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Pakistan's Earthquake and Tsunami Hazards Potential Impact on Infrastructure

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Abstract. Interaction of the Indian, Arabian and Eurasian tectonic plates has resulted in the formation of major active fault systems in South Asia. Compression along the tectonic boundaries results in thrust or reverse type of faulting and zones of crustal deformation characterized by high seismic activity and continuing Orogenesis. The more intense seismic activity occurs near regions of thrust faulting which is developing at the Himalayan foothills. In northern Pakistan, the Hindu Kush Mountains converge with the Karakoram Range to form a part of the Himalayan mountain system. Northern, western as well as southern Pakistan, Kashmir and northern India and Afghanistan are along such zones of high seismic activity. In Pakistan, most of the earthquakes occur in the north and western regions along the boundary of the Indian tectonic plate with the Iranian and Afghan micro-plates. The active zone extends from the Makran region in the southwest to the Hazara-Kashmir syntaxial bend in the north. Southwest Pakistan is vulnerable to both earthquake and tsunami hazards. In 2005, earthquakes devastated northern Pakistan and Kashmir and severely affected the cities of Muzaffarabad, Islamadad and Rawalpindi, causing severe destruction to the infrastructure of the northern region. A major earthquake along an extensive transform fault system in 1935 destroyed the city Quetta and the adjoining region. A major earthquake along the northern Arabian sea in 1945 generated a very destructive tsunami along the coasts of Baluchistan and Sindh Provinces. The region near Karachi is vulnerable as it is located near four major faults where destructive earthquakes and tsunamis have occurred in the past. Given Pakistan's vulnerability and extensive infrastructure development in recent years, the present study reviews briefly the earthquake and tsunami risk factors and assesses the impact that such disasters can have on the country's critical infrastructure - which includes nuclear facilities and power reactors.

Introduction

Pakistan is vulnerable to many natural and man-made disasters that can impact on people and infrastructure and severely slow down the country's economic development. Floods, earthquakes, landslides and tsunamis are among the important natural hazards. Flooding and earthquakes have had the greatest impact in recent years. Floods in 2010 killed over 1,100 people and resulted in the displacement of hundreds of thousands. Although climate change has been blamed to be the cause of the extensive flooding, over development and the timber business, especially in the Khyber-Pakhtunkhwa region, have devastated watershed areas which make much easier the generation of flash floods. Additionally, earthquakes and landslides have had a significant impact on Pakistan's roads, railroad air networks and other infrastructure. Although tsunamis do not occur frequently, the historic record indicates that their re-currence could have an important impact on the country's shipping and overall economy. The Makran subduction zone in the northern Arabian sea is a potential source region for large tsunamigenic earthquakes that can affect Pakistan's entire coastline and the two of its international ports - Karachi and Port Muhammad bin Qasim, Karachi is vulnerable to earthquakes since it is bounded by numerous faults where large events occurred in the past. Finally, the safety and security of Pakistan's nuclear complex is very vulnerable to earthquakes and collateral disasters, particularly for the facilities located near the Hazara-Kashmir syntaxial bend. The present paper provides a cursory assessment of risk factors of potential earthquakes and tsunamis that could affect Pakistan and slow down its socio-economic development. A specific risk assessment analysis of important infrastructure facilities will require a detailed study of local conditions and of potential local hazards. The present analysis includes only a brief review of the country's overall tectonic setting and the impact of past earthquake and tsunami disasters.

Tectonic Setting - Geological Instability - Regional Seismic Activity

Approximately 20 million years ago India was connected to the south-eastern tip of Africa. Forces within the earth's mantle caused the development of a rift in the crust, thus separating the Indo-Australian tectonic plate from the continent of Africa. For millions of years, this great tectonic plate drifted in a north/northeast direction. Several millions of years later, its leading deep sea-floor edge began colliding with the Eurasian tectonic plate. The migration and collision broke and folded the earth's crust, creating fractured microplates, great faults and subduction zones – also developing a diffuse zone of seismicity and deformation along the entire south Asia region (Fig. 1).

Compression along the tectonic boundaries resulted in thrust or reverse type of faulting and upward displacement of crustal material. Such process of Orogenesis formed the Himalayan Mountain Range as well as the Pamir, Karakoram, the Hindu Kush ranges and the Tibetan Plateau. Over millions of years, the complex kinematic earth movements created the active fault systems that now traverse Pakistan, Kashmir as well as northern India and Afghanistan. In northern Pakistan, the orogenetic processes created the Hindu Kush Mountains, which converge with the Karakoram Range, a part of the Himalayan mountain system. Zones of high seismic activity developed in northern India and in western, northern and southern Pakistan, as well as in Tibet, Afghanistan and Iran (European Geophysical Society. 2003). Presently, the more intense seismic activity occurs near regions of thrust faulting which developed along the boundary of the Indian tectonic plate at the Himalayan foothills in both northern Pakistan and northern India, as well as along the western region boundary with the Iranian and Afghan micro-plates (Fig. 2). Pakistan vulnerability to earthquakes derives from the movement of the Indian tectonic plate in a north/northeast direction at a fast rate of about 40 mm/yr (1.6 inches/year).

The Chaman Thrust Fault System

The Chaman Thrust Fault system is a continuation on land of an extensive transform fault system in the Arabian Sea known as the Owen Fault Zone (Lawrence *et al.,* 1992). This zone forms the boundary between the Arabian and the Iranian micro-plate, where the former subducts beneath the latter. Thrust zones run along the Kirthar, Sulaiman and Salt ranges. The Chaman Fault is a major fracture, which begins near Kalat in the northern Makran range of the Baluchistan Province, passes near Quetta and extends along Pakistan's western frontier with Afghanistan and continues in a north-northeastern direction to Kabul - after branching off to form the Main Karakoram Thrust (MKT) System (Fig 2).

The great Quetta earthquake (M.7) of 31 May 1935, which devastated the city of Quetta and the adjoining

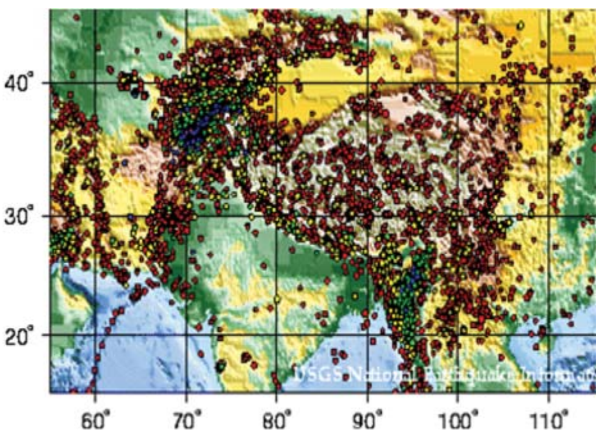

Fig 1. South Asia seismicity (USGS)

region, occurred along the Chaman Fault (Pakistan Meteorological Department, 2005). Other major thrust zones exist along the Kirthar, Sulaiman and salt mountain ranges.

The Main Mantle Thrust System (MMT)

The Main Mantle Thrust (MMT) system parallels the Chatham Fault System on the east side of the Pishin Basin (Fig. 2). Both the MKT and the MMT turn eastward in the Hazara-Kashmir syntaxial bend near the Main Boundary Thrust (MBT), the region of major tectonic plate collision (Fig. 2). The October 8, 2005 earthquake occurred near this active seismic zone in northern Pakistan in the Himalayan foothills. Its focal mechanism and slip and strike components are consistent with the compressive type of thrust faulting which is characteristic for the region and has resulted in folding and the formation of extensive anticlinal ridges in the vicinity of Muzaffarabad.

Major Faults near Karachi

Four major faults exist in and around Karachi, other parts of deltaic Indus, and along the southern coast of Makran (Pararas-Carayannis, 2006). The first of these is the Allah Bund Fault (Fig. 3). It traverses Shahbundar, Jah, Steel

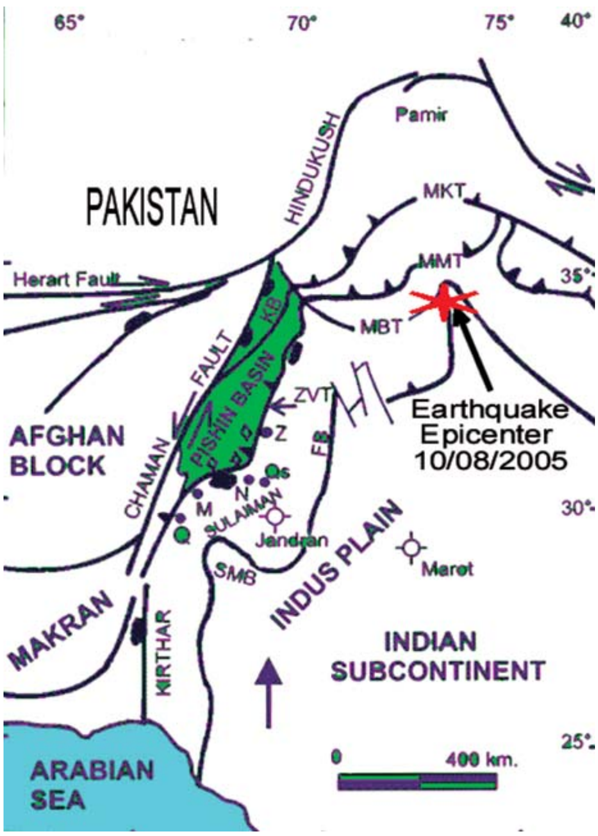

Fig 2. The 2005 earthquake occurred in the Hazara-Kashmir syntaxial bend near the Main Mantle Thrust (MMT), the Main Karakoram Thrust (MKT) and the Main Boundary Thrust (MBT) (Modified base map of Pakistan Geological Survey – after Bakht, 2000).

Mills and continues to the eastern parts of Karachi – ending near Cape Monz. Earthquakes along this particular fault have been responsible for considerable destruction in the past (Fig. 3). For example, a major earthquake in the 13th century destroyed Bhanbhor. Another major earthquake in 1896 was responsible for extensive damage in Shahbundar.

The second major fault near Karachi is an extension of the one that begins near Rann of the Kutch region. The third is the Bhuj fault which ends into Arabian sea near the Makran coast. Finally, the fourth major fault near Karachi is located in the lower Dadu district, near Surajani. A major thrust fault which runs along the southern coast of the Makran coast and parts of deltaic Indus is believed to be of the same character as the west Coast fault along the coast of Maharashtra, where a tsunami may have been generated in 1524, near Dabhol (Pararas-Carayannis, 2006 and 2006). Earthquakes

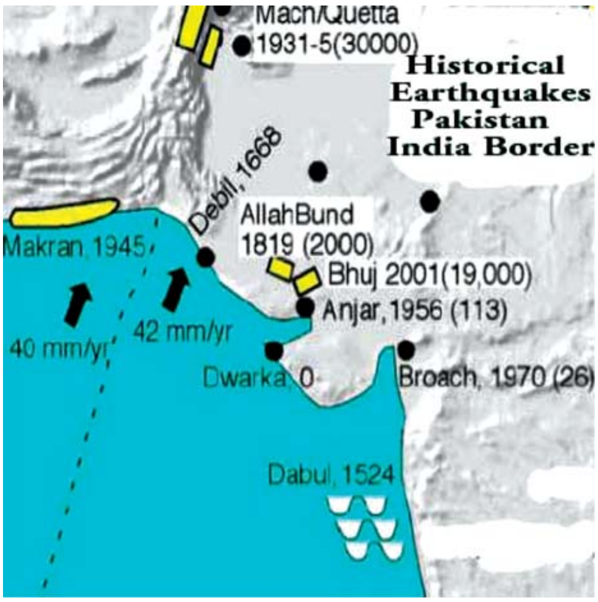

Fig 3. Faults near Karachi – past and recent earthquakes

occurred on these faults in the past but also in recent times.

The Makran Accretionary Prism and Coastal Orocline

Active tectonic convergence of the India plate with the Arabian and Iranian microplates of the Eurasian tectonic block has created a tectonic margin. The plates converge at an estimated rate of about 30 to 50 mm/y (Platt *et al.,* 1988). The northward movement and subduction of the Oman oceanic lithosphere beneath the Iranian micro-plate at a very shallow angle of subduction of about 20 degrees, has dragged Tertiary marine sediments into an accretionary prism at the southern edge of the Asian continent (Pararas-Carayannis, 2004) - thus forming the Makran coastal region, a belt of highly folded and densely faulted mountain ridges which parallel the present shoreline. The Makran Orocline is shown in Fig. 4 and in a NASA satellite photo (Fig. 5). Major tectonic elements along this particular zone of deformation were formed during the Cenozoic and Mesozoic eras.

To the west of the accretionary prism, continental collision of about 10 mm/yr has formed the Zagros fold and thrust belt. To the east, the area comprises of a narrow belt, which truncates against the Chaman transform fault - - an extensive system that extends on land in a north-northeast direction along Pakistan's frontier with Afghanistan. The zone extends from the Makran coastal region in south-west Pakistan to the Hazara-Kashmir syntaxial bend in the north (Fig. 2) and is characterized by high seismic activity. The coastline of Pakistan along the Arabian Sea extends for about 1,050 km with 800 km belonging to the Baluchistan Province and 250 km to the Sindh Province. The Makran coastal range forms a narrow strip of mountains along about 75 percent of the total coast length, or about 800 km. The steep mountains rise to an elevation of up to 1,500 m (5,000 ft).

The Makran coast is rugged and tectonic in origin with uplifted terraces, cliffs and headlands. The entire coastline

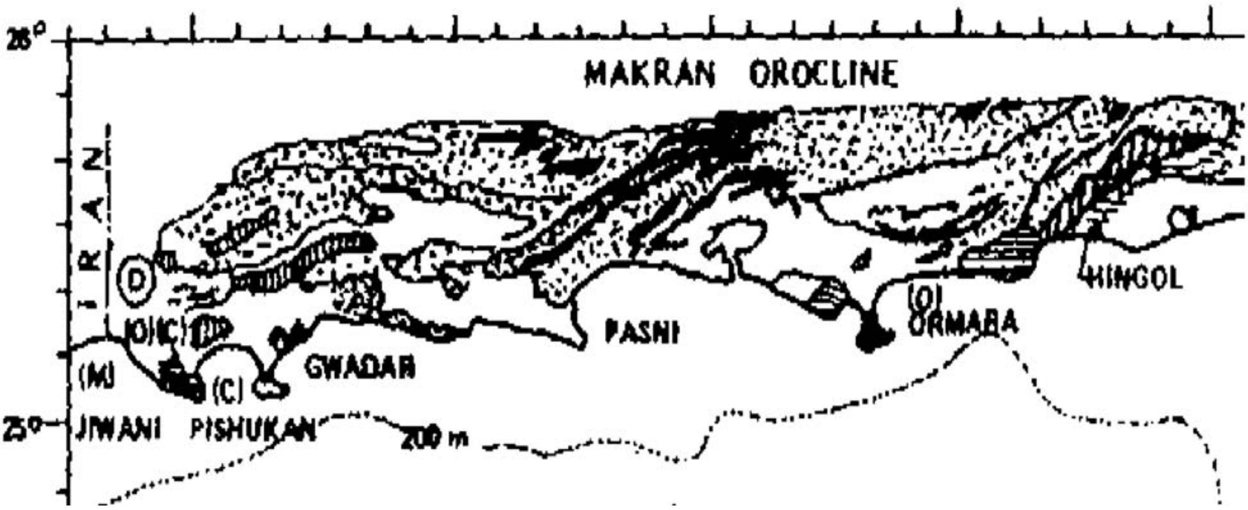

Fig 4. Makran Orocline

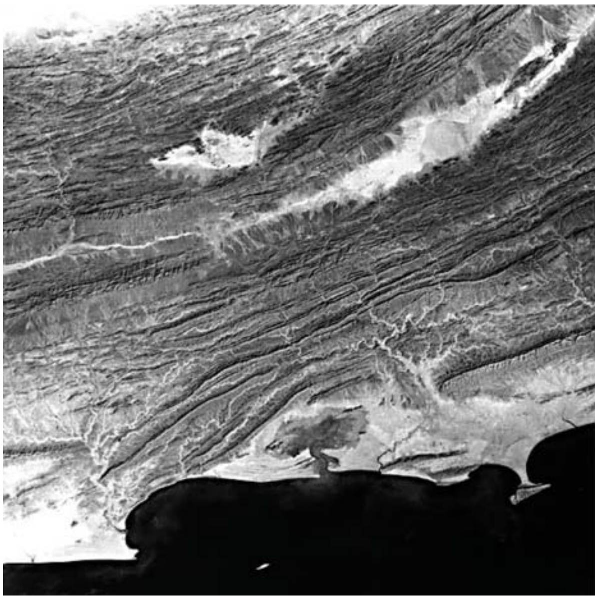

Fig 5. NASA Satellite photo of a section of the Makran rugged and tectonic coastline showing uplifted terraces, headlands, sandy beaches, mud flats, rocky cliffs, bays and deltas. Numerous mud volcanoes are present along the shores.

is characterized by extreme sediment accretion (White and Loudon, 1983; Platt *et al.,* 1985; Minshull *et al.,* 1992, Fruehn *et al.,* 1997). It is one of largest sediment accretionary wedges on earth, with up to 7 km of sediments deposited in the Gulf of Oman to the west and major rivers contributing vast amount of sediment to the offshore region in the east. The accretionary complex is more than 900 km long, has an east-west orientation and is bounded on both sides by large transform faults associated with tectonic plate boundaries. The significance of sedimentation to tsunami generation is examined at a subsequent section.

The Makran Subduction Zone

The tectonic collisions have also created an active subduction zone along the boundary of the Arabian plate in the north Arabian sea. An east-west trench has been formed south of the Makran coast and a volcanic arc has emerged - specifically the Chagai volcanic arc, which extends into Iran. The Koh-e-Sultan volcano and other volcanic cones in the Chagai area are side products of the active subduction (Schoppel, 1977). The major fault system along the offshore Makran coast (Baluchistan and Sindh Provinces) is the result of the active subduction where major earthquakes have occurred in the past (Dorostian and Gheitanchi, 2003). However, the seismicity of the Makran region is relatively low compared to the neighboring regions, which have been devastated regularly by large earthquakes (Jacob and Quittmeyer, 1979). The morphology of the region is further complicated by the extensive sedimentation, which takes place as a result of erosion of Himalayan mountain ranges and the numerous rivers flowing into the north Arabian sea. A very thick sedimentary column enters the subduction zone (White and Louden, 1983), so the trench associated with the present accretionary front in the offshore region of Makran has been buried by sediments and does not have much of a morphological relief as other trenches around the world's oceans.

The great Makran earthquake of 28 November 1945 is an example of the size of earthquakes this fault can produce. Although infrequent, large earthquakes do occur from time to time along the Makran coast and appear to be preceded by increasing activity of smaller events. For example, for ten years prior to the 1945 earthquake, there was a concentration of seismic activity in the vicinity of its epicenter. This quake generated a destructive tsunami in the northern Arabian sea. The tsunami, its generation mechanism and potential for future events, are examined in a subsequent section.

Earthquake Vulnerability

Figure 6 illustrates the seismicity of Pakistan from 1990 to 2000. As indicated, most earthquakes in Pakistan occur in the north and western sections of the country along the boundary of the Indian tectonic plate with the Iranian and Afghan micro-plates (Fig. 1, 2, 6). Numerous earthquakes occur along the Chaman Fault System, which – as indicated - runs along Pakistan's western frontier with Afghanistan from Kalat in the northern Makran range, past Quetta and then on to Kabul, Afghanistan (Fig. 2). Also, a fault system runs along the Makran coast and is believed to be of the same nature as the west Coast fault system along the coast of Maharashtra in India. As indicated, there is an active subduction zone off the Makran coast in the north Arabian sea. The great 1945 earthquake – occurred in this offshore region.

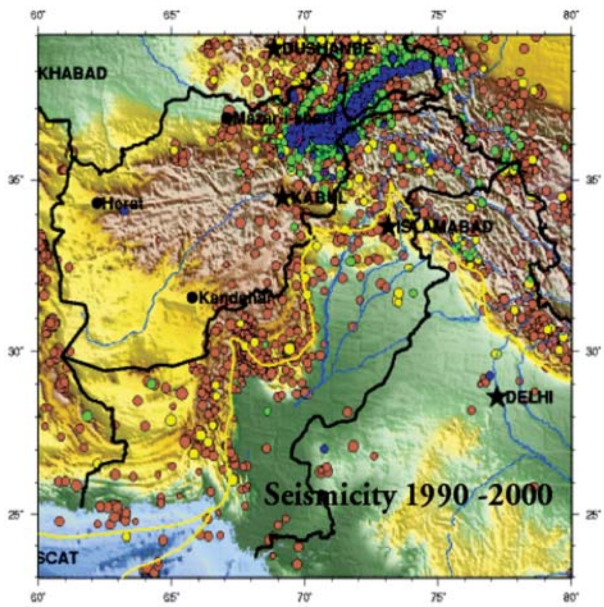

Fig 6. Northward movement of the Indian tectonic plate has resulted in major fault systems in Pakistan, Kashmir and northern India. Epicenter of the 8 October 2005 earthquake (Modified base map after Jadoon and Khurshid, 1996). Seismicity of the region from 1990-2000 (modified USGS graphic).

Pakistan's earthquake risk factors and vulnerability can be best illustrated by reviewing some of the major events that occurred recently and in the past and the impact they had in different regions of the country. The following is only a brief summary of the more recent earthquakes, which resulted in deaths, damage, and destruction of infrastructure.

The Earthquake of October 8, 2005 in Northern Pakistan

On Saturday, October 8, 2005 at 03:50:38 (UTC), a massive earthquake struck Pakistan and parts of India and Afghanistan. Its epicenter was at 34.402 degrees north, 73.560 degrees east, about 90 km north-northeast of Islamabad (Fig. 2, 7). The moment magnitude was measured to be 7.6 (U.S. Geological Survey), 7.5 (Pakistan Meteorological Service) and 7.8 (Japan Meteorological Agency). A final estimate of the moment magnitude was Mw7.7. The earthquake was relatively shallow and thus had greater intensity and destructiveness. According to the U.S. Geological Survey the focal depth was at about 10 km. More than 20 aftershocks ranging from 4.5 to 6.3 in magnitude struck the area in 18 hours following the main shock (Pararas-Carayannis, 2005).

This was the strongest earthquake in Pakistan during the last hundred years and by far the most destructive disaster in the region. Strong ground motions were felt in major cities in Pakistan and India, including Islamabad, Lahore and New Delhi. Close to 80,000 people were killed and at least 50,000 more were injured in the northern areas of Pakistan and at Kashmir and Jammu-Kashmir. There were numerous deaths also in Islamabad and Rawalpindi. A 10-story residential building (known as the Margalla Tower) collapsed completely in Islamabad killing most of the occupants. Thousands of houses were destroyed. Muzaffarabad, was severely affected and almost half of its homes were damaged or destroyed. The Jammu-Kashmir region was severely damaged with hundreds of dead and injured, mostly in the town of Uri.

No earthquake of similar strength as that of 2005 had occurred in northern Pakistan or Kashmir in recent years.

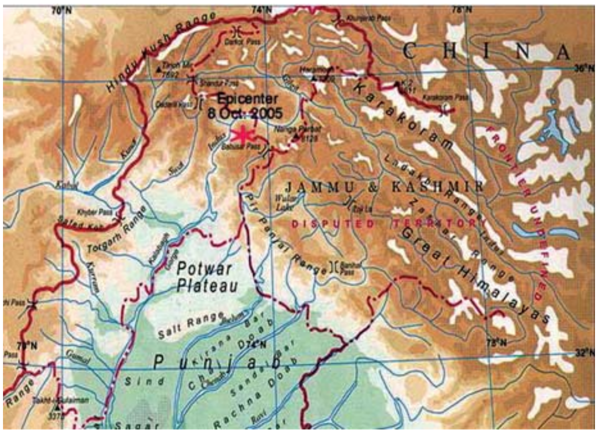

Fig 7. Physical map of northern Pakistan and of the Kashmir region affected by the 2005 earthquake.

The more recent event in the same general area was a 6.4 magnitude earthquake in northwestern Kashmir on 20 November 2002. This quake affected the same region and was widely felt in Islamabad, to the southwest of the epicenter. However, the death toll in northern Pakistan was by far lower. Only 17 people died and 65 more were injured. However, the devastating 2005 earthquake had been preceded by a pair of earthquakes of 5.5 and 5.4 magnitude events in February 2004 in northern Pakistan. These smaller magnitude quakes killed at least 21 people and injured dozens more. Even though these events were of relatively small magnitude, hundreds of homes built of mud, stone and timber were destroyed in the rugged, mountainous area about 90 miles northwest of Islamabad.

Quetta Earthquake of May 31, 1935

The historic record shows that up to the October 2005 earthquake in northern Pakistan, the largest quake had been near Quetta along the Chaman fault - a very active seismic region in the Baluchistan province (Thompson, 1936; Pinhey, 1938; Wadia, 1938; Ramanathan and Mukherji, 1938; Pararas-Carayannis, 2007). The Quetta earthquake, as it was named, occurred on 30 May 1935 (19:00:46.9 UTC; 31 May 1935 local date), had a Moment magnitude (Mw) of 8.1 - revised from a previously assigned Richter magnitude of M7.7. Its epicenter was at 27.4 N and 88.75 E. and its focal depth was 17 km (Fig. 8).

The city of Quetta was completely devastated. There was extensive destruction and thousands of deaths in Quetta, Mastung and in all the villages between Quetta and Kalat. Official reports indicate that 35,000 people were killed; although some estimates of up to 50,000 were subsequently provided. No foreshocks occurred prior to the main earthquake but there were numerous aftershocks that lasted until October 1935. The strongest – with magnitude Mw 5.8 - occurred on June 2, 1935 and caused additional damage in Mastung, Maguchar and Kalat, but

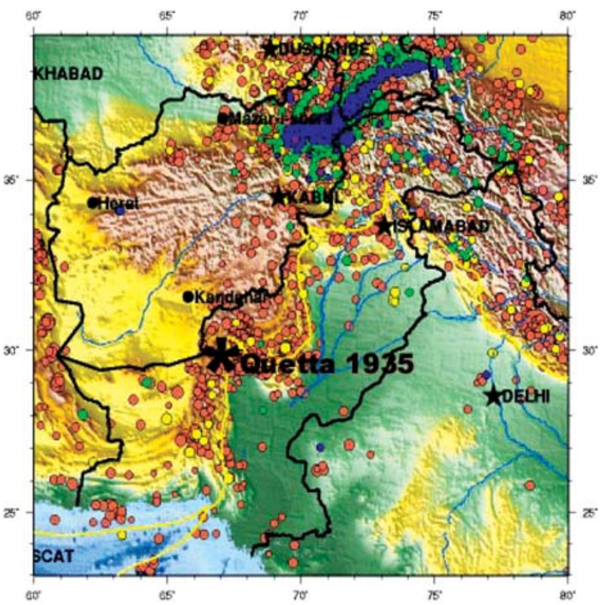

Fig 8. The 1935 Quetta earthquake.

not at Quetta. Some damage from the aftershock occurred at Nushki. There were unusual phenomena associated with this earthquake. According to reports, bright lights were observed prior to the main shock particularly one west of Quetta. Near Kalat flashes of light were observed along the flanks of the mountains.

Makran Earthquake of November 28, 1945

On 28 November 1945 (at 21:56 UTC, 03:26 IST), a great earthquake (Mw8.0) - off Pakistan's Makran coast - generated a destructive tsunami in the northern Arabian sea and the Indian ocean (Times of India, 1945; Pararas-Carayannis, 2001b). The quake's epicenter was at 24.5 N 63.0 E., about 100 km south of Karachi and about 87 kms SSW of Churi (Baluchistan). Its magnitude was given as 7.97 (Mw), 7.8 (Ms), 8.2 (ML). It was strongly felt in Baluchistan and the Lasbela area. In the western and southern sections of Karachi the strong surface motions lasted for about 30 seconds. The underwater cable link between Karachi and Muscat (Oman) was damaged, disrupting communications. The lighthouse at Cape Moze - 45 miles from Karachi - was also damaged. The earthquake was strongly felt also at Manora, where the lighthouse was damaged. It was moderately felt in Panjgaur and Kanpur. The earthquake caused the eruption of a mud volcano a few miles off the Makran coast. This eruption formed four small islands. It was reported that a large volume of gas emitted at one of these islands, sent flames "hundreds of meters" into the sky. Such mud volcanoes are not uncommon in the Sindh region off the Makran coast. Their presence indicates the existence of petroleum deposits (Harms *et al*., 1984). They are known to discharge flammable gases such as methane, ethane and traces of other hydrocarbons.

More than 4,000 people were killed along the Makran coast by the combined effects of the earthquake and tsunami. The tsunami caused great loss of life and destruction along the coasts of Iran, Oman, Western India and possibly elsewhere. This event is further discussed in a subsequent section related to Pakistan's tsunami vulnerability.

Kangra Earthquake of April 4, 1905

This was a major earthquake in the Dharamshala-Kangra area in Himachal Pradesh of northern India (Ambraseys and Bilham, 2000; Pararas-Carayannis, 2007). It was one of the deadliest in India's history and also caused extensive destruction and deaths in Lahore. It occurred at 00:49:48 UTC / 06:19:48 IST on April 4, 1905. Its epicenter was at 32.10N and 76.40 E. Reportedly the ground motions lasted at least 2 minutes. According to historic records 19,727 people were killed in Dharamshala, Kangra and the neighboring towns and villages. The high death toll can be attributed to the timing of the quake, when most people were indoors. The worst damage occurred at Kangra where all buildings were destroyed or severely damaged. There were reports of numerous landslides in and around Kangra. The quake caused extensive destruction in the towns of Dharamshala and Palampur (Middlemiss, 1910). In the Punjab plains in northern India (now northern Pakistan), there was slight to considerable damage. There were reports of sand vents and earthquake fountains in the vicinity of Bijnor, Khanki, Haridwar and Roorkee. Buildings were seriously damaged and some even partially collapsed at many major cities in the region, such as Amritsar, Lahore, Jullunder, Sialkot, Jammu, Rawalpindi and Amballa. The Lahore Town hall was damaged and so was the Lahore Railway station and the Mayo hospital (Middlemiss, 1910).

Kashmir Earthquake of November 20, 2002

The most destructive recent earthquake in the same general area occurred on 20 November 2002 in northwestern Kashmir. This earthquake had a magnitude 6.4 and its epicenter was 245 km NNE of Islamabad. According to official reports at least 19 people were killed, 40 were injured, and hundreds of buildings were extensively damaged.

Gujarat Earthquake of January 25, 2001

Earthquakes in India's western region of Gujarat have been extremely destructive in the past. The magnitude 7.7 earthquake of January 25, 2001 also caused damage and deaths in Pakistan. Approximately 20,000 people died, but mostly in India. In Ahmedabad, as many as 50 multistory buildings collapsed and several hundred people were killed. Total property damage was estimated at $5.5 billion and rising. Details are provided in the literature (Pararas-Carayannis, 2001a).

Zonation of Pakistan's Earthquake Hazard

Pakistan's meteorological department prepared a map, which divides the country into four seismic zones on the basis of expected ground accelerations of earthquakes (Fig. 9). Accordingly, the most vulnerable areas are parts

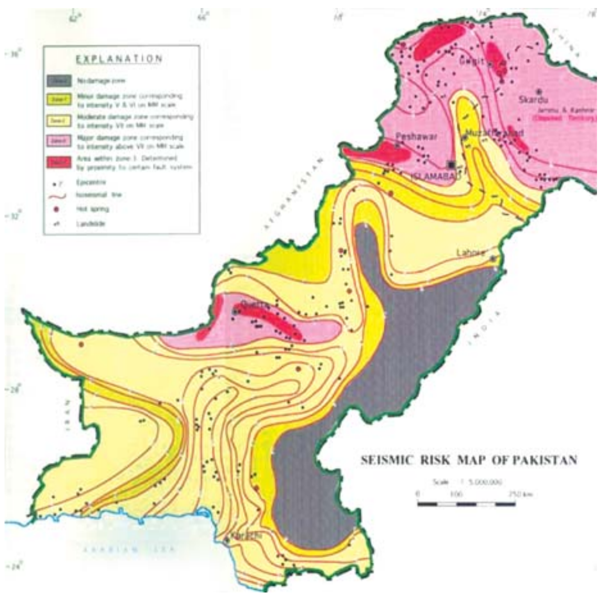

Fig 9. Pakistan - seismic risk map
(Pakistan geological survey)

of the western Baluchistan province in and around Quetta extending to the Afghan border - which include the Makran coast to the border with Iran. Earthquakes in this region could be expected to have a maximum peak ground acceleration (PGA) ranging between 0.24-0.4g. Thus, the area surrounding Quetta along the Makran coast and parts of the North-West Frontier Province (N.W.F.P.) along the border with Afghanistan are designated to be in Zone 4. The rest of the NWFP lies in Zone 3 but the southern parts of this province lie in Zone 2. The remaining segment of Pakistan's south coast to Karachi lies in Zone 3. According to the map, the rest of Pakistan lies in Zone 2. Major cities such as Peshawar, Rawalpindi and Islamabad are in zone 2. The upper westernmost part of Baluchistan and regions along the border with India lie in Zone 1. This zone includes the city of Lahore, which sustained serious damage by the 1905 Kangra earthquake in India.

Segments of northern Punjab could have maximum PGA values in the range of 0.24g to 0.32g. Similar PGA values can be expected in N.W.F.P. and around Karachi. For the rest of the country the maximum PGA values do not fall below 0.8g but steadily decrease towards the border with India. The region between Khangarh and Fort Abbas, along the international border with India, is the region with the lowest maximum PGA.

Landslide Vulnerability

The high relief of unstable mountains makes northern Pakistan very vulnerable to extensive landslides when an earthquake strikes. Heavy monsoon rains - particularly if they occur before or after an earthquake, can be the catalyst to further devastating landslides. For example, the October 2005 earthquake was responsible for many landslides. Strong earthquake aftershocks triggered additional landslides of unstable mountain slopes and endangered villages in the region. As it can be seen from the two images below taken by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) before and after the earthquake, there were extensive landslides in and around the city of Muzaffarabad (Fig. 10).

The landslides blocked the roads, thus further isolating the stricken region. Also, the 1935 Quetta earthquake and its aftershocks caused numerous landslides in the Shirinabad valley and rock falls in the Chiltan range in the western region of Pakistan. There were reports of dust clouds from these landslides and rock falls rising up to 500 meters above the mountains.

Tsunami Vulnerability

Southern Pakistan is potentially vulnerable to tsunamis generated from earthquakes along the Makran subduction and Accretionary prism zones, the Karachi and deltaic indus regions, the Owens fault zone as well as the Kutch Graben region in the Gujarat province of India. Although the record for past tsunamis is incomplete, it is believed that some were destructive on the coasts of Pakistan, Iran, India and Oman and possibly had significant effects on islands and other countries bordering the Indian ocean (Berninghausen, 1966; Pararas-Carayannis, 2004).

Potential Tsunami Generation Along the Karachi and the Indus Deltaic Region

There are no known records of whether any tsunamis were generated near the coastal regions of Karachi and the deltaic Indus area. However, because of the proximity of thrust faults to coastal areas and the unstable, heavily-sedimented, coastal slopes of the deltaic region, future earthquakes have the potential to generate destructive local tsunamis that could affect coastal areas near Karachi as well as areas in the Kutch region of India and even the coasts of the Maharashtra region (Pararas-Carayannis, 2004).

Potential Tsunami Generation along the Kutch, Bombay, Cambay and Namacia Graben Regions of India

Lateral transition between subduction and collision of the Indian and Arabian tectonic plates has formed the Kutch, Bombay, Cambay and Namacia Grabens, in north-western India. In the Kutch region, remote sensing and gravity investigations have determined a spatial pattern of tectonic lineaments along which seven big earthquakes with magnitudes (M>6) occurred in the last 200 years. Fig. 11 illustrates the tectonic forces in the Gujarat region in India where large grabens have been formed and where

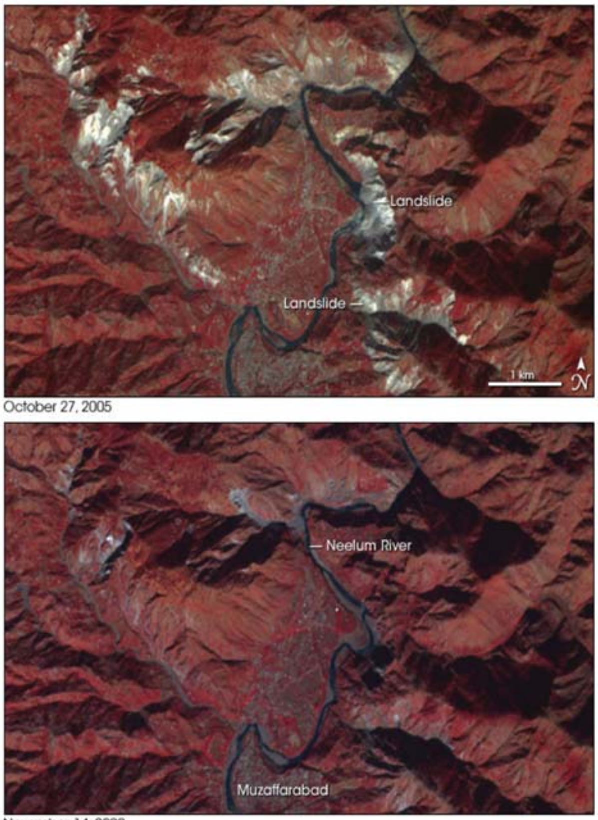

Fig 10. NASA images of landslides in Pakistan created by Jesse Allen, earth observatory, using data obtained from the University of Maryland's Global Land Cover facility.

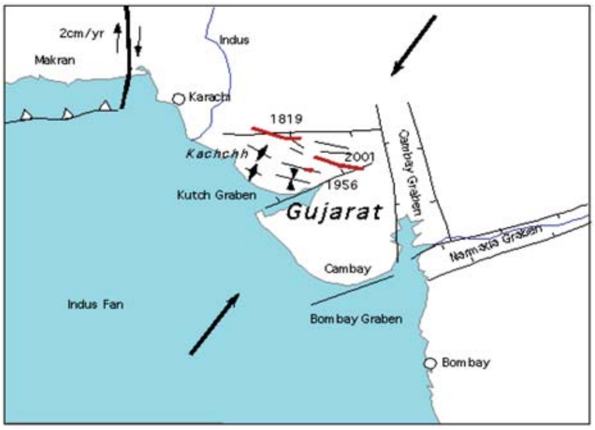

Fig 11. Tectonic forces in the Gujarat region of India where large grabens have been formed and where major earthquakes and major tsunami-like flooding has occurred.

major earthquakes have occurred in the past, including the earthquake of 25 January 2001 (Pararas-Carayannis, 2001a, 2004).

Past earthquakes in this region have also affected Karachi and other cities in present Pakistan. Although infrequent, several destructive earthquakes in the coastal Sindh region occurred in 1524, 1668, 1819, 1901 and 1956, (Pararas-Carayannis, 2001b). The larger earthquakes involved extensive vertical crustal uplift over land areas paralleling the orientation of the Kutch Graben. For example, the 1819 earthquake in Rann of the Kutch, bordering the Sindh region, was associated with thrust uplift of up to 30 feet along the Allah Bund fault and slippage depression of up to 10 feet along coastal fault plains. Although poorly documented as having generated a tsunami, the 1819 event was reported as having resulted in major sea inundation, destruction of coastal settlements and permanent changes to the coastline and the drainage of major rivers, such as Indus. Probably the 1524 earthquake in the same region, also resulted in major inundation by the sea (Pararas-Carayannis, 2001b).

Potential Tsunami Generation along the Owens Fault Zone

As previously discussed, the Owen fault zone extends from the Gulf of Aden in a northeast direction towards the Makran coast where it enters the Baluchistan region. Then it continues as a land fault known as the Chaman Fault. Large destructive earthquakes can occur on both the Owen and the Chaman fault zones, but there are no records of historical tsunamis (Pararas-Carayannis, 2007). Although the Chaman is a transform fault, earthquakes near the coast could trigger underwater landslides and local tsunamis. Thus, the potential for local tsunami generation from a large earthquake along Pakistan's coastal segment of the Chaman fault, needs to be properly evaluated.

Potential Tsunami Generation Along The Eastern Makran Subduction Zone

The seismicity of the Makran region is relatively low compared to the neighboring regions, which have been devastated regularly by large earthquakes (Jacob and Quittmeyer, 1979). Although the historic record is incomplete, it is believed that tsunamis generated from this region in the past were destructive in Pakistan, along the coasts of western India and on islands and other countries bordering the Indian Ocean. Larger tsunamigenic earthquakes usually occur on the eastern segment of the Makran subduction zone. The destructive tsunami generated by the great earthquake of 28 November 1945, is an example of the size of earthquakes and tsunamis that the Eastern Makran subduction zone can produce (Mokhtari and Farahbod, 2005; Pararas-Carayannis 2005 and 2006). Usually, small earthquakes signal the occurrence of a larger event. For example, for ten years prior to the 1945 event, there was a concentration of seismic activity in the vicinity of its epicenter. Recent seismic activity indicates a similar pattern, thus a large tsunamigenic earthquake is possible in the region west of the 1945 event **(**Quittmeyer and Jacob, 1979**)**. The Posni-Ormara zone in eastern Makran represents at the present time a mature seismic gap. Also foci migration of background seismicity of the Pasni zone trends toward the northwest region and this could be signaling the occurrence of a significant earthquake that could generate a destructive tsunami (Pararas-Carayannis 2005, 2006).

The Tsunami of 28 November 1945

The tsunami generated by the 28 November 1945 earthquake in the northern Arabian sea resulted in loss of life and great destruction along the coasts of Pakistan, Iran, Oman and Western India. The tsunami generating area is shown in Fig. 12. Waves ranging from 1 to 13 m (40 feet) struck the Makran coast within minutes after the quake, destroying fishing villages and caused great damage to port facilities. More than 4,000 people died, mostly by the tsunami. The waves completely destroyed Khudi, a fishing village about 30 miles west of Karachi, killing its entire population. At Dabo creek, 12 fishermen were swept out to sea. The towns of Pasni and Ormara were badly damaged. Pasni's postal and telegraph offices, government buildings and rest houses were destroyed. A significant number of people were washed away.

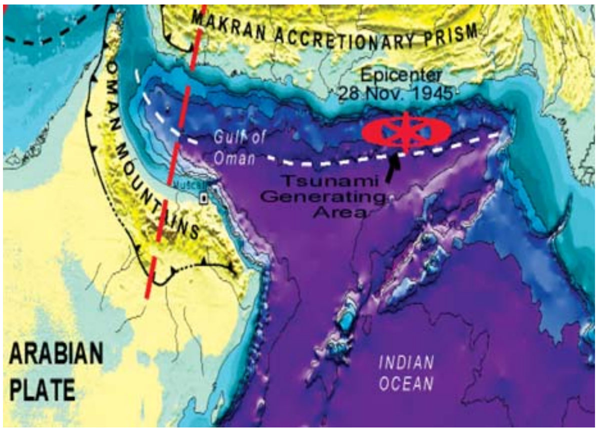

Fig 12. The Tsunami of 28 November 1945 along the Makran coast of Pakistan in the northern Arabian sea.

Karachi was struck by waves of about 6.5 feet in height (Pakistan meteorological department, 2005). The first wave was recorded at 5:30 am, and subsequent waves at 7:00am, 7:15am and finally at 8:15am. The last wave at 8:15 was highest. The tsunami came from the direction of Clifton and Ghizri, ran along the oil installations at Keamari and flooded a couple of the compounds. There was no damage either to the port or to the boats in Karachi Harbor. More information on the tsunami can be found in the literature (Pararas-Carayannis, 2001b).

Also, there was similar loss of life and crafts along the coasts of Mekran, Iran and Oman. The tsunami was recorded at Muscat and Gwadar. In India, waves up to 11.5 m struck the Kutch region of Gujarat (Pararas-Carayannis, 2006), causing extensive destruction and loss of life. Eyewitnesses reported that the tsunami came in like a fast rising tide. The waves reached as far south as Mumbai, where the maximum height reached 2 meters, washing away fifteen (15) persons. Five people died at Versova (Andheri, Mumbai), and six more at Haji Ali (Mahalaxmi, Mumbai), Several fishing boats were torn off their moorings at Danda and Juhu. The tsunami did not do any damage to Bombay Harbor. Most persons who witnessed the tsunami said that it rose like the tide coming in, but much more rapidly.

Factors Contributing to Tsunami Destructiveness Along the Eastern Makran Subduction Zone

Astronomical Tide - A factor that could contribute to the destructiveness of a tsunami along the Makran coastline is the relatively large astronomical tide, which is about 10-11 feet. A tsunami generated during high tide would be significantly more destructive.

Influence of Sedimentation on Potential Tsunami Generation - The Baluchistan section of the Makran coast has several small river deltas. Also, in the eastern Sindh region the Indus river has formed one of the largest deltas in the world (Fig. 13). Past meandering of Indus has formed extensive deltas east of Karachi.

Extensive sedimentation from the erosion in the Himalayas has widened the continental shelf of the Sindh coast to about 150 km. Along the Baluchistan region where there is less sedimentation; the continental shelf measures only 15-40 km. The compacted sediments in this entire zone of subduction could contribute to a tsunami of greater height and destructiveness. A bookshelf type of failure within the compacted sediments - as that associated with the 1992 Nicaragua earthquake - could generate a more destructive tsunami (Pararas-Carayannis, 1992). Folding of the sediments at the toe of the accretionary prism could also contribute to larger vertical displacements of the sea floor and a larger tsunami – with a mechanism similar to that associated with the March 11, 2011 destructive event along the coast of Honshu in Japan (Pararas-Carayannis, 2011).

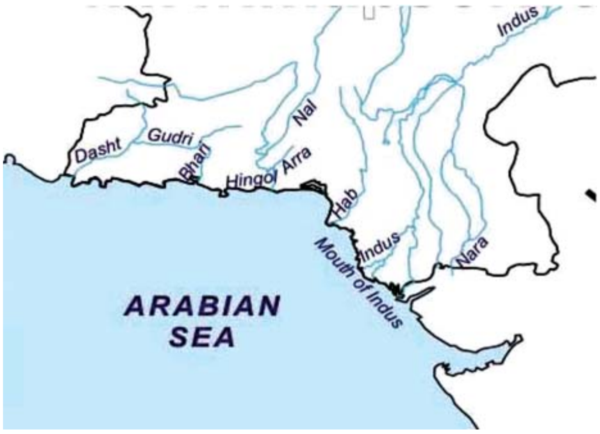

Fig 13. Rivers in the Indus delta

Potential Tsunami Generation Along the Western Makran Subduction Zone

There are no known records of tsunami generation along the western segment of the Makran subduction zone. The western segment - along eastern Iran and southwestern Pakistan – exhibits a lesser degree of seismicity than the eastern segment. Much of the tectonic plate movement along the western segment appears to be accommodated by aseismic slip (Byrne *et al.* 1992). However, the region has the potential for upthrust events, which can generate destructive tsunamis. The differences in the mechanics of subduction along the eastern and western segments are provided in the literature (Pararas-Carayannis, 2006). Recent and past seismicity of the entire Makran region were analyzed and compared with the geology and tectonic plate motions. Most earthquakes in Western Makran occur within the down going plate at intermediate depths. In contrast to the east, the plate boundary in Western Makran has no clear records of historic great events and there are no records of any recent shallow thrust events. In Iran, for example, the foci depth of events indicates that the Benioff zone continues to the volcanic arc of Bazman-Taftan-Soltan along which many mud volcanoes exist (Fig. 14) (Jadoon, 1992).

Past Historical Tsunamis

Destructive tsunamigenic earthquakes have occurred in

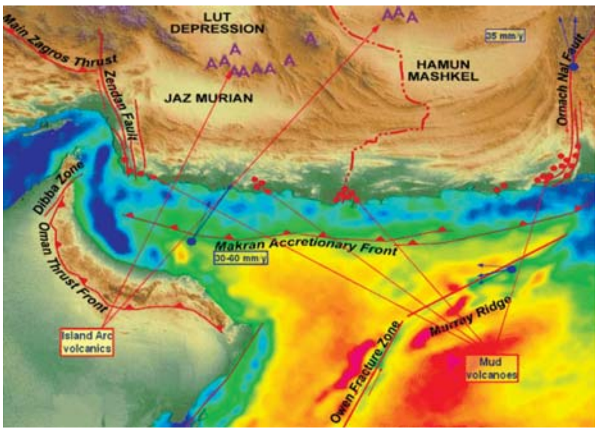

Fig 14. The Makran accretionary front. eastern and western segments – apparently discontinuous.

the north Arabian sea throughout geologic history. Most of these events have not been adequately reported or documented. Past tsunamis from this region affected southern Pakistan, India, Iran, Oman, the Maldives and other countries bordering the Indian ocean. The oldest known tsunami in the region may have been generated by a large magnitude earthquake, which occurred in the Indus delta/Kutch region in 326 B.C. The tsunami destroyed ships of Alexander the Great's Macedonian fleet on its journey back to Greece after India's conquest (Pararas-Carayannis, 2006). As indicated, the earthquakes of 1524 and 1819 in the Kutch region probably generated destructive tsunamis.

Conclusion

Based on this documentation and cursory analysis, it can be concluded that Pakistan is particularly vulnerable to large destructive earthquakes and tsunamis. The country's northern and north-western regions are particularly vulnerable to large destructive earthquakes and from tsunamis generated by large earthquakes along the Makran Subduction zone and in the Kutch Graben, Karachi and deltaic Indus regions. Mitigation strategies must be implemented to alleviate future impacts. Potential future disasters could have significant collateral catastrophic consequences on critical structures in Pakistan. It is outside the scope of the present report to comment on the vulnerability of specific infrastructure facilities in Pakistan, but in view of the recent disaster at the Fukushima Daichi nuclear plant in Japan following the March 11, 2011 earthquake and tsunami, a brief commentary on the vulnerability of nuclear and other infrastructure in Pakistan is appropriate. Infrastructure facilities near seismic zones 2 and 3 near the Hazara-Kashmir syntaxial bend, the Main Mantle Thrust (MMT), the Main Karakoram Thrust (MKT) and the Main Boundary Thrust (MBT) need to be re-evaluated for safety from potential earthquake impact and potential PGA values ranging from 0.24g to 0.32g or more. Facilities, which must be examined, include the Kahuta (Khan Research Laboratory – a large-scale uranium enrichment facility) and several other nuclear research reactors near Wah, Goltra, Sihala, Rawalpindi and Islamabad. Also, facilities along Pakistan's long coastlines remain extremely vulnerable to future tsunami disasters. The safety of the heavy-water power reactor near Karachi needs to be examined, as well as the potential impact on port facilities from a tsunami generated in the Northern Arabian sea.

Proper land use is probably the most effective method for mitigating the impact of future earthquake and tsunami hazards in Pakistan. This tool is largely underutilized. For example, to mitigate the impact of future disasters along coastal regions that are potentially vulnerable to tsunami, local governments should take steps to designate the danger zones that put parts of the population at risk by preventing certain kinds of development. Critical infrastructure and industrial facilities should not be built in coastal areas likely to be flooded by tsunamis. Construction and development should be prohibited in areas that put at risk the general population.

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