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A TSUNAMI AVOIDABLE SUSCEPTIBILITY INDEX

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ABSTRACT

Tsunamis strike coasts and penetrate inland, creating conditions hazardous to both people and property in a zone which is particularly valuable for housing and certain economic activities. The hazard from tsunamis can be computed, based on two factors; (1) the probability that a tsunami of X runup height and Y inland inundation distance will strike a coast, and (2) the extent of human use of the same stretch of coast. If either of these factors is zero, there is no hazard. The first factor can be estimated for tsunami-prone areas by means of the coastal flood-insurance maps. The second factor is a function of the number of people and the value of property within the zone. A Tsunami Avoidable Susceptibility Index (TASI) can then be computed by multiplying factor 1 by factor 2. The 100 year tsunami runup height is a measure of factor 1. Factor 2 is the sum of a number of sub factors, each related to human use of the hazard zone. The sub-factors are activities such as housing, schools, hospitals, retail business, hotels, ports, marinas, fish canneries, etc. Points are assigned to each activity, with the greater number of points assessed to activities that are the most hazardous and which do not need to be located near the coast.

Tsunamis are important natural hazards in many coastal regions. These waves, caused by impulsive disturbances of the ocean or a connected body of water, usually due to a sudden displacement of the earth's crust under the sea (Cox, 1961; Cox, 1964; Weigel, 1974), become hazardous when there is an interrelationship between the destructive natural event and human use of the environment (Kates, 1971), in this case a coastal region. Distant tsunamis originate in impulsive disturbances far from the affected coast Local tsunamis are the result of nearby disturbances. The natural event cannot be controlled, but susceptibility to the natural hazard can be reduced by controlling human activities in the hazardous zone. Since tsunamis occur infrequently, even in the most vulnerable regions, it is reasonable to accept a certain degree of risk in determining optimal use of a coastal zone. The development of an index for evaluating the tsunami hazard is based on the premise that governments should determine acceptable risk and control human uses of hazardous areas to keep the risk within reasonable limits. This index, the Tsunami Avoidable Susceptibility Index (TASI), is determined by regulating the human use factor and thus avoiding susceptibility to the natural event, the tsunami.

SOME BASIC SUPPOSITIONS

The development of a TASI is based on the following:

--Susceptibility is a function of both the natural event and its magnitude and the extent of human use of the hazardous area.

--Tsunamis create a hazard to both human life and property, and each must be given an appropriate value. The human life hazard will be valued as the greater of the two.

--Rational use of the coastal zone requires that some risks be taken.

-- An index of susceptibility should be based on an appropriate weighting of human use factors according to their: density, coastal dependency, and inherent potential for loss of life and property.

AN EQUATION FOR A TASI

Since both the natural event (the physical component of the hazard) and the human use factor are, in combination, the principle ingredients that make up the hazard the equation for a TASI can be written simply as:

$TASI = P\ (H)$ where P is the physical component and H is the human use factor. H is equal to the sum of the various human uses of the coastal zone.

It is the product of P and H that determines the degree of hazard and hence the TASI. One or two examples will suffice to explain.

Examples

Lituya Bay, Alaska has the world's highest P value, having had a tsunami with a runup height of 1,740 feet in 1958. However, the shores are not occupied and the bay does not sustain any commercial activity. Hence, the sum of human use factors, H, is zero. The product of P and H is $1,740 \times 0 = 0$.

On the other hand Hilo, Hawaii has suffered damage and loss of life in two tsunamis in the last 36 years. In 1946 and 1960 there was considerable loss of life and property damage. The 100 year tsunami runup height is 30' (Houston et al, 1977) certainly modest by Lituya Bay standards. But, the H factor was high, since housing, retail and wholesale establishments, a port and a fishing industry were located in the tsunami hazard zone. Therefore, the TASI value computed prior to 1946 would have been quite high. After 1946 a safety zone near the waterfront was established. The TASI would then have been lower. However, considerable hotel and tourist activity development took place in the Banyan Drive area of Hilo both prior to and after the tsunami of 1960. After the 1960 tsunami a large part of the city was rezoned to create open space in the areas which had been inundated by the tsunamis of 1946 and 1960. The TASI was thus lowered. But, the Banyan Drive area has seen considerable additional tourist growth since then and the reduction in hazard by the post-1960 rezoning has been offset, at least partially, by increased hotel facilities in a hazardous zone.

The P factor

Since the height of a tsunami expected to occur once every 100 years (the 100 year tsunami) has been accepted as the standard definition of risk allowable for purposes of the Federal Flood Insurance Program it is reasonable to use this value for P. Where data are not sufficient to calculate the height of the 100 year tsunami the value of the highest runup in the historical record should be substituted. This is reasonable since when sufficient historical data are lacking it is usually because the historical record is too short. Hence, the highest runup frequently is based on a record of 100 years or less. For the purposes of calculating a TASI the value of P should be stated in feet.

The H factor

The value of H is more difficult to determine. Ideally it would be desirable to establish a monetary value for each of the human uses which make up the H factor. There are some difficulties in this approach, the first of which is the determination of the value of a human life. Insurance companies and the courts have, on occasion valued human life, but the dollar values have been inconsistent from case to case and may have been unduly influenced by the varying skills of lawyers. For other components of H the dollar value is determinable, but there are a number of qualifications which must be carefully stated and the calculations may be tedious and unwieldy.

In determining the value of the H factor the question of what is the tsunami hazard area must be addressed. How far inland does the hazard area extend? If the region is covered by Federal Flood Insurance Program (FIP) maps the necessary information is obtained from the maps, which delineate the hazard area for the purpose of prescribing land-use restrictions. If the area is not yet covered by the FIP it is wise to use the maximum extent of tsunami inundation known for historical tsunamis in the area.

The next problem is to determine how long a coastal stretch should be considered for computing a TASI. Should one compute a TASI for the entire coast of Alaska, for the island of Hawaii, for the city of Hilo, or for a few blocks of Hilo waterfront? The optimum coastal length to consider must be determined separately in each case. It is dependent on the geography of the coastal region, including both physical characteristics of the coast which determine tsunami wave runups and the human use of the region which determines the H factor in the TASI equation. There are no simple rules; however, here are some examples and illustrations.

The Hamakua Coast on the east side of the island of Hawaii between Pololu and Waipio Valleys is sparsely populated, and during the tsunami of 1946 wave heights were uniformly high along the stretch of steeply cliffed coast. In view of the uniformity of physical and human geography, and the history of tsunami runup heights, a coastal segment between the two valleys is a logical choice for the purposes of hazard management.

The south shore of the island of Molokai is shallow and protected by a broad coral reef. There have been relatively low wave heights along the coast and little or no previous tsunami damage. The coast can therefore be reasonably viewed as a unit for examining the tsunami hazard.

In Japan, the Sanriku Coast of northern Honshu has been long recognized as a tsunami-prone region. Physically, the coast is typified by the presence of rias, a coastal form presumably particularly susceptible to high tsunami runups. (Noh, 1966). Culturally, there are a large number of small towns and cities where commercial fishing is a principal economic activity. Consequently, there is a uniformity of tsunami hazard, since both physical and human-use characteristics are conducive to loss of life and property from tsunamis. The Sanriku coast is the classic example of the tsunami hazard in Japan, and, for that matter, throughout the world. It can be treated as a unit for tsunami hazard planning, or, alternatively, the individual municipalities can examine their individual situations and plan accordingly. The latter approach was taken after the 1960 tsunami by various towns, while the Japanese government and the governments of the prefectures in the affected district made general plans for considering the entire coast as a tsunami hazard zone. (Morgan, 1979).

CALCULATION OF TASI: SEMI-SUBJECTIVE METHOD

While the TASI is dependent on but two factors, P and H its calculation is not simple, since H is the sum of a great many sub-factors, each of which must be analyzed for its contribution to the tsunami hazard. The greater the potential of the sub factor for loss of life and property the greater the contribution to the TASI. High TASI's are undesirable; low TASI's which are also consistent with rational use of the resources of the coasta zone are desirable.

In table 1 coastal zone uses are listed in the first column. The second column categorizes the various conceivable uses of the tsunami hazard zone according to coastal dependency. Some activities must be carried out close to the water if they are to be carried out at all. Others might find a coastal location desirable but not essential. For still others the location of the activity is immaterial. Column 2, puts coastal dependency into five categories, from essential to immaterial. In some cases a waterfront location is essential if the activity is to be carried out, but the essentiality of the activity itself is questionable. These items are footnoted in the table. Column three of the table translates coastal dependency into a contribution of the activity to the TASI score. It is shown as the maximum TASI contribution for that factor which can be assigned. Of course, the maximum should not be assigned unless there is very high density use of the hazard area for that activity. Lesser values are assigned by the user of the table, according to his assessment of the relative degree of use.

Each of the sub factors must be assigned a value by the user of the TASI method. Some considerations for asignment of points for the various activities follow:

Ports

It would be possible to rank any

Table 1 - TASI H Factors

H Factor		Coastal dependency	Maximum TASI Contribution
p1	Port	Essential	5
h1	Hotels	Highly desirable	15[1,2]
m	Marinas	Essential	10[3]
f1	Fishing (commercial)	Essential	5
f2	Fishing (recreational)	Essential	10[3]
h2	Houses	Beneficial	25[2]
s1	Schools	Immaterial	30[2]
h3	Hospitals	Immaterial	30[2]
r1	Retail stores	Beneficial	20
w	Warehouses	Desirable	15
s2	Sewage treatment plants	Essential	5
t	Theaters	Immaterial	30[2]
p2	Parks	Highly desirable	5[4]
o	Offices	Immaterial	25
r2	Restaurants	Desirable	20[2]
a	Airports	Highly desirable	10
n	Nuclear power plants	Essential	10[5]

[1] See text for further explanation and possible modifications.
[2] High population density use. Five additional TASI contribution points assigned.
[3] Waterfront location essential for activity, but activity itself not considered essential. Five additional TASI contribution points assigned.
[4] Low density use. Five less TASI contribution points assigned.
[5] Five additional TASI contribution points assigned due to potential for wide-spread disastrous effects.

In general: Essential = 5, Highly desirable = 10, desirable = 15,
Beneficial = 20, Immaterial = 25

port according to one or more of the following: value of facilities, amount of cargo handled, numbers of vessels and tonnages using the port, contribution to economy of the region, esentiality considering other transportation available. Ports in the Hawaiian Islands and Alaska do not rank high among U.S. ports. Even Honolulu does not rank among the top 30 ports of the nation according to most listings. However, for Hawaii and Alaska ports are of tremendous importance. Virtually all (better than 95%) of the cargo reaching Hawaii, for instance, arrives by ship, and the state's two principal exports, raw sugar and processed pineapple, require a port for transportation to the principal market, the mainland U.S.

Considering the above, an active port in the tsunami hazard zone should generally be given the maximum value, 5, unless there is another port nearby that is not in the hazard zone and can carry out the same functions. As examples: The island of Hawaii has ports at Hilo and Kawaihae. Hilo is in a tsunami hazard zone, and in previous tsunamis port facilities, including the breakwater, have been damaged severely and the port put out of commission. However, the port at Kawaihae is in a less hazardous location and could conceivably substitute for the Hilo facilities for some commodities. Sugar could be shipped in bulk from Kawaihae, and essential imports from Honolulu could likewise be handled. But Hilo has roll on/roll off facilities enabling cargo to be transported directly from the west coast of the U.S. to Hilo, while shipping through Kawaihae would require a transshipment through Honolulu and might have to be made in smaller ships or by tug and barge. There are two ports on the island of Kauai, Nawiliwili and Port Allen. They are in two separate sub areas from the standpoint of tsunami hazard. If one is damaged the other might be able to take up the slack, but once again the facilities and capabilities of each should be examined to determine the essentiality of the port to the local economy and welfare of the residents.

Hotels

If a tourist industry is an essential contributor to the economy there must be hotels. But the location of hotels in a hazard zone may not be essential. A comparison between tourism on Oahu and Hawaii is useful. Waikiki might be the most extensive beachfront hotel area in the world; certainly it is among the top few. Hotels in Hilo, on the other hand are fewer in number and generally less lavish in their appointments. If one were to compare the two areas, ranking Waikiki as a maximum contributor to the TASI (15) then a case could be made for assignment of only a few points to Hilo's hotels. But there is much more to it than that. Hilo is a much smaller city, and on a per capita basis the contribution of tourism to the Big Island's economy might be quite large. It is the effect of the tsunami on the local economy that is most important, not merely a ranking of hotels in Hilo against the world standard Waikiki Beach. Moreover, the essentiality of a beachfront location should be carefully considered. While, in general, hotels are given a "highly desirable" ranking in the coastal dependency column of table 1 there can be some exceptions. The waterfront location of Hilo hotels might not be nearly as essential as that of Waikiki hotels. There is far less sunshine in Hilo, and beach activities are not common. Why then locate the hotels on the waterfront, particularly in a known tsunami hazard area? If the principal attraction of Hilo tourism is the nearby Hawaii Volcanoes National Park then perhaps a more inland location, closer to the Kilauea volcano might be desirable for more than one reason.

On the other hand, hotels on the leeward or Kona side of the island depend more on the traditional beach activities. This is the dry, sunny coast, and a beachfront location is clearly more desirable.

Hotels in other waterfront cities sometimes serve a different purpose. San Francisco, for instance, is a tourist destination for many, and it has a number of hotels. There is no need for them to be on the waterfront, and any proposal to build a waterfront hotel in a tsunami hazard zone should be penalized accordingly by assigning a high TASI point value. The coastal dependency of highly desirable is, strictly speaking, applicable only to traditional tourist locations that depend on sea, sun and beaches. It should be modified when applicable and assigned an immaterial ranking in some cases.

Marinas

Certainly marinas must be located on the waterfront if they are to be located anywhere; hence, their coastal dependency is high. However, since marinas are generally a recreational land use and are not considered essential to the economy of most places their essentiality is modified by assigning an additional 5 points to the TASI factor.

Fishing

Both commercial and recreational fishing depend on waterfront locales. Commercial fishing requires boats, piers, and nearby canneries or other processing facilities.

By recreational fishing is meant primarily charter boats, which, like commercial fishing craft require pier facilities. Somewhat arbitrarily, fishing of the reacreational variety is considered less essential than commercial fishing, although owners of charter boats might certainly disagree. Since they are considered less essential more TASI points are assigned to their presence in a hazard zone.

Houses

It is certainly not essential that houses be located near the water, but it is desirable in many cases. A waterfront location, or even a view of the water, makes the house more valuable. Hence, the coastal dependency for houses is "beneficial". Since houses are associated with people the hazard to human life is increased when there is high housing density in a tsunami hazard zone. In assessing the number of points to assign to housing there are a number of essential considerations. First, of course, is the density of housing in the zone. A few houses should not be penalized as much as a high density development. Since warning systems are designed primarily to save lives, not property, the effectiveness of such systems should be evaluated in assessing the hazard to human life associated with housing in a tsunami hazard zone. Some questions to ask are: Is the hazard primarily due to local or distant tsunamis? Are the roads and streets adequate to serve as evacuation routes? Are the residents aware of the nature of the hazard and the actions to be taken? Are the civil defense and police organizations well trained and skilled in hazard situations? Are there siren signals nearby and can they be heard by the residents?

If the hazard is primarily from distant tsunamis and the warning system, including the work of civil defense and police personnel, is efficient there should be no loss of human life. If the hazard is from local tsunamis it is doubtful if any warning system can be very effective. Residential zoning in an area subject to local tsunamis should not be permitted.

Schools, hospitals, theaters

These three are high population density uses which should not be permitted in a tsunami hazard zone. They have been classified "immaterial" from the coastal dependency standpoint and have been assessed additional TASI points due to high population density. In the event of a tsunami evacuation of people from schools, hospitals or theaters would be particularly difficult. Any school, hospital or theater in a tsunami hazard zone should be assessed the maximum number of points.

Restaurants

There is some desirability for seafood restaurants to be located on the water, and many of them are. The location is "desirable", not "essential." Restaurants are another high population density activity, and in the event of a tsunami there would be loss of life, perhaps, as well as property. Seafood restaurants are frequently part of the "tourist scene", and since visitors may not be familiar with tsunamis it is essential that personnel employed in waterfront restaurants understand evacuation procedures and warning signals. In determining the point score for waterfront restaurants the density factor, the training and knowledge of restaurant employees, the location of warning sirens, the efficiency of the warning system and character of nearby streets serve as evacuation routes should be considered.

Retail stores

The only possible reason why retail stores might be desirably located in a tsunami hazard zone is if they are primarily tourist shops and are in or near resort hotels. Retail stores that are not in that category should be located outside hazard zones.

Warehouses

Locating warehouses near the waterfront may be desirable in port communities. Hence, warehouses are given a "desirable" designation from the standpoint of coastal dependency. Otherwise, there is no need for warehouses to be near the water.

Offices

Office buildings can be located anywhere within a city, and a coastal location is not particularly needed. Hence, it is "immaterial" where they are located. Office buildings are frequently high rise. Only the lower floors present a tsunami hazard, and it is quite feasible to construct the buildings so that the lower floors contain lobbies, or otherwise unoccupied spaces.

Airports

In coastal cities airports are frequently sited so that take off and landing patterns are over the water. This provides an additional degree of safety for the city since crashes are more likely to be over water than over the city. In some cases, Honolulu for example, runways have been especially constructed in shallow waters by using fill. This provides, in addition to the additional safety factor, some relief from the excessive noise modern jet aircraft make during landings and takeoffs. The use of coastal zones for airports is considered "highly desirable" and little TASI penalty should be assigned to such use.

Parks

In a tsunami hazard zone recreational or park use is considered "highly desirable", since this is a generally low density use and there is little in the way of construction to be damaged by the tsunami. Since the recreational attributes of the water and beaches can be put to desirable use in areas which would be otherwise wasted parks, as a form of open space zoning, are a particularly suitable land use. For that reason they are assessed less than the normal number of TASI points. In other words, there is a bonus for using tsunami hazard areas as parks.

Sewage treatment plants

Since it is essential that sewage be treated before being disposed of in the ocean sewage treatment plants must be located near the water. Coastal dependency is rated as "essential".

Nuclear power plants

The oceans serve to provide cooling water for nuclear power plants, which generate tremendous heat. A waterfront location is considered essential. But the potential for wide-spread disastrous effects if a nuclear power plant is damaged by a tsunami must be considered. Hence, in table 1 five additional TASI points are assigned.

USE OF THE TASI

The primary virtue of the TASI is that it provides a logical methodology for rational planning for land use in areas that are subject to a tsunami hazard. Regulations associated with the Federal Flood Insurance Program have been criticized by some as being too restrictive and illogical. In many cases a literal interpretation of permissible uses in the flood zone makes the area virtually unusable. The use of a device such as the TASI allows reasonable use of the hazard zone while still keeping the overall hazard within reasonable bounds. Thus it is a more flexible method of land use control than the Flood Insurance Program regulations, which prescribe a number of absolute restrictions.

Planners and those who make decisions concerning permissible land uses can use the TASI as part of their decision-making process. They are able to evaluate the results of their decisions in the light of the degree of hazard they consider acceptable. While there is no single value of the TASI which must not be exceeded--each governmental organization can set its own standards--the calculation is sufficiently quantitative to insure that a tsunami-prone area does not become excessively hazardous by ad hoc additions of structures.

The TASI can encourage the planner and decision maker to use a logical check-off list as he considers the appropriate point score to assign to various land uses. He will examine the nature of the roads in the area with regard to their utility as evacuation routes. He should note whether there are nearby warning sirens and whether the local police and civil defense organizations are up to the task of supervising an evacuation of the local populace under conditions which are less than ideal. He can question the knowledge held by the public concerning tsunamis and the damage they cause, and thereby he can assess whether or not there is need for better education systems.

Most important, the TASI provides the decision maker with a logical framework for regional planning; he is freed from the problem of making each decision on a case by case basis.

For those counties that opt not to join the Federal Flood Insurance Program it is essential that there be some method for rationally determining the degree of tsunami hazard and insuring that the human use factor remains within reasonable bounds. But planners in all coastal regions subject to tsunamis can benefit from use of a methodology that puts decision making on a rational basis that considers both the degree of hazard and the need to use land wisely.

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NATIONAL GEOPHYSICAL DATA CENTER DATABASES SUPPORTING INVESTIGATIONS OF GEOLOGICAL HAZARDS

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ABSTRACT

The National Geophysical Data Center and co-located World Data Center A for Solid Earth Geophysics provide numerous data products to support investigations of geological hazards. Those for seismology, glaciology (snow and ice), and regional geophysical investigations are briefly described. In addition, the contents of the Center Natural Hazards Photograph File is outlined.

INTRODUCTION

The Environmental Data and Information Service (EDIS), a part of the National Oceanic and Atmospheric Administration, has been given the task of collecting, managing, and disseminating the great mass of information produced by the scientific observation of the physical environment. The National Geophysical Data Center (NGDC) is a branch of EDIS, and World Data Center A for Solid Earth Geophysics is co-located with it. Following is a description of NGDC data bases which specifically relate to natural hazards.

SEISMOGRAM DATA

Standard seismograms are routinely received by NGDC from the 115 observatories of the Worldwide Standard Seismograph Station Network (WWSSN), 25 stations in the Canadian Network, 17 stations in the People's Republic of China Network, and miscellaneous stations. For international events of magnitude 7.5, several dozen stations send seismograms through an international data exchange agreement. There are approximately 5 million seismograms on file at NGDC.

The WWSSN stations send their data to the U.S. Geological Survey (USGS) where the records are examined to see that standards are being maintained. These data are then sent to NGDC where they are combined with data received directly from other networks and are filmed using special high resolution cameras. These data are available on 35-mm microfilm, 70-mm film chips, microfiche, and paper copy. Several million copies of seismograms are distributed annually. Digital records from about 20 stations are available on magnetic tape since March 1977.

There is also a historical seismogram film file. This file contains several hundred thousand historical seismograms from 1903 to 1962 for selected significant earthquakes.

STRONG MOTION DATA

These strong motion records are generated when an event causes an acceleration greater than 0.01 g (1/100 of the acceleration of gravity), that is when the event occurs near one of the recording instruments. These conditions are met only a few times a year. Usually, each of these events generates 1/2 dozen or so records. The file at NGDC contains the most significant strong motion records from the United States and other areas of the world for the period from 1933 to 1981. In addition to the digitized data, which are available on magnetic tape, records are also available in microfilm, microfiche, and paper. The file contains 347 events and approximately 500 stations.

Stations participating in the United States Geological Survey network forward their records to the USGS Seismic Engineering Branch in Menlo Park, California. There, the significant records are digitized and forwarded to NGDC, where they are standardized and then made industry compatible. NGDC then advertises and disseminates these data.

EARTHQUAKE DATA FILE

This file contains locations of more than 350,000 worldwide earthquakes and other recorded earth disturbances. In addition to the USGS, more than 20 worldwide sources have provided data. The parameters that may be specified in obtaining data from this file include: geographic coordinates, time period, date and time of occurrence, modified mercalli intensity, depth, and magnitude range. In addition to computer listings, computerdrawn maps and cathode-ray tube plots are available.

When an earthquake event occurs, reports are compiled from seismogram records. The U.S. Geological Survey receives these telegraphic reports from stations throughout the world. The U.S. Geological Survey Global Seismology Branch then uses these data to derive global earthquake parameters. When the results of a month's effort is completed, NGDC is notified. NGDC then taps into the U.S. Geological Survey's computer system and extracts the event records, provides quality control and enters the data into the Earthquake Data File.

EARTHQUAKE EFFECT DATA

The effect file consists of 115,000 earthquake intensity observations for the United States since the beginning of the century, gleaned from canvasses, newspaper clippings, the Reid Catalog, etc. Each record in the file contains date and time of occurrence and location of the earthquake, geographic coordinates of the event, two-digit state code and coordinates of the observing cities, and the observed intensity at each city. A search can be performed for any geographic area in the United States for any specified time period, and for any intensity level. Computer plots on mylar film and cathode-ray tube plots are available.

When an earthquake occurs in the United States, questionnaires are sent to postmasters in communities surrounding the earthquake. These questionnaires are filled out and returned to the USGS Global Seismology Branch in Golden, CO, where they are analyzed and intensities are assigned to each community. These data are published in an annual report entitled United States Earthquakes. After publication, the data are entered into the NGDC digital file entitled The Earthquake Effect File. The questionnaires are forwarded to NGDC where they are placed on microfilm and archived.

SIGNIFICANT EARTHQUAKE DATA

This data file contains records of 2500 worldwide earthquakes reported in 114 scientific sources covering the time span from 2000 BC to 1979 AD and meeting at least one of the following criteria: Damage of one million or more in 1979 dollars, ten deaths, magnitude 7.5 or greater or, where the magnitude is unknown, intensity of X or greater. The date and time of occurrence, latitude, longitude, depth, magnitude, number of casualities, damage, references, and political geography are given for each earthquake. This data is available as a wall map entitled Significant Earthquakes 1900-1979, and as a publication entitled Catalog of Significant Earthquakes 2000 B.C. - 1979.

TSUNAMI DATA

Nearly 3000 tide gage records dating back to 1850 from U.S. and foreign tide stations in the Pacific are available on microfiche. The National Ocean Survey (NOS), a part of the National Oceanic and Atmospheric Administration, has loaned these records to NGDC for filming and distribution. Each tide station has supplied records that contain a 5-day span of wave data encompassing the tsunami event with adequate gage quiet time. Tide station reports describing the inspection and calibration of the tide gages themselves are available for most stations since 1940. The number of stations available for a given event range from 1 to 50. A limited number of records from foreign countries are available. Five hundred twenty (520) paper copies of tsunamigrams are also archived at NGDC. A data base entitled the Pacific Tsunami Historic File (PTHF) is being prepared by Doak Cox. Some or all of the following parameters are included for each tsunami event listed: event, date, source region, validity rating, latitude, longitude, depth and magnitude of the generating earthquake, tsunami magnitude, tsunami intensity, and literature citations. A tsunami data report and an earthquake data report can be generated from this data base for all events listed. The PTHF data base can be searched for tsunamis which have occurred in a specified region during a specified period of time. A number of other parameters may also be specified. NGDC plans to have the Institute of Ocean Sciences in Sidney, British Columbia, digitize about 40 marigrams. Future plans include the production of a wall-sized multi-color map showing tsunami source locations. Other parameters that may be included are: earthquake magnitude, tsunami magnitude or intensity, frequency of occurrences, and travel time lines. The map may be accompanied by tabular data for pre-20th century events.

Another project will be the production of tsunami travel time maps using detailed bathymetric data for a few key locations. NGDC is preparing a listing of tsunami events in the Mediterranean, Atlantic, and Indian Oceans to supplement the work being completed by Dr. Cox. Three hundred twenty-five (325) events dating to the second millenium B.C. are included in this list.

NGDC has a collection of about 30,000,000 bathymetric observations of the U.S. coastal areas, collected since 1930 by the U.S. Coast and Geodetic Survey and its successor, NOS. These data are on magnetic tape and can be formatted to provide plots, even-spaced grids, or profiles.

VOLCANOLOGY

Volcanoes have been known to destroy entire civilizations; consequently, they rank very high on a list of serious geological hazards. Data associated with volcanoes come in many forms -- from maps (that depict Volcanoes of the World), to photographs (over 250 available from NGDC), to computer files. Computerized files, too are available in a number of differing formats -- containing such data as: compilation of all volcanic events during the last 12,000 years (created by the Smithsonian Institution); geothermal data; aeromagnetic data before and after the eruption of Mt. St. Helens; and geochemistry of volcanic rocks.

GLACIOLOGY (SNOW AND ICE)

Glaciological data, such as information on snow cover, sea (and Great Lakes) ice, avalanches, and ice cores, are often very useful to those evaluating risks associated with perhaps the most hazardous geological mineral -- ice. Operated under the auspices of the National Geophysical Data Center is the World Data Center-A (WDC-A) for Glaciology (Snow and Ice). Available through this WDC-A are numerous data reports, photographs, and digital inventory and data files.

REGIONAL INVESTIGATIONS

To evaluate risks and source mechanisms for earthquakes or high geothermal gradients, scientists often evaluate geophysical data collected over areas of specific interest. Typically, this includes studying seismic reflection, gravity, magnetics, topography, and well log data. Files of all these data are available at the National Geophysical Data Center.

A notable region which has been extensively surveyed to determine its oil and gas potential, is the National Petroleum Reserve in Alaska (NPRA). This 24-million-acre area in northern Alaska is currently being leased for commercial drilling. Data available for the Reserve include: over 13,000 line miles of seismic reflection, well logs and data reports for over 44 wells, and gravity and aeromagnetic observations.

NATURAL HAZARDS PHOTOGRAPHS

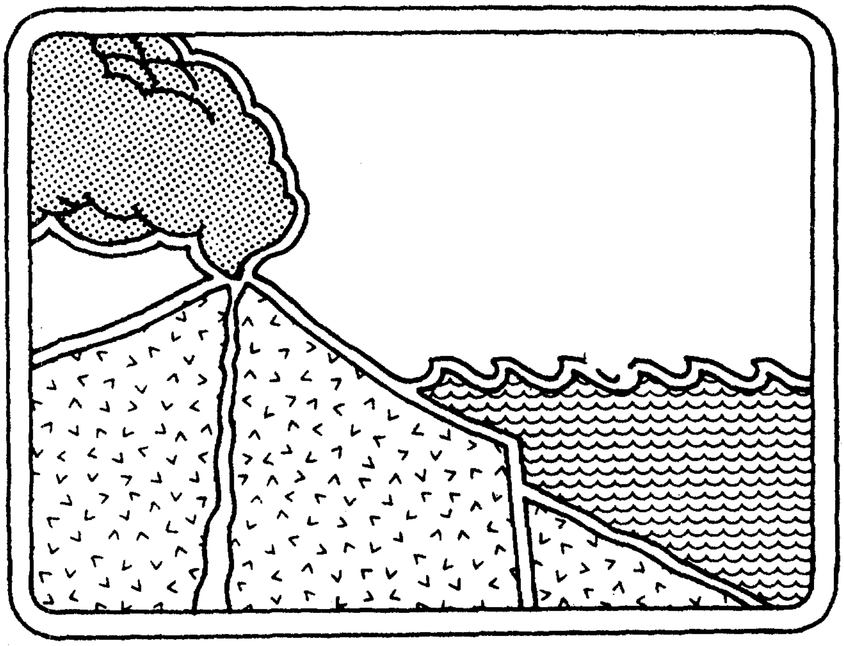
The Natural Hazards Photographs File contains nearly 2000 photographs depicting earthquake, tsunami, and volcanic eruption damage and effects. The file is global in coverage, includes 93 earthquakes and/or tsunami events, and spans more than 150 years. Photographs, slides, and negatives are available for the cost of reproduction and processing of the order. NGDC can fill requests for specific types of damage or damage occurring in specific locations from its photograph file. An earthquake damage slide set including outstanding photographs of earthquake damage is available.

NGDC data bases can provide valuable research tools to those involved in natural hazards research and mitigation.

For further information write:

National Oceanic and Atmospheric
Administration
National Geophysical Data Center D62
325 Broadway
Boulder, CO 80303
U.S.A.

Earthquake of March 27, 1964, Anchorage, AK. Slumping occurred when soil liquefied in an exclusive subdivision located on a bluff. Property damage resulting from this earthquake was set at $1.02 billion. Photograph Credit: NOAA/EDIS.



THE ALL-UNION MEETING ON TSUNAMI IN YUZHNO-SAKHALINSK

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A meeting on the tsunami problem was held in Yuzhno-Sakhalinsk on 10-12 August, 1981, under the title of "Problems of Long-Time and Operative Prediction of Tsunami". It was co-organized by the Tsunami Commission (TC) of the State Committee's for Science and Technology (SCST) Scientific Council for the problem "The Study of Oceans and Seas and the Use of their Resources", the Marine Seismology and Tsunami Commission (MSTC) of the Interdepartmental Council for Seismology and Earthquake Engineering (ICSAE) under the USSR Academy of Sciences Presidium, the Sakhalin Complex Scientific Research Institute (SCSRI), Far East Science Center (FESC) of the USSR Academy of Sciences, the Sakhalin Administration of the USSR State Committee for Hydrometeorology.

Ninety-nine papers from 30 scientific and scientific-industrial organizations were submitted for the meeting. Therefore the Organizing Committee decided that all the papers be presented by the panel method, except for the opening paper by S. L. Soloviev, chairman of the Tsunami Commission, that reviewed the present state and objectives of tsunami studies in the USSR.

The papers were divided into the following four sections:

1. Analytical theory of tsunami generation and propagation.
2. Numerical and physical modeling of tsunami generation and propagation. Observations of natural events.
3. Operative and long-time tsunami prediction.
4. Methods to process information and technical means. Tsunami United Automatic System (TUAS).

E. N. Pelinovsky, A. A. Poplavsky, S. L. Soloviev and I. M. Shenderovich were the conveners of the sections respectively. The participants were given abstracts of the papers. The papers were discussed after each section session. On 12-14 August, the meeting was accompanied by an auxiliary meeting of co-authors of works for creation in the Far East of United Automatic System for observation of tsunami generation and propagation and warning (Tsunami UAS), prepared by the Sakhalin Administration of the USSR State Committee for Hydrometeorology.

At Section I, the paper "On a Method of Study of the Cauchy-Poisson Problem" by Prof. A. I. Yanushauskas (Institute of Mathematics, Siberian Branch, USSR Academy of Sciences) and the paper "An Approximate Solution to the Cauchy-Poisson Problem" by A. Y. Buklin, a post-graduate student (Institute of Theoretical and Applied Mechanics, SB, USSR AS), were dedicated to the search of initial systems of differential equations to describe tsunamis more adequately than the common wave equations for long waves. In these equations, the term $-\frac{1}{2} h^2 \Delta \zeta_{tt}$ appears additionally, where h is the basin depth (assumed to be small), ζ is the water elevation, taking into account a number of dispersion effects. The paper "On the Correctness of the Optimum Control Problem to Interpret the Process of Wave Generation in Shallow Water" by O. V. Vasiliev and V. A. Terletsky (Irkutsk University) shows that in principle it is possible to find the sea-floor motion from an observed tsunami wave profile by means of reducing the common Cauchy problem to the problem of optimum control of a system of three quasi-linear hyperbolic equations that describe wave motions of liquid. The dynamics of the sea-floor motion serves as control. It is shown how to make functional gradient computation correct, which, by the way, can be accompanied by a certain upper limitation of the iteration number by means of which a system of equations is solved. In the paper "Evolution of Non-axis-symmetrical Tsunami Waves in the Open Ocean" by S. F. Dotsenko, B. Y. Sergeyevsky and L. V. Cherkesov

(Marine Hydrophysical Institute, Ukraine, USSR AS), tsunami from an arbitrary initial water elevation is derived in a linear fashion by means of superposition of solutions for elementary axis-symmetrical sources of a certain type; radiation directivity is shown and analyzed.

In another paper by S. F. Dotsenko "Tsunami Waves in a Continuously Stratified Ocean" and in the paper "Propagation of Gravity Waves in a Two-Layer Liquid of Finite Depth" by N. P. Konstantinova and I. A. Malkin (SCSRI, Moscow Physico-Technical-Institute) it is shown that in addition to "surface" tsunami waves there also originate slowly propagating inner and inertial waves which, together with the geostrophic vortex that is formed in the source, can serve as tsunami source "indicators" during considerable time. Pulsation type oscillations have been revealed in a two-layer medium having layers of similar thickness and essentially different density.

The paper "On the Structure of a Non-linear Wave Mode of a Tsunami Wave Propagating over a Submarine Ridge" by E. N. Pelinovsky and N. A. Soustova (Institute of Applied Physics, USSR AS) presents estimates of non-linear corrections for a linear wave-guide solution, and shows that non-uniformity of the medium can distort the behavior pattern of higher overtones essentially. E. A. Kulikov, A. B. Rabinovich and I. V. Fain (SCSRI) in "The Study of Long Waves in the Boundary Area of the Ocean and the Tsunami Problem", using the shore-line wave number-frequency dispersion diagram, continued tentative analysis of a set of long "trapped" and "radiated" waves in a shelf and continental slope area: single and double Kelvin waves, gravity and "geostrophic" edge waves, Poincare interference waves, etc., V. Y. Maramzin and A. V. Skripnik (SCSRI) in their paper "Generation of Long Waves by Meteorological Disturbances", basing on treatment of long series of observations of ocean level oscillations near Shikotan I. during which long-wave disturbances of unknown origin were recorded several times, showed that these can include oscillations that originate when the shore-line is crossed by rapidly moving deep storms and are observed over considerable distances.

V. P. Belokon, V. N. Savchenko, L. B. Nikitina, A. F. Rodkin and N. A. Smal (Far Eastern University) presented four papers in which they continue to study the Earth's anomalous magnetic field caused by Tsunami generation and propagation: In particular, they studied the effect of the Earth's good-conducting asthenosphere (located at depths of the order of 30-80 km) and "mareoelectric" section features of the hydrosphere, as well as the principal possibility to estimate the parameters of this section from the magnetic field that accompanied a tsunami.

In Section II numerical calculations of tsunami generation were performed by N. A. Urban (SCSRI). She has shown that any sharp directivity of tsunami radiation can be obtained in the limits of common linear treatments for a complex residual sea-floor deformation that consists of elementary vertical displacements of different sings. I. V. Fain, G. V. Shevchenko and E. V. Kulikov (SCSRI) studied numerically the degree of trapping of tsunami energy by the Kuril-Kamchatka continental slope and shelf depending on the distance of a point isotropic source from the shore. The trapping degree turned out to be within 0.3-0.7 in a depth range of 3000-6000 m. E. A. Kulikov and S. L. Soloviev (SCSRI, Institute of Oceanology, USSR AS), using spectral-temporal analysis of shore (mainly Japanese) mareograms, observed the propagation along the coast of the main and first modes of edge-trapped tsunami waves caused by the 13 October, 1963, Urup earthquake. B. Y. Maramzin (SCSRI) estimated the amplification of a tsunami wave in the South Kuril Strait at its resonance frequencies; the estimated values of seiche periods within a period range of 1-3 hours are in good agreement with observed ones.

An empirico-analytical linear theory of wave run-up onto a shore was offered in the paper by R. K. Mazova, E. P. Pelinovsky and S. K. Shavratsky (Institute of Applied Physics). A. N. Militeyev and M. S. Sladkevich (Hydroproject RV, Moscow Engineering Building Institute) offered a method to calculate run-up of tsunami type long waves onto a shore taking into account planned inundation, based on a finite-difference system of equations approximating Saint-Venant's equations. A. V. Mishchuyev, N. A. Prikazchikov and M. S. Sladkevich (Moscow Engineering Building Institute) made a number of theoretical studies and one-dimensional hydraulic modeling to estimate the load on protecting constructions from tsunami waves as a hydraulic bore. It has been shown that complex currents are formed in front of and beyond the barrier, sometimes the flow gets shallow beyond the wall. Standard state regulations are being prepared based on these results. A real possibility to model tsunami by means of underwater and near-bottom explosions in basin of limited dimensions has been analyzed in the paper by B. I. Basov, V. M. Kaistrenko, Y. P. Korolyov, B. V. Levin, A. A. Poplavsky, K. V. Simonov and A. A. Kharlamov (SCSRI) taking into account experimental work.

The papers that presented results of open-ocean tests of various hydrophysical systems drew the greatest attention. The paper "A Cable Hydrophysical Complex on the Shikotan I. Shelf" by V. N. Mitrofanov, V. A. Jamagaliyev and B. D. Dikhan (SCSRI) presented results of 10-months' continuous recording of near-bottom pressure at a depth of 100 m 12 km off shore, which allowed good study of background phenomena in the boundary area of the ocean.

Oscillations of tidal and non-tidal origin have been distinguished, their spectral analysis has been made. E. A. Kulikov, V. N. Mitrophanov, A. V. Rodionov and I. E. Khaidurov (SCSRI) told about measurements of current velocity oscillations in the Shikotan Island shelf area by the method of recording variations of the vertical component of the electric field. The paper by V. M. Zhak and A. V. Rodionov (SCSRI) and that by M. R. Garber, Y. D. Korbas and V. E. Konnov (Far Eastern Research Institute, State Committee for Hydrometeorology) discussed results of one-year self-contained hydrophysical complexes that were installed twice: in 1980 and 1981 from "Ocean". The hydrophysical complexes included measurements of near-bottom pressure, temperature, integrated velocity and acoustic signals of earthquakes; these were installed at a depth of 35-45 m in the Philippine Sea and at a depth of 135 m off Shikotan Island. The two complexes installed in 1981 are to be picked up in the middle of 1982. In order to test various instrumental and methodical problems (gauges, recording systems, hydroacoustic channel of communication, energy supply systems, etc.), eleven short-time installations have been made which yielded a large amount of data on measurements of different ocean parameters. The experience of such works is very important for development of future Tsunami UAS, therefore, their importance can hardly be over-estimated. It is supposed that similar installments will be regular in future and will be done at great depths in several closely spaced points.

Among the results of Sections I and II, attention should be drawn first of all to the progress in analytical studies, numerical and hydraulic modeling of tsunami run-up onto a shore, detailed studies of tsunami background long-wave oscillations in the near-Kuril part of the Pacific Ocean, considerable expansion of continuous stationary observations of the sea level and other hydrophysical parameters in the open ocean, beginning of serious works on estimation of antitsunami resistance of coastal constructions.

The papers presented at Section III can be divided into the following trends: (1) analysis of seismological processes that cause tsunami, (2) improvement of the existing tsunami warning service, including its partial automation, (3) principally new methods of operative tsunami prediction, and (4) tsunami zonation.

There were five papers relating to the first trend. B. V. Baranov and L. I. Lobkovsky (Institute of Oceanology) in their papers "The Character of Focal Motions of Tsunamigenic Earthquakes in the Kuril Island Arc" and "Tsunami in Back-Arc Areas", firstly, offered a distribution scheme of stresses and seismic focal planes in the Wadati-Zavaritsky-Benioff (WZB) layer, and made an attempt to use the scheme to explain the origination mechanism of tsunamigenic earthquakes, and, secondly, they showed that the seismicity of marginal seas (Okhotsk, Japan, Bering and other) lags behind about a year in phase as compared to that of island slopes or trenches. V. L. Lomtev and V. N. Patrikeyev (SCSRI), in their two papers "A Possible Character of Sea-floor Surface Displacements in the Kuril-Kamchatka Trench Area (as related to the tsunami generation problem)" and "Thrust Structure of the Pacific Continental Slope of Honshu I. (as related to the tsunami generation problem)", based on regional geophysical and geological survey of the Kuril-Kamchatka and Honshu Trenches, support the viewpoint that both slopes of the trenches are of thrust imbricate structure and that the WZB and Tarakanov zones are probably related to these thrust movements. R. Z. Tarakanov, C. U. Kim and N. V. Levy (SCSRI) showed that the WZB layer is divided in plan into alternating blocks with high and low seismic wave velocities that are correlated with the islands and straits of the Kuril Range, respectively. Hypocenters of tsunamigenic earthquakes are attributed mainly to block boundaries; more rigid blocks that are correlated with islands are believed to be more active. Low tsunami activity of the central part of the Kuril Arc is in agreement with its deep structure peculiarities.

The effect of the source proximity to the rim of a near-island underwater plateau on the on-shore tsunami intensity is stressed in the paper by V. V. Ivanov and M. Z. Narbutabekova.

The greatest number of papers belonged to trend 2 and all of them were made by SCSRI scientists, with partial cooperation by representatives of other institutes. Threshold magnitude values to issue tsunami warning in different Far East areas are improved in the papers by A. I. Ivashchenko and A. A. Poplavsky; C. N. Go, A. I. Ivashchenko and S. L. Soloviev; V. F. Vyalikh, F. D. Zhuk and A. I. Ivashchenko; L. S. Oskorbin, E. A. Vorobyova, R. S. Sen and A. K. Ignatov. L. N. Poplavskaya estimated the real accuracy of epicenter location of tsunamigenic earthquakes by the operating tsunami stations. E. A. Vorobyova and V. N. Fercheva improved the possibility of operative determination of epicentral distances from the difference of P, Rayleigh and Love wave arrivals. The papers by R. N. Burimskaya and S. L. Soloviev, and R. N. Burimskaya deal with effectiveness of using new features of tsunamigenic earthquakes revealed by R. N. Burimskaya. The papers by I. V. Nikiforov and I. N. Tikhonov; A. A. Poplavsky, I. N. Tikhonov, N. A. Konstantinova and I. V. Nikiforov show that it is possible to automize the processes of determination of P wave (and S)- arrival time from a seismogram, and determination of the depth interval of an earthquake epicenter from a set of features distinguished within interval S-P.

Only one paper belonged to trend 3. It was presented by V. A. Apanasenko, Y. S. Belavin and A. I. Sharetsky. It suggested that the passing of a tsunami be judged from acoustic field variation between remotely spaced radiators and receivers.

The paper by V. A. Bernshtein summarized results of studies on detailed tsunami zonation of Kuril Isles that have been made in SCSRI for several years. Geologo-geomorphological survey has been made of practically the whole inhabited coast of the islands. One-dimensional calculations of tsunami run-up have been made that make it possible to estimate amplification (attenuation) coefficients of a wave as it runs up and that are used for hydraulic modeling. Further studies on tsunami zonation are hampered by the absence of programs to calculate run-up onto a shore that is non-uniform in plan.

An interesting possibility to determine the actual inundation zones of specific shores by past tsunami is described in the paper by V. V. Ivanov and K. V. Simonov (SCSRI). It has been established that the ring width in cross sections of trees for inundation years is significantly less than the neighboring rings and than the width of rings for the same years in cross sections of the trees that were not inundated. Purely geomorphological signs of inundation of shores by historic tsunami have also been revealed.

The papers of Section IV were closely related to discussions of the meeting of the co-authors of works to create the Tsunami UAS in the Far East. It is quite logical to consider the session of Section IV and the above meeting together.

The papers presented at these two meetings can also be divided into three trends: (1) algorithms and functional schemes of the Tsunami UAS and its subsystems, (2) the structure of telemetric channels for the Tsunami UAS communication, (3) instruments to record tsunami and earthquake parameters in the Tsunami UAS.

At trend 1 a paper on general structure and main tasks of the Tsunami UAS was presented by Y. R. Orshansky (Sakhalin Administration, State Committee for Hydrometeorology). Individual elements of the system are to be operative in the XI five-year plan, and the Far East Tsunami UAS is to be completed in 1990. K. P. Rizhkov (State Committee for Hydrometeorology) told about the new All-Union Scientific-Technical Program to realize the Tsunami UAS.

The papers by A. A. Poplavsky, E. A. Kulikov and I. N. Tikhonov were dedicated to elaboration of algorithms for the Tsunami UAS operation in general, as well as for its hydrophysical and seismological subsystems operation. Real advance and quality of tsunami prediction depend greatly on the location of a probable tsunami source relative to the shore and recording elements of the Tsunami UAS, therefore allowance is made for different system operation regimes, and switch from one regime to another is done by the central controller. The mathematical apparatus of the system includes several packages of programs, many of this have already been worked out and successfully tested. In his paper B. V. Ilyichev (State Committee for Hydrometeorology) states the principles of future integration of the Tsunami UAS with the State System of Climate Observation and Control, and V. M. Uslisty (Sakhalin Administration, State Committee for Hydrometeorology) told about the progress in designing capital constructions for the Tsunami UAS centers.

There were six papers belonging to the second trend. L. G. Kaurov (Kharkov Institute of Radioelectronics) offered a project of telemetry for a marine complex of the Tsunami UAS. A preliminary analysis of measurement methods and their instrumental realization made it possible to reduce the problem of selection of a telemetry structure for a marine complex to the standard form of the problem of optimum mathematical programming. The paper "A Subsystem of a Zone Communication Network" by S. Y. Kolomiichenko, V. K. Persikov, T. P. Petruchek and T. N. Skorikova deals with the principles of organizing a radiochannel between marine measuring complexes and on-shore information collection and processing points. Organization of a radiochannel in the USW band using a radio-relay communication line is believed to be most promising.

In his two papers, K. G. Karnaukh (Scientific Industrial Union of Automatic Control Systems, Kharkov) suggests that standard technical means of local information-control system created based on Soviet microelectronic technique be used in telemetric channels and low-level elements of a marine measuring complex. A set of such means has sufficient information capacity and reliability to ensure primary processing of the information that comes in from the sensors. The paper by A. S. Kasimanov (Irkutsk Branch of the Kiev Institute of Automatics) discusses the structure of a technical means complex of centers of collecting and processing of information that is supplied by Tsunami UAS sensors. The paper by K. G. Panchenko (Kharkov Branch of the All-Union Research Institute of Electroinsulating Materials) offers casing solutions for a marine complex of tsunami UAS instruments. It should be noted that all the papers in this trend dealt with theoretical works mainly which are still far from real implementation, and can be treated as basis for working out detailed technical problems.

The greatest number, 13, of reports belonged to the third trend. The paper "Principles of Constructing Instruments to Measure and Record Water Level and Tsunami Waves" by I. M. Shenderovich and G. N. Mar (Research Institute of Instrumentation, State Committee for Hydrometeorology) describes measuring devices designed by the authors on the basis of a float recorder. The devices can be used to automatically distinguish tsunami waves at the background of tidal and other level oscillations in advance and reliably. A remote level gauge based on the hydrostatic principle is described in another paper by the same authors "Instruments for the Study of Water Level Oscillations in the Sarezskoye Lake". In both cases the primary signal (level, pressure) is transformed into a frequency-pulse modulated electric signal due to which it becomes possible to use hybrid (frequency-digital) filter with needed characteristics in the infralowfrequency range to distinguish tsunamis. The paper "Hybrid (frequency-digital) Filters to be Used in Long Wave Measures" by the same authors and S. A. Folimonov was dedicated to the same problem. M. A. Rakov, Y. T. Dub and M. S. Rozenblat (Physico-Mechanical Institute, Academy of Sciences of the Ukrainian SSR) in their paper "Construction Problems of Lowfrequency Spectrum Analyzers" suggested the use of infralowfrequency analyzers that realize special digital filters on a multi-digit element base for distinguishing tsunami.

The problem of selection of tsunami gauges with reliable metrological characteristics is still urgent. An automatic tsunami observation system should be based on bottom stations, and various hydrophysical parameters should be best measured by quartz gauges that ensure greater recording stability and accuracy than vibrotizon or strain gauges, but unfortunately the available Soviet developments of quartz gauges have not reached commercial production. One such development was discussed in the papers "Quartz Gauges of Hydrostatic Pressure and Water Temperature, and Seas Amplitude and Period" by A. B. Smagin and "Electronic Transformers of Quartz

Gauges" by V. A. Golubev (Kharkov State University). In his paper V. I. Krilovich (Institute of Applied Physics, AS of Bielorussian SSR) suggests the use acoustic measures developed under the author's guidence for recording spatial velocity vector of currents.

Two papers were dedicated to seismological observations instruments in the Tsunami UAS. B. T. Vorobyev (Institute of Physics of the Earth) informed about new developments of long-period DC-BP seismographs to be used in tsunami service and about several other technical means to obtain seismological information. The paper "Automatic Complex for Digital Recording and Primary Processing of Earthquakes" by A. V. Kochergin, A. N. Morgunov and Sen Rak Se (SCSRI) describes a digital complex designed on the basis of the "Planeta-3" computer which is in test operation since 1980 at the Yuzhno-Sakhalinski Station and fulfills primary processing of recorded earthquake signals in the real time scale for tsunami warning purposes.

In general the tsunami meeting was successful. The adopted resolution acknowledges that certain progress has been made in tsunami studies since the previous meeting which is easily seen from the above brief review of the papers. At the same time the meeting revealed certain drawbacks in current tsunami studies. These are (1) absence of reliable methods and computer programs to estimate two-dimensional run-up of a tsunami wave onto a shore, which hampers the solution of the detailed tsunami zonation problem, (2) poor knowledge of hydrophysical processes that occur in the ocean as a tsunami is generated by an earthquake; (3) absence of methods for early detection of tsunami from data of open ocean observations, and (4) insufficient knowledge of most economical means, methods and systems to record tsunami in the open ocean.

The meeting adopted a number of recommendations aimed at directing the main scientific efforts at solution of practical problems related to realization of the Tsunami UAS, rapid implementation of the avilable methods and those under development into the operating Far Eastern operative tsunami warning service and at solution of principal problems of theoretical character.

In spite of unfavorable weather conditions due to the typhoon Phillis that had hit Sakhalin, many participants of the meeting had a chance to go sightseeing in Yuzhno-Sakhalinsk and its vicinity and go on a week's excursion to Kuril Isles.

USE OF THE ABE MAGNITUDE SCALE BY THE TSUNAMI WARNING SYSTEM

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INTRODUCTION

Within the last decade a number of advances have been made in the field of tsunami research which can be of considerable benefit to the Tsunami Warning Centers. In addition, improved methods of quantifying the size of potentially tsunamigenic earthquakes, as well as determining the focal mechanisms, can lead to the possibility of forecasting the likelihood of occurrence and of estimating tsunami wave heights at distant gauges.

In this paper I shall briefly review the procedures followed at the Alaska and Pacific Tsunami Warning Centers in response to earthquakes of sufficient size to activate the centers' alarms. I shall then present the results of some recent tsunami research which could enhance these procedures. In particular I shall describe how data derived from the determination of the Abe tsunami magnitude can be used to estimate tsunami heights at distant gauge sites.

TSUNAMI WARNING CENTER PROCEDURES

The initial task of the centers is to determine the location and size of an alarm earthquake. The location of the earthquake usually presents no problem; the Alaska center is currently recording, in real time, a network of seismographic stations extending from the westernmost Aleutians to New Mexico which is capable of locating a Pacific Basin earthquake to within a few degress accuracy. This data is given to the Pacific center over the telephone and, in turn, the Pacific center supplies data sent from observatories in the southwest Pacific which is used to improve the accuracy of the initial epicenter.

The determination of the size of the alarm quake can be a problem. The Warning centers' procedures are based upon the surface-wave magnitude of the alarm earthquake. This choice of scale was quite reasonable for Pacific rim earthquakes recorded at the Pacific center where epicentral distances are greater than 20°, but at the Alaska center, large earthquakes occur at local and regional as well as teleseismic distances. At the Alaska center, other scales such as a local or body-wave magnitude scale must be used for earthquakes at relatively close distances. Assumptions then have to be made about the relationships of the various magnitude scales in order to perform the appropriate procedure.

Once an alarm earthquake's location and size are determined, appropriate messages are disseminated through various channels. The messages range from a simple exchange of data between the warning centers to the issuance of tsunami warnings via telephone, teletype, and radio to large segments of the Pacific Basin in population. At present, unless the epicenter of a potentially tsunamigenic earthquake is fortuitously near a tide gauge, confirmation of a tsunami can take several tens of minutes to hours. When a tsunami is observed, pertinate data such as observed gauge heights and runups are disseminated in subsequent messages. Finally, when further threat of tsunami damage is over, the tsunami warning is cancelled.

MOMENT MAGNITUDE

Work by a number of investigators has shown limitations on the applicability of magnitude as a measure of the size of earthquakes. Indeed, Richter and Gutenberg recognized limitations of the original magnitude scale which led to their developing the surface-wave scale, M_s, for more distant earthquakes and then the body-wave scale, m_b, to deal with deeper focus earthquakes. These scales are based on the amplitude of a particular seismic wave at a given period as recorded on an appropriate seismograph. As the size of an earthquake increases, and source parameters change, the degree to which the seismographs can faithfully record the appropriate seismic waves in a true logarithmic manner diminishes. Thus for the largest earthquakes, those most likely to generate tsunamis, the scales become inaccurate. For great earthquakes considerable scatter was observed in the relationship of the M_s-scale to other earthquake source parameters because of these inherent inaccuracies.

Kanamori, having shown that the seismic moment can be related to other source parameters such as the source area or seismic energy in a mathematically linear fashion, devised the moment magnitude scale M_w. This scale coincides with the M_s scale for earthquakes in magnitude 6 and 7 range and yet provides a measure which accurately describes the size of even the greatest earthquakes, $M_w > 8$, relative to other source parameters.

The seismic moment can be determined in a number of ways ranging from geodetic measurements and aftershock studies to seismic spectrum analyses and observed versus synthetic waveform correlations. The latter techniques hold promise of being applicable to the warning systems' procedures. A by-product of the moment magnitude determination can be the source mechanism which is an important factor in tsunami generation.

ABE TSUNAMI MAGNITUDE

As an example of how recent research can be applied to the warning centers procedures, consider the Abe tsunami magnitude scale. In 1979, Abe introduced a scale, M_t, such that,

$$M_t = \log H + B$$

where H is the observed maximum wave amplitude (half the crest-to-trough height) recorded on a tide gauge. The factor, B, is a constant for various source-receiver pairs experimentally adjusted so the tsunami magnitude equals the moment magnitude. Abe's purpose for devising this scale was to extend the data base of great earthquakes back into a period when tide gauge data was available but seismic data was not. The relationship of Abe can, of course, be applied in the opposite sense. If given an estimate of the moment magnitude for an earthquake in a particular source area, a forecast of wave heights for gauges in various receiver areas can be made. For example, using the Utsu-Seki relationship, M = log S + 4, it is possible to predict gauge heights for potential earthquakes in the Alaska-Aleutian seismic gaps as follows:

			Honolulu		Hilo		California	
			B = 9.2		B = 9.1		B = 9.3	
Gap	S(km^2)	Mw	logH	H(m)	logH	H(m)	logH	H(m)
Yakataga	15,000	8.2	-1.0	.10	-0.9	.13	-1.1	.08
Shumigan	70,000	8.8	-0.4	.40	-0.3	.50	-0.5	.32
Commander	40,000	8.6	-0.6	.25	-0.5	.32	-0.7	.20

When earthquakes actually occur in these gaps, it will be necessary to determine the moment magnitude in a timely manner in order to forecast the expected gauge heights.

CONCLUSIONS

Recent research has shown that the surface-wave magnitude scale, M_s, is not a reliable indicator of the size of great, potentially tsunamigenic, earthquakes. For example, Figure 1 from Ward (1982), graphically illustrates the effect of focal mechanism on the surface wave amplitude. If forecasting the occurrence of tsunamis and their expected wave heights is a goal of the warning centers, then it will be necessary to find some reliable measure of these great earthquakes. A possible solution to this problem is to apply the methods of seismic spectrum analysis or synthetic seismogram correlation to make a timely determination of the seismic moment and the associated moment magnitude, M_w.

Given a reliable scale of the size of tsunamigenic earthquakes, it will then be possible to make forecasts of wave heights using techniques as simple as the Abe relationship shown here or using more sophisticated techniques involving hydrodynamic wave-propagation relationships.

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LANDSLIDES AND MUDFLOWS IN A YOUNG VOLCANIC HAWAIIAN TYPE STRUCTURE

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A. STRUCTURAL AND CLIMATIC CONDITIONS OF DEVELOPMENT

In the Mascarene group, the emerged part of Reunion Island was built since barely two million years from fluid basalt lava flows and ash layers emitted by two volcanoes whose structure and relief are very similar to the Hawaiian archipelago's youngest constructions.

Still active, younger Piton de la Fournaise (alt. exceeding 2300 m) raises on the southwestern part of older Piton des Neiges (alt. exceeding 3000 m). Both volcanoes give its almost rounded shape to the island whose area does not exceed 1000 square miles (2500 square km).

Striking erosion forms are mainly the result of the sharp topographic contrasts and of general directions suggested by faulting. (Fig. 1).

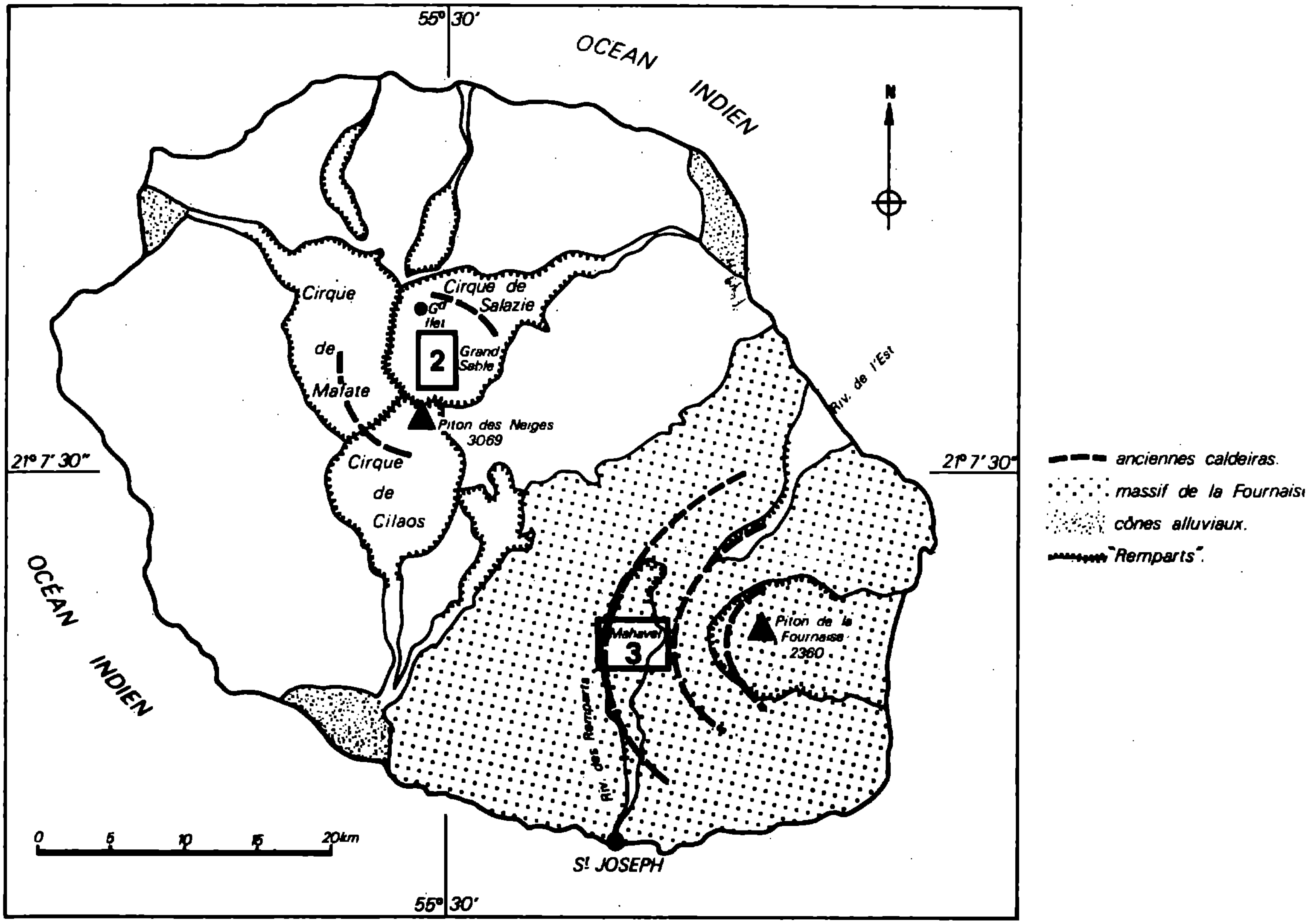

Fig. 1: LA RÉUNION — Structure générale et grandes formes de l érosion.

Three huge amphitheaters or cirques as they are locally known were hollowed out on the northeastern, northwestern and southwestern part of the Piton des Neiges since less than 20,000 years. Their bottom is partly filled up with detritic and clastic material issued from the impressive and steep slopes surrounding them. (Angular slopes up to 70 degrees--height between 500 and more than 1000 m). These slopes are known as Remparts (outer walls, ramparts). Parts of late lava flows poured down from the former summit of the volcanic construction are also present. Gullies and ravines (locally known as ravines) often delimit patches of flat land known as ilets (small islands), most of which were lately occupied at the beginning of the 19th Century by poor white colonists who could not afford buying slaves and expensive coastal land to cultivate sugar cane. Since then, hamlets and even small villages still exist on the ilets of the cirques and in the bottom of the main deep valleys of Piton de la Fournaise (Riviere de l'Est and Riviere des Remparts). Cirque de Salazie and cirque de Cilaos still retain the largest population in this kind of settlement, which nevertheless represent only a minority (a few thousand people) of a whole population (550,000 inhabitants) mainly living in coastal settlements. (Pl. 1-2). Favored by the topography and the structure, erosion is still exaggerated by heavy rains seasonally reinforced by torrential rainfall of hurricanes. Even the sheltered excavations of cirques record more than 3500 m/m per year (average) on windward and 2300 m/m on leeward. Intensity and importance of hurricane's rains may be striking: During the last very serious hurricane which hit the island in 1980, more than 5000 m/m of rainfall were recorded in several altitude locations. Grand Ilet station, (cirque de Salazie), at an altitude of 1110 m, recorded more than 5240 m/m during the same period, the record for 24 hours being 1742 m/m.

In spite of the general permeability of the structure, which accounts for the lack of run-off in most of the younger part of the island, the average flow of the main rivers may be multiplied by 400 or 500 during the ensuing floods. All these factors are highly favorable to the occurence of an extensive range of catastrophic soil movements which actually are one of the prominent features of the erosional processes in Reunion Island.

B. TYPES AND EXAMPLES OF LANDSLIDES

Depending on the nature of the material involved and on the size of the phenomenon, several types of movements are known, from the classical landslide started by the rotational slipping process into a deep clayey material, to the mudflow, through the rock avalanche.

It seems easier for our purpose to establish them into two main families: The superficial and narrowly localized landslides and the deep ones, involving large amounts of material. During or following periods of heavy rains, slopes stability may be locally broken by the weight of water percolated into a permeable layer, or the regression erosion of a spring suddenly reactivated. Superficial landslides so triggered on generally steep slopes pull down the soil and the vegetation with an increasing momentum and efficiency as the mass runs downwards. This case is very commonly met. (Pl. 3-4).

Important to huge landslides involving sometimes quasi instantly the movement of several ten million cubic meters of material are more impressive but fortunately not so frequent. Yet it is clear that a significant part of the amphitheaters and of the major valleys was formed from such events. Clastic material of slides often dammed the rivers, the dams being later broken by floods, then mudflows spreading the elements of former landslides downstream and sometimes down to the entrance of the gorge by which each cirque is open towards the coast. Numerous outliers of such sequences may be observed. The island has been settled since barely more than three centuries, but even during this short period of time, and most probably under a present climate less aggressive than under some past quaternary episodes, several hugh landslides have been observed. With population increase, this hazard has even proved to be a danger not only for economic activities but for man, too. The characteristics of three big landslides are summarized hereunder.

Grand Sable's landslide occurred on 11.25.1875 in the southwestern part of cirque de Salazie. Tiers, already depressed under the level of the top crest of Piton des Neiges fell, most probably because of the drawing off of downstream thermal springs. The landslide was channelled on a distance of two kilometers between altitudes 1800 and 900 M. by a small valley. It was stopped by a detritic hill which was partly destroyed (Piton de Grand Sable) and dammed temporarily another valley (Riviere des Fleurs Jaunes) from which its channel was a tributary. Material was about 40 to 50 meters thick and the volume was estimated, depending on authors, between 20 and more than 70 million cubic meters. Witnesses said that the flow took no more than 2 to 3 minutes to reach its final location. Boulders were thrown on the surface of an ilet more than 100 meters above the bottom of the valley des Fleurs Jaunes and earth shaking triggered a few minor landslides downstream. Sixty-two people were killed, buried with their houses (Fig. 2).

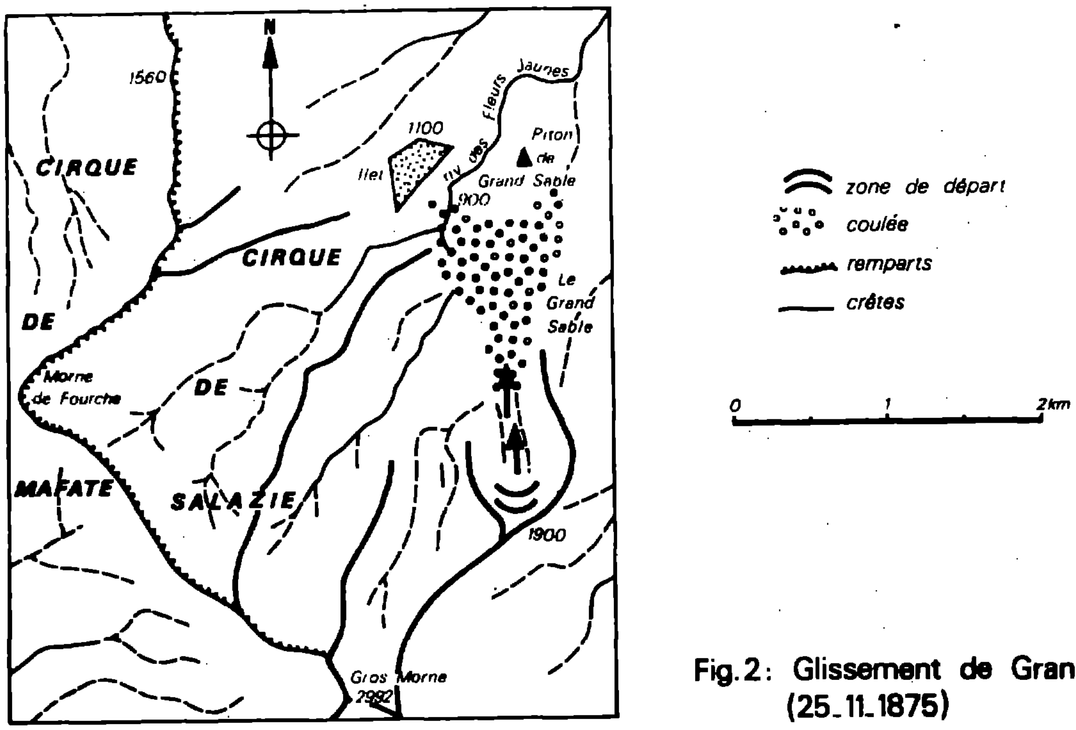

Fig. 2: Glissement de Grand Sable. (25.11.1875)

Bras de Mahavel's landslide took place on 05.06.1965, after a period of continuous rainfall in April, at the end of the rainy season. Material came from the edge of the catchment area of a tributary of the Riviere des Remparts. Structure and dip favored drawing off in an highly permeable surrounding of young volcanic material. Deep cracks were noticed later beyond the edge of the catchment zone.

The material of the landslide was heterogeneous, yet very wet ash, scoria and clay dominated and were mixed with blocks, often bigger than one cubic meter. The flow took also a very short time to went down on a distance of about 4 km from around 2000 - 23000 m. to less than 700 m. in the bottom of the Riviere des Remparts. Vegetation was destroyed up to more than 100 m. above the bottom of the Bras de Mahavel on the slopes near the junction with the main river. Here again, the tributary valley channelled the flow which dammed the main valley. The dam was 40 to 50 m. high, its width exceeding locally 500 m. The volume of the landslide was estimated between 20 and 50 million cubic meters. As there was no settlement in the junction zone of the two valleys but only ilets upstream and downstream in the Riviere des Remparts, there were no casualties. A channel was dug out in the upper part of the dam, which was closely watched to ensure the security of the little town of Saint-Joseph, built on the coast at the river's mouth. Yet underground run off proved to be so important that only a short lived lake was formed behind the dam (Fig. 3).

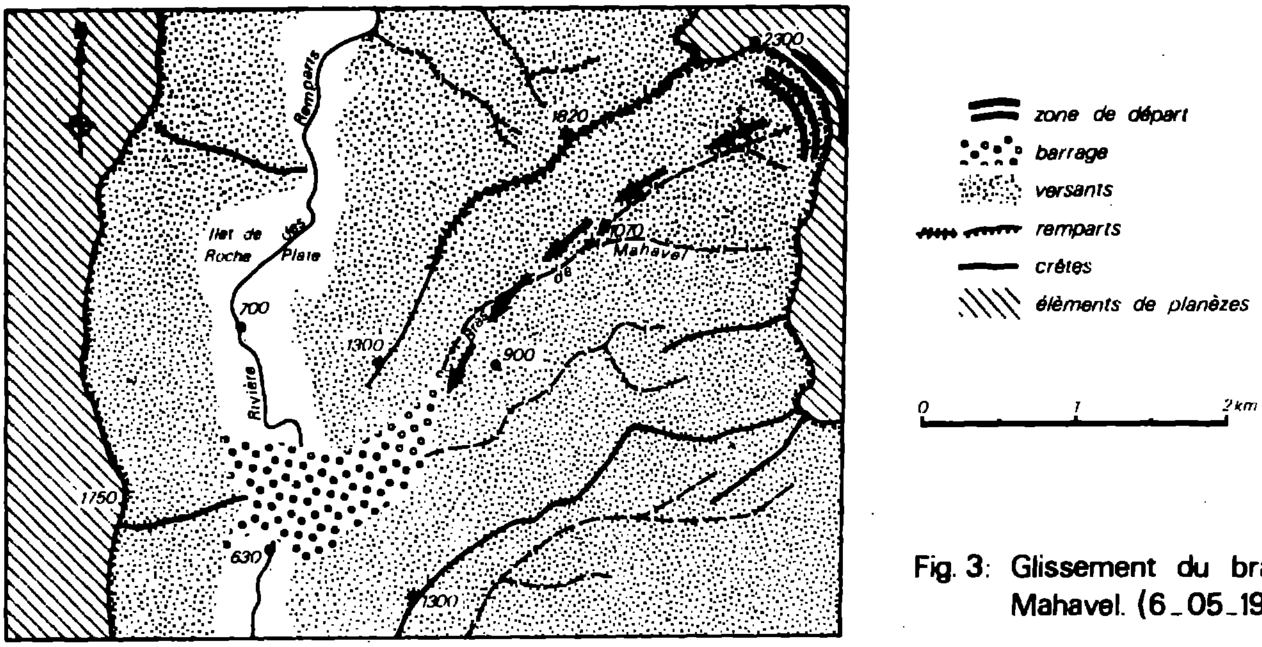

Fig. 3: Glissement du bras de Mahavel. (6_05_1965)

During the very serious hurricane Hyacinthe, which recently hit Reunion Island (01-15/29-1980) more than half of the 25 deaths were caused by landslides. Ten people were killed in the western part of cirque de Salazie, near Grand Ilet Village. A landslide, involving clastic material and channelled by a gully, moved on 1 km. between altitudes 850 and 650 m. High impregnation by heavy rains (exceeding 5000 m/m in 12 days) and the presence of an underground sill dipping downstream seem enough to explain the triggering. The landslide took place at the end of the rains brought by the hurricane (01.28. 1980) (Humbert, Pasquet, & Stieljes, 1981).

C. PREPAREDNESS AND MITIGATION

After hurricane Hyacinthe, the French Bureau de Recherches Geologiques et Minieres (BRGM), National Geological Service, prepared detailed maps of the different "Geological risks" for the two cirques of Salazie and Cilaos where landslide hazard is the most obvious for local populations.

Maps are at the scale of 1:25000 and show risk zones for each physiographic unit in the cirques:

- Remparts and their edge
- Main inlets
- Isolated prominent summits of the bottom or the rim of cirques
- Valley bottoms

For each subdivision of these units, where risks have been represented according to the geomorphological maps symbols are given in addition:

- An historical record of the striking known phenomenons
- The detailed list of geological risks (rockfalls, landslides, subsidences, earth falls, gullying)
- Recommendations and priorities for mitigation.

BRGM more generally recommends:

- To reinforce watching during heavy rain periods in settled zones identified as "high risk zones"
- To improve vegetation cover in all vulnerable zones, wherever possible
- To better adapt public equipment (roads, telephone, etc.) to what should be considered as a permanent risk, only aggravated during "climatic crises" (hurricanes).

Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM) tries, in a paralled direction, to compute the balance of natural hazards in the French overseas Departements and Territories as a whole. This study will be partly done for the Pacific Territories, in cooperation with the regional project of East West Center (Pacific Islands Development Program) on natural hazards preparedness and mitigation in the South Pacific countries.

This research program involves integrated mapping of the zones of risk for different hazards, based on historical records, and including equipments, resources and productions indexes, and population location, for a better mitigation approach and consequently a better integration of hazards into regional planning.

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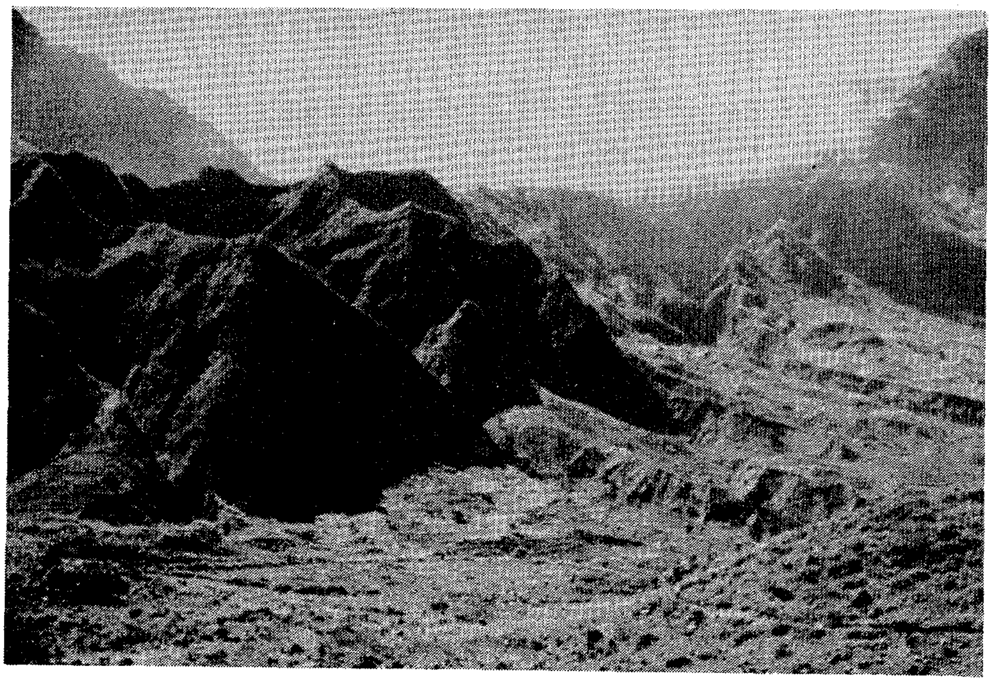
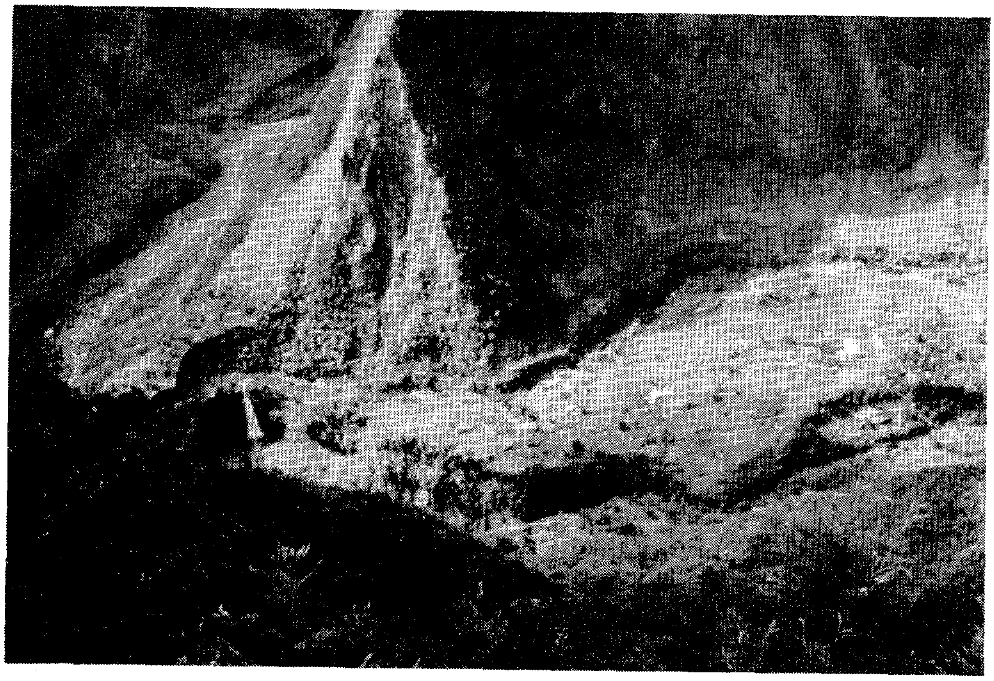
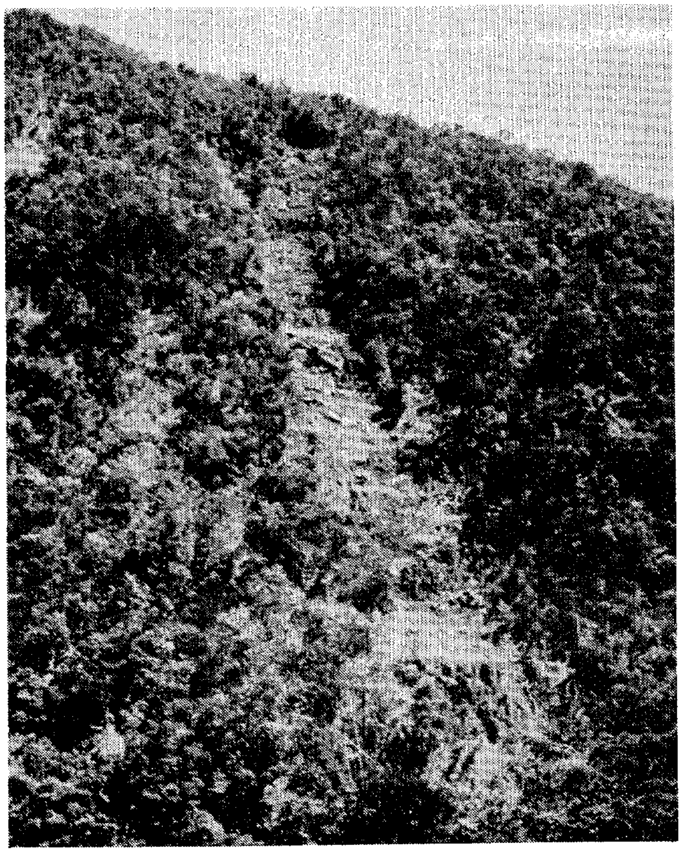


1. Reunion Island : Type of landscape in the "cirques" (cirque de Mafate). Depressed tiers in front of surrounding "Remparts" and detritic filling of the bottom are deeply dissected.



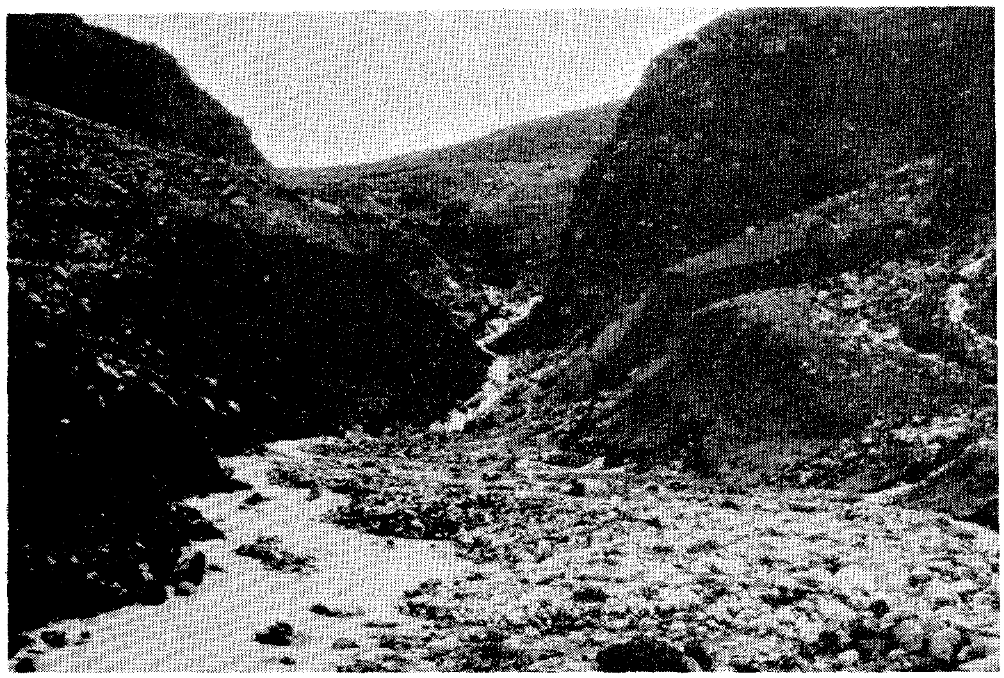
2. Reunion Island : Type of landscape in one of the main deep valleys. An "Ilet" and its settlement in the bottom.



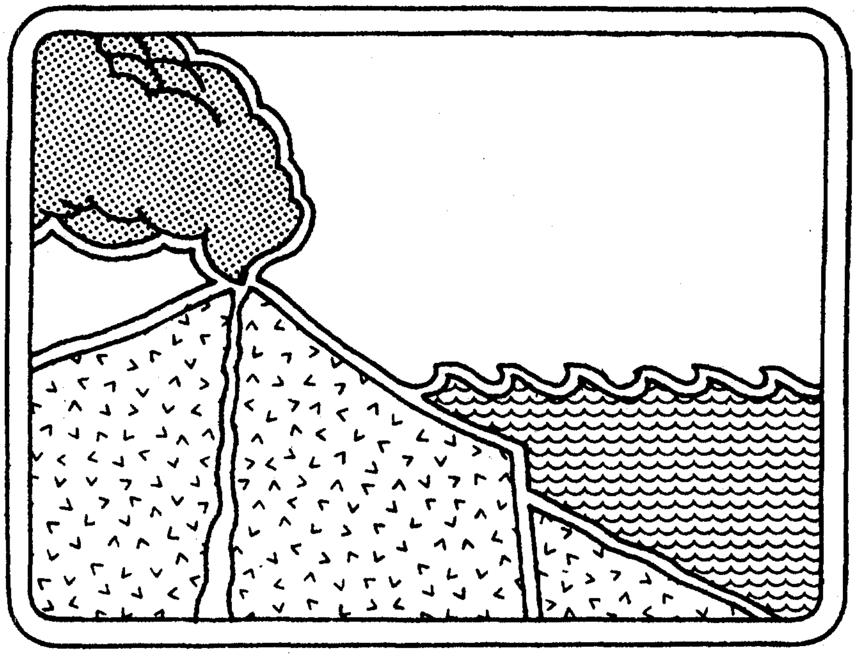
3. Réunion Island : Superficial landslide on a steep slope.

4. Reunion Island : Downstream part of the same landslide showing the vegetation pulled down.

5. Reunion Island : Huge deep landslide of the Bras de Mahavel (05.06.1965). General view, looking upstream, of the landslide which came from right hand and dammed the Riviere des Rempart's valley.



6. Reunion Island : Close view of the central part of the dam resulting from the Bras de Mahavel's landslide. Looking upstream.



A NUMERICAL TRACKING OF THE 1883 KRAKATOA TSUNAMI

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ABSTRACT

The 1883 Krakatoa tsunami around the Sunda Strait was studied by using a simple numerical model of finite difference method which had already established in a computer programme. It is well known the fact of 1883 Krakatoa eruption but the tsunami. As the author reviewed some of old publication concerned to Krakatoa eruption, he felt it to be necessary to track 1883 Krakatoa tsunami numerically. For simplicity, equivalent parameters for the tsunami source were introduced as Nakamura did in his numerical models previously, that is, vertical displacement of water surface in the source area and its duration time. The source area in the numerical computation was assumed to be almost same to the area of Krakatoa Island. Grid spacing was taken to be 22 km to east and west in the area of 4°S to 9°S and 102°E to 108°E. The author tried to find properties of the tsunami front, arrival time and tsunami height on the basis of the numerical computation. Estimated value of the wave energy trapped in the Sunda Strait was about 54 % of the initial increase of an equivalent potential energy at the tsunami source area as a vertical displacement of the water surface. This result seems to be suggestful for a tsunami in a strait or channel of similar dimension, for example, the Kii Channel in Japan. An energy pertition was discussed refering to the numerical tsunami model and the energy of the eruption evaluated by Yokoyama(1981).

I. INTRODUCTION

The most part of Krakatoa volcano above the sea dissappeared at a big eruption on 27th August 1883. This eruption affected to the climate in the world. As for this eruption, many of scientific reports were prepared and published, for example, a report which was published by the Royal Society in 1888(Symons,1888). Surveys has been continued even at present to learn the activity of the Krakatoa and natural conditions around Krakatoa. In the third chapter of Symons' report, Captain W.J.L. Wharlton gave a statement on the data of the tsunamis accompanied by the eruption. He noted the seismic sea waves at the sites around the Indian Ocean, i.e., on the Indonesian coast and on the Australian coast. We can easily find the other works on the eruption (cf. Pigeaud,1968; Dept.Pertanian, 1968; Kusumadinata,1979; Perpustakaan, 1938; Judd,1899), while these reports the eruption and earthquakes to the details and only a little of tsunamis on the coast. According to the report(p.142) written by Symons(1888), the eruption caused to the sudden seismic sea waves at 4:00 pm on 27th August at Cossack(20°41'S, 117°11'E) on the coast of the Western Australia The maximum disturbance was 5 feet. At Geraldton, the sea level drew down to 6 feet suddenly at 8:00 pm on 27th August. On the other hand, a chronological catalogues of tsunami(Iida et al.,1967; Soloviev and Gao,1974) state that the tsunamis accompanied by the Krakatoa eruption affected to the sea level on the sea level on the south American coast facing the Pacific and the disturbances of the sea level were 0.5 to 1 m.

Nakamura(1979, 1980) has studied statistically to predict generation and occurrence of tsunamis on the coast of Indonesia. In his studies, he focused only for analysis of tsunamis generated by the earthquakes under the sea for his convenience with a reasoning that the tsunamis accompanied by the eruption was physically different from the tsunamis caused by the earthquakes under the sea in its generating mechanism. The author feels that the Krakatoa tsunami should be studied even with a limited reference

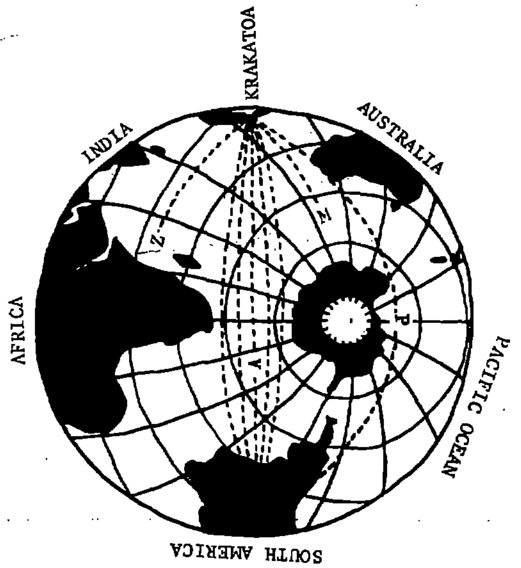

Fig.1 Wave rays of the 1883 Krakatoa tsunami

data not only oceanographically but volcanologically or seismologically. Soloviev and Gao(1974) classified the 1883 Krakatoa tsunami as a volcanic tsunami to separate seismic tsunami, and they noted that the tsunami generated at Krakatoa eruption at 10:02 on 27th August 1883 and the highest sea level was 4 m on the south coast of Sumatra and 2 to 2.5 m on the west and south coasts of Java.

Terada(1923) gave a remark on waves generated by the eruption in his oceanographic text book as follows: waves generated at the Krakatoa eruption propagated to affect the sea level not only on the Indian Ocean but the Pacific and Atlantic Oceans. His estimated arrival time of the tsunami at each site showed that the actual arrival time was not so early as estimated but delayed as far as he refered to the long wave theory of $v = \sqrt{g(h+a)}$, which gave wave velocity v for given water depth h and tsunami height a. In this case he noted the period of the waves coincided well to that of the secondary undulations induced in the water between Java and Sumatra.

As for studies on tsunamis accompanied by landslides or volcanic activities, we can find numerical experiments of tsunami around Shimabara Peninsula, Kyushu, Japan(Aida, 1975). We should have a scientific qualification at evaluation of such volcanic tsunamis. In this study, the author assumes that a tsunami generated at a volcanic eruption can be studied similarly to tsunamis accompanied by earthquakes under the sea and that a finite difference method, utilized previously(Loomis, 1972; Nakamura, 1981a,b; 1982), is applied to numerical experiment of the 1883 Krakatoa tsunami. Refering to the numerical result, propagation, height and arrival time of a tsunami in the experiment are studied with an introduction of a set of equivalent tsunami source parameters,i.e., vertical displacement of the water surface and its duration time in the source area. Tsunami energy trapped in the Sunda Strait is also estimated as the Sunda Strait is similar to the Kii Channel in Japan in its scale the numerical result seems to be suggestful to learn properties of tsunamis around the Kii Channel. The estimated tsunami energy in the numerical model was compared with the eruption energy evaluated by Yokoyama(1981) to discuss partition of the energy of the eruption energy or transfer of the energy to form tsunami.

II. AREA FOR NUMERICAL STUDY

It is noted that the 1883 Krakatoa tsunami propagated and affected to not only the Indian Ocean but the Pacific and Atlantic Oceans. Possible paths of the tsunami can be drawn by dotted lines as shown in Fig.1. A possible path from the Sunda Strait to the Pacific coast of the south America through the circum-polar sea could be shown by a path P in Fig.1. A path A must be that of the tsunami propagated to the south American coast facing the Atlantic Ocean. We have no record of the 1883 tsunami on the coasts of Africa and of Antarctica, though the tsunami surely affected to both of the coasts. If nobody witnessed the tsunami, there should be no trace or no record. Even with the above bold tracing of the tsunami, is it reasonable that the tsunami height of 0.5 to 1 m was observed on the Pacific coast of the south America? It is necessary to have a global understanding of the tsunami propagation, however the author, at present, cannot give any direction to this.

In this study, the study area is taken as shown in Fig.2, where the area is in the ranges of 1 to 11°S and of 101 to 109°E respectively. A grid spacing of 1/5 degree was taken for the numerical experiment. The bathymetry in this area was taken from the nautical charts published by the Hydrographic Office, Japan Maritime Safety Agency and the water depth at each grid point was obtained by an interporation. In this area, the maximum water depth in Java Sea was about 50 m neighbour Jakarta and the maximum water depth in the Sunda Trench was about 5,600 m. With conditions for the water depth and the grid spacing, time stepping was selected to be Δt = 0.01913 hour in order to satisfy Neumann's condition of stability for numerical computation.

III. WAVE SOURCE

In this study, an equivalent tsunami source was taken as a square of about 44×44 km^2 which covered four grid points corresponding the Krakatoa volcano in the Sunda Strait. In order to characterize the initial disturbance in the tsunami source area, the vertical displacement of the sea level W and its duration time T were introduced as were previously (Nakamura, 1981a,b; Nakamura and Allison, 1981). For a convenience to a numerical computation, the author assumed $W = 0.1$ m. The duration time was taken as $T = 100$, 200, 400 and 800 sec respectively. With these initial conditions and the given boundary conditions, we can get a numerical result for all grid points in the water area. The author focused

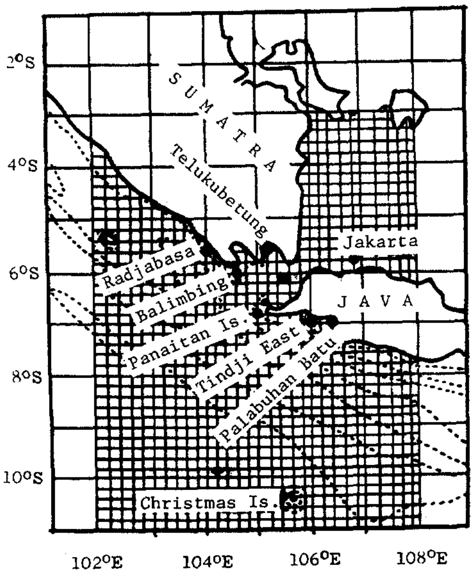

Fig.2 Schematic grid spacing diagram for numerical experiment

only to the numerical evolutions of the water level at Telukubetung in the Sunda Strait, Balimbing and Radjabasa on the coast of the Indian Ocean, Jakarta on the north coast of Java, Tindji East and Palabuhan Batu on the south coast of Java and Christmas Island(cf. Fig.2).

IV. TSUNAMI FRONT

Now, consider an initial displacement of the sea level as much as 0.001 time of the vertical displacement W in the tsunami source area as an indicator of the tsunami front the propagation pattern of this front can be shown as in Fig.3. This pattern is independent of the duration time T in the numerical model. In Fig.3, the front propagated into the Indian Ocean in 0.2 hour after the disturbance was occurred in the source area. After 1 hour elapse, the front in the Indian Ocean passed Christmas Island, and the front in the Java Sea is not so far from the north entrance of the Sunda Strait. The propagation pattern of the front in the Indian Ocean looks like that of a Cauchy-Poisson wave.

V. TSUNAMI IN COASTAL ZONE

Numerical evolution of tsunami for W = 0.1 m and T = 100 sec is as shown in Fig.4(a) and is in Fig4(b) and (c) for T = 200 sec and 400 sec with W = 0.1 m respectively. In the range of the duration time T considered in this study, the disturbance at a given time and a grid point is numerically proportional to T as a trend. This proportionality was already confirmed in the previous studies of numerical tsunami model (Nakamura, 1981a,b; Nakamura and Allison, 1981; Nakamura, 1982). Generally speaking, the waves generated as above in the model could be like a Caichy-Poisson wave if T was sufficiently small and could be like an undular bore if T is large enough. Although, the realistic value of T must be in a certain range between two values of not too small and not too large concerning to the condition

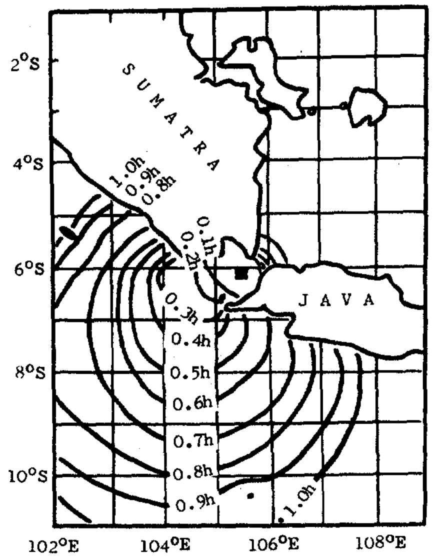

Fig.3 Propagation of tsunami front

of the Krakatoa eruption. At present it is possible to take an arbitraty combination of W and T. Yet we have to confirm whether the arbitrary combination is realistic or not in the numerical model. On the other hand, the bathymetry and geometry of the Sunda Strait is so complicated that the generated waves transforms into complex waves after repeating reflection, refraction and diffraction. If we could have a mareogram including the tsunami in the considering area, we can learn whether the numerical model is appropriately reproduced or not.

Terada(1923) noted that the Krakatoa tsunami had a significantperiod which coincided well to the period of the secondary undulation in the Sunda Strait, however the numerical result as shown in Fig.4 suggests that this secondary undulation is significant only in the area of the Sunda Strait. With a bold assumption of mean water depth $h = 90$ m and width of the Strait $L = 60$ km for the secondary undulation in the area between Sumatra and Java, we have a Merian's period $T_m = 1.1$ hour of an uninodal oscillation. This merian's period T_m seems to be reasonable to understand the

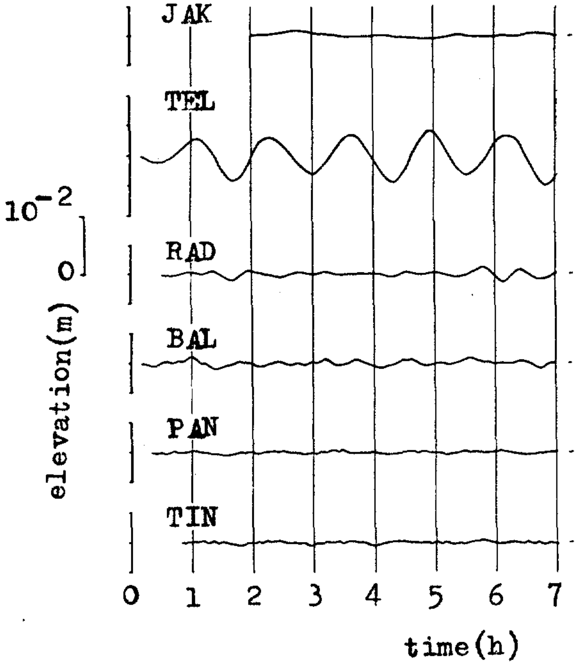

Fig.4(a) Computed mareograms of 1883 Krakatoa tsunami model for $W = 0.1$ m and $T = 100$ sec

JAK:Jakarta
TEL:Telukubetung
RAD:Radjabasa
BAL:Balimbing
PAN:Panaitan Is.
TIN:Tindji East
PAR:Parabuhan Batu
CHR:Christmas Is.

wave pattern at Telukubetung as shown in Fig.4(a) to (c).

As stated above, the author evaluated the period of a normal mode in the Sunda Strait about 1.1 hour with a bold assmption. While, a maximum of autocorrelation was found at the lag time of 1.30 hour for the model tsunami at Telukubetung. The relation between the autocorrelation and the lag time was obtained from the numerical tsunami evolution of Fig. 4(a) for 6.4 hours(128 data read every 3 min) after 0.6 hour elapse from the initial disturbance. The result shows that the tsunami evolution is consisted simply by a main component with a period of 1.30 hour.

With a fast Fourier transform(FFT) analysis for the above data by using a micro-computer PS-85 made by TEAC, a diagram of the amplitude spectrum was obtained to show the first ten harmonics out of 64 harmonics. The result of the analysis shows that a single sharp peaking is at the fifth harmonics, i.e., the corresponding period is 1.28 hour which coincides well to the lag time of 1.30 hour for the first maximum of the autocorrelation. This significance suggests that the oscillation induced in the Sunda Strait is almost monochromatic, and that a possible mode must be an uninodal lateral oscillation in the Strait.

In addition, as easily found from Fig.4(a) to (c), the initial disturbance is a draw-down at each place, i.e., Telukubetung, Rajabasa, Balimbing and Panaitan Island. In this

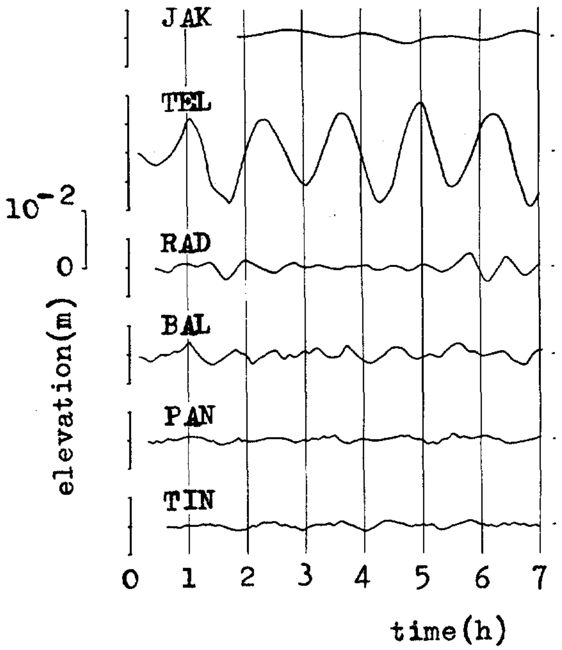

Fig.4(b) Same as Fig.4(a) except T = 200 sec numerical computation, an initial raise of the sea level was considered in the source area so that the sea level around the source area should be drawn down to hold conservation of the water mass instantaneously in the considering area quite similar to a sudden disturbance at the mid of a closed basin.

VI. SPACIAL PATTERN OF TSUNAMI

A disturbance generated in the source area propagates into the surrounding area with time elapse. The numerical propagation of the tsunami for W = 0.1 m with T = 100 sec is shown in Fig.5 (a) to (f). In this case the disturbance of 0.001 time of W is taken to indicate the tsunami front. Full lines in Fig.5 show the sea level coincide to the initial level after passing the tsunami front. Disturbances above and below the initial sea level in Fig.5 are shown by crosses and by dots respectively. So that, in Fig.5(a) the water level is lower than the initial level just around the wave source area at the instance of the disturbance appeared as well as the water level is higher than the initial level in the southern part of the Sunda Strait facing the Indian Ocean. This pattern varies its place time to time. From Figs.4 and 5, it is easily understood that the disturbances in the Indian Ocean is smaller than that in the Sunda Strait. Although, the spacial pattern of the disturbance is not necessarily so simple.

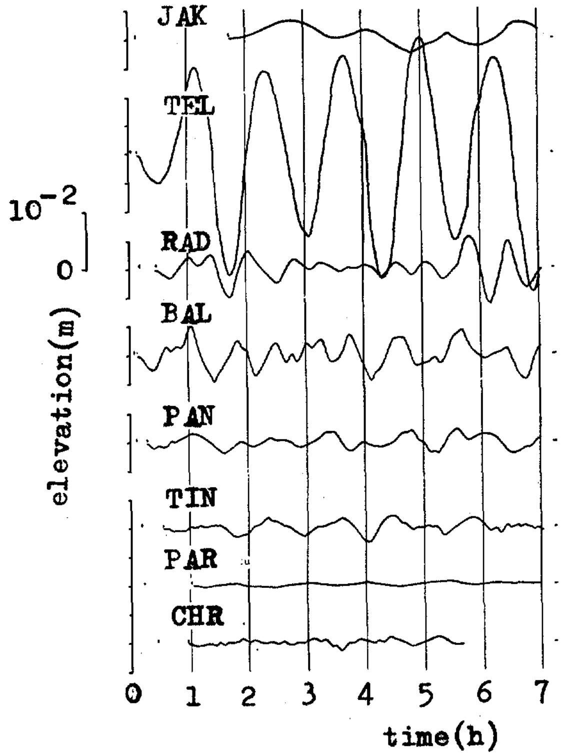

Fig.4(c) Same as Fig.4(a) except T = 400 sec

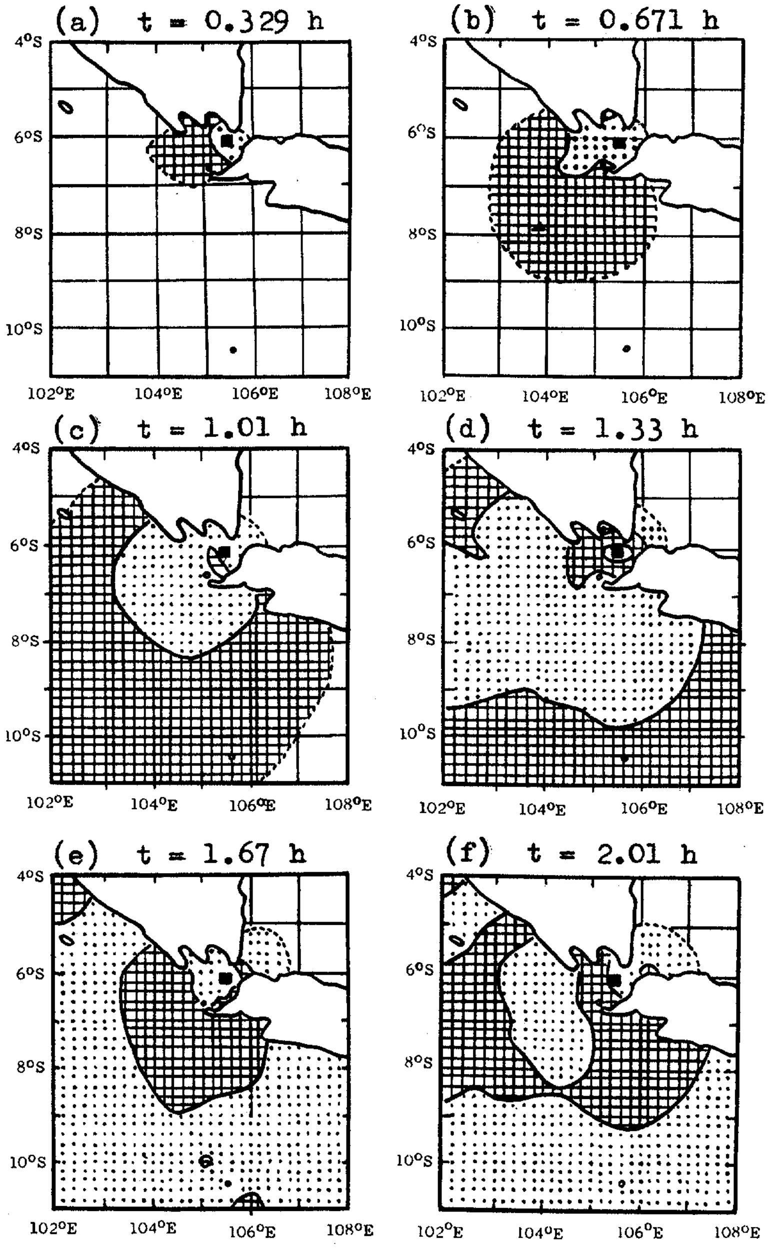

Fig.5 Time-stepping wave patterns of 1883 Krakatoa tsunami model

VII. ARRIVAL TIME OF TSUNAMI

Nakamura(1981a,b) considered that arrival time of tsunami could be defined by times P and Q. In numerical computation the time P, defined as the time when an initial disturbance was appeared in the numerical model, is so early with a very small initial-disturbance that it is hard to distinguish and identify the corresponding disturbance on an analog record even if a tsunami is superposed by the tides. On the other hand, the time Q in numerical computation could be almost same to so called "arrival time of tsunami" which was determined on mareogram which was defined as the time when the disturbance exceeded several millimeters in practice. A numerical example for Krakatoa tsunami was shown in Table 1, where the source conditions were $W = 0.1$ m and $T = 100$ sec. From this table, it is easily understood that the time Q_4 or Q_5 was hardly obtained from any mareogram including a tsunami. Although, the time Q_4 or Q_5 can be obtained from a time-stepping numerical computation. In addition, the time Q_4 at some station looks to indicate an arrival time of a gravity long wave with a propagation speed of $\sqrt{gh}$, where g:gravitational accereletion and h:water depth respectively. The propagation of a wave with a speed of $\sqrt{gh}$ must be that noted in Terada's text book of oceanography (1923). On the other hand, what Munk(1980) noted about his experience of 1951 nuclear bomb experiment seems easily understood by introducing the times P and Q defined by Nakamura in 1981 as stated above. The time P can be obtained only numerically or theoretically, while the time Q can be read even from a mareogram.

VIII. TSUNAMI HEIGHT

With a numerical experiment of tsunami height, we expect to find an empirical relation between the size of the water surface disturbance and

Table 1 Arrival time of Krakatoa model tsunami

Station	P (arrival of disturbance)		Q	
	displacement (m)	time (h)	Q_5 (h) $[\lvert H\rvert=10^{-5}\text{m}]$	Q_4 (h) $[\lvert H\rvert=10^{-4}\text{m}]$
Jakarta	1.32×10^{-22}	0.134	1.57	1.97
Telukubetung	-7.23×10^{-7}	0.0574	0.0957	0.153
Radjabasa	-8.09×10^{-2}	0.172	0.383	0.498
Balimbing	-1.03×10^{-6}	0.0766	~0.11	~0.15
Panaitan Island	-6.89×10^{-11}	0.0957	~0.22	~0.3
Tinji East	-1.06×10^{-7}	0.172	~0.53	~1.1
Christmas Island	9.14×10^{-47}	0.421	~0.88	~1.8

Table 2 Height of Krakatoa model tsunami

Station	Duration time			
	$T=100$ sec	$T=200$ sec	$T=400$ sec	$T=800$ sec
Jakarta	6.52×10^{-4} (m)	1.30×10^{-3} (m)	3.25×10^{-3} (m)	7.08×10^{-3} (m)
Telukubetung	4.06×10^{-3}	8.11×10^{-3}	2.01×10^{-3}	4.27×10^{-2}
Radjabasa	1.16×10^{-3}	2.32×10^{-3}	5.68×10^{-3}	1.14×10^{-2}
Balimbing	1.10×10^{-3}	2.17×10^{-3}	5.17×10^{-3}	9.28×10^{-3}
Panaitan Island	4.87×10^{-4}	9.52×10^{-4}	2.14×10^{-3}	3.40×10^{-3}
Tindji East	3.86×10^{-4}	7.81×10^{-4}	1.92×10^{-3}	3.23×10^{-3}
Christmas Island	2.32×10^{-4}	4.44×10^{-4}	9.85×10^{-4}	1.89×10^{-3}

the tsunami. If we take the disturbance $W = 0.1$ m with its duration time $T = 100$, 200, 400 and 800 sec, the maximum water level for initial 13 hours can be obtained from a wave evolution of a numerical as shown in Table 2.

When a reference is taken what is written in the chronological catalog of tsunami(for example, Soloviev and Gao, 1974), i.e., the tsunami height at the 1883 Krakatoa eruption was 30 m in the Sunda Strait, 4 m on the south coast of Sumatra, 2 to 2.5 m on the north and south coasts of Java, the author tends to consider that this historical records must have a corresponding property to the waves for $T = 100$ sec numerically and qualitatively. There are complex coastlines and complicated bathymetry in the area for numerical computation. Adding to that, the waves could be characterized by a nonlinear effect in its transformation, however simply a linear consideration was given to find an essential property of the waves. With this and by taking a tsunami height scale of 7000 times for $T = 100$ sec in Table 2, we have numerical tsunami height of 28 m at Telukubetung in the Sunda Strait, 7.7 m at Balimbing on the south coast of Sumatra and about 3.5 m at Panaitan Island, south of Java. This numerical result seems to suggest that an equivalent disturbance can be characterized by $W = 700$ m. A remark should be reminded that the tsunami height shown in Table 2 was not necessarily corresponded to the crest height of the first wave.

Nakamura(1981a) tried to confirm whether the numerical model reproduced a tsunami superposed on a mareogram for grid spacing $\Delta x = \Delta y = 4{,}540$ m. As for 1977 Sumbawa tsunami on the Indonesian coast, a numerical experiment for 20 km grid spacing has been considered to be appropriate in its reproductivity only for recorded traces of the highest water level. Adding to the above, Nakamura and Allison(1981) confirmed that a numerical model of 27.5 km grid spacing for 1977 Sumbawa tsunami on the western Australian coast reproduced a smoothed tsunami evolution after 3 hours running mean processing. With these experiences, we have to confirm carefully whether the 1883 Krakatoa tsunami is well reproduced or not. Refering to Terada's note (1923), a secondary undulation in the Sunda Strait can correspond to the wave evolution at Telukubetung. As far as we take that the 1883 Krakatoa tsunami is reproduced by the numerical model, the numerical result in this work can be taken as a meaningful result.

IX. TSUNAMI ENERGY

In Fig.4, we can find that an oscillation at Telukubetung is almost regularly periodical and its duration must be more than 7 hours without any significant dissipation. If we consider an extensive linear relation between the values of W and the height of Krakatoa model tsunami as shown in Table 2, and take $W = 700$ m, then the oscillation at Telukubetung can be characterized by 49 m of wave height and 1.1 hour of wave period. In this case, we have to find a reasonable and physical understanding for little decay of the wave with a fairly large amplitude for a long time even though the given bathymetry is very complex. A part of the wave energy must be dissipated by effect of friction at the sea bed and by formation of eddies and turbulences, and some parts of its energy are transfered into the Indian Ocean and into Java Sea. With our knowledge about oscillations of water in bays, channels and closed basins(for example, Nakamura,1981c), we tend to consider that the tsunami energy in the Sunda Strait is effectively used to form a normal oscillation in the Strait, and that its energy seems almost completely trapped in the Strait.

When the water level changes as much as $\Delta h = 700$ m in the source area, this gives an increase of potential energy of the water column in the source area, that is,

$$E'_p = \rho g \Delta h \sim 7{,}000 \text{ N.m} = 7{,}000 \text{ joule} = 7\times 10^{10} \text{ erg}$$

So that, total increase of the above potential energy E_p over the whole area S of the source could be given by

$$E_p = (\rho g \Delta h)\, S$$

If the source area is taken to be covered by the area represented by four grid points, then,

$$S = 4\times(22)^2 \text{ km}^2$$

and

$$E_p = 1.355\times 10^{13} \text{ N.m} = 1.355\times 10^{13} \text{ joule} = 1.355\times 10^{20} \text{ erg}$$

On the other hand, let us consider to evaluate boldly the energy of the oscillation induced in the Sunda Strait. The energy for a unit area is

$$E'_t = \frac{1}{8}\rho g H^2$$

for a given wave height H. If the total area of the Sunda Strait is A, the total energy of the oscillation in the Strait is obtained by

$$E_t = \left(\frac{1}{8}\rho g H^2\right) A$$

where $H = 25$ m and $A \sim 25\times(22)^2\text{km}^2$. Thence,

$$E_t \sim 7.33\times 10^{12} \text{ N.m} = 7.33\times 10^{12} \text{ joule} = 7.33\times 10^{19} \text{ erg}$$

With these values of E_p and E_t, the tsunami energy emitted into the Indian Ocean out of the Sunda Strait can be evaluated as

$$\Delta E = E_p - E_t \sim 6.22\times 10^{12} \text{ N.m} = 6.22\times 10^{12} \text{ joule} = 6.22\times 10^{19} \text{ erg}$$

This shows that the emitted energy into the ocean is about 46 % of E_p and the wave energy trapped in the Strait is amounted as about 54 % of E_p. In Fig.4, it is found that the first crest height is almost same to the successive crest height as is for wave height. So that, this energy partition process must be established in a short time, i.e., 1 to 2 hours after the tsunami generated.

Recently, Yokoyama(1981) worked on the 1883 Krakatoa eruption as a geophysical interpretation. He evaluated the energy of the 1883 Krakatoa eruption

$$E_{er} \sim 1.4\times 10^{24} \text{ erg}$$

Comparing to the energy of the 1883 Krakatoa tsunami estimated above as

$$E_p = 1.355\times 10^{20} \text{ erg}$$

it can be taken as that almost ten-thousandth of the eruption energy was transfered into the tsunami energy.

The above estimate should be confirmed whether it is reasonable to the details refering to the data which cannot be utilized in this numerical experiment. An extensive work of the 1883 Krakatoa tsunami in a global scope is yet left to be solved.

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HURST PHENOMENON IN TSUNAMI-GENIC EARTHQUAKE DATA

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ABSTRACT

Global tsunamic-genic earthquake data for the period 1883 to 1980 was subject to Hurst analysis. The results showed that whereas earthquakes in the Richter magnitude range of up to less than 8.5 might not be totally random, the very large earthquakes (with magnitudes 8.5 or greater) may occur totally randomly in time and it probably is impossible to predict the time of their occurrence.

1. Introduction

The last two to three decades of research on earthquake prediction has shown (e.g. see Murty, 1977) whereas those earthquakes with Richter magnitude of up to 8.0 might be somewhat predictable, those earthquakes with magnitudes approaching 8.5 or greater might never be predictable and these largest earthquakes occur totally in a random fashion. This has very interesting but somewhat disturbing implications for the prediction of tsunamis which are mainly generated by the largest undersea earthquakes. If the above result is true, then major tsunami-generating earthquakes might never be predictable as to the time of their occurence.

Making use of the observational data on tsunami-genic earthquakes for the period 1883-1980 (Wigen, 1977) for 19 different regions of the globe (Figure 1), we used the concept of Hurst phenomenon to check if indeed the largest earthquakes have occurred randomly in time.

2. Hurst Phenomenon

Let $X_1, X_2, \ldots, X_n$ be a sequence of n values uniformly distributed in time with mean μ and variance σ^2. One defines the set of adjusted partial sums $\{z_i\}$ as (Gratton, 1979)

$$\{z_i\} = \{\sum_{j=1}^{i} (X_j - \alpha\mu)\}\ , \quad 0 \le \alpha \le 1 \tag{1}$$

where α is an adjustment factor. Define

$$M_n = \text{Max}\ \{z_i\} \tag{2}$$

$$m_n = \min\ \{z_i\} \tag{3}$$

$$S_n^2 = n^{-1} \sum_{i=1}^{n} (X_i - \alpha\mu)^2 \tag{4}$$

be the maximum, minimum and mean square deviations of the adjusted partial sums respectively. The adjusted range and adjusted rescaled range (R/S) are defined by

$$r_n = M_n - m_n \tag{5}$$

$$R_n = r_n/S_n \tag{6}$$

where S_n^2 is now the sample variance.
Hurst (1951, 1956, 1957) showed that

$$R_n \sim (n/2)^k \tag{7}$$

where k is referred to as the Hurst coefficient and usually has a value between 0.5 and 1.0.

Non-stationarity in the mean can be considered as a sufficient, but not a necessary condition to generate the Hurst phenomenon. The closer the value of k to 0.5, the more random the process is and the closer the value of k to 1.0 the less random is the data or the physical process that defines the data.

3. Determination of the Hurst coefficient

When the autocorrelation structure of a process is known, the Hurst coefficient, k, can be estimated from its autocovariance function.

When the autocorrelation structure is unknown, three methods may be used to estimate the Hurst coefficient (Gratton, 1979). A general estimation procedure for k has been provided by Mandelbrot and Wallis (1969) through the use of pox diagrams which reflect a scatter of points corresponding to the rescaled ranges of not only the full length of a given sample but also of a set of subsamples extracted from the full sample on the basis of the prespecified set of sample sizes. A least squares technique has been used by Wallis and Matalas (1970) for estimating the slope of pox diagrams which leads to the estimation of the Hurst coefficient.

The data used for the pox diagrams is shown in Table 1. Figure 2 shows plots of log time versus log (R/S) for tsunami-genic earthquakes in four different magnitude ranges. Table 2 lists the Hurst coefficients estimated from the slopes of the straight lines in Figure 2. From these results we can deduce that whereas earthquakes of magnitude 8.5 or greater occur in a random fashion, for earthquakes in the 7.0 to less than 8.5 magnitude range, there is a strong long-run dependence. These results are compared with those of Gratton (1979) who determined the Hurst coefficient for 16 time series of meteorological variables and 23 oceanographic time series. He found average values of 0.63 for the meteorological variables and 0.90 for the oceanographic variables. Thus the meteorological variables appear to vary in a more random fashion than oceanographic variables, somewhat similar to tsunami-genic earthquakes.

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Table 1 Global tsunami-genic earthquake data for the period 1883 to 1980.

Year	No. of earthquakes with Richter magnitude				Year	No. of earthquakes with Richter magnitude			
	<7.5	7.5 to <8.0	8.0 to <8.5	≥8.5		<7.5	7.5 to <8.0	8.0 to <8.5	≥8.5
1883	0	0	0	0	1923	15	2	2	0
1884	0	0	0	0	1924	5	1	2	0
1885	0	0	0	0	1925	13	2	0	0
1886	0	0	0	0	1926	12	3	1	0
1887	0	0	0	0	1927	11	1	0	0
1888	0	0	0	0	1928	9	4	2	0
1889	0	0	1	0	1929	9	2	1	1
1890	0	0	0	0	1930	8	0	0	0
1891	0	0	0	0	1931	11	5	1	0
1892	0	0	0	0	1932	2	1	2	0
1893	0	0	0	0	1933	6	2	0	1
1894	0	1	0	0	1934	9	3	1	0
1895	0	1	0	0	1935	12	3	1	0
1896	1	1	0	0	1936	15	1	0	0
1897	0	2	0	2	1937	11	2	0	0
1898	0	1	0	0	1938	15	6	0	2
1899	0	0	1	0	1939	11	1	3	0
1900	0	4	4	0	1940	13	2	1	0
1901	0	6	2	0	1941	14	3	1	1
1902	0	4	3	0	1942	13	1	3	1
1903	0	2	4	0	1943	18	7	2	0
1904	0	4	4	0	1944	19	1	1	0
1905	6	10	1	0	1945	20	1	1	0
1906	10	6	3	2	1946	18	3	2	0
1907	10	4	1	0	1947	17	1	0	0
1908	4	4	2	0	1948	12	3	1	0
1909	15	5	1	0	1949	17	3	1	0
1910	16	4	1	1	1950	17	2	2	0
1911	1	2	1	1	1951	7	1	0	0
1912	5	4	0	0	1952	8	1	1	1
1913	9	6	2	0	1953	9	2	1	0
1914	6	2	1	0	1954	8	0	0	0
1915	3	4	1	0	1955	11	2	0	0
1916	5	8	3	0	1956	5	1	0	0
1917	5	6	1	2	1957	18	3	1	0
1918	7	4	2	0	1958	3	3	0	1
1919	5	3	2	0	1959	6	1	1	0
1920	2	1	2	0	1960	10	0	1	0
1921	4	2	0	0	1961	6	0	0	0
1922	7	2	1	0	1962	9	0	0	0

Table 1 Global tsunami-genic earthquake data for the period 1883 to 1980. (cont.)

Year	No. of earthquakes with Richter magnitude				Year	No. of earthquakes with Richter magnitude			
	<7.5	7.5 to <8.0	8.0 to <8.5	≥8.5		<7.5	7.5 to <8.0	8.0 to <8.5	≥8.5
1963	12	0	1	0	1972	1	0	0	0
1964	7	2	0	1	1973	0	0	0	0
1965	0	0	0	0	1974	2	0	0	0
1966	0	0	0	0	1975	10	2	0	0
1967	0	0	0	0	1976	6	3	1	0
1968	1	1	0	0	1977	7	2	0	0
1969	2	0	0	0	1978	5	2	0	0
1970	1	0	0	0	1979	2	3	0	0
1971	2	0	0	0	1980	5	1	0	0

Table 2 Summary of results

Tsunami-genic earthquakes Richter magnitude (x)	Hurst coefficient
$7.0 \le x < 7.5$	0.92
$7.5 \le x < 8.0$	0.85
$8.0 \le x < 8.5$	0.80
$8.5 \le x$	0.52

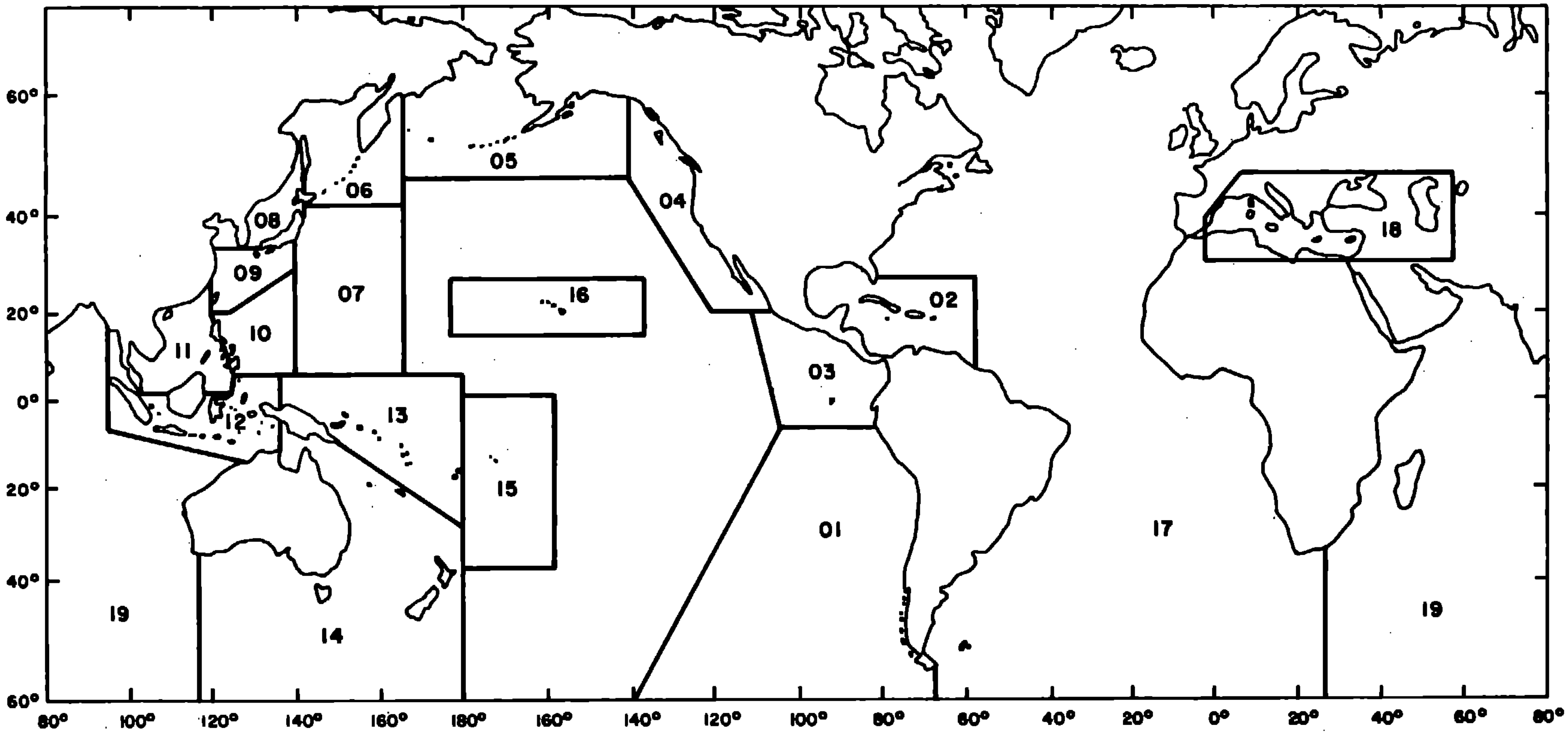

Figure 1 The 19 different regions of the globe for which tsunamigenic earthquake data were compiled (modified from Wigen, 1977).

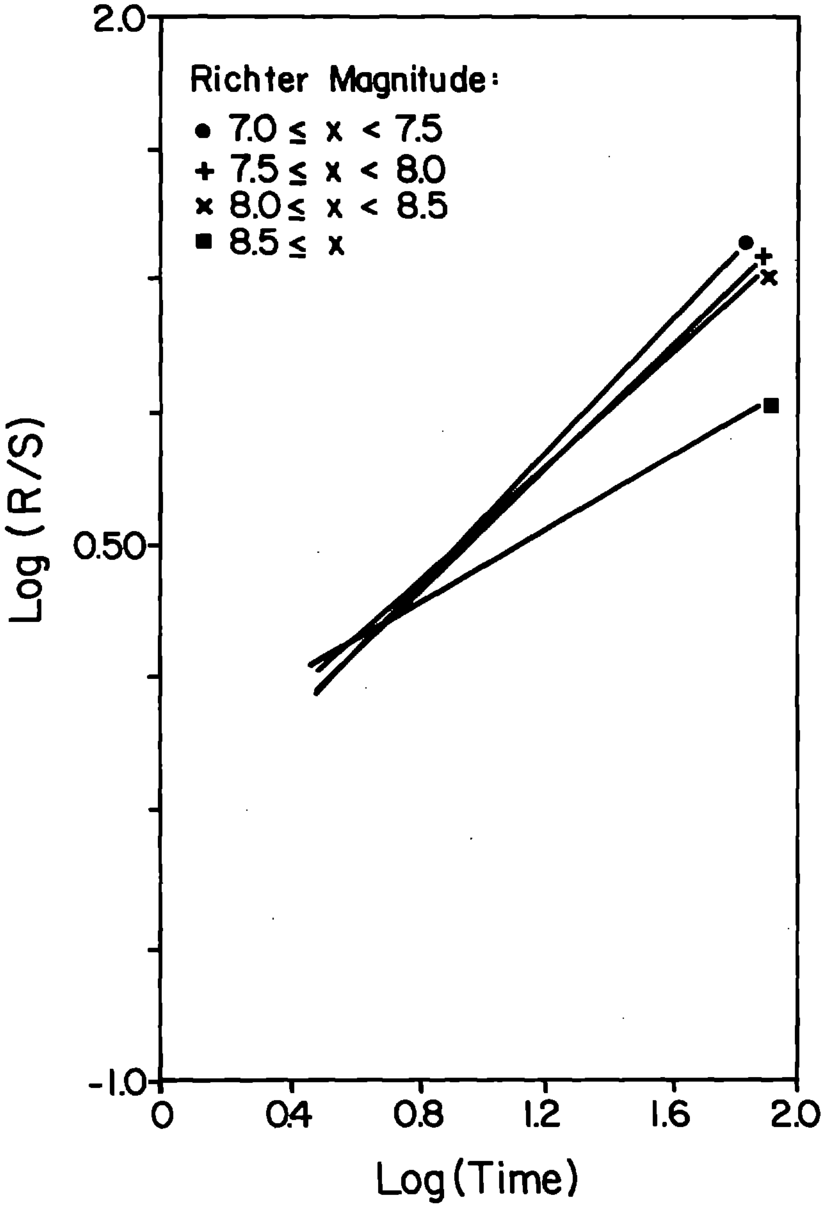

Figure 2 Plots of log time versus log (R/S) for tsunami-genic earthquakes in four different Richter magnitude ranges.

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