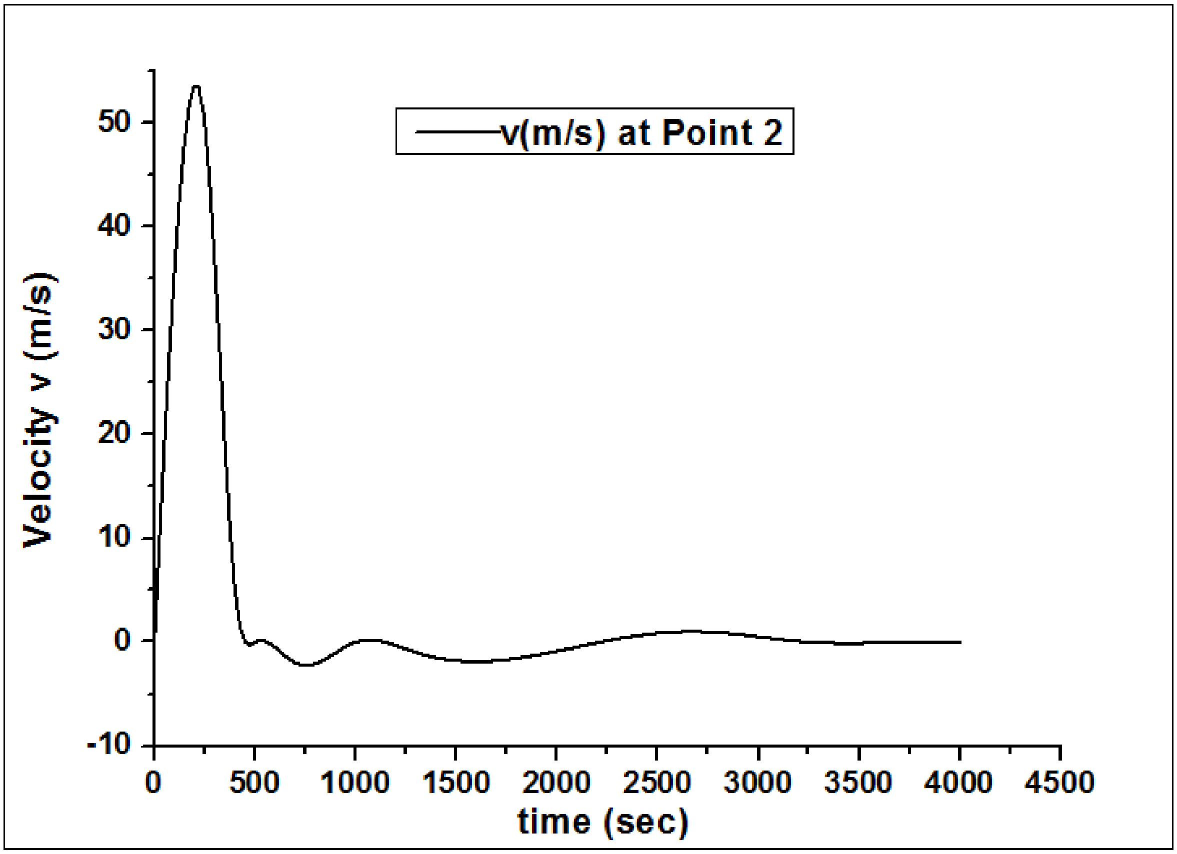

Figure 15. Evolution of Vertical velocity *v* (m/s) for Point2.

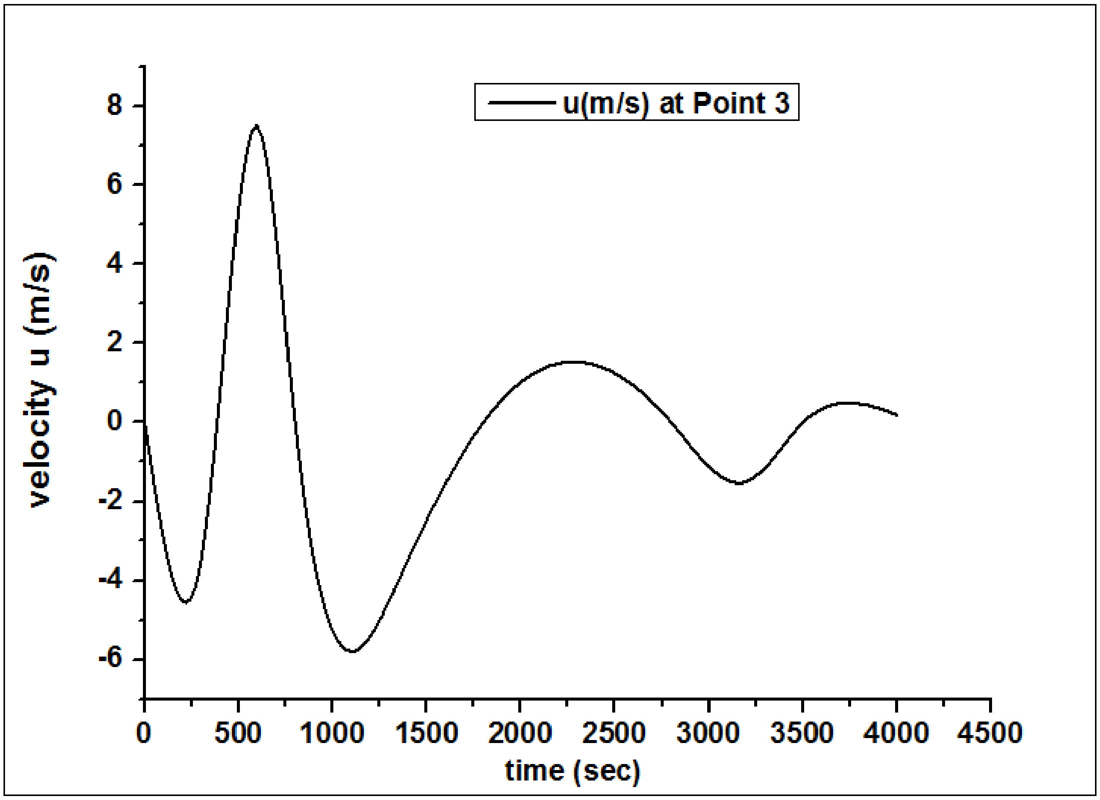

Figure 16. Evolution of Horizontal velocity *u* (m/s) for Point3.

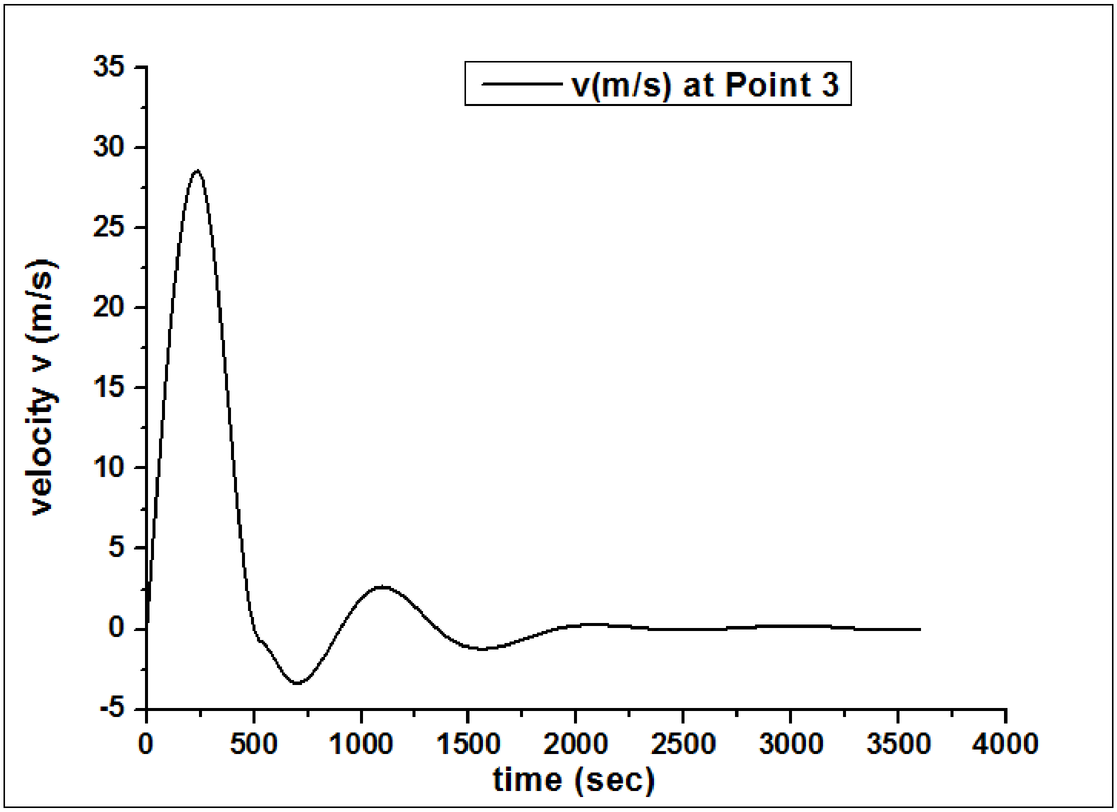

Figure 17. Evolution of Vertical velocity *v* (m/s) for the Point3.

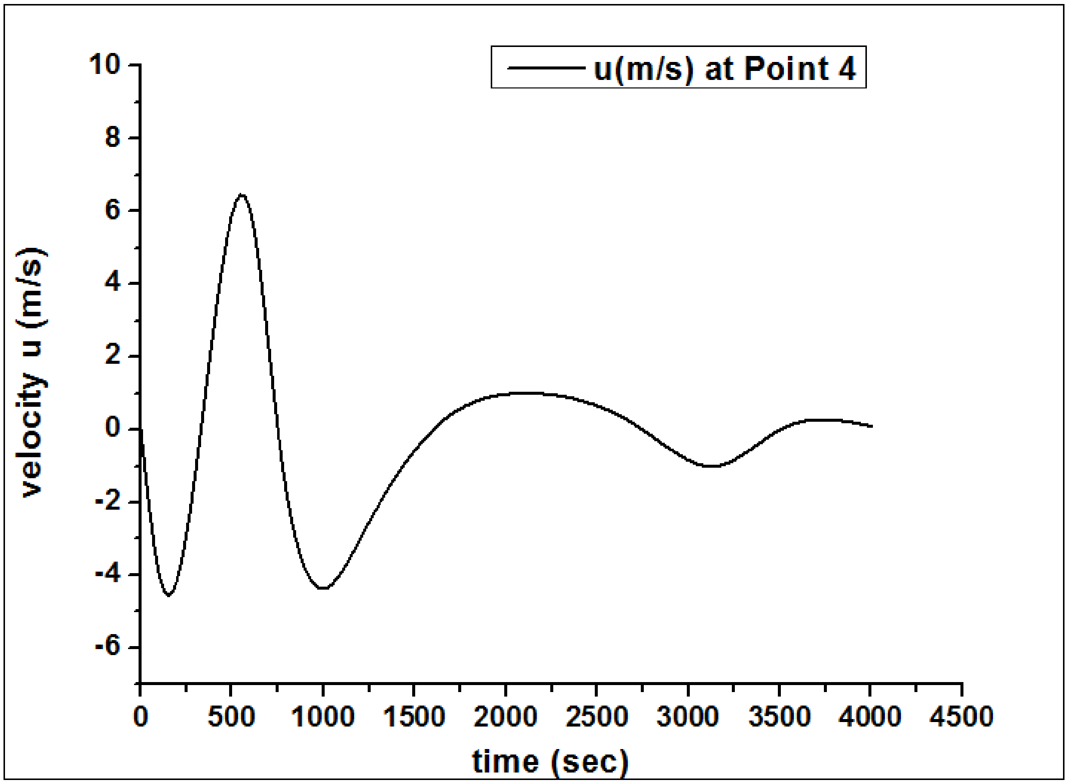

Figure 18. Evolution of Horizontal velocity *u* (m/s) for Point4.

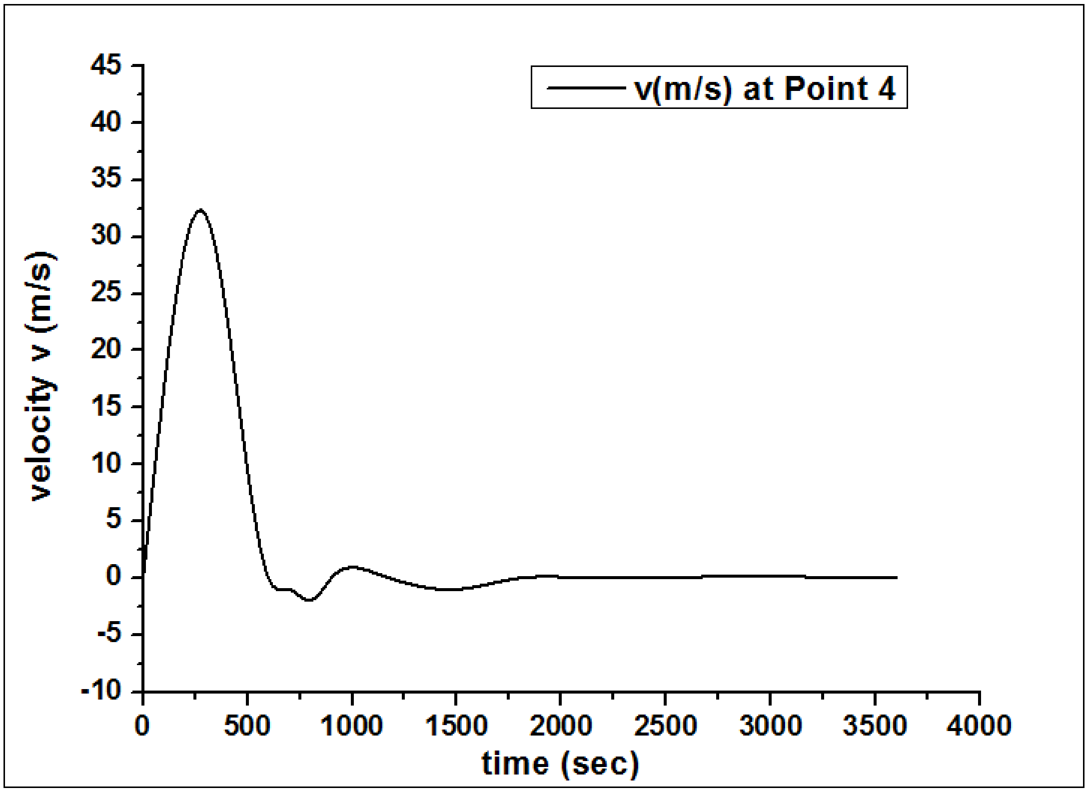

Figure 19. Evolution of Vertical velocity *v* (m/s) for Point4.

The results show that the speed *v* is greater than the speed u for all the points.

The highest value for the velocity *v* is obtained e the level of point 2 to about 50 m/s.

Comparable velocities are estimated for points 1, 2, and 3 to about 8 m/s for the u component and 30 to 50 m/s for the component v.

The lowest speed for the u component corresponds to point 4.

The tsunami wave reached the front of the bay of Algiers (point4) after 10 minutes of an earthquake with a velocity of 32.65 m/s. The direction of the tsunami wave in Algiers Bay is NW-SE.

The energy conservation led to an increase in the height of the waves and a decrease in velocity near the coast (point 1).

Figure 20 presents the simulated wave heights for point 1 with and without considering the coefficient of friction of the bottom.

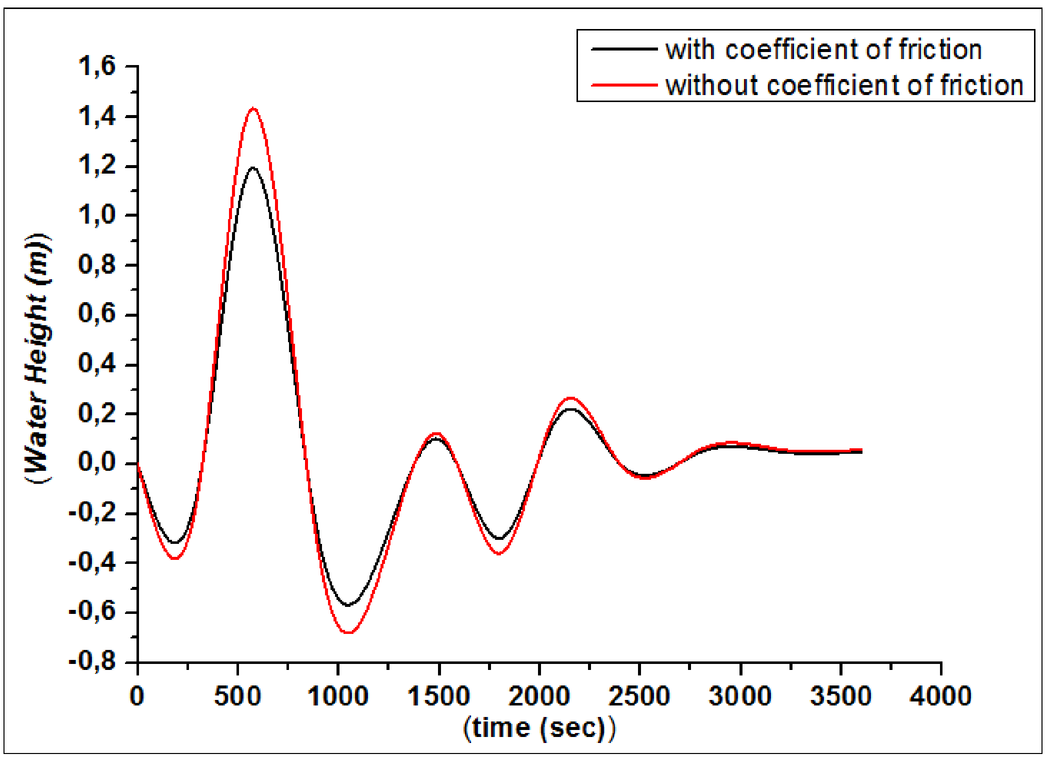

Figure 20. Comparison of the wave height result simulated at point1, with friction, and without friction effect.

The results show that the roughness parameter is important in wave-shore interaction, including shallow water. The friction effect could lead to an overestimated wave amplitude of around 20 % but obscure debris flow dynamics.

Validation of results

To validate our model, we will compare our results with those obtained from another model (Amir, Dahlab, Douaifia, & McAdoo, 2015) in a synthetic case with similar initial conditions.

The question test proposes to use the same principle of bathymetry described and illustrated in the previous paragraph (figure 3); the study area extends from 2.85° E to 3.29° E for latitude and 36.68° N to 37.38° N for the longitude. With the same parameters of the earthquake of our study (an earthquake of magnitude of 7.6 with the length and the width of the fault (73.3 x 29.3 km) and a vertical slip of 3.5 meters), the epicenter is located at 2.98E, 36.98N (Heddar *et al.*, 2012). Further, a Manning coefficient has been set at 0.025 for depths below zero. The modeling was set to 01 hour.

The results obtained were compared with the work on the study of a new tsunami hazard assessment scale for establishing a warning system for the bay of Algiers (Lavigne *et al*., 2011).

Figure 21 shows the result of the simulated wave height change over time, simulated for the comparison point located at 3.1E, 36.85N. In general, qualitatively, the results of the two models are pretty compatible, especially near the vicinity of the flooding phase on the coastal part; the TELEMAC2D model displays an offset of 0.2 m. The resulting discrepancies between the two models come primarily from the definition of momentum.

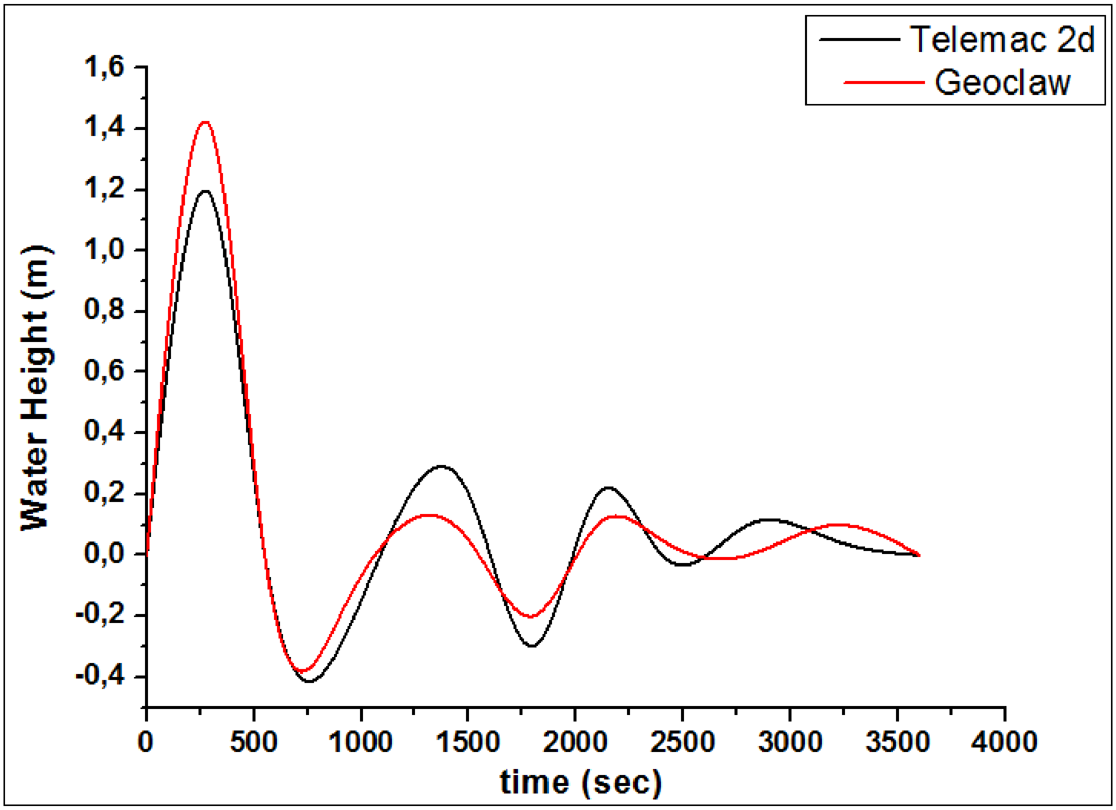

Figure 21. Comparison of the simulated wave height result between two tsunami models, the Geoclaw package model in red and the TELEMAC-2D model in black.

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Conclusion

The numerical modeling of tsunamis on the coasts of Algiers was carried out using a two-dimensional model. The study made it possible to produce precious maps showing the maximum wave heights, speeds, and tsunami arrival times over the whole field of calculation. The results of the simulations indicate that the maximum wave height values are about 1.2 meters, and the speed vary from 30 to 50 m/s. The results also show that the maximum speed is higher as close as possible to the coast of Algiers, which means our area is more prone to infrastructure damage.

The amplification and maximum flood distance depend on the bathymetry, topography, shape of the bay, and roughness, reducing the flood depth.

The results obtained allow the mapping of coastal areas vulnerable to tsunami flooding, using the results of the calculation of maximum wave heights and tsunami wave speeds.

Prevention mapping is the subject of the establishment of a decision support tool based on a geographic information system (GIS) based on the calculation of a hybrid index resulting from a crossing of the Flood Vulnerability Index (FVI) and Structural Vulnerability Index (SVI). With this new approach, it is possible better to characterize the risk of tsunami flooding in urban areas.

The exploitation of the results is substantial for developing a Tsunami inundation hazard mitigation plan and initiating an emergency action plan (PAE), in which the appropriate measures to be taken are identified by authorities to reduce damage to human life and property in the event of a Tsunami.

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