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EFFECTS OF THE DECEMBER 26, 2004 SUMATRA EARTHQUAKE AND TSUNAMI ON PHYSICAL INFRASTRUCTURE

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ABSTRACT

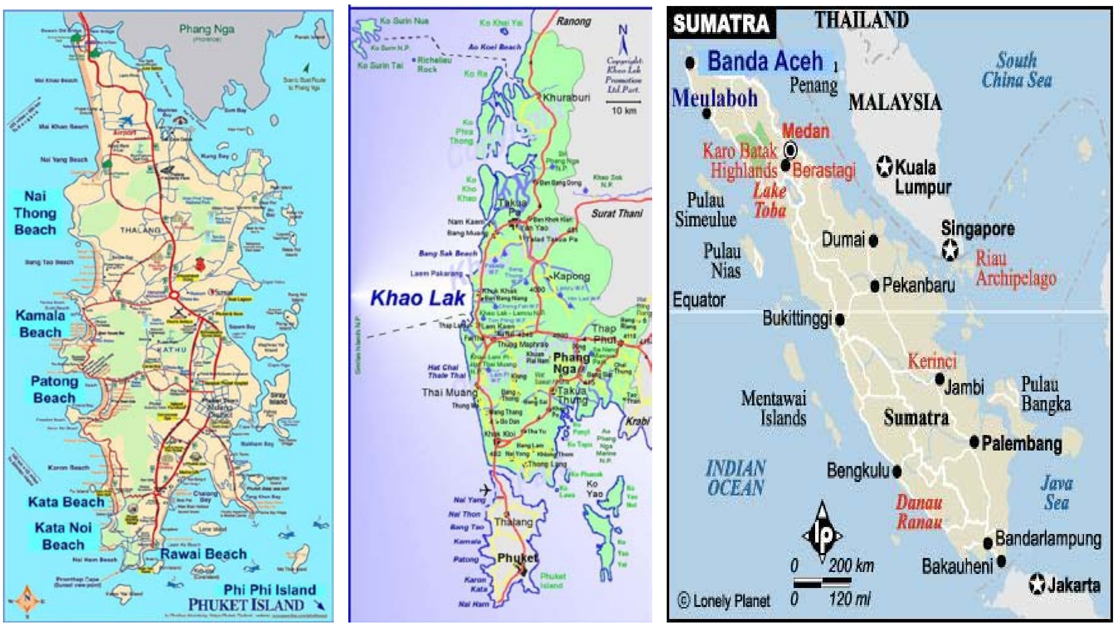
A devastating earthquake and the resulting tsunami hit coastal areas of Indian Ocean on December 26, 2004. A team of Canadian engineers conducted a reconnaissance in Thailand and Indonesia. Their findings are presented in the paper in terms of performance of buildings, bridges, coastal structures and other physical infrastructure. It was observed that non-engineered reinforced concrete structures, low-rise timber frames and unreinforced masonry buildings suffered extensive damage due to hydrodynamic pressures generated by tsunami and impact forces induced by floating debris. Banda Aceh, Indonesia suffered extensive damage due to seismic excitations. A large number of non-engineered and engineered reinforced concrete frame buildings experienced partial or total collapse. A number of 3 to 5 story engineered reinforced concrete government buildings and shopping centers were damaged due to lack of proper seismic design practices. The engineering significance of disaster is presented in the paper with observations made during the reconnaissance visit.

KEYWORDS: Disasters, Hazards, Infrastructure, Earthquakes, Tsunamis

INTRODUCTION

A subduction earthquake, with a Richter magnitude of 9.3, occurred on December 26, 2004, off the coast of the Indonesian island of Sumatra, at 7:59 a.m. local time. Extensive seismic damage to engineering infrastructure occurred in northern and north-western Sumatra. A devastating tsunami was generated with wave heights exceeding 20 m, inflicting widespread destruction in Indonesia, Malaysia, Myanmar, Thailand, Bangladesh, Sri Lanka, India and 12 other countries around the Indian Ocean. The effects of tsunami were felt as far away as Somalia, Tanzania and Kenya along the east coast of Africa. The casualties were in excess of 310,000. Millions of people were affected, many losing their homes and suffering from tremendous grief. The economic impact on the countries surrounding the Indian Ocean was very significant.

A team of Canadian Engineers conducted a reconnaissance visit to Thailand and Indonesia. The visit focused on urban areas with engineered constructions, closest to the epicenter. Rawai Beach, Kata Noi Beach, Kata Beach, Patong Beach, Nai Thon Beach and Kamala Beach on the Thai island of Phuket were visited first, followed by Phi-Phi island, about 48 km south east of Phuket and the coastal town of Khao Lak about 100 km north of Phuket. Two locations were visited in Indonesia; the city of Medan located north-east of the island of Sumatra and Banda Aceh, the capital of Indonesia’s Aceh Province at the northern tip of Sumatra. There was no damage observed in Medan, though the earthquake was felt significantly, causing limited damage to building contents and creating fear among the residents. Banda Aceh, with a population of about 300,000 suffered extensive seismic damage. The city of Meulaboh, with a population of about 40,000, along the west coast of Sumatra reportedly also suffered seismic damage, but could not be visited because of difficulties in transportation. Figure 1 shows the areas where site investigations were carried out.



(a) Phuket, Thailand (b) Khao Lak, Thailand (c) Banda Aceh, Indonesia

Fig. 1 Locations visited in Thailand and Indonesia (Geocities[1]; Mapsoftheworld [2])

SEISMOLOGICAL BACKGROUND

The earthquake of December 26, 2004 occurred due to the rupturing of the subduction zone between the Indian plate and the Burma microplate. The Indian plate has been moving north-east at a rate of approximately 60 mm per year, subducting under the overriding Burma microplate. The epicenter of the quake was about 155 km west of Sumatra and about 255 km south-east of Banda Aceh, Indonesia (USGS[3]). The focal point was at a depth of 30 km. The ruptured fault length was estimated to be 1300 km. The rupturing initiated near the south end and progressed towards north gradually, taking approximately 500 to 600 seconds. Vertical uplift reportedly ranged between 7 to 10 m at the ocean floor, displacing a huge amount of water that led to tsunami. Figure 2 illustrates the tectonic structure of the area with the epicenter of the quake indicated.

CHARACTERISTICS OF THE TSUNAMI

The vertical offset of the ocean floor by 7 to 10 meters during the December 26, 2004 Sumatra earthquake displaced massive volumes of water, resulting in a destructive tsunami. Because of the north-south direction of the fault line, the tsunami was the strongest in the east-west direction. The wave height in deep water (open ocean) was measured through satellites to be approximately 60 cm, while traveling at a speed of 500 to 800 km/hr. The velocity decreased to only tens of kilometers per hour in shallow water near the shoreline, depending on the local bathymetry. This, however, resulted in large and destructive waves that reached run-up heights of 20 to 30 meters in Banda Aceh. In coastal areas of Thailand and Sumatra the flood extended as far as 4 km inland. The tsunami reached Banda Aceh at the northern tip of the Indonesian island of Sumatra in about 15 minutes. It reached Sri Lanka and east coast of India after approximately 2 hours. Although Phuket is much closer to the ruptured fault line than Sri Lanka, it took the waves about 90 minutes to reach Phuket because of the relatively shallow sea depth on the eastern side of the fault, which resulted in a slower water movement as compared to the western waves which traveled across deep-ocean. The tsunami waves reached east African coast after about 8 hours and southern Africa after 9 to 11 hours. Figure 3 illustrates the travel time of tsunami waves. The water height measured on buildings was found to vary between 6 m and 12 m from the sea level along the west coast

[1] Website of Geocities, www.geocities.com
[2] Website of Mapsoftheworld, www.mapsoftheworld.com
[3] Website of Earthquake Hazard Program of USGS, http://earthquake.usgs.gov/eqinthenews/2004/usslav/

of Phuket and Banda Aceh. However, water run-up was observed to be higher, causing structural damage at elevations higher than 12 m. The maximum run-up was measured to be 48.8 m in Rhitting, near Banda Aceh, as reported by Shibayama (2005).

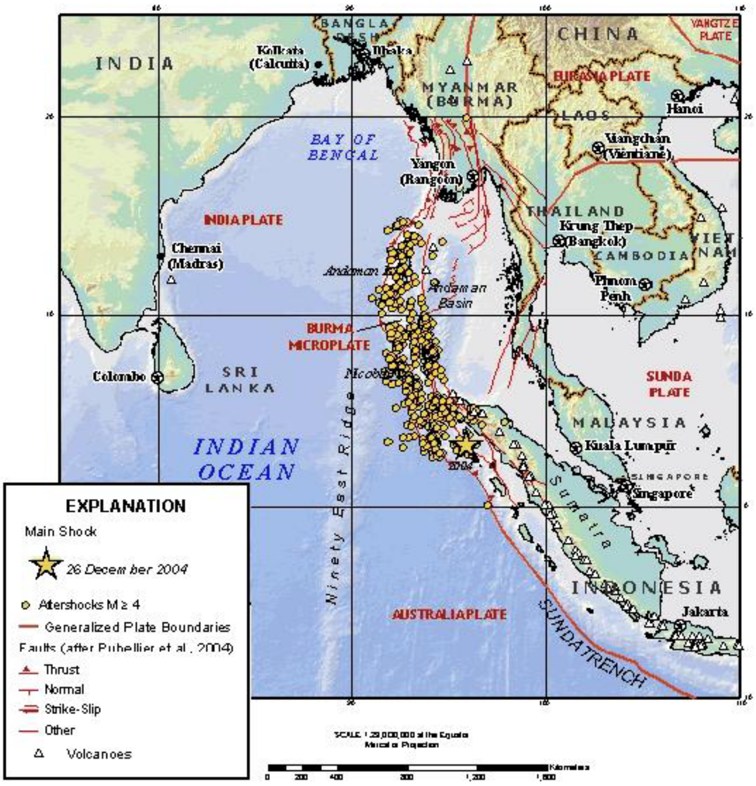


Fig. 2 Tectonic structure of the north Indian Ocean region (USGS)

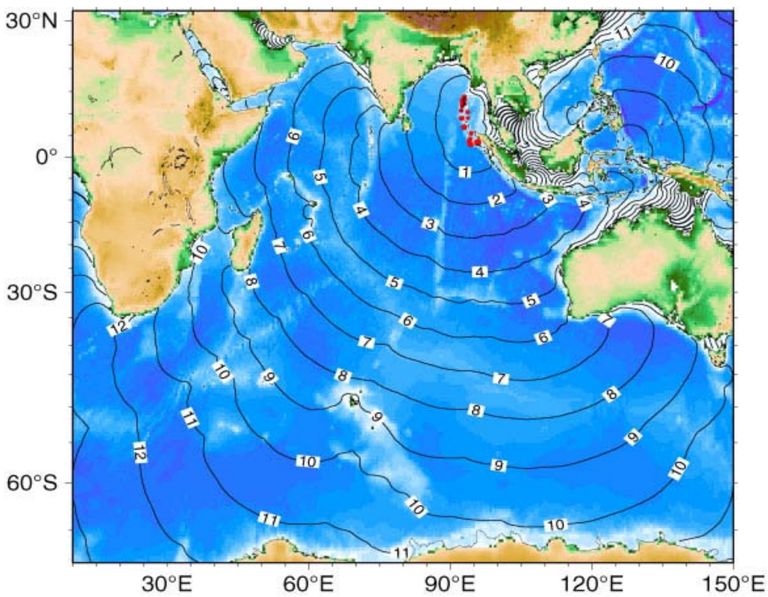


Fig. 3 Tsunami travel time in hours (Satake, 2005)

Damage along southern Phuket beaches was limited to coastal erosion and partial failures of non-engineered reinforced concrete and timber frame structures along the coast. The term non-engineered implies structures built without engineering design. The measured water height was approximately 4.0 m from the ground in Kata Beach, causing damage to low-rise buildings, including roof tiles, as illustrated in Figure 4. The most populated beach town along the west coast of Phuket was Patong Beach, which suffered extensive damage to low-rise buildings. The measured water mark on buildings was found to vary between 2.0 m to 4.0 m from the ground. The building inventory in Patong Beach consisted of a large number of non-engineered one to two story reinforced concrete and timber frame shops and hotels. There were also a number of multistory engineered reinforced concrete hotels. Extensive damage to masonry infill walls was observed. Limited damage occurred in reinforced concrete structural elements, though significant damage was seen in timber structural elements. The entire shopping district of Patong Beach was destroyed within an area extending approximately two kilometers inland from the shore, as illustrated in Figure 5.

Fig. 4 Damage to single story non-engineered buildings in Kata Beach

Fig. 5 Damage in Patong Beach

GENERAL OBSERVATIONS

Nai Thon Beach, further north of Patong Beach on the island of Phuket, suffered extensive structural and non-structural damage to reinforced concrete frame buildings. The water height, relative to ground, was in excess of 10 m, especially in areas between the shore and the nearby hilly terrains, which led to water run-ups. Figure 6 illustrates the extent of structural damage observed in this area.

Fig. 6 Structural damage in Nai Thon Beach due to tsunami waves

An area that was entirely devastated by the tsunami is Khao Lak Beach, about 100 km north of Phuket. The water height was measured to be in excess of 10 m, causing extensive structural damage. The failure of first-story masonry infill walls and structural collapse of low-rise reinforced concrete frame buildings are shown in Figure 7. Many resort hotels were completely destroyed. Some multistory reinforced concrete hotels survived the tsunami pressure, with damage limited to the first-story infill walls.

Further north of Khao Lak Beach is the harbor. This area was also hard hit by the tsunami, destroying the harbor and floating boats inland. The town near the harbor was devastated as shown in Figure 8.

Phi Phi Island is a small island located about 48 km south east of Phuket. The topography of the island is such that east and west sides are entirely covered with steep hills, with a low laying area between the two, where most of the island's inhabitants live (Figure 9, left). This area is only a few meters above the sea level and was hit by the tsunami from both sides. Most structures on the island were destroyed, with the exception of a few well built reinforced concrete frame buildings, a steel frame building and some non-engineered construction. Many of the one and two story non-engineered reinforced concrete and timber frame buildings of the island collapsed entirely due to tsunami wave pressures. Figure 9 illustrates the extent of damage on the island.

Fig. 7 Structural and nonstructural damage in Khao Lak Beach

Fig. 8 Damage to Khao Lak harbor town

Fig. 9 Damage to Phi Phi island, Thailand

Banda Aceh, Indonesia is a city with a population of about 300,000 inhabitants before the tsunami. It was subjected to damaging forces of not only the tsunami but also the earthquake. The majority of casualties were in this city. Coastal areas were entirely swept away by tsunami waves, leaving piles of timber as the remains of building infrastructure. A large number of non-engineered reinforced concrete buildings suffered structural damage, especially in their first floor columns. Multi-story engineered reinforced concrete government buildings suffered seismic damage due to poor seismic design and detailing practices. A large number of mosques survived the disaster, though they also suffered damage to masonry walls. Figures 10 and 11 illustrate the extent of damage observed in Banda Aceh.

Fig. 10 Tsunami damage in Banda Aceh, Indonesia

Fig. 11 Earthquake damage in Banda Aceh, Indonesia

EFFECTS OF TSUNAMI

Tsunami waves imposed dynamic water pressures on coastal structures as well as buildings and bridges near the coastline, inducing serious damage to the entire surrounding infrastructure located up to approximately 4 km inland. The resulting impulsive pressures of breaking waves and hydro-dynamic pressures associated with water velocity, inflicted partial and full collapses of non-structural and structural components. The damage observed in Thailand was almost entirely due to water pressures that varied from impulsive pressures of breaking waves at the shore, to reduced dynamic pressures inland as water velocity decreased due to surface friction. There was some impact loading generated by the floating debris, though this was most pronounced in Banda Aceh, where large objects were observed to have impacted on structures.

Equation (1) gives an empirical expression for the estimation of impulsive water pressure of breaking waves, developed by Goda (1985). Accordingly, wave impulse pressure is a function of specific gravity of water, water celerity, wave height and impact duration. The variation of wave pressure obtained from Equation (1) is plotted in Figure 12(a) as a function of water height:

$$p_{\max} = \frac{\pi \gamma c H_w}{4 g \tau} \qquad (1)$$

with

γ = Specific gravity of sea-water (10.3 kN/m^3)

c = Celerity of wave in m/sec (estimated from recorded video to be 13 m/sec)

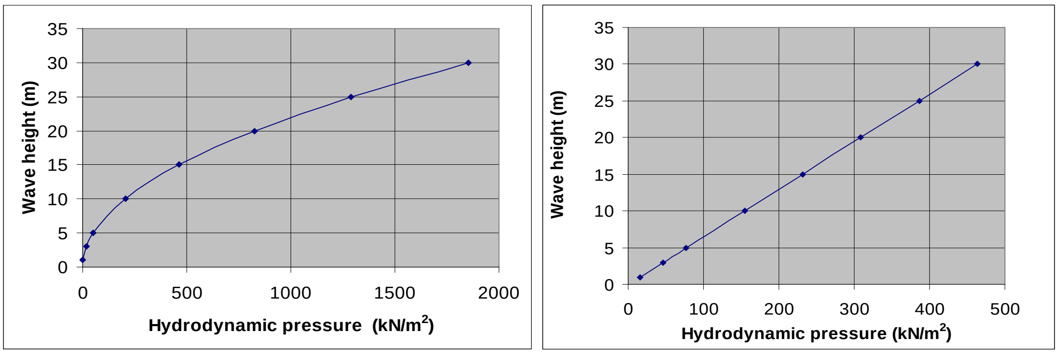
τ = Impact duration (approximately equal to 0.2 sec)

H_w = Wave height in m.

A simpler expression that is more applicable to the mechanism of tsunami wave impact was suggested by Hiroi (1919) for the estimation of uniform dynamic pressure as a function of sea-water specific gravity and wave height. The expression is given in Equation (2). The variation of uniform lateral pressure, as computed from Equation (2), is plotted in Figure 12(b):

$$p = 1.5 \gamma H_w \qquad (2)$$

The hydrodynamic tsunami wave pressure obtained from Equation (2) was compared with wind design pressure specified in the National Building Code of Canada (CCBFC, 1995) on a building located at the coastal city of Vancouver, Canada. It was found that the tsunami pressure at the first floor level could be approximately 26 times the design wind pressure in Vancouver, explaining the widespread damage to masonry walls observed within the first stories of most buildings. Design lateral forces due to wind and seismic effects were compared with the estimates of lateral forces generated by a tsunami of 5 m water height. A sample 6-story, 3-bay reinforced concrete frame structure in Vancouver, Canada was used for this purpose. The comparisons of lateral forces are shown in Figure 13. It was found that the total base shear due to tsunami was about twice the base shear due to wind and 60% of that caused by elastic seismic forces and 2.5 times the inelastic seismic design base shear for a ductile moment resisting frame building. While this comparison is presented to provide a feel for the magnitude of tsunami forces on buildings in Thailand, it is important to recognize that the same comparison could give vastly different results for buildings with different heights, different exposure conditions and different structural mass, especially for different tsunami water heights. Another important aspect of tsunami pressures on structures is the nature of the exposed area. Because of the relatively high level of tsunami pressures generated, non-structural elements, like infill masonry walls, often collapse immediately after the application of tsunami wave pressure, and reduce the portion of the load transmitted to the structural elements. The non-structural elements, though suffer extensive damage under tsunami pressures, tend to act like a fuse for the load carrying system, reducing the amount of lateral loads transferred to the structure. Consequently, a more detailed investigation of the mechanism of tsunami load transfer among exposed elements should be conducted before the tsunami loads can be assessed accurately.



(a) (b)

Fig. 12 Estimates of breaking wave impact pressure on a structure at the coast: (a) wave pressure as per Equation (1) (Goda, 1985); (b) wave pressure as per Equation (2) (Hiroi, 1919)

1. Performance of Timber Construction

Both Thailand and Indonesia coastal towns had a large number of low-rise timber frame buildings. These buildings had timber columns and beams, supporting timber joist floor systems. The roofs either had light corrugated tin coverage or clay roofing tiles. Figure 14 illustrates the framing system used and the types of damage observed.

2. Performance of Unreinforced Masonry Walls

The majority of buildings in Thailand and Indonesia had frames infilled with unreinforced masonry walls. The masonry units used were consistently of the same type, with 50 mm thickness. Both hollow clay bricks and concrete masonry blocks of the same thickness were used, as illustrated in Figure 15. These walls suffered punching shear failures due to the tsunami wave pressure applied perpendicular to the wall plane. These resulted in large holes in walls, sometimes removing the masonry almost entirely. The remaining walls around the frames did not show any sign of diagonal tension cracks, contrary to expectations, unless the failure was caused by seismic excitations, which was limited to Banda Aceh only. Figure 16 shows the type of punching failures observed in masonry infill walls.

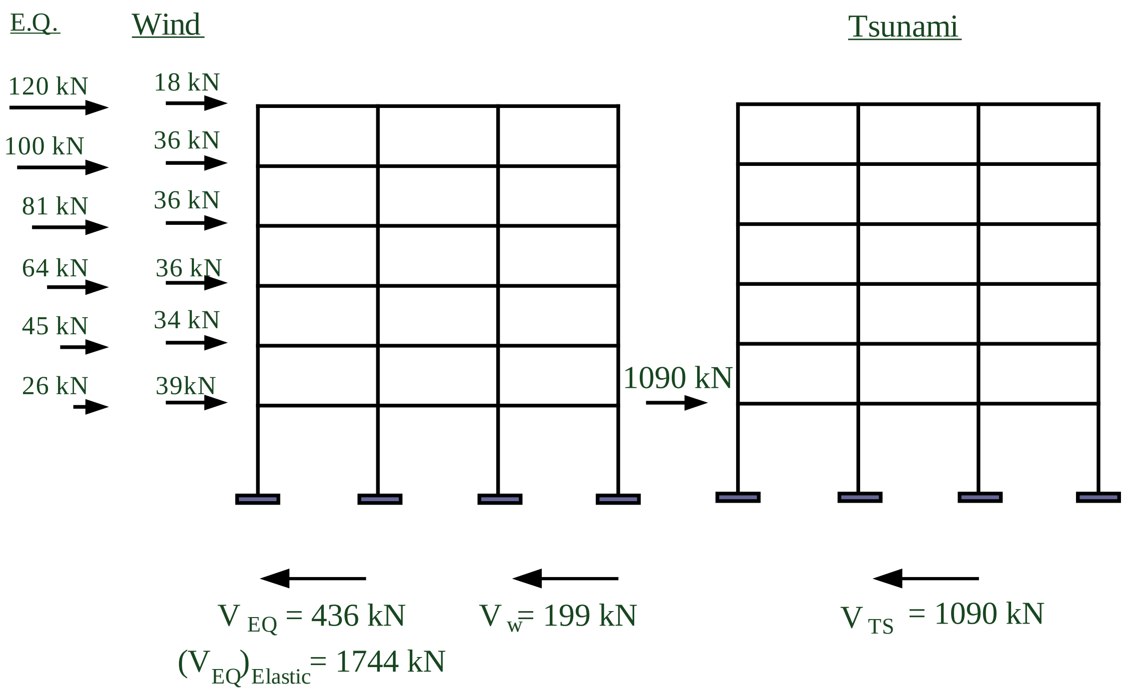


Fig. 13 Comparisons of lateral forces due to earthquake, wind, and tsunami for an interior frame of a 6 story reinforced concrete building in Vancouver, Canada for 5.0 m tsunami water height, 6.0 m transverse span length and seismic force reduction factor of $R = 4.0$

Fig. 14 Damage to timber frame buildings in Phi Phi Island, Thailand

Fig. 15 Clay brick and concrete masonry block units with 50 mm thickness

(a) Kamala Beach (b) Khao Lak Beach (c) Banda Aceh

Fig. 16 Punching failure of masonry infill walls caused by tsunami wave pressure

(a) Khao Lak Beach (b) Phi Phi Island (c) Banda Aceh

Fig. 17 Column failures in non-engineered reinforced concrete constructions

3. Performance of Non-engineered Reinforced Concrete Buildings

The majority of one to two story low-rise buildings were constructed using site-cast concrete, without much evidence of engineering design. The columns were of very small cross-section (about 200 mm square), containing 4 smooth or deformed corner bars with 8 mm diameter, resulting in approximately 0.5% reinforcement ratio. Their flexural capacity, based on 4 columns per frame providing resistance, was computed to be significantly below the moments imposed by tsunami waves as computed by Equation (2) and water height of 3.0 m (assumed tributary area of 4.5 m^2). The column flexural capacity was slightly below the moments imposed by hydrostatic pressure of 3.0 m water height. Figure 17 illustrates column failures in non-engineered reinforced concrete frame buildings due to the tsunami wave pressure.

Observations on column behavior indicated that many failures occurred at mid-height, especially in Banda Aceh. This was attributed to the effects of debris impact, over and above the tsunami wave pressure. Indeed, floating building remains, as well as floating large objects like fishing boats and cars impacted on the columns, causing column failures near their mid-heights. This is illustrated in Figure 18.

Fig. 18 Column failures due to debris impact in Banda Aceh

4. Performance of Engineered Reinforced Concrete Buildings

There were many low to mid-rise reinforced concrete frame buildings which appeared to have been engineered in the visited areas of Thailand and Indonesia. These frame buildings survived the tsunami pressure without structural damage, though they suffered damage to non-structural elements, especially the first story masonry walls. Figure 19 shows reinforced concrete hotel buildings in Thailand that survived the tsunami without any sign of structural damage, although nearby non-engineered buildings were either partially or fully collapsed. There were some exceptions to this observation in Nai Thon Beach, where water run-up affected slender reinforced concrete columns of a shopping centre, causing a partial collapse.

(a) Hotel on Phi Phi Island (b) Hotel on Phi Phi Island (c) Hotel in Nai Thon

Fig. 19 Engineered concrete buildings survived tsunami forces without structural damage

A common precast slab system that was used in Thailand consisted of prefabricated reinforced concrete strips, supported by cast-in-place beams. These strips had 50 mm thickness, 300 mm width and 2.0 m length, reinforced with 4-6 mm diameter smooth wires, equally spaced in the centre of the section. Figure 20 shows the specifics of the slab system. Because of lack of proper connection to the supporting beams, these strips lifted up due to water pressure, causing slab failures. One good example was a shopping centre in Patong Beach on Phuket Island, Thailand, where the lower level below grade was filled up with water, lifting and destroying the first floor slab panels, as illustrated in Figure 20. A similar type of slab failure was also observed in the concrete dock of the Kao Lak Harbor, as shown in Figure 21, though the strips used in the harbor dock were slightly thicker.

Fig. 20 Failure of precast slab strips in Patong Beach

5. Performance of Steel Structures

There was only one steel frame building that was investigated during the visit. The structure was located in Phi Phi Island in an area that was totally devastated by tsunami pressures. The frame consisted of steel "I' sections as illustrated in Figure 22. The building was not affected by tsunami forces and survived the disaster without any sign of structural damage.

Fig. 21 Failure of Kao Lak Harbor dock

Fig. 22 Steel frame structure in Phi Phi Island

6. Damage to Lifelines

There was extensive damage to bridges in the Aceh province of Indonesia caused by tsunami wave forces, causing many to collapse and jeopardizing relief efforts. Figure 23 shows a two-span steel truss bridge in western Banda Aceh that failed and displaced approximately 50 m from its piers and abutments which were not damaged. The Indonesian army constructed a Bailey bridge on the same supports to maintain access to the nearby cement plant. Similarly, in eastern Banda Aceh a two-lane, multi-span reinforced concrete bridge was swept off its piers, as illustrated in Figure 24(a). Two of the bridge piers were also destroyed while the others remained in place. Another multi-span, reinforced concrete bridge, over the same river further away from the ocean, survived the tsunami wave pressure as shown in Figure 24(b). This bridge is likely to be of the same type as that collapsed (shown in Figure 24(a)), judging by the spans and the piers, though this point could not be confirmed.

The transportation system in Banda Aceh was completely paralyzed by the tsunami. Main arteries as well as small streets were all destroyed, jeopardizing response and relief efforts. Foreign aid crews put in a substantial effort to clean and open streets that had been covered by the debris of collapsed buildings and destroyed trees. Access to urban areas was lost, in particular the 150 km coastal road to Meulaboh was washed away and bridges on the way lost their superstructure due to the tsunami wave pressure.

The storm drainage system in Banda Aceh, as well as in Medan, Indonesia consists of concrete open channels located along main streets. These channels are sometimes covered with prefabricated concrete slabs, especially in populated regions. This drainage system suffered extensive damage in Banda Aceh. Cover slabs were broken and displaced and the channels were blocked by mud and debris, further contributing to flooding. A major part of the clean-up operation was to clean the drainage channels to make them functional again, as illustrated in Figure 25.

Fig. 23 The failure of steel truss bridge in eastern Banda Aceh

(a) (b)

Fig. 24 Multi-span reinforced concrete bridges in eastern Banda Aceh: (a) bridge completely swept off by tsunami; (b) bridge that survived the tsunami

Fig. 25 Open channel drainage system in Banda Aceh

Fig. 26 Damage to pipeline attached to the underside of bridge girders in Banda Aceh

Water supply in Banda Aceh was disrupted due to the failure of water mains. A number of main pipelines were broken as they were attached to bridges to cross the rivers that pass through the city. These pipes were damaged either by the floating debris or collapsed bridge components. Figure 26 illustrates damaged pipelines attached to bridges.

EFFECTS OF EARTHQUAKE

The earthquake of December 26, 2004 was the second largest ever recorded by a strong motion seismograph (Northwestern University[4]). The duration was long but the focal point was at about 30 km depth. The area was covered by soft soil, contributing to the amplification of seismic waves. The strongest shaking was felt in Banda Aceh, causing significant damage. There was no seismic damage observed in Thailand. The only strong motion seismograph in the area was in India, but it was not operational on the day of the quake. Non-engineered and engineered reinforced concrete frame buildings formed the majority of building stock in Banda Aceh. There was no new lesson learned from the earthquake, but many of the seismic deficiencies of buildings, known to cause poor structural performance, were clearly visible throughout the city.

1. Strong Beams and Weak Columns

Most of the reinforced concrete frame buildings, which appeared to have been engineered, had strong and relatively deep beams supported by smaller-size columns. Therefore, hinging of columns was widespread throughout the area while the majority of the beams remained elastic until the collapse of the structure, triggering overall stability failures of frames. Figure 27(a) shows an example of this type of failure of a shopping centre located in downtown Banda Aceh, although this building also suffered from an additional problem of lack of joint reinforcement. Hinging of weak columns relative to beams also resulted in the pancaking of slabs, as illustrated in Figure 27(b).

(a) Shopping centre in Banda Aceh (b) Office building in Banda Aceh

Fig. 27 Deep and strong beams supported by smaller-size and weak columns

2. Soft Story Failures

Open spaces at entrance levels resulted in soft stories in most commercial buildings. Increased deformation demands on the first story columns of these buildings, coupled with lack of confinement and column deformability, resulted in column failures. The failure of first story columns triggered the collapse of entire story. Older and newer buildings alike suffered from soft story failures as illustrated in Figure 28 (left and right, respectively).

3. Lack of Transverse Reinforcement

The investigation of damaged columns revealed lack of seismic design practices, including properly spaced and detailed hoops. This resulted in column flexural failures, especially in soft stories and where strong-column weak-beam design philosophy had not been implemented. While non-engineered building columns had definite lack of required volumetric ratio, as well as the spacing and detailing of column ties, engineered building columns did not contain sufficient transverse reinforcement either. Column failures and resulting building collapses associated with the lack of transverse reinforcement are illustrated in Figure 29.

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[4] Website of Northwestern University, Department of Geological Sciences, http://www.earth.northwestern.edu/people/seth/research/sumatra2.html

Fig. 28 Soft story failures in Banda Aceh

(a) Column failure in Tax Office (b) Column failure in Customs Building

Fig. 29 Lack of concrete confinement and resulting failures in Banda Aceh

Many failures were attributed to lack of transverse reinforcement in beam-column connections. Furthermore, lack of transverse reinforcement in column splice regions, coupled with inadequate splice lengths resulted in additional column failures. Lack of shear reinforcement, aggravated by short column effects, resulted in column shear failures. Figures 30 and 31 show additional examples of column failures in Banda Aceh.

(a) Failure of beam-column connections (b) Lack of joint reinforcement

Fig. 30 Lack of confinement and resulting failures in Banda Aceh

(a) Column shear failure (b) Column shear failure (c) Splice failure

Fig. 31 Column failures in Banda Aceh

4. Performance of Masonry Walls

Unreinforced masonry walls were used extensively in all areas visited. Brick and block walls were used as exterior and interior infill walls, as well as partition walls. These walls increased the building mass and attracted seismic forces. They were able to brace buildings until their elastic limits were exceeded. When this happened, they developed either sliding shear failures or diagonal tension cracks followed by the crushing of diagonal compression struts. Figure 32 illustrates different types of damage inflicted on unreinforced masonry walls.

5. Performance of Concrete Shear Walls

Very few structures had shear walls. A frame building, forming part of a shopping centre in Banda Aceh, had an inadequate shear wall which was not sufficient to provide lateral bracing, and developed a wide diagonal tension crack as shown in Figure 33(a). Similarly inadequate reinforced concrete shear walls were used at the base of a concrete water tower in central Banda Aceh. The walls suffered from extensive diagonal cracking. They also developed sliding shear failure due to the window openings within the walls. This is illustrated in Figures 33(b) and 33(c). Some of the masonry walls behaved as shear walls in terms of providing lateral bracing. However, if and when their elastic limit was exceeded, they developed diagonal tension cracks and diagonal compression crushing.

(a) Sliding shear failure (b) Diagonal tension failures

Fig. 32 Masonry damage in Banda Aceh

(a) Diagonal crack in a shear wall (b) Water tower (c) Shear wall at the base of tower

Fig. 33 Performance of concrete shear walls in Banda Aceh

CONCLUSIONS

The following conclusions can be drawn from the reconnaissance visit conducted in Thailand and Indonesia to assess engineering significance of the December 26, 2004 tsunami and earthquake disaster, with lessons learned and re-learned, as stated below:

- Lateral forces generated by tsunami wave pressure can be significantly higher than typical design wind pressures, generating out of plane forces high enough to damage unreinforced masonry walls within the wave height. The observations indicated widespread failure of masonry infill walls within the first story level of most frame buildings. These failures were often in the form of large circular openings.

- The base shear due to lateral tsunami forces was assessed to be approximately 60% of elastic seismic design forces for a 6-storey, 3-bay reinforced concrete building in a seismically active region. While the relative level of forces will change from one building to another, depending on the characteristics of the building, the type of exterior enclosure, proximity to shoreline, topography of the region and other seismic and tsunami characteristics, tsunami-generated base shear in buildings can be at a level that is comparable to seismic-induced base shears.
- Non-engineered low-rise reinforced concrete frame buildings, with small size structural elements, are vulnerable to partial or full collapse due to lateral tsunami pressures. Columns of such buildings are further vulnerable to impact forces generated by floating debris caused by tsunami, often leading to flexural failures of columns within their mid-heights.
- Engineered reinforced concrete frames appear to have sufficient strength against tsunami forces. There was very little damage observed in structural components of engineered concrete buildings. Often, nonstructural elements failed before the effects of tsunami pressure reached a critical level for structural components of such buildings, relieving pressure on structural elements. There was one steel frame building investigated, which survived the tsunami pressure without any sign of distress.
- Prefabricated reinforced concrete slab strips, commonly used in the area, suffered from uplift forces caused by hydrostatic pressures. Lack of proper anchorage to the supporting beams was blamed for the failure of these slab systems.
- Bridge infrastructure was devastated by tsunami forces. Many bridges were swept away from their supports, disabling the transportation network.
- Storage tanks should be well anchored to their foundations to resist tsunami pressures. Many steel storage tanks, as well as other unanchored structures floated away long distances due to the uplift pressure generated by tsunami.
- Light timber frame buildings are extremely vulnerable to tsunami wave pressures. Many residential districts with timber residential buildings in Banda Aceh were entirely wiped out by tsunami waves.
- Reinforced concrete frames, designed and built without seismic design and detailing practices, suffered significant damage due to ground shakings associated with the earthquake. Extensive use of unreinforced masonry, strong beams and weak columns, and lack of column and joint transverse reinforcement could be blamed for seismic damage. Furthermore, soft stories experienced widespread damage, often resulting in the collapse of first stories, sometimes leading to total building collapses.

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