A Study on Tsunami Wave Penetration and Storm Surge Impact after the Construction of Sethusamudram Ship Canal

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Abstract: *This paper describes a study on tsunami wave penetration after the construction of the proposed Sethusamudram Ship Canal Project (SSCP). In order to fulfill this objective a hydrodynamic model set up based on linear shallow-water equations was used to simulate tsunami propagation and storm surges from the source in offshore to the nearshore around Sri Lanka. Numerical model results were compared with data from field measurements and tide-gauge records for the existing condition. There were two tropical cyclones in 1978 and 1964 that affected the northern and eastern coast of Sri Lanka which were used to set up the model. The numerical simulation suggests that SSCP will have a minor impact in terms of tsunami wave penetration into the Gulf of Mannar (i.e., 2-5% increase in wave amplitude compared to existing) and the storm surge height is increased by approximately 5% along the Jaffna and Mannar coasts.*

Keywords: *Sethusamudram Ship Canal, Storm surge, Tropical cyclone, Water levels, Tsunami, Sri Lanka, Indian Ocean*

1. INTRODUCTION

Sethusamudram Shipping Canal Project is a proposed project to establish a shipping route between India and Sri Lanka in the shallow straits. The ocean floor between India and Sri Lanka near the Mannar coast is not navigable due to shallow water depths. Due to this India does not have a continuous shipping channel connecting her west coast to east coast. Therefore, the government of India has proposed the dredging of the sea between India and Sri Lanka to create a navigational canal to save up to 780 km of navigating distance and 30 hours of sailing time allowing ships to navigate from west to east coast of India instead of having to circumnavigate Sri Lanka. The total length of Sethusamudram Shipping Canal would be around 260 km; in the Gulf of Mannar the distance is about 120 km from Tuticorin Port to Adam's Bridge and a further 140 km from Adam's Bridge to Bay of Bengal in the Palk Bay. The proposed depth of the canal is 12 m enabling 10,000 to 12,000 GRT vessels to pass through.

1.1. Introduction to Tsunami and Storm Surge

The Sri Lankan coastline was devastated by the Indian Ocean Tsunami on 26 December 2004 which was caused by a gigantic submarine earthquake 400 km west of northern Sumatra. The name Tsunami comes from the Japanese words “tsu” meaning the harbour and “nami” meaning the wave. As deep ocean water depths ranged between 4000 to 5000m, such waves can voyage at speeds up to 800km/hour; hence they can shield trans-oceanic distances in a matter of hours. However, due to these massive wavelengths tsunami waves generally occupy periods in the vicinity of 10 to 30 minutes and amplitudes, in bottomless water, typically smaller than 1m. It is very vital to understand that the combined action of nearshore processes and local geomorphologic features influence the degree of the final effect at a given location. The threat of tsunami lies not in deep water, but rather when they come ashore. As the tsunami wave leaves the deep water and reaches shallow waters near the shore, it undergoes an alteration called wave shoaling. Apart from the shoaling process, the wave is also subject to refraction, diffraction and reflection resulting in very large distinctions in the run up height.

Sea surface temperature rise due global warming might increase the intensity and recurrence frequency of the extreme weather phenomena such as tropical cyclones, flooding and torrential rain in the future. Storm surges are generated primarily by the extreme winds from low pressure atmospheric systems. Further, secondary factors such as atmospheric pressure drops, surface waves, earth's rotation and associated wave setup also influence the intensity of the storm surge. Hence, a storm surge is a rise of sea water level above the predicted astronomical tide level, resulted from the combined effects of strong winds, reduced atmospheric pressure over a shallow water body and other secondary factors. Bay of Bengal is a place where cyclones are generally originated. As Sri Lanka is situated near Bay of Bengal these cyclones affect Sri Lanka as well (Ramesh, 2005). Storm surges and flooding are considered the main impacts of cyclones.

The objective of this research is to estimate the impact of tsunami and storm surge events after the construction of the SSCP through the use of hydrodynamic modelling.

2. LITERATURE REVIEW

2.1. Storm Surge Models

Storm surge is an abnormal rise in sea level accompanying a tropical cyclone or other intense storm, and whose height is the difference between the observed level of the sea surface and the level which would have occurred in the absence of the cyclone (i.e. astronomical tide level). In the past several decades, there are many storm surge studies conducted world wide. Harris (1956) is the first person to start systematic studies on storm surges due to tropical cyclones on the East Coast of the United States. In his paper 'characteristics of the hurricane storm surge', Harris (1963) summarized five distinct processes that can alter the water level in tidal water regions during a storm surge (Vatvani, 2012). There are pressure effects, the direct wind effect, effect of waves, the effect of the earth's rotation and the rainfall effect. Pore (1964,1965) included two more factors involved in the generation and modification of storm surges. Those are the height of the tide and modifying effects of coastline and bathymetry.

Numerical model studies of hurricane-induced storm surge began in the early 1970s. Jelesnianski (1972) developed the Special Program to list Amplitude of Surges from Hurricanes in 1972. After that, Sea, Lake, and Overland Surges from Hurricanes (SLOSH) was developed and widely used by NOAA for coastal flooding and inundation forecasts along the Gulf Coast and Eastern Seaboard of the United States (Shen, 2009). Despite its popularity, the SLOSH model has several disadvantages which need to be improved. First, because its use of structured grid, the SLOSH model has a limitation in resolving complicated coastlines and thus severely restricts its capability for accurate simulation of inundation. Second, the advection terms in the momentum equations are neglected in this model, which will influence the accuracy of the simulation. In recent decades, many other models using different numerical schemes have been developed for the simulation of storm surges in different areas (Vatvani, D, 2012). One of these models is the ADCIRC model, which employs the unstructured grid and is able to resolve the complex coastline as well as the bathymetry of shallow water quite well.

2.2. Tsunami Models

During the Indian Ocean tsunami of 26 December 2004, the southern part of Kerala was generally safe from a major tsunami, mainly because the tsunami waves from Sumatra region travelling south of the Sri Lankan island, moderately diffracted northward and affected the central part of the Kerala coast. Since the tsunami is a long gravity wave during the diffraction process, the rather wide turn it has to take spared the south Kerala coast. On the other hand, excavating the Sethu Canal might provide a more direct route for the tsunami and this could influence south Kerala. The project will have serious bad impact in Kerala Coast. The Bay of Bengal entrance of a sea canal project linking India's coasts should be readjusted from facing east to northwest to protect the Kerala coast from future tsunamis (Ramesh, 2005*a*). Kenji Satake's tsunami simulation model has been accepted but it was corrected by international tsunami authorities. The model explains tsunami propagation in general terms, but fails to give us a clear idea of tsunami wave action in Palk Bay area. Tsunami simulation models by Steven N. Ward of University of California, explain graphically the way of tsunami waves action in Palk Bay on December 26th (Ramesh, 2005*b*).

3. METHODOLOGY

3.1. Model Domain

In this modelling exercise, the whole land area of Sri Lanka, part of India and the sea around Sri Lanka including Bay of Bengal and Arabian Sea were included. This domain consists of 5 UTM zones, i.e. 42 - 46. The boundaries of the domain are shown in figure 1.

- Minimum longitude : 66.25 degrees (+East)
- Maximum longitude : 93.92 degrees (+ East)
- Minimum latitude : 2.16 degrees (+ North)
- Maximum latitude : 21.51 degrees (+ North)

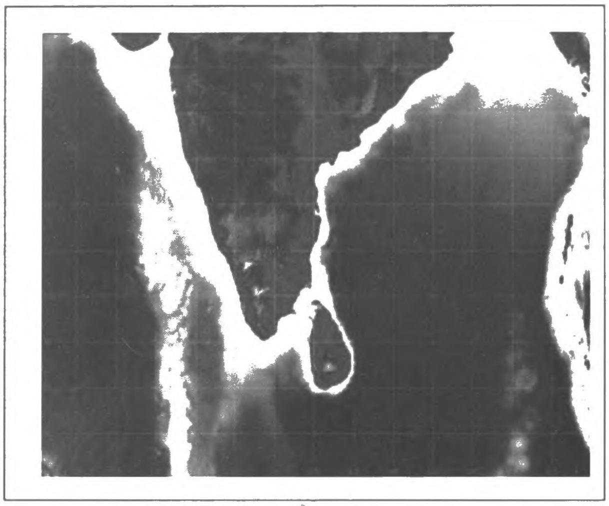

Figure 1 Model domain

3.2. Bathymetry Data

Bathymetric data provides a representative bottom configuration that is to be constructed to represent the SSCP. A well-produced high resolution bathymetry data ensures the tsunami wave transformation is properly simulated in the model. Bathymetry data was extracted from Marine Geoscience Data System at 60 m, 240 m and 1000 m resolution. Low resolution data (60m) were used in the shallow area between Sri Lanka and India.

3.3. Delft3D Modeling System

To simulate the evolution of tsunami waves and storm surge in the coastal ocean the Delft3D-FLOW module was used. The FLOW module of Delft3D computes wave propagation, wave generation, wave interactions and dissipation. These results were attributed for a given bottom topography, water level, maximum water level, wind field in waters of deep, intermediate and finite depth of the ocean. Curvilinear grids were used in this model.

3.4. Model Grid Generation

The wave-related factors for suspended load and bed load were set to zero value in order to prevent the formation of unrealistic cross-shore profiles. The RGFGRID module makes easy to create refine, orthogonal curvilinear grids that follow land boundaries which are complicated subsurface features. Grid generation process was initiated with a rough sketch of the grid by splines. The depth values at XYZ locations were interpolated to the grid. Grid cell averaging of the samples gives better model results rather than using local data only, where the samples are denser than the local grid.

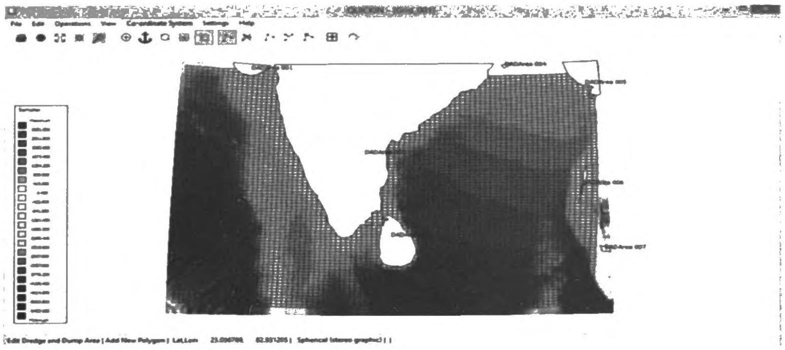

Figure 2 Computational grid

3.5. Land Boundary

The land boundary was used to identify the land and define the land-water interface. The land boundary that need to be highlighted was the north western coastal area of Sri Lanka where the Sethusamudram project is located.

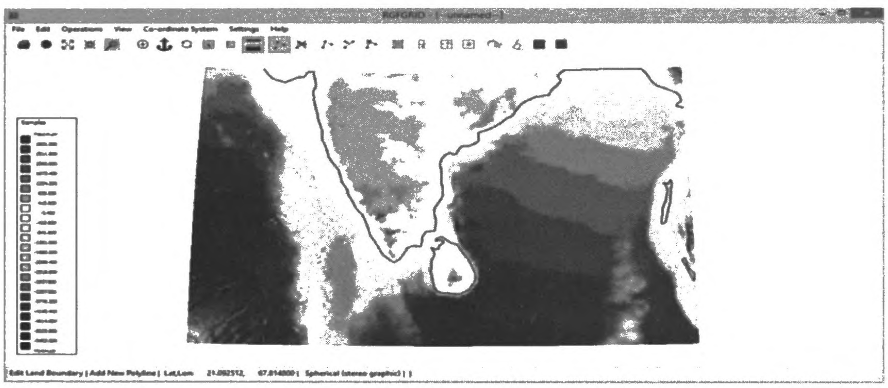

Figure 3 Land boundary

3.6. Model Set up and Running

Using QUICKPLOT facility in the Delft3D, the results were extracted from the output files. Depth averaged values was plotted over the bathymetry. The Master Definition Wave file (MDW-file) is the input file for the wave program. This file contains all data that is necessary to define the wave model such as tidal constituents and run a wave computation.

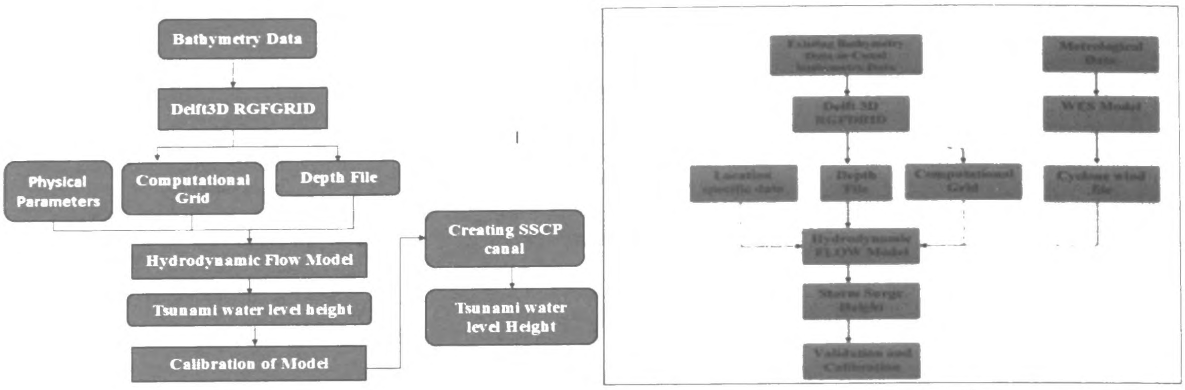

Figure 4 Flow chart of Delft3D for Tsunami modelling and Storm surge

3.7. Sethusamudram Canal Creation

Proposed ship channel alignment, dredging segment length and dredging zone data were extracted from Sethusamudram Corporation Limited in India. The path was designed using 60m resolution bathymetry data. The desired area was created by using the mathematical functions (Ms. Excel) and ArcGIS. The width of the canal is 300m. Therefore, the width of the canal is represented by 5 grid points.

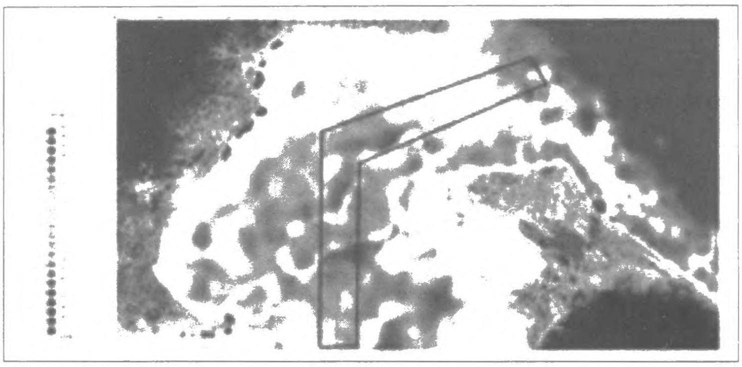

Figure 5 Sethusamudram canal between Sri Lanka and India

4. RESULTS AND DISCUSSION

4.1. Calibration of the Tidal Model

The tidal constituents O1, M2, S2, and K1 were selected for Trincomalee and tidal elevation was plotted for several locations. The measured tidal data were extracted from the sea level database from the European Institute for Protection and Security of the Citizens. As shown in Figure 6, the modelled tidal elevation time series agrees reasonably well with the measured.

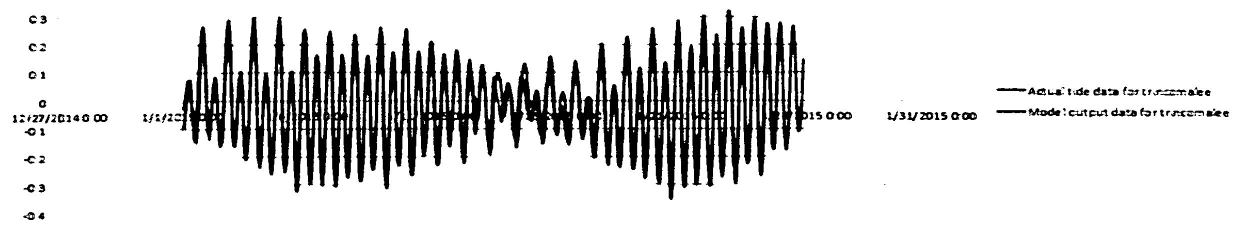

Figure 6 Comparison of measured and modelled tidal elevation for Trincomalee

The constructed tidal flow model was calibrated by adjusting the calibration parameters. Manning's roughness coefficient, horizontal eddy viscosities were changed between -10% to 10 % but these calibration parameters were not sensitive to change. Therefore, values of tidal constituents were slightly changed to get the required agreement with the measured water levels.

4.2. Calibration of the Tsunami Model

The model was calibrated against water levels observed during 2004 tsunami. The tide level and tsunami elevation (i.e., a long sinusoidal wave in deep water boundary) were superimposed on the same time base as for the 2004 tsunami. The superimposed time series was used as the model boundary. Error between the modelled and observed tsunami water levels near the shoreline was less than 3%. Therefore, the model was considered sufficiently accurate to study the effect of the SSCP.

4.3. Hydrodynamic Modelling of the Canal and Surrounding Area

After the Canal creation in the bathymetry the model was run for post-construction scenario and the results were compared with the existing. Eastern, Southern and Western provinces were in a shadow zone, whilst Northern Province and Gulf of Mannar were directly affected by the Tsunami waves.

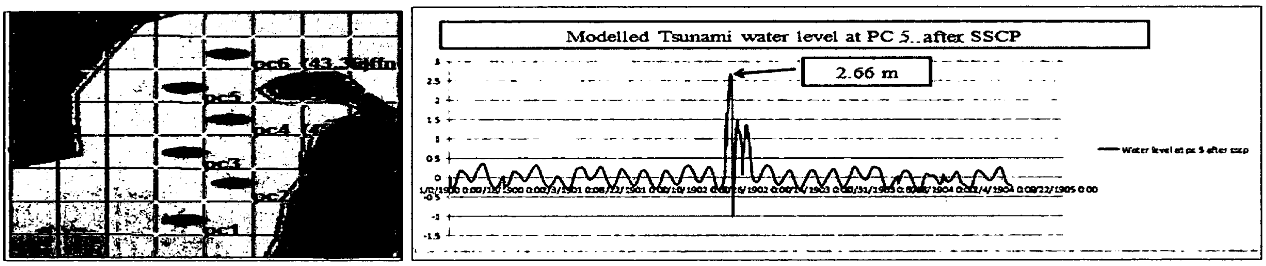

Figure 7 Left Observation points (Jaffna and Gulf of Mannar) and Right; Modelled maximum water level at pc5 after SSCP

Table 1 Variation of Tsunami water level (m MSL)

Area	Before SSCP	After SSCP	Percentage increase in water level
PC1	0.78	0.80	2.56
PC2	0.92	0.96	4.34
PC3	1.23	1.29	4.87
PC4	1.90	1.98	4.21
PC5	2.55	2.66	4.31
Jaffna	2.98	3.04	2.00
Mannar	0.60	0.61	1.67

4.4. Hydrodynamic Model for Cyclonic Conditions

The Delft 3D FLOW model was used for storm surge modelling. FLOW model was simulated with the output from the built in WES model which provides the wind field. Bathymetry data which was previously described and default physical parameters such as wind drag coefficient, viscosity and manning's coefficient were initially used. Astronomical tide was given as the boundary conditions. Consequently, tidal forces were taken into account in this simulation. Ultimately the output water levels should be calibrated and validated. Table 2 shows the calibration and validation of the model for cyclone condition for various locations near the coasts of Sri Lanka and India.

Table 2 Calibration and validation of storm surge model

Cyclone year	Location	Simulated surge height (m)	Actual surge height (m)
1964 cyclone	Mannar	5.5	4.6
	Dhanushkodi	5.4	5.0
1978 cyclone	Batticaloa	2.8	2.72
	Thondi	3.4	4.0

A comparison of Storm Surge heights before and after the construction of SSCP is shown in Table 3.

Table 3 Storm Surge heights before and after the canal implementation

Location	Surge height without canal (m)	Surge height with canal (m)	Percentage increase (%)
Jaffna	1.9	2.0	5.26
Mannar	2.0	2.1	5.00
Thondi	3.4	3.5	2.94

5. CONCLUSIONS

This research was conducted to investigate the impact of Tsunami and Storm Surges on Sri Lanka and India after the construction of the Sethusamudram Ship Canal. It was observed through modeling that the storm surge height is increased by approximately 5% along the Jaffna and Mannar coasts.

Hydrodynamic simulations indicated that the Gulf of Mannar has a minor impact of between 2% to 5% in terms of water level increase due to tsunami wave penetration after the construction of the Sethusamudram Ship Canal.

The resolution of the bathymetry data used for this research was 60 m, 240 m and 1000 m. This might influence the water levels in the near shore. Increased resolution of the bathymetry data increases accuracy of results. Therefore, it is recommended to develop this model with high resolution bathymetry data to obtain more precise results in the nearshore. Cyclone tracks may change from historical events. Therefore, research should be carried out to understand the effect of changed cyclone tracks.

6. ACKNOWLEDGMENTS

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