Damage Investigation and the Preliminary Analyses of Bridge Damage caused by the 2004 Indian Ocean Tsunami

by

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ABSTRACT

At 08:07 a.m. local time on December 26, 2004, a large-scale earthquake with magnitude 9.0 occurred at the western coast of Northern Sumatra Island, Indonesia, which was the forth largest earthquake since 1900. The earthquake generated the tsunami with wave height exceeding 20 m. The tsunami affected the whole Indian Ocean area, and the damage became one of the heaviest natural disasters in human history with casualty more than 200,000 people as well as destructive damage to houses/buildings and infrastructures. The one of authors went to investigate the damage to the city of Banda Aceh, North Sumatra Island, as a member of the Japan Society of Civil Engineers (JSCE) Reconnaissance Team in March 2005, about two months later after the earthquake.

This paper presents the damage to the bridges caused by the earthquake. The significant damage including washout of bridge superstructures were caused by tsunami waves. Based on the investigation so far, the findings and lessons are summarized although more detailed investigation and careful review of the damage of bridges is still needed. Furthermore, preliminary analytical results to simulate the bridge wash-out damage mechanism is presented.

KEYWORDS: Indian Ocean Tsunami, Highway Bridges, Damage Investigation, Simulation Analysis

1. DAMAGE TO BRIDGES AND ROADWAYS

1.1 Area Investigated

Figure 1 shows the North Sumatra Island. City of Banda Aceh is located at the north of the island and Lhoknga is the west city and City of Meulaboh is located at about 250km south from Banda Aceh. The tsunami exceeding about 30m high maximum was estimated to affect the coast area from Lhoknga to Meaulaboh. In these areas, significant damage including complete washout of bridge superstructures and soil structures caused by tsunami waves were found. In the followings, the damages to bridges in cities of Banda Aceh and Lho'nga, and on the route between cities of Banda Ache and Meulaboh are briefly summarized.

1.2 City of Banda Aceh

The city of Banda Ache is located at the north of the Sumatra Island. 42 bridges in the affected area by tsunami at Banda Aceh were investigated. The height of the tsunami in the seaside area was estimated to be about 5-10m. The superstructures of 3 bridges were completely washed out and fallen down, and 5 bridges were remarkably affected with lateral displacement of 10cm–1m by the effect of Tsunami.

Photos 1 and 2 show one of the significantly damaged bridges. The simply-supported prestressed concrete girder bridge with span length of about 20m was washed out by the tsunami effect. The girder was just set on the top of abutments and there seemed to be no shear connection at the bearing supports. Tsunami height was just as the same height as the ceiling level of the 1st story of the houses. After the earthquake, a temporary bridge was provided to assure the traffic.

At the time of investigation when it was about two months later from the earthquake, the washed-out girder was reused and already settled

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on the original location as a permanent repair.

Photos 3 and 4 show the other bridge where the superstructures were completely washed out. It was reported that the bridge had a relatively shallow superstructure made of wooden materials. Substructures were made of masonry materials filled with concrete mortar.

The photo is not shown here but the complete washout of superstructures was found at one more bridge. It was made of a prestressed concrete girder with shallow deck with 1 lane. The concrete members of substructures to support the girder laterally were failed by the lateral force effect of tsunami and then the girders were washed out.

Photos 5 to 8 show the typical damage to a bridge in which the significant lateral displacement was developed by the effect of tsunami wave. The superstructure of the bridge was 3 span simply-supported reinforced concrete girder and was supported by the wall type reinforced concrete piers. The rubber sheet type bearings were used and there was no shear key to laterally connect between girder and substructures. The decks were moved about 50cm laterally but the rotation was developed at the decks then the decks were wedged geometrically between the both abutments. The handrails were partly but heavily damaged and it was estimated that the handrails were broken down by the effect of the hit of boats or driftage. The washout effect at the backfill soils of abutments was also found.

Photos 9 and 10 show another bridge where the significant lateral displacement was developed. The bridge is a simply-supported reinforced concrete girder with span length of about 20m. The deck was moved in the transverse direction about 1m by the tsunami effect. The girder was supported by the rubber sheet type bearing and there was not any shear connection between girder and substructures.

Although several bridges were significantly damaged caused by the tsunami effect, on the other hand, there are several bridges without any significant damage even they seemed to be strongly affected by the tsunami. Photos 11 and 12 show a bridge without any significantly damage by tsunami. The height of tsunami was estimated about several meters over the bridge deck level. Heavy damage to houses and buildings was found around the bridge. The bridge was a long bridge with 10 span simply-supported concrete girders which were supported by circular reinforced concrete columns. The rubber bearings were used and the concrete block shear keys were provided between girders. Although the attached facilities beside the girders which were estimated as electricity or others were heavily failed but the main body of the bridge was not damaged. Slight damage to the shear keys as cracking was found. It is needed to investigate more including the tsunami height, but it is estimated from the bridge behavior that the shear keys seems to work well to resist against the lateral force caused by tsunami.

Photos 13 and 14 show another bridge to show the slight damage to shear keys. The bridge was 3 span simply-supported concrete girders and was supported by the rubber bearings and concrete block shear keys. The bridge was not affected by the tsunami. The shear keys were slightly damaged including the concrete cracking and failure. The damage was estimated to be caused by the earthquake ground motions.

As will be discussed later, many truss bridges with relatively longer spans were washed out in the west coast route from Banda Aceh to Meulaboh. The detailed investigation could not be made for all of the collapsed bridges but some collapsed bridges did not have the connection and shear keys between decks and substructures. Photos 15 and 16 show the behavior of the truss bridge with stiff bearing connections between deck and substructures. Since the bridge is located at the east of Banda Aceh, the tsunami height might not be so significant. But the tsunami height was clearly exceeded over the height of the upper truss member. There found no damage at the bridge. It is needed to investigate more in detail but the stiff bearing connection may be one of the reasons for no damage.

1.3 City of Lhoknga

The city of Lhoknga is located at the west of Banda Aceh. The area was significantly affected by the tsunami and the tsunami height is estimated to be over 30m at maximum. Photos 17 to 19 show the complete washout of 2 span simply-supported steel truss bridge, which was supported by the wall type reinforced concrete columns. The decks were supported by the bearings and a bolt was provided to connect deck and substructures. There was no stiff shear connection between deck and substructures except one bolt connection. Since the truss girders were washed out to the upstream side and the bolt to connect between deck and substructure were bended toward the upstream side, it was estimated that the decks were washed out by the tsunami wave in the direction of upstream side. This route is important route to connect between the north and the south, the temporary bridge was provided for emergency measures. It should be noted here that it is estimated the truss type bridge is employed for a relatively longer span bridge in the area.

Photos 20 and 21 show the behavior of the reinforced concrete box culvert bridges. The bridge is located in the cement factory which was significantly damaged by the Tsunami. Some damage was found at the sidewall but there was almost no damage at the main body of the bridge.

1.4 Route from Banda Aceh to Meulaboh

The city of Meulaboh is located at about 250km south from the city of Banda Aceh. There is a seaside route which is only roadway to connect between two cities. The tsunami was the most significantly affected on the route. According to the data investigated by the Katahira & Engineers International, total section of 56.6km of roads was unpassable and 126.7km was seriously damaged. Also, there were 186 bridges along the roads and 81 bridges were washed out or heavily damaged. JSCE team could not investigate the all of bridges by a land route but the investigation from the helicopter was made.

Photos 22 to 26 show the typical washout of the bridges in the route. All photos shown here were taken by UN. There are several steel truss bridges and the deck was completely washed out toward the upstream side. Since the most piers and abutments remained at the original location, it is estimated that the superstructures were washed out by the effect of tsunami. Photos 27 shows the washout of the roadways which were completely eroded by the tsunami effect. The settlement of land was also estimated along the coast and the erosion of the coastline was quite significant.

3. PRELIMINARY ANALYSIS

To simulate the dynamic behavior of bridges structures subjected to the Tsunami effect, the analytical study was made.

Figure 2 shows the section of the bridge superstructure analyzed. A steel I girder and the RC Slab with bridge length of 40m was assumed. The girder weight is assumed as about 5.4kN/m/girder. The deck is assumed to be supported by bearings. Deck height is assumed as 5m at the bearing level.

Figure 3 shows the assumed effect of Tsunami. Tsunami height is assumed as 30m considering the west coast at North Sumatra Island. And the velocity is assumed as 68km/h (about 20m/s) considering the observation and empirical equation. The analysis was made using the discrete element method assuming the particle of 10cm diameter. The flow was loaded from the right to left sides.

Figure 4 shows the time history behavior of the deck. It is found that the numerical analysis can roughly simulate that superstructure moves laterally by the effect of Tsunami. From this kind of analyses, forces which affect the bridge superstructures can be evaluated.

4. SUMMARY OF DAMAGE TO BRIDGES AND ROADS

More detailed investigation and careful review of the damage is still needed, but based on the above investigations, the following findings were so far obtained.

1) Tsunami Effect: Since tsunami is basically fast, strong and thick water flow with driftage, then lateral water pressure, floating effect and washout effect are the primary mechanical effect.

2) Concrete Bridges: If a bridge had a concrete deck with appropriate shear keys at bearing

supports, the bridge did not have a significant displacement or was not washed out during the tsunami effect. If there was no shear key, there were some bridges in which the deck was completely washed out or significantly displaced in the transverse direction.

3) Steel Bridges: The detailed investigation for all of the collapsed steel truss bridges could not be made. The washed-out truss bridge located in Lhoknga did not have any shear key, on the other hand, one truss bridge with stiff bearings at the east of Banda Aceh did not suffer any damage. Therefore, it is estimated that the shear keys may work well against the lateral tsunami force. The floating effect can be also controlled by the uplift stopper which connects between superstructures and substructures at bearing supports.

4) Foundations: It was found that some of the substructures as well as superstructures were completely washed out and missing. It is also important to protect the substructures from the washout. Wall-type piers, which are usually employed in this area, seemed to be survived well, and the foot protection work around foundations is effective if there is surrounding material which is easily washed out.

5) Abutment Backfill Soils: There found several damage to abutments where the backfill soils were washed out. To fill the soils as a temporary measure to assure the traffic is relatively easy. But if such damage should be prevented for abutments in which the longer repair work are needed after the earthquake, the bank protection at the abutment is effective.

6) Soil Structures: If the roads are constructed on the stiff ground (possibly, cutting ground, stiff clay layer/rock and so on), the roads seemed to be survived. On the other hand, the roads are on the soft or sandy soils (possibly, soil embankment with soft materials which is easy to be washed away), the roads seemed to be completely washed out. Such sandy soils sections are generally located closed to the seaside line, or the current or past river areas. Also, the erosion effect was very significant.

7) Ship Effect: The driftage of large ships seemed to influence the damage significantly. But the direct consideration of the effect of the hit of ships in the structural design does not generally become reasonable. Such ship control measures during tsunami are also important.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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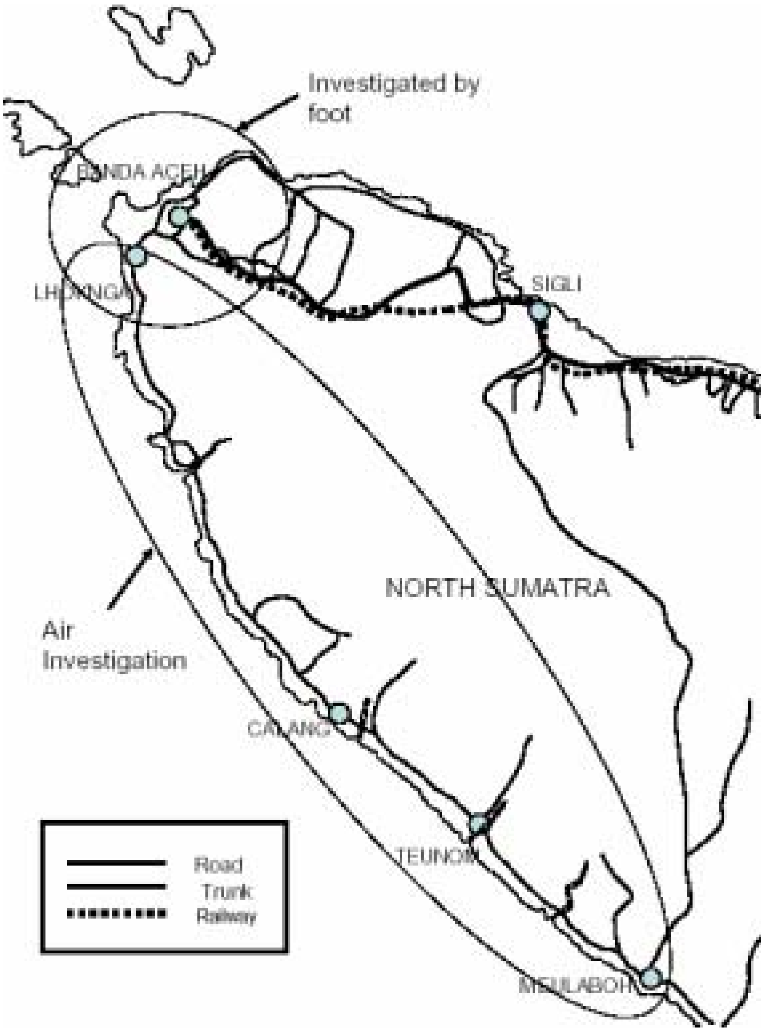


Figure 1 North Sumatra Island

Photo 1 Repair of Washed-out Girder

Photo 2 Collapse of Water Pipes Bridge

Photo 3 Complete Washout of Bridge
(reported as Wooden Superstructure)

Photo 4 Masonry Substructure and Washout Effect of Surrounding Soils

Photo5 Damaged Bridge

Photo 6 Washout Effect of Backfill Soils

Photo 7 Lateral Displacement of Deck

Photo 8 Rubber Sheet Type Bearing
and Lateral Displacement at Bearing

Photo 9 Lateral Displacement of Deck

Photo 10 Displacement at Bearing

Photo 11 Undamaged Bridge by Tsunami

Photo 12 Concrete Block Shear Keys

Photo 13 Bridge affected by Shaking

Photo 14 Slight Damage to Shear Keys by Shaking


Photo 15 Steel Truss Bridge without Damage


Photo 16 Steel Bearing Supports


Photo 17 Washing out of Steel Truss


Photo 18 Temporary Bridge


Photo 19 Bearing Support and Bolt to connect between Deck and Substructures

Photo 20 Concrete Box Culvert Bridge

Photo 21 Concrete Box Culvert Bridge

Photo 22 Washout of Truss Bridge (1)

Photo 23 Washout of Truss Bridge (2)

Photo 24 Washout of Truss Bridge (3)

Photo 25 Washout of Truss Bridge (4)

Photo 26 Washout of Truss Bridge (5)

Photo 27 Erosion of Road and Coastline

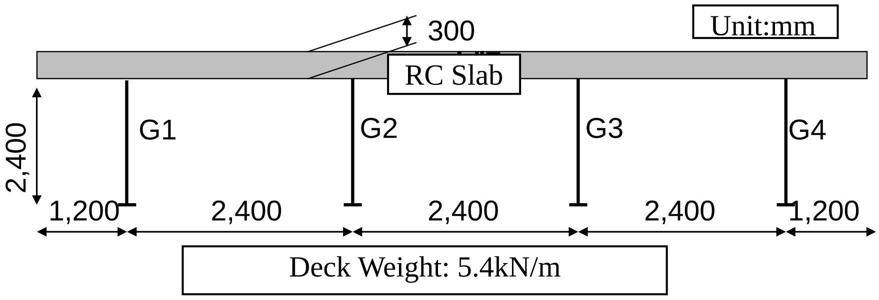


Figure 2 Assumed Deck Structure Analyzed

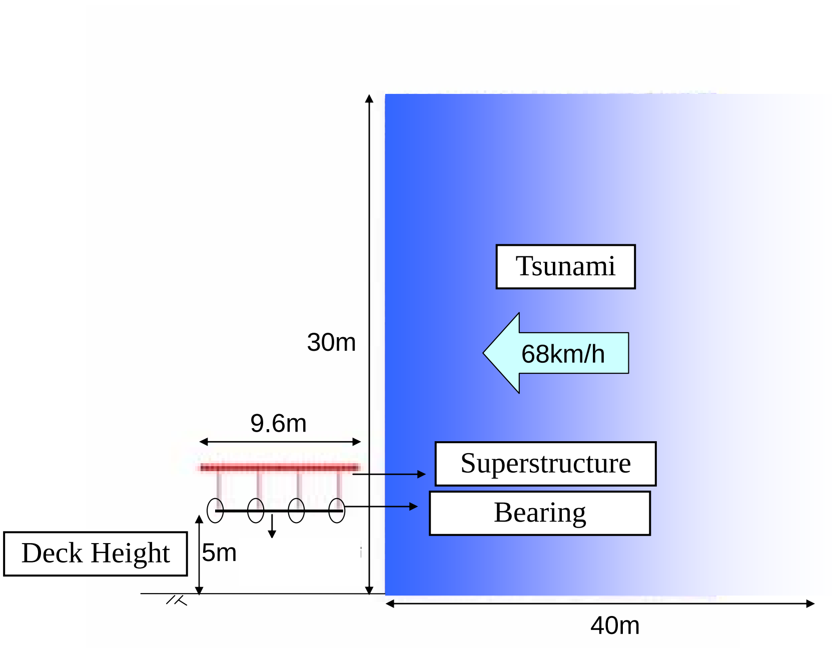
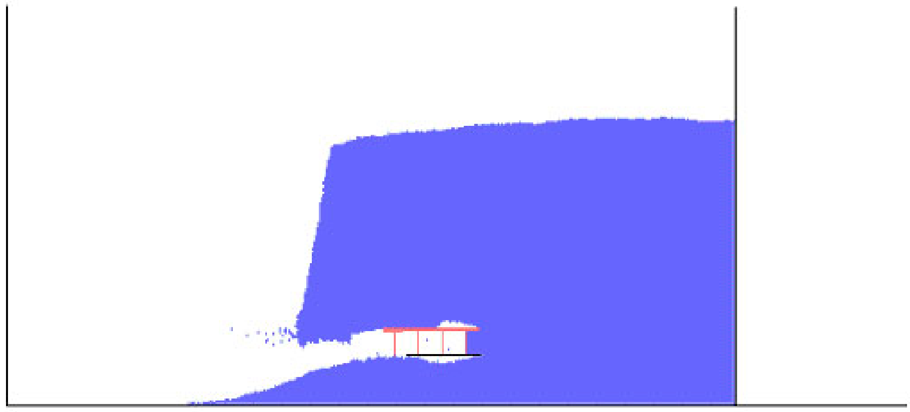
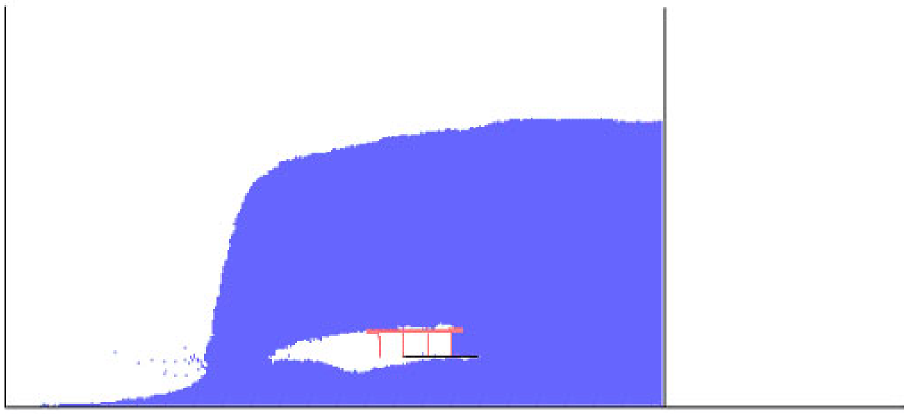


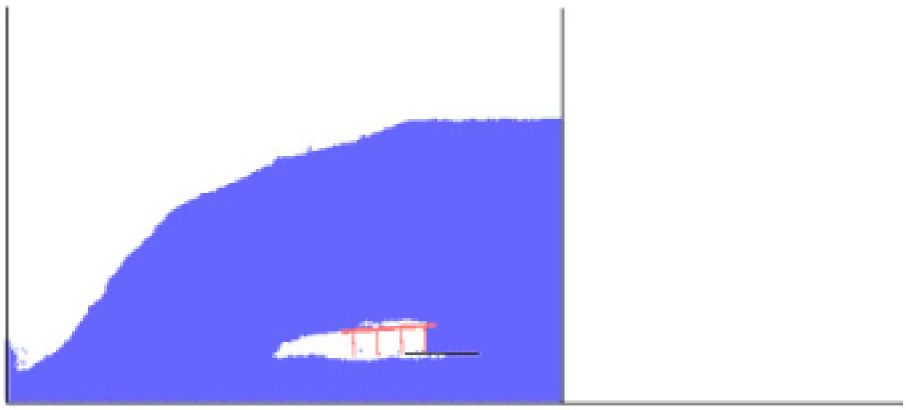
Figure 3 Assumed Effect of Tsunami



(a) 1.0 Second



(b) 1.5 Second



(c) 2.0 Second

Figure 4 Examples of Time History Behavior