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Steps Towards the Implementation of a Tsunami Detection, Warning, Mitigation and Preparedness Program for Southwestern Coastal Areas of Mexico

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Abstract—The highly vulnerable Pacific southwest coast of Mexico has been repeatedly affected by local, regional and remote source tsunamis. Mexico presently has no national tsunami warning system in operation. The implementation of key elements of a National Program on Tsunami Detection, Monitoring, Warning and Mitigation is in progress. For local and regional events detection and monitoring, a prototype of a robust and low cost high frequency sea-level tsunami gauge, sampling every minute and equipped with 24 hours real time transmission to the Internet, was developed and is currently in operation. Statistics allow identification of low, medium and extreme hazard categories of arriving tsunamis. These categories are used as prototypes for computer simulations of coastal flooding. A finite-difference numerical model with linear wave theory for the deep ocean propagation, and shallow water nonlinear one for the near shore and interaction with the coast, and non-fixed boundaries for flooding and recession at the coast, is used. For prevention purposes, tsunami inundation maps for several coastal communities, are being produced in this way. The case of the heavily industrialized port of Lázaro Cárdenas, located on the sand shoals of a river delta, is illustrated; including a detailed vulnerability assessment study. For public education on preparedness and awareness, printed material for children and adults has been developed and published. It is intended to extend future coverage of this program to the Mexican Caribbean and Gulf of Mexico coastal areas.

Key words: Tsunamis, coastal flooding, vulnerability assessment, warning system instrumentation, mitigation and preparedness, middle-America trench off Mexico.

1. Introduction

The southwest coast of Mexico has been heavily affected by local tsunamis generated by large earthquakes in the adjacent Middle America Trench, where the Cocos Plate collides with and subsides underneath the North American Plate. In addition, the Pacific coast of Central America and Colombia encompass a source of regional tsunamis, while the colliding tectonic plate borders, called the "Ring of

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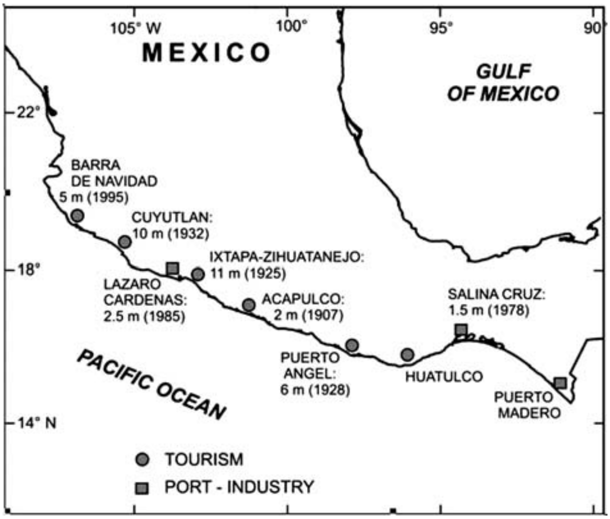

Figure 1
Port, industry, urban developments and tourist resorts in the Pacific ocean coast of Mexico. Dates and wave heights of destructive tsunamis.

Fire'', all around the coasts of the Pacific ocean constitute a source of distant ones for Mexico. Different travel times from their source to the arrival sites for each case, gives from a few minutes to a few hours to half a day or more, to issue effective early tsunami warning messages to the affected communities.

This coast is highly vulnerable due to the presence of an extensive industrial port, tourism, fisheries and densely populated urban developments. Figure 1 shows the 1000 km vulnerable coastal corridor scenario and the maximum wave heights and dates of the largest past tsunami occurrences.

It is intended to extend future coverage of this study to the Caribbean plate colliding border zones, which present a tsunami threat to the southeast coast of Mexico.

2. History and Prototypes

Statistics of 56 tsunamis affecting the Mexican West Coast in a 272-year period, roughly one every 5 years, (SÁNCHEZ and FARRERAS, 1993), show that, besides the smaller and very frequent ones with less than 1 meter wave height, two categories which represent low and medium hazard with 3 and 5 meters maximum wave heights and an average return time of a quarter and half a century, respectively, are prevalent. These categories can be used as prototypes for computer simulations of coastal flooding.

In addition, high hazard extreme tsunamis with 10 meter estimated wave heights have materialized only twice in contemporary times, 16 November 1925 and 22 June, 1932. Their reccurrence time cannot be estimated at the present time. SINGH *et al.* (1998) ruled out a local earthquake shock as the cause of the 1925 tsunami, and indicated a sea-floor slumping as the possible source. The 1932 singular event is extensively described in SOLOVIEV and GO (1975) and SÁNCHEZ and FARRERAS (1993), among others.

The most recent low and medium hazard category events were the 19 September, 1985 and the 9 October, 1995 tsunamis with maximum wave heights of 2.5 and 5 meters respectively, which produced widespread damage in several communities along the coast (FARRERAS and SÁNCHEZ 1987, BORRERO *et al.*, 1997).

3. Strategy

Although Mexico presently has no national tsunami warning system in operation, important steps are taking place towards its development. A pannel of scientific expert advisors to the Civil Protection National System from the Secretary of the Interior, issued a recommendation to implement a National Program on Tsunami Detection, Monitoring, Warning and Prevention (SINAPROC, 1998). Key elements of this program are:

- operational infrastructure for detection, monitoring, and early warning message dissemination capabilities,
- training of personnel, managers and decision makers,
- zoning of expected inundation area extensions with water depth estimations,
- vulnerability studies and land use regulations,
- public outreach education for preparedness and awareness, and
- emergency response plans.

Early in 2005, after the devastating experience of the 26 December, 2004 Indian Ocean tsunami, several research institutions and local civil protection agencies from Mexico agreed on the need to share responsibilities and start the implementation of these tsunami program key elements.

4. Accomplishments

4.1. Operational

For distant tsunamis, where travel times could be of half a day or more, Mexico relies entirely on Pacific Tsunami Warning Center (PTWC) information. Since 1990, the federal Scientific Research and Higher Education Center of Ensenada (CICESE) in cooperation with the Mexican Navy installed and mantains in Manzanillo, Isla Socorro and Cabo San Lucas, three sea-level gauge stations equipped with real-time signal transmitters to the GOES satellite, for the PTWC network.

PTWC watch and warning bulletins are curently received at the Mexican National Weather Service via dedicated WMO circuits, and at CICESE via Internet, where they are redistributed to federal and local civil protection agencies.

For travel times of less than 4 hours for regional tsunamis, and no more than one hour and a half for the local ones we cannot rely entirely on PTWC remote network information, but we must establish a system for rapid detection and analysis of our own local or nearby seismic and sea-level data to issue early warnings in time.

The National Research Institute for Earth Science and Disaster Prevention (NIED) from Japan, under an agreement with CICESE, provided partial financial support to develop this aspect of the operational program. A robust and low-cost high frequency sea-level tsunami gauge, sampling every minute and equipped with 24 hours real-time transmission to the Internet, was designed and installed. The signals from a bottom pressure sensor are carried to the ground by a hydrographic cable, and all the ground components of the system (solar panel, transmitter, antenna) are located at the top of a 10 meter height strong pole, to make it capable of withstanding the tsunami attack (Fig. 2). The prototype of this instrument is

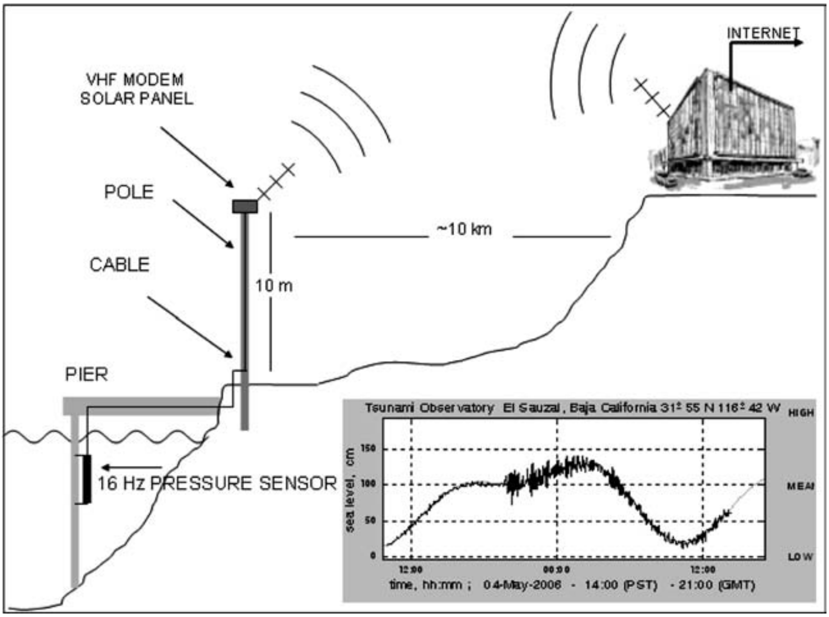

Figure 2
High frequency sea-level tsunami gauge, sampling every minute, equipped with real time transmission to the Internet; and actual sea-level record updated every minute, as can be seen at http://observatorio.cicese.mx

currently in operation at the port of El Sauzal, Baja California (31°55′N, 116°42′W) and the signal can be viewed permanently at the http://observatorio.cicese.mx Internet site.

It is intended to establish a network of these real-time sea-level sensors with one instrument installed every 100 kilometers covering the Pacific Ocean coast of Mexico, the Central American countries and Colombia.

Simultaneously, to increase the effectiveness and reliability of this early warning system for regional and local tsunamis, a database of forecast estimated arrival heights and times were computed from wave forms of synthetic tsunamis. These tsunamis, numerically computed by solving the shallow water long-wave equations, were generated from groups of impulse functions of a collection of segmented rupture area sources of prototype earthquakes along the Pacific coast of Mexico, Central and South America. The predicted height and time arrivals were so obtained from a linear superposition of the specific group of Green's functions corresponding to the segments of the rupture areas (ASTE, 2003). In a real case, for a rapid estimation of a tsunami occurrence, the magnitude of the coseismic dislocation and the location of the rupture has to be evaluated from early determinations of the earthquake parameters (i.e., USGS, Harvard) and/or from an inverse analysis of early observations of the tsunami in the vicinity of the generation area, adjusted as time progresses.

4.2. On Prevention and Planning

To reduce the loss of life and property, and minimize the socioeconomic disruption caused by tsunamis, microzonation risk analysis and vulnerability assessment studies are being performed. At this initial stage, the following sites are included in this study: Manzanillo (19°03.2′N, 114°19.8′W), Lázaro Cárdenas (17°57.5′N, 102°11.5′W), Zihuatanejo (17°36.5′N, 101°33.0′W), Acapulco (16°50.4′N, 99°55.0′W) and Salina Cruz (16°09.6′N, 95°12.2′W). An important element for the analysis and studies is the determination of probable tsunami wave elevations and expected inundation limits at each location. Presently, the best alternative to determine these parameters is through numerical simulation of wave generation and propagation from the source to the shoreline and inland areas (FARRERAS and SÁNCHEZ, 1991).

With the financial support of the Japanese International Cooperation Agency (JICA), the University of Tohoku under the Tsunami Inundation Modeling Exchange (TIME) program transferred tsunami numerical modelling technology to Mexico to produce tsunami inundation maps for prevention purposes.

The TIME model consists of the shallow-water nonlinear vertically integrated equations of motion (1 and 2) and the equation of continuity (3), without Coriolis effect term (GOTO *et al.*, 1997):

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{D}\right)+gD\frac{\partial \eta}{\partial x}+\frac{gn^2}{D^{7/3}}MQ=0 \tag{1}$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{D}\right)+gD\frac{\partial \eta}{\partial y}+\frac{gn^2}{D^{7/3}}NQ=0 \tag{2}$$

$$\frac{\partial \eta}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0 \tag{3}$$

where η = vertical displacement of the water surface above the still water level, $D = (\eta + h)$ instantaneous total water depth, h = average depth of the water column, M and N = vertically integrated components of the horizontal and vertical transport per unit width (flow flux), g = acceleration of gravity, $Q = (M^2 + N^2)^{1/2}$ = transport magnitude, and n = 0.025 Manning's roughness parameter, considered constant.

The above set of equations are solved by finite differences in an explicit rectangular staggered leap-frog scheme in a set of interconnected grids that allows the use of the linearized set of equations in deep water, and the conservation of the nonlinear and friction terms in the inner higher resolution grid for the selected coastal regions. One of the most important capabilities of this model is the inclusion of wave run-up estimates in the inner higher resolution grid, where the nonlinear field acceleration terms and bottom friction are kept. Whether a computation cell is dry or submerged is judged in terms of the total water depth, as follows:

$$\begin{aligned} &D=\eta+h>0, \quad \text{then the cell is submerged, and}\\ &D=\eta+h<0, \quad \text{the cell is dry.} \end{aligned} \tag{4}$$

For a wave front located between the dry and submerged cells, the discharge across the boundary between the two cells is computed if the ground height in the dry cell is lower than the water level in the submerged cell. In other cases, discharge is considered zero. The boundary conditions at the seaside of the inner grid are taken from the intermediate resolution grid, whereas the radiation condition at the offshore boundary in the low-resolution grid is taken from the characteristic solution of the wave equation

$$(M, N) = \pm\eta\sqrt{gh}, \tag{5}$$

where the sign is taken in such manner that the wave will propagate outward from the computational domain.

For the initial condition, the model assumes that the instantaneous topography of the sea-surface deformation approximates the vertical deformation of the sea floor produced by the earthquake. This deformation is determined from analytical expressions for the internal deformation of a continuous media due to shear and tensile faulting (e.g., MANSINHA and SMYLIE, 1971). It considers a simple rupture geometry and uniform slip distribution on the fault plane.

Prototype tsunamis, as defined early above, were simulated with this model in a computer by CICESE to produce inundation maps indicating flooding extensions and expected wave heights, for several industrial ports and coastal cities.

An illustrative example is the heavily industrialized port of Lázaro Cárdenas in the state of Michoacán. This port is located on the sand shoals of the Balsas River delta along a 6-km-wide strip parallel to the coast, in a region where numerous marshes, ponds, coastal lagoons and estuarine branches were land-filled, raised and leveled up to 2 or 4 meters above sea level. The industrial zone includes two steel mill plants producing 4.4 million tons/year, a fertilizer factory producing 2.9 million tons/year, a container port, metal and mineral docks, grain storage silos with 80,000 tons capacity, a Navy base and a marine oil terminal capable of storing 541 million barrels of gasoline, diesel, jet fuel and fuel oil. One thermoelectric and two hydroelectric power plants provide 2,340 mega watts to this mega port-industrial-naval complex. Most of the port facilities, structures, services, roads and utility lines are settled on the low flat sedimentary coastal terraces of the river delta shoals, and are vulnerable to tsunami attack. The estimated population is presently 250,000. Figure 3 shows the location and distribution of the port and industrial structures, and the urban area in a topographic map. Not all the sites considered for this study have topographies available with a resolution as detailed as Lázaro Cárdenas.

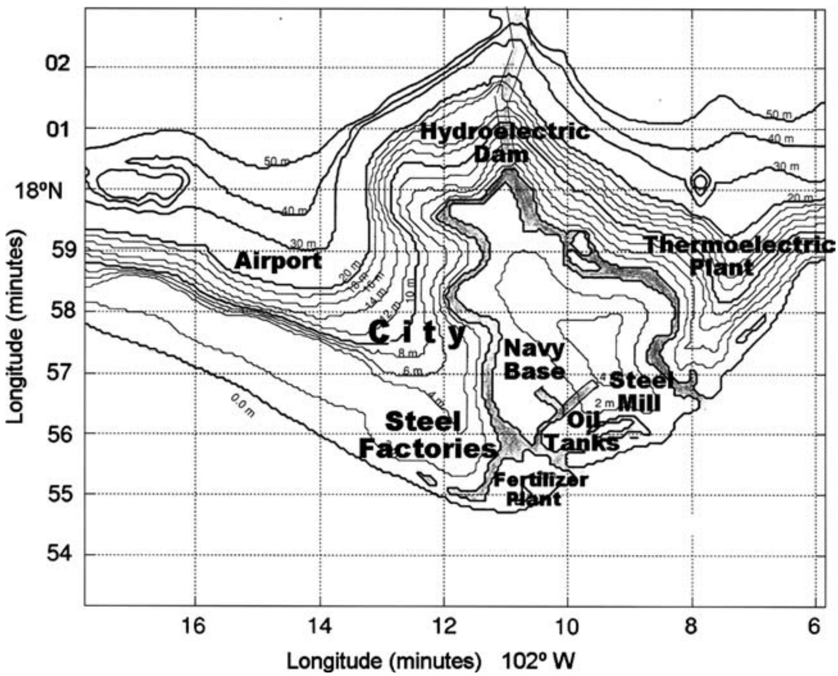

Figure 3
Port of Lázaro Cárdenas industrial installations and urban area, in the River Balsas delta.

On 19 September, 1985 an 8.1 Ms earthquake (ANDERSON *et al.*, 1986) occurred in a subduction zone segment of the Middle America Trench northwest of Lázaro Cárdenas. Waves of 2.5 meters maximum height from the generated tsunami reached the port and flooded a horizontal distance of approximately 500 meters inland. Major damage was attributable to the inundation. Approximately 1.5 km of railroad tracks were destroyed because the bank under the tracks was eroded. An earth embankment bridge providing access to the fertilizer plant was also washed out. Beach configuration changes attributable to approximately 2 m vertical piling of sand were also observed. Results of a survey with detailed damage patterns were presented elsewhere by FARRERAS and SÁNCHEZ (1987) and URBAN REGIONAL RESEARCH (1988). This tsunami stands as slightly lower than a low hazard category event as defined above.

For the computer simulations the following two cases, similar to those which have occurred, so that their recurrence could be reasonably expected, were selected:

- a slightly larger than a low hazard category event, with maximum wave heights of 3.5 m (40% higher wave heights than the 19 September, 1985 tsunami), and
- a medium hazard category event, with maximum wave heights of 5.0 m (similar to the 9 October, 1995 tsunami).

The rupture zone was assumed in the Middle America Trench in front of Lázaro Cárdenas, with earthquake fault parameters derived from the preliminary Harvard Moment Tensor solution and adjusted by trial-and-error method constrained by the analytical relation defining the seismic moment. ETOPO-2 digital bathymetry was used for the offshore wave propagation, and Mexican Navy bathymetric charts for the near shore propagation and coastal interaction. A reverse fault of 40 km width by 100 km length along the strike for the first case and 50 km width by 120 km length for the second case were used. Four and six meter dislocations along a constant dip-slip angle of 15 degrees were assumed for each case, respectively.

Figure 4 shows in an aerial photograph the boundaries of the inundation areas determined by the numerical simulations of each category event. The coastal strip flooded by the 19 September, 1985 tsunami, as surveyed, is also indicated.

A vulnerability assessment study (FARRERAS *et al.*, 2003) indicates that the shallow small island in the middle of the delta, where the container docks and the fertilizer factory sit, is the most vulnerable area to tsunami inundation. Both category events will completely flood the structures, with extensive damage and casualties to be expected. About 15 to 25% of the total area of the two main steel factories can be affected, according to the severity of the tsunami. The oil storage tanks, steel mill and coal yard sitting in the coastal strip of the main island of the delta may experience slight to severe damage from tsunami flooding in about 30 to 60% of their installations. The Mexican Navy base, the grain silos, the urban

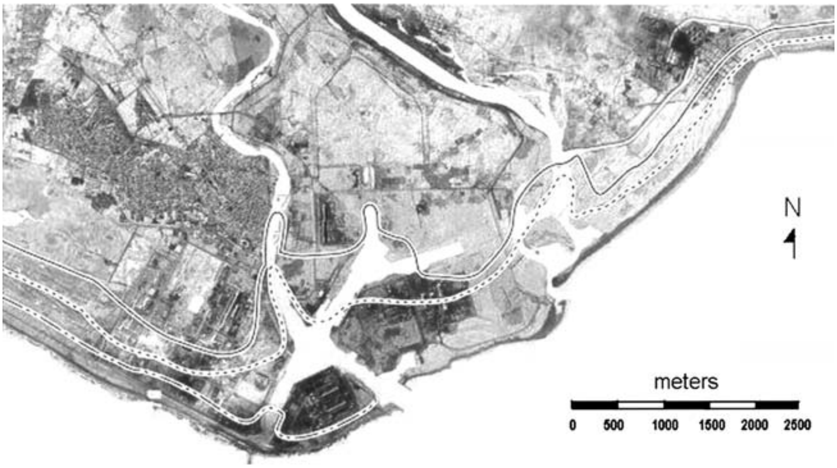

Figure 4
Boundaries of tsunami inundation for Lázaro Cárdenas: – —— – coastal strip flooded by the 19 September, 1985 tsunami, maximum wave heights = 2.5 m (survey), - - - - - slightly larger than a low hazard category event, maximum wave height = 3.5 m (simulation), ————— medium hazard category event, maximum wave height = 5.0 m (simulation).

area of the city and the hydroelectric and thermoelectric power plants are estimated not to be at risk of inundation by these two categories of tsunami. Secondary damage and destruction may happen by the impact of floating objects and ships carried by the tsunami waves, against fixed coastal structures like storage tanks. Fires, explosions, and contamination from oil and chemical spills in the inside harbor can cause severe damage and toxic effects to the population and the marine flora and fauna. Some liquid fertilizers, nitrogen solutions, sodium nitrate and hydroxide, sulfuric acid and urea are water reactive and could give off toxic fumes.

Additional recommendations on urban development to minimize the loss of life, and reduce the damage to property, include: Relocation of the steel factory railroad tracks and roads further inland, protect the most vulnerable industrial port installations and storage facilities, and establish evacuation routes and open space buffer zones for the population to evacuate promptly to emergency shelters at higher elevations or far inland from the risk area.

Similar inundation maps for the Mexican ports of Ensenada, Zihuatanejo and Salina Cruz, produced by numerical simulations as described above, are published elsewhere (CENAPRED, 2001).

4.3. On Preparedness and Awareness

Public education is a key element for preparedness, awareness, the effective application of civil protection measures and the adequate response from the

Figure 5
Awareness/educational tsunami publications: Children book and adult booklet.

population to an early warning system. CICESE altogether with the National Center for Disaster Prevention from the Mexican Secretary of the Interior, developed, published and distributed a Spanish translation and adaptation of the Intergovernmental Oceanographic Commission of UNESCO Children's book on tsunamis (FARRERAS *et al.*, 2002), a 40-page booklet called *Fasciculo on Tsunamis* (FARRERAS *et al.*, 2005), brochures and several other printed materials for the general public (Fig. 5).

5. Conclusions

Three steps to create a tsunami-resistant community are to (BERNARD, 1999):

- Produce tsunami hazard maps to identify areas susceptible to tsunami flooding
- Implement and maintain an awareness/educational program on tsunami dangers
- Develop early local warning systems to alert coastal residents that danger is imminent.

Mexico has recognized that at least these three steps are important key elements for a National Program on Tsunami Detection, Monitoring, Warning and Mitigation. Efforts are taking place to successfully accomplish this objective.

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With the financial support of the Japanese International Cooperation Agency (JICA), the University of Tohoku under the Tsunami Inundation Modeling Exchange (TIME) program transferred tsunami numerical modelling technology to Mexico to produce the tsunami inundation maps.

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