DISASTER RISK ASSESSMENT OF THE CHINA/TAIWAN CROSS-STRAITS REGION
Planning for Disaster Mitigation

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ABSTRACT

Fast-growing, coastal mega cities along China's east coast and the rim of the Cross-Straits region, in particular, are becoming increasingly more vulnerable to potential natural disasters such as earthquakes, tsunamis, typhoons, storm surges and floods. The provinces of Shanghai, Guangdong, Fujian, and Zhejiang, as well as Taiwan, are threatened by common disasters. Advancing Cross-Straits ties in mitigating the impact of such disasters is extremely important for the sustainability of economic growth and the stability of the region. Building important infrastructure facilities on coastal areas on both sides of the Straits to support regional development and population growth require long term planning and adaptation of proper guidelines that will help mitigate catastrophic impacts in this important economic region. Mitigating the impact of future disasters requires an integrated multi-disciplinary planning approach which entails, first identifying disasters, then assessing their impacts, defining geographical limits of vulnerabilities, predicting recurrence frequencies, developing possible scenarios of future socio-economic impacts, resolving Land Use conflicts of vulnerable areas and, finally, preparing a comprehensive plan for preparedness. This presentation analyzes and assesses potential earthquake, tsunami, typhoon, and storm surge and flood disaster risks along the Cross-Straits region. Furthermore, it outlines sustainable, adaptive measures and strategies that must be implemented to help minimize potential future losses of lives and damage to property. Finally, it proposes guidelines for the preparation of a comprehensive disaster plan - a plan that will further advance ties for the Cross-Straits region, by encouraging and facilitating cooperation, not only for disaster mitigation but in various other fields, including education, science and technology.

1. INTRODUCTION

The east coast of China is vulnerable to all types of disasters because of its long coastline, which extends for 1800 km from its border with Korea in the north to its border with Vietnam in the south and includes 6,500 coastal islands. Eight coastal provinces, two mega cities, several medium and small-sized cities and one autonomous region border this extensive coastline. More than 40 percent of the population, or about 500 million people live in coastal areas - a trend which continues at a high rate. Critical infrastructure facilities have been built with inadequate risk assessment or the need for more stringent engineering guidelines for both static and dynamic stabilities from the impact of future extreme disaster events. The present analysis provides a brief overview of historical data, discusses some of the major past earthquakes, tsunamis, typhoons and storm surges and outlines regional and local vulnerabilities in the Cross-Straits region. To illustrate future challenges in mitigating the potential impact that disasters can have, the presentation summarizes the geological and geophysical characteristics of the two prominent seismic zones that can produce destructive earthquakes and tsunamis - the Fuzian Province's seismic zone along the western side of the Cross-Straits and Taiwan's seismic zone of active subduction and collision. Additionally, the presentation provides a brief overview of recent typhoon disasters, scenarios of potential future events, and dynamic mechanisms that can produce flooding of low-lying areas from storm surge. Finally, the presentation explains some of the maximum probable events which engineers and planners may face in the future and summarizes the approach that must be taken to develop the necessary criteria for proper land use, adequate building codes, engineering guidelines and recommends strategies that can be adopted to mitigate the future impact of different disasters for the sustainable development of coastal cities along the Cross-Straits region (Fig. 1).

Fig. 1. China / Cross-Straits Region

2. SEISMOTECTONICS OF CHINA'S CENTRAL, COASTAL AND CROSS-STRAITS REGION.

The following overview of the seismotectonics of China's Central and Coastal regions provides background information on the complex, long term, geodynamic development of the Cross-Straits region and potential for destructive earthquakes, tsunamis and other collateral hazards.

2.1 China's Seismotectonic Evolution

Before the Paleozoic Era, the Eurasian tectonic plate mainly controlled China's geological activity. However, in the middle of the Cenozoic Era, the activity was affected mainly by the interactions of the Pacific and Indian plates (Hellinger et al, 1985). The high seismicity of central and eastern Asia resulted from the northward collisional convergence (at 50 mm/y) of the India tectonic plate against the Eurasian plate.

This tectonic convergence - which begun about 55 million years ago - uplifted the Asian highlands and resulted in the growth of the world's largest orogenic belt, the Himalayas, and the associated Qinghai - Tibet Plateau, which has an average elevation of over 16,000 feet - the highest and largest plateau on Earth (Fig. 2).

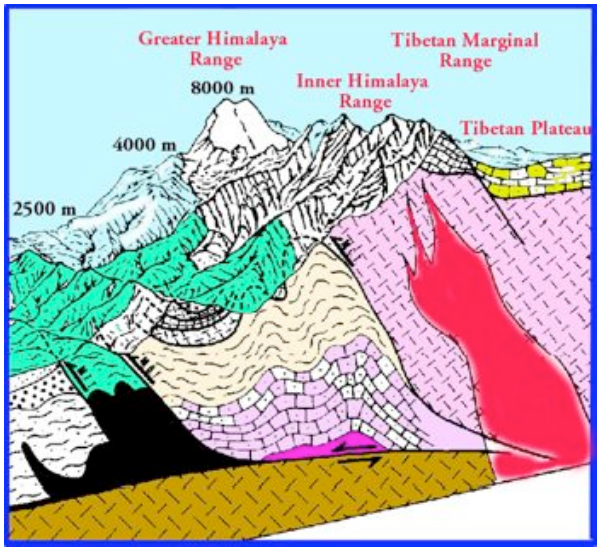

Fig 2. Uplift of the Himalayas, and of the Qinghai - Tibet Plateau

The active collision is the continuing cause of frequent large earthquakes between India and Tibet and throughout the surrounding areas. As the India plate kept on moving northward and intruding into Asia by as much as 1,200 kms, regions north of the Himalayas moved laterally to the east and southeast along large strike slip faults such as the Altyn Tagh, pushing into central China and furthermore resulting in extrusion and crustal movement. As the collision continued, there were hundreds of kilometers of crustal block displacement to the east and to the southeast in the direction of China. China's overall seismicity is the result of such collision during the earliest Eocene (~50 Ma) (Ye et al. 1985).

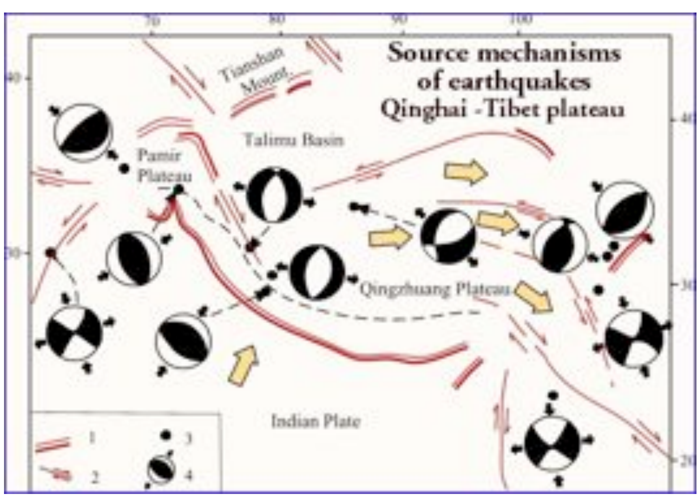

Fig. 3. Interpretation of source mechanism of earthquakes occurring in the Qinghai-Tibet plateau (modified after Zheng Sihua, 1992)

Figure 3 illustrates the source mechanisms of earthquakes in the Qinghai - Tibet plateau region and the extension that takes place to the southeast and to the east in the direction of China.

Also, the early seismotectonic evolution is characterized by the merger of several micro-continents throughout the entire Phanerozoic (Zhang et al., 1984; Hendrix and Davis, 2001). The collision and associated convergence and extension have created 64 major tectonic zones in China, and these can be subdivided into a smaller number of tectonic "regions" (Zhang et al., 1984; Yin and Nie, 1996). Most of the present-day earthquakes in China are generated in the area of plate-connecting belts within the continent where severe geological changes continue to take place. The destructive Sichuan earthquake of May 12, 2998 is a recent example of such continuing changes (Fig. 4, 5) (Pararas-Carayannis, 2008d).

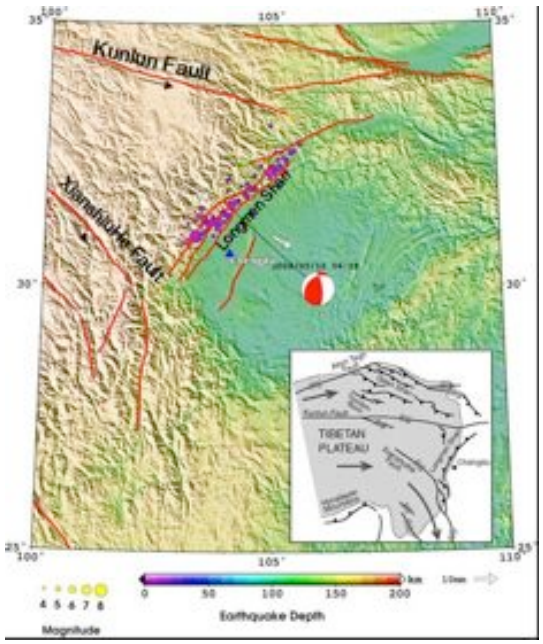

Figure 4. Formation of the Longmen Shan Fault

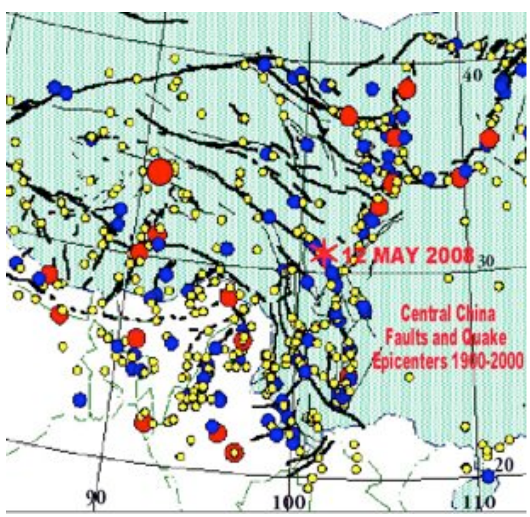

Fig. 5. Central China Faults and Earthquake Epicenters 1900 - 2000.

2.2 Seismotectonic Evolution of China's Coastal, Cross-Straits Region.

China's coastal region underwent complex changes that can account for the present seismotectonic setting of the Cross-Straits region. Both India-Eurasian tectonic collision and Pacific plate subduction may be responsible for structural changes and the formation of several dense seismic zones along the Yellow and the South China Seas. As a result of earlier Tethyan tension, China's coastal regions are now traversed by numerous faults where major earthquakes have occurred and can be expected to occur again in the future (Fig. 6).

Fig. 6. Schematic map showing the conjugate fault systems in the continental margin of northern South China Sea and surrounding areas (after Ma et al., 1998)

Specifically, since the late Cretaceous period, multi-episode and multi-stage tectonic events resulted in the formation of variable conjugate shear systems in the northern continental margin of the South China Sea (Qiu & Zhou, ?) Adjacent to the Cross-Straits coastal region, the present day coastal Guanzhou-Fujian Seismic Belt was formed less than 5Ma by a conjugate shear system with NWW-SEE compression. The west side of this seismic belt runs from the Zhejiang province to the Guangdong province. Also, as Fig. 6 illustrates, this belt is crisscrossed by a conjugate system that has EW compression and numerous transcurrent faults where major earthquakes could be generated in the future. For example, the Guanzhou-Fujian seismic belt is responsible for past large earthquakes in the region.

However, large earthquakes do not only occur along this zone. Large earthquakes along the eastern coast of China and in the Taiwan region are believed to have generated tsunamis in the past, which may have also impacted the Cross-Straits coastal region. Unfortunately however, the available historical information is limited. A first step in fully assessing the impact of historical earthquakes and tsunamis and the potential future risk, should be based on a thorough examination of the historical records. The following is only a brief review of past historical earthquakes and tsunamis along China' coasts and the Cross-Straits region.

2.3 Taiwan's Seismotectonic Evolution

On the eastern Cross-Straits the regional seismotectonics become even more complex in that they involve both subduction and plate convergence. Taiwan is located on the convergent boundary between the Eurasian and the Philippine Sea tectonic plates. Earlier tectonic plate convergence was marked by an apparent eastward subduction of the Eurasian plate underneath the Luzon arc on the Philippine Sea plate. However, this shear motion moved westward with time, forming a broader zone of deformation involving subduction, collision, and plate consumption, rather than a discrete well-defined plate boundary (Pararas-Carayannis, 1999). Thus, tectonic processes do not take place along a simple plate boundary or a subduction zone as commonly conceived, due to the difficulty of subducting a portion of the continental crust, which is significantly buoyant (Fig. 7). Apparently, the wider distributed shear system developed during different stages of arc-continent collision (Fig. 8).

The present day northward movement of the Philippine Sea plate beneath the Eurasian plate is closely related to the Ryukyu and Luzon arc-trench systems, characterized by subduction, convergence and rotation, but marked primarily by the collision of the Luzon volcanic arc with the Asian continental margin (Pararas-Carayannis, 1999). The Ryukyu arc is to the east and northeast, while the Luzon Arc System is southeast of Hong Kong and south of Taiwan. Both volcanic arcs continue onto Taiwan and this wide belt of deformation extends for about 100 km from the western to the eastern offshore region of the island. On the eastern side of the Cross-Straits Region, the seismotectonic belt has an almost N-S orientation.

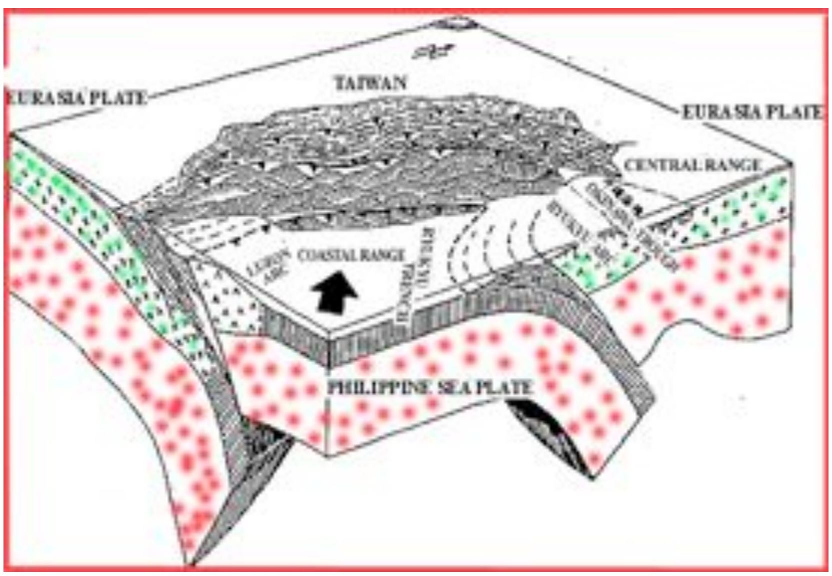

Fig. 7. Northward subduction of the Philippine Sea plate beneath the Ryukyu arc on the Eurasian plate along the Ryukyu Trench.

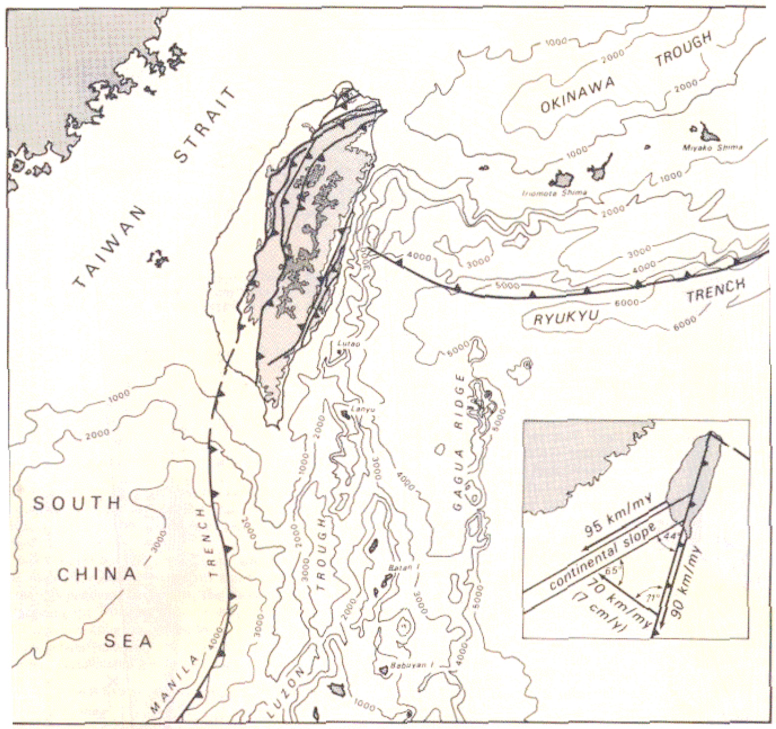

Fig. 8. Arc-continent collision. Triple-point collisional junction in the Taiwan area, east of the Cross-Straits Region.

3.0 EARTHQUAKE AND TSUNAMI RISK ASSESSEMENT OF THE CHINA/TAIWAN CROSS-STRAITS REGION

Earthquake and tsunami risk analysis of the China/Taiwan, Cross-Straits region requires examination of the regional seismicity and a review of all available data of past disasters. The following is only a brief overview of a few, major tsunamigenic earthquakes along China's east coast and along the Cross-Straits earthquakes with mostly land impact (Fig. 9). A more detailed review will be required for a comprehensive risk analysis.

3.1 Historical Earthquakes and Tsunamis Along China's Eastern Coasts and the Cross-Straits Region.

According to historical records four thousand one hundred seventeen (4,117) earthquakes of magnitude greater than 4.75 on the Richter scale occurred in China from 1831 B.C. to 1980 A.D. From about 47 B.C. to 1921, it has been estimated that about fifteen of these earthquakes, generated tsunamis on China’s east coast (Pararas-Carayannis, 2007, 2008a, b, c). What is also characteristic of earthquakes in the Cross-Straits region is that most are shallow events and thus, some of those occurring along thrust faults, have the potential to generate tsunamis.

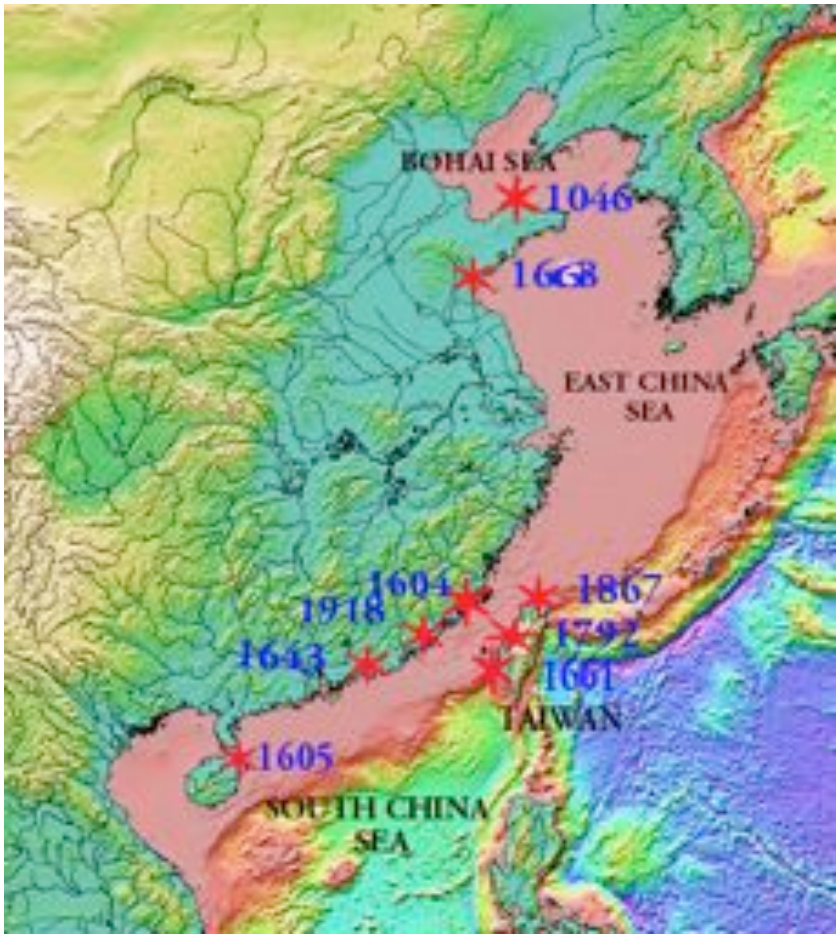

Fig. 9. Epicenters of Historic Tsunamigenic Earthquakes along the East Coast of China and the Cross-Strait Region.

Three of the events characterized as tsunamis in the literature, may have been storm surges. However, even this data given in Figure 9 may be incomplete and in conflict with historical events reported elsewhere in the literature. Major tsunamis that caused 10,000 or more fatalities occurred in 1045, 1329, 1458, 1536, 1776 and 1782 but no specific information could be found. However, there may be mistakes in the historical data as to the dates of these events. For example, the tsunami reported as having occurred in the year 1046 in the Bohai Sea, may be the same event as that reported for 1045. Similarly, there is no information as to where the tsunamis of 1329, 1458, 1536, 1776, or 1782 may have occurred. There may be errors in dates that need to be further investigated and Chinese calendars need to be properly reconciled with the present astronomical calendar.

The data for more recent tsunami events is much more reliable. There have been at least three fairly well documented tsunamis along the eastern coast of China. The first was generated on July 18, 1969 by a 7.4 magnitude earthquake in the Bohai Sea and reportedly caused certain losses in the coastal area near Tangshan, in Hebei Province (Pararas-Carayannis, 2008a, 2009). The second occurred on January 1-2, 1992 at the southern tip of the Hainan Island and caused some damage (Zhou & Adams, 1986). This event was adequately observed and instrumentally recorded. For example, at the Yulin tide gauge the recorded height of the tsunami was 0.78 meters while at the Sanya port the reported height ranged from 0.5-0.8 meters. The third tsunami occurred in 1994 in the Taiwan Straits but no losses were reported. The following is information on some older tsunamigenic events.

3.1.1 The Earthquake and Tsunami of December 29, 1604

The most significant tsunamigenic earthquake in the Cross-Straits region occurred on December 29, 1604 (Fig. 10). Given the high intensities of this earthquake as described in the literature (Zhou & Adams, 1986; Pararas-Carayannis, 2007), this was a large magnitude, disastrous event that must have affected Fujian Province and the entire Cross-Strait Region. Its epicenter was in the offshore area of Quanzhou, close to the coastal Guanzhou-Fujian Seismic Belt. No details are available for this early event. However, according to historical records there were widespread effects which included "cracking of the ground", "movement of the water" and the sinking of many boats. Obviously the old descriptions indicate that a tsunami was generated strong enough to sink boats. The generating area of the tsunami was probably within the offshore area where the earthquake's intensities of 9 and 10 can be extended.

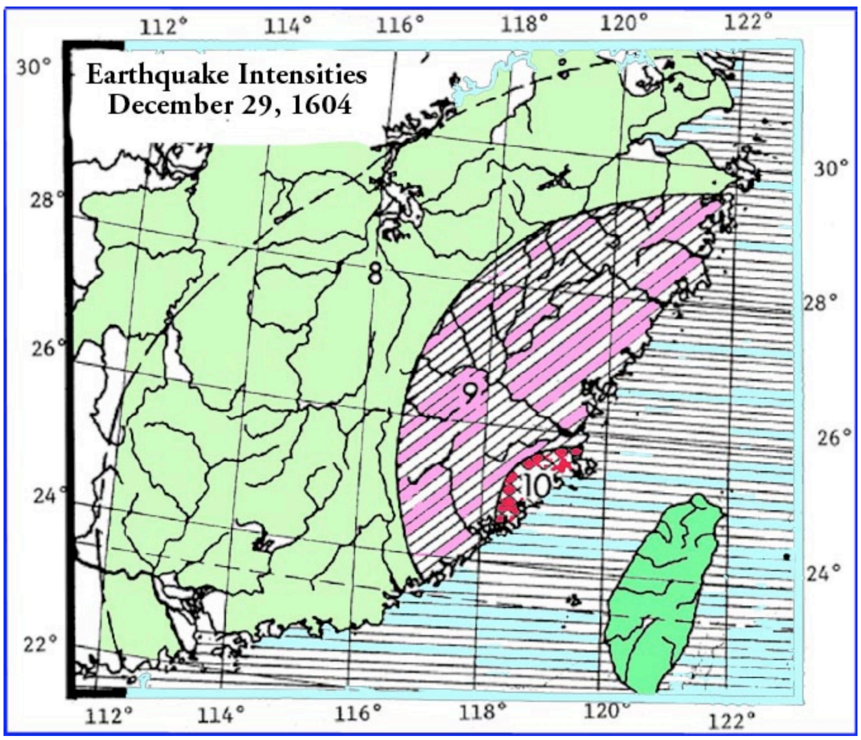

Fig. 10. Intensities of the Earthquake of December 29, 1604. A tsunami was probably generated in the region of intensity 10 and probably intensity 9 (Modified graphic - Nat. Bur. Seismology, 1981).

3.1.2 The Earthquake and Tsunami of July 25, 1668

This was a tsunamigenic earthquake, which affected mainly the Juxian and Shandong Provinces but not Fujian (Zhou & Adams, 1986; Pararas-Carayannis, 2007). It occurred in an area between Juxian and Dancheng of the Shandong Province on a fault zone, which is presently characterized by uplift caused by compressive thrusts of the ongoing crustal extension (Fig 11). Since compressive thrust and coastal uplift occurred, it is believed that this event caused a considerable tsunami, which needs to be better documented by a risk analysis.

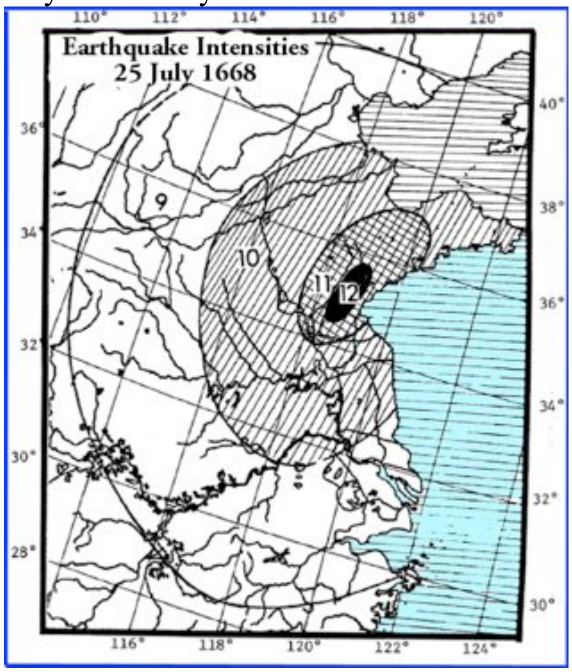

Fig. 11. Intensities of the Earthquake of December 29, 1604. A tsunami was probably generated in the region of intensity 10 and 11 (Modified graphic, Nat. Bur. Seismology, 1981).

3.1.3 The Earthquake and Tsunami of February 13, 1918

A large earthquake occurred near Nano in the Guangdong Province and caused extensive damage. As with the December 29, 1604 event, the 1918 event was generated on the same seismic belt of the Fujian-Guangdong coast, but further north (Fig. 12). Specifically, the epicenter of this earthquake was near Zhenghe-Haifeng. Crustal movement involved counterclockwise rotation (Nat. Bur. Seismology, 1981a, Zhou & Adams, 1986).

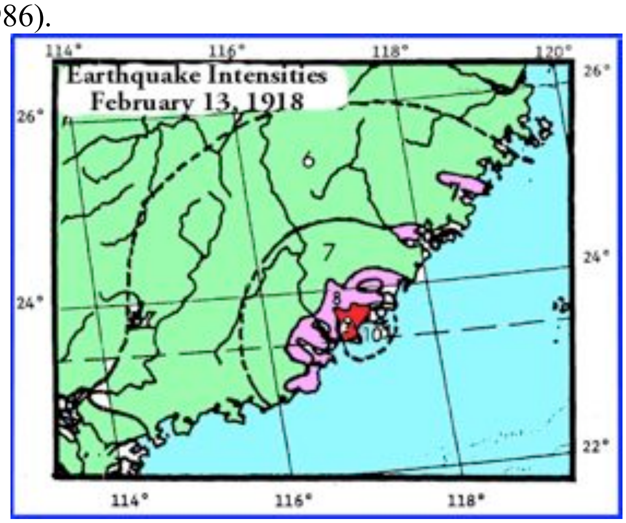

Fig. 12. Intensities of the Earthquake of February 13, 1918. A tsunami was probably generated in the region of intensities 9 and 10 (Modified graphic - Nat. Bur. Seismology, 1981).

3.1.3 Earthquakes and Tsunamis in the Bohai Sea

The shallow earthquake of July 18, 1969 in the Bohai Sea with an estimated Richter magnitude of M 7.4 generated a small tsunami with a height ranging from 1~2 m. above normal tide level. The tsunami was responsible for losses in the coastal region near Tangshan in the Hebei Province, but no details are available. Also, no details are available as to the height of the tide at the time of the earthquake and whether the 1 to 2 meter reported tsunami occurred at high or low tide (Pararas-Carayannis, 2008a). The earthquake occurred on the Zhangjiakou-Bohai Sea seismotectonic zone, which controls the present-day strong earthquake activities in the northern part of the North China region. Several earthquakes and tsunamis have been generated in this region (Fig. 13).

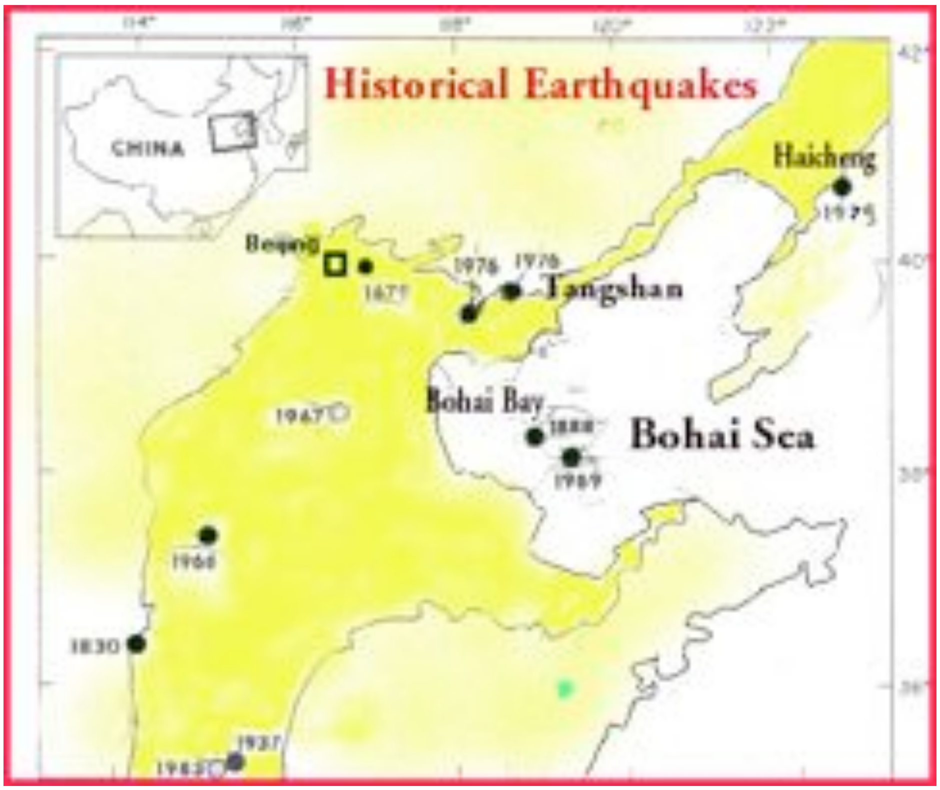

Fig. 13. Earthquakes and Tsunamis in the Bohai Sea (Pararas-Carayannis, 2009)

The subsequent 1975 Haicheng and the 1976 Tangshan earthquakes were extremely destructive in the Bohai Bay region (Pararas-Carayannis, 2007, 2009). The two 1976 Tangshan earthquakes in Hebei Province resulted in the greatest death toll in recent history. Their impact on land around Tangshan has been described adequately in the literature but there has been no information on whether a tsunami was generated. However, the seismic intensities, the aftershock distribution and the observed crustal movements of the Tangshan quakes indicate that the coastal region of Bohai Bay was impacted, and therefore a local tsunami must have been generated, but not reported. Although not reported, it is believed that the July 26, 1976 Tangshan earthquake also generated a tsunami in Bohai Bay (Fig. 14). Apparently, the degree of earthquake destruction on land shrouded the damaging effects and impact from a tsunami.

Fig. 14. The Earthquake and Tsunami of July 28, 1976 in the Bohai Bay (Pararas-Carayannis, 2009).

3.1.4 The Earthquake of 20 September 1999 in Taiwan

The complex, 7.7 earthquake, which struck Taiwan on 20 September 1999, is an example of the type of severe events that can occur in the region (Pararas-Carayannis, 1999). Figure 15 illustrates the high seismicity of both Eastern and Western Taiwan, including the Cross-Straits, for a twenty-year period (1977 - 19997) and shows the epicenter of the disastrous earthquake of 20 September 1999.

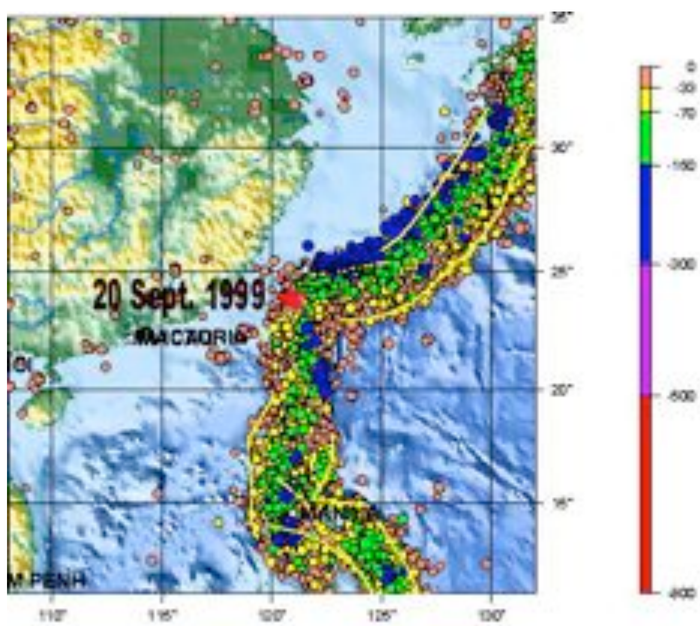

Fig. 15. Seismicity of Taiwan and of the Cross-Straits Region from 1977 to 1997. Epicenter of the September 20, 1999 earthquake (modified graphic of the USGS National Earthquake Data Center).

3.1.5 The Earthquake and Tsunami of August 9, 1792

This earthquake occurred near Jiayi, Taiwan (see Fig. 9). Although it was not a very strong earthquake, it caused a lot of damage. According to the historical record the "water was uplifted several meters", the field "slumped down" and water flooded lower elevations" (Gu et al., 1983, Zhou & Adams, 1986).

4.0 RECENT TYPHOONS, STORM SURGES AND FLOODS IN THE CROSS-STRAITS REGION

Nearly one-third of the world's tropical cyclones form within the Western Pacific region. The peak months are from August to October. Every year, the Cross-Straits region suffers from numerous heavy storms, typhoons and typhoon-associated flooding. Fujian, Guangdong and Zhejiang provinces as well as Taiwan, have experienced severe wind and flooding damage. Several typhoons in recent times were very damaging in the Cross-Straits region and resulted in great losses of lives. For example, one of the most recent extraordinary years for destructive storm systems that affected the region was the year 2000. Fig. 16 shows the tropical storm tracks for that year alone. In September and October of 2005, typhoons "Talim", "Khanun" and "Damrey" killed more than 130 people and disrupted rail, flight and shipping services out of Fuzhou, in Fujian Province. A total of 730,000 people were evacuated from coastal areas of Fujian, Zhejiang and Guangdong.

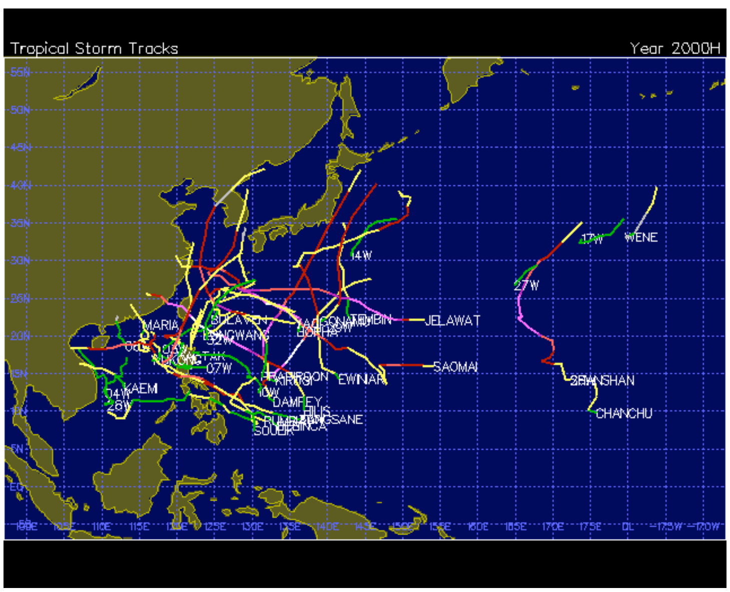

Fig. 16. Tropical Storm Tracks for the Year 2000

The following is a brief overview of some of recent storm systems that have impacted the Cross-Straits region - which illustrates the yearly, seasonal recurrence of such destructive weather related disasters.

4.1 Typhoon "Bilis" - In August of 2000, Typhoon "Bilis", with sustained winds of 205 km/hr, was one of the worse super-typhoons to impact the region. Fig. 17 illustrates its path and wind velocities.

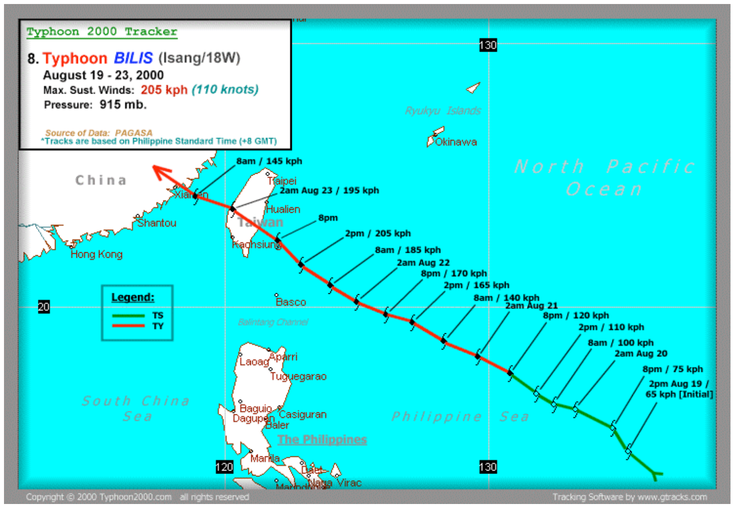

Fig. 17. Track of Typhoon Bilis in August 19-23, 2000

4.2 Typhoon "Longwang" - After striking Taiwan in early October 2005, Typhoon "Longwang" continued to Fujian Province where it caused flooding of up to 2 meters in certain areas. In Fujian, the severe storm affected more than 3.7 million people in 62 cities and counties, toppled about 5,500 houses, damaged about 98,000 hectares of crops and resulted in 65 death. There was massive flooding in the City of Fuzhou (Fig. 18) and along major tributaries of the Yellow and Yangtze rivers.

Fig. 18. A general view of the flooded center of the city Fuzhou, in Fujian Province, on October 3, 2005 after it was hit by Typhoon "Longwang" (Reuters photo).

4.3 Typhoon "Kaemi" - On July 25, 2006, typhoon "Kaemi" made landfall in Jinjiang and Fujian Provinces causing also heavy rains and flooding in Taiwan (Fig. 19). The storm killed at least 32 people in China with another 60 people missing. The typhoon had wind velocity of over 75 miles per hour at the time it made landfall. Areas affected by the typhoon saw rainfall of between two and four inches and major flooding.

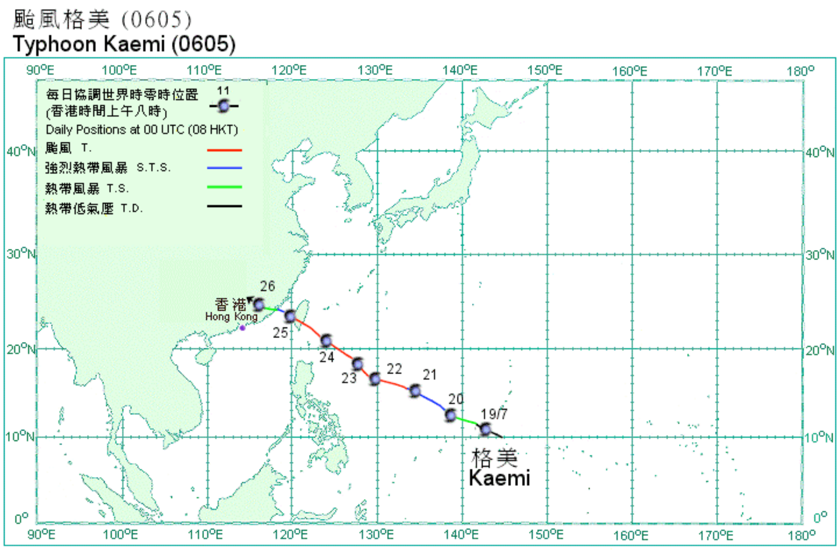

Fig. 19. Track of Typhoon Kaemi and landfall in Taiwan and the Cross-Straits region.

4.4 Typhoon "Saomai" - On Thursday August 10, 2006, typhoon Saomai slammed into the coastal town of Mazhan in the Zhejiang Province. Saomai was classified as the most powerful typhoon to hit China in the last five decades. More than 1.3 million people had to evacuate its path. Typhoon Saomai wrought havoc in the southeastern provinces of Zhejiang, Jiangxi and Longyan's Fujian Province. Wind speeds were measured in excess of 135 miles per hour.

4.5 Typhoon "Sepat" - Also on August 18, 2007 super typhoon "Sepat", with winds up to 184 kilometers per hour, struck Taiwan and the Cross-Straits region but weakened when it made its second landfall on China's east coast a day later. Besides Fujian, the Guangdong and the Zhejiang Provinces were affected.

4.6 Typhoon "Krosa" - In October 2007 typhoon "Krosa" slammed Taiwan with winds of 180 kilometers an hour, then continued towards the coastal city of Wenling in Zhejiang province. More than one million people were evacuated from Zhejiang and Fujian Provinces. Fujian recalled nearly 37,000 vessels.

4.7 Typhoon "Kalmaegi" - On July 18, 2008, Typhoon Kalmaegi killed at least 20 people and caused extensive flooding, landslides and crop damage on the island. In the provinces of Fujian and Zhejiang, authorities evacuated more than 500,000 people and called back nearly 80,000 fishing vessels. Ferry services between the mainland and Taiwan were suspended, too.

4.8 Typhoon "Fung Wong" - On July 28, 2008, the powerful typhoon "Fung Wong" hit Taipei with wind gusts of up to 190 kph then made landfall at Donghan town of Fuqing city, with winds of up to 119 kph. The typhoon lashed Fujian province with heavy rains and major flooding.

4.9 Typhoon "Sinlaku" - On September 13, 2008, typhoon "Sinlaku" made landfall on Taiwan as a Category 2 typhoon, then moved to the northeast, moved back into the South China Sea and started moving slowly towards Japan. The typhoon made landfall at Taiwan's Yilan County disrupting air flights and train services. Typhoon Sinlaku was the 13th tropical storm to hit the Chinese mainland that year and forced the evacuation of about 260,000 people from low-lying coastal regions in Fujian and Zhejiang provinces. High waves hit the coast as typhoon Sinlaku approached Nanfangauo. Sinlaku hit the coast of Zhejiang with winds of up to 126 km per hour and caused heavy flooding. Nearly 230,000 residents were evacuated in Zhejiang and 30,000 fishing boats were recalled to harbor. The storm had far reaching effects even in eastern Shanghai, where the water level in the upper reaches of the city's Huangpu River rose to levels requiring warnings.

4.10 Typhoon "Jangmi" - A month later, on September, 28, 2008, typhoon "Jangmi" made landfall in northeastern Taiwan, then headed for Fujian and Zhejiang Provinces forcing massive evacuations and the closing of schools and offices in the Cross-Straits region. Fortunately, it lost strength and was downgraded to a tropical storm.

5.0 EARTHQUAKE, TSUNAM, AND MARINE HAZARD RISKS AND VULNERABILITIES OF THE CROSS-STRAITS REGION.

The Cross-Straits region is most populous and of highest economic value to China and Taiwan. Earthquakes on land have had great impact in the past. Also, marine disasters, such as tsunamis or typhoon surges, can have a significant impact on coastal populations and the economy of the region. The following is a brief overview of direct and collateral factors that can enhance the generation and impact of tsunami and of other marine and weather-related hazards - such as storm surges.

As previously stated, China's overall earthquake and tsunami vulnerabilities are enhanced by the complex and active seismotectonic zones along its coasts, where major destructive earthquakes occur frequently. Earthquakes in the Cross-Straits region are a major risk that needs to be carefully examined to fully evaluate potential future impacts and recurrence frequencies. Also, there is a need to evaluate the risk of tsunamis generated from larger magnitude earthquakes and from collateral mechanisms, such as stratigraphic folding of the thick sedimentary layers, en-echelon bookshelf failures, or by the triggering of submarine landslides. To assess such potential tsunami mechanisms, the structural and tectonic evolution of the Cross-Straits region must be analytically re-examined and further evaluated. Similarly, typhoons and storm surge flooding are a major threat that needs further study. As the historic record indicates, the Cross Straits region is extremely vulnerable to typhoons and flooding due to storm surges.

5.1 Earthquake and Tsunami Hazards and Vulnerabilities - Potential for Tsunami Generation in the Cross-Straits Region.

Some of the deformational seismic events have the potential to generate destructive local tsunamis. The orientation of the crustal strain beneath the Taiwan Strait appears to be dominated by a North-South extension rather than the East-West compression as along eastern Taiwan (Pararas-Carayannis, 1999). As the historic record indicates, destructive earthquakes occur frequently in the Cross-Straits region. The Straits region is seismically active and capable of generating earthquakes greater than 6.0. For example, the most recent large earthquake in the Taiwan Strait occurred on 16 September 1994. The Peng-Hu Earthquake (mb=6.5), in the western part of the Tainan basin was a very shallow event (depth of 13 km). Its focal mechanism indicated a sea floor movement consistent with normal faulting with its axis along a N-S direction. With earthquake larger than 6, tsunami generation is possible while earthquakes with magnitude greater than 7 and with a large vertical component have the ability to trigger more damaging tsunamis (Pararas-Carayannis, 1999).

5.2 Tsunami Generation from Collateral Mechanisms

With a few exceptions, most of the earthquakes in the region involve primarily crustal movements with lateral strike-slips. Such earthquakes do not generate large tsunamis. However, strong motions from such events could trigger submarine landslides or other collateral events that could contribute to destructive local tsunamis.

Apparently, geological changes have played an important role in the tectonic evolution of the crustal basement and have controlled the scale of palaeochannel development and the changes of ancient river systems and channels which, although now buried by sediments, continue into the Cross-Straits region (Xu et al. 1996). Major rivers deposit large loads of sediments in the Cross-Straits region and this deposition has created unstable slopes on the shelf that could become potential sources of landslide-generated tsunamis. The tectonic movements associated with the larger earthquakes - and the compressive forces they generate - could interact with the submerged fluvial regimes that contain high sediment loads and thus could generate massive sediment movements - even on relatively gentle bathymetric slopes (Pararas-Carayannis, 2009). Such movements could contribute to local tsunami generation. Folding and en-echelon bookshelf type of failures of the deeper consolidated sediment layers could become collateral mechanisms for greater tsunami generation. Such collateral mechanisms can contribute significantly to the generation of destructive local tsunamis anywhere in the region, but particularly closer to the denser seismic zones of the coastal Guanzhou-Fujian Seismic Belt or along the N-S trending seismotectonic belt on the eastern side of the Cross-Straits Region.

5.3 Tsunamis of Distant Origin

Tsunamis of distant origin do not seem to pose a major threat, mainly because of the sheltering effect of Taiwan and of the island arcs. However, tsunamis originating from earthquakes along the Manila Trench or the Ryukyu Islands could potentially have some impact in the Cross-Straits region. For example, on April 24, 1771, a large earthquake (estimated at 7.4) occurred near the southernmost Ryukyu Islands (South of the Ishigaki Island area controlled at that time by the Japanese Satsuma Samurais). A tremendous tsunami was generated (records claim maximum run-up of 50m to 85m). The tsunami devastated the islands of this group as well as the more distant islands of the Miyako group (Pararas-Carayannis, 1999). Huge blocks of coral were carried by the waves. A block was found 2.5 km inland. About 11,000 people were killed in the Ryuku islands, however there is no information in the literature about its impact in Taiwan, the Cross-Straits region or anywhere else along the coasts of China.

Tsunamis originating in the Sea of Japan do not appear to pose a major risk for coastal areas along the Yellow or the East China Seas. For example, very little energy entered the Yellow and East China

Seas when a destructive tsunami was generated by the earthquake of May 26, 1983 in the Sea of Japan (Fig. 20). Although, the tsunami affected the coastal area of China near Shanghai and possibly other coastal areas along the Yellow and the East China Seas, its height was not significant. A tide station near Shanghai recorded a tsunami of only 42 cm in height.

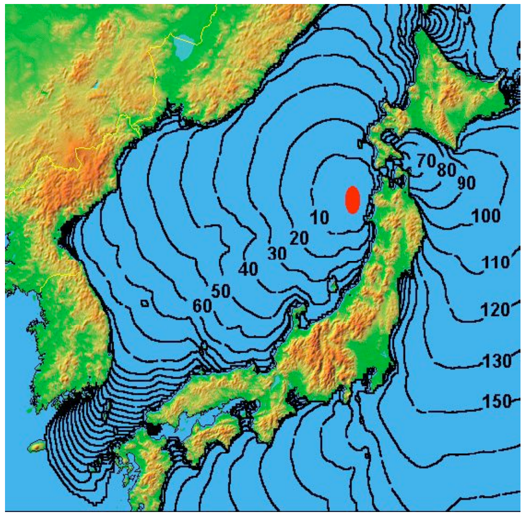

Fig. 20. The Earthquake and Tsunami of May 26, 1983, in the Sea of Japan. Very little tsunami energy entered the East China Sea.

5.4 Effects of Bathymetry

Coastal vulnerability to tsunamis and other marine hazards is greater in the Cross-Straits region and elsewhere along the eastern coasts of China because of the shallow depth of the adjacent seas. The continental shelf adjacent to the provinces of Zhejiang and Fujian is relatively shallow and the water depth averages only a few meters. The greatest depth is about 100 meters. South of the Yangtze River in the East China Sea, the water depth averages about 40 meters but increases to about 300 meters. With such shallow bathymetry and gentle underwater slopes, tsunamis generated from submarine landslides (triggered by earthquakes or other disturbances) would tend to be localized.

5.5 Effects of Astronomical and Atmospheric Tides

Similarly, a significant variability in the astronomical tidal range can contribute to greater coastal vulnerability, particularly if a tsunami or a storm's or typhoon's landfall occur near the time of the higher tidal range. The tides in the region are diurnal. The highest perigean tide in the China Sea is about 3 meters. However, along the shores of Zhejiang and northern Fujian the spring tide reaches a maximum of 5.7 meters. Closer to the coast of Hangzhou, the spring-tide range is 8.0 meters. Shallow bathymetry and local coastal geomorphology may be the reasons for differences in astronomical tidal forcing functions that cause the higher tides. The harmonics of fundamental frequency variations need to be studied to explain such unusual localized deviations along China's eastern coasts and along the Cross-Straits region. Also, further analysis may help understand the unusually high degree of flooding and the high tidal flows that have been observed in Fujian Province and elsewhere in the Cross-Straits region at the onset of typhoon surges.

5.6 Vulnerability of Nuclear Plants and Oil Platforms in the Cross-Straits Region

Typhoons and associated marine hazard risks and flooding are the more frequent, seasonal disasters that affect the region and need careful re-assessment. Numerous more oil platforms exist in the Yellow as well as the South China Seas. At least 7 nuclear power plants are either operating or under construction along China's east coast (Fig. 21). Two of these plants in operation are located in the Fujian Province, in close proximity to the Guanzhou-Fujian Seismic Belt and to the coastal area subject to flooding by typhoon surges. It may be wise to review again the safety of these sites and of the oil platforms operating in the region for the impact of earthquakes similar to the 1604, as well for the adequacy of elevation of the nuclear plants' cooling systems to possible extreme typhoon surges.

Fig. 21 China's Nuclear Power Plants and Plants Operating in Fujian Province.

5.7 Estimating Wind Forces and Potential Storm Surges and Flooding

The brief overview in Section 4 of this report illustrates that typhoons, tropical storms and surges constitute great and frequent seasonal hazards for the Cross-Straits region. One of the greater challenges in mitigating the impact of such hazards is the prediction of flooding resulting from the combined meteorological, oceanic, and astronomic effects coincident with the arrival of a typhoon at the coast. Such information is important in warning the public and in the planning and the design of important coastal structures.

Increasing requirements for large coastal installations, have required conservative criteria in obtaining estimates of potential storm surges from typhoons or tropical storms. Thus, many numerical models and techniques have been developed to provide forecasts and predictions for engineering projects. Although, modern technology and satellite imagery allow presently the early detection of storms and the tracking of their paths, the impact of storm systems is not always fully predictable.

Specific factors which can combine to produce extreme water fluctuations at a coast during the passage of a typhoon include: storm intensity, size, path, duration over water, atmospheric pressure variation, speed of translation, winds and rainfall, bathymetry of the offshore region, astronomical tides, initial water level rise, surface waves and associated wave setup and run up due to wind frictional effects (Pararas-Carayannis, 1975). The capability to predict storm surges is based primarily on the use of analytic and mathematical models, which estimate the interactions between winds and ocean. The prediction of sea surges resulting with the arrival of a typhoon at the coast is a rather difficult problem to solve. The reason is that a typhoon is a three-dimensional, weather system with ever changing dynamic conditions of wind speeds, directions and atmospheric pressures. Although it is outside the scope of this report to explain exactly how the problem is solved, a brief overview is provided.

Many sophisticated mathematical models have been developed in recent years to provide accurate three-dimensional estimates of energy flux, rise of water on the open coast and of the flooding that can be caused by a passing hurricane/typhoon. Most of the models include an approximation to the complete storm-generation process, of the wind field and make use of the Bathystrophic Storm Tide Theory (Pararas-Carayannis, 1975, 2006.). However all models, regardless of sophistication, are limited by the number of initial conditions and assumptions that must be made by the ever-changing dynamic conditions of the storm system - taking into account the combined effects of direct onshore and along shore wind-stress components on the surface of the water, the effect of the earth's rotation (known as the bathystrophic effect) and the different pressure and frictional effects (Pararas-Carayannis, 1975, 1992, 2004, 2006).

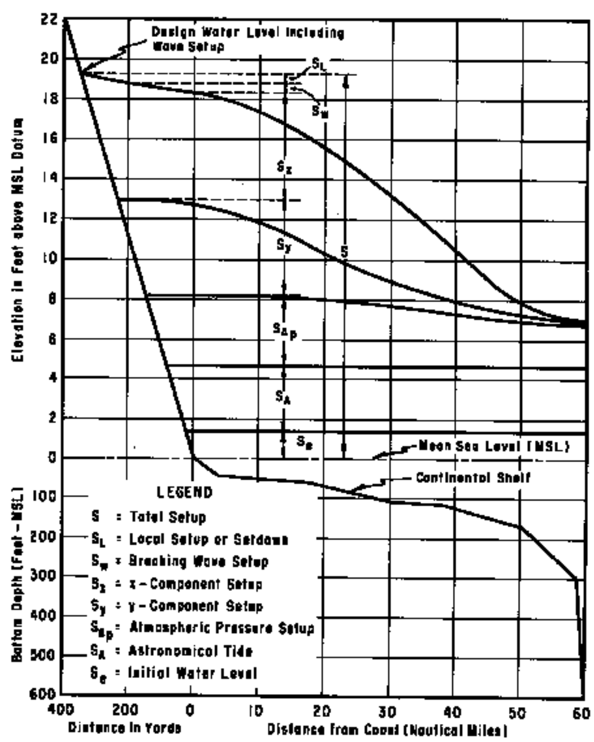

Fig. 22 Diagram showing various components contributing to the hurricane/typhoon surge on the shore (Pararas-Carayannis, 1975).

The more recent numerical models use a three dimensional approach, faster and more efficient computers, more accurate weather data from satellites and, thus, have greater potential for more accurate predictions. However, the fundamental principles in the prediction of hurricane/typhoon surges described here, remain essentially the same.

Fig. 22 illustrates graphically the various components that contribute incrementally to the total typhoon surge height on an open coast and to potential flooding (Pararas-Carayannis 1975). However, coastal morphology may also affect the extent of rise of water.

6.0 PLANNING FOR DISASTER MITIGATION IN THE CROSS-STRAITS REGION

There is nothing that can be done to prevent the occurrence of natural disasters. Disasters will continue to result in losses of lives, destruction to property and the disruption of the social and economic fabric of entire communities in the Cross-Straits region. The losses will continue to increase because of population growth in vulnerable areas. But while disasters cannot be prevented, their impact on loss of life and property can be drastically reduced with proper risk assessment and planning (Pararas-Carayannis, 1986, 1988).

The need for proper natural disaster risk assessment cannot be overemphasized. There is a need for good understanding, not only of the physical nature of the disaster phenomena in the region but also of each vulnerable area's combined physical, social, economic and cultural factors. The specific methodology for such planning has been described in detail in the literature (Pararas-Carayannis, 2007). Disaster-related fatalities, injuries, and property destruction can be avoided or minimized by correct planning, construction, engineering, land utilization and effective public education and preparedness. Structures can be built that are disaster resistant. Many buildings and homes in the Cross-Straits region can be reinforced at a small cost to withstand the effects of a disaster such as an earthquake, a typhoon or a tsunami. Construction codes can be upgraded.

Regardless of the frequency of a disaster or the available warning time, an assessment of potential risk and the planning for disaster mitigation must be made well in advance. A good starting point in assessing the specific vulnerability of each specific region should be the complete identification of potential disasters, the establishment of a historical database of past events, the delineation of the geographical distribution of potential maximum disaster impacts, and the preparation of a plan to mitigate adverse effects and protect life and property. Perhaps disaster risk assessment has been completed for certain disasters and for certain areas in the region. However, these should be reviewed from time to time to ensure their adequacy. The following is only a brief overview of some of the general concepts and basic principles that apply to risk assessment and the mitigation of the most important of the natural disasters that threaten the Cross-Straits region.

6. 1 Identification of Disaster Risks in the Cross-Straits Region

Advances in science and technology provide the means to reduce significantly losses from disasters. But, in order to apply the needed techniques, it is important to first identify the potential disasters that may strike the Cross-Straits region. Any given area may be vulnerable to one or more natural disasters. Some areas in the Straits may be more vulnerable to earthquakes and tsunamis. Other areas may be more vulnerable to typhoons and surge flooding, while still others may be threatened by landslides or other localized hazards. Identifying the most important disasters and associated hazards for each specific area is the first priority in developing a risk assessment study for the Cross-Straits region. For each type of potential disaster the risk assessment study will require a different approach. However, there are some common elements in assessing the impact of all disasters in the region.

6.2 Development of Historical Disaster Databases

After identifying the disasters that may be of threat to the Cross-Straits region, a good starting point for the disaster risk assessment study is the collection of data of all the historical events that caused destruction in the past (Pararas-Carayannis, 1986). The data collection becomes easier if good records have been kept. A historical disaster database can be developed for the region by researching miscellaneous archives of newspapers and of public records. If such historical data is unavailable, the data may be developed from indirect sources. Indirect ways in developing a historical data base for past events may be the examination of old correspondence of government officials or of accounts of early settlers. In the absence of historical data, past disaster events can be determined by studying the geologic stratigraphy of a region and using radiocarbon, other isotope dating techniques or dendrochronolgy to establish past disaster occurrences and their severity. For example, by studying past seismic activity, geologists can often speculate on what controls the dynamics of earthquakes and make predictions. Often one earthquake may nucleate an offset along the trace of a fault and such offsets and measurements of strain build-up can be used to forecast, not necessarily the exact time of the next earthquake event further down the fault rupture, but at least its magnitude and location (Pararas-Carayannis, 2007).

The development of a comprehensive and systematic compilation of historical data on disasters is an indispensable tool for disaster risk analysis and can also serve in the operational analysis and real-time evaluation of potential disaster threats by early warning systems. Finally, a historical disaster database can be widely used for coastal zone management, engineering design criteria, educational purposes and disaster preparedness. Internet communications and software can also help make interactive retrieval of historical data on disasters feasible for global sharing, and for international programs of disaster mitigation.

6.3 Disaster Frequency in the Cross-Straits Region

The most important parameter in assessing risks in the Cross-Straits area and for the planning for disaster mitigation is the determination of the disaster's recurrence frequency. Assuming that the historic record is long enough for the region and there have been many years of direct observations, it is possible to establish approximately when a disaster may be expected again. However, if the historic record is limited, statistical methods are of little use.

The problem is that large catastrophic disasters may take place so infrequently in any one location that there may be no locally available data on which to predict risk and produce a zonation of the hazard. The lack of historical data should not be misinterpreted to mean that there is no danger. Therefore, the prediction of infrequent disasters such as earthquakes, tsunamis or floods - are often given in statistical terms but with a great deal of ambiguity. For example, when a statistical prediction is made that "there is a 90 percent chance that an earthquake will occur in the next 50 years," in a certain area known for its seismicity, this does not mean that the predicted earthquake cannot happen tomorrow or that it may not be delayed by 50 years (Chinnery and North, 1975). Similarly, floods are estimated in terms of statistical probability of being 50, 100 or 200-year events – which nature may very well prove wrong. Obviously, statistical predictions of infrequent disasters may not be within a reasonable time frame that can be of usefulness to planners, policy makers, and those in government who deal with public safety. However, the statistical analysis of seasonal disasters such as hurricanes or storms can be forecasted more easily and can be fairly accurate. In conclusion, if a good historical database exists, it is possible to develop the statistical probability of a disaster's recurrence in the Cross-Straits region.

6.3 Planning for Appropriate Land Use

In developing a viable disaster preparedness plan for the Cross-Straits region, all environmental hazards need to be examined in order to protect the public and to locate, design, construct and determine the safety and reliability of important infrastructure facilities, particularly in the coastal zone. For example, in evaluating the earthquake hazard, the seismic regions should be identified in terms of geographical distribution, the frequency of earthquake occurrences determined and the probabilities of recurrences estimated. The risk assessment should include evaluation of expected peak ground accelerations (horizontal and vertical) and the designation of appropriate building codes. Disaster recurrence frequencies should be estimated with care in differentiating between expected yearly or seasonal occurrences - such as those related to atmospheric disturbances - and for extreme events such as earthquakes or tsunamis that have much longer cycles (Pararas-Carayannis, 2002).

6. 4 Disaster Risk Mapping

Having completed the preliminary stages, the analysis of the disaster risk must now be translated and reduced from technical and scientific terms to simple forms that can be adopted and used effectively. The analysis must be simplified further into forms that can be understood easily. Thus, the final product of historical, statistical or modeling studies that may be conducted must indicate the spatial variations of the hazard risk in the form of maps. Maps can be prepared for all natural hazards that may impact the Cross-Straits region. The production of maps depicting variations in the degrees of disaster risk is an invaluable tool for the planning process and for proper land management (Pararas-Carayannis, 2002). In this way, high-risk areas can be avoided or used for low intensity development and safe areas can be designated for public shelters and evacuation of the public. Similarly, the total risk at any point can be easily established, as well as the probability of occurrence for insurance purposes.

6.5 Variation and Acceptability of Risk

Determining the variation of risk in the Cross-Straits region is a key element in planning and preparing for future disasters. For example, based on historical earthquake or typhoon activity, appropriate maps can be prepared depicting the risks for each region. For example, four zones usually represent seismic risk in accordance to expectancy of earthquake damage.

According to this type of zoning, areas may be designated that have no reasonable expectancy of earthquake damage; areas where minor damage can be expected; areas where moderate damage can be expected; and finally areas where destructive earthquake effects can be expected. Typhoon maps may show their customary tracks, seasonal and chronological occurrences, and areas of past impact and heights of surge inundation (Pararas-Carayannis, 2002).

6.6 Microzonation of Disaster Risks in the Cross-Straits Region

Although mapping of hazards is useful for overall risk assessment, the selective nature of a disaster's destruction along the Cross-Straits region requires mapping which takes into consideration specific local conditions. Public officials and planners can develop better disaster response and recovery plans if they know the possible physical and economic damage and the various disaster scenarios and collateral impacts which may affect structures and businesses. Also, structural engineers need more accurate analysis and more detailed information in the form of microzonation maps of the hazard so that they can design structures that will withstand the impacts and additional structural static and dynamic loads. Such detailed maps are essential to planning and disaster mitigation. For example, in assessing the specific earthquake risk of a given area in the Cross-Straits region, an earthquake source must be postulated of a given magnitude and location. Then all geological materials in the area with similar physical properties can be grouped together. Subsequently, the effects of the postulated earthquake for each geologic unit can be predicted by the type of hazard for failure, specific type of ground shaking, surface rupture, flooding, land sliding, and liquefaction potential. With such maps engineering geologists can estimate potential amplification of ground motions during an earthquake and engineers can design proper new structures or retrofit existing ones (Pararas-Carayannis, 2002).

6.7 Ensuring Safety from Frequent Seasonal Disasters in the Cross-Straits Region.

The Cross-Straits region is the worse hit area for natural disasters, particularly typhoons and rainstorms. A meteorological disaster control system is already under construction to serve Fujian and Taiwan. Although apparent progress has taken place in improving onshore weather monitoring services, there is also a further need to improve the capabilities in marine climate monitoring, analysis and forecasting in the Cross-Straits region by increasing the number of observing stations, data transmission and communication systems, along with a more advanced weather forecast and warning system.

6.8 Ensuring Public Safety

Of paramount importance in land use analysis should be public safety and the means by which it can be assured through proper planning and land utilization. Development policies and decisions on public safety must be based on a comprehensive disaster risk assessment of all environmental hazards impacts that may be unique to a region. Government agencies have the responsibility to formulate land-use regulations that will result in greater public safety. Proper land utilization policies must prohibit urban development in zones that the disaster assessment study identified as potentially vulnerable and may put parts of the population at risk. Furthermore, the government agencies must designate evacuation procedures, post signs and provide proper instructions to the public. Property and business owners could also be educated about steps they can take voluntarily to protect their investments, if these are located in risk areas.

6.9 Disaster Mitigation Through Preparedness

The safety and security of the public in the Cross-Straits region will continue to be threatened by numerous disasters. The main reasons for such vulnerabilities may be erroneous perceptions of disasters and the lack of proper planning and preparedness. Therefore, equally important in mitigating loss of life and damage to property is the perception of potential disasters by the people of each threatened region. Disaster perception by the public is based on a technical understanding of the phenomenon, at least at the basic level, and a behavioral response stemming from that understanding and confidence of the public for the authorities to provide safety, timely disaster warnings, and prompt post disaster recovery. Thus, once a disaster risk assessment study has been completed, a program of proper education that promotes disaster awareness and safety rules is an important function of government civil defense authorities.

It is paramount that Emergency Management Planning should become an ongoing activity for all participating agencies in the region and meetings should be held frequently to review disaster scenarios and how potential hazards could be prevented or their impact be mitigated. Such interagency coordination is extremely important and can be optimized through frequent meetings of managers and by encouraging good interpersonal relationships. Furthermore through hearings, citizen and private involvement should be encouraged to review and evaluate community concerns about potential emergencies. Maintaining comprehensive records during a disaster is another extremely important responsibility in correcting planning deficiencies and mitigating future disaster impacts. Thus a public information function must be clearly defined and established.

The ultimate objective of disaster planning and the mitigation of disaster impact is the safety of the public and the protection of property. Therefore, internal alerting procedures must also be established by the responsible agencies, bearing in mind that their ability to alert the public must be maximized through effective warning systems that use all available means of public information, communications and the media.

7.0 SUMMARY AND CONCLUSIONS

The Cross-Straits is a region that is densely populated and has high economic value. Natural disasters such as earthquakes, tsunamis, typhoons and other collateral hazards can have a great impact. Earthquake disasters occur frequently. Tsunamis do not pose as much of a threat, but locally destructive tsunamis could be generated in the future which can be expected to have more significant impact since most of the recent development has taken place along low-lying coastal areas where several mega cities are located and infrastructure facilities exist or are under construction. Local tsunamis may be also generated in the Cross-Straits region by a combination of collateral mechanisms that could involve folding of thick sedimentary layers, landslides, destabilization/dissociation of gas hydrates deposits and mass sediment flows. Future tectonic movements associated with larger earthquakes on either side of the Cross-Straits could interact with the now submerged fluvial regimes that contain high sediment loads and thus could generate massive sediment movements. Folding and en-echelon bookshelf type of failures of the deeper consolidated sediment layers could become collateral mechanisms for greater tsunami generation, particularly in areas where denser seismic zones are concentrated, the seismicity is stronger, and greater sedimentation has occurred. Thus the potential for tsunami generation is exacerbated by the thick accumulation of sediments and the multi-layered stereographic distribution of sediments with different shear strengths, densities and rigidities.

Dissociation of the abundant gas hydrate deposits by earthquake ground motions, particularly near offshore oil platforms, could result in large-scale slip and sediment mass flows.
Typhoon and associated marine hazards, pose the greatest threat because of their yearly seasonal recurrence. The risks associated with weather related hazards in the Cross-Straits region needs to be carefully evaluated.

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