

# TSUNAMI HAZARD ASSESSMENT IN ISTANBUL USING BY HIGH RESOLUTION SATELLITE DATA (IKONOS) AND DTM

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## ABSTRACT:

Historical tsunami events have impacted the Istanbul coasts along the Sea of Marmara. Offshore seismic sources may trigger these tsunamis directly or through coseismic underwater failure. The 1999 İzmit Bay tsunami led to more comprehensive analyses of these events which are generally caused by underwater failures close to the target coastline. Waves so generated can arrive at nearby coastlines in minutes, causing extensive damage and loss of life. Here this paper propose, on the basis of tsunami models in the Sea of Marmara and methodology used internationally, first generation tsunami inundation maps for the areas along the southern coast of Istanbul using by High Resolution Satellite Data (IKONOS) and Digital Terrain Data (DTM). Such maps and images for selected areas help to understand the possible effects on those regions and should only be used for evacuation planning and reducing possible hazard.

## 1. INTRODUCTION

The coastal area of the Sea of Marmara is subjected to a near-field hazard – a tsunami generated in something under 2 hours tsunami travel time to the locality. Such a tsunami can propagate in any direction and thus, dependent on the location of the source, path of propagation and near-shore morphology form a risk to any vulnerable coastline.

Throughout history, Istanbul, which is the most populated historical city of Turkey, has been beset by different-size tsunamis. In the case of tsunami hazard, the southern coastal area of Istanbul is subjected to a near-field hazard. Different from far-field tsunamis, it may be difficult to generalise the effects of near-field tsunamis, because there is a large variability over short distances of the height of tsunamis and their destructiveness. The long interval between events in a specific position makes the problem more complicated.

Even the historical records of near-field tsunamis is often incomplete due in large part to inadequate data and data of questionable quality, especially in the case of older events, there are many events well documented for our case. During last 1600 years, at least 21 historic tsunamis are known to be felt in İstanbul (368, 407, 447, 477, 478, 480, 557, 740, 989, 1231, 1265, 1332, 1343, 1344, 1419, 1509, 1571, 1646, 1766, 1878 and 1894). Nearly half of them impacted its coasts (Altinok et al., 2001).

In 407, ships were damaged in Istanbul. In 557, 1231, 1343 and, 1344 the sea inundated 2-3 km to the land. In 1509, the

tsunami wave height was most probably more than 6 m above sea level. Sea inundated the area behind the city walls and invaded the streets. In 1766 the waves were recognised inner parts of the Bosphorus. In 1894 the sea receded up to 50 m and then returned. The wave height was less than 6 m. The bridges on the Golden Horn estuary were under the water. In 1912 the sea lifted a rowing-boat up to a height of 2.7 m at Yesilköy. In the middle of the Strait of Istanbul, the waves demolished an anchored yacht. Finally in 1999 some abnormal events were observed around the Prince islands and in the Strait of Istanbul.

## 2. MODELING FOR UNDERWATER FAILURES

Numerical simulations are useful tools for analysing tsunami propagation and coastal amplification. The tsunami waves generated by earthquakes depend on the size and the impact of the source mechanism on the displaced water. On the other hand, those generated by underwater landslides are governed by the landslide geometry and its kinematics (Grilli and Watts, 1999).

By estimating different underwater landslide and earthquake scenarios in the Sea of Marmara, Yalciner et al. (2001; 2002) have modelled tsunamis. They proposed 3 different hypothetical tsunami scenarios; an underwater failure at offshore Yenikapi, another one offshore Tuzla, and an earthquake on the Armutlu Fault and two accompanying landslides located along this fault. These scenarios showed that the tsunami waves can reach the nearest coastal area within 5-10 minutes. The numerically

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simulated run-up elevations showed that the maximum positive tsunami amplitudes near the shore can exceed the 3-m level on some parts of the coast, even reaching the 5-m level at some localities depending on the source and the coastal topography. Temporal histories, i.e. sequence and relative height of tsunami waves, showed similar appearances.

The results should be considered as important risks for the shores of the Sea of Marmara where the coastline is densely populated and widely used for many purposes.

### 3. MAPPING METHOD AND INLAND PENETRATION

The inundation map was produced by numerically simulating the resulting tsunami waves due to scenario underwater failures, and mapping the maximum inland flooding limit. The first part was done by computer methods. The last step was accomplished chiefly by prior conclusions about inland penetration depending on the circumstantial characteristics of the inundation area and available topographic data (Priest, 1995).

Tsunami flooding or the volume of water carried onshore is directly related with the size of tsunami and its wave period. On the other hand, the cross-sectional area of coastline flooded by a tsunami is almost equal to that of water under the tsunami wave crest close to shore (Hills and Mader, 1997). The limit of landward incursion is the maximum distance that run-up can penetrate inland and can be given the following formula;

$$x_{\max} = (Hs)^{1.33} n^{-2} k \quad (1)$$

where  $k$  is a constant and taken as 0.06 for many tsunamis. The term  $n$  is another constant and depends on the characteristics of the inundation area. It is 0.015 for smooth terrains such as grasslands or tidal plains, 0.03 for areas covered in buildings and 0.07 for landscapes densely covered with forest.

Dry-land inundation distance across relatively flat ground was inferred by extrapolating the run-up elevation at the shoreline inland until a barrier was encountered or until a lateral distance was reached that conforms approximately to the above equation. A tsunami 2.6 m high can penetrate 950 m inland for smooth plains. However, since the study area is a developed land on flat coastal plains, such a tsunami can only penetrate 250 m inland.

#### 3.1 Mapping Tsunami Inundation

For definition of the inundation limit, a Digital Terrain Model (DTM) with a vertical resolution of  $\pm 1.2$  m was used. On the basis of elevation data of the surface, a DTM creates topography by geometric surfaces in a computer environment. This method provides best approach to a 3D terrain surface using elevation points which were defined on a horizontal plane, from various data sources such as measured data, topographic maps, bathymetric data and images. Our DTM was produced from 1:25,000-scale topographic maps and has a cell size of 50 m. In order to define the environmental condition of the inundation area (smooth terrain, areas covered in buildings or forest), we have merged the DTM with respective IKONOS with 1 m resolution. Finally, calculated inundation limits based on some assumptions were drawn on these maps (Figure 1-4).



Figure 1. Inundation map drawn for the coastal area in front of Küçükçekmece lagoon. The line shows how far inland and uphill a tsunami caused by an underwater failure is expected to go. Taking into consideration the simulated tsunami waves due to scenario underwater failures, topographic elevations, settlement conditions and geographic characteristics of the inundation area, the maximum inland flooding limits were developed for the wave heights of 2 m at shore.



Figure 2. Inundation map drawn for the coastal area of Yesilkoy airport, Ayamama creek and Ataköy Marina. Each line shows how far inland and uphill a tsunami caused by an underwater failure is expected to go. Taking into consideration the simulated tsunami waves, the maximum inland flooding limits were developed for the wave heights of 2, 2.5 and 3.0 m at shore, respectively.



Figure 3. Inundation map drawn for the coastal area in front of Zeytinburnu port. Line definitions are same as in Figure 2. The inundation distance was calculated on the basis of circumstantial characteristics of the inundation area along the coastal zone which was classified for smooth terrains and areas covered in buildings.



Figure 4. Inundation map drawn for the Haydarpaşa Port and Kadıköy inlet placed at the Bosphorus junction of the Sea of Marmara. Occasional steep coastal terrain at some localities limits inundation. These lines are subject to changes on the basis of prehistoric tsunami deposits found along the coast, further computer tsunami modelings, and scientific studies of other tsunamis that occurred in the Sea of Marmara.

### 3.2 Precision and Accuracy of the Inundation Lines

One of the largest sources of error is uncertainty in the absolute run-up elevation at the open coast. Therefore, it is assumed to be 2, 2.5 and 3 m in our calculations.

The numerical grids were refined enough to simulate the details of the land topography (pixel size  $\pm 50$  m). Therefore uncertainty in the inundation distance (horizontal accuracy) is small.

Due to the inherent uncertainties in tsunami models, the parameters we used in calculations (models, topography etc) and our judgement to infer inundation, the resulting error is difficult to quantify. Vertical precision, for example, depended on the spacing of the elevation contours and the proximity of the contours to the inferred run-up elevation. The maximum uncertainty between contours is 100 percent of the contour interval. Where the inundation distance fell by chance at or very close to an elevation contour, the precision is better. In addition, the precision may be large at inlets, lagoons, river mouths and estuaries and smaller at steep shorelines. In all cases the precision of the inundation lines is limited by the resolution of the images to no better than  $\pm 5$  m horizontal and  $\pm 1.2$  m vertical.

In normal conditions, sea level changes should be considered and possible co-seismic subsidence should be added to results of inundation limit as an additional run-up. Tides are small in amplitude; however maximum effective wave height in the region is as much as 3.3 m in winter. During persistent southerly winds, surges caused by wind setup are as high as 1 m along the northern coasts of the Marmara. On the other hand, co-seismic subsidence must be considered in some alluvial flats along the European coasts. Subsidence inferred from the prehistoric geologic record may increase in large estuaries. Such factors may make minor differences in the mapped inundation.

## 4. CONCLUSION

Tsunamis are unpredictable events and increasing the uncertainty of preventive action, contribute to a very low social memory on these phenomena that is inversely related with a high demand for decision criteria based on scientific knowledge. On the basis of this contextual situation which shows us the urgent necessity to develop integrated actions research, tsunami risk maps in a microzonation sense along the Sea of Marmara coasts of Istanbul were produced. The absolute run-up elevation at the coast is assumed to be 2, 2.5 and 3 m in our calculations. For particular areas, the inland distance of inundation is apparently greater. Küçükçekmece lagoon is separated from the coast by barriers with present elevations on the order of a few metres. The inferred inundation is high enough, within the uncertainties of the run-up estimates, to inundate this lagoon.

We have produced 3 different case scenarios for absolute run-up elevations of 2, 2.5 and 3 m at the coast. In fact, in normal conditions, a single line representing a worst case scenario was preferable, for it simplified the preparedness response of city officials and it better informed the general public (Synolakis et al., 2001). However, a comparison of low and high risk lines on a same map indicates most vulnerable localities and helps us to

rank the relative risk from different scenarios. These resulting maps should be used for the tsunami impact in relations to the natural environment, land use/land cover types and road network.

One should not forget that a local tsunami generally produces run-up significantly higher than that of a distant generated tsunami, provided that the source earthquakes were of similar magnitude. Therefore, the tsunami waves may be destructive along the Marmara coasts of Istanbul and for shallower areas (<20 m). The effect of tsunami can be minimised on flat coastal plains (e.g. Cekmece lagoons, Ayamama, Bakirköy, and Zeytinburnu) by planting tree belts between shorelines and areas needing protection. At Büyükçekmece lagoon and in small harbours or marinas, very strong currents and extensive damage to property may occur if the tsunami amplitude is more than 2m. It may also be expected loss of life in addition to general loss of property, if the runup exceeds 2.5 metres. Constructing breakwaters at harbours entrances, avoidance of potential areas for settlement and having streets aligned perpendicular to the wave advance may solve such problems.

Our inundation mapping efforts depend upon the numerical tsunami modes based on the landslide and slump hazards in the Sea of Marmara. Such kind of models developed for tsunami generation, propagation and coastal amplification are not enough to know the maximum run-up with any certainty. On the basis of new marine surveys, shallow water models should be developed and upgraded to a better convenient faster accurate level. Simulation of historical events is important. Comparisons between simulated results and other observations allow the first estimation of the source energy.

A monitoring system for acquisition of seismic signal and water level displacement simultaneously must be installed to favouring the study of the tsunami generation in a selected area. At least two digital mareographic stations based upon a submerged pressure gauge and a microbarograph must be installed; one in the İmralı island.

The rises in sea level from storms at the time of an actual tsunami could change the run-up elevation by  $\pm 1-1.5$  m from the mean sea level assumed in the simulation. This would also make significant changes in the horizontal position of the inundation lines.

Narrow estuaries and straits may maintain or amplify the wave height of open coastal tsunamis. Wave propagation modelling studies are suggested for the Strait of Istanbul and the Golden Horn estuary. The coastal run-up is assumed to decrease inland in barrier-protected bays and estuaries. Experiments showed that a run-up is locally higher if the tsunami partially or completely overtops the barrier, strikes a shoreline directly behind the entrance to an estuary, or enters a constriction in the estuary. Such errors should be added to the average run-up value to obtain the final run-up elevation.

In future, if any area is found to be underlain by deposits inferred to be from historic or prehistoric tsunamis, these areas should be included in the inundation boundaries we have defined. Since tsunamis can inundate without leaving behind a sediment deposit, presence of deposits was considered a good indication of minimum inundation.

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