NUMERICAL MODELING OF GUADALUPE ISLAND RESPONSE TO TSUNAMI ARRIVALS

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ABSTRACT

Guadalupe Island, located off the coast of Baja California (Mexico), is considered as an eventual sea level reporting stations for a regional 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 neighboring mainland communities. The scattering of tsunami waves by the island is examined by solving the long wave equation through a time and space centered finite difference scheme. 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 happen with short tsunami periods and close to energy convergence zones, where refraction is important. For large tsunami periods, reflection and diffraction become the dominant processes. The location under consideration to install a wave reporting station has adequate amplification characteristics for a tsunami warning system.

Keywords: Baja California, tsunami scattering, warning system.

INTRODUCTION

Several remote source tsunamis have affected the coastal communities of the Baja California peninsula in northwest Mexico (Farreras and Sanchez 1991). Guadalupe Island, lying outside the continental shelf, 250 km off the coast of Baja California (Figure 1) is capable to become a sea level reporting stations for a regional as well as the international Pacific Tsunami Warning System. The installation of a sea level pressure gauge, in the same place as the one that operated in the past, is presently in process.

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

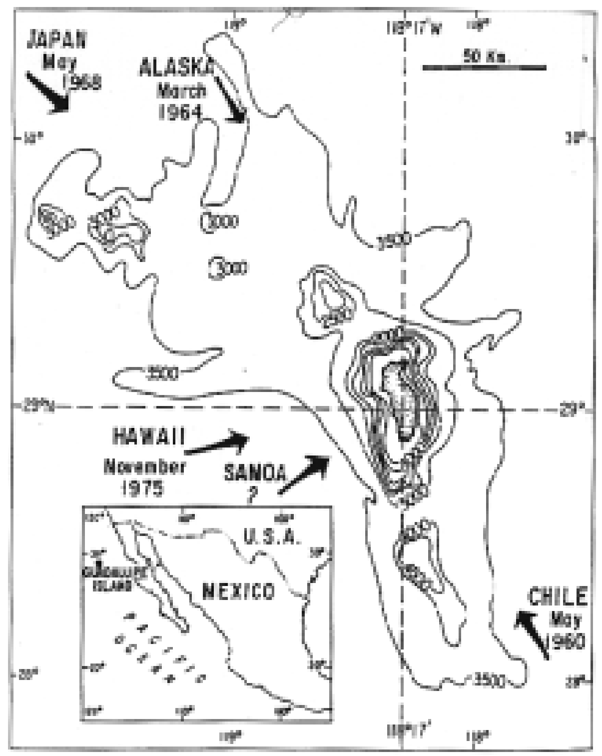

Figure 1. Guadalupe Island location, surrounding bathymetry, and approach direction of the five tsunami cases modeled in this study. Depths are in fathoms (one fathom = six feet).

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). At the arrival to an island, tsunami waves may split into two, with one wave propagating around each side of the island, and both meeting at the sheltered region with a subsequent amplification in amplitude and destructive flow. This was the case in the 1992 Babi Island tsunami, as confirmed by numerical modeling and laboratory experiments (Yeh et al. 1994). Linear wave theory application to tsunami wave interaction with a continental shelf, although arguable (Voit 1987), has been successfully applied to the modeling of tsunami-island interactions by Houston (1978) and Tsuji (1985).

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

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

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 $\frac{\partial\zeta}{\partial r}=0$ and the radiation to infinity condition for the waves scattered outward $\frac{\partial\zeta_s}{\partial t}+(gD)^{1/2}\frac{\partial\zeta_s}{\partial r}\rightarrow 0$, 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,ß) 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.

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

$$\frac{1}{gs^2}\frac{\partial^2\zeta}{\partial t^2}=\rho\frac{\partial}{\partial\rho}\left(\rho D\frac{\partial\zeta}{\partial\beta}\right)+\frac{\partial}{\partial\beta}\left(D\frac{\partial\zeta}{\partial\beta}\right) \qquad (2)$$

where s is a scale factor.

This equation is solved numerically for monochromatic plane incident waves, $\zeta_I = e^{i(\kappa r\cos\theta-\omega t)}$ where κ 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, to satisfy the stability criterian.

APPLICATION AND RESULTS

Five remote source tsunami arrival cases were modeled. Four of them correspond to real past events with the highest wave heights recorded in the Baja California coastal region according to Sanchez and Farreras (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, by the time the former sea level gauge station was in operation. The fifth case corresponds to a hypothetical arrival proceeding from Samoa. Directions of incidence for this five cases are shown in Figure 1.

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 2) shows:

a) for the variable depth real bathymetry, an amplification maximum in the sharp southwest 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.

Isolines of relative amplitude and phase in a period-azimuth space, for tsunamis arriving from Japan (Figure 3), 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 southwest 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 southwest and northeast corners for periods higher than 15 minutes;

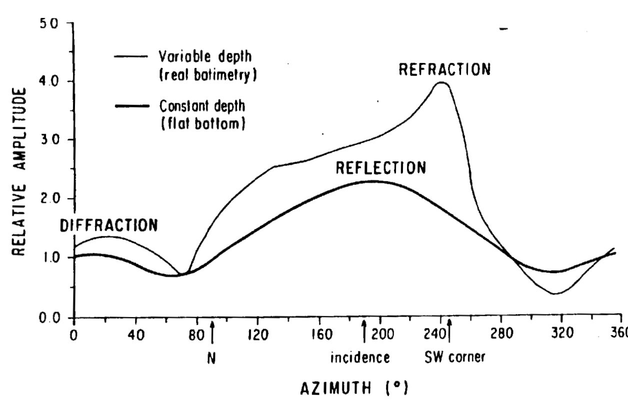

Figure 2. Relative amplitude distribution along contour azimuth positions for a ten minute period tsunami arriving from Hawaii.

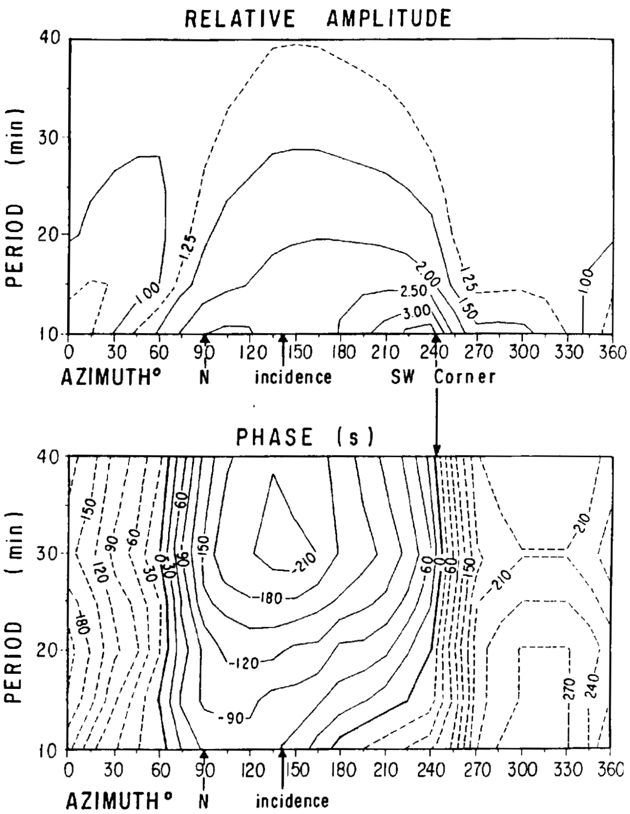

Figure 3. Amplitude and phase response along Guadalupe Island contour for tsunamis of several periods arriving from Japan (azimuth of incidence = 138°).

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 southwest corner shows significant amplification for most of the periods considered (particularly the short ones) independently of the direction of incidence (Figure 4). This characteristic ensures enough sensitivity for tsunamis of the order of centimeter open ocean wave heights 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.

CONCLUSIONS

The linear model gives a suitable approximation of the tsunami response at Guadalupe Island, that can be used later on as an initial condition for an inland run-up non-linear simulation.

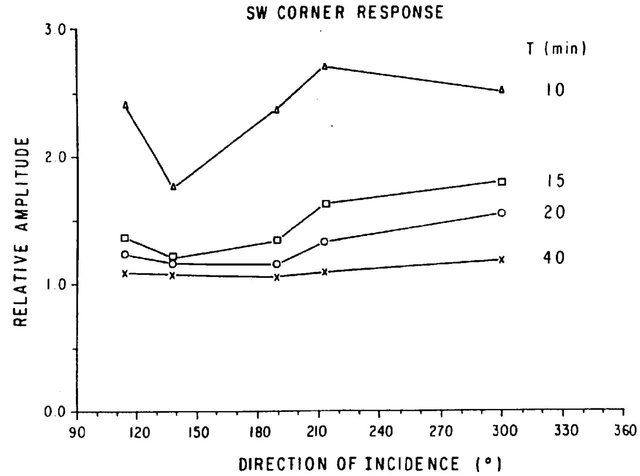

Figure 4. Amplitude response of Guadalupe Island Southwest corner for tsunami arrivals of several periods and directions of incidence.

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

Maximum amplifications, due to refraction, occur for short periods near energy convergence zones.

Amplifications are smaller, and mainly due to diffraction and reflection, for long periods.

The southwest corner can be recommended as a permanent site for a sea level reporting station of regional or international tsunami warning systems because of its sensitivity to tsunami arrivals, its accessibility, and its reasonable storm wave protection.

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