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UNIVERSITY OF CALIFORNIA, SAN DIEGO
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ADVANCED OCEAN ENGINEERING LABORATORY

FINAL TECHNICAL REPORT ✓

OVERPRESSURES DUE TO EARTHQUAKES PROJECT

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This Final Summary Report reflects the technical status of a project conducted within the Advanced Ocean Engineering Laboratory at the Scripps Institution of Oceanography. The project is: Overpressures Due to Earthquakes -- a study of earthquakes and resultant overpressures as they effect ocean-going vehicles and sub-surface structures.

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FINAL TECHNICAL REPORT

OVERPRESSURES DUE TO EARTHQUAKES PROJECT

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FINAL TECHNICAL REPORT

During the course of subject contract we have reported on (1) design and construction of pressure measuring instruments and auxiliary equipment for studying earthquake aftershocks. Instruments were made for deployment by aircraft and by surface craft. (2) Design and construction of a vibrating string accelerometer instrument which AEC contractors installed on a shore cable near Amchitka to monitor earthquakes, (The shore-cable has subsequently failed). (3) The physical processes whereby earthquakes might damage submarines. We made preliminary estimates of the size of the effect; we surveyed the applicable literature, and initiated an important theoretical study of seaquake pressures by Dr. Paul Richards.

The present report completes work on subject contract with presentation of a Submarine Hazards Chart. Although a hazard calculation made without experimental data on seaquakes may turn out to be wrong, it does seem important to produce a tentative hazard chart based on earthquake statistics plus the meager strong motion data from continental earthquakes, and current models of earthquake source mechanisms. The chart gives statistical estimates of the likelihood that a submarine will experience a 20% change in apparent depth during a year of submerged operation. Conversion factors for other pressure changes are also given.

A ROUGH HAZARD CHART FOR SUBMARINES IN EARTHQUAKE ZONES

Abstract

A tentative earthquake hazards chart for submarines is developed. It gives a rough statistical estimate of the likelihood that a submarine will experience significant increase in apparent depth because of a nearby earthquake. The chart has been calculated for 20% pressure increase, lasting for about 1 sec. Factors are presented for converting to other pressures.

Introduction

Although an extensive literature exists regarding observed effects of earthquakes on surface ships (Richter, 1958), (Rossi, 1969), there is little if any published information on what happens to a submerged submarine near an earthquake. In an unpublished letter, Carter (1970) indicates that the depth gauge suddenly showed a depth increase of approximately 15%, then a reduced depth, and finally settled back to normal within a total time of less than four seconds. The response characteristics of the depth gauge were not described, but the actual pressure excursion was probably larger than the gauge indicated since the gauge was probably overdamped.

The reason for the pressure pulse can be described qualitatively in simple terms; but an accurate quantitative statement cannot be given, even in statistical terms, because few accelerograms showing motion near to earthquakes are available. Estimates of earthquake characteristics made earlier in the contract were based on discussions with Dr. James Brune, and on a number of theoretical and empirical relations for seismic motions (Aki 1967, 1968), (Bradner 1962, 1963), (Brune 1968, 1970), (Bath and Duda 1964), (Fedosenko and Cherkesov 1968), (Haskell 1969), (Kanai 1961), (King and Knopoff 1968), (Newlands 1952), (Press 1965), (Richards 1971).

The present estimates are based on engineering tables of expected accelerations, areas affected, and other earthquake characteristics in a recently published book, Earthquake Engineering (Wiegel, 1970). Though this book provides the primary data for the present hazard calculation, other literature will also be cited where it may have importance in more refined future calculations of hazard. The engineering data show a rapid fall-off of acceleration with distance, and hence imply that the hazard to submarines may be smaller than estimated early in the contract.

The reader is referred to chapters 1 and 4 of Wiegel for background information on earthquake waves in the vicinity of the earthquake source, and the character of strong ground motion.

Strong motion earthquake information is being extended rapidly (largely by work out of California Institute of Technology by Housner, Hudson, Trifunac and others). Present results indicate that accelerations may frequently be greater than the predictions of Wiegel (1970). The hazard to submarines should be reappraised in one or two years when a large number of strong motion records will have been analyzed.

Calculation of Hazards Chart

The calculation involves four main parts, (1) The ground acceleration spectrum vs. distance and earthquake magnitude, (2) the water pressure vs. depth, acceleration, and oscillation frequency, (3) the statistics of earthquake occurrence, (4) the combination of the first three parts to produce the hazards estimates. The steps will be discussed in this order.

The reader is cautioned that the calculations are very rough. We feel that the resultant Tentative Hazard Estimates may be accurate to a factor of two or three. They are probably not wrong by a factor of five.

1. Ground Acceleration:

Qualitative Argument - Acceleration vs. Pressure

When a vertical compressional wave passes through water, each element of fluid effectively increases or decreases in weight in proportion to its vertical acceleration. An element accelerated upward 8 ft. sec^{-2}, or 1/4 g, would appear 25% heavier than its static weight. If the wavelength of the compressional wave is greater than the depth of the submarine (a common situation in a seismic wave) then the whole column of water above the submarine is accelerated upward at the same time, and the submarine can be subjected to a large increase in compressional force. In the numerical example given above, the 1/4 g vertical acceleration would increase the pressure on the submarine by 25%.

Quantitative Argument - Acceleration

The increase of pressure on a submarine at any depth could be calculated if the earthquake acceleration spectrum at that depth were known. Housner (in Wiegel, chap. 4) discusses existing measurements of strong motion ground acceleration and describes the accelerations qualitatively in terms of the earthquake magnitude, fault slip dimensions, and distance.

In Table 4.3 of Wiegel, Housner tabulates idealized maximum ground accelerations and durations of strong phase of shaking. This table is reproduced as Table I of the present paper. Housner states, "Although the maximum ground accelerations decrease with distance from the causative fault, the rate of decrease is relatively small over a distance comparable to the vertical dimension of the slipped fault. Table 4.3 lists idealized maximum ground accelerations in the vicinity of causative faults for earthquakes of various magnitudes". Housner indicates that his values are, in general, on the high side; but subsequent data from the 1971 San Fernando Earthquake indicate that Housner's data are on the low side. More data are clearly needed. We used Wiegel (1970) chart in preparing the hazards, since that was the most complete engineering appraisal of strong motion earthquakes available at the time.

Table 4.4 of Wiegel, Housner shows the area in thousands of square miles that would experience a given percent of g acceleration, for various magnitudes of earthquake. This table is reproduced as Table II of the present paper. The magnitude entries are interpreted according to our Note 1 on Table II.

Housner also displays some observed earthquake spectra in Chapter 4, and discusses qualitatively the shape of the spectrum for various sizes of earthquake. In section 4.6, Housner states, "Although there is not a rich supply of recorded ground accelerations of destructive earthquakes, there are enough recordings to indicate general trends related to magnitude, distance from fault, etc. Idealized earthquake ground motions can then be described that will portray the general characteristics of the earthquake problem, in a probability sense. The recorded ground accelerations have been obtained mostly on relatively firm deep alluvium, so that the idealized earthquakes described in the following paragraphs are representative of ground motions on such ground. Actual ground motions, of course, may deviate from the idealized motions."

Bolt (in Wiegel, Sect. 1.3) shows that a low-rigidity surface layer can increase the amplitude of ground motion by a large factor. He calculates as an example that a 100 meter thick layer of alluvium over-lying shale bedrock will increase the amplitude of a 3Hz compressional wave by a factor of about five. Brune (personal communication) notes that the situation is complicated further by the question of whether the ocean bottom in a particular earthquake is immediately against the faulting rock or is separated from it.

Although Housner states that the largest acceleration recorded in the United States during an earthquake of large magnitude was 0.33 g, accelerations in the order of 1 g have been observed in other earthquakes; and, in fact, an acceleration of 1.25 g was measured during the 1971 San Fernando earthquake (Jennings, 1970) after Housner's chapter was published. Comparative data on several large earthquake accelerations are presented in Table III (Data abstracted from Table 4, p. 135, of Jennings).

A number of attempts have been made to develop empirical or theoretical descriptions of earthquake motion. Kanai (1961) presented an empirical formula for the spectrum of strong earthquake motions, taking into account a surface layer over a semi-infinite medium. He assumed that the spectrum of ground velocity without the surface layer is constant between about 10Hz and a lower limit that depends on the earthquake magnitude. Aki (1967) assumed a flat spectrum of ground acceleration, in developing a scaling law of seismic spectrum for distant earthquakes. Brune (1970) describes near and far field displacement-time functions and spectra by considering a simple dislocation model of earthquakes. The theory implies a flat acceleration spectrum for periods shorter than a characteristic time τ which is the order of the dimension of the fault break divided by the shear wave velocity. Brune (private communication) indicates that the spectrum can be taken as having an upper limit cut-off about 10Hz. Brune's theory seems to be generally accepted as giving an adequate description of earthquake motion, when attenuation due to spreading and dissipation is taken into account. The dissipation (Q approx. 200) causes actual earthquake acceleration spectra to be peaked, except at locations very close to the source. This point will be discussed later, in considering the effect of acceleration spectrum on the change of pressure vs. depth.

In a remarkable paper, Richards (1971) has developed a theoretical expression for the pressure that will be produced by a large class of earthquake fault ruptures under the ocean. His treatment is exact for a solid boundary under a fluid half space. He has calculated that the maximum pressure pulse on a deep submarine, from a rupture according to Brune's model, will be equivalent to a depth increase of 650 ft. This maximum pressure can be produced by moderate-sized earthquakes, since according to Brune's model, the energy release per unit area of fault rupture is nearly constant. Large earthquakes imply the rupture of large fault areas, and, therefore, will produce the pressure over large regions of the ocean. Richards' theory can be extended to include the case of a submarine near the water surface.

2. Water Pressure Due to a Seismic Wave

Consider a vertical plane wave traveling through the water and reflecting from a smooth air-water interface. In steady state, the acceleration at any point in the water can be written as the sum of the upward and downward waves,

$$a = \omega^2 A \cos(\omega t - kh) + \omega^2 A \cos(\omega t + kh)$$

$$= 2\omega^2 A \cos(\omega t) \cos(kh)$$

This can be rewritten in terms of the surface acceleration a_0

$$a = a_0 \cos(kh)$$

The pressure at any depth, h, can be viewed as the weight of the column of fluid above h. Upward acceleration of an element of volume dv and density ρ is exactly equivalent to an increase $a\rho dv$ of its weight. Hence the plane wave will produce a pressure Δp at a depth h,

$$\Delta p = \int_{h=0}^{h} \rho a \, dh$$

$$= \rho a_0 \sin(kh)/k$$

The hydrostatic pressure at h is ρgh, so

$$\Delta p/p = a_g \sin(kh)/gkh$$

Thus near the surface, the fractional increase in pressure is equal to the fractional g acceleration. At greater depths the effect is reduced by the factor $\sin(kh)/kh$.

Seismic waves will travel nearly vertically in the ocean because of the refraction produced by the large difference in sound velocity in water vs. ocean bottom rocks. The effect of this nonvertical component, and the effect of sea surface roughness can both be shown to be small. Focusing effects of individual earthquakes by ocean-bottom inhomogeneities may be large, but are not thought to change the statistical conclusions of this study very much.

The shape of the seismic spectrum will affect the depth at which the $\sin(kh)/kh$ term becomes important. If Brune's flat acceleration spectrum with 10 Hz high frequency cut-off is assumed, without dissipation, then the correction factor of $\frac{\sin(kh)}{kh}\,dk$ is approximately 0.4 for a submarine at 300 ft. depth. However, actual observed earthquake acceleration spectra are not flat. The spectrum of the 1971 San Fernando earthquake (Jennings, p. 18) was peaked sharply between 2.5 and 3.5 Hz. Also, four out of the six spectra shown in Wiegel, pp. 85-89 were peaked sharply between about 2 and 4 Hz. The size of the pressure pulse at 300 ft. depth from such spectra will only be reduced 20%. Table IV shows calculated values of $\sin(kh)/kh$ for a number of representative depths and frequencies. In the absence of more information, a correction figure of 0.8 will be arbitrarily adopted for all entries in the hazard calculation.

3. Earthquake Statistics

The ground accelerations shown in Tables I and II imply that shallow earthquakes of Richter magnitude 6.5 and above must be considered. (This magnitude will hereafter be listed as $M_{6.5}$.) Shallow earthquakes of magnitude between M_6 and $M_{6.5}$ may also give large enough accelerations to present a hazard out to distances of a few miles.

The list of earthquakes compiled by 10-degree latitude and longitude intervals for the World Seismicity Maps (Barazangi and Dorman, 1969) has been used to find the number of shallow earthquakes in each 10-degree square of latitude and longitude during a seven-year period. Dorman (personal communication) indicates that while the depths and locations are sufficiently accurate, the magnitude statistics cannot be inferred accurately from these data. Many earthquakes of M_6 and even M_5 are not reported because of the widely spaced observation stations. Therefore, the list of earthquakes has been used only to determine relative numbers of shallow earthquakes in the 10-degree squares. The statistics have been corrected, and the magnitude distribution has been computed according to the Gutenberg and Richter figures (1945) for worldwide yearly numbers of shallow earthquakes, (Table V). They show a yearly number of 7123 shallow earthquakes of $M \geq 4$, or a total of 49,461 in seven years compared with 21,780 in the list for the World Seismicity Map. The difference is assumed to be due to those earthquakes that were missed by the worldwide network. It is thus assumed that the true corrected number of earthquakes of $M \geq 4$ in a 10-degree square is 49,461/21,780 times the listed number, and further, that the true corrected number of earthquakes of $M_7 - M_{7.5}$ is 70.7/21,780 times the listed number of earthquakes $M \geq 4$ (See Table V).

Gutenberg and Richter give an empirical equation for the worldwide yearly number of shallow shocks. The present study uses a slightly different relation for the number n of earthquakes per unit magnitude:

$$\ln n = 17.85 - 2.05 M$$

which fits the region above M_5 very well, as shown in column 3 of Table V.

The total yearly number of shocks in any magnitude interval $M_a - M_b$ will then be

$$N = \int_{M_a}^{M_b} e^{17.85 - 2.05 M} \, dM$$

This empirical relation has been used to calculate the relative numbers of shocks in the half-magnitude ranges of Table II. Table VI shows the result of multiplying these relative numbers of shocks by the areas affected, and thus is indicative of the relative probability that an area will experience a given acceleration during a year. Note for each level of acceleration, that the contributions from the different magnitude earthquakes are quite similar.

The last two columns of Table VI show the ratio of total area affected by all earthquakes to the area affected by earthquakes of $M_7 - M_{7.5}$ and by earthquakes of $M_8 - M_{8.5}$, respectively.

4. Hazard Estimates

Hazard charts are presented in Figures 1 and 2. These are the Barazangi and Dorman (1969, 1970) charts overlaid with numbers that show the calculated percent probability that a submarine will experience a 20% pressure change during one year of submerged operation in seismic regions that are shown as dense areas of dots. Regions of less than 1/2% probability are not marked.

The Barazangi and Dorman seismicity charts are based on a seven-year length of observations; and therefore are not truly representative of long-term seismicity in some parts of the world. The seismic activity appears anomalously high around the western tip of the Aleutian chain because of the Rat Island earthquakes. The long term seismic activity around Japan may be roughly a factor of three higher than it was during the 1961-1967 period. The activity around Chile is reported to be sporadically high, with extended quiet periods. 1961-1967 was a quiet period.

The assumptions made in calculating the chart are listed briefly here:

1) The worldwide number of shallow earthquakes is correctly given by Gutenberg and Richter (1965).

2) The magnitude distribution everywhere follows the relation, $\ln n = 17.85 - 2.05\ M$.

3) The Barazangi-Dorman (1969, 1970) tabulations of earthquakes are valid in location and depth, but not in magnitude or total number. Many earthquakes of M_4 and M_5 were omitted.

4) The Barazangi-Dorman shallow earthquake distributions in 10° latitude-longitude regions can be corrected by applying (1) and (2) to them.

5) The area covered by ground accelerations of different percentages of g is correctly given by Housner (in Wiegel, 1970). (See discussion below).

6) The relative total areas affected at different levels of ground acceleration can be obtained by combining (2) and (5), to get Table VI.

7) The total area affected at any one level of gound acceleration can be found by calculating the actual area affected by earthquakes of M_7 to $M_{7.5}$, and multiplying by the appropriate ratio factor in Table VI. The same procedure will work with earthquakes of M_8 to $M_{8.5}$, but with probably less accuracy.

8) The submarine will experience an effective fractional change in depth equal to 80% of the fractional g acceleration. (See discussion below).

9) The probability of experiencing such a pressure pulse is equal to the ratio of affected area to the oceanic area of high seismicity in the 10° latitude-longitude region.

10) The hazard is taken to be the probability that a submerged submarine will experience at least 20% increase in pressure at some time during one year of submerged operation in the immediate region of high seismic activity.

11) An area of high seismicity is considered to be a region

with a concentration of earthquake epicenter dots on the chart. Operation 100 miles outside a well defined area of high seismicity will reduce the hazard to a negligible value. (See discussion below).

12) The hazards of other values of pressure increase can be calculated by multiplying M_8 entries in Table II by Table VI.

13) The probability of a 20% pressure increase in any 10° latitude-longitude square will be taken as

$$\text{Hazard} = \frac{TNKArf \cos L}{FS}$$

where T is time of submerged operations (in years)

N is uncorrected number of earthquakes of 0-100 km depth per seven years in 10° latitude-longitude zone; from Barazangi and Dorman. (See assumption 3).

K is correction factor for converting N to the true number of M_7 - $M_{7.5}$ earthquakes. (Taken as 70.7/21,780. See discussion below).

A is area that will experience an acceleration of $>$ 0.25g from an earthquake of M_7 - $M_{7.5}$. (See Table II and assumption 5).

r is ratio of total area affected by all earthquakes, to area affected by earthquakes of M_7 - $M_{7.5}$. (See Table VI and assumption 6).

f is fraction of seismic events of 10° zone that occur in the ocean.

F is fraction of 10° zone that shows seismic activity. (See assumption 11, and discussion below).

L is latitude of the zone (for calculating its area).

S is area of 10° latitude-longitude zone at equator.

5. Discussion of Factors Used in Hazards Calculation (Assumptions 5, 8, 11 and 12)

Ground Acceleration (Assumption 5)

Table II has been used for ground acceleration in this hazards estimate. It is thought to present reasonable values for expected accelerations from undersea earthquakes, though it does not show the highest accelerations that might occur. Note, for example, that the highest accelerations measured in the 1971 San Fernando earthquake (1.25g) and the 1940 El Centro earthquake (0.33g) were at least five times as large as extrapolations of Table II would lead one to expect.

Correction Factor for Submarine Depth (Assumption 8)

The discussion in the early part of this paper emphasized that the correction factor for submarine depth is sensitively dependent on the shape of the earthquake acceleration spectrum. The observed spectra imply that the variation with depth will not be greater, for the normal range of submarine operation. (See Table IV). Observed data have been used for all parts of the hazards calculation, and an arbitrary value of 0.8 has been taken as sufficiently accurate for all submarine depths. The resulting estimates of pressure may be too conservative in deep submarine operation.

Region of High Seismicity (Assumption 11)

The fraction of seismic events in a 10° square that occur in the ocean and the fraction of the 10° square with high seismicity were both estimated by looking at the large-scale Barazangi and Dorman World Map of epicenters at 0-100 km depth. The edge of the highly seismic zone was considered to be reached where the number of epicenters per unit area dropped to about 1/4 of their concentration inside the zone. The estimates of active zone area in a 10° square are subjective, and easily may be inaccurate to a factor of two in some zones of moderate hazard.

The areas of high seismicity in latitudes above 70° North were estimated in a similar way from the Barazangi and Dorman (1970) Arctic map.

Probability of Other Size Pressure Increase (Assumption 12)

The hazard chart has been calculated for a 20% depth change. Hazard estimates for other pressures; i.e., other accelerations than 0.25g have been calculated by multiplying the area covered by an M_8 quake in Table II, times the appropriate entry from the last column of Table VI. The resulting values have been normalized to give the following conversion factors for hazard of different effective depth changes than 20%:

To	find	hazard	of	12%	pressure	increase,	multiply	chart	figures	by	5.4
"	"	"	"	20%	"	"	"	"	"	"	1
"	"	"	"	24%	"	"	"	"	"	"	0.45
"	"	"	"	28%	"	"	"	"	"	"	0.18
"	"	"	"	32%	"	"	"	"	"	"	0.04

Brune's theory would imply a less rapid fall-off of acceleration with distance. For conservatism the last entry should be increased to 0.1 or 0.2 instead of 0.04.

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TABLE I

MAXIMUM GROUND ACCELERATIONS AND
DURATIONS OF STRONG PHASE OF SHAKING

Magnitude	Peak acceleration (% g)	Duration of strong motion (sec)
5.0	9	2
5.5	15	6
6.0	22	12
6.5	24	18
7.0	37	24
7.5	45	30
8.0	50	34
8.5	50	37

TABLE II

AREA IN 1000 mi^2 COVERED BY GROUND ACCELERATION (% g)

	$M^{(1)}$						
Acceleration	5.0	5.5	6.0	6.5	7.0	7.5	8.0
≥ 5	0.4	1.6	3.6	6.8	13.	28.	56.
≥ 10		0.6	1.6	3.6	7.6	14.	32.
≥ 15			0.6	2.0	4.4	9.6	21.
≥ 20				0.9	2.5	6.0	14.
≥ 25					1.3	4.0	10.
≥ 30					0.25	2.0	6.4
≥ 35						0.6	4.0
≥ 40							1.2

Note (1) **M** 7.0 is taken to mean the magnitude range 7 - 7.5, etc.

TABLE III

Earthquake	Magnitude	Distance, km	Peak Acceleration g
San Fernando 1971	6.1	5	1.25
El Centro 1940	6.4	10	0.33
Parkfield 1966	5.5	0.2	0.55
Koyna, India	6- 6.3	5	0.63

TABLE IV

CALCULATED $\left|\frac{\sin(kh)}{kh}\right|$ CORRECTION VALUES

FOR VARIOUS DEPTHS AND SEISMIC WAVE FREQUENCIES

Depth (feet)	Frequency (Hz)			
	1	2	3	4
200	1	1	0.9	0.8
500	1	0.8	0.5	0.2
1000	0.7	0.2*	0.2*	0.2

*The first zero of $\frac{\sin(kh)}{kh}$ occurs between 2 and 3 Hz, at a depth of 1000 ft. It lies beyond 4 Hz at 500 ft depth.

TABLE V

FREQUENCY OF OCCURRENCE OF SHALLOW EARTHQUAKES

Magnitude Range	Number of shocks per year	Calculated Number(1)
3 - 4	49,000	50,000
4 - 5	6,200	6,500
5 - 6	800	800
6 - 7	108	108
7 - 7.8	13	13
7 3/4 - 8.7	2.2	3.3
7 - 7.5		10.1

(1) Number of shocks has been calculated by the empirical relation

$$\ln n = 17.85 - 2.05 M.$$

This differs from Gutenberg and Richter's relation but fits their tabulated values better.

TABLE VI

RELATIVE TOTAL AREAS AFFECTED BY EARTHQUAKES DURING 7-YEAR PERIOD (1)

Acceleration % of g	Magnitude(2) 6	6.5	7	7.5	8	Ratio of total to M_7	Ratio of total to M_8
≥ 15	4.6	5.6	4.4	3.4	2.7	4.7	8.0
≥ 20		2.5	2.5	2.2	1.8	3.6	5.3
≥ 25			1.3	1.4	1.3	3.1	3.1
≥ 30			0.25	0.7	0.82	7.1	2.15
≥ 35				0.22	0.51	—	1.4
≥ 40					0.15	—	1

(1) Normalized to a value of 2.5 for 0.2g acceleration from M_7 quake.

(2) Magnitude 7 means in the magnitude range 7 - 7.5, etc.

Earthquake Hazards Chart

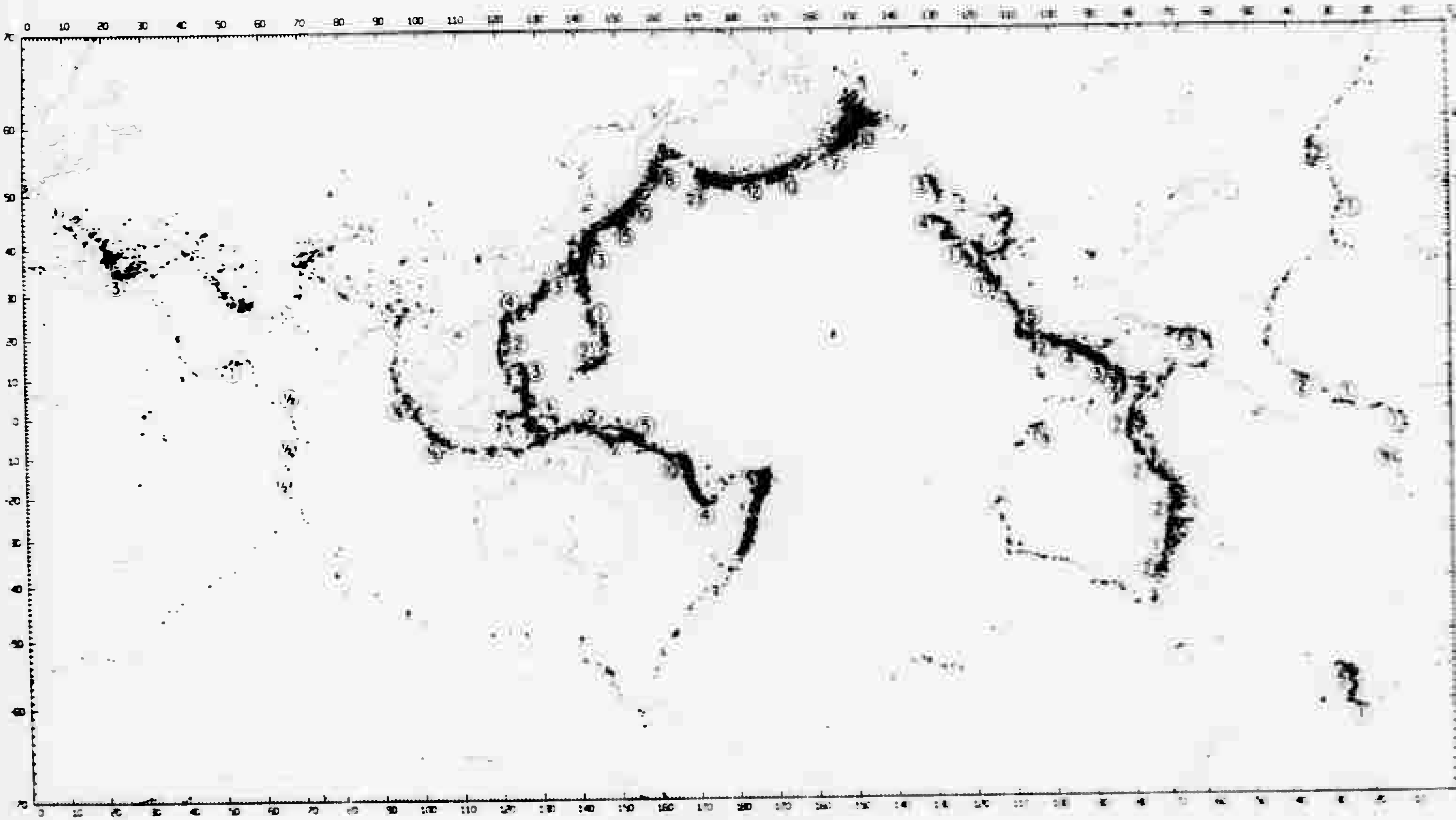
Fig 1

Calculated probability that submarine will experience 20% pressure change during one year of submerged operation. Calculations are based on world-wide seismic network observations for 1961-1967. The 23% value near the western tip of the Aleutian chain is anomalously high because of the Rat Island series of earthquakes. The 2% and 3% values near Chile and Japan are anomalously low compared with long-term observations in those regions.

Earthquake Hazards Chart - Arctic Region

Fig 2

Calculated probability that submarine will experience 20% pressure change during one year of submerged operation.



SEISMICITY OF THE EARTH, 1961-1967. ESSA. CGS EPICENTERS

DEPTHS 0-100 KM.

Figure 1

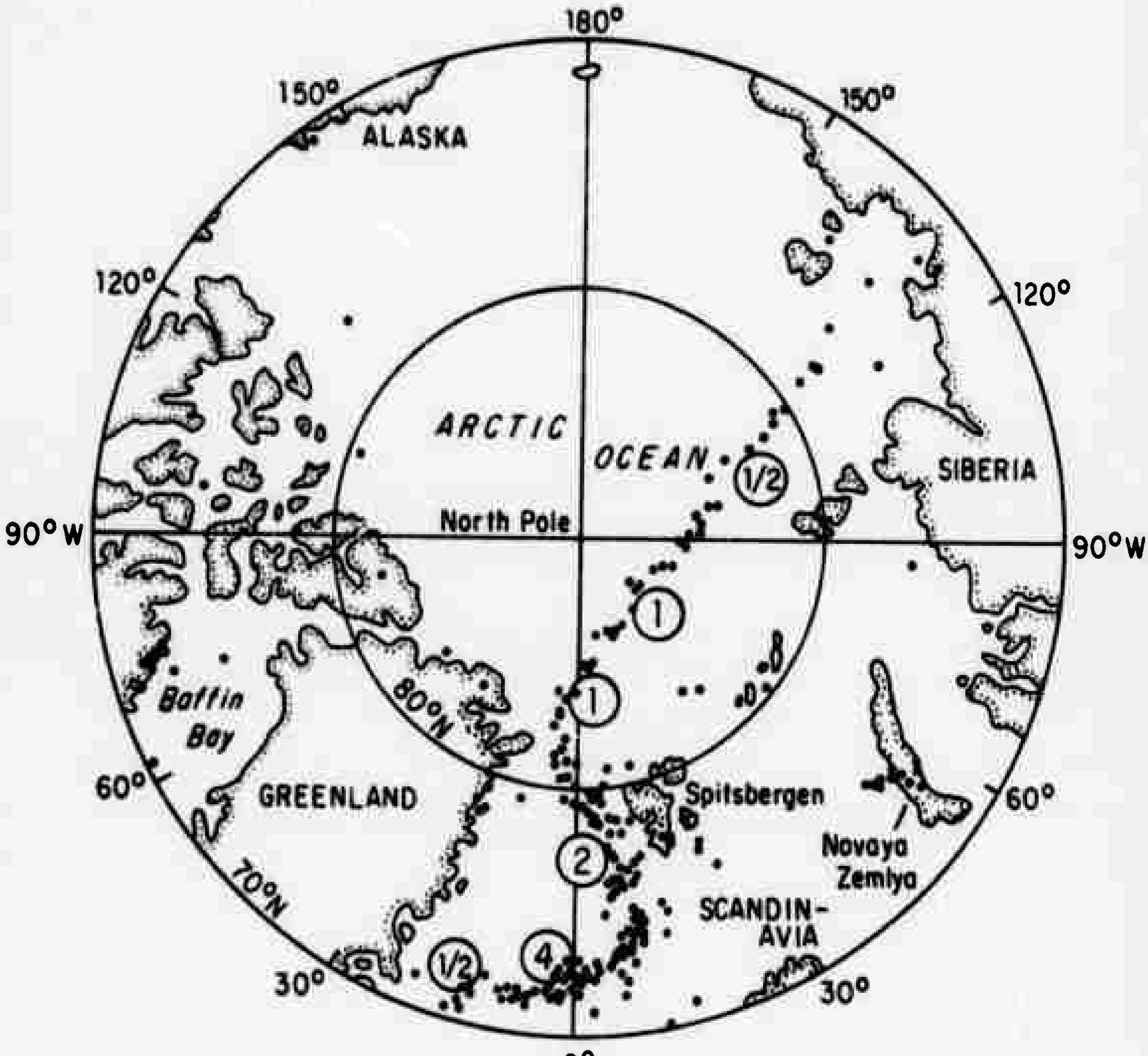

180°
150°
ALASKA
150°
120°
120°
ARCTIC
OCEAN
1/2
SIBERIA
90° W
North Pole
90° W
1
Baffin
Bay
80° N
1
60°
GREENLAND
Spitsbergen
60°
Novaya
Zemlya
2
70° N
SCANDIN-
AVIA
1/2
4
30°
30°
0°

Figure 2