

TSUNAMI RESPONSE SIMULATION AT GUADALUPE ISLAND (MEXICO)

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ABSTRACT

Guadalupe Island, located off the coast of Baja California (México), is one of the wave reporting stations equipped with a data collecting platform presently in operation for the Pacific Tsunami Warning System. The knowledge of the tsunami response at the island can give an estimation in advance of the severity of the attack to be expected at neighbouring mainland communities.

The scattering of tsunami waves by the island is examined by solving the linear long wave equation through a time and space centered finite difference approach. The model involves a conformal mapping of a polar coordinate grid onto an image plane where the orthogonal contours reproduce the real island shape at the unit circle, but approach to a circular shape as the radius in the polar system is increased.

Relative amplitude and wave phase lag at several points along the island contour, for the most probable tsunami periods and incident directions to occur according to historical records, are computed.

Maximum amplifications (400%) happen with short tsunami periods (10 minutes) and close to energy convergence zones, where refraction is important. For large tsunami periods (30 minutes), reflection and diffraction become the dominant processes, with amplifications of less than 25%.

The present location of the wave reporting station is confirmed to have adequate amplification characteristics for the tsunami warning system.

Results of the model may be used to obtain tsunami inundation estimates.

INTRODUCTION

Several remote source tsunamis have affected the coastal communities of the Baja California peninsula in northwest México, as it is historically documented (Ferreras and Sánchez, 1991). Guadalupe Island, lying outside the continental shelf, 250 km off the coast of Baja California (Figure 1) is one of the wave and sea level reporting stations for the Pacific Tsunami Warning System (Intergovernmental Oceanographic Commission, 1987), the Pacific Satellite Sea Level Network, and the Baja California Regional Tsunami Warning System. It is presently equipped with a sea level pressure gauge connected to a satellite data collecting platform.

Islands, far out from the continental shelves, provide a good option to obtain tsunami records in conditions near to those in the open ocean.

The objective of this study is to determine the tsunami amplitude and phase response along Guadalupe Island contour for several wave periods and incident directions; and obtain through this an estimation of the incoming tsunami wave

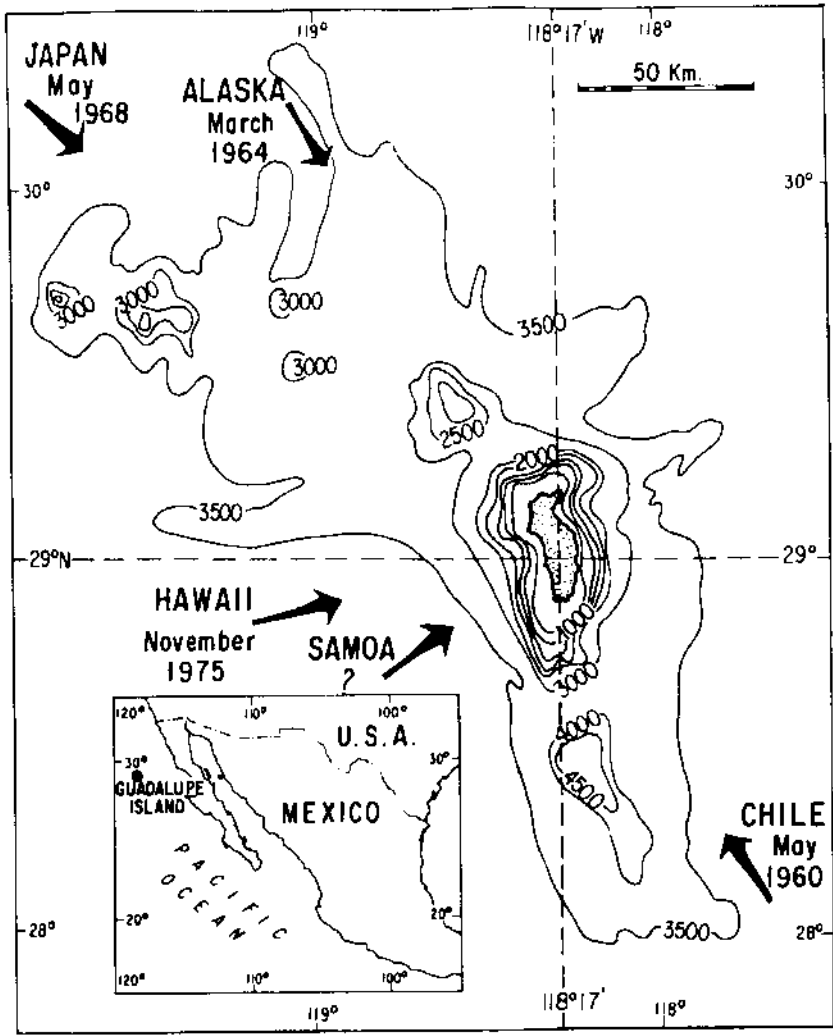


Figure 1. Guadalupe Island location, surrounding bathymetry, and approach direction of the 5 tsunami cases modeled in this study. Depths are in fathoms (1 fathom = 6 feet).

parameters in the open ocean. This estimation can give an information to neighbouring mainland coastal communities on the arrival time and severity of the attack to be expected, before tsunami waves reach them.

METHODOLOGY

Reflection, refraction, shoaling, and diffraction in the local bathymetry and coastal configuration are the main physical processes occurring in the interaction of water waves with an island. About 25% of the tsunami energy is reflected at the continental shelf, while 100% do so at the arrival to the coast (Soloviev and Go, 1974). Miyoshi(1983) states that refraction is the most important interaction process for a tsunami converging onto an island.

Diffraction cause more harm to the coast when the size of the obstacle is comparable with the incident wave length (Dean and Dalrymple, 1984). Although the suitability of linear wave theory application to tsunami wave interaction with a continental shelf is still a matter of discussion (Voit, 1987), it has been succesfully applied to the modeling of tsunami-island (Bernard and Vastano, 1977; Houston, 1978) and tsunami-coast (Tsuji, 1985) interactions.

The linearized long wave equation in polar coordinate(r, θ) and time t is:

$$\frac{\partial^2 \zeta}{\partial t^2} = g \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r D \frac{\partial \zeta}{\partial r} \right) + \frac{D}{r^2} \frac{\partial^2 \zeta}{\partial \theta^2} \right] \quad (1)$$

where ζ is the free surface elevation, D is the mean water depth, and g is the gravitational acceleration.

Bottom friction, surface wind stress, and Coriolis effect are neglected.

Zero component of radial flow $\frac{\partial \zeta}{\partial t} = 0$ and Sommerfeld (1949) radiation condition for the waves scattered outward to infinity $\frac{\partial \zeta_s}{\partial r} + \sqrt{gD} \frac{\partial \zeta_s}{\partial t} \rightarrow 0$, are considered as inner and outer boundary conditions respectively.

To solve the equation, a Riemann's conformal mapping of the polar coordinate grid (r, θ) onto an image plane (ρ, β) where the orthogonal contours reproduce the real island shape at the unit circle, but approach a circular shape as the polar system radius is increased, is performed. The conformal mapping preserves the angles, modifies the radial scale, and adjusts the inner boundary to the real contour to help solve the equation. The transformed grid with 50×120 nodes (shown abridged in Figure 2) has a maximum radial increment of 5 km in the outer boundary, decreasing in value towards the coast, where the wave interaction requires more resolution, and a maximum arc length of 13 km. This spacing is consider as adequate for linear tsunami modeling by Tuck (1979). The grid extends 250 km outward and the maximum cell size and its overall dimension are selected so as to obtain a desirable resolution. In the most sharp corners of the island contour resolution is also increased by the high density of rays. The deep open ocean is simulated by a far field of 3.5 km constant depth extending 80 km outwards. The

origin of the coordinate system (Figures 1 and 2) is located such as to avoid or minimize multivaluations of the radius as a function of the directional angle.

After the conformal mapping, the wave equation takes the form:

$$\frac{\partial^2 \zeta}{\partial t^2} = g s^2 \left[\rho \frac{\partial}{\partial \rho} \left(\rho D \frac{\partial \zeta}{\partial \beta} \right) + \frac{\partial}{\partial \beta} \left(D \frac{\partial \zeta}{\partial \beta} \right) \right] \quad (2)$$

where s is a scale factor.

This equation is solved numerically for monochromatic plane incident waves

$$\zeta_1 = e^{i(\chi r \cos \theta - \omega t)}$$

where χ is the wave number and ω is the angular frequency, by means of Vastano and Reid (1966) space-time centered finite difference algorithm. An integration time step of one second is used, considering Richtmeyer (1957) stability criteria.

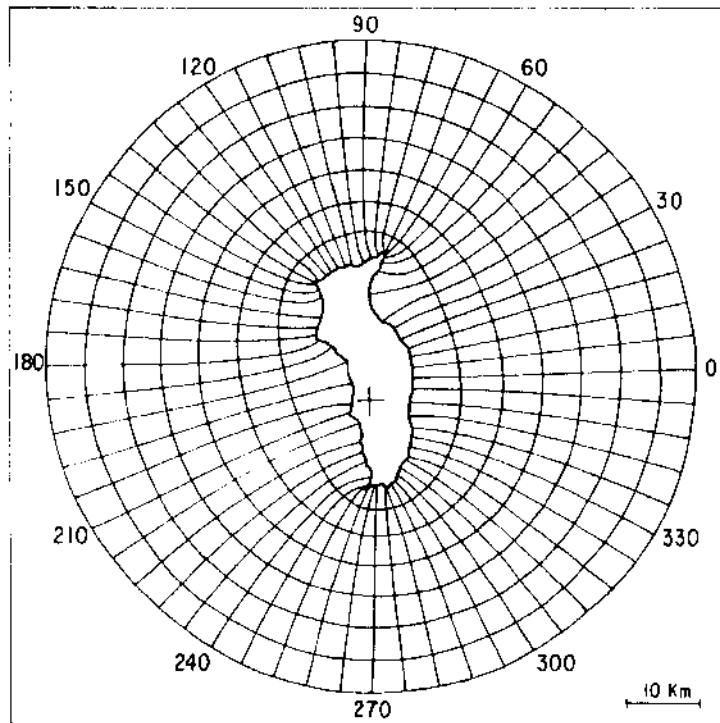


Figure 2. Abridged version of the coordinate grid used for the integration, after conformal mapping

APPLICATION AND RESULTS

Five remote source tsunami arrival cases are modeled. Four of them correspond to real past events with the highest wave heights recorded in the Baja California coastal region according to Sánchez and Ferreras (1992): 22 May 1960 from Chile, 28 March 1964 from Alaska, 16 May 1968 from Japan, and 29 November 1975 from Hawaii. The tsunami arriving from Hawaii was the only one recorded at Guadalupe Island, after the sea level gauge installation. The fifth case corresponds to a hypothetical arrival proceeding from Samoa. Location of the source, date if occurred, maximum wave height recorded somewhere in the coast of México, and azimuth of incidence in Guadalupe Island for this five cases are given in Table 1; directions of incidence are shown in Figure 1.

Table 1. Tsunami arrival cases modeled

Location	Tsunami Source		Date		Azimuth of Incidence	Maximum Wave Height
	Latitude	Longitude	(if occurred)		(°)	(m)
Chile	39.5° S	74.5° W	22 May	1960	300	2.5
Alaska	61.1° N	147.6° W	28 March	1964	114	2.4
Japan	41.5° N	142.7° E	16 May	1968	138	0.4
Hawaii	19.4° N	155.1° W	29 November	1975	189	0.5
Samoa	15.0° S	172.0° W	--	----	213	--

For each approach direction, tsunami wave arrivals of 10, 15, 20, 25, 30, 35, and 40 minute periods were simulated. Amplitudes relative to the incident wave train and phase lags referred to the far field wave timing at an azimuth 90° from the direction of the incident wave train, were obtained as results.

Relative amplitude distribution along contour azimuth positions for a 10 minute period tsunami arriving from Hawaii (Figure 3) shows:

- a) for the variable depth real bathymetry, an amplification maximum in the sharp SW corner where wave energy converges due to refraction; and
- b) for a constant depth flat bottom, a typical symmetric reflection-diffraction response curve with one main maximum in the wave incidence direction and a secondary one 180 antipodal to the first.

The smoothness of the constant depth response curve, typical of an analytic solution for a simple geometry contour, indicates that Guadalupe Island is in the lower limit of object sizes that may significantly interact through diffraction with tsunami waves of such a period.

Relative amplitude distributions for the other arrival cases are similar.

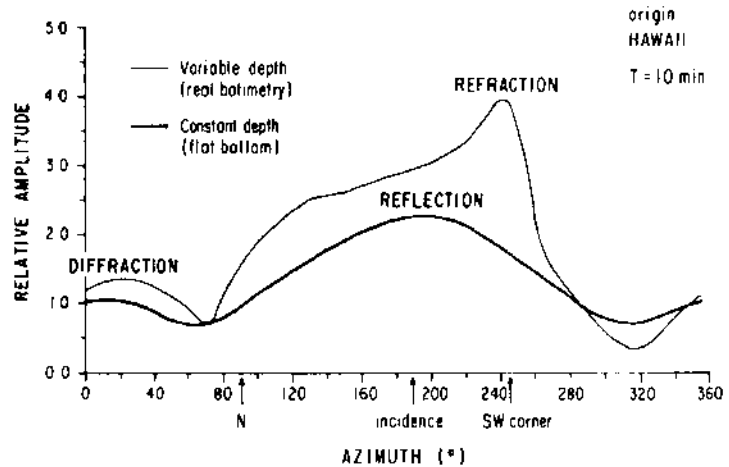


Figure 3. Relative amplitude distribution along contour azimuth positions for a 10 minute period tsunami arriving from Hawaii

Isolines of relative amplitude and phase in a period-azimuth space, for tsunamis arriving from Japan (Figure 4), but similar to the other cases modeled, show:

- a) an amplification maximum, due to reflection, for all periods at the azimuth of incidence;
- b) another amplification maximum at the sharp SW corner, where refraction is important, but only for less than 15 minute periods;
- c) amplification decrease with period increase for all contour azimuthal locations; becoming almost 1.0 or less for periods higher than 35 minutes.
- d) almost vertical phase isolines; an indication that this linear model is very little phase-dispersive: waves of different periods travel at about the same speed, without phase lags;
- e) near-zero phase at the sharp SW and NE corners for periods higher than 15 minutes;
- f) small azimuthal phase gradient in the incidence zone as a result of the wave front arrival almost parallel to the coastal contour; and
- g) an increase of the above zone width, until the gradient almost disappears (horizontal isolines), with decreasing periods. This indicates that the wave front aligns in a larger lateral extension to the coastal contour (simultaneous arrival at all points) as refraction becomes more important.

The response at the SW corner shows significant amplification for most of the periods considered (particularly the short ones) independently of the direction of incidence (Figure 5). This characteristic ensures enough sensitivity for tsunamis of the order

of centimeter open ocean waveheights to be detected and recorded by instruments in this site. This location is also reasonably protected from storm wave action and is easily accessible as to become a permanent sea level and wave reporting station.

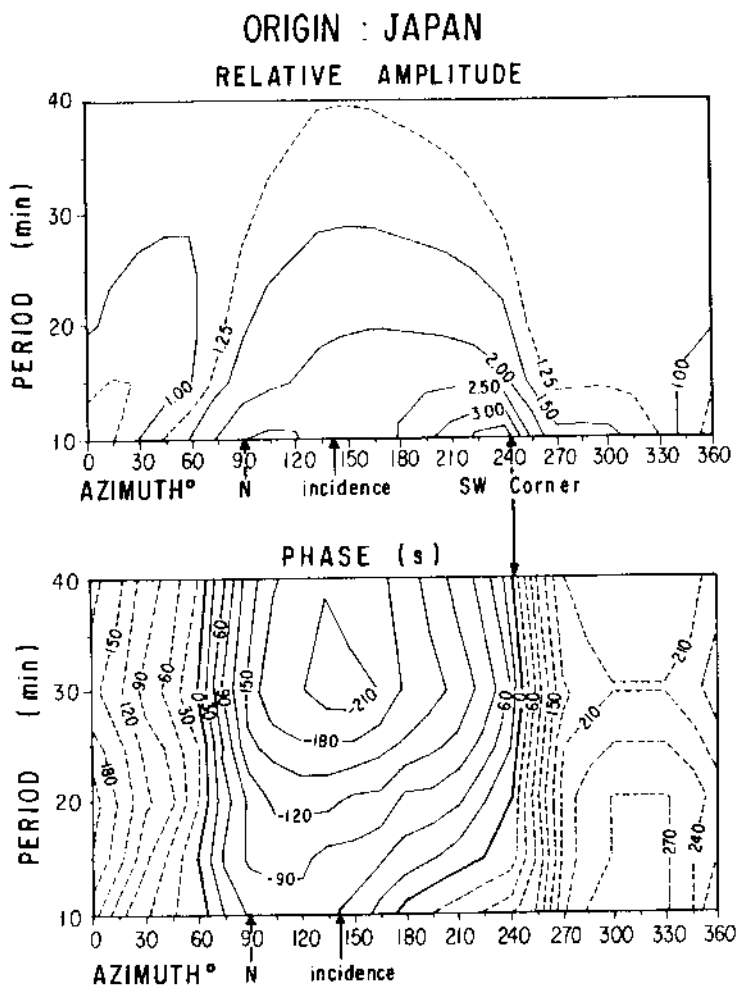


Figure 4. Amplitude and phase response along Guadalupe Island contour for tsunamis of several periods arriving from Japan (azimuth of incidence = 138°)

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The linear model gives a reasonable first approximation of the tsunami response at Guadalupe Island. The results may be used as an input for a near-shore propagation and inland run-up non-linear simulation.

The model needs to be tested with data from future tsunami arrivals.

Guadalupe Island size does not significantly affect the propagation of tsunami waves with periods greater than 35 minutes.

Maximum amplifications (400 %), due to refraction, occur for short periods (less than 10 minutes) near energy convergence zones.

Amplifications are smaller (less than 25%), and mainly due to diffraction and reflection, for periods larger than 30 minutes.

The SW corner is recommended as the permanent site for the sea level and wave reporting station of the tsunami warning systems because of its sensitivity to tsunami arrivals, its accessibility, and its reasonable storm wave protection. An alternate site could be the less accessible NE corner.

The tsunami response of those mainland communities to be protected with the alert information coming from Guadalupe Island, needs to be modeled.

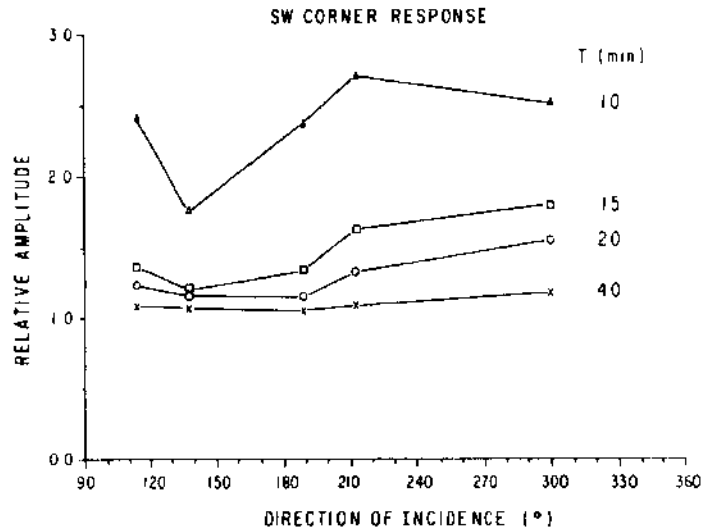


Figure 5. Amplitude response of Guadalupe Island SW corner for tsunami arrivals of several periods and directions of incidence

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