INTERNATIONAL JOURNAL OF
COASTAL & OFFSHORE ENGINEERING

IJCOE Vol.6/No. 3/Summer 2021 (40-48)

Available online at: www. Ijcoe.org

Integration of Geographical Information System and Tsunami Generation / Propagation Models in the Makran Region (North of the Arabian Sea)

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ARTICLE INFO

Article History:
Received: 07 Dec. 2020
Accepted: 16 Sep. 2021

Keywords:
Tsunami
Propagation
Numerical Models
Data Management
GIS

ABSTRACT

Two numerical models of tsunami generation/propagation have been run in the Makran region. These models are one of the necessary components in the warning systems in this region. The outputs of these models are not in regular international data model standards. In order to get the best result from these models, the models' outputs must be managed in a database system. An ideal data management system for tsunami warning system has three essential parts included: data convertor, Geographical Information System (GIS) and Relational Database Management System (RDBMS). The schematics and properties of the proposed data management system have been shown in this paper. 3D, spatial, temporal and statistical analysis of tsunami models data exported to the proposed system based on GIS capabilities and data processing routines. Some examples of data analysis of tsunami propagation in the Makran region (north of the Arabian Sea) have been shown.

1. Introduction

Tsunamis have caused significant damage and casualties along the coastlines, even after spreading wide distances across open oceans. Emergency managers and governors need immediate operational tools to provide accurate tsunami forecasting as a quick and essay decision guide. Hazards from tsunamis are now mitigated by the instance of early warnings to evacuate coastal areas at risk. Observational networks will never be dense because the ocean is vast. It is technically difficult and costly expensive to establishing and maintaining monitoring stations in deep waters. These early warnings are based on seismic and tide gage data transferred to the warning stations, deep ocean recorders and simulated scenarios [1]. The uncertainty in bathymetric data affects the accuracy of numerical models. Integration of in situ measurement and numerical modeling techniques can provide more reliable tsunami forecasts [2]. One of the fastest techniques for tsunami early warning system is the utilization of pre-computed generation/propagation forecast database. In this method, seismic parameters and tsunami modeled parameters are used to search through a pre-computed forecast database and select the most appropriate scenarios which closely matches the observational and modeled criterion. In this regard, scenarios are an adequate tool for estimating the tsunami parameters in deep water, and they could be considered as an initial condition for further processing. Forecasting the maximum height of tsunami waves are calculated using statistical techniques which should be developed for a specific case study [3]. The results of tsunami scenario and statistical methods provide early warning tools for hazard assessment that help decision makers and emergency managers. These tools are used to forecast the tsunami amplitudes, and they assist emergency managers during tsunami warnings [1]. However, tsunami propagation modeling and forecasting systems clearly need data manipulation and here by there is no way to have a good data management system for tsunami warnings and also its hazard decision making and management.

Such as of many other oceanic phenomenon, knowledge of tsunami generation/propagation and decision for reducing its hazardous effects needs data and information. At the technical level, integrated management of the ocean and seas relies on two basic tools: modeling and data [4]. Within the decision-making process, modeling acts as a tool so that the environment modeling-decision making relationship is developed as a bridge between scientific research and policy analysis [5]. There is a significant gap between information needs on environmental decision making and information produced by the current systems of data collection and management [6]. Now most significant means of collecting, processing, storing and communicating data have been developed, but we still suffer from poor information when we attempt to make a decision for oceans and seas from the available data [4]. This gap can be filled in by appropriate monitoring, management and modeling of data [5]. However, availability of raw and modeled data is not a sufficient condition to produce the required information about the oceans and seas. It is the utility or usefulness of data that contributes to production of information. Transfer of tsunami wave raw and modeled data into information involves several activities such as spectral, Statistical, spatial and temporal analysis [7]. Each of these activities contributes to retrieval of the required information from raw data. Spatial nature, large volume and organization of Tsunami modeled and raw data and information are the most important aspects in the Tsunami data management and visualization that directly support the good decision making for coastal protection against tsunamis. However, through the use of Geographical Information System (GIS) and the associated software; these data can be managed, compiled, and processed. Integration of GIS with environmental phenomenon modeling algorithms accomplishes a number of significant functions such as: planning, calibrating, modifying, data analysis and visualization [5]. GIS improves the ability to incorporate spatial details beyond the existing capability of numerical models [8].

This paper tries to bring forward a methodology for data management of tsunami generation/propagation model using GIS, and to show the importance of data management in tsunami warning systems and decision making for coastal protection. Makran region at the northern part of the Arabian Sea has been selected to carry out these prospective because it has the potential of Tsunami generation and also it is an important region for the Indian Ocean Tsunami Warning System.

2. Data and methods

2.1. Study area

The first Tsunami record in the Makran has been off the Makran Coast at Date 28th November 1945, Epicentre: 87.1 km, SSW of Churi (Baluchistan) Pakistan, Latitude: 24.500° N, Longitude: 63.000°E, Origin Time: 21:56 UTC (03:26 IST), Magnitude: Mw 8.0, Ms 7.8 (Figure 1) [9]. This was the last major tsunami-generating earthquake in the Arabian Sea. More than 4,000 people were killed in the devastation caused by the earthquake and tsunami on the coasts of Makran [10]. After this earthquake a great tsunami was triggered. The wave height of tsunami reached to 40 feet height in some coastal regions of Makran and caused great damage to the entire coastal region. In general, similar damages and mortality were observed along the coasts of Makran in Iran and Oman. The effect of tsunami damages and some mortality were also recorded at Muscat and Gwadar. The 6.5 feet height of tsunami waves were recorded in Karachi. The first wave was recorded at 5:30am, then at 7:00am, 7:15am and finally at 8:15am. The highest wave was observed at 8:15am. The tsunami had a height of 11.0 - 11.5 m in Kutchh, Gujarat. At 8:15am, it was observed on Salsette Island i.e Mumbai. It was recorded in Bombay Harbor, Versova (Andheri), Haji Ali (Mahalaxmi), Juhu (Ville Parle) and Danda [10, 11, 12].

The northward movement of Indian oceanic lithosphere has created the Makran Subduction Zone (MSZ). MSZ is often affected by the Iranian micro-plate at a very shallow angle of about 20 degrees [13]. The length of MSZ is more than 800 km along east-west direction. The MSZ includes very thick sedimentary columns that enter into the subduction zone with thickness of up to 7 km [14, 15]. The deeper structure of the MSZ, the wedge sediments and the subducted oceanic crust has been surveyed recently by wide-angle and seismic reflection [16]. Convergence rate between the Arabian and Eurasian Plates has been estimated to 30-60 mm/y. The thrust faults are oriented nearly perpendicular to the direction of convergence. There is no obvious topographic trench associated with the present accretionary front. The oceanic crust of this area have been formed during the Cretaceous (108-79 Ma), and no significant magnetic anomalies have been observed in relation to ocean floor spreading in the Oman Sea. The subducting plate has a northward dip of >20° till 270N, then bending down to an angle of ~300 (Figure 1) [10, 16, 17, 18].

The east-west oriented complex is one of the largest accretionary wedges on earth. It is more than 800 km long, bounded to the east and west by large transform faults which define the plate boundaries [19]. In Makran Accretionary Complex a fairly high earthquake activity should be expected, as in many of the other major accretionary complexes/subduction zones around the world but the Makran zone is remarkably low in seismicity [20, 21]. The earthquake epicenters during the last century is shown in Figure 2 [10]. Although large earthquakes along MSZ are infrequent, the potential for a devastating tsunamis in the Northern Arabian Sea cannot be ignored.

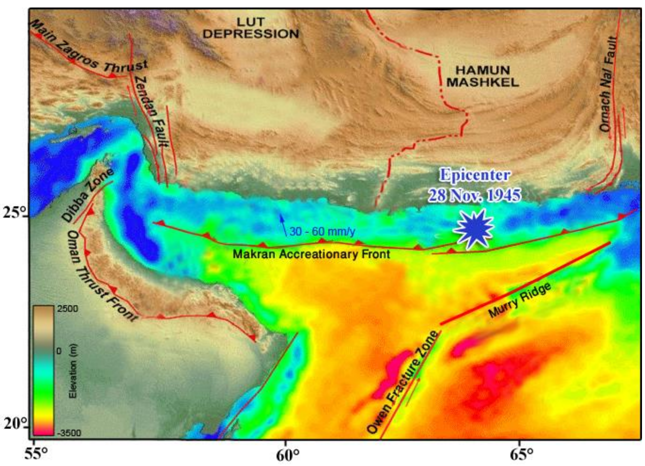

Figure 1. Major faults and the Zone of Tectonic Subduction in the Northern Arabian Sea (from: Fruehn et al, 1997).

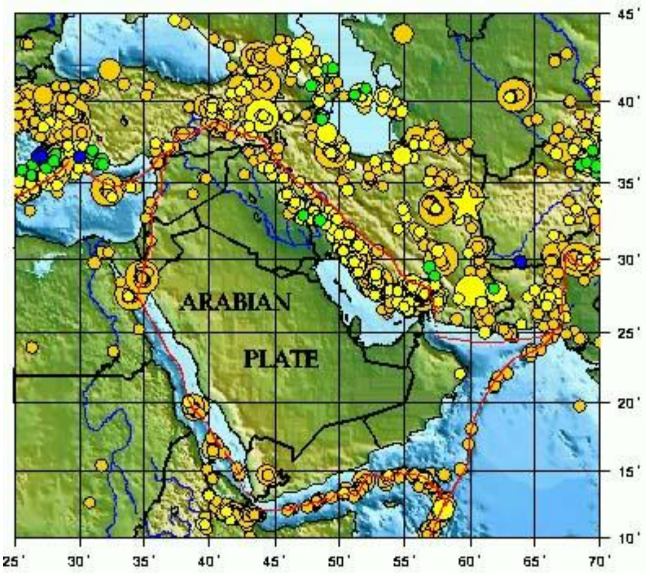

Figure 2. Distribution of earthquake epicenters along the boundaries of the Pakistan, Afghanistan, Iran and Arabian microplates (from: Mokhtari and Farahbod, 2005).

2.2. Tsunami propagation models

The 2004 tsunami tragedy in Indian Ocean highlighted the need to develop technical capabilities on tsunami modeling as a highly-needed capability in the field of tsunami hazard assessment. Very few institutions in Southeast Asia, the Pacific, and the Indian Ocean are presently skilled in conducting their own tsunami modeling. Models by Imamura and Hashi [22], Satake and Tanioka [23], Lynett et al [24], Imamura et al [25] and also European JRC (Joint Research Center) Tsunami Propagation model [26], MOST (Method of Splitting Tsunami) model [27], AVI-NAMI [28], SiTPros (Siam Tsunami Propagation Simulator) model [29] are the most reliable tsunami generation/propagation models for the Indian ocean region. In general, all of these models examine the influence of both initial conditions and analytical approximation on the results of hydrodynamic simulations. They carry out numerical simulations using both the Non-Linear Shallow Water (NSLW) equations, which assumes a less strict condition on the ratio of water depth to wavelength and take into account the frequency dispersion of the wave [30, 31]. These models usually can estimate tsunami height, inundation and arrival time information.

Intergovernmental Oceanographic Commission (IOC) has introduced the AVI-NAMI (http://avi-nami.ce.metu.edu.tr/) and SiTPros (http://www.schuai.net/SiTProS/) tsunami generation/propagation models as a quick and simple operational models for decision makers, who are interest in quick response action against natural hazards [32]. Here, these models were selected for tsunami generation/propagation in the Makran region, and the results are presented.

2.3. Data management methods

AVI-NAMI and SiTPros use the bathymetry of the area as one of the input data. The bathymetry of the area is usually stored as data file that consists of three values: X coordinate, Y coordinate and the depth values. However, data files must be converted into an evenly spaced grid before using as input file of the models. Grid files contain header lines that provide information about the size and limits of the grid, followed by a list of Z values. The Z values are stored in roe-major order stating with the minimum Y coordinate. The value of the lower left corner of map is the first Z value in the grid file. The second Z value is the next adjacent grid node in the same row.

The first output file of the models is the initial wave in the sea which contains the water surface height at each grid point of the bathymetry data. Simulated wave height at each time step for all grid points is saved in a separate grid file. Hence, there will be N grid file for N time steps simulation. The detailed information of processing routines of the models has been shown in the Figure 3.

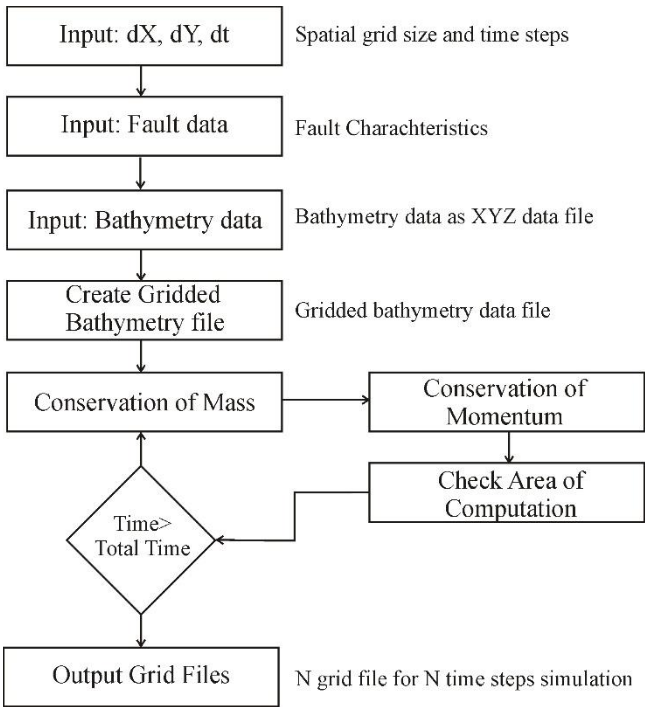

Figure 3. Processing routines of tsunami propagation models used in this paper.

3. Results and discussion

The AVI-NAMI and SiTPros models require the bathymetry of the area as well as the fault characteristics and earthquake parameters as input data. The data concerning the fault consists of the following parameters: The coordinates of the starting point and the end point of the fault, the width of the fault in meters, the dip direction, dip angle, slip angle in degrees, the dislocation and the depth of earthquake

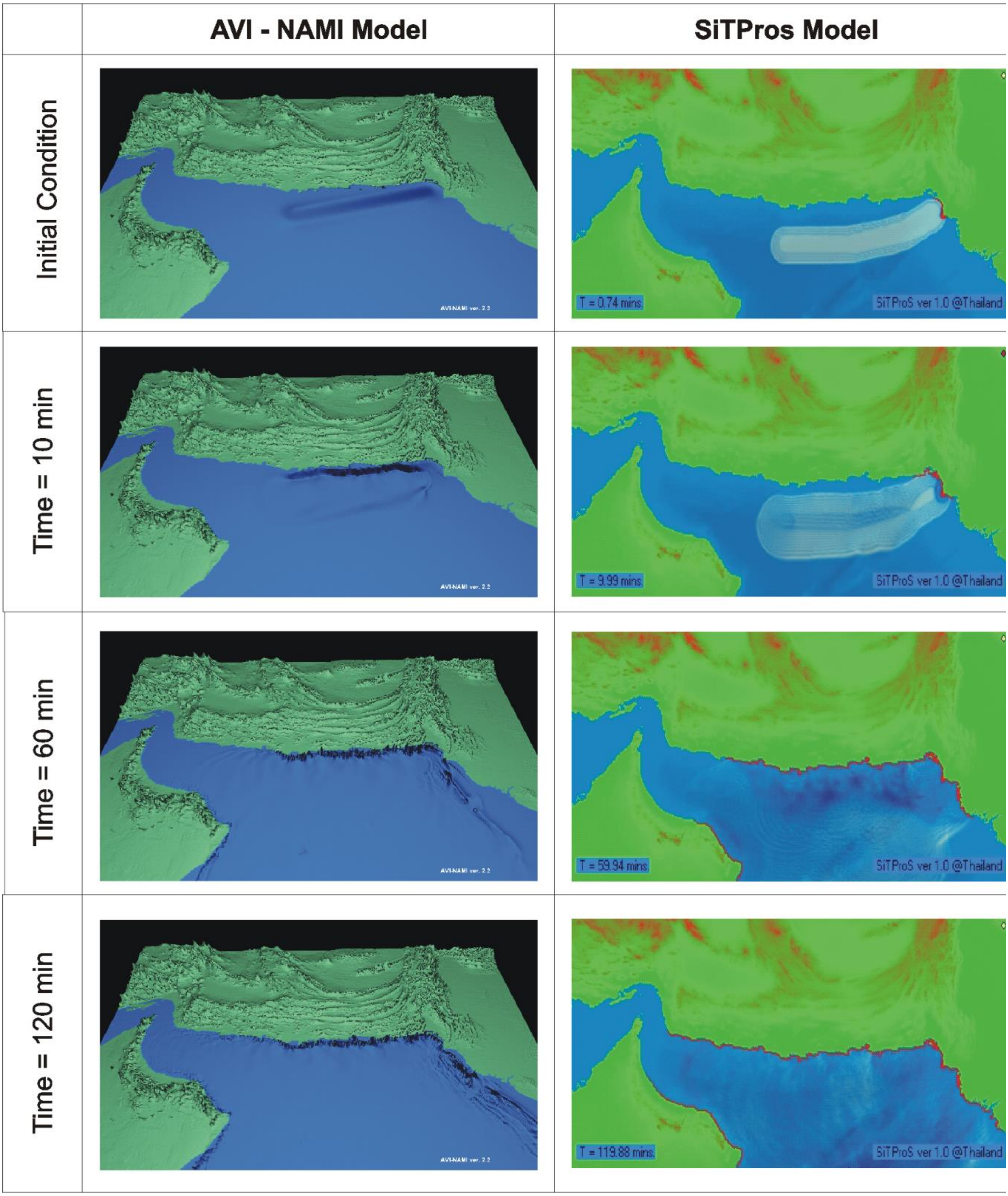

Figure 4. Propagation of a hypothetical tsunami in the Makran region using two numerical models.

epicenter in meters. As noted above, the only earthquake generating tsunami has been occurred along the Makran Accretionary Fault (MAF) on Nov. 28 1945, and hence characteristics of this fault and an earthquake like the last one tsunami generator have been selected for the ocean bottom rupture parameters for tsunami generation/propagation in the Makran region using these two models. The ETOPO2 bathymetry data is available for the whole world with a good resolution (2 minutes) through the NOAA website. The models were run using these data as input parameters for two hours of simulation for the Makran region (Figure 4).

In order to get the best results, the output files are needed to be converted into diagrams or graphs so that

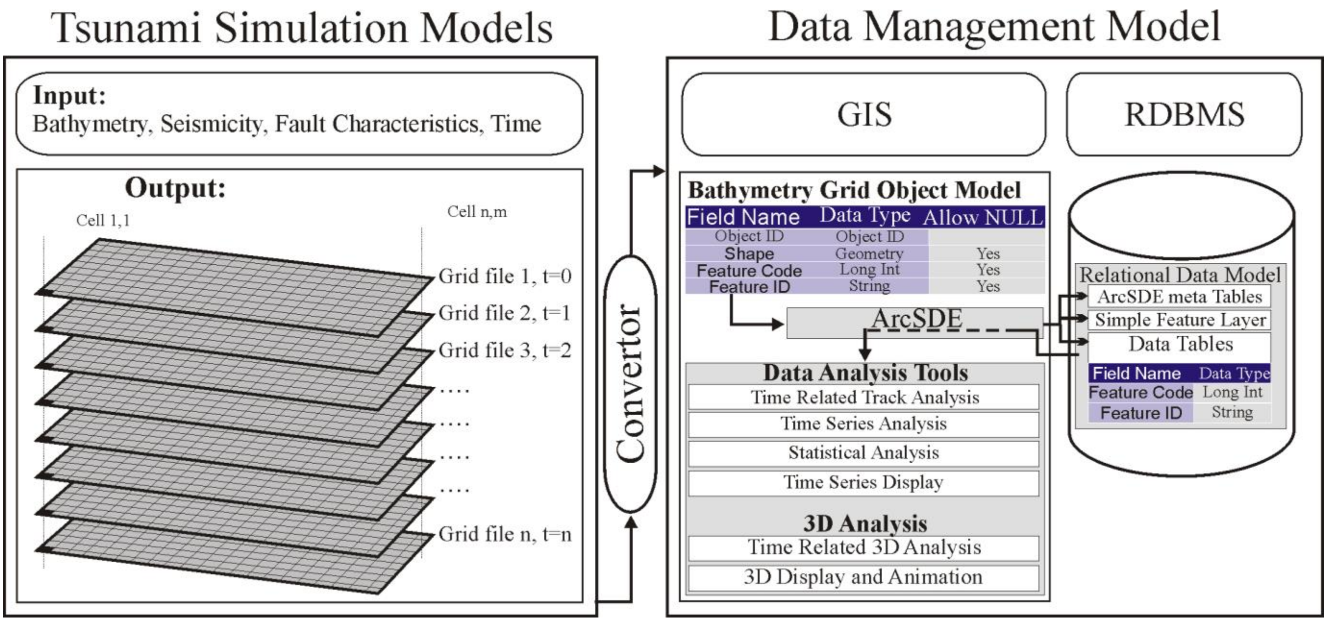

Figure 5. Schematic view of the proposed combined modeling and data management system for tsunami propagation and data analysis.

the interpretation and the comparison of different data can be achieved easily and also comparison of the real time data and the numerical analysis of the tsunami can be done which is a way of checking the accuracy of the simulation. Conversions of numerous output grid data files of the tsunami models to the required information will generate some problems in the warning systems include:

- data could not be searched one by one
- Data are saved in too many files which confused the users
- Users have to work with too many files to get the required informations
- Data visualization must be done for separate files one by one, and comparisons of all time steps simulation results need the processing of all output grid files
- Time series data analysis for a grid point must be run for that point in all output grid files which requires the programming and advanced training
- GIS application for these grid files is a time wasting procedure and it should be done for each simulation run
- We have to use few softwares for output grid file processing and this method will confuse the warning system operators
- Archiving, updating and maintenance of the output files is very troublesome and the warning system operators must be take care about the simulation outputs missing.

Relational Database Management Systems (RDBMS) are the best solution for time series and girded data [33]. RDBMS can joint with GIS softwares for data management and analysis. In this software system, data are saved in different tables which have logical and mathematical relations that provide the data accessibility based on different query algorithms [34]. A grid map just like the bathymetry grid is created that contains a unique code for each grid cell. This grid map will be used for spatial data management and visualization. All cell characteristics data are stored in an internal database of the GIS and tabular data, which are the results of the simulation, are stored in a RDBMS. Data structures in these data tables provide a one to many relations between each map grid cell and tabular data, and hence each grid cell contains the related time series data resulted from simulation. In this tabular relation, the ID field of grid cells and tabular data in RDBMS is a unique key and used for data query by SQL.

The warning system operators can extract data for each grid map cells easily when the GIS-RDBMS systems were established. The GIS component of the system gets the ID and other characteristics data of the selected grid cell, and sends it to the RDBMS using SQL and finally tabular data will be queried from database. SQL provides an interface to relational tables that allows user to select rows based on the values contained in the fields. A SQL statement can range from simple to complex, allowing user to compose virtually any type of query from basic column types. The result of a query is a set of rows meeting the criteria established by the SQL statement. In this study, SQL Server and ArcGIS have been selected for RDBMS and GIS softwares respectively, and ArcSDE has been selected for these two software bridge. The overall schema of the proposed system has been shown in Figure 5. In this system, a software

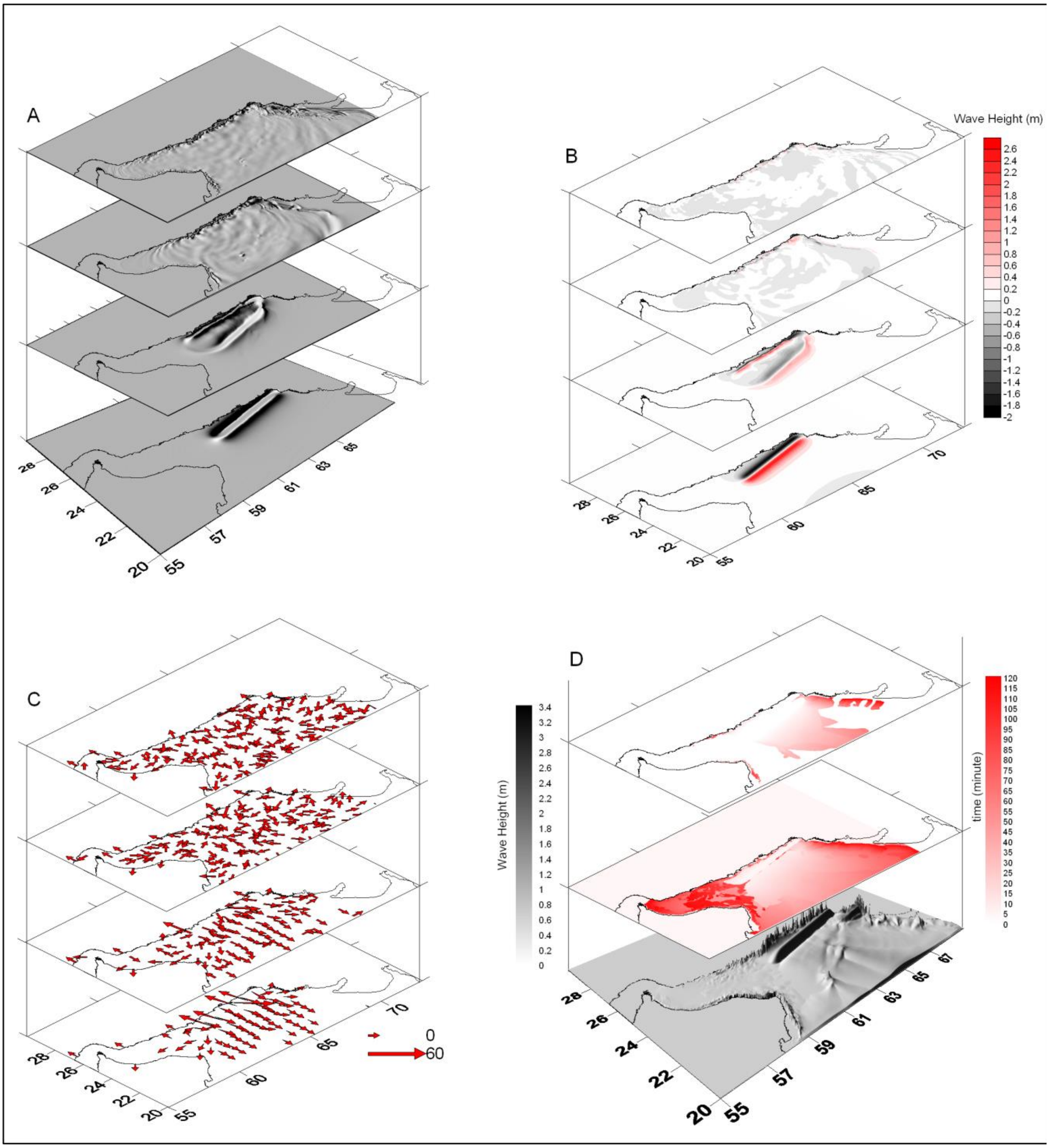

Figure 6. 3D analysis of tsunami propagation model in the Makran region. (a) 3D view of wave propagation at different times. (b) Maximum wave height at different times. (c)- Wave vector of tsunami propagation at different times. Layers in figures A to C from bottom to top show the tsunami wave characteristics at 0 (initial condition), 10, 60 and 120 minutes following tsunami generation. (d) Miscellaneous plots of propagation characteristics: from bottom to top, maximum wave height of tsunami after 120 minutes of modeling; arrival time of maximum wave height; and arrival time of the first 2.5 meter and more wave tsunami.

convertor processes all the simulation output grid files and convert them to time series tabular data with a unique ID for each grid cell data and then insert TS data to the SQL server.

The output grid files of these models were converted to a proposed data management system (Figure 5). Furthermore, some statistical analyses include time series plots and 3D views of the hypothetical tsunami were done using GIS capabilities (Figure 6 and 7). 3D model of tsunami propagation shows that the Strait of Hormuz and Persian Gulf are not in tsunami domain (Figure 6a). The maximum wave height will affect the east and north-east of the Makran region coasts. In these regions propagation and rollback of sea water at coastal areas is extremely high during this hypothetical tsunami (Figure 6b, c). However, 3D data analysis shows that the maximum wave height will be

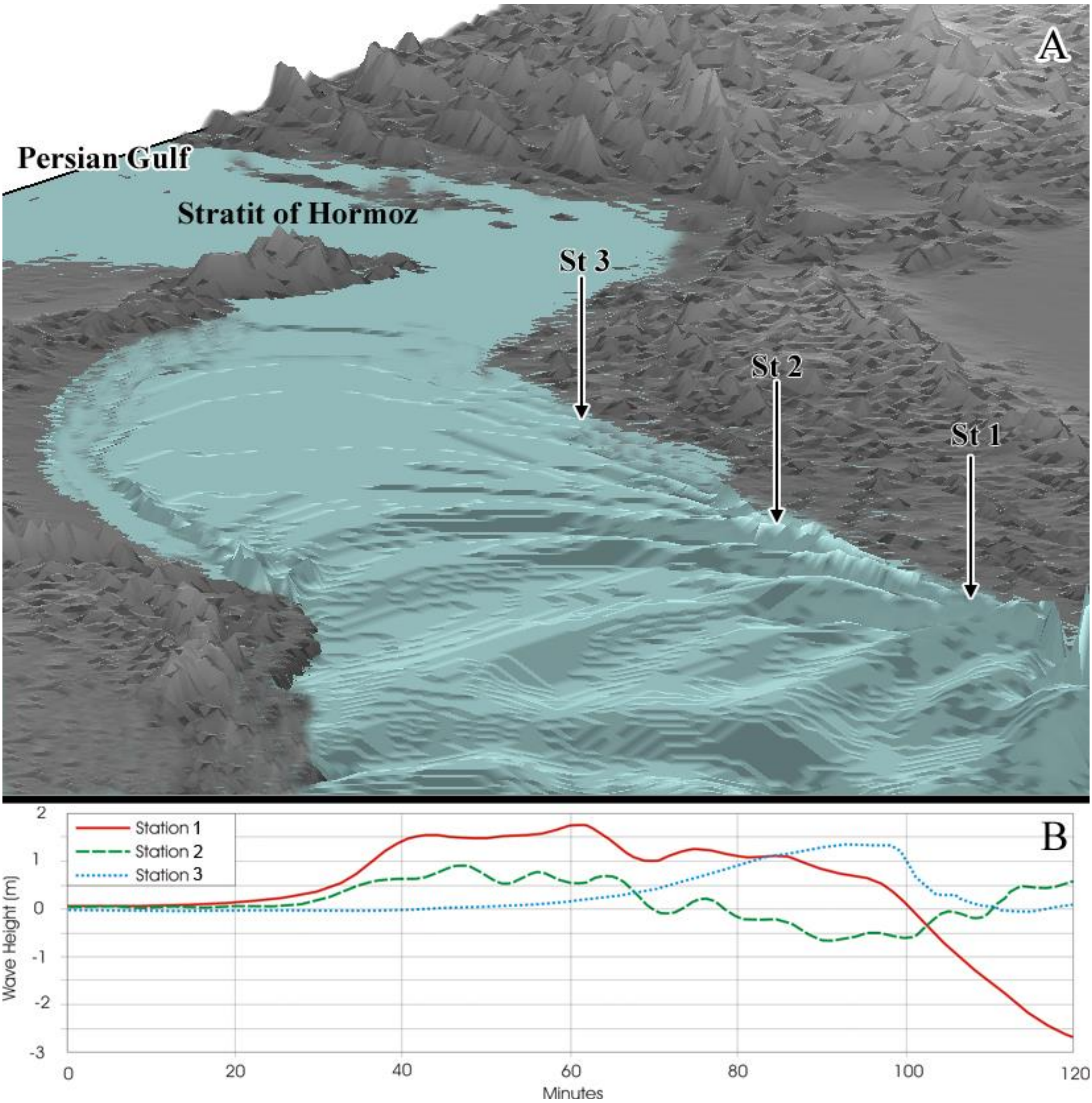

Figure 7. (a)- 3D close up of hypothetical tsunami propagation in the Oman Sea and Strait of Hormuz. (b)- Time series plot of tsunami wave height for three stations at the Iranian coastal areas.

at the central part of Arabian Sea and at the India and Pakistan coastal regions. Also, high waves will reach to these areas in less than 10 minutes (Fig 6D). A close up view of Strait of Hormuz for the tsunami propagation after 60 minutes is presented in Fig 7. This is an example of time series data extraction from the proposed data model for three points at the Iranian coasts of the Oman Sea. This shows that the first tsunami waves will reach to the Iranian coasts after 20 minutes following tsunami generation, and wave height will not be more than 2 meters during this hypothetical tsunami propagation. However, it is clear from the Figure 7A that the gentle slope at the neck of Strait of Hormuz acts as a barrier against tsunami propagation.

4. Conclusion

The process of computing the three stages of tsunami modeling, wave generation and propagation-inundation has been accelerated by generating a database of pre-computed scenarios. The pre-computed database represents the tsunami propagation information in the open ocean. An initial source is selected from the pre-computed database, while a tsunami event occurs. The appropriate scenario is selected from available propagation information to compute the wave inundation. In order to get a reliable, strong and easy to use tsunami database for warning systems, it is accepted that the outputs of tsunami models must be converted to information. To do this, data management systems must be considered as one of the essential parts of the tsunami warning systems. Available tsunami models have an irregular data formats which are not in an international standard formats in operational data management systems. In addition, GIS is a powerful tool for data management and analysis that should be used in data management systems. The proposed data management system for the tsunami warning systems have at least three essential parts include: software convertor, GIS and relational database. The results of a database management system in the tsunami generation, propagation and inundation study should include information about the maximum wave height and maximum current speed as a function of location, maximum propagation/inundation line, time series of wave height indicating wave arrival time, and too many other analyses in upon the users' request. This information can be used by emergency managers and urban planners primarily to establish evacuation routes and location of vital infrastructure.

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