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Bed Profile Changes due to Tsunami Effects on Near Shore Coasts: Tuzla Case Study

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ABSTRACT

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The concern of this study is the investigation of tsunami effects on the seabed profile as these may be important for the coastal structures, like sea outfalls or breakwaters. Tsunami is well known with its huge wave heights and destructive effects on the coastal region. A 2D numerical model was set using the software, COSMOS to calculate the cross-shore sediment transport and to evaluate profile changes in the coastal seabed. The study area is Tuzla region, a densely populated industrial coastal area in the South East of Istanbul. The model was run for different kinds of tsunami waves. Not only the bed profile changes, but also the wave heights, breaker depths, peak wave bottom orbital velocities, wave set-up and cross-shore sediment transport rates were determined. The results indicated that, at a water depth around 40~50 m, some tsunamis were found to have a wave height at the order of 15 m, which became about 5 m at a depth of 10 m. The wave set up near the coast was about 1.5~2 m. The results also implied that tsunami waves, with their destructive nature, could lead to dramatical vertical changes of the seabed.

ADDITIONAL INDEX WORDS: *Long waves, sea bed evaluation, cross-shore sediment transport.*

INTRODUCTION

Tsunami is one of the most complex phenomena ever faced by the human kind. It has always been an important point of concern for both oceanography and coastal engineering with its interesting and hazardous nature.

In the literature tsunami is usually considered as a long wave (MOFJELD *et al.*, 2000) or a solitary wave (SYNOLAKIS, 1991), and the propagation mechanism is explained accordingly. Tsunamis principally occur following undersea earthquakes of magnitude greater than 6.5 (Richter scale) having focal depths less than 50 km, although landslides, bottom slumping, and volcanic eruptions have been cited as primo-genitors in certain cases. Not all such earthquakes produce tsunamis, and the generation mechanism-which presumably is associated with vertical dislocations of the sea floor-undoubtedly differs from event to event. Since the majority of them originate at great depths in the sea, their precise origins will probably remain forever obscure. But because of their long periods and wave heights they are shallow water waves ($d/L < 0.5$) at the instant they are formed.

Once formed, however, the wave system resembles nothing so much as that produced by tossing a stone into the middle of a large shallow pond. In simplest aspect (more complex sources are thought to exist), the wave pattern is asymmetric at early times, and consists of concentric rings of crests and troughs, bounded at the outside by an intangible "front", that expands everywhere outwards at the limiting velocity $C_0 = \sqrt{gd}$ for free waves in water of depth d (g is the gravitational acceleration), and all subsequent waves travel more slowly. At any instant of time the radial separation between successive crests (wave length) is largest near the front and becomes progressively smaller towards the centre. In the absence of boundaries, which produce reflections, individual waves of the system retain their identity, in contrast to the wind-generated swell, which grows and disappears before the eye in the interval of a few seconds (MOFJELD *et al.*, 2000).

Some parameters are given as follows for waves propagating in shallow water:

Wave celerity for a single wave and group celerity

$$C = C_0 = \sqrt{gd} \tag{1}$$

Wave length

$$C = T\sqrt{gd} \tag{2}$$

Horizontal velocity

$$u = \frac{H}{2}\sqrt{\frac{g}{d}}Cos\theta \tag{3}$$

Horizontal Acceleration

$$a_x = \frac{\pi H}{T}\sqrt{gd}\,Sin\theta \tag{4}$$

As the waves approach the boundaries of ocean and pass into shallower water, the individual wave amplitudes become larger, because the energy increment contained within each wave is concentrated in an increasingly smaller volume of water. Eventually, as shoaling and wave growth continue, the wave amplitudes amount to an appreciable fraction of the water depth.

There are plenty of studies on the tsunami waves, most of which concentrates on the generation and propagation and less on dissipation mechanism of tsunamis. Besides mathematical models, there are also physical, numerical and combined model studies on tsunami waves (GUESMIA *et al.*, 1996, TINTI *et al.*, 2000).

Is an opposite relationship between tsunami waves and landslides possible? Considering the powerful and destructive nature of tsunami, it is obvious that tsunami waves affect the sea bottom, yet the form and order of the effect is variable. The main concern of this study is this issue.

The study area is Tuzla region (Figure 1), a densely populated industrial coastal area of Marmara Sea in the South East of Istanbul. Tsunami events had happened in Marmara Sea before (YALÇINER *et al.*, 2002); especially the tsunami happened Marmara Earthquake in August 17th 1999 proved once more that Marmara Sea is under the risk of tsunami attack (ALTINOK *et al.*, 2001).

METHODS

Description of the Model

A numerical model study has been carried out in order to achieve the sea bottom profile changes under effects of tsunami,

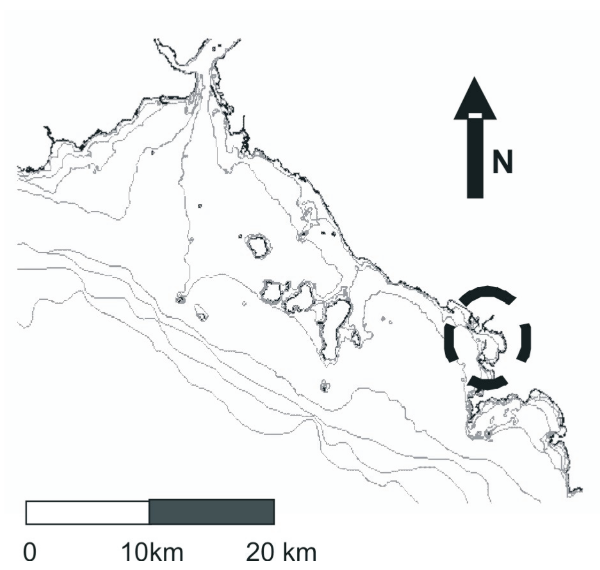

Figure 1. General view of study area.

A numerical model study has been carried out in order to achieve the sea bottom profile changes under effects of tsunami, which may be seen after an earthquake occurred in Marmara Sea bottom because of the North Anatolia Fault. The software used for numerical modelling is COSMOS, which has been developed by HR Wallingford, U.K. It is a model for near shore hydrodynamics, sediment transport and seabed evolution (morphodynamics) (WALLACE, 1994).

The numerical model includes the following physical processes:

a) Wave transformation by refraction (by depth variations), shoaling, Doppler shifting, bottom friction and wave breaking,
b) Wave set-up determined from the gradient of wave radiation stress,
c) Cross-shore undertow velocities using a three layer model of the vertical distribution of cross-shore currents
d) Transition zone effects (the transition zone is the distance between where a wave starts to break and where turbulence becomes fully developed).
e) Cross-shore sediment transport rates using an *energetics* approach.
f) Seabed level changes due to cross-shore sediment transport using a Lax-Wendroff scheme.

Actually the model assumes a straight coastline with parallel depth contours. This lateral symmetry essentially reduces the problem to one of calculations in the cross-shore horizontal dimension only.

The calculations are made within the chainage intervals (grid spacing) separated by nodes (grid points). These points are chosen along a cross-shore line at spatial intervals which need not be uniform. Normally as the wave properties change rapidly in the surf zone, using closely spaced chainage points in this region will be appropriate. During such a morphodynamic run a new feature such as a bar may develop. Such a bar will need to be resolved with several grid points; otherwise its development cannot be accurately followed. A feature covered by too few grid points may also contain unrealistically sharp changes in bed slope, which may generate instabilities.

In our case, because the tsunami waves have very long periods and wave heights, the surf zone is much wider than the storm waves. In other words, waves are affected from the sea bottom nearly all along their journeys. This brings morphological changes on a very large area.

Calculation of the time-averaged cross-shore flows, both within and above the bottom boundary layer, are made considering both broken and unbroken waves. In the main part of the flow, outside the bottom boundary layer, the mean flow is described following the approach of DEVRIEND and STIVE (1987). A vertical profile of the time-averaged velocity under random waves is derived. The principal driving force of the mean flow (or undertow) in breaking waves is due to the reduction in radiation stress related to wave energy dissipation across the surf zone. The time-averaged flow in the bed boundary layer of the surf zone is also calculated following an adaptation of the method described by SVENDSON *et al.* (1987). Langrangian mass transport under unbroken waves is included in the DEVRIEND and STIVE approach based on a modification of the Longuet-Higgins conduction solution.

The undertow velocity required for the sediment transport calculation is selected as concentration weighted average. The concentration profile through the vertical is calculated employing the NIELSEN (1979) expression for suspended sediment concentration under broken and unbroken waves.

Orbital velocities and related parameters are calculated using the vocoidal wave theory developed by SWART (1987).

The sediment transport rates are calculated in each profile section based on the energetics approach introduced by Bagnold and adapted by BAILARD (1981) and BOWEN (1980) for coastal sediment transport. This technique assumes that the sediment is mobilised by wave action and transported by three different mechanisms; time-averaged flows (such as undertow or longshore currents), asymmetric orbital velocities, and gravity in the downslope direction. The fall velocities are calculated as a function of grain size based on the expression of FROMME (1977).

Once the sediment transport estimates have been made the bottom level changes can be calculated using the sediment continuity equation. The equation is now solved using a second-order Lax-Wendroff scheme which also calculates the timestep necessary for stability of the bed.

Input Data

Data about probable tsunami in Marmara Sea have been very limited. For this reason an approximate prediction has been made by using similar data obtained from the areas all over the world. Wave periods for tsunamis used in the study was in the range of 0.5~1.5 hours. Wave heights have been selected between 1 cm and 1 m to represent a large range of possibilities (KIRCA, 2003).

The digitised bathymetric maps of Marmara Sea have been taken from Turkish Navy, Oceanography and Hydrograph Department, Çubuklu, Ýstanbul. The cross section was extended until 50 m depth (about 5000 m from the coastline) in the model (Figure 2). The chainage interval (grid spacing) for the calculations was selected to be about 15 m and depth of each grid point is interpolated.

On the other hand, in reshaping of seabed and sediment transport process the properties of the available sediment material are at least as important as the wave properties. The sediment characteristics, of course, differ from point to point along the cross section. In this study a mean value of D_{50} = 4 mm was used as the sediment size, describing non-cohesive soil.

RESULTS AND DISCUSSIONS

The results obtained by using numerical model have been introducing quite interesting conditions, summarized in Table 1. They state that tsunami may have maximum height of 15~17 m at the depth of approximately - 40 m area where 2000~4000 m from the coastline and may decrease such that its height is 5~6 m at -10 m depth almost 1000 m far from the coastline.

Also it can be mentioned that the wave runup changes in between 0.10 m and 2.2 m. Considering a mean slope of 1/100, this means a wave intrusion through inland up to an order of 150~200 m which agrees with the tsunami attack seen after the 1999 Marmara Earthquake (ALTINOK *et al.* 2001).

The range of sea bottom profile changes have been enlarged towards offshore while increasing tsunami magnitudes. This is because the higher waves can break in deeper water depths. The evaluated seabed with the tsunami attack was shown in Figure 2.

Moreover, during the tsunami attack, peak orbital velocities were seen to be very high such that hydrodynamic conditions at the sea bottom deeper than - 40 m are almost similar with the supercritical flow conditions in a river. That is why very strong and intensive sediment transport may be created.

The order of bed erosion was seen reaching up to an order of 25 m (occurring as a slope failure or an overall failure) for maximum tsunami conditions which. For more reasonable conditions it was at the order of 3~4 m (Figure 2) occurred about 30 m depth.

While tsunami moves toward coastline the most critical area was seen to be between - 30 m and - 50 m depth because the maximum wave height, minimum mean sea level, maximum change of water depth and most intensive wave breaking were seen in this area. Most of the coastal structures are constructed shallower locations than this depth range, except some offshore structures and some kinds of sea outfalls. But related to the order of tsunami waves (height and period) it was seen that it could threaten the structures at shallower depths not only from bed erosion but also from wave forces point of view.

The numerical model has also been run for successive tsunamis with decreasing heights as expected in natural conditions (last row in Table 1). The final sea bottom profile obtained was as the superposition of the maximum changes of each individual rather than a linear superposition.

It has also been observed that the sea bottom profile tends to have a single sloped shape under tsunami effect. This is of course directly related with the natural bottom topography. For instance, there are two main *steps* on the seabed profile of Tuzla used in this study: The smaller one of them is at - 15 m ~ - 20 m and the larger is located at - 25 m ~ - 40 m depth. After the tsunami attack the general picture shows the intension of formation of a smoother seabed, which brings the topographic variability of tsunami effect.

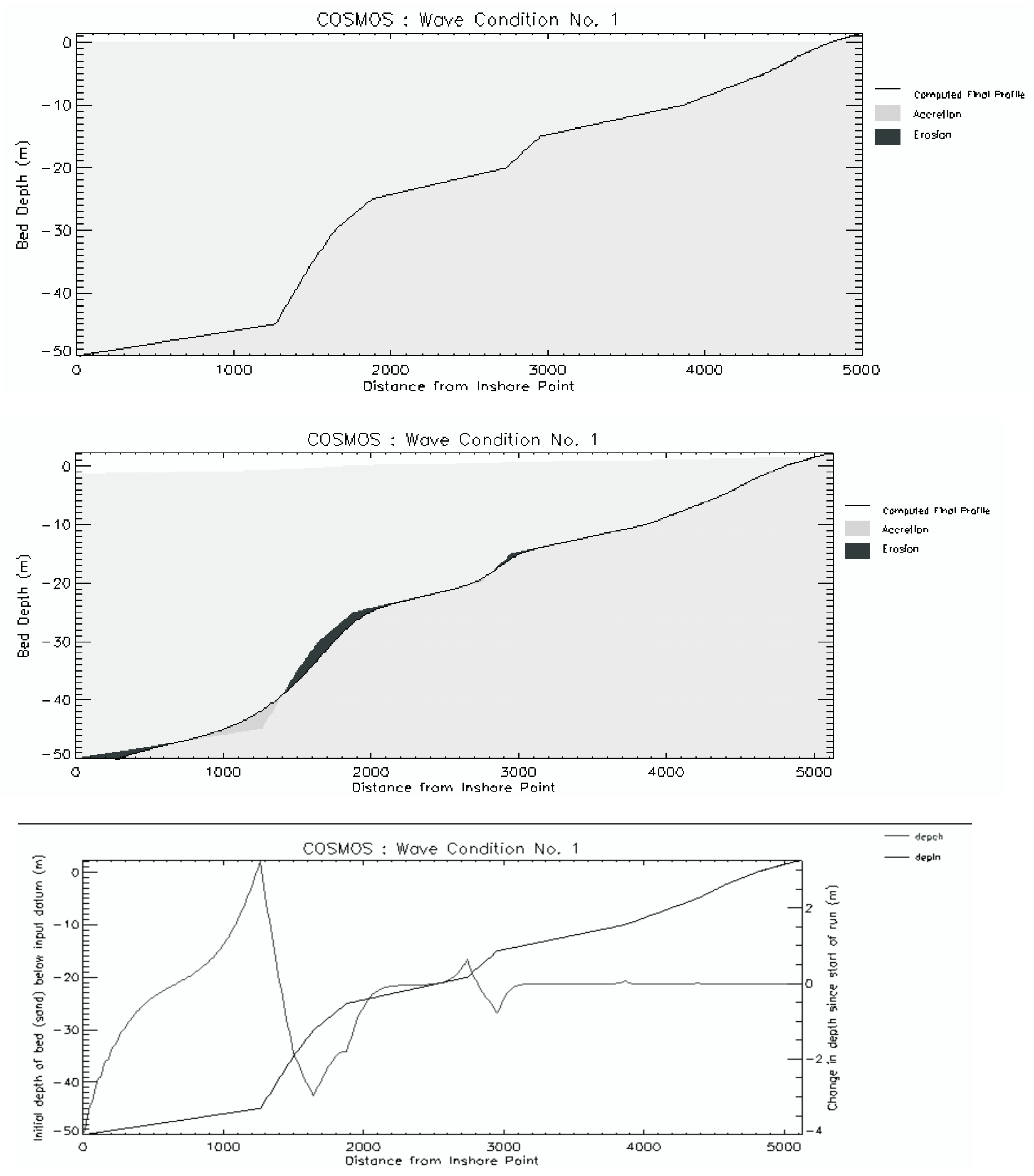

Figure 2. The seabed evaluation after the attack of a tsunami wave with 0.70 m height and 0.50 hour at its origin.

Table 1. *Summary of results obtained at the end of numerical model study.*

Wave Period (hour)	Wave Height (m)	Maximum Wave Height (m)	Depth of Maximum Wave Height (m)	Wave Set up at the Shore (m)	Maximum Change in Bed (- erosion) (m)	Depth of Maximum Bed Change (m)	Maximum Cross-shore Transport Sediment Rate (m3/m/s)	%50 Wave Breaking Depth (m)	%100 Wave Breaking Depth (m)	Pick Wave Orbital Velocity on Seabed (m/s)
0.50	**0.01**	0.63	1.68	0.10	0.01	1.47	2.34300E-05	1.87	1.58	0.77
	0.05	2.30	6.00	0.30	0.03	5.10	3.46130E-04	6.81	5.97	1.48
	0.10	4.00	10.38	0.50	-0.14	15.05	1.16490E-03	11.85	10.38	1.96
	0.30	9.73	24.77	1.05	0.88	45.05	2.87900E-02	28.97	24.74	3.05
	0.50	14.60	39.16	1.35	3.95	45.00	3.73780E+00	45.50	39.20	3.74
	0.70	19.67	49.47	1.55	> -4.00	> 50.00	> 0.2833	> 50.00	49.20	4.33
	1.00	> 28.45	> 50.00	2.14	> -24.67	> 50.00	> 1.3285	> 50.00	> 50.00	> 5.30
	0.5+0.3+0.1	14.60	39.16	1.35	4.04	45.00	3.7378	28.75	24.68	3.74
1.00	**0.01**	0.64	1.68	0.10	0.01	1.45	2.00190E-05	1.88	1.58	0.77
	0.05	2.30	6.06	0.30	0.05	5.10	2.18470E-04	6.83	5.85	1.48
	0.10	4.01	10.50	0.50	-0.19	15.02	7.89000E-04	11.88	10.44	1.96
	0.30	9.74	25.01	1.05	1.14	45.00	1.77400E-02	28.80	24.73	3.05
	0.50	14.63	39.98	1.35	4.40	45.00	8.51000E-02	45.70	39.97	3.74
	0.70	19.85	49.27	1.59	> -5.74	> 50.00	> 0.21125	> 50.00	49.21	4.35
	1.00	> 28.40	> 50.00	2.10	> -23.15	> 50.00	> 0.60867	> 50.00	> 50.00	> 5.35
1.50	**0.01**	0.64	1.67	0.10	0.01	1.47	2.01820E-05	1.89	1.57	0.78
	0.05	2.30	6.10	0.30	0.07	5.00	1.72400E-04	6.82	5.98	1.48
	0.10	4.02	10.49	0.50	-0.22	15.00	6.04000E-04	11.95	10.43	1.96
	0.30	9.75	24.78	1.05	1.32	45.00	1.44130E-02	28.65	24.77	3.06
	0.50	14.68	44.62	1.35	4.71	45.00	7.76000E-02	45.83	39.98	3.75
	0.70	19.96	49.05	1.62	> -6.92	> 50.00	> 0.1808	> 50.00	49.05	4.37
	1.00	> 28.44	> 50.00	2.14	> -24.87	> 50.00	> 0.7875	> 50.00	> 50.00	> 5.3

CONCLUSIONS

A numerical model study was carried out in order to evaluate the tsunami effects on seabed at near shore coast of Tuzla. With the seabed evaluation, some of the hydrodynamic properties of tsunami waves necessary for the completion of this task was tried to be determined.

To compare the order of seabed erosion, another model run was carried out with the same bed conditions at Tuzla coast. A storm with 10 hours duration is simulated having a 3.90 m root mean square wave height and 10 seconds mean wave period (This wave properties corresponds to a 70 years return period storm wave for Tuzla). Resulting maximum seabed erosion was 0.09 m occurred about - 12 m depth. The maximum cross-shore sediment transport rate was about 0.0004 m^3/m/s. Even at end of a 10 hours attack of such a strong storm wave the order of sediment transport and bed erosion are very small compared with the effect of tsunami waves.

It can be concluded that tsunami may create very strong and intensive sea bottom motions and resulting profile changes. If occurred, these changes would undoubtfully affect nearly all the coastal structures located at the region.

Not only harbours, marine terminals, coastal protection structures that usually encounter wave forces, but also other utilities, like sea outfalls or marine pipelines, will be adversely affected such that the pipes may be uncovered (KABDAŞLI *et al.*, 2002). On the other hand coastal structures cannot be designed by taken account of tsunami effects because of the cost and aesthetic reason, yet a certain risk should be considered. Tsunami should be considered in mitigation processes as a coastal hazard.

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