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The Tsunami Threat on the Mexican West Coast: A Historical Analysis and Recommendations for Hazard Mitigation

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Abstract. From an inspection of all tide gauge records for the western coast of Mexico over the last 37 years, a data base of all recorded tsunamis was made. Information on relevant historical events dating back two centuries, using newspaper archives, previous catalogs, and local witness interviews, was added to produce a catalog of tsunamis for the western coast of Mexico. A description of the 1932 Cuyutlán tsunami is given. This is considered to be the most destructive local tsunami which has ever occurred in the region for which historical accounts are available. It was preceded by two precursor events, a not uncommon occurrence in that zone. A summary of the generation and coastal effects from the 1985 Michoacán tsunamis is also given. These Michoacán tsunamis are the most recent local events in that zone.

This information, and knowledge of local undersea faulting characteristics along the Mexican Pacific coast, leads to a clear differentiation of two zones of potential tsunami hazard: locally generated tsunamis south of the Rivera fracture, in the Cocos plate subsidence region, and remotely generated tsunamis north of this zone. Based on this zonation, two types of tsunami warning systems are proposed: real-time for the southern zone, and delayed-time for the northern. A description is provided of the Baja California Regional Tsunami Warning System that is presently operational in the northern zone.

Several major industrial ports and tourist resort areas are located in the southern zone, and are therefore most vulnerable to local destructive tsunamis. Some of these sites represent important socioeconomic resources for Mexico, and have therefore been chosen for a vulnerability assessment and microzonation risk analysis. Land use patterns are identified, risks defined, and recommendations to minimize future tsunami impact are given. One case is illustrated.

Key Words. Tsunami catalog, precursors, warning system, public education, risk assessment, Mexico, Mesoamerican subduction.

1. Introduction

The main goals of tsunami research include: helping to save lives, reducing property damage, and minimizing lifeline disruption and economic dislocation. These goals can be reached through a better understanding of the nature and extent of exposure to the phenomenon, the implementation of a reliable early warning system, and the development of enhanced pre-event preparedness programs. To achieve these goals in Mexico, the authors have started a preliminary action program with the cooperation of their institutions and other government agencies. This preliminary program is presently limited to the following elements:

(a) Compilation of an historic and recorded tsunami data base catalog for the western coast of Mexico.
(b) Implementation of the Baja California Regional Tsunami Warning System (BCRTWS); in the near future, the BCRTWS and a National Tsunami Warning System for Mexico will both be linked to the Pacific Tsunami Warning System (PTWS), with public education policies as a priority consideration.
(c) Microzonation of coastal areas according to an assessment of their vulnerability to tsunamis and their land-use patterns, followed by recommendations on countermeasures and an elaboration of the preparedness programs.

This approach may be considered as a prototype example of a disaster preparedness strategy that links scientific knowledge with socioeconomic policies, within the framework of the International Decade for Natural Disaster Reduction.

2. Data Base – Catalog and Precursor Events

Recognizing the importance of historical data bases for operational analysis, the Intergovernmental Oceanographic Commission (IOC) outlined a historical data and information program for tsunamis (IOC, 1987). Pararas-Carayannis (1987), as Director of the International Tsunami Information Center (ITIC), recommended that a comprehensive and exhaustive historic tsunami study be done in Mexico. Following the IOC and ITIC guidelines, a systematic compilation of tsunami information from newspaper archives, previous catalogs, historical reports, recent mareographic records, and local witness interviews was conducted. This information was structured and assembled in a bilingual (Spanish-English) catalog of tsunamis on the western coast of Mexico (Sánchez and Farreras, 1990).

A total of 68 records from 21 events (9 local and 12 remote sources) detected during the 37 years of operation of the tide gauge network since 1952, were found and reproduced in the catalog. Most of these rather recent events were small in nature and did not pose any substantial threat. Figure 1 summarizes date, gauge location, and source type of the records. Over the last 10 years, only the Acapulco station has produced usable tsunami records. All other tidal stations were either inoperable, or were converted to digital recorders with a 30 min sampling interval. Rehabilitation of some old stations is highly desirable to support present and future tsunami research in Mexico.

The catalog also includes detailed information on the first wave and maximum rise or fall parameters, descriptive accounts of the events from historical chronicles, and photographs. Contrary to what is generally believed, historic accounts from the

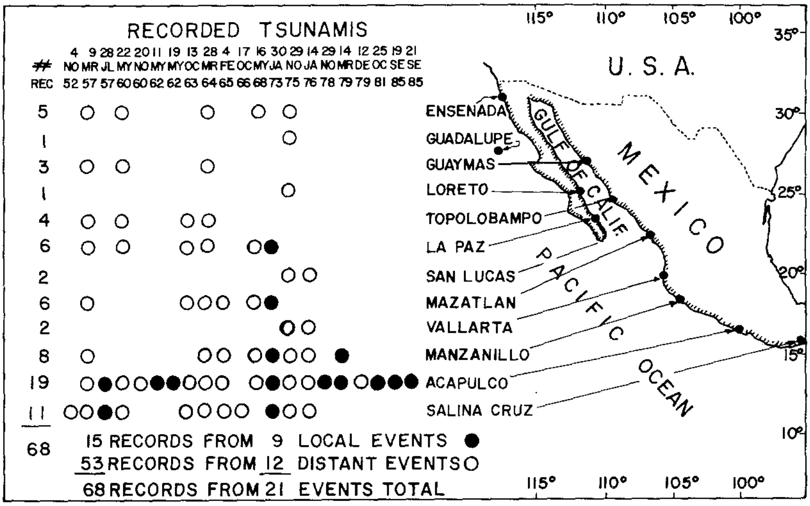

Fig. 1. Date, gauge location, source type, and number of tsunami records in existence, from the western coast of México.

last three centuries show that tsunamis that are locally generated in the Mesoamerican subduction zone constitute a serious threat to the southwestern coast of Mexico. The well-documented 16 November 1925 Zihuatanejo and 22 June 1932 Cuyutlán tsunamis, with estimated 7 to 11 and 10 m maximum wave heights respectively, were the two largest and most destructive contemporary events in the zone. Table I lists the date, the recorded or estimated maximum wave height, if available, and the location of primary observed damage or coastal effects for the destructive events. Table II lists the date, site, and height for the most recent non-destructive events.

The 10 m Cuyutlán tsunami of 22 June 1932 (7.7 Ms earthquake) was preceded by two smaller tsunamis on the 3rd and 18th of the same month with wave heights of 2 and 1 m (Excelsior, 1932a; El Universal 1932a), generated by two earthquakes with epicenters in the same region, but with magnitudes of 8.2 and 7.8 Ms, respectively (Geller and Kanamori, 1977). A similar sequence was also observed for the following strong seismic events:

(a) 7.6 Ms on 20 January and 7.1 Ms on 16 May 1900 in Jalisco;
(b) 7.5 Ms on 26 February, 7.8 Ms on 18 April 1902, and 7.7 Ms on 16 July 1903 in Chiapas;
(c) 8.1 Ms on 14 April 1907, 7.8 Ms on 29 March 1908, 7.5 Ms on 30 July 1909, and 7.8 Ms on 16 December 1911 in Guerrero;
(d) 7.7 Ms on 22 March, 8 Ms on 17 June, 7.6 Ms on 4 August, and 7.8 Ms on 9 October 1928 in Oaxaca;
(e) 6.6 Ms on 11 May and 6.5 Ms on 19 May 1962 in Guerrero; and
(f) 8.1 Ms on 19 September and 7.5 Ms on 21 September 1985 in Michoacán; as documented by Nishenko and Singh (1987).

Table I. Destructive tsunamis along the Mexican west coast

Date	Location of maximum damage	Recorded or estimated wave height (m)
25 February 1732	Acapulco	3.0
1 September 1754	Acapulco-San Marcos	4.0
28 March 1787	Acapulco-Igualapa	3.0
4 May 1820	Acapulco	2.0
14 March 1834	Acapulco	not available
7 April 1845	Acapulco	not available
12 August 1868	Acapulco	not available
24 February 1875	Manzanillo	not available
14 April 1907	Acapulco-Ometepec	2.0
30 July 1909	Acapulco-San Marcos	9.0
16 November 1925	Zihuatanejo	11.0
16 June 1928	Puerto Angel	6.0
22 June 1932	Cuyutlán-San Blas	10.0
28 July 1957	Acapulco	2.6
22 May 1960	Zihuatanejo	3.0
28 March 1964	Ensenada	2.4
29 November 1978	Salina Cruz-Puerto Escondido	1.5
19 September 1985	Lázaro Cárdenas	2.5

Table II. Non destructive tsunamis recorded at tidal stations along the Mexican west coast

Date	Location of tidal station	Maximum wave height (m)
4 November 1952	Salina Cruz	1.22
9 March 1957	Ensenada	1.04
20 November 1960	Acapulco	0.13
11 May 1962	Acapulco	0.81
19 May 1962	Acapulco	0.34
13 October 1963	Salina Cruz	0.49
4 February 1965	Salina Cruz	0.46
17 October 1966	Salina Cruz	0.24
16 May 1968	Acapulco	0.43
30 January 1973	Manzanillo	1.13
29 November 1975	Ensenada	0.46
14 January 1976	Manzanillo	0.21
14 March 1979	Acapulco	1.31
12 December 1979	Acapulco	0.30
25 October 1981	Acapulco	0.09
21 September 1985	Acapulco	1.20

The duration of these sequences is on a scale of days, months, or even a few years. Some sequences are composed of a main shock followed by aftershocks in a series of events that rupture the same segment of the plate interface (Anderson *et al.*, 1985), and others are complex modes of rupture of different segments of the plate boundary, which take several years to complete (Nishenko and Singh, 1987). In all cases, at least one and sometimes all of the seismic events in a sequence generated small or large tsunamis. This sequential pattern of strong tsunamigenic earthquake occurrence seems to be characteristic of the Mesoamerican subduction zone, and should be exploited to provide key precursor event information for incorporation into the tsunami warning policies of the region.

3. The Great June 1932 Cuyutlan Tsunami

At approximately 7 a.m. local time, on 22 June 1932, a strong earthquake ($Ms = 7.7$; Gutenberg and Richter, 1954) affected the coastal region of the States of Jalisco and Colima. No more than three minutes later, the ocean waters in front of Cuyutlán beach resort receded violently 300 to 400 m, piling up one over the other in a layer-like manner until it reached the appearance of a huge vertical wall about 9 to 10 m high (Excelsior, 1932b). Suddenly, with unexpected speed, the water advanced toward the beach, preserving the appearance of a vertical wall, until it reached the two-story Santa Cruz Hotel building, which was situated on a sand bar that separated the village from the sea. After overtopping the building, the huge wave broke onto the village square, lifting up stone paving blocks on the main street, eroding a trench, and falling like a 2–3 m thick blanket that flooded the entire village (recounted by witnesses Pio Ventura and Heriberto Sánchez). Everything was washed away and destroyed, included five large hotels, the church, about 80 wooden houses, and several small cottages; even the Hotel Ceballos, the only concrete structure in town, could not withstand the tsunami (Excelsior, 1932c). A truck loaded with sand was carried 200 m inland. The wooden floor of the church was transported 500 m. The water invaded a distance of about 1 km inland within 2 to 3 min, until it reached the railroad tracks embankment, where it deposited trees, sand and debris, obstructing a 2 km long extension of track (El Nacional, 1932a). A few people and horses were left at the top of palm trees. It took the water approximately two hours to return to its normal state (El Universal, 1932b). After the tsunami waves receded, the village was strewn with a mixture of human corpses, dead sharks and fish, cattle, trees, sand and debris. Ten to seventy-five casualties were estimated by different sources. The waves flooded destructively alongshore for approximately 5 km, but the phenomenon was observed for 25 km along the coast (El Nacional, 1932b). Other smaller coastal communities nearby, such as Tenancillo and Palos Verdes, were completely destroyed (El Universal, 1932c).

Two additional tsunamis which were smaller and reached only the main square of Cuyutlán, were caused by aftershocks of the main earthquake over the next two days (El Universal, 1932b).

4. The September 1985 Michoacán Tsunamis

On 19 September 1985 an 8.1 Ms earthquake, composed of two subevents with 80 km source separation and a 26 sec time lag, occurred in the subduction zone of the northwest portion of the Cocos Plate (Anderson *et al.*, 1986). The generated tsunami affected several coastal communities in the States of Michoacán and Guerrero. Waves of approximately 2.5 m height arrived at the heavy industry-based port of Lázaro Cárdenas during the earthquake shaking, and flooded a horizontal distance of approximately 500 m inland. The estimated runup was based on the finding that the waves covered a dock that stands 3.15 m above mean sea level. Jetties at the entrance of the harbor were completely covered by the waves, but were left undamaged. Major damage was attributable to inundation. Approximately 1.5 km of railroad track were destroyed because the bank under the track was eroded away. The fence protecting the railroad tracks from storm and tidal action was washed out. An earth embankment bridge providing access to a fertilizer plant was also washed out. Little or no impact or drag effect were observed; the water flow neither tipped over empty railroad cars on the tracks close to the shore nor removed the rocks on the beach groins and river entrance jetties. Beach configuration changes attributable to approximately 2 m vertical piling of sand were also observed. Results of a survey with detailed damage patterns are presented elsewhere by Urban Regional Research (1988). A large perturbation followed by a train of small waves, resembling an undular bore was observed propagating upstream as far as the second bridge, 7.5 km from the river mouth (Farreras and Sánchez, 1987).

In Playa Azul, a local tourism-based coastal community, there were four to five 2.5 m high waves filling and emptying the beach approximately once every half-hour. The tsunami waves invaded a distance of about 100–150 m inland, carrying away the frail palapa-built restaurants and furniture and depositing a ledge of sand approximately 25 m wide × 2 m high at the upland edge of the beach.

In Ixtapa, an international tourism-based coastal community, four to five tsunami waves were observed, and it was reported that the water receded, then the bay filled up and the beach became 'like a bathtub' several times. At the highest runup the water came over a 1.5 m wall and into the swimming pool of the Sheraton Hotel.

On 21 September 1985, a 7.5 Ms aftershock occurred in the southern portion of the so-called 'Michoacán seismic gap', with a much smaller rupture zone area than the previous main shock. The generated tsunami affected mainly the traditional fishing village of Zihuatanejo. The water in the bay receded, then there were seven to eight 2 m to 3 m high waves, and then the water remained oscillating for 9 h due to the resonant conditions of the semi-enclosed bay. The water overtopped the Municipal Pier and invaded a distance of about 200 m inland. Considerable flood damage was caused by the water that came to the first floor of the major beachside hotels and restaurants. A similar oscillating resonant pattern was observed in Zihuatanejo during the devastating 11 m wave height tsunami on 16 November 1925.

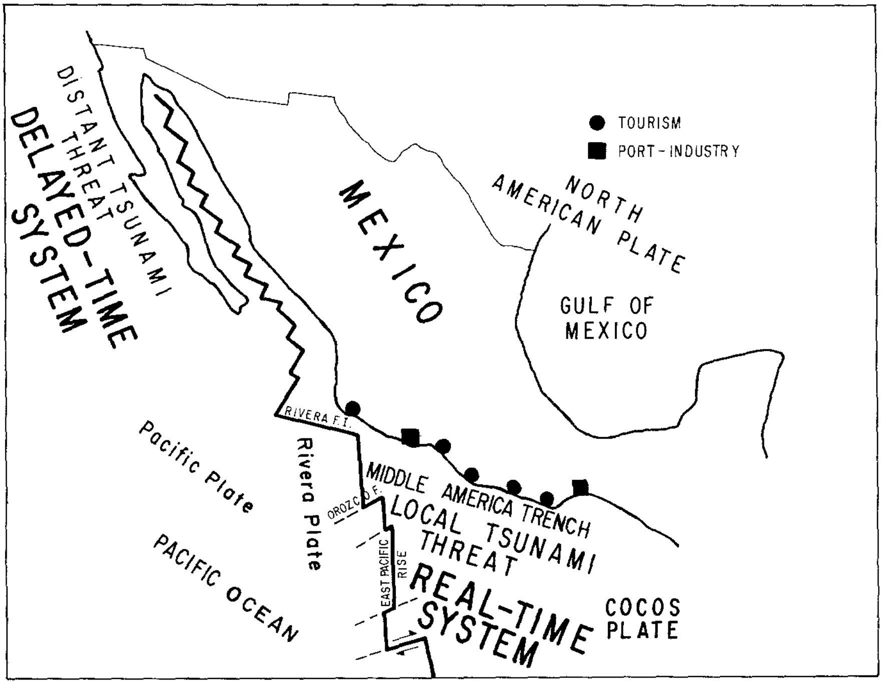

Fig. 2. Seismotectonic setting, predominance of tsunamis, and type of warning systems proposed along the Mexican Pacific coast.

No casualties were reported in any of the affected communities as a direct result of the 19 and 21 September 1985 tsunamis.

5. Tsunami Warning Systems

Based on the nature of undersea faulting and tectonic plate interaction, Sánchez and Farreras (1987) defined two hazardous zones along the Mexican west coast, each with different implications for tsunami generation and arrival (Figure 2). Southeast of the East Pacific Rise and along the Middle America Trench, the Cocos Plate subsides beneath the North American Plate at rates of 2.5 to 7.7 cm/yr (McNally and Minster, 1981). Large earthquakes occur at fairly regular intervals in this zone, and some have produced devastating local tsunamis. Northwest of the East Pacific Rise, the Pacific Plate slides north with respect to the North American Plate, along the Gulf of California strike-slip fault; and the Rivera Plate rotates without subduction at a rate of 1.6 cm/yr at the margin. Generation of large tsunamis in this zone is unlikely, as confirmed by historical information; but several small and moderate tsunamis generated by remote sources, have been recorded.

The distinctive nature of the tsunami threat in each zone indicates the need for two different types of warning system: a real-time system in the southern zone, and a delayed-time system in the northern zone.

In the northern zone, the BCRTWS is presently administered by the CICESE Research Center. CICESE and the local Oceanographic Station of the Mexican Secretary of the Navy in Ensenada operate the three reporting wave stations in the network. These stations are located in Ensenada, Isla Guadalupe, and Cabo San Lucas (Figure 1), and the observers have permanent 24 hr/365 days-a-year communication facilities available via radio or telephone to the Center or the Navy Station.

To improve siting and installation, a study has been conducted to determine the theoretical response of reporting stations to tsunami waves. Figure 3 shows the relative amplitude and phase response of several azimuthal locations along Isla Guadalupe contour to tsunami waves of various periods arriving from Japan. These computations were made using the Vastano and Reid (1966) diffraction-refraction numerical model, and other results of this study are presented by Reyes-Rodríguez de la Gala (1990).

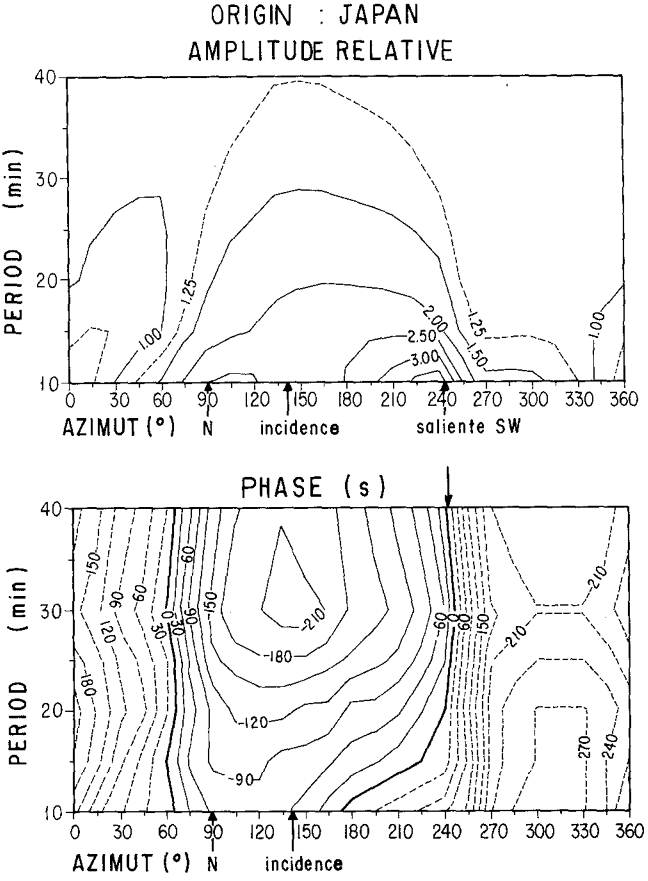

Fig. 3. Relative amplitude and phase response of azimuthal locations around Isla Guadalupe to tsunami waves incident from Japan.

The CICESE Research Center also acts as a dissemination agency for messages to and from the Pacific Tsunami Warning Center. Cabo San Lucas presently operates as a wave reporting station for the PTWS (National Oceanic and Atmospheric Administration, 1988), and the addition of the Isla Guadalupe station to the network has been requested by the IOC (1987).

The BCRTWS works jointly with the Baja California Civil Protection System (BCCPS), and the local army and navy authorities. Figure 4 shows the operational diagram of the BCRTWS. Ten thousand copies of a brochure in Spanish titled 'Que Hacer en Caso de Maremoto' (What to do in a Tsunami event) were prepared by the authors under the framework of the BCRTWS; these were edited and then distributed by the BCCPS among coastal community residents as part of a public education program for disaster prevention (Figure 5). Tsunami drills have been conducted by BCCPS with the cooperation of BCRTWS. These two agencies have also recently initiated a joint study of land-use patterns, evacuation routes, and shelter and services distribution for urban planning along coastal zones in Baja California that are vulnerable to tsunamis.

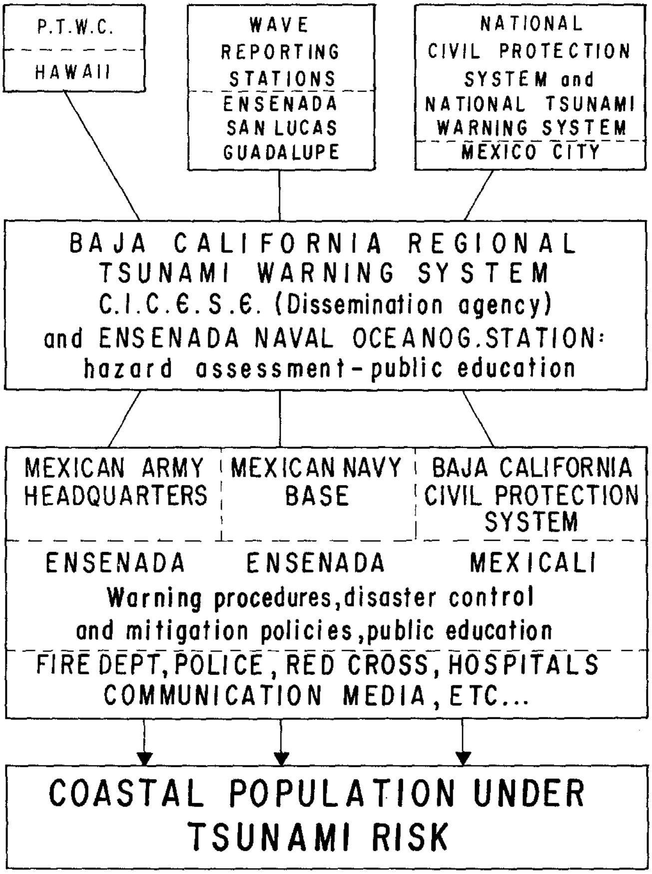

Fig. 4. Baja California Regional Tsunami Warning System operational diagram.

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La Mejor Decisión

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MAREOGRAFO No. 1

Cuidado con la Ola

Que hacer
en caso de
MAREMOTO

SECRETARIA DE MARINA
CICESE
UNIDAD ESTATAL DE PROTECCION CIVIL
GOBIERNO DEL ESTADO DE BAJA CALIFORNIA

Fig. 5. Tsunami public education brochure in Spanish, entitled 'What to do in a Tsunami event'.

BCRTWS is also in contact with the recently-formed National Civil Protection System of Mexico to help establish a National Tsunami Warning System for the southern active subduction zone. Farreras (1986) submitted a proposal for a real-time system for this zone using satellite technology similar to that of the THRUST project (Bernard *et al.*, 1988), but using the Mexican telecommunications satellite 'Morelos'.

6. Microzonation Risk Analysis and Vulnerability Assessment

The Cocos Plate subduction zone contains a consistent and regular history of great earthquakes, and has been the source of numerous locally destructive tsunamis with maximum recorded or estimated wave heights of 1.5 to 11 m (Table I and Figure 6). Nishenko and Singh (1987) identified 13 segments along this zone with histories of large earthquakes, three of which are classified as seismic gaps with a 60% to 80% probability over the next 10 years of the recurrence of magnitude 7.5 Ms or

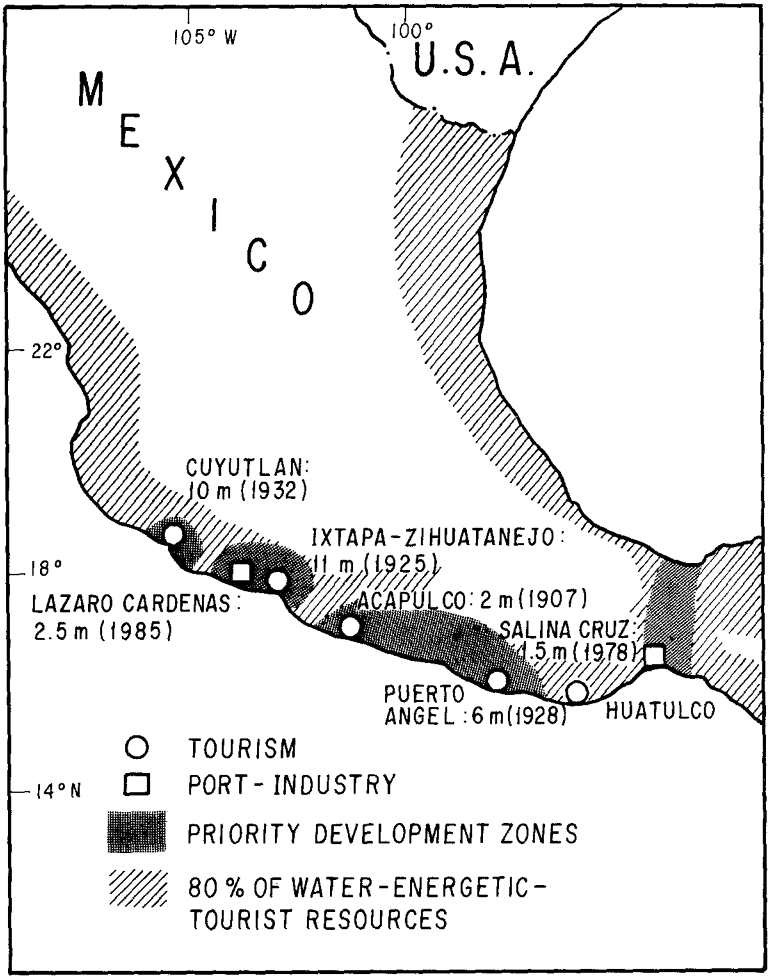

Fig. 6. Main industrial ports and tourist resorts along the priority development zone identified by the National Urban Development Plan of Mexico, with maximum wave heights and dates of occurrence of past tsunamis.

larger events. The highly vulnerable coastal area adjacent to this subsidence zone is also considered to be a priority area for decentralization and development by the National Urban Development Plan of Mexico. It possesses an important part of the water-energy-tourism resources of the nation, and is the site of two major industrial ports: Lázaro Cárdenas and Salina Cruz. Approximately 1000 km of tourist resorts form a corridor from Cuyutlán to Huatulco (Figure 6).

Facilities in Lázaro Cárdenas include two steel mill plants, a fertilizer factory, a container port, metal and mineral docks, grain storage silos, and a 45 ha marine terminal under construction. The marine terminal will be capable of storing 541 000 million barrels of gasoline, diesel, jet fuel, and fuel oil. The estimated population is

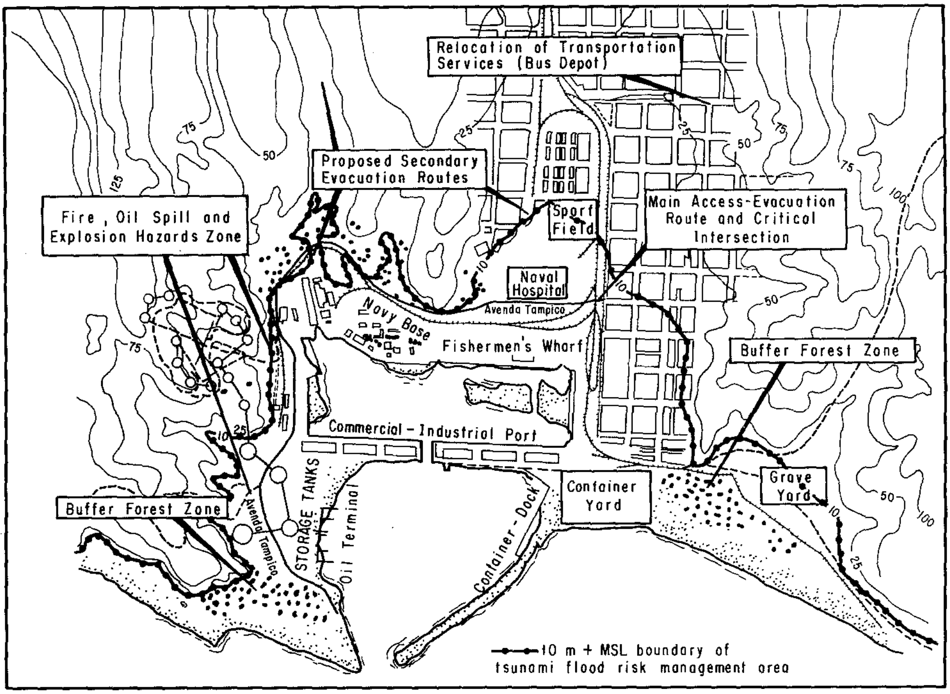

Fig. 7. Salina Cruz land use pattern, vulnerability assessment, and recommendations. The 10 m flooding zone contour corresponds to a worst-case tsunami inundation scenario.

150 000. Most of the construction is concentrated on the sand shoals of the Balsas River delta, after the region was raised to 5 m above mean sea level by landfill. This area recently suffered moderate damage by two local tsunamis on 19 and 21 September 1985 which were each 2.5 m high (Farreras and Sánchez, 1987).

Salina Cruz will be the west coast terminus for 160 miles of pipeline that will carry crude oil across the Tehuantepec Isthmus to the Pacific, alleviating the need for tankers to travel the Panama Canal. This port presently has a container terminal, facilities for bulk cargo, fuel storage tanks and a 400 vessel fishing fleet (Figure 7). A 150 000 barrels-per-day expansion of the present oil refinery and export terminal will be completed in the near future.

Typical of the many new tourist resorts now under development are the 2 500 ha of beaches of the nine Huatulco Bays. These lie along an 18 mile stretch north of Salina Cruz, and are separated from each other by tropical vegetation and steep hillsides. The National Tourism Development Bureau (FONATUR) has invested over 10 million dollars in infrastructure to support the proposed development; water and sewer facilities, a coastal highway and an international airport have been completed to date. A Sheraton and a Club Med Hotel have been built on the beaches at Tangolunda Bay, and FONATUR plans that hotel rooms will increase from 850 in 1989 to 6700 by 2018, with a corresponding population increase from

12 800 to 308 000. Most of this tourist development is in the coastal zone and are thus vulnerable to tsunami wave impact.

Several of these locations were selected for a microzonation risk analysis and vulnerability assessment study; such studies are aimed at reducing the loss of life and property, and minimizing the socioeconomic disruption caused by tsunamis.

The methodology to use in a microzonation risk analysis includes the following elements:

(a) Identification of a target area for the study according to historical evidence of past tsunamis, neighbouring tectonic scenarios such as seismic gaps, present and future socioeconomic development, and suspected implications of a disruption by a major tsunami.
(b) Determination of probable tsunami wave elevations and expected inundation limits, through some of the following alternatives: calculation of wave-height probabilities from tidal harmonic constituents and recorded or estimated historic tsunami heights, wave-diffraction diagrams from rupture zones that generated tsunamis in the past or are suspicious to generate in the future, direct assignment of the calculated shoreline runup heights to the entire reach of the inland zone, and numerical simulation of the wave propagation from the source to the shoreline and inland areas considering, among other factors, the beach slope, bottom friction, tectonic subsidence or uplifting, wave profile and directionality, and the presence of vegetation and man-made structures. The boundaries of the inundation area will define a Flood Damage Control Zone.
(c) Field survey within the Flood Damage Control Zone to establish with the help of aerial photographs, municipal charts and local urban development plans, the present and future trends in land use patterns, including: population density distribution, location and type of public office buildings, schools, hospitals, hotels, industrial installations, port facilities, marine structures, businesses, family housing, public services, utility plants and networks, fuel storage tanks, resort areas, vacant lots, roadways and transportation networks. Information on soil stability should be added too.
(d) Assessment of vulnerability to primary causes (inundation, hydrodynamic forces and loss of ground support) and secondary causes (impact of floating debris, hazardous releases, fire and contamination) of the population, buildings, marine structures, lifelines, and others (beach facilities, aquaculture).
(e) Mapping of risk zones based on the land use patterns and the vulnerability assessment.
(f) Development of recommendations for countermeasures such as the redistribution of population, structures and services, improvement of evacuation routes, location of shelters and buffers that may act as barriers against the tsunami action and implementation of a public education program.

Some of the guidelines given above and their application to the microzonation risk analysis of Ixtapa-Zihuatanejo and Lázaro Cárdenas are presented elsewhere (Urban Regional Research, 1988).

Land-use patterns, vulnerability assessment, and recommended countermeasures for Salina Cruz are summarized in Figure 7 (Preuss *et al.*, 1989). The contour line corresponding to 10 m above the mean sea level delineates the worst case scenario of maximum probable tsunami inundation, based on historical information along the entire subduction zone. Salina Cruz is characterized by intensive industrial use of the coastal areas and high day-time population density. Furthermore, the only access at present into and out of the port is an extremely congested intersection crossed by railroad tracks. The population is therefore left with almost no possibility of safe evacuation in the event of a tsunami. Recommendations for Salina Cruz include the establishment of alternative evacuation routes, buffer tree forestation near the beaches as an effective means of reducing tsunami wave impact on the container yard and downtown area, protection of the nearshore fuel storage tanks against tsunami wave or floating debris impact, the development of evacuation plans and drill exercises by the local authorities and the population, and implementation of a public education program on tsunami hazard mitigation policies.

7. Conclusions and Recommendations

Locally-generated tsunamis constitute a significant hazard to the southwest coast of Mexico along the Middle America Trench. A real-time tsunami warning system using satellite communications technology, should be implemented as soon as possible for this coastal area.

Strong tsunamigenic earthquakes in the subsidence zone have historically been characterized by a sequential pattern of occurrence that could be exploited to develop criteria for the identification of potential precursors to large tsunamis. This information could then be incorporated into the tsunami warning policies for the region.

The microzonation risk analysis and vulnerability assessment studies must continue and expand to cover all of the west coast communities of Mexico vulnerable to tsunamis. Numerical modeling should be conducted to provide estimates of inundation patterns for each site.

Public education on tsunami hazard mitigation must be included in disaster preparedness programs for each region.

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