CHAPTER 192

Studies of Tsunami Hazard

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ABSTRACT: Tsunami hazard is investigated using the indirect approach with simple seismological and hydrodynamic models. It is assumed that earthquakes of random magnitude may originate anywhere with equal likelihood from a single straight fault and the site is located on the perpendicular plane bisecting the fault. The ground displacement is instantaneous and consists of a block uplift type of movement which may be circular or elongated in the plan view. The hydrodynamic model is based on linear long wave theory wherein the ocean is of constant depth and infinite in the horizontal extent, and the earth is flat. Tsunami hazard is computed for various values of the parameters and a sensitivity study is carried out to examine the effect of certain parameters on hazard.

INTRODUCTION

Tsunami hazard has been investigated using various approaches. Where historical information and measurements regarding tsunami innundation are available, a direct statistical analysis has been used (Houston et al. 1977, Loomis, 1976, Wiegel, 1970). Where such data are scarce, resort has been made to Bayesian estimation (Rascon, 1975) and the concept of indirect analysis (Garcia and Houston, 1975, Houston and Garcia, 1974). The indirect method follows closely the idea underlying seismic hazard analysis for facilities on land (Cornell, 1968, Der Kiureghian and Ang, 1975). The indirect approach, as carried out by Houston and Garcia (1974) and Garcia and Houston (1975), consists essentially of utilizing the information available regarding the magnitude, rate of occurrence and location of past tsunamigenic earthquakes in the region affecting the site, together with the knowledge of tsunami wave propagation based on hydrodynamic considerations to compute the hazard of tsunami at the site. Straightforward application of the indirect method of analysis, however, is time-consuming because of the large amount of numerical computation required to solve the hydrodynamic equations governing the propagation of tsunami waves from source to site. Since the frequency of occurrence, location, and magnitude of tsunamigenic earthquakes are random and there are uncertainties associated with some parameters and characteristics of ground motion, determination of the probability function of the wave elevation at the site due to tsunami by Monte Carlo simulation is difficult to achieve. It is therefore desirable that sensitivity studies be first performed to assess the importance of the various parameters on tsunami hazard. To conduct such an investigation,

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the models employed must be sufficiently simple so that the probability computation may be kept at a minimum. For this purpose, an earlier study by Lin and Tung (1982) was undertaken.

In Lin and Tung (1982), it is assumed that earthquakes may originate anywhere with equal likelihood from a well-defined simple straight fault and the site is located on the perpendicular plane bisecting the fault (see Fig. 1a). The ground displacement consists of a block uplift type of movement which takes place instantaneously and is circular in the plan view with a uniform offset (see Fig. 1b). The source area S is empirically determined from the seismic moment m_o (see Fig. 2 and Eq. (4)) characterized by the value of the parameter C_1 and the magnitude of offset $\bar{D}$ is related to the seismic moment m_o by way of definition (see Eq. (3)). The seismic moment in turn depends on the frequency of occurrence of tsunamigenic earthquakes in the region (see Fig. 3) defined by the parameter β from which the probability density function of seismic moment is obtained (see Eq. (12) and Lin and Tung, 1982). The hydrodynamic model is that of linear dispersive waves given by Kajiura (1963) wherein the ocean is infinite in the horizontal extent, sphericity of the earth is ignored and water is of constant depth. The maximum wave elevation at the site due to earthquake of seismic moment m_o is shown by Lin and Tung (1982) to be given by

$$Z = CW\left(\frac{m_o}{r}\right) \tag{1}$$

where C is a constant, $W(\cdot)$ is a nonlinear function and

$$r = (D^2 + r_o^2)^{1/2} \tag{2}$$

is the distance from the source to the site (see Fig. 1) the probability density function of which may be obtained from that of the uniformly distributed random variable D. The tsunami hazard is shown to be simply dependent on $U(z) = P(Z > z) = 1 - F_Z(z)$ where $P(\cdot)$ denotes the probability of the event enclosed in the parentheses and $F_Z(z) = P(Z < z)$ is the probability distribution function of Z which is determined from the probability density functions of the statistically independent random variables m_o and r according to Eq. (1). A sensitivity study is performed to determine the influence of the various parameters on the hazard. The parameters considered are β (see Fig. 3), fault length L (see Fig. 1), C_1 (see Fig. 2) and the upper-bound seismic moment m_{ou}. It is found that values of β and L have little effect on the hazard but the hazard is sensitive to the values of C_1 and m_{ou} if one is interested in large values of tsunami wave elevation at the site. The obvious implication of this finding is that the values of C_1 and m_{ou} must be selected with care when important facilities are designed against extreme conditions.

In the above study, an important feature of the tsunamigenic earthquake that is left out of consideration is the shape of ground displacement. It is known that the ground displacements associated with tsunamigenic earthquakes are generally elongated in the plan view (see Figs. 4 and 5) and their orientation has significant effect on tsunami wave height at the site (Kajiura, 1970).

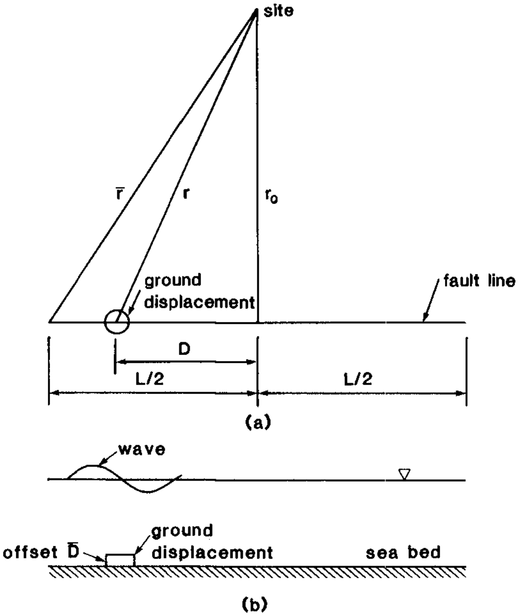

Figure 1. Seismic Model Used in Lin and Tung (1982)

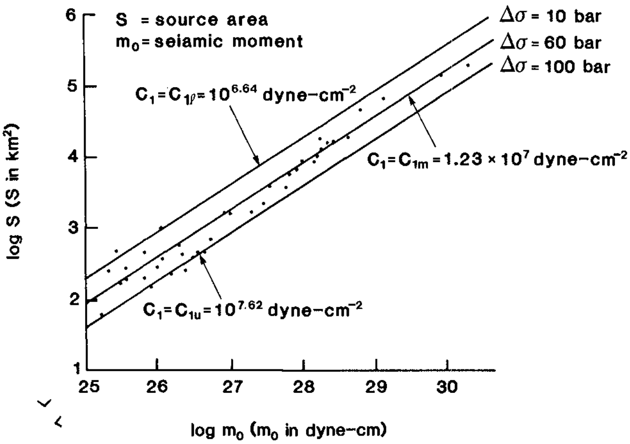

Figure 2. S - m_o Relation

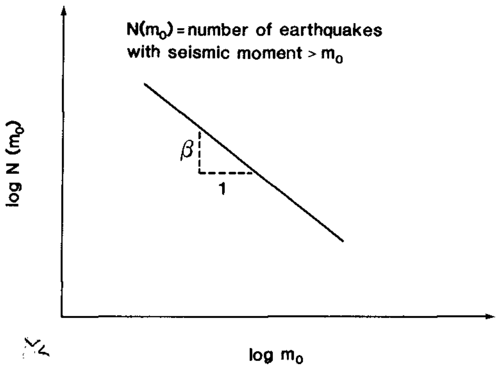

Figure 3. $N(m_o)$ - m_o Relation

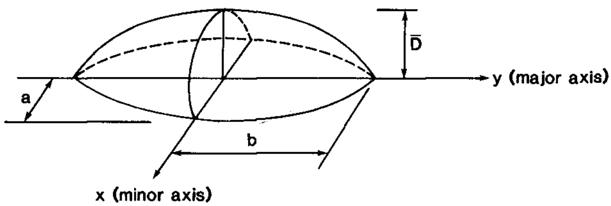

Figure 4. Ground Displacement

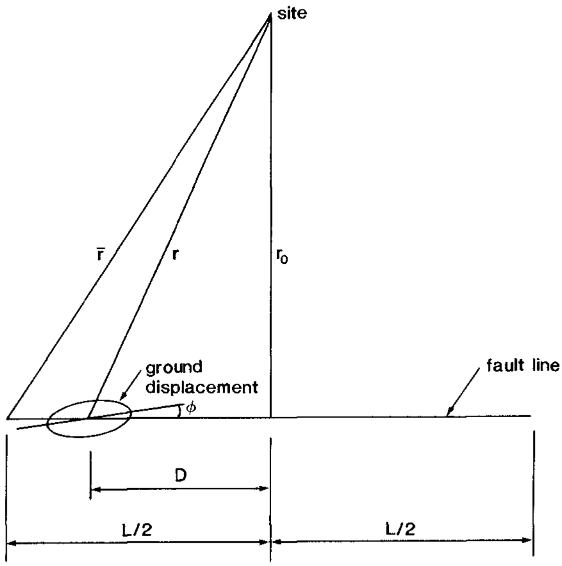

Figure 5. Source - Site Relation

The objective of this study is to consider elongated ground displacement. Specifically, the ground displacement is elliptical in the plan view with an elliptical crest (see Fig. 4). The remaining part of the seismological model is the same as that used in the earlier study (Lin and Tung, 1982) (see Fig. 1). That is, earthquakes may occur anywhere along a straight fault with equal likelihood and the site is situated on the perpendicular bisector of the fault. These assumptions may be removed without causing undue difficulty as pointed out by Der Kiureghian and Ang (1975). In fact, a finite number of fault lines with arbitrary orientation and location with respect to the site may be included. The major axis of the elliptical ground displacement may be inclined making an angle ϕ with the fault (see Fig. 5) and ϕ is taken as a random variable uniformly distributed in the arbitrarily chosen range $(-\pi/12, \pi/12)$. The hydrodynamic model in this study is different from the linear dispersive wave model used in Lin and Tung (1982) and is based on the linear non-dispersive long wave theory given by Kajiura (1970) wherein the ocean floor is also considered flat, the water is of constant depth and infinite in the horizontal extent. The reasons for selecting this particular model are (a) the resulting expression of wave elevation due to tsunami waves at the site is convenient to use and (b) when the elliptical ground displacement (see Fig. 4) is specialized to circular shape, the results may be checked against those obtained in the earlier study (Lin and Tung, 1982) to examine the sensitivity of the hazard to the two different hydrodynamic models used.

Numerical results of tsunami hazard are obtained for various value of the parameters. Since it is found in Lin and Tung (1982) that the values of β (Fig. 3) and fault length L (Fig. 1 or 5) have little effect on the hazard, these quantities are given fixed values. The remaining parameters, the site-fault distance r_o (see Fig. 5) and the shape factor $B = b/a$ (see Fig. 4) are assigned various values in this study. A sensitivity study is performed to evaluate the effect of the upper bound seismic moment m_{ou} and the value of C_1 (see Fig. 2) on the hazard.

In the following, for easy reference, relevant details of the seismological and hydrodynamic models used in this study, shown in more detail in Lin (1985), are given.

SEISMOLOGICAL MODEL

The seismic moment denoted m_o is defined as (Kanamori and Anderson, 1975, Kanamori, 1977)

$$m_o = \mu S \bar{D} \tag{3}$$

where μ is the rigidity of the medium, S is the plane area of ground displacement and $\bar{D}$ is the average offset (see Fig. 4). Based on earthquake data, Kanormi and Anderson (1975) obtained the empirical relation between the seismic moment m_o and the source area S given by

$$m_o = C_1 S^{3/2} \tag{4}$$

as shown in Fig. 2 where the average value of C_1 is $C_{1m} = 1.23 \times 10^7$ dyne-cm^{-2} with S measured in square centimeters. From Eqns. (3) and (4), the average offset $\bar{D}$ is

$$\bar{D} = \frac{(m_o C_1^2)^{1/3}}{\mu} \tag{5}$$

For elliptical ground displacement

$$S = \pi ab = \pi a^2 B \tag{6}$$

where $B = b/a$ is the shape factor so that

$$a = \frac{(m_o/C_1)^{1/3}}{(\pi B)^{1/2}} \tag{7}$$

It is seen that the source area S (hence a and b) and the offset $\bar{D}$ of the ground displacement are all simply related to the seismic moment m_o.

HYDRODYNAMIC MODEL

The hydrodynamic model is that of linear non-dispersive long waves due to Kajiura (1970) in which the earth's sphericity is ignored and the ocean is assumed to be of infinite horizontal extent and constant depth. The maximum wave elevation at the site due to an instantaneous elliptical ground displacement shown in Figs. 4 and 5 is given by

$$Z = A_1 \frac{\sqrt{m_o}}{q} \tag{8}$$

Details of the derivation of Eq. (8) are given in Lin (1985) and are not shown here. In Eq. (8),

$$A_1 = \frac{0.495}{\mu} \left(\frac{C_1^2 B^3}{\pi}\right)^{1/4} \tag{9}$$

is a constant and

$$q = \frac{(A_2 D^2 + A_3 D - A_4 + A_2 r_o^2)^{3/4}}{(D^2 + r_o^2)^{1/2}} \tag{10}$$

where

$$A_2 = 1 + (B^2 - 1)\cos^2\phi$$

$$A_3 = r_o(B^2 - 1)\sin 2\phi \tag{11}$$

and

$$A_4 = r_o^2(B^2 - 1)\cos 2\phi$$

The quantities D, r_o and ϕ are all defined in Fig. 5.

Hazard Analysis

In Eq. (8), the maximum wave elevation Z at the site is a function of the random seismic moment m_o, the uniformly distributed random variable D specifying the location of the source, and the uniformly distributed random variable ϕ, representing the angle between the major axis of the ellipse and the fault line. The three random variables are assumed to be statistically independent and the probability density function of m_o was determined in Lin and Tung (1982) to be

$$f_{m_o}(m_o) = \nu\beta m_{o\ell}^{\beta} \frac{1}{(m_o)^{1+\beta}} \qquad m_{o\ell} \leq m_o < m_{ou} \tag{12}$$

where

$$\nu = \frac{1}{1 - (\frac{m_{o\ell}}{m_{ou}})^{\beta}} \tag{13}$$

is a normalizing constant. Since earthquakes with seismic moments smaller than a certain lower limit have no engineering significance and the energy released by an earthquake is also limited, the lower and upper bound magnitudes, denoted $m_{o\ell}$ and m_{ou}, are specified.

The tsunami hazard is defined as the probability that for a given length of time, the water level Z at the site exceeds a certain specified value z. It is shown in Lin and Tung (1982) that the hazard depends on the knowledge of U(z), the probability that $Z > z$, given that an earthquake has occurred, which may be determined by the standard technique of transformation of random variables from Eqns. (8), (10), (11) and (12). Details of the manner in which U(z) is obtained is given in Lin (1985).

RESULTS

To compute U(z), the values of the parameters must be specified. It is assumed that the rigidity of the medium is $\mu = 3 \times 10^7$ dyne-cm^2, and the lower and upper-bound seismic moments are $m_{o\ell} = 10^{22.05}$ and $m_{ou} = 10^{29.55}$ dyne-cm which correspond to earthquake magnitudes $m_\ell = 4$ amd $m_u = 9$, respectively. In Lin and Tung (1980), it is found that the hazard is not sensitive to the values of β and fault length L. Thus, $\beta = 0.8$ and L = 6000 km are used here. In selecting the value of r_o, it is noted that the hydrodynamic model (Kajiura, 1970) used in this study requires that the site be at least moderately far away from the source; therefore values of r_o = 2000, 6000, and 10000 km are selected. To examine the effect of shape factor B = b/a on hazard, values of B = 1 and 5 are assigned, where B = 5 is the case as shown in Fig. 5 and B = 1 represents the case of circular ground displacement.

In Figs. 6 and 7, U(z) are plotted for B = 5 and 1 respectively and for r_o = 2000, 6000 and 10,000 km. The abscissa z is the wave elevation at the site in centimeters. Enlarged insets are inserted. Comparison

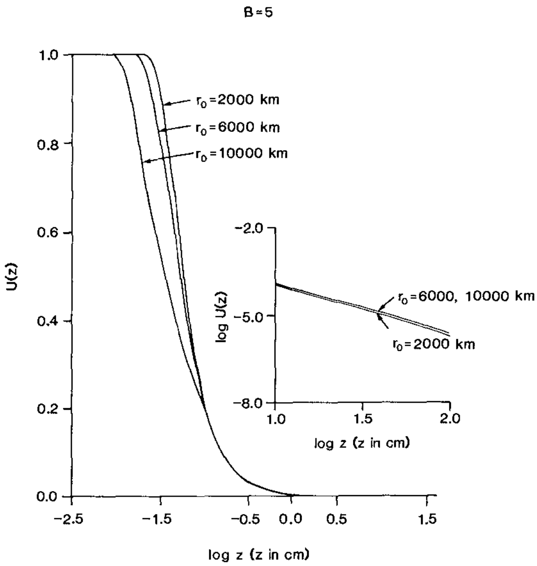

Figure 6. U(z) for B = 5

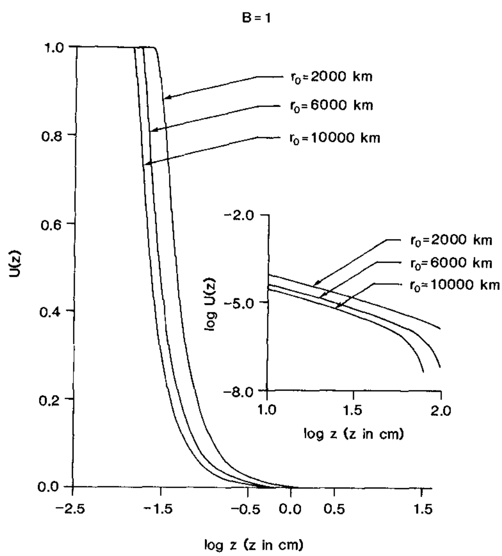

Figure 7. U(z) for B = 1

of Figs. 6 and 7 shows that the elongated ground displacement (B = 5) gives rise to larger values of the hazard.

It is of some interest to compare the results of the case B = 1 with those obtained in Lin and Tung (1982) in which the ground displacement is circular in its plan view. The hazard computed in the present case is much larger than in Lin and Tung (1982). This difference is due primarily to the two different hydrodynamic models used.

In obtaining the results shown in Figs. 6 and 7 we also considered the simplified case in which the angle ϕ between the major axis of the elliptical ground displacement (see Fig. 5) and the fault line is set identically equal to zero in which case the quantity q in Eq. (8) is simply related to the single random variable D as

$$q = \frac{(B^2D^2 + r_o^2)^{3/4}}{(D^2 + r_o^2)^{1/2}} \tag{14}$$

Our results show that the error incurred in U(z) is insignificantly small.

SENSITIVITY STUDIES

Many of the parameters in the models contain uncertainties. It is shown in Lin and Tung (1982) that uncertainties in the values of β and L do not affect the hazard to any significant extent. In this study, only the sensitivity of the hazard to the values of m_{ou} and C_1 are examined for different values of r_o and B.

Sensitivity of Hazard to Upper-bound Seismic Moment

To examine the sensitivity of the hazard to upper-bound seismic moment m_{ou}, U(z) is computed using different values of m_{ou} in much the same way as is done in Der Kiureghian and Ang (1975) and Lin and Tung (1982). For specified water level z, let $U_1(m_{ou})$ be the value of U(z) for the arbitrary value of m_{ou}, and U_2, the value of U(z) for m_{ou} = 32 dyne-cm. The ratio $\bar{R} = U_1(m_{ou})/U_2$, termed the hazard ratio, is plotted as a function of m_{ou} in Figs. 8 and 9 for B = 5 and B = 1 respectively for r_o = 2000 km and r_o = 10000 km. Fig. 8a (B = 5, r_o = 2000 km) shows that, for z = 50 cm, for example, if $m_{ou} = 10^{29}$ dyne-cm, the computed hazard is about 75% of that using $m_{ou} = 10^{32}$ dyne-cm. For $m_{ou} = 10^{31}$ dyne-cm, the ratio is close to unity. However, for z = 10 cm, a change of m_{ou} from 10^{32} to 10^{29} dyne-cm would result in a decrease of the hazard of only 3% (versus 25% for z = 50cm). That is, the influence of m_{ou} on the hazard is important when one is interested in large values of the maximum wave elevation at the site. Comparing Fig. 8a with Fig. 8b (r_o = 10000 km), it is seen that as r_o increases the curves become steeper indicating that the hazard is more sensitive to changes in m_{ou} if r_o is larger.

Figs. 9a and 9b are drawn for r_o = 2000 and 10000 km using B = 1 (circular ground displacement). The observations made above for the case B = 5 remain valid. Comparison of Figs. 8 and 9 shows that for the

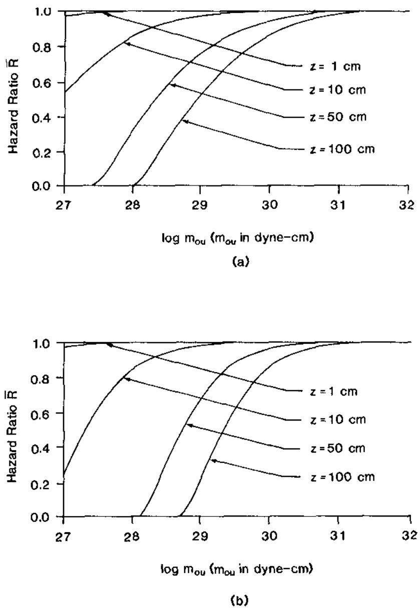

Figure 8. Hazard Ratio $\bar{R}$ for B = 5, r_o = 2000, 10000 km

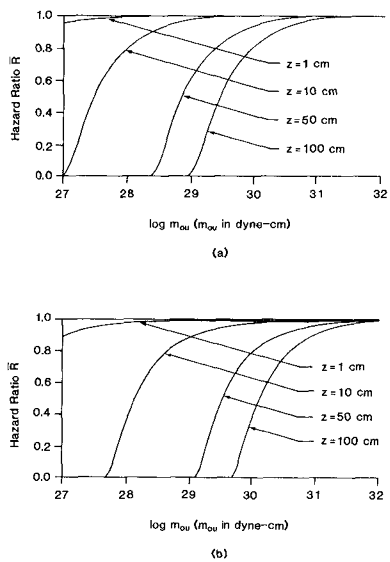

Figure 9. Hazard Ratio $\bar{R}$ for B = 1, r_o = 2000, 10000 km

Lin and Tung

same values of z and r_o, the curves in Fig. 9 are steeper. That is, the influence of m_{ou} on the hazard is more important when the ground displacement is considered to be circular in the plan view.

Sensitivity of Hazard to Value of C_1

Kanamori and Anderson (1975) used data of 41 earthquakes to construct Fig. 2 relating seismic moment and source area. The data points in the figure are scattered between stress drop values of $\Delta\sigma$ = 10 bars and $\Delta\sigma$ = 100 bars. The value of C_1 in Eq. (9) used in computing U(z) is $C_1 = C_{1m} = 1.23 \times 10^7$ dyne-cm^{-2} and is based on $\Delta\sigma$ = 60 bars. Corresponding to $\Delta\sigma$ = 10 and 100 bars, the values of C_1 are $C_{1\ell} = 10^{6.64}$ and $C_{1u} = 10^{7.62}$ dyne-cm^{-2} respectively. The subscripts ℓ, u and m are introduced to refer to lower and upper limits and mean value of C_1.

To examine the extent the value of C_1 affects the hazard, let $U_\ell(z)$, $U_m(z)$ and $U_u(z)$ be the hazard values corresponding to $C_1 = C_{1\ell}$, C_{1m} and C_{1u} respectively for arbitrary but specified values of z. The ratios $R_1 = U_\ell(z)/U_m(z)$ and $R_2 = U_u(z)/U_m(z)$ may be plotted as functions of z for various values of r_o and B. Fig. 10 gives R_1 and R_2 for r_o = 6000 km and B = 5. From the figure, it is seen that when z < 0.05 cm the ratios are near unity; for a wide range of z, from 0.05 cm to 50 cm, the ratios R_1 = 2.7 and R_2 = 0.4 remain practically constant and when z reaches 50 cm the ratios undergo a rather drastic change.

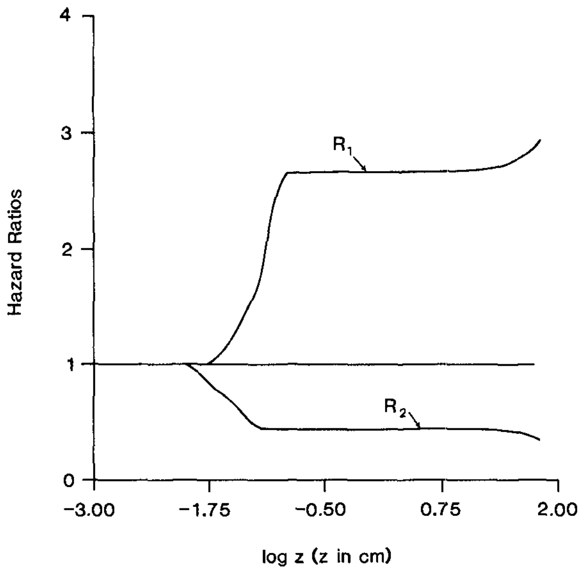

Figure 10. Hazard Ratios R_1 and R_2 for B = 5, r_o = 6000 km

Results were also obtained for B = 5 and r_o = 2000 and 10000 km, and for B = 1, r_o = 20000, 6000 and 10000 km. The ratios are almost identical to those shown in Fig. 10 and are therefore not given. Finally, comparison of these ratios with those of Lin and Tung (1982) shows that influence of C_1 on hazard is much more significant in the present case than in Lin and Tung (1982).

CONCLUSIONS

Based on the results of this study and those of Lin and Tung (1982), the following conclusions may be drawn:

(1) Shape of ground displacement (in plan view) has important effect on hazard; elongated ground displacement gives rise to larger values of hazard than circular ground displacement.

(2) The angle between the major axis of the elliptical ground displacement and the fault line need not be treated as random and may be set equal to zero without affecting hazard to any appreciable degree unless the geological condition indicates that the angle should assume a specific value.

(3) The hazard is critically dependent on water wave theory used.

(4) The value of upper-bound seismic moment has an important effect on the hazard if the maximum wave elevation of interest is large; more so if the site is further removed from the fault line and if ground displacement is circular in plan view.

(5) The hazard is appreciably affected by the value of C_1 for $z > 0.05$ cm.

(6) In future studies, elongated ground displacement should be used unless geological condition indicates otherwise.

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REFERENCES

Cornell, C. A., "Engineering Seismic Risk Analysis," Bulletin of the Seismological Society of America, Vol. 58, No. 5, 1968, pp. 1583-1606.

Der Kiureghian, A., and Ang, A. H-S., "A Line Source Model for Seismic Risk Analysis," Structural Research Series No. 419, UILU-ENG-75-2023, University of Illinois at Urbana-Champaign, Urbana, Illinois, 1975.

Garcia, A. W. and Houston, J. R., "Type 16 Flood Insurance Study: Tsunami Predictions for Monterey and San Francisco Bays and Puget Sound," Technical Report H-75-17, Hydraulic Laboratory, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, 1975.

Houston, J. R., Carver, R. D., and Marckle, D. G., "Tsunami-Wave Elevation Frequency of Occurrence for the Hawaii Islands," Technical Report H-77-16. Hydraulics Laboratory, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, 1977.
Hou
Houston, J. R., and Garcia, A. W., "Type 16 Flood Insurance Study: Tsunami Predictions for Pacific Coastal Communities," Technical Report H-74-3, Hydraulics Laboratory, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, 1974.

Kajiura, K., "The Leading Wave of a Tsunami," Bulletin of the Earthquake Research Institute, University of Tokyo, Tokyo, Japan, Vol. 41, 1963, pp. 535-571.

Kajiura, K., "Tsunami Source, Energy and the Directivity of Wave Radiation," Bulletin of the Earthquake Research Institute, University of Tokyo, Tokyo, Japan, Vol. 48, 1970, pp. 835-869.

Kanamori, H., "The Energy Release in Great Earthquakes," Journal of Geophysical Research, Vol. 85, No. 20, 1977, pp. 2981-2987.

Kanamori, H., and Anderson, D. L., "Theoretical Basis of Some Empirical Relations in Seismology," Bulletin of the Seismological Society of America, Vol. 65, No. 5, 1975, pp. 1073-1095.

Lin, I-Chen, "An Investigation of Tsunami Hazard," doctoral dissertation, North Carolina State University, Raleigh, North Carolina, 1985.

Lin, I-Chen, and Tung, C. C., "A Preliminary Investigation of Tsunami Hazard," Bulletin of the Seismological Society of America, Vol. 72, No. 6, 1982, pp. 2323-2337.

Loomis, H. C., "Tsunami Wave Run-up Heights in Hawaii," Report No. HIC-76-5, Hawaii Institute of Ceophysical Research, University of Hawaii, Honolulu, Hawaii, 1976.

Rascon, O. A., and Villarreal, A. G., "On a Stochastic Model to Estimate Tsunami Risk," Journal of Hydraulic Research, Vol. 13, No. 4, 1975, pp. 383-403.

Wiegel, R. L. (ed.), Earthquake Engineering, Chapter 11, Prentice-Hall, Englewood Cliffs, New Jersey, 1970, pp. 253-306.