PROBABILISTIC MODEL FOR TSUNAMI-WAVE ELEVATION ALONG THE ALBORÁN SEACOAST

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Abstract

In this study the tsunami-wave run-up along the Alborán Seacoast (Spain) have been evaluated. An indirect statistical method has been used to estimate the tsunami risk along the southeastern Spanish coast. This method can be summarized as: (1) analysis of the global neotectonic setting, the geodynamic processes as well as seismicity of the region; (2) tsunami source model; (3) generation, propagation and run-up numerical models; and (4) the risk model. The purpose of this study is to establish tsunami-wave elevation at the shoreline versus the return period curves for different locations along the Alborán seacoast. It is concluded that, the tsunamis generated in the Alborán basin have a medium-to-low intensity, with the most important elevations in the Málaga, Adra and Melilla areas.

Introduction

The Alborán seacoast is located along the southwestern Mediterranean Sea and occasionally, this area is affected by tsunami water waves (see figure 1 where some of the tsunamigenic epicenters are shown).

During the last few decades, the southeastern coast of Spain (Almería, Málaga and Marbella) has suffered an enormous transformation due to the tourism "boom" and the demand for coastal use. For this reason, a great number of infrastructures have been built (marinas, beaches, highways, boardwalks, hotels, etc.), which could be affected by tsunamis. The objective of this study is to establish the tsunami-wave elevation risk along the Alborán Sea. Since the frequency of occurrence, location, and magnitude of tsunamigenic earthquakes are random, the risk analyses must be based on probabilistic considerations.

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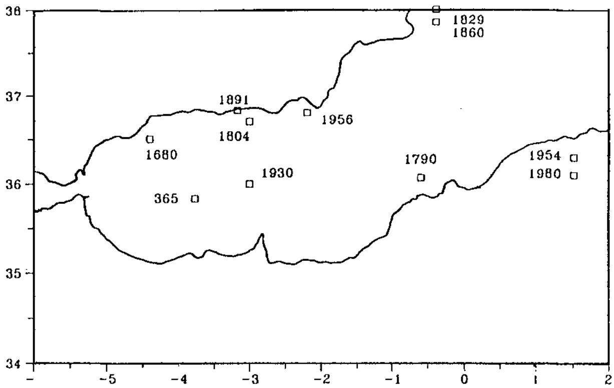

Figure 1. Historical tsunamigenic events

Tsunami hazard has been investigated using various approaches. Where historical information and measurements regarding tsunami inundation are available, a direct statistical analysis has been used (Houston, 1977; Wiegel, 1970); where such data are scarce the concept of indirect analysis has been applied. The indirect approach, as carried out by Houston et al. (1974) and García et al. (1975), consists essentially of utilizing: (1) the historical information available in order to estimate the frequency of tsunamis of various intensities at the sources, and (2) the knowledge of tsunami wave propagation based on hydrodynamic considerations to compute the risk of a tsunami at the site.

The catalog of tsunamis that have occurred along the Alborán seacoast includes only a few events, since tsunamis are rather infrequent and since, in the past, positive scientific attention to these natural phenomena was scarce or even absent in the Alborán seacoast as in many other countries. Given this, no data concerning the source parameters (bed sea dislocations, source area, etc.) are available. In this study, a tsunami risk analysis following the idea of Houston et al. (1974) and García et al. (1975) is performed. However, seismological and probabilistic models similar to Lin et al. (1986) are used in order to determine the seabed dislocations in the source area.

The indirect method applied in this study can be summarized as:

- Selection of the tsunamigenic sources and seismic parameters.
- Tsunami source model (seismological model).
- Hydrodynamic numerical models (generation, propagation and run-up).
- Risk model.

Tsunamigenic Sources

Taking into account the global neotectonic setting, the geodynamic processes as well as the seismicity of the considered region, it is possible to determine potential tsunamigenic sources, whether or not they are historically active. It is likely that the major cause of catastrophic tsunamis is underwater shallow focus earthquakes of Richter magnitud 5.0 or greater (Iida, 1970, 1963). However, not all such earthquakes produce tsunamis since the generation mechanism is usually associated with vertical dislocations of the sea floor in dip-slip faults normal or reverse faults.

Neotectonic features

The Alborán Sea in the southwestern Mediterranean is a very active region of the wide area of continental collision generated by the northward movement of the African plate relative to the European plate (Dewey et al., 1989). The unusual tectonic situation of a small sea caught between two major plates is characterized by a complex sea floor physiography, with several basins separated by structural highs and ridges (Maldonado et al., 1992a, c; Woodside et al., 1992). Furthermore, some authors (Udías et al., 1976; Buforn, 1988b, c; Udías et al., 1992 and Mezcua et al., 1997) have proposed different geodynamic models based on source mechanisms of earthquakes, that permit the determining of the fault system in the Alborán Sea. The tectonic features are characterized by a fault system composed of short strike-slip faults and short dip-slip faults, as shown in figure 2. This short fault system is due to the crustal shocks of the African and European plates, where a beniof or subduction zone is not evidenced.

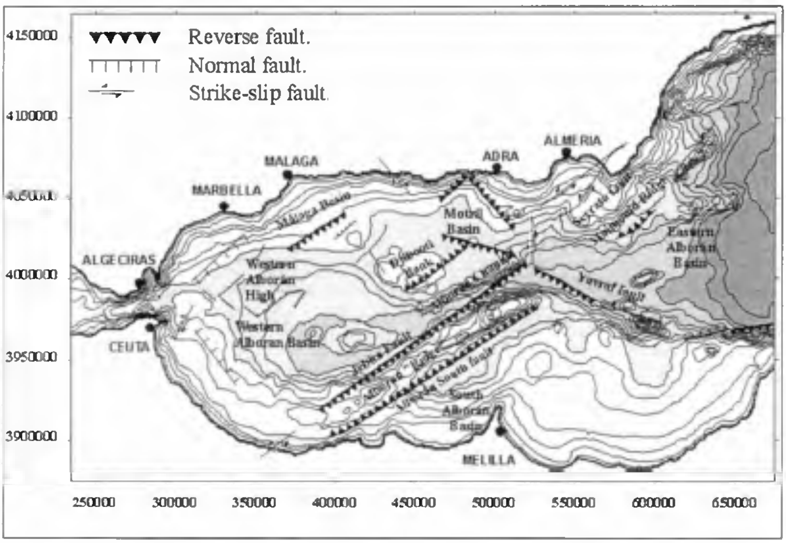

Figure 2. Schematic summary of principal neotectonic and geomorphologic elements in the Alborán Sea

Seismic pattern

The spatial distribution of seismicity could be considered a manifestation of the lithospheric weakness zone where the stresses applied are released, that, joined with some seimic parameters, permit the choice of potential tsunamicgenic sources. The Alborán Sea presents high seismic activity, with moderate earthquake magnitudes and shallow epicenters. The earthquakes are associated with the local fault system.

The data for the earthquakes were taken from: (1) the Spanish National Seismic Catalog from the period 1916-1996: (2) the Spanish seismic risk maps from the National Geographic Institute (NGI) from the period 1320-1920. In figure 3, different Richter magnitudes of the earthquakes from the 1916-1996 period are shown for ($M_s \geq 5.0$).

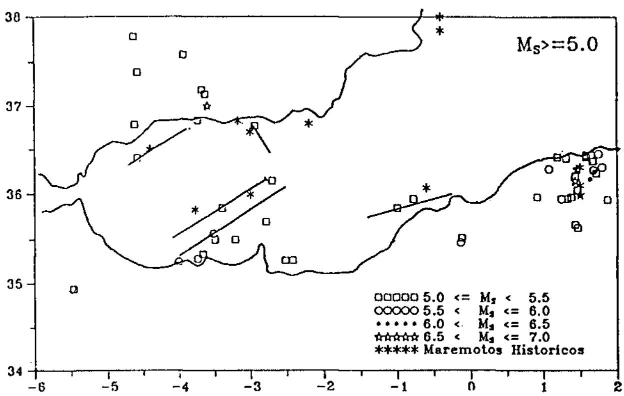

Figure 3. Relocated seismicity ($M_s \geq 5$), for the period 1916 - 1996 and potential tsunamigenic sources

Potential faults

Five potential tsunamigenic sources have been selected for the Alborán Sea, taking into account: (1) the historical tsunami data (figure 1); (2) the analysis of the dip-slip faults (normal and reverse); and (3) analysis of seismicity. This kind of analysis is used as an important tool to estimate the potential for tsunamigenic earthquakes (Alami and Tinti, 1991). Only the seismic data with magnitude greater than 5.0 on the Richter scale with focal depths less than 50 km and greater than 20 km, are included in the analysis (Iida, 1963, 1970).

Tsunamis of distant origin (Italian and Greek sources) are not considered a threat to the study area. Furthermore, although the Atlantic Ocean sources (Azores - Gibraltar fault system) can generate great tsunamis, they do not cause any perceivable perturbations in the Alborán Sea. Historical events and numerical simulations confirm that the Strait of Gibraltar acts as an important tsunami filter. In figures 3 and 5, the five potential tsunamigenic sources selected for the Alborán Sea area are shown.

Tsunami Source Model

In this study, the offset is assumed to be a vertical ascendant movement generated by submarine earthquakes of tectonic origin, which are associated with the five selected potential sources. It is also assumed that the sources are simple straight faults with a focus located in the middle point (see figure 5). The bed displacement is defined by: (1) the source location; (2) the plane area of the ground displacement, S; (3) the average offset or vertical dislocation, D; and (4) the velocity of the displacement, $\xi(t)$. Figure 4 shows a diagram of the bed movement.

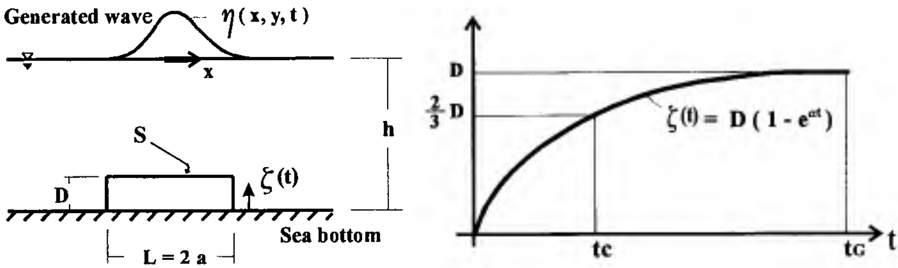

Figure 4. Schematic sea bottom displacement

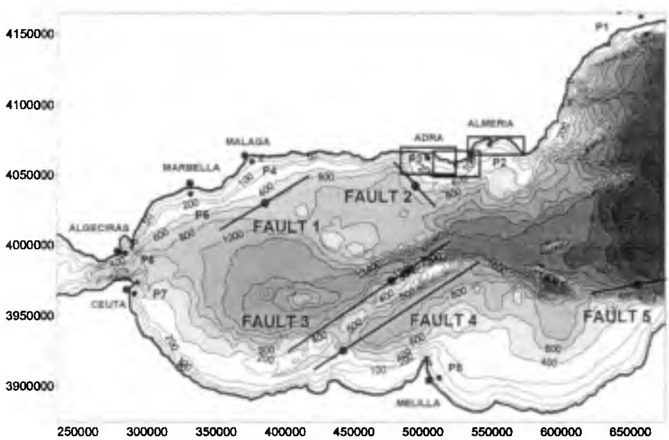

Figure 5. Location map showing global and detailed grids and potential tsunamigenic sources

The most widely used quantitative measure of the strength of an earthquake has been its magnitude (M_s). However, it is well-known that there is difficulty in relating magnitude with other important source characteristics such as strain-energy release, fault offset, stress drop and source dimensions, etc. (Kanamori and Anderson, 1975). For large earthquakes, the seismic moment denoted M_o, is defined as:

$$M_o = \mu\, S\, D \tag{1}$$

In which μ= rigidity of the medium (μ= 2 - 3 · 10^{11} dyne - cm^2).

Tsunamigenic earthquakes of tectonic origin are those submarine earthquakes on shallow faults and of large magnitude. As such, tsunamigenic earthquakes are most conveniently measured by seismic moment. In fact, tsunami records in the Pacific have been correlated with and used to calibrate seismic moments (Kanamori, 1977).

The number of occurrences of earthquakes with seismic moment, M_0, greater than or equal to m_0 has been shown to be given as:

$$N(m_0) = \alpha\, m_0^{-\beta} \tag{2}$$

where α and β are numerical constants determined from earthquake records. Discussion of values of these quantities is given by Molnar (1979) as well as by Kanamori and Anderson (1975) and the Fundación Leonardo Torres Quevedo (1997). Equation (2) will be used to determine the probability distribution function of seismic moment in the section "Risk model for tsunamis".

Important physical dimensions of an earthquake are the offset: vertical dislocations and, length and width of ground dislocation. Based on earthquake data, Kanamori and Anderson (1975) obtained the empirical relation between the seismic moment M_o and the source, S, given as:

$$M_o = C_1 S^{\frac{3}{2}} \tag{3}$$

In which C_1 = 1.23 · 10^7 dyne - cm^2 width S measured in km^2.

In order to relate seismic moment, M_0, with Richter magnitude, M_s, different authors have proposed empirical relations. Mezcua et al. (1991) obtained for the Azores-Gibraltar-Alborán Sea, the following empirical relationship:

$$\mathrm{Log}\, M_o = 1.16\, M_s + 17.93 \tag{4}$$

An expression that can be used to relate M_s with source parameters.

In this study an elliptical ground displacement in plan view is assumed, with an exponential time-displacement function which Hammack (1972) defined as:

$$\xi(t) = D(1 - e^{-\alpha t}) \quad 0 < t < t_G \tag{5}$$

with $\alpha = 1.1/t_c$, where t_c is the time to rise 2/3 D (t_c ~1 - 20 g.) and t_G is the total generation time (1 - 2 min.).

In accordance with the tsunami source model, the most important parameters that have to be determinated are the source location and the seismic moment, M_o.

Hydrodynamic Numerical Models

In order to simulate tsunami generation and propagation a coupled numerical model was applied. The run-up in some cross-shore locations was estimated matching the coupled model with a one-dimensional, time-dependent numerical model.

Tsunami Generation numerical model

Many authors have applied an elliptical water surface shape similar to the ground displacement for the waves near the source (Houston et al., 1980; Lin et al., 1986; Camfield, 1992). This kind of surface water displacement has also been applied in this study, defined as:

$$\eta(x, y, t) = \xi(t)\left[1 - \left(\frac{x}{a}\right)^2 - \left(\frac{y}{b}\right)^2\right]^{\frac{1}{2}} \tag{6}$$

where $\xi(t)$ is the equation (5), and the coordinate system origin for the x and y axes is located in the middle of the ellipsoid (or source area).

Tsunami Propagation numerical model

Nonlinear, nondispersive, shallow water equations were used to model the propagation of tsunamis in the Alborán Sea.

For a distant tsunami, traveling distance could be much greater than the characteristic wave length of the tsunami. In these cases, both the frequency dispersion and coriolis terms could play an important role (Liu et al., 1994). However, due to morphological characteristics of the Alborán Sea (see figure 5) which is a small basin (approximately 400 km length, 200 km width and water depth less than 2 km) these two terms can be neglected.

As tsunamis propagate into the shallow water region, wave amplitude increases and wave length decreases due to shoaling. The nonlinear convective inertia force becomes increasingly important while the importance of frequency dispersion diminishes (Liu et al., 1994).

The model equations are solved by an implicit finite difference method. The finite difference scheme is similar to that presented by Leendertse (1970). The model used, as a temporal initial condition, the elliptical deformation of the water surface presented by the relations (5) and (6). An absorbing boundary condition is employed for the seaward boundary and a reflecting condition in the coastline.

A global propagation grid 440 x 290 km^2 was adopted (see figure 5). The numerical computational mesh size and time-step size were fixed, $\Delta x = \Delta y = 1000$ m, $\Delta t = 5$ s. for propagation and $\Delta t = 0.5$ s. for the wave generation. In order to reduce numerical errors, the spatial grid size should be such that one local wave length includes more than 20 grid points. Therefore, a finer spatial grid size was adopted, $\Delta x = \Delta y = 200$ m for water depth less than 50 m. Three finer grids between Adra and Almería are shown in figure 5.

A propagation tsunami example generated in fault 5 ($M_s = 7.5$), is shown in figure 6, where the computed water surface appears at t = 18 min. and t = 33 min.

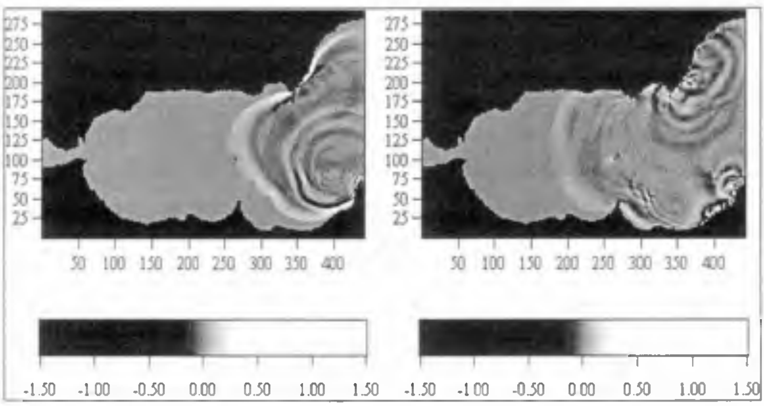

Figure 6. Propagation example tsunami wave elevation (t = 18 and 33 min.), epicenter at fault 5, with $M_s = 7.5$

Tsunami Run-up Numerical Model

A one-dimensional, time-dependent numerical model (Kobayashi et al, 1994 a), is used to simulate the tsunamis flow over some cross-shore profiles along the coast between Adra and Almería. The finite amplitude shallow-water equations (mass, momentum and energy) including the effects of bottom friction over rough impermeable cross-shore slopes, are solved numerically in the time domain using an explicit dissipative lax-wendroff finite-difference method (Kobayashi and Otta, 1987). The run-up model used, as seaward boundary, the tsunami-wave elevation recorded at a numerical gauge in the finer grid. Several cross-shore profiles were selected, starting seaward in 10 m water depth and including the topography of high and low coastal areas.

The bottom friction factor (f) was not considered constant along a cross-shore profile. In profile areas with smooth slopes, as is the case in sandy beaches a f = 0.005 was used. On the other hand, a f = 0.01 was used in rough slopes, for example in urban areas and step structure slopes.

Risk Model

The tsunamigenic earthquake is not a deterministic phenomenon; both source location and seismic moment, M_0, have to be defined as random variables. Since the occurrence of future tsunamis is difficult to predict, risk analyses must be based on probabilistic considerations. One of the elements involved is the probability of tsunami inundation of various levels at a given place in a given return period. This probability is generally referred to as hazard or risk.

Eight points (see figure 5) of the Alborán seacoast and some cross-shore profiles between Adra and Almeria were selected to perform the risk analysis. The risk analysis consists of: (1) A Monte Carlo simulation, which is based on a probabilistic model in order to obtain the synthesized record of tectonic deformations of the seabed; (2) The tsunami source model, which permits us to relate the physical dimensions (S, D) of the displaced bottom source [eq. (1) and (3)]; and (3) the hydrodynamic numerical models which are used to simulate propagation and run-up of the tsunami caused by each of the synthetic seabed deformations.

Probabilistic model for tsunamigenic earthquakes

In order to obtain the synthesized record of seabed deformations, it is necessary to define the three basic random variables involved in risk analysis: (1) the occurrence of tsunamigenic earthquakes events; (2) the earthquake source; and (3) the seismic moment, M_0.

The tsunamic mean frequency of occurrence was obtained based on the eight events which occurred in the last 200 years, due to the fact that there is no historical catalog of tsunamis before 1800. Therefore, it is assumed that one tsunami event occurs once every 25 years on average.

As stated previously, five potential individual faults, were selected. However, the probability of occurrence of tsunamigenic earthquakes in each one of these is different. In order to obtain these probabilities, the following hypothesis are assumed: (1) the faults are independent and once every 25 years one event occurs in one of the five faults; (2) a tsunamigenic earthquake originates from a single, well-defined, straight fault; (3) earthquakes can occur anywhere along a fault with equal likelihood but the focal point is located in the middle of a straight fault (see figure 5); and (4) the probability of occurrence of tsunamigenic earthquakes of a specific fault increases, with the number of events with Richter magnitudes ($M_s > 5$) and focal depths ($D_f < 50$ km). Figure 7 shows the probability function obtained for each one of the potential faults.

The probability distribution function, $F_{M_o}(m_o)$ of M_o was determined, using equation (2) by Lin and Tang (1982), as:

$$F_{M_o}(m_o) = \left[1 - \left[\frac{m_{ol}}{m_o} \right]^{\beta} \right] \cdot \left[1 - \left[\frac{m_{ol}}{m_{ou}} \right]^{\beta} \right]^{-1} \qquad m_{ol} \leq m_o \leq m_{ou} \tag{7}$$

where m_{ol} is the lower magnitud of seismic moment, in accordance with (Iida, 1970, 1963), $m_{ol} = 10^{23.73}$dyne-cm ($M_s = 5.0$ on Richter scale). The maximal energy released by a earthquake in a fault, is limited depending on the neotectonic and the geodynamic of the potential fault. Due to the characteristics of the Alborán Sea, m_{ou} was defined as $m_{ou} = 10^{26.65}$ dyne-cm ($M_s = 7.5$). Equation (7) was applied for the five potential faults (see figure 8), taking into account the seismological data to obtain β, and the empirical relation between M_s and M_o (equation 4).

Results

The risk analysis due to tsunamis is represented by curves which permit us to obtain the maximal tsunami-wave elevation in given sites along the Alborán seacoast for two confidence levels (50% and 99.99%) and return period (years).

As an example of these curves, figures 9 and 10 show the risk analysis in the city of Adra. Figure 9 shows the run-up in a cross-shore city profile and the figure 10 represents the horizontal flooded landward distance, measured from local mean water level. In figure 11, for a return period of 2,500 years, the risk analysis for different places along the Alborán Sea in water depths of 6 m is shown. This figure shows a higher risk in areas near Adra, Málaga and Melilla. The complete results and propagation details can be found in Fundación Leonardo Torres Quevedo (1997).

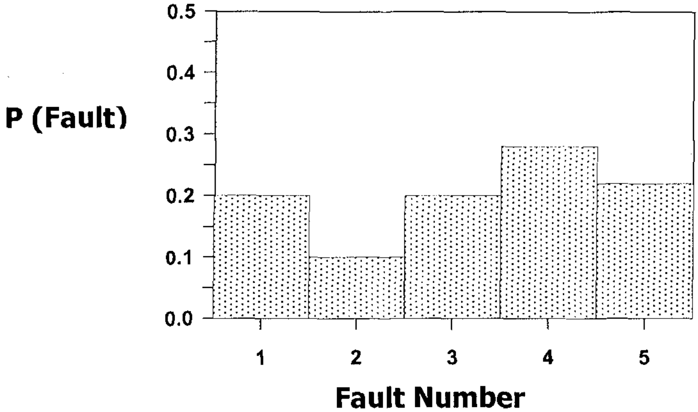

Figure 7. Probability function of tsunami occurrence in potential faults

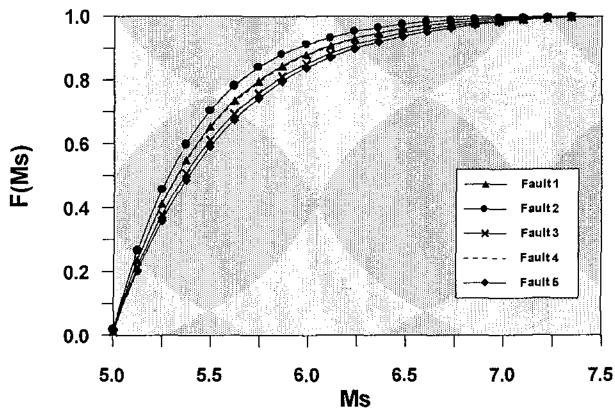

Figure 8. Distribution function of seismic moment, M_0, for the five potential faults.

Conclusions

- Given the global neotectonic setting, the geodynamic processes as well as the seismicity of the Alborán Sea, the tsunamis generated in the area present a medium-to-low intensity.
- Five potential tsunamigenic faults have been determined in the area (figure 5).
- Using simple tsunami source, hydrodynamic and risk models, tsunami risk in different sites along the Alborán Sea has been computed.
- Due to morphological characteristics and the setting of potential faults, zones close to Málaga, Adra and Melilla have a greater tsunami wave elevation than the rest of the Alborán Sea locations.

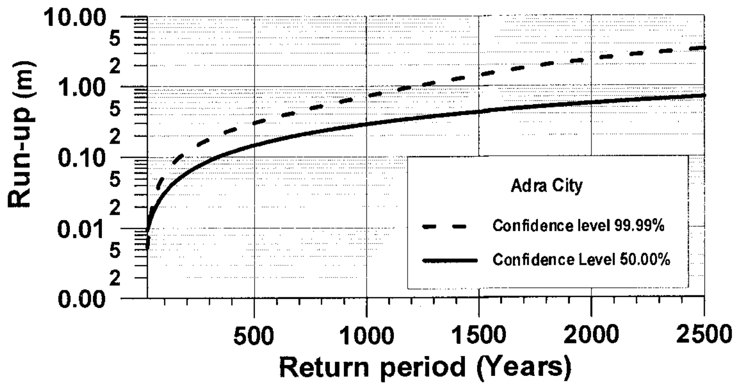

Figure 9. Tsunami risk example. Run-up in the city of Adra

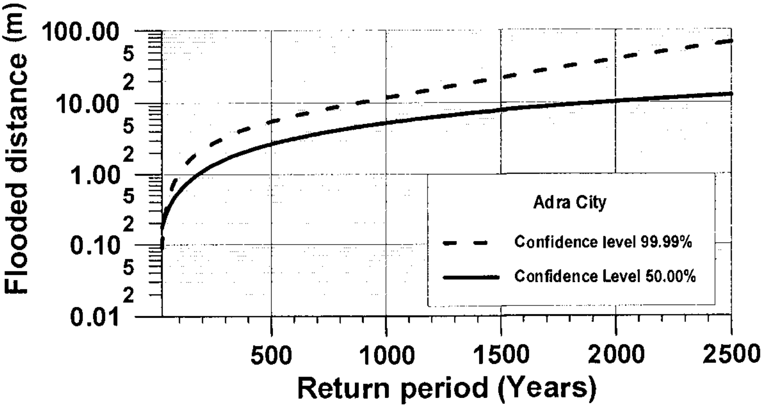

Figure 10. Flooded landward distance in the city of Adra (distance measured from the mean water level)

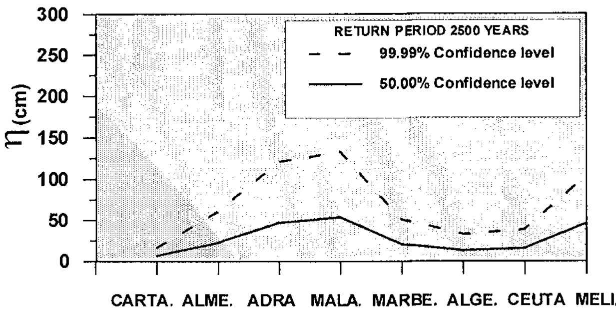

Figure 11. Tsunami risk example. The 2,500 year return period curve in different points along the Alborán Sea (h = 6 m)

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