ASSESSMENT OF INLAND TSUNAMI PARAMETERS AND THEIR EFFECTS ON MORPHOLOGY

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ABSTRACT

ASSESSMENT OF INLAND TSUNAMI PARAMETERS AND THEIR EFFECTS ON MORPHOLOGY

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Recent tsunami events clearly showed the potential of massive destruction on buildings, infrastructure, coastal protection structures and also morphological changes by tsunami waves. This thesis covers investigation of tsunami motion at inundation zone considering different factors (smoothed ground without buildings, or with buildings), and related changes of inland tsunami parameters and their effects on morphology. For the applications, the simulations have been performed using different topographic conditions at Antalya Belek area. The deterministic tsunami source has been selected to occur by the fault at Cyprus Antalya direction. The difference of the inland tsunami parameters according to the different topographic conditions have been compared and presented with discussions.

Keywords: Tsunami modeling, tsunami inundation, morphological changes, friction coefficient, Antalya, GIS
ÖZ

KARASAL TSUNAMI PARAMETRELERİNİN DEĞERLENDİRİLMESİ VE MORFoloji ÜZERİNDEKİ ETKİLERİ

Pamuk, Aykut
Yüksek Lisans, İnşaat Mühendisliği Bölümü

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“To My Dear Mother and Father”
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LIST OF SYMBOLS

$C$: Concentration at boundary of both layers
$\bar{C}_B$: Mean concentration of bed load layer
$\bar{C}_S$: Mean Concentration of suspended load layer
$d$: Median grain size
$D$: Total water depth ($\eta + h$)
$f$: Darcy friction factor
$g$: Gravitational Acceleration
$h$: Undisturbed water depth
$h_B$: Depth of bed load layer
$h_S$: Depth of suspended load layer
$k$: Bottom friction coefficient
$M$: Discharge flux in x- direction
$N$: Discharge flux in y- direction
$P$: Pick-up rate
$q_B$: Bed load rate
$R_0$: Rouse number
$s$: Density of sand in water
$u$: Flow velocity
$u^*$: Shear velocity
$w_{ex}$: Exchange load
$w_s$: Settling velocity
$Z_B$: Bed level
$\beta$: Ratio of sediment diffusion to momentum diffusion coefficients
$\eta$: Water surface elevation
$\kappa$: The von Karman constant
\( \lambda \) : Porosity

\( \nu \) : Kinematic viscosity

\( \rho \) : Density of water

\( \rho_s \) : Density of sediment particles

\( \tau_0 \) : Bed shear stress

\( \tau_* \) : Shields parameter

\( \phi_B \) : Non-dimensional bed load transport rate

\( \psi_{\text{rise}} \) : Non-dimensional rise rate
CHAPTER 1

INTRODUCTION

Tsunami is a special type of wave that occurs in water bodies such as, oceans, lakes or estuaries. Cause of tsunamis is displacement of large water bodies. Therefore, an event that cause displacement of water bodies can be a triggering factor of tsunamis. Generally, earthquakes, volcanic eruptions, landslides are the main source mechanisms. Since, these events are capable of creating such displacements in the water bodies.

The term tsunami refers to harbor (tsu) wave (nami) in Japanese. Tsunamis have small or moderate wave amplitude in deep sea. Also, wave length of tsunamis are very long. Therefore, tsunamis are hard to spot in deep sea. According to the tale, Japanese fishermen have not noticed the tsunami after an earthquake in deep sea. However, when they have gone back to the harbor, they have seen the destruction of tsunami. Therefore, they have considered that tsunamis occur in the harbors. So, they called these waves as tsu (harbor) nami (wave).

Tsunami events are not observed homogeneously in the shorelines. According to Bryant (2008), tsunamis occur most frequently in Pacific Ocean with the rate of 25.4 %. In this thesis, main focus will be in Mediterranean Sea, where 10.1 % of tsunamis have occurred (Table 1).
Table 1: Percentage distribution of tsunami in World’s Oceans and Seas (Bryant 2008)

<table>
<thead>
<tr>
<th>Location</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlantic East Coast</td>
<td>1.6</td>
</tr>
<tr>
<td>Mediterranean</td>
<td>10.1</td>
</tr>
<tr>
<td>Bay of Bengal</td>
<td>0.8</td>
</tr>
<tr>
<td>East Indie</td>
<td>20.3</td>
</tr>
<tr>
<td>Pacific Ocean</td>
<td>25.4</td>
</tr>
<tr>
<td>Japan-Russia</td>
<td>18.6</td>
</tr>
<tr>
<td>Pacific East Coast</td>
<td>8.9</td>
</tr>
<tr>
<td>Caribbean</td>
<td>13.8</td>
</tr>
<tr>
<td>Atlantic West Coast</td>
<td>0.4</td>
</tr>
</tbody>
</table>

In recent decades, tsunamis have caused devastating damage to coastal regions. Especially, two of the deadliest natural disasters in modern times, 2004 Indian Ocean Earthquake and Tsunami and 2011 Great East Japan Earthquake and Tsunami have drawn the attention to tsunamis. Damages created by tsunamis can be summarized as casualties, property damages, pollution due to drifting materials (oil etc.) and spread of diseases after the events.

Numerical modeling of tsunami is used in the world as an important tool to predict a future tsunami wave propagation and inundation. It can provide data about inundation patterns and may support early warning, evacuation, planning and vulnerability analyses (Taubenböck et al. 2009).

Inundation and run-up are main reasons of destruction. The aim of this thesis is to investigate the effects of buildings, structures, forests on the inundation characteristics of tsunamis. Ground material, plantation and rigidity of may affect the flow of water in to the land. It is important to include these parameters in to the consideration. So, in this thesis, employing topography, with and without buildings or the benefit of using spatial distribution of friction matrix in the numerical
modeling and corresponding result of tsunami parameters in inundation zone will be discussed.

Tsunamis are capable of creating sediment transport in the near shore area. Takahashi et al. (2000) have stated that tsunamis can carry considerable amount of sand and erosion and/or deposition on harbors can reduce the port functions. For example, intake of cooling system of power plants may suffer from deposition of sea sand. Also, for the identification of past tsunamis, sedimentary traces are the only direct evidences. In this thesis the sediment transport and morphological changes due to tsunamis will be also investigated and discussed.

In the following sections, a literature survey is presented in Chapter 2. Methodology is summarized in Chapter 3. Historical tsunami sources and possible tsunami scenarios for Eastern Mediterranean are presented in Chapter 4. Then, tsunami inundation modeling with numerical simulations are explained in Chapter 5. In Chapter 6, possible morphological changes were discussed. Finally, conclusion and discussion of the analysis results were given in Chapter 7.
CHAPTER 2

LITERATURE SURVEY

In this section, literature survey about tsunami inundation modeling and morphological changes due to tsunami attack will be presented. Firstly, studies about tsunami inundation modeling will be discussed.

Velocity and flow depth are two main parameters that cause damage during the inundation of tsunamis. It is important to model these tsunami characteristics as accurate as possible in order to predict damages of a future tsunami can make. Therefore, in the literature, there are some studies about the techniques to reach an accurate modeling.

One of the first studies was carried out by Goto and Shuto (1983). They realized that large obstacles such as buildings or sea walls in the inundation zone can block the tsunami inundation. Therefore, it is expected that obstacles may reduce the inundation. Authors have proposed a method to reproduce this effect. According to this method, buildings and sea walls can be modeled as the equivalent roughness using the Manning’s coefficient. They have compared the model with hydraulic experiments for unsteady flow and equivalent roughness model have shown good agreement.

For detailed inundation modeling, accurate bathymetry and topography are essential. Taubenböck et al. (2009) used a high resolution bottom topography. Therefore, building shape and height information was integrated into the Digital Elevation Model (DEM). This model leads to more physical accuracy in terms of topography. Authors have realized that using this method gives higher velocities in
major streets due to the channeling effect. Also, building mask information gave lower inundation extent comparing to conventional tsunami modeling with plain DEM without buildings.

Gayer et al. (2010) studied tsunami inundation in densely populated areas. In this study, authors have given a method for detailed roughness maps. Equivalent roughness values, determined from literature or experiments, were assigned according to land use classes. Some of these classes were forests, buildings, water bodies and streets. Also, it was mentioned that for buildings, there are several options. One of them was declaring building locations as non-calculation elements. Another one is to integrate building height information into DEM. The third one is to use equivalent roughness values for buildings. For this study, authors have chosen third option. To assign the spatial distribution of roughness coefficients, satellite images have been used. Consequently, use of different roughness coefficients not only changes the inundation depth but also flow velocity. Also, authors have used several data sets to establish bathymetry/topography information. Finally, 10 m grid size were used to represent streets, buildings etc.

Muhari et al. (2011) carried out a study that is very similar to this thesis. They have analyzed three different tsunami run-up models. First one was the conventional tsunami modeling with uniform roughness coefficient in the study area (Constant Roughness Model, CRM). Second one had a very detailed high resolution bottom topography which was capable of representing buildings (Topographical Model, TM). Third model was using different roughness coefficients according to the land use (Equivalent Roughness Model, ERM). Also, abbreviations of the study are used in this thesis. Some problems with the use of high resolution data were mentioned in the study. One of them is lack of available bathymetry and topography information with desired accuracy. Significant efforts are needed to create such database. Another problem is the long computation times due to fine grid sizes. In the simulations, authors have used nonlinear shallow water equations. Consequently, results were compared and discussed by the authors. Maximum inundation distance was significantly affected in TM and ERM models comparing with CRM. CRM gave higher maximum inundation extent. From flow velocity
point of view, ERM was not very good at representing like in the case of TM. Authors said that it may be because ERM cannot represent the cross sectional properties. However, it is suggested that if high resolution bottom topography with building height information is not present, one can use ERM.

Another very similar study has been performed by Kaiser et al. (2011). They have modeled a tsunami with 3 different approach. Building height integration into DEM, varying Manning coefficients and constant Manning for entire domain were these 3 approaches. Manning’s n values that were used in the study are presented in Table 2. To obtain high resolution topography, data from an airborne flight campaign were used. Consequently, bathymetry and topography information was obtained with 1 m grid size. For inundation modeling, authors have used a wave series obtained from a nested simulation using a source data. In these nested simulation coarser grid sizes have been used. This procedure has been applied because high resolution topography and bathymetry leads very long computation times in large domains. By using wave series, one can model inundation in land with high resolution and less computation times. Then, findings from simulations have been compared with observations from 2004 Indian Ocean Tsunami. According to the study, topography is the most important factor on the tsunami modeling. Since, inundation characteristics are very sensitive to small changes in topography which can be modeled only with high resolution topography with building height information. Also, varying Manning values can significantly affect the maximum inundation border and flow velocities. Authors suggested that for accurate inundation, buildings should be presented as elevation data or as roughness. Furthermore, it is stated that sediment transport and morphological changes due to tsunami may affect the inundation patterns and extent of damage.

Ohira et al. (2012) have studied effect of forest for reduction of tsunami inundation. Numerical simulations has been performed under various forest widths. In order to implement the forest effect into the simulation, Manning’s roughness coefficient was used. For forest area, Manning’s n value was taken as 0.025. Bathymetry/topography information were obtained with 20 meters of grid sizes and shoreline was corrected with the help of satellite image. 10 meters of grid sizes were
used in the simulations with interpolation. According to the results of the study, forests can decrease inundation depth and flow velocity of tsunami. As the width of forest increases, inundation depth and flux decreases gradually. Also, it was assumed that if inundation depth is higher than 4 meters, forest will begin to be destroyed.

**Table 2:** Manning values for land cover classes (Kaiser et al. 2011)

<table>
<thead>
<tr>
<th>Land Cover Class</th>
<th>Manning’s n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barren land/mud, sand beach, roads</td>
<td>0.0310</td>
</tr>
<tr>
<td>Grassland</td>
<td>0.0360</td>
</tr>
<tr>
<td>Young Plantation</td>
<td>0.0370</td>
</tr>
<tr>
<td>Scrubland</td>
<td>0.0380</td>
</tr>
<tr>
<td>Cashew Plantation</td>
<td>0.0430</td>
</tr>
<tr>
<td>Other Plantation</td>
<td>0.0430</td>
</tr>
<tr>
<td>Coconut Plantation</td>
<td>0.0458</td>
</tr>
<tr>
<td>Semi Open Landscape</td>
<td>0.0550</td>
</tr>
<tr>
<td>Oil Plantation</td>
<td>0.0573</td>
</tr>
<tr>
<td>Middle Density Urban Area</td>
<td>0.0600</td>
</tr>
<tr>
<td>Melaleuca Forest</td>
<td>0.0550</td>
</tr>
<tr>
<td>Rubber Plantation</td>
<td>0.0609</td>
</tr>
<tr>
<td>Casuarina Forest</td>
<td>0.0731</td>
</tr>
<tr>
<td>Inner Beach Forest</td>
<td>0.0744</td>
</tr>
<tr>
<td>High Density Urban Area</td>
<td>0.0800</td>
</tr>
<tr>
<td>Other Forest/Rainforest</td>
<td>0.0850</td>
</tr>
<tr>
<td>Outer Beach Forest</td>
<td>0.0870</td>
</tr>
<tr>
<td>Mangrove Forest</td>
<td>0.0951</td>
</tr>
<tr>
<td>Buildings (non-resistant)</td>
<td>0.0900</td>
</tr>
<tr>
<td>Buildings (resistant)</td>
<td>0.4000</td>
</tr>
</tbody>
</table>
Adriano et al. (2013) have carried out a study about tsunami inundation mapping in Lima. In this study, they have used a numerical code developed by Disaster Control Research Center (DCRC), Tohoku University Japan. Name of the code is TUNAMI-N2 (Tohoku University Numerical Analysis Model for Investigation of Near-field tsunami No.2). Nonlinear shallow water equations were used in order to simulate the tsunami propagation and inundation. Two approaches were mentioned for the inundation modeling. First one is the topographical model with constant roughness coefficient for the entire domain with a high resolution topography data that can contain building height information. Second approach is the equivalent roughness model. In this model, different Manning’s roughness values are assigned to each cell according to the land cover/land use. In the study, authors have used topographic model with different Manning’s values. Though, for the scope of the work, they did not carry out a comparison. However, it is important to see that these approaches are being used in the tsunami inundation studies, extensively.

Gopinath et al. (2014) have carried out numerical simulations and validated the findings with field survey data collected after 2004 Indian Ocean Tsunami. It is mentioned that in order to simulate the inundation accurately, resolution of topography is very important. Also, land use/land cover information can be effective due to the various friction coefficients. In the simulations, nonlinear shallow water equations were employed. This study compared with the simulations with constant roughness model and friction matrix approaches. Topographical model containing building height data was not studied. According to the results of the study, friction matrix did not create a significant difference in run-up and inundation comparing with constant roughness model. Furthermore, according to the authors, due to the modeling uncertainties, for buildings a conservative Manning’s value is most efficient strategy.

According to the studies about inundation modeling, high resolution topographic information is very important for the accuracy of simulations. Therefore, representing topography with high resolution is necessary. Also, one way of including buildings, forests, roads etc. into the modeling phase can be to use different roughness coefficients for each land cover/land use class. Furthermore, it
is realized that in general, nonlinear shallow water equations are used for the tsunami simulations.

From this point forward, scientific investigations on morphological changes due to tsunami attack will be presented. Generally, studies can be divided into two subsections. One of them is related to after tsunami surveys. In these studies, authors give general description of damages and morphological changes induced by the tsunami events. Other subsection is related to the equations to model the morphological changes. Physical or numerical tests are carried out in these studies.

Morphological changes are not only a cause of incident waves but also a cause of return flow. Especially, river beds increase the effect of return flow. Therefore, river mouths needs special care.

Morphology changes due to 2011 Great East Japan Earthquake and Tsunami have been studied by Tanaka et al. (2012) for Miyagi Prefecture, Japan. According to authors, Miyagi Prefecture was one of the most affected areas by 2011 Great East Japan Tsunami. Run-up height has been measured up to 19.5 meters by the Joint Survey group. Significant erosion and breaching have been observed along the coast. Furthermore, in this study morphological changes due to tsunami have been investigated by aerial photographs taken before and after the event. Considering the study area of the thesis, investigating similar locations would be more appropriate. For example, Natori River is a similar site to the study area of this thesis and can be worth investigating. There is a lagoon behind a sandy beach, which makes a similar location to the non-residential area in the study location.

Therefore, firstly, observations of Tanaka et al. (2012) about Natori River will be mentioned. For Natori River, according to the field survey by Mori et al. (2012), wave height of the tsunami was around 14 m. In the region, tsunami has caused flooding and destruction. Morphological changes can be clearly seen from the aerial photographs. Under the tsunami attack, beach was severely eroded and some breaching has been occurred. Eroded sand deposited in land by incident wave or in sea by return flow. Also, shoreline position has shifted landward. Furthermore, in the entrance of the river, river bed has eroded significantly, doubled at some
sections. A similar area is the Nanakita River. Again a lagoon formation was present behind a sandy beach. Tsunami waves completely destroyed the beach. Also, according to authors, former rivers and drainage channels should be carefully inspected. Since, these areas can easily eroded due to the strong return flow caused by the catchment area.

There are similar studies regarding 2004 Indian Ocean Tsunami. Pari et al. (2008), has given the morphological changes at Vellar estuary, India under the impact of 2004 Indian Ocean Tsunami. According to Pari et al. (2008), significant morphological changes have been observed in the Vellar coast. River mouth were totally destroyed, sand dunes were flattened.

Another study about morphological changes due to 2004 Indian Ocean Tsunami was carried out by Feldens et al. (2009). This study mainly focused on the offshore effects of the morphological changes in Pakarang Cape, Thailand. Again, river mouths were subject to morphological changes due to the strong return flows. However, study was held 3 years later the event. Still, effects have been observed. Especially, boulder transport due to tsunami has been verified.

For 2011 Tohoku Earthquake and Tsunami, PIANC (The World Association for Waterborne Transport Infrastructure) has prepared a report “Tsunami Disasters in Ports due to Great East Japan Earthquake”. In this report, bathymetry changes at channels and basins were investigated. According to the observations, scours occurred at tips of breakwaters where currents are concentrated and eddies are generated. Therefore, possible causes of scours are concentration of flows and eddies around structures. Also, at the centers of inner-port regions, deposition were observed. It is suggested that, in order to estimate morphological changes, models need to be improved.

Modeling of sediment transport due to tsunamis has been studied mostly after 2000s. Takahashi et al. (2000) proposed a model in order to evaluate erosion, deposition and sand movements. And, proposed model was applied to 1960 Chilean Tsunami in Kesennuma Bay. This study includes bed load rate, suspended load rate and exchange load rate. Two important parameters were realized. One of them is
the coefficients used in the formulas. Generally, these coefficients are determined from laboratory experiments. And, in the laboratory experiments, small Shields parameters are used. However, in case of tsunamis, Shields parameters are higher. Second problem is with suspended load. If one assumes an equilibrium concentration, for erosion case, calculated suspended transport will be overestimated. For deposition case, underestimation occurs. In order to clear these problems, an exchange load is introduced. In this two layered model, suspended load is supplied with pick-up rate and reduced by the settling rate.

Diagram of this proposed model is in Figure 1. In this figure, $\rho_s$ is density of sediment particles, $\bar{C}_B$ is mean concentration of bed load layer, $\bar{C}_S$ is mean concentration of suspended load layer, $C$ is concentration at boundary of both layers, $q_B$ is bed load rate, $M$ is flow flux, $\lambda$ is porosity, $h_s$ and $h_B$ are depth of suspended load layer and bed load layer, respectively, and $Z_B$ is bed level. As balance between rising and settling load, an exchange load is provided.
Figure 1: Diagram of proposed model by Takahashi et al. (2000)

Governing equations are determined according to this diagram (Eq. 1 and Eq. 2). \( w_{\text{ex}} \) is the exchange load and \( h \) is water depth.

\[
\frac{\partial Z_B}{\partial t} + \frac{1}{1 - \lambda} \left( \frac{\partial q_B}{\partial x} + w_{\text{ex}} \right) = 0 \tag{1}
\]

\[
\frac{\partial \bar{C}_s M}{\partial x} - w_{\text{ex}} + \frac{\partial \bar{C}_s h}{\partial t} = 0 \tag{2}
\]

From the hydraulic experiments, the regressed formulas are as follows.

\[
\phi_B = 21 \tau_*^{3/2} \tag{3}
\]
\[ \psi_{\text{rise}} = 0.012\tau_*^2 \]  

(4)

\( \phi_B \) is non-dimensional bed load transport rate and \( \tau_* \) is Shields parameter, \( \psi_{\text{rise}} \) is non-dimensional rise rate. Then, Takahashi et al. (2000) applied this model to Kesennuma Bay for the 1960 Chilean Tsunami. A parameter, which is ratio of deposition volume to erosion volume, was introduced to verify the results. In the real event, parameter was measured as 0.28. However, in the numerical modeling, this parameter was found as 0.84 which is much different than the real case. Consequently, it is realized that the model can simulate the sediment transport well, where the tsunami flow simulated well. Therefore, it is said that in order to have an accurate simulation, velocity computations should be simulated carefully.

Another study about the modeling of morphological changes due to tsunami was done by Yoshii et al. (2010). It was a similar study to Takahashi et al. (2000). However, some improvements were made for the pick-up rate formula. Since, former model does not take into account the sand grain size. For pick-up rate the following equation was proposed.

\[
\frac{P}{\sqrt{s gd}} \left( \frac{s gd^3}{v^2} \right)^{0.2} = 0.15 \left( \frac{w_s}{\sqrt{s gd}} \right)^{0.8} (\tau_* - \tau_{*cr})^2
\]  

(5)

In this equation, \( P \) is the pick-up rate, \( v \) is the kinematic viscosity, \( s \) is density of sand in water, \( g \) is gravitational acceleration, \( d \) is grain size and \( w_s \) is settling velocity of sand. If grain size is taken as 0.2 mm for the proposed formula, the equation will be as follows.

\[
\frac{P}{\sqrt{s gd}} = 0.015(\tau_* - \tau_{*cr})
\]  

(6)
Equation 6 is similar to Equation 4. However, the coefficient is 0.015 instead of 0.012. According to Yoshii et al. (2010), Equation 5 can predict more accurate pick-up rate compared with Takahashi et al. (2000).

Pritchard and Dickinson (2008) have drawn attention to deposits of historical tsunamis. “Inverse” and “forward” problems were introduced. Inverse problem means that reconstructing hydrodynamics of a tsunami from the deposits. Sedimentary effects are the only direct evidence about the scale of a tsunami. Forward problem is to predict the sediment transport of a possible future tsunami from the simulation. As for the sediment transport model, authors considered bed load and suspended load modes for sediment transport. Also, it was mentioned that for tsunami waves suspended load is more effective. For Shields parameter, authors have suggested that critical Shields parameter is very small than Shields parameter for tsunami case. Therefore, in this study, critical Shields parameter was taken as zero. From the results of the study, net transport is driven by maximum velocities under the wave.

Imamura et al. (2008) have studied boulder transportation due to tsunami flow. For boulders, it was observed that, transportation mode is generally rolling or saltation. Boulder transportation is mainly related to hydraulic forces and current velocities. However, these parameters are difficult to estimate from field survey. Therefore, authors conducted a numerical simulation to find the hydraulic forces and current velocities. In numerical simulations, they have used nonlinear shallow water equations. Also, Manning’s n value was taken as 0.0125.

Nakamura et al. (2009) have studied three-dimensional coupled fluid-sediment model with bed and suspended load transport. Study was mainly considers the sediment transport due to tsunamis. Three different models have been investigated. One of them was sediment transport model (STM) which was developed by Takahashi et al. (2000) which was explained before. Second one was similar to STM with modification to Shields parameter in order to consider the effect of infiltration/exfiltration flow velocity. Third model was a further developed model with inclusion of effective stress fluctuations inside the sand layer, namely effective
stress model (ESM). From the hydraulic experiments, ESM was in relatively good agreement with experimental data. Therefore, for future studies, authors recommended to use ESM.

Li et al. (2012) have worked on coastal changes due to tsunami attack for Painan, West Sumatra, Indonesia. A scenario based study with the focus on sediment movement and morphological changes has been carried out. For the tsunami propagation and inundation simulation, COMCOT software has been used. Nonlinear shallow water equations have been used in the simulations. For sediment movement, XBeach software package has been used. XBeach is a 2DH numerical model for sediment transport and morphological changes of nearshore area, beaches and dunes. Relevant information about XBeach can be found in Roelvink et al. (2009). It was observed that significant sediment transport and severe scour may occur in the region. It may also be important that, the calculated average speed of wave front is around 2 m/sec and flow velocities reached about 5 m/sec. These velocities can erode large amount of sediment near shore and can create scours. Also, it has been stated that scouring occurs within less than 1 hour for tsunami flows.

Sakakiyama et al. (2011) have carried out laboratory experiments in order to investigate topography change due to tsunami attack inside harbors. Deposition was observed in the center of harbor where vortex occurred. Shields number from experimental results were not close to field measurements. However, Rouse number (relation between fall velocity and sand diameter) was almost equivalent to field observations.

Morphological changes in Lhok Nga, west Banda Aceh, during 2004 Indian Ocean Tsunami have been studied by Li et al. (2012). A coupled hydrostatic and morphodynamic model COMCOT-SED was used. Basic conclusions of the study were that during uprush and backwash periods deposition happens. Also, another conclusion of the study was that topography can affect the characteristics and spatial distribution of tsunami deposits. Furthermore, availability of sand and sediment supply affects thickness of tsunami deposits.
Also, Gusman et al. (2012), Kihara et al. (2012), Ranasinghe et al. (2013), Cheng and Weiss (2013), studies about the numerical modeling of morphological changes due to tsunamis. However, equations used in the modeling generally have the same characteristics.

Sugawara et al. (2014a) have summarized the current numerical models for tsunami induced sediment transport. Different sediment transport models are available, namely Delft3D, XBeach, C-HYDRO3D and STM. These models divide the sediment transport generally into bed load, suspended load and exchange load. Previous given equations for Takahashi et al. (2000) and Yoshii et al. (2011) are used in STM model.

Delft3D model is a 2DV/3D hydrostatic model and uses Van Rijn (1993) and Van Rijn et al. (2004) as bed load formulas. For suspended load, Van Rijn (2007a, b) and for settling rate again Van Rijn (1993) model is used. Mixed grain-size can be used in the model.

XBeach model is a 2DH model and uses Van Rijn (1993) and Soulsby (1997) equations for bed load formulation. Also, formulation for settling rate is taken from Van Rijn (1993). Mixed grain-size can be used in this model.

C-HYDRO3D is a 3D hydrostatic model. In the model, Van Rijn (1984a) for bed load formulation and Van Rijn (1984b) for suspended load formulation are used. As the settling rate formulation, Soulsby (1997) is used.

Sugawara et al. (2014b) have listed the issues that needs to be improved for tsunami sediment modeling: (1) the applicability of sediment pick-up rate formulations, (2) Manning’s roughness and bottom friction coefficients, (3) change of flow characteristics with the intrusion of sediment into flow, (4) turbulence effects, (5) 3D sediment transport formulations for complex topographies, (6) usage of mixed grain-sizes, (7) lateral variation of flow, (8) pore water pressure gradient and exfiltration/infiltration of water. Therefore, for the tsunami sediment transport models, improvements are necessary in order to compute morphological changes associated by tsunami flows.
There are also other methods in order to assess the sediment transport due to tsunami attack. Weiss (2004) have mentioned the Hjulström-Sundborg diagram (Figure 2). This diagram is used for the river flow. It helps to determine whether a river will erode, transport or deposit the bed material. According to this diagram, for a grain size, there are thresholds for erosion, deposition and transportation. Note that, large particles needs higher current velocities as expected. Also, for fine particles, again high currents are needed for erosion. The diagram is easy to use. However, Hjulström-Sundborg diagram does not have a proper scientific or mathematical background (Miedema 2008). Also, it is easy to find Hjulström-Sundborg diagrams with different thresholds, which leads to low credibility.

Figure 2: An example of the Hjulström-Sundborg Diagram (Weiss 2004)

Another method has been presented by Yeh and Li (2008) for tsunami scour and sedimentation. Shear stress can be represented by a dimensionless number, which
is the Shields parameter. It is the ratio of shear stress to buoyant sediment weight. Shields parameter can be calculated as

\begin{equation}
\tau_* = \frac{\tau_0}{\rho gd(s - 1)} = \frac{fu^2}{8gd(s - 1)}
\end{equation}

where \( \tau_0 \) is bed shear stress, \( \rho \) is density of water, \( f \) is the Darcy friction factor and \( u \) is the flow velocity. Darcy friction factor \( f \) is in the range of \( f = 0.006 \sim 0.039 \). Yeh and Li (2008) have assumed the \( f \) as 0.01 for the tsunami condition.

Also, Yeh and Li (2008) have considered another dimensionless number, which is Rouse number, to classify the modes of sediment transport. Rouse number is the ratio of particle settling velocity to shear velocity. It can be calculated as

\begin{equation}
R_0 = \frac{w_s}{\beta \kappa u_*}
\end{equation}

where \( u_* \) is shear velocity \( \beta \) is the ratio of sediment diffusion to momentum diffusion coefficients which is close to 1. The von Karman constant is \( \kappa \) and equal to 0.4. Settling velocity \( w_s \) can be calculated as

\begin{equation}
w_s = \frac{8v}{d} \left( \sqrt{1 + \frac{(s - 1)gd^3}{72v^2}} - 1 \right)
\end{equation}

Where \( u_* \) is the shear velocity and can be approximated as

\begin{equation}
u_* = u \left( \frac{f}{8} \right)
\end{equation}

According to the Rouse number, modes of transport can be determined. The approximate required Rouse numbers for transport as bed load, suspended load and wash load are given in Table 3.
Table 3: Modes of transport according to the Rouse Number

<table>
<thead>
<tr>
<th>Mode of Transport</th>
<th>Rouse Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initiation of Motion (Deposition)</td>
<td>$R_0 &gt; 7$</td>
</tr>
<tr>
<td>Bed Load</td>
<td>$2.5 &lt; R_0 &lt; 7.5$</td>
</tr>
<tr>
<td>Suspended Load: (50% Suspended)</td>
<td>$1.2 &lt; R_0 &lt; 2.5$</td>
</tr>
<tr>
<td>Suspended Load: (100% Suspended)</td>
<td>$0.8 &lt; R_0 &lt; 1.2$</td>
</tr>
<tr>
<td>Wash Load</td>
<td>$R_0 &lt; 0.8$</td>
</tr>
</tbody>
</table>
CHAPTER 3

METHODOLOGY

Tsunami modeling requires reliable data. These data can be summarized as basically, bathymetry and topography information and source mechanisms that causes a tsunami. In this thesis, bathymetry data has been taken from GEBCO (General Bathymetric Chart of the Oceans). Topography information has been taken from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer). These are open-access data which can be retrieved easily.

However, due to the grid size of these data, buildings, rivers, roads etc. are not available in the digital elevation models. Therefore, an improvement may be necessary in order to represent the topography accurately. To achieve a high resolution data, buildings, rivers and any other important structural and natural patterns should be included into the DEM. Therefore, in this thesis, firstly rivers and breakwaters has been included into the DEM using the Google Earth satellite image.

Afterwards, the sensitivity of tsunami inundation has been tested for addition of building location into the DEM and spatial distribution of different friction coefficient according to land cover. Again locations of buildings, roads, forests, agricultural lands has been determined from Google Earth satellite image.

One of the most essential data in tsunami modeling is source parameters. To determine most representative tsunami source, historical data on tsunamis and seismic data can be useful to develop alternatives of the tsunami sources. Using this information one of the worst case scenarios can be selected and used in the
simulations. Determination of study area and processing the proper input data for tsunami modeling is another important task. In Chapter 4, the method of processing input data and the selected source mechanism used in the simulations will be explained.

River mouths are important locations for morphology changes considering the previous catastrophic events in Indian Ocean and Japan. In general, the inundation at residential areas is needed to investigate in detail to observe how tsunami inundation can be effected or diverted by the existence of the buildings. Furthermore, the influence of different bottom roughness coefficients on the inundation at the agricultural areas or forests can also be investigated.

As for the study area in this thesis, a region near Belek, Antalya, Turkey has been selected. This is an important region for Turkey due to its touristic significance. According to Republic of Turkey Ministry of Culture and Tourism, around 12 million people have visited Antalya region in 2012. Also, tourists visit Antalya region mostly due to sea tourism. Therefore, a tsunami event that will happen in summer can cause significant loss of lives. Figure 3 shows the study area. In the right side, a lagoon and a sand spit in between lagoon and the sea are present in front of a forest. In the left side, there is the residential area where resorts and hotels are present. Also, in the middle, there are two jetties in front of the river mouth. Therefore, this area has been selected as the study domain.

<table>
<thead>
<tr>
<th>Table 4: Boundaries of the study area</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coordinate System</strong></td>
</tr>
<tr>
<td><strong>Longitude</strong></td>
</tr>
<tr>
<td><strong>Latitude</strong></td>
</tr>
</tbody>
</table>

For tsunami simulation, a numerical model NAMI DANCE has been used with nonlinear shallow water equations. It is developed by Profs Andrey Zaytsev, Ahmet Yalciner, Anton Chernov, Efim Pelinovsky and Andrey Kurkin especially for
tsunami modeling. Model has been tested and verified in international workshops that have been organized specifically for validation of tsunami models (NAMI DANCE Manual, 2010).

Figure 3: Location of Study Area (Google Earth)
CHAPTER 4

TSUNAMI SOURCES IN THE EASTERN MEDITERRANEAN

In this chapter, historical tsunami sources, tsunami catalogues and tsunami scenarios for Eastern Mediterranean will be discussed.

It is well known that in the past Mediterranean Sea coasts were attacked by tsunamis (Tinti et al. 2005). In the literature, there are many studies regarding the tsunami events in the Eastern Mediterranean. Geological surveys and historical documents reveal that throughout the history, Eastern Mediterranean has been one of the hotspots of tsunamis due to high seismicity and volcanic activities.

Tsunami catalogues can help to determine the tsunami potential of a region. Identification of tsunami sources and tsunamigenic mechanisms can be found in the tsunami catalogues (Tinti et al. 2001). There are various studies regarding the tsunami catalogues in Eastern Mediterranean. Some tsunami catalogues were compiled by Galanopoulos (1960), Ambraseys (1962), Antonopoulos (1979), Papadopoulos and Chalkis (1984), Comninakis and Papazachos (1986), Soloviev (1990), Amiran et al. (1994), Soloviev et al. (2000), Papadopoulos (2000), Fokaefs and Papadopoulos (2007), and Yolsal et al. (2007).

One of the most recent study has been performed by Altinok et al. (2011). In this study, catalogue data are present for 134 tsunami events around Eastern Mediterranean, Aegean Sea, Marmara Sea and Black Sea. Mostly, tsunami records are in the form of a collection from previous catalogues and literature papers.
In Table 5, historical sources that create tsunamis are presented in Eastern Mediterranean and Southern Aegean according to the study of Altinok et al. (2011).

**Table 5**: Tsunamis in Eastern Mediterranean and Southern Aegean (from 1410 BC to 1961) (Altinok et al. 2011)

<table>
<thead>
<tr>
<th>Time</th>
<th>Region</th>
<th>Cause</th>
<th>Lat. (N)</th>
<th>Long. (E)</th>
<th>Reliability</th>
<th>Earthquake Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1410 ± 100 BC</td>
<td>South Aegean</td>
<td>VA</td>
<td>36.5</td>
<td>25.5</td>
<td>3</td>
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<tr>
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</table>
Table 5: Tsunamis in Eastern Mediterranean and Southern Aegean (from 1410 BC to 1961) (Altinok et al. 2011) (continued)

<table>
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<tr>
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<th>Cause</th>
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<th>Long. (E)</th>
<th>Reliability</th>
<th>Earthquake Magnitude</th>
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</tbody>
</table>
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<table>
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<tr>
<th>Time</th>
<th>Region</th>
<th>Cause</th>
<th>Lat. (N)</th>
<th>Long. (E)</th>
<th>Reliability</th>
<th>Earthquake Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1408</td>
<td>Eastern Mediterranean</td>
<td>EA+EL</td>
<td>35.8</td>
<td>36.1</td>
<td>3-4</td>
<td>7.4</td>
</tr>
<tr>
<td>1481</td>
<td>South Aegean</td>
<td>ER</td>
<td>36.2</td>
<td>28.5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>1489</td>
<td>South Aegean</td>
<td>ER</td>
<td></td>
<td></td>
<td>2-3</td>
<td></td>
</tr>
<tr>
<td>1494</td>
<td>South Aegean</td>
<td>ER</td>
<td>35.5</td>
<td>25.5</td>
<td>4</td>
<td>7.2</td>
</tr>
<tr>
<td>1546</td>
<td>Eastern Mediterranean</td>
<td>EA</td>
<td>32</td>
<td>35.1</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>1609</td>
<td>South Aegean</td>
<td>ER</td>
<td>36.4</td>
<td>28.4</td>
<td>4</td>
<td>7.2</td>
</tr>
<tr>
<td>1612</td>
<td>South Aegean</td>
<td>ER</td>
<td>35.5</td>
<td>25.5</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>1650</td>
<td>South Aegean</td>
<td>VO</td>
<td>36.4</td>
<td>25.4</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>1741</td>
<td>South Aegean</td>
<td>ER</td>
<td>36.2</td>
<td>28.5</td>
<td>4</td>
<td>7.3</td>
</tr>
<tr>
<td>1743</td>
<td>Eastern Mediterranean</td>
<td>ER</td>
<td></td>
<td></td>
<td>2-3</td>
<td></td>
</tr>
<tr>
<td>1752</td>
<td>Eastern Mediterranean</td>
<td>ER</td>
<td>35.6</td>
<td>35.75</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>1759</td>
<td>Eastern Mediterranean</td>
<td>EA/EL</td>
<td>33.1</td>
<td>35.6</td>
<td>4</td>
<td>6.6</td>
</tr>
<tr>
<td>1759</td>
<td>Eastern Mediterranean</td>
<td>EA/EL</td>
<td>33.7</td>
<td>35.9</td>
<td>4</td>
<td>7.4</td>
</tr>
<tr>
<td>1822</td>
<td>Eastern Mediterranean</td>
<td>EA</td>
<td>36.1</td>
<td>36.75</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>1837</td>
<td>Eastern Mediterranean</td>
<td>EA/E R</td>
<td>32.9</td>
<td>35.4</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>1843</td>
<td>South Aegean</td>
<td>ER</td>
<td>36.3</td>
<td>27.7</td>
<td>3</td>
<td>6.5</td>
</tr>
<tr>
<td>1851</td>
<td>South Aegean</td>
<td>ER</td>
<td>36.4</td>
<td>28.7</td>
<td>4</td>
<td>7.1</td>
</tr>
<tr>
<td>1851</td>
<td>South Aegean</td>
<td>ER</td>
<td>36.4</td>
<td>28.7</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>1855</td>
<td>Eastern Mediterranean</td>
<td>ER</td>
<td></td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1863</td>
<td>South Aegean</td>
<td>ER</td>
<td>36.5</td>
<td>28</td>
<td>2-3</td>
<td>7.8</td>
</tr>
<tr>
<td>1866</td>
<td>South Aegean</td>
<td>ER</td>
<td>36.4</td>
<td>25.4</td>
<td>1-2</td>
<td>6.1</td>
</tr>
<tr>
<td>1872</td>
<td>Eastern Mediterranean</td>
<td>EA</td>
<td>36.2</td>
<td>36.1</td>
<td>4</td>
<td>7.2</td>
</tr>
<tr>
<td>1933</td>
<td>South Aegean</td>
<td>ER</td>
<td>36.8</td>
<td>27.3</td>
<td>2</td>
<td>6.6</td>
</tr>
</tbody>
</table>
Table 5: Tsunamis in Eastern Mediterranean and Southern Aegean (from 1410 BC to 1961) (Altinok et al. 2011) (continued)

<table>
<thead>
<tr>
<th>Time</th>
<th>Region</th>
<th>Cause</th>
<th>Lat. (N)</th>
<th>Long. (E)</th>
<th>Reliability</th>
<th>Earthquake Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1941</td>
<td>Eastern Mediterranean</td>
<td>ER</td>
<td>35</td>
<td>34</td>
<td>2</td>
<td>5.9</td>
</tr>
<tr>
<td>1948</td>
<td>South Aegean</td>
<td>ER</td>
<td>35.51</td>
<td>27.21</td>
<td>4</td>
<td>7.1</td>
</tr>
<tr>
<td>1953</td>
<td>Eastern Mediterranean</td>
<td>ER</td>
<td>34.76</td>
<td>32.41</td>
<td>3-4</td>
<td>6.2</td>
</tr>
<tr>
<td>1956</td>
<td>South Aegean</td>
<td>ER</td>
<td>36.69</td>
<td>25.92</td>
<td>4</td>
<td>7.5</td>
</tr>
<tr>
<td>1961</td>
<td>South Aegean</td>
<td>ER</td>
<td>36.6</td>
<td>28.3</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Events were assessed in the study according to GITEC catalogue criteria for the reliability levels. These reliability levels are:

(0) Very improbable. The event has been documented, but is impossible to confirm and there is no general agreement.

(1) Improbable. Insufficient data or evidence for confirmation are available.

(2) Questionable. Probable tsunamis noted in various sources and catalogues, but with discrepancies, or confirmed in a single source of doubtful reliability.

(3) Probable. Sources specific and reliable, but occurrence dates old. Discrepancies present in some sources and catalogues. Reliable report, but confirmed in only a limited number of sources.

(4) Definite tsunami. The most reliable tsunamis which took place more recently. Multiple reliable sources: historic documents, church manuscripts, manuscripts by various authors, state archives, biographers, essays, private letters, magazines and reports.
The causes of tsunamis were inserted according to a cause code. This cause code is as follows: Volcanic associated (VA), Earthquake associated (EA), Earthquake landslide (EL), Submarine earthquake (ER), Submarine eruption (VO).

According to Altinok et al. (2011), most up to date tsunami catalogues are products of recent European Union projects, namely GITEC and GITEC-TWO (Genesis and Impact of Tsunamis on the European Coasts) and TRANSFER (Tsunami Risk and Strategies for the European Region). These projects have greatly contributed for establishing and developing unified criteria for tsunami parameterization, standards for the quality of the data, the data format and the database general architecture.

According to the historical information in front of the study area, there is no reliable tsunamigenic source that can be used in the tsunami modeling. However, with some events, Antalya is mentioned as one of the affected areas. These are 1303, 1489 and 1743 events. However, due to reliability levels and information regarding the sources, use of tsunami scenarios can be more appropriate to use in the modeling phase.

Some scenario studies have been done for Eastern Mediterranean. According to Tinti et al. (2005), Eastern Hellenic Arc can create an earthquake with a magnitude of $M_w=8.0$. Source parameters for this scenario can be seen in Table 6. Fault parameters were given for an earthquake that can happen in the Eastern Hellenistic Arc. However, epicenter of the earthquake is not given explicitly. The snapshots of tsunami propagation is presented in Figure 4.
Table 6: Fault parameters for the hypothetical thrust fault along the Eastern Hellenic Arc (Tinti et al. 2005)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>L (km)</td>
<td>190</td>
</tr>
<tr>
<td>W (km)</td>
<td>35</td>
</tr>
<tr>
<td>Strike (degree)</td>
<td>300</td>
</tr>
<tr>
<td>Dip (degree)</td>
<td>20</td>
</tr>
<tr>
<td>Rake (degree)</td>
<td>90</td>
</tr>
<tr>
<td>Slip (m)</td>
<td>5</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>100</td>
</tr>
</tbody>
</table>

The corresponding approximate values of the magnitude $M_W$ and of the seismic moment $M_o$ are respectively 8.0 and $1.1 \times 10^{21}$ N·m.

Figure 4: Snapshots of tsunami propagation computed for the Eastern Hellenic Arc (Tinti et al. 2005)
Another study was held by EUR-OPA Major Hazards Agreement of the Council of Europe, Euro-Mediterranean Centre on Insular Coastal Dynamics (ICoD) Malta and Ocean Engineering Research Centre, Civil Engineering Department, Middle East Technical University (METU). The project name is “Risk of and Vulnerability to Sea Level Rise and Tsunami of Selected Low Lying Coastal Areas in the Maltese Islands and Turkey. In this study, possible tsunami sources in the Eastern Mediterranean were presented (Figure 5).

According to this study, source with the code of 13-z32 can be used in the modeling. The fault and rupture parameters of the source 13-z32 is presented in Table 7.
Table 7: Fault and Rupture Parameters of the source 13-z32

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Epicenter</td>
<td>32.1 E 35.4 N</td>
</tr>
<tr>
<td>Length of fault (km)</td>
<td>156</td>
</tr>
<tr>
<td>Strike Angle (° W)</td>
<td>305</td>
</tr>
<tr>
<td>Width of Fault (km)</td>
<td>40</td>
</tr>
<tr>
<td>Focal Depth (km)</td>
<td>20</td>
</tr>
<tr>
<td>Dip Angle (degrees)</td>
<td>45</td>
</tr>
<tr>
<td>Slip Angle (degrees)</td>
<td>45</td>
</tr>
<tr>
<td>Displacement (km)</td>
<td>6</td>
</tr>
<tr>
<td>Height of initial wave (m)</td>
<td>1.84</td>
</tr>
<tr>
<td>Max. Positive amp. (m)</td>
<td>1.61</td>
</tr>
<tr>
<td>Min. Negative amp. (m)</td>
<td>-0.23</td>
</tr>
</tbody>
</table>

In the modeling of tsunami for the thesis, another source has been used. This source is obtained from the suggestion of thesis supervisor Prof. Dr. Ahmet C. Yalciner. Estimated rupture parameters of the source is presented in Table 8. This source can generate an earthquake with a magnitude of M=8.5. This can be considered as one of the worst case scenario for the study region, Antalya. In Figure 6, location and initial sea state of selected tsunami source is plotted.
Table 8: Estimated Fault and Rupture Parameters of Tsunami Source

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Epicenter</strong></td>
<td>32.0 E 34.75 N</td>
</tr>
<tr>
<td>Length of fault (km)</td>
<td>230</td>
</tr>
<tr>
<td>Strike Angle (° W)</td>
<td>290</td>
</tr>
<tr>
<td>Width of Fault (km)</td>
<td>158</td>
</tr>
<tr>
<td>Focal Depth (km)</td>
<td>35</td>
</tr>
<tr>
<td>Dip Angle (degrees)</td>
<td>30</td>
</tr>
<tr>
<td>Slip Angle (degrees)</td>
<td>70</td>
</tr>
<tr>
<td>$F_{\text{displacement}}$ (m)</td>
<td>4.35</td>
</tr>
<tr>
<td>Height of initial wave (m)</td>
<td>1.941</td>
</tr>
<tr>
<td>Max. Positive amp. (m)</td>
<td>1.886</td>
</tr>
<tr>
<td>Min. Negative amp. (m)</td>
<td>-0.055</td>
</tr>
</tbody>
</table>
According to KOERI (Kandilli Observatory and Earthquake Research Institute) in 28 December 2013, an earthquake happened in offshore of Antalya Gulf. Magnitude of the earthquake was measured as $M_l=6.0$ and the focal depth was 30 kilometers. However, this event did not cause any tsunami threat to the coasts. Coordinates of epicenter of the earthquake were 35.9870 N and 31.3422 E.

**Figure 6: Location and Initial Sea State of Selected Tsunami Source**
In this part of the thesis, numerical modeling of the tsunami inundation according to the source scenario is performed.

Numerical simulations are used extensively to assess wave propagation and inundation that a future tsunami can generate. Three approaches are generally accepted in the modeling of tsunamis. In the first approach, which is the conventional modeling, tsunami simulations are performed with constant roughness and without integrating building heights. Another approach is building location and height integration into the digital elevation model (DEM) with high resolution topography/bathymetry. One different approach is to use friction matrix which is prepared according to different bottom roughness coefficients for each land covers and land use. In other words, friction matrix is obtained by the spatial distribution of friction coefficients.

Basically, detailed topography and bathymetry information should give better estimations in the modeling. Since, using high resolution data brings closer to physical reality. However, there are some problems with the use of such detailed data. One of the problems is availability of high resolution bathymetry/topography information (Muhari et al. 2011). Available data for bathymetry/topography have generally coarse grid sizes which leads to low physical accuracy. Therefore, such data does not reflect the physical reality. For example, structures, small rivers etc. cannot be presented in the DEM. On the other hand, to implement building height information into DEM is costly and time consuming. Also, to have an accurate database, annual updating is necessary. One another problem is the computation
times of simulations. Use of fine grids leads to longer computation times, and can be considered inefficient.

In this thesis, one of the main objectives is to estimate the morphological changes under tsunami attack. However, to achieve this purpose, a reliable tsunami inundation model is necessary. Therefore, 5 different simulations have been performed and discussed. The general flow chart of the tsunami inundation modeling is presented in the Figure 7.

![Flow chart for tsunami inundation modeling](image)

**Figure 7:** Flow chart for tsunami inundation modeling

Tsunamis can be considered as shallow water waves with typical wave length is several times the water depth. Generally, this phenomenon is represented by non-linear shallow water equations (NLSW) or Boussinesq type equations. Considering the computation time, NLSW equations has been chosen for this thesis. Also, dispersive effects are less dominant in the near shore region (Taubenböck et al. 2009). Main equations are as follows:
\[
\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0
\]  
(11)

\[
\frac{\partial M}{\partial t} + \frac{\partial}{\partial x} \left( \frac{M^2}{D} \right) + \frac{\partial}{\partial y} \left( \frac{MN}{D} \right) + gD \frac{\partial \eta}{\partial x} + \frac{k}{2gD^2} M\sqrt{M^2 + N^2} = 0
\]  
(12)

\[
\frac{\partial N}{\partial t} + \frac{\partial}{\partial x} \left( \frac{MN}{D} \right) + \frac{\partial}{\partial y} \left( \frac{N^2}{D} \right) + gD \frac{\partial \eta}{\partial y} + \frac{k}{2gD^2} N\sqrt{M^2 + N^2} = 0
\]  
(13)

\(\eta\) = water surface elevation

\(M\) and \(N\): discharge fluxes in \(x\) and \(y\) direction respectively

\(D\): total water depth

\(h\): undisturbed basin depth

\(k\): bottom friction coefficient

In the modeling of tsunamis, NAMI DANCE software has been used. NAMI DANCE is developed in C++ programming language in collaboration with Ocean Engineering Research Center, Middle East Technical University, Turkey and Institute of Applied Physics, Russian Academy of Science, Russia. Model solves the governing equations by the finite difference method with leap-frog scheme. NAMI DANCE has been tested and verified parallel to TUNAMI-N2 in the international workshops (NAMI DANCE Manual, 2010).

Use of high resolution bathymetry/topography leads to long computation times as mentioned before. One of the ways to overcome this problem is to work on relatively small domain. However, in this case source location may stay outside of the domain. For example, in this thesis, source location (determined in Chapter 4) remains outside of the study area. In order to handle this problem, a wave series that represents the source is sent from the boundaries of study area.
The wave series is obtained using the gauge points of a nested simulation with domains B-C-D (Figure 8). Domain B has the coarser grid and a grid spacing of 405 m. Domain C has a grid spacing of 135 m. And, domain D has the finer grid and a grid spacing of 45 m. In order to establish a stable simulation, 1:3 rule is applied to nested domains. D domain with study area can be seen in Figure 9. Simulation time is 2 hours (7200 seconds). Imaginary wave gauges are placed at the boundary of the study area. According to data from these gauges, the wave series that will be used in the further simulations is obtained (Figure 10).
Figure 8: Domains of Nested Simulations

Figure 9: Domain D with study area and the gauge location where time history of water surface elevation was obtained
Modeling of tsunamis requires bathymetry/topography information. In this thesis, for land part of the study area, topography information was obtained from ASTER satellite image with 30m resolution. GEBCO (General Bathymetric Chart for the Oceans) database was used for bathymetry. In order to correct the shoreline, Google Earth image was used. The shoreline is digitized according to the image and integrated to the digital elevation model. Also, in the region, there are three rivers. It is important to include these rivers into the topography. Since, one of the main interests of this thesis is to estimate morphological changes and river mouths can be vulnerable to tsunami attack. Furthermore, data from satellite images often

**Figure 10:** Time history of water surface computed by nested simulations at selected numerical gauge point at the Border of Domain D
ignores small rivers due to grid spacing. Therefore, Google Earth image has been used again. Digitizing work has been done in SURFER 11 software. Then, elevations of rivers have been decreased by 4 meters. Also, same procedure has been applied to the breakwaters. Elevations of breakwaters have been increased also by 4 m. Then, bathymetry/topography has been obtained with 6 m grid spacing by Kriging method (Figure 11).

![Figure 11: Study area](image)

In this study, 5 different simulations have been examined. In the first simulation, Manning’s roughness coefficient is set to 0. It means there is no friction. Also, digital elevation model is not edited for buildings. ASTER data was taken without any change. This case is named as CRM (0) (Constant Roughness Model).

In the second simulation, again roughness coefficient was set to 0 and digital elevation model was prepared according to the building heights. (TM (0) (Topographical Model))
Manning’s roughness coefficient is constant and was set to 0.015 in the third simulation and DEM was not edited. (CRM (0.015)) Generally, for tsunami modeling, the uniform bottom roughness coefficient is used as 0.010 to 0.025.

In the fourth simulation, friction coefficient was 0.015 and topographical model was used. (TM (0.015))

In the fifth simulation, building height information was not implemented and friction matrix was used (FM) (Friction Matrix).

**Table 9: Simulations**

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Friction</th>
<th>DEM</th>
<th>Remark</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>ASTER</td>
<td>Without buildings (n=0)</td>
<td>CRM (0)</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>Topographic Model</td>
<td>With building (n=0)</td>
<td>TM (0)</td>
</tr>
<tr>
<td>3</td>
<td>0.015</td>
<td>ASTER</td>
<td>Without Building (n=0.015)</td>
<td>CRM (0.015)</td>
</tr>
<tr>
<td>4</td>
<td>0.015</td>
<td>Topographic Model</td>
<td>With Building (n=0.015)</td>
<td>TM (0.015)</td>
</tr>
<tr>
<td>5</td>
<td>Friction Matrix</td>
<td>ASTER</td>
<td>Without Building</td>
<td>FM</td>
</tr>
</tbody>
</table>

In the conventional tsunami modeling, topography does not contain mainly buildings, roads etc. because of the low resolution data. In general, a representative constant value of uniform roughness coefficient is applied throughout the domain. In the 3rd simulation, a constant value of friction coefficient 0.015 is used and named CRM (0.015).
5.1. Friction Matrix Approach

In the absence of building data, roughness maps may be used in the modeling. This phenomenon has been studied by Taubenböck et al. (2009), Gayer et al. (2010), Goseberg and Schlurmann (2011), Kaiser et al. (2011), Muhari et al. (2011), Ohira et al. (2012), Park et al. (2013), Fraser et al. (2013) and Gopinath et al. (2014). According to these studies, flow velocities and inundation can be affected by implementing friction matrix rather than using a uniform roughness. Friction Matrix contains spatial distribution of friction coefficient.

According to Gayer et al. (2010), simulations with friction matrix considerably affects run-up and inundation comparing with uniform roughness. Also, it is stated that this method can be applicable to relatively large areas, such as cities. This is an important expression because study area considered in this thesis is relatively small area and, also, there are not much residential areas. Therefore, the effect of using friction matrix instead of constant friction in this thesis results in a small difference at residential areas.

According to Muhari et al. (2011), in the absence of building height information, one can use friction matrix approach. This study shows that friction matrix can affect flow velocity distribution and inundation. However, one should notice that the study area in the work of Muhari et al. (2011) is relatively large with huge residential area.

For friction matrix, different Manning’s roughness coefficients are assigned according to the land use and land cover classes (LULC). In order to create friction matrix, satellite image from Google Earth has been used. According to visual elements (texture, shape, tone, etc.), LULC classification has been handled. According to this classification, study area has been digitized as forests, roads, agricultural lands, buildings, beaches, breakwaters, greenhouses, water bodies in SURFER 11 software. Then, Manning’s roughness coefficients have been assigned to each class (Table 10). Different Manning’s values are present in the literature.
Manning’s values have been obtained from Gayer et al. (2010), Kaiser et al. (2011), Muhari et al. (2011) and Gopinath (2014). For buildings, Kaiser et al. (2011) used 0.4 as the Manning’s value. However, in order to stop the flow, 1 is used for the building locations.

**Table 10:** Manning’s Roughness Coefficients for LULC Classes

<table>
<thead>
<tr>
<th>Land Use Land Cover Classification</th>
<th>Manning’s n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>0.150</td>
</tr>
<tr>
<td>Buildings</td>
<td>1.000</td>
</tr>
<tr>
<td>Agricultural Lands</td>
<td>0.040</td>
</tr>
<tr>
<td>Sandy Beach</td>
<td>0.020</td>
</tr>
<tr>
<td>Breakwater</td>
<td>0.210</td>
</tr>
<tr>
<td>GreenHouses</td>
<td>0.100</td>
</tr>
<tr>
<td>Roads</td>
<td>0.030</td>
</tr>
<tr>
<td>Pools</td>
<td>0.011</td>
</tr>
<tr>
<td>Water Bodies</td>
<td>0.010</td>
</tr>
</tbody>
</table>

Then, friction matrix is developed with 6 m grid spacing (same as bathymetry/topography) by triangulation with linear interpolation method. The spatial distribution of friction coefficient (friction matrix) is shown in the Figure 12.
Another accepted model for the tsunami inundation modeling is the topographical model (Muhari et al., 2011). In this model, building height information are integrated into the DEM. Due to higher physical accuracy in the topography, tsunami inundation can be represented better with topographical model.

To construct the DEM, building heights are needed to be implemented. Using the satellite image obtained from Google Earth, building locations are digitized with SURFER 11 software. However, for the study area, building height information is not present and only spatial location is available from satellite image. As Adriano et al. (2013) have also used an estimation with a two-story height, in this thesis, it is assumed that each building has a height of 10 meters. In the inspected region, there are hotels and resorts, which are likely to have around 10 meters of heights.

**Figure 12:** Friction Matrix (Spatial Distribution of Friction Coefficient)
However, it can be considered as a rough data. Then, DEM with buildings has been obtained with 6 meters of grid size.

Furthermore, topographical model has an important assumption. According to this assumption, buildings should not collapse during the earthquake and withstand against tsunami flow. Also, water may flow through doors and windows of the buildings. However, in this thesis, buildings are treated as a block.

After obtaining high resolution topography/bathymetry, friction matrix and topographical model, simulations have been handled. Simulation time is for 2 hours, time step is 0.05 second and grid spacing is 6 meters. Computation time for the simulations are nearly 11 hours with a computer of 8-processor (2.40 GHz) and 8 GB RAM.

5.3. Results and Discussions

In this section, maximum inundation border and maximum flux differences obtained by 5 different simulations will be discussed. Afterwards, simulation results of a chosen model will be presented.

5.3.1. Maximum Inundation Border

Firstly, maximum inundations in land for CRM (0), CRM (0.015) and FM will be compared in order to see the effect of friction matrix. Figure 13 shows the maximum inundation distance of simulations 1, 2 and 5. It is clearly seen that, CRM (0) has the longest inundation distance both in residential and non-residential areas. It was expected because CRM (0) model has no friction. However, if we look up to the differences between CRM (0.015) and FM models, some minor discrepancies occurs behind the residential area. However, in non-residential area, there is no
significant changes in the inundation distance. As mentioned before, in the study domain, residential areas are relatively low. Probably, friction matrix model would give better results for large residential areas (Gayer et al. 2010).

**Figure 13:** The Comparison of Maximum Inundation Border computed for CRM (0), CRM (0.015) and FM

CRM (0.015) and FM gives similar results. These results indicate that the use of friction matrix does not cause any significant difference in the results. In the forest area 10 times higher roughness coefficient is used with friction matrix method comparing with the CRM approach. However, it does not affect the maximum inundation border significantly. So, it can be concluded that equations are not very sensitive to the roughness coefficient. Consequently, it would be more appropriate to compare the topographical model with conventional model. Therefore, topographical model will be compared with CRM (0.015). As mentioned before, CRM (0.015) model can be considered as conventional tsunami modeling. Figure 14 shows maximum inundation distances for CRM (0.015) and TM (0.015). It can be expected that in non-residential forest area, there should be no difference.
Figure 14 shows the comparison of maximum inundation border computed for CRM (0.015) and TM (0.015). According to Figure 14, in forest area there is almost no change in the maximum inundation distance. However, impact of implementation of buildings is clearly observed. In the topographical model (TM (0.015)), maximum inundation border is closer to the shoreline. That shows, buildings restrained the tsunami flow further inland.

![Figure 14: The Comparison of Maximum Inundation Border computed for CRM (0.015) and TM (0.015)](image)

Also, it may be important to compare results from friction matrix and topographical model. Figure 15 shows the maximum inundation distances for TM (0), TM (0.015) and FM. According to Figure 15, FM model has similar characteristics with TM (0) model in the residential area. This finding may lead to that friction matrix models can be used like topographical models. Especially, in larger areas instead of using small grid sizes, one can use greater grid sizes with friction matrix model in order to solve the problem of computation time (Muhari et al. 2011).
However, in non-residential area, TM (0) shows some differences like in the case of CRM (0) comparing with CRM (0.015), TM (0.015) and FM. This situation was expected. Since, in non-residential area, both CRM and TM have same topography. Also, no friction case is valid for the both case. So, obtaining similar results in non-residential area is not a surprise. Also, it was found that FM, TM (0.015) and CRM (0.015) have similar characteristics in the non-residential area. Use of no friction may be an overestimation because in a real case friction will influence the flow of water. Therefore, comparing with friction matrix, use of a uniform bottom roughness of 0.015 can be used. However, building effect should be considered also. Since, building height and shape implementation brings the model closer to physical reality. Therefore, from maximum inundation distance perspective, it is more reasonable to use TM (0.015) model.

**Figure 15:** The Comparison of Maximum Inundation Border computed for TM (0), TM (0.015) and FM

As, CRM (0) gives the highest inundation distance, one can also use CRM (0) to be on the safe side. According to Muhari et al. (2011), in order to estimate the damages of a future tsunami, constant roughness models should be used for maximum
inundation border of a tsunami attack due to high uncertainties. Figure 16 shows the difference between CRM (0) and TM (0.015) in order to demonstrate the difference in two model. At the residential area, maximum inundation border can decrease up 50%, however, in non-residential area, differences are negligible.

![Figure 16: The Comparison of Maximum Inundation Border computed for CRM (0) and TM (0.015)](image)

5.3.2. Maximum Discharge Flux

One of the important parameters while assessing the morphological changes and damages due to tsunamis is the flux values. In order to have an accurate assessment on morphological changes, flux values should be calculated with care. Here, firstly, maximum flux differences of 5 different simulations will be discussed.

Some differences in flux are expected between topographical and constant roughness models. Fluxes may increase between buildings in topographical model
due to channel effect. This case was well represented in Kaiser et al. (2011). In order to examine this phenomenon, firstly, maximum flux differences of CRM (0.015) and TM (0.015) will be discussed (Figure 17).

Figure 17 is prepared by subtracting the maximum discharge flux values that is computed at each grid. Maximum discharge flux for TM (0.015) is subtracted by maximum discharge flux for CRM (0.015) and divided by maximum discharge flux for CRM (0.015). Note that, if maximum flux value is higher for TM (0.015), it is represented with a positive sign. If maximum flux value is higher for CRM (0.015), that area has a negative sign.

Figure 17: The percent difference of maximum discharge flux for TM (0.015) - CRM (0.015)

As you can see from the Figure 17, most of the difference in maximum flux occurred in the residential area, where hotels and resorts are present. Generally, in residential area, constant roughness model gives higher flux values comparing with topographical model up to 70 percent. Therefore, the channel effect is not very effective in this region. That can be because buildings are not uniformly distributed in the area, as in the case of cities. They are distributed randomly. Also, limited
number of buildings are present in the area. Furthermore, 100 percent difference can be seen in the figure. It is because flow does not reach further inland for the case of topographical model. So, figure gives 100 percent difference where flow with CRM (0.015) approach reaches but flow with TM (0.015) approach does not.

In the right side of the map, some small differences are observed in front of the forest. That is because, there is a building in the beach area. Therefore, it affected the maximum flux result. Other than that, in the forest area maximum fluxes are very similar as expected.

Secondly, performance of friction matrix can be seen in the Figure 18. In this figure, differences of maximum fluxes of CRM (0.015) and FM models are presented. Figure 18 is prepared by subtracting the maximum discharge flux values that is computed at each grid. Maximum discharge flux for FM is subtracted by maximum discharge flux for CRM (0.015) and divided by maximum discharge flux for CRM (0.015). Note that, if maximum flux of CRM (0.015) is higher than FM model, difference is represented with negative value. Positive values means that FM model gives higher maximum flux values.
Figure 18: The percent difference of maximum discharge flux for FM - CRM (0.015)

In FM model, according to land cover-land use classification, different Manning’s roughness values were assigned to each grid. From Figure 18, difference of maximum fluxes of CRM and FM models are rather low. This shows us, friction matrix model is not effective as much as topographical model to represent fluxes. Still, FM creates 20 to 30 percent difference comparing with CRM. However, comparing Figure 18 with Figure 17, topographical models creates major changes in the maximum flux values.

Also, highest difference is occurred between CRM (0) and TM (0.015) simulations. It may be good idea to show the differences of these simulations. Since, both of them may be used while assessing the tsunami inundations. Figure 19 shows the difference of maximum fluxes of CRM (0) and TM (0.015). Figure 19 is prepared by subtracting the maximum discharge flux values that is computed at each grid. Maximum discharge flux for TM (0.015) is subtracted by maximum discharge flux for CRM (0) and divided by maximum discharge flux for CRM (0). As mentioned before, positive values means that TM (0.015) gives higher values comparing with CRM (0). Negative values means that CRM (0) gives higher values. According to
Figure 19, CRM (0) gives higher values comparing with TM (0.015). In the residential area, maximum discharge flux differences can reach up to 70 to 80 percent. However, in the non-residential area, difference in maximum discharge flux is nearly 20 to 30 percent and it is mostly due to the friction term.

Figure 19: The percent difference of maximum discharge flux for TM (0.015) - CRM (0)

As a result, topographical models can change inundation and fluxes significantly. However, validation of a model is not possible due to no data is available from historical earthquakes. So, it cannot be said that a model is better than the other for the study area. Therefore, a method should be selected according to the related studies in the literature.

According to Muhari et al. (2011), constant roughness model has limitations over topographical model and friction matrix. Since, the CRM considers only bare ground elevation and a uniform roughness coefficient.

According to Kaiser et al. (2011), inundation patterns are very sensitive to topography information. Also, constant roughness model, topographical model and friction matrix approach were compared with 2004 Indian Ocean Tsunami data. As
a result, topographical model approach matched best with observed data. Furthermore, lack of high resolution data on land cover or buildings may lead to less accurate simulations.

Topographical models or friction matrix models show better approximations with higher physical accuracy on inundation mapping (Taubenböck et al. 2009, Gayer et al. 2010, and Kaiser et al. 2011). Consequently, in this thesis, topographical model with a uniform roughness of 0.015 is used in the assessment of morphological changes due to tsunami attack.

5.3.3. Time Histories of Water Surface Elevations and Discharge Fluxes for TM (0.015) and CRM (0)

In this section, time histories of water surface elevation and discharge fluxes for TM (0.015) and CRM (0) will be presented.

Locations of gauges are presented in Figure 20. Gauge G is in front of the residential area. Gauge H is between buildings and Gauge L is in the forest area. These gauges are located in land and their elevations are for Gauge H 6.17 meters, for Gauge G 3.4 meters and for Gauge L 4.2 meters above from the mean sea level.
Figure 20: Locations of selected gauge points

Figure 21, Figure 22 and Figure 23 show the time history of sea surface elevation for the selected gauges. Note that when a gauge is in the land, the code gives zero until the wave arrives. However, after the wave arrives, code understands that gauge is wet, so the water surface elevation does not drop to zero again and remains in the elevation of the gauge.
Figure 21: Time History of Water Surface Elevation for Gauge H
Figure 22: Time History of Water Surface Elevation for Gauge G
Figure 23: Time History of Water Surface Elevation for Gauge L

According to these figures, gauge L and G gives very similar water surface elevation. Only 10 to 15 percent change is observed in these gauges. Differences are mostly due to the friction terms. However, between buildings where gauge H is present, 25 to 30 percent change is observed. Therefore, topographical model leads less water surface elevation.

Figure 24, Figure 25 and Figure 26 show the time histories of current velocities for these gauges.
Figure 24: Time History of Discharge Flux for Gauge H
Figure 25: Time History of Discharge Flux for Gauge G
According to these figures, the discharge fluxes are different for both residential area (Gauge G and H) and non-residential area (Gauge L). For Gauge H, constant roughness model gives higher discharge fluxes up to 40 to 50 percent comparing with topographical model. In the Gauge H (Between the buildings), channel effect may be expected. However, buildings are distributed randomly in the region. Therefore, no channel effect is observed in Gauge H. Gauge G gives higher discharge flux difference for constant roughness model up to 80 percent. However, in the forest area (Gauge L), differences are minor comparing with other gauges.

**Figure 26:** Time History of Discharge Flux for Gauge L
Therefore, topographical model can create lower discharge fluxes both in residential and non-residential area.

5.3.4. Results of Tsunami Inundation Modeling

In this section, simulation results of TM (0.015) will be presented.

Figure 27 shows the computed maximum flow depth at land at grid points in terms of meters.

![Figure 27: Maximum flow depth at land for TM (0.015)](image)

Figure 28 shows computed maximum total discharge flux at every land grid points during the simulation. The unit for the discharge flux is m$^3$/sec/m.
Computed wave characteristics are presented below. Firstly, Figure 29 shows the locations of imaginary gauge locations. Table 11 shows the computed wave characteristics and locations of gauge points in earth coordinates. Unit of depth of gauge points is meters. Negative sign means that gauge is located in land. Positive sign means that gauge is located in sea. Also, table contains arrival time of the initial wave and maximum wave in minutes. Maximum and minimum wave amplitudes in meters are also in the Table 11.

Then, time histories of sea surface elevation of these gauge locations are presented with Figure 30, Figure 31, and Figure 32.

Furthermore, time histories of total discharge flux is presented with Figure 33, Figure 34, and Figure 35. Unit for discharge flux is m$^3$/sec/m.

Figure 36, Figure 37 and Figure 38 show the time histories of current velocities at the selected gauge points. Unit for current velocity is meter per seconds.
Angle of discharge fluxes are given in Figure 39, Figure 40 and Figure 41. Computed angles are in terms of degrees and clockwise from the North.

### Figure 29: Selected Gauge Locations in the Study Area on Google Earth Image

### Table 11: Summary of Results of Tsunami Simulation at Selected Gauge Locations

<table>
<thead>
<tr>
<th>Name of Gauge Point</th>
<th>Depth of Gauge Point (m)</th>
<th>X-Coord (o)</th>
<th>Y-Coord (o)</th>
<th>Arrival Time of Initial Wave (min)</th>
<th>Arrival Time of Max. Wave (min)</th>
<th>Maximum Positive Amplitude (m)</th>
<th>Maximum Negative Amplitude (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.50</td>
<td>30.8973</td>
<td>36.8525</td>
<td>4.28</td>
<td>68.9417</td>
<td>7.98</td>
<td>-1.41</td>
</tr>
<tr>
<td>B</td>
<td>-4.30</td>
<td>30.8973</td>
<td>36.8545</td>
<td>54.4125</td>
<td>68.9142</td>
<td>8.22</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>1.50</td>
<td>30.9006</td>
<td>36.8530</td>
<td>4.3533</td>
<td>68.5842</td>
<td>8.24</td>
<td>-1.36</td>
</tr>
<tr>
<td>D</td>
<td>-5.61</td>
<td>30.9006</td>
<td>36.8545</td>
<td>54.825</td>
<td>68.6483</td>
<td>8.6</td>
<td>0</td>
</tr>
<tr>
<td>E</td>
<td>3.60</td>
<td>30.9214</td>
<td>36.8535</td>
<td>4.1975</td>
<td>68.5292</td>
<td>9.82</td>
<td>-2.9</td>
</tr>
<tr>
<td>F</td>
<td>5.50</td>
<td>30.9193</td>
<td>36.8523</td>
<td>3.8858</td>
<td>68.5842</td>
<td>9.74</td>
<td>-4.49</td>
</tr>
<tr>
<td>G</td>
<td>-3.40</td>
<td>30.9193</td>
<td>36.8545</td>
<td>23.9242</td>
<td>68.5658</td>
<td>10.09</td>
<td>0</td>
</tr>
<tr>
<td>H</td>
<td>-6.17</td>
<td>30.9193</td>
<td>36.8556</td>
<td>55.6408</td>
<td>68.7675</td>
<td>9.36</td>
<td>0</td>
</tr>
<tr>
<td>I</td>
<td>1.70</td>
<td>30.9240</td>
<td>36.8534</td>
<td>4.2158</td>
<td>67.9425</td>
<td>9.84</td>
<td>-1.7</td>
</tr>
<tr>
<td>J</td>
<td>2.60</td>
<td>30.9510</td>
<td>36.8544</td>
<td>3.895</td>
<td>69.0242</td>
<td>8.95</td>
<td>-2.6</td>
</tr>
<tr>
<td>K</td>
<td>-1.50</td>
<td>30.9510</td>
<td>36.8562</td>
<td>12.4842</td>
<td>69.675</td>
<td>9.05</td>
<td>0</td>
</tr>
<tr>
<td>L</td>
<td>-4.20</td>
<td>30.9510</td>
<td>36.8593</td>
<td>55.4667</td>
<td>69.6383</td>
<td>9.12</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 30: Time Histories of Sea Surface Elevations at Gauges A-B-C-D.
Figure 31: Time Histories of Sea Surface Elevations at Gauges E-F-G-H
Figure 3.2: Time Histories of Sea Surface Elevations at Gauges I-J-K-L.
Figure 33: Time Histories of Discharge Flux at Gauges A, B, C, D
Figure 3-4: Time Histories of Discharge Flux at Gauges E-F-G-H
Figure 35: Time Histories of Discharge Flux at Gauges I-J-K-L.
Figure 36: Time Histories of Current Velocities at Gauges A-B-C-D
Figure 37: Time Histories of Current Velocities at Gauges E-F-G-H
Figure 38: Time Histories of Current Velocities at Gauges I-K-L.
Figure 39: Time Histories of Angle of Discharge Fluxes at Gauges A B C D
Figure 40: Time Histories of Angle of Discharge Fluxes at Gauges E-F-G-H
Figure 4.1: Time Histories of Angle of Discharge Fluxes at Gauges I-K-L.
CHAPTER 6

ASSESSMENT OF MORPHOLOGICAL CHANGES DUE TO TSUNAMI ATTACK

From the previous studies, it is clear that tsunami flow can create significant morphological changes in the coastal zones. Some examples to these morphological changes can be sediment transport, erosion, deposition, breaching, scour, boulder transport etc.

Assessing morphological changes due to tsunami is still a developing field of study. Sediment transport due to tsunamis have been investigated mostly since 2000s. In this area still extensive studies need to be performed. However, due to the nature of tsunami, it is very difficult to validate any method with a real event. In order to validate a method, scientists need before and after data for topography and bathymetry. Yet, such data is not available right now. Li et al. (2011) have pointed out that sediment transport is one of the least understood tsunami behaviors due to no real time measurement during tsunami events. Therefore, methods to assess the morphological changes caused by tsunami are generally derived from laboratory experiments or from river analogy.

As presented in literature survey, numerical simulations are used extensively in order to model the sediment transport and morphological changes. However, some problems exists with models. According to Nakamura et al. (2009), effective stress change inside bed due to exfiltration/infiltration has not been studied extensively. Also, Sumer (2014) has drawn attention to flow-bed-structure interactions. According to the author, this interaction is more complex than computing currents
or other hydrodynamic processes. Lack of knowledge in the area of interaction between tsunami, seabed and structures has been criticized by the author. These interactions can be summarized as, coastal hydrodynamics, sediment transport, scour and erosion processes, soil weakening, liquefaction, shear failure and failure of structures.

In this thesis, Rouse number is used in order to assess the morphological changes due to tsunami attack. It is a non-dimensional number and used for identifying the transport modes of sediments. It is a ratio between settling velocity of sediment to shear velocity. With the limits of Rouse number, mode of sediment transport can be determined as bed load, suspended load, wash load and no motion. For example, a value that is greater than 2.5 leads to little or no suspension of sediment. However, a value less than 0.8 leads to wash load which is fully supported by the flow. So, as Rouse number increases chance of sediment transport in suspension decreases. Also, sediment transport can increase as Rouse number decreases. Limits of Rouse number is presented in Table 12.

Table 12: Modes of Transport According to Rouse Number

<table>
<thead>
<tr>
<th>Mode of Transport</th>
<th>Rouse Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initiation of Motion</td>
<td>( R_0 &gt; 7 )</td>
</tr>
<tr>
<td>Bed Load</td>
<td>( 2.5 &lt; R_0 &lt; 7.5 )</td>
</tr>
<tr>
<td>Suspended Load: (50% Suspended)</td>
<td>( 1.2 &lt; R_0 &lt; 2.5 )</td>
</tr>
<tr>
<td>Suspended Load: (100% Suspended)</td>
<td>( 0.8 &lt; R_0 &lt; 1.2 )</td>
</tr>
<tr>
<td>Wash Load</td>
<td>( R_0 &lt; 0.8 )</td>
</tr>
</tbody>
</table>

In order to assess the morphological changes induced by tsunami flow, results from hydrodynamic model TM (0.015) are used. Flow characteristics of TM (0.015) such as current velocities, inundation depths and flux discharges have been presented in Chapter 5.
In order to employ the Rouse number, settling velocity should be determined. In order to calculate the settling velocity, grain size distribution of sediment should be obtained. So, a relevant study in the Southern Turkey has been carried out by Ergin et al. (2007) (Table 13).

Table 13: Grain Size Distribution of Belek

<table>
<thead>
<tr>
<th>Beach Name</th>
<th>Belek</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pebble (&gt; 4 mm)</td>
<td>1.3</td>
</tr>
<tr>
<td>Granule (4.0-2.0 mm)</td>
<td>0.4</td>
</tr>
<tr>
<td>Very Coarse Sand (2.0-1.0 mm)</td>
<td>0.4</td>
</tr>
<tr>
<td>Coarse Sand (1.0-0.5 mm)</td>
<td>5.8</td>
</tr>
<tr>
<td>Medium Sand (0.5-0.25 mm)</td>
<td>70.7</td>
</tr>
<tr>
<td>Fine Sand (0.25-0.125 mm)</td>
<td>20.6</td>
</tr>
<tr>
<td>Very Fine Sand (0.125-0.0625 mm)</td>
<td>0.8</td>
</tr>
<tr>
<td>Silt + Clay (&lt;0.0625 mm)</td>
<td>0.1</td>
</tr>
<tr>
<td>Mean Grain Size (φ)</td>
<td>1.67</td>
</tr>
<tr>
<td>Mean Grain Size (mm)</td>
<td>0.31</td>
</tr>
</tbody>
</table>

In this thesis, uniform medium sand is assumed throughout domain. Actually, study area should be examined entirely for soil characteristics. So, at each grid point the settling velocity can be computed accurately. However, in this thesis, entire domain is represented with 0.31 mm of mean grain size.

Actually, like in the case of friction matrix, a settling velocity map may be used with manipulating grain size diameter. For example, for the forests, roads, agricultural lands instead of using 0.31 mm grain size, different grain sizes may be assigned. However, there is no such study found in literature. Therefore, instead of creating a settling velocity map, in this thesis, uniform medium sand is assumed for the entire domain.
Also, settling velocity and shear velocity calculations require some typical constants. These are kinematic viscosity and density of sea water, gravitational acceleration and density of sediment particles. Used values for these parameters are given in Table 14.

**Table 14: Typical constants**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu ), Kinematic Viscosity</td>
<td>( 1.0 \times 10^{-6} \text{ m}^2/\text{s} )</td>
</tr>
<tr>
<td>( g ), Gravitational Acceleration</td>
<td>9.81 m/s²</td>
</tr>
<tr>
<td>( \rho ), Density of Water</td>
<td>1025 kg/m³</td>
</tr>
<tr>
<td>( \rho_s ), Density of Sediment Particles</td>
<td>2650 kg/m³</td>
</tr>
</tbody>
</table>

Settling velocity is calculated with the following equation (Yeh and Li, 2008). For the entire domain, settling velocity is determined as 0.0446 meters per second.

\[
\begin{align*}
ws &= \frac{8\nu}{d} \left( \sqrt{1 + \frac{(s - 1)gd^3}{72\nu^2}} - 1 \right) = 0.0446 \text{ m/s} \\
\text{(14)}
\end{align*}
\]

Current velocity at each grid point has been calculated in the modeling of tsunami inundation and propagation in Chapter 5. In order to calculate the Rouse number, following equation is used (Yeh and Li, 2008).

\[
R_0 = \frac{ws}{\beta ku_*} = \frac{0.043036}{1 * 0.4 * u * \sqrt{0.01}} = \frac{3.1509}{u} \\
\text{(15)}
\]

Consequently, Rouse numbers are calculated with 6 meters of grid size at each time step. With the help of Rouse number, sediment transport modes are found. Lower Rouse numbers lead to more severe erosion in the topography and higher Rouse numbers lead to less severe erosion or depositon.
Lowest Rouse numbers in each grid during the simulation is presented in Figure 42. This figure shows us near the shoreline possibly breaching can occur in the lagoon which is in front of the forest area. It is a similar site to Natori River mouth. In the 2011 Great East Japan Earthquake and Tsunami, river mouth was significantly eroded and breaching was observed in the lagoon. Also, trees were washed away by the tsunami flow (Tanaka et al. 2012). Therefore, breaching and erosion can be expected in the lagoon area.

Figure 42: Minimum Rouse Numbers in each grid during the simulation

In order to see the sediment transport movements, instantaneous Rouse numbers can be more important rather than minimum Rouse numbers. Since, maximum current does not occur at the same time for the entire domain. Therefore, some of the instantaneous Rouse numbers will be presented.

First wave that inundates in land comes after 55 minutes later. Figure 43 shows the instantaneous Rouse numbers for 55\textsuperscript{th} minute. By looking at this figure, tsunami flow can carry sediments as suspended and wash load in the right and left side of the map. However, in the lagoon and residential area, sediments are transported as bed load or little suspension.
Figure 43: Instantaneous Rouse Numbers for 55th minute

Figure 44 shows the instantaneous Rouse numbers for the 70th minute. Here, stronger waves attack to the shore and creates more significant sediment transport. In the residential area, due to the channeling effect, wash load is observed which can lead to significant scour around buildings and erosion.
Figure 44: Instantaneous Rouse Numbers for 70th minute

Figure 45 shows the instantaneous Rouse numbers for 75th minute of the tsunami simulation. At this instant, backflow occurs. Strong backflow causes significant suspension in the lagoon area. Also, some strong currents in the residential area can be observed. Probably, the eroded sand will be deposited in land by incoming wave or in sea by the strong return flow. Also, changes in the shoreline position can be expected.
Figure 45: Instantaneous Rouse Numbers for 75th minute
CHAPTER 7

CONCLUSION

In this thesis, a tsunami simulation has been performed for the Belek coast in the Antalya region which is located at the South of Turkey. Source parameters and high resolution bathymetry/topography are important input data for a reliable tsunami modeling. As the source parameter, a tsunami scenario prepared for the Eastern Mediterranean has been used. For bathymetry information GEBCO and for topography information ASTER databases have been used. In order to obtain the buildings in the topography, Google Earth image has been used for digitizing works.

For the tsunami simulations of propagation and inundation, NAMI DANCE numerical code has been used with the mentioned input parameters. From the literature survey and results of the simulations, it can be concluded that using high resolution topography with buildings, sea walls etc. is the most appropriate way of obtaining accurate results in tsunami modeling.

Tsunami modeling in non-residential areas can be done without extensive work for producing a friction matrix. Since, according to the results of inundation modeling, friction matrix and constant roughness models gave similar results in non-residential area. However, in the residential areas, it is recommended to model tsunamis with high resolution bathymetry and topography by inclusion of obstacles (buildings, sea walls etc.), roads, pathways and rivers in front of the tsunami flow. Hence, calculated velocities and inundation depths will be much more accurate and reliable. For maximum inundation border, topographical model can result in 50% less distance comparing with a constant roughness model with no friction in the
residential area. Also, 40 to 50% changes in maximum discharge flux can be observed in the residential area for this study.

Morphological changes due to tsunami attack has been interpreted by a non-dimensional parameter Rouse number. With the help of this number, possible changes has been identified and commented. Numerical simulation has not been performed in this study. Extensive work on the sediment transport due to tsunamis are still required. In order to validate any method, real time measurements are necessary. Since, laboratory experiments give limited information about the tsunami flow.

For the early tsunami warning system, creating a strong database for tsunami scenarios may be suggested. Tsunami inundation simulations should be performed before hand with high resolution bottom topography. Since, computational times with high resolution data is very long and after tsunami alert there may not be much time to prepare a simulation.

Previous experiences have shown that for disaster prevention and mitigation the most important matter is the education. So, people need to be educated about tsunami threat. Study area of this thesis is highly populated during the summer time. So, with the help of signboards, evacuation routes need to be determined. Agencies that are responsible for tsunami threat should be always prepared for a tsunami.

As suggestions and future recommendations, topographical model can be improved with the enhancement in satellite and computer environments. Large open access databases and the enhancement in satellite technology can reduce the amount of work to create a high resolution bathymetry and topography. Also, in the data enhancement phase of the modeling, due to personal mistakes, errors can occur. High resolution data from satellites should lead to more proper modeling. Also, developments in computer technology will give less computation times in the simulations.

Morphological change that is created by tsunami attack is still a developing field of study. Models needs to be improved and be validated with a real event. Also, for
sediment transport modeling due to tsunamis, Rouse number is a promising approach. However, more efforts should be performed in future studies. For example, erodible and non-erodible areas can be identified and a settling velocity map can be obtained. Furthermore, in the modeling of sediment transport instead of Shields parameter, Rouse number can be a new choice since as mentioned before, in laboratory experiments calculated Rouse numbers are close to real events comparing with Shields parameter. It may be interesting if the code computes Rouse number instantaneously to estimate spatial change of sediment movement.
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