Report on the Tsunami Damage of Bridges in Banda Aceh and Some Possible Countermeasures

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A survey conducted in Banda Aceh after the Great Sumatra Earthquake reveals that many bridges were severely damaged by tsunami water. Some of them are even completely washed away. Calculations have shown that water velocity as low as 11 kilometers per hour is capable of displacing a concrete bridge deck and girder. Meanwhile, an estimation by other researchers using video records shows that water-flow velocities in Banda Aceh were between 18 to 21 kilometers per hour. Therefore the water drag forces acting on the bridge should have been significantly large. Nevertheless, some bridges could survive just because the deck lateral movement was non-uniform so that the decks were locked to each other.

Unseating is the problem for a bridge suffering from water drag forces. Meanwhile, in earthquake engineering, unseating is also the problem for bridges under severe ground excitation. Therefore, it is expected that prevention system for the seismic unseating problem would be applicable for those by tsunami water force as well. For example, water drag force is around 1.2 times of the weight of the bridge, whereas a severe inter-plate earthquake produces maximum force of about 1.0 times of the bridge weight. Therefore, unseating prevention system for water drag force needs stronger piers and abutments in the lateral direction.

Debris floating with water is also potential in damaging a bridge. Calculations show that debris impact force is quite significant. Some kind of soft and dampening bumper systems would be helpful in reducing debris impact forces. There are also other factors advantageous for reducing water forces: stream-lined shape of the deck and girders, and weak railing of the bridge. The stream-lined shape will reduce water drag force, whereas weak railing will break when debris hit it so that the debris can flow freely over the bridge.

Key Words : *Tsunami, bridge damage, unseating, water drag force, debris force, bridge shape*

1. INTRODUCTION

The fourth largest earthquake in the world since 1900 has happened on December 26, 2004, at 00:58:53 UTC (or 07:58:53 local time), off the west coast of Northern Sumatra, Indonesia. The magnitude was 9.0, the focal depth was 30 km, and the epicenter position is Latitude 3.30 North and Longitude 95.96 East. The epicenter is 255 km from Banda Aceh, the nearest provincial capital in Sumatra. The earthquake was felt (IX) at Banda Aceh, (VIII) at Meulaboh, and (IV) at Medan, Sumatra, in the Modified Mercalli Intensity Scale commonly used in the US (USGS, 2005). The earthquake itself caused some damages and casualties in Banda Aceh and Meulaboh.

The subsequent tsunami killed more than 125,468 people, and left 94,550 people missing in Northern Sumatra region (Bakornas PBP, 2005). In total, at least 283,100 people were killed by the earthquake and subsequent tsunami in 10 countries in South Asia and East Africa. The tsunami caused more casualties than any other in recorded history.

In a quick response to the disaster, a group of Japanese researchers led by the first author departed for Banda Aceh city and surrounding areas in an attempt to study the effect of such huge earthquake and tsunami on structures. The study is expected to provide information and lessons on the disaster and how the effect of such disaster in the future can be reduced.

2. BRIDGE DAMAGES

(1) Ulee Lheue Bridge Damages

Figure 1 shows the satellite photos of Meuraxa ward, Banda Aceh city, before and after the tsunami. Massive damage is seen on the area caused by the tsunami. Bridges shown in the figure were surveyed on March 3rd and 4th, 2005. The bridges surveyed are numbered as Nos. 2, 1, and 20. Maximum water height is at least 10 meter in this area, which is well beyond the bridge height.

Figure 2 shows bridge No.2, Ulee Lheue Bridge. Site survey on March 3rd, showed that this is a three-span bridge supported by two abutments and two piers. One span consists of a deck supported by five prestressed-concrete girders (Figure 3).

Scouring and settlement happened at the approaches near the abutments. Scouring at the downstream side is more severe than the upstream side (Figure 4). The railing of the bridge is damage only on the south side (Figure 5). This might be caused by uneven debris floating with waters.

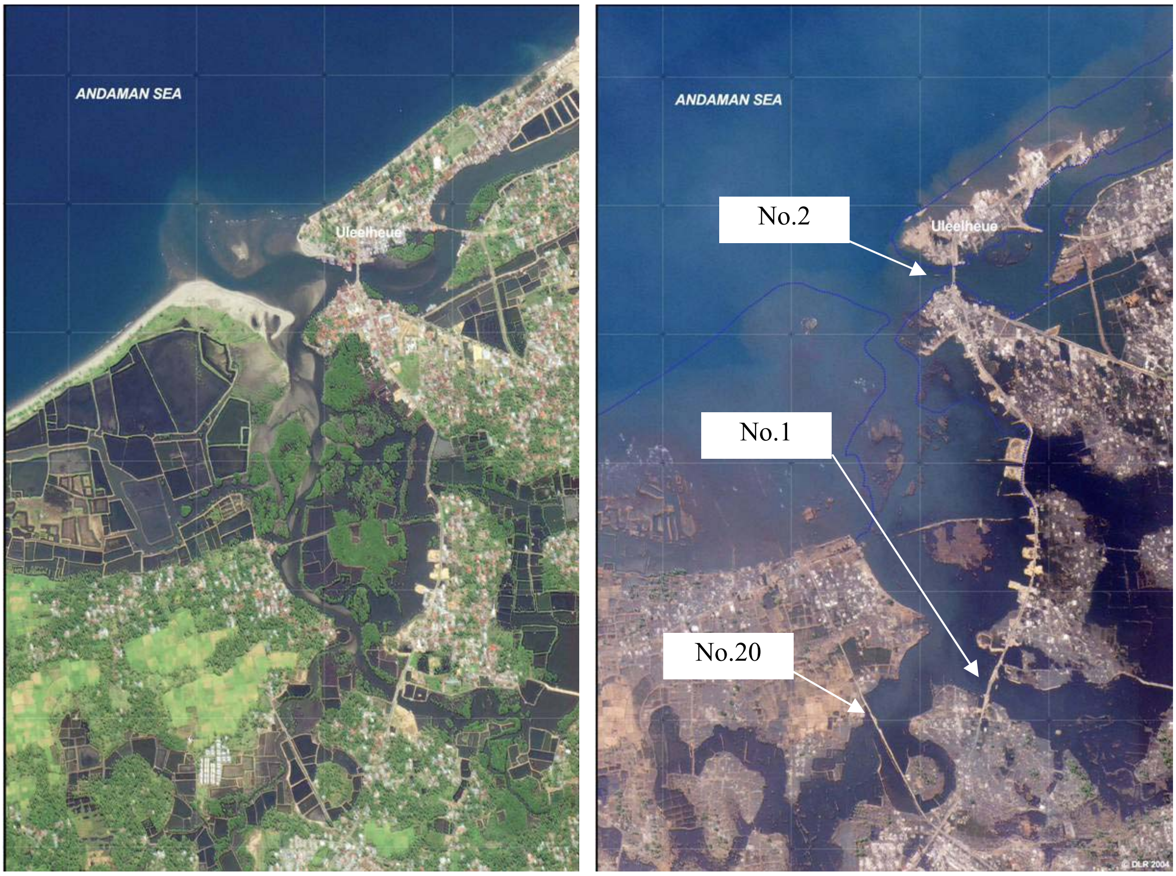

Figure 1. Locations of studied bridges at satellite photos (a) Jan. 10, 2004 (b) Dec. 29, 2004
(Source: DigitalGlobe® http://www.digitalglobe.com)

Figure 2. Three-span Ulee Lheue Bridge (No.2), March 03, 2005

Figure 3. Prestressed-concrete girders supporting a deck

Figure 4. Scouring of approaches near abutments, downstream side

Figure 5. Damage to railings (also showing scourings at the upstream side)

The bridge was displaced 35 cm upstream (south-east direction, Figure 6). There are gaps between decks. The gap is measured as 15 cm at the upstream side and 7 cm at the downstream side. The bridge was displaced non-uniformly in the lateral direction. This non-uniform displacement make the decks locked to each other and prevented from further lateral movements. Dimensions and displacements of the bridge are shown in Figure 6.

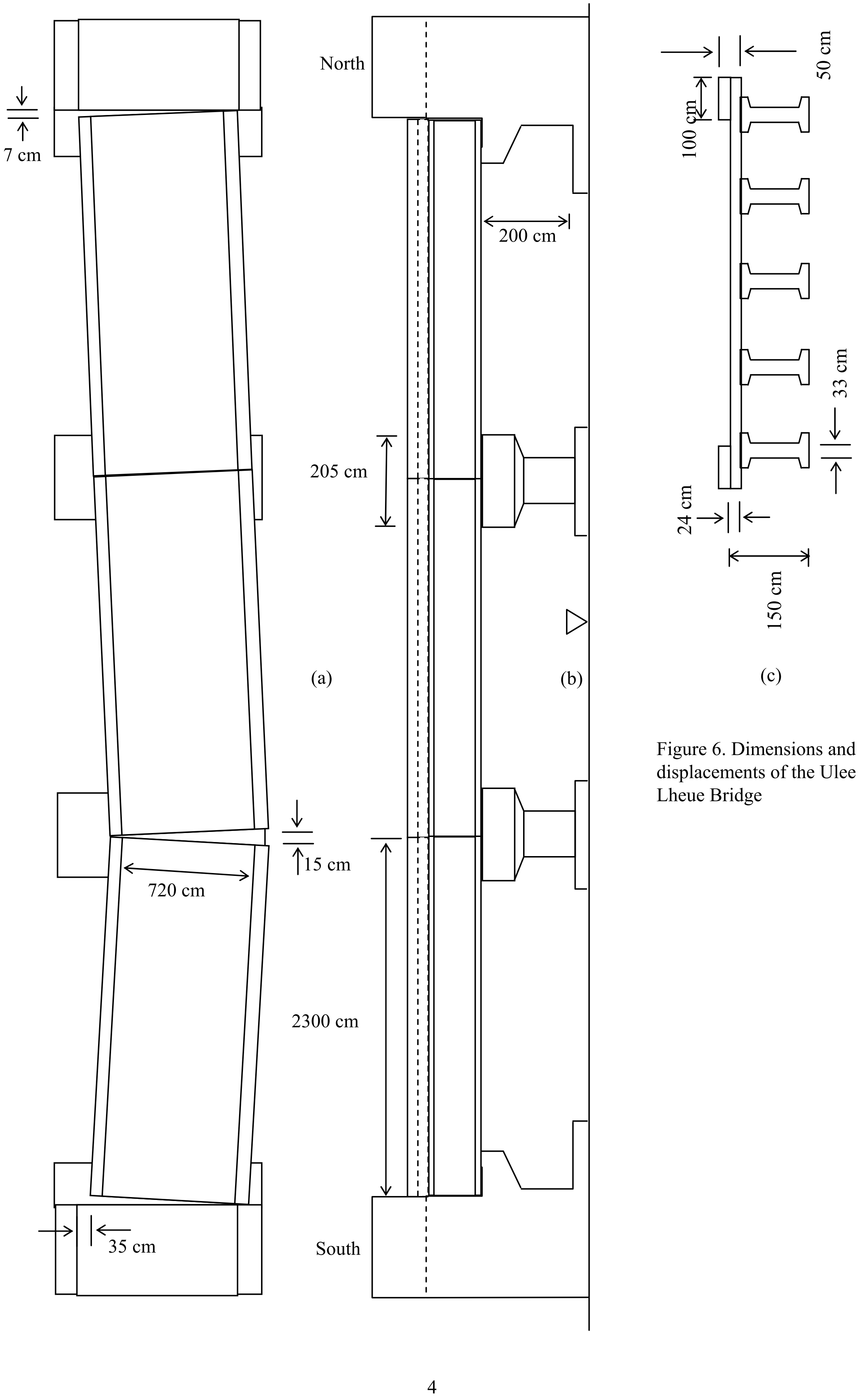

Figure 6. Dimensions and displacements of the Ulee Lheue Bridge

(2) Asoe Nanggroe Bridge Damages

Figure 7 shows bridge No.1, Asoe Nanggroe Bridge. It is a two-span bridge supported by two abutments and one pier (Figure 7a). One span consists of a deck supported by six reinforced-concrete girders (Figure 7b).

Heavy scourings happened at both abutments in the upstream side (Figure 8). However, the scouring did not make the abutments settled or moved. Recovery of earth infill at the abutments is expected to be sufficient to return the capacity of the abutments.

Meanwhile, the decks were severely displaced in the lateral direction. Fortunately, non-uniformly lateral displacements made the deck locked to each other and prevented from further lateral movements (Figure 9).

(a)

(b)

Figure 7. Asoe Nanggroe Bridge, March 04, 2005

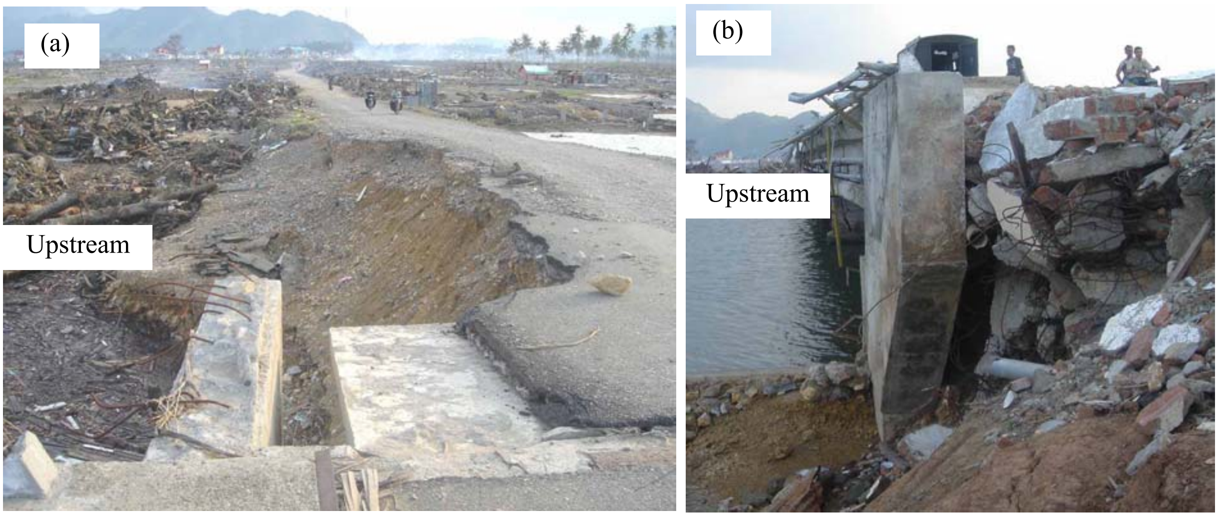

Figure 8. Scouring at the upstream side (a) North abutment and (b) South abutment

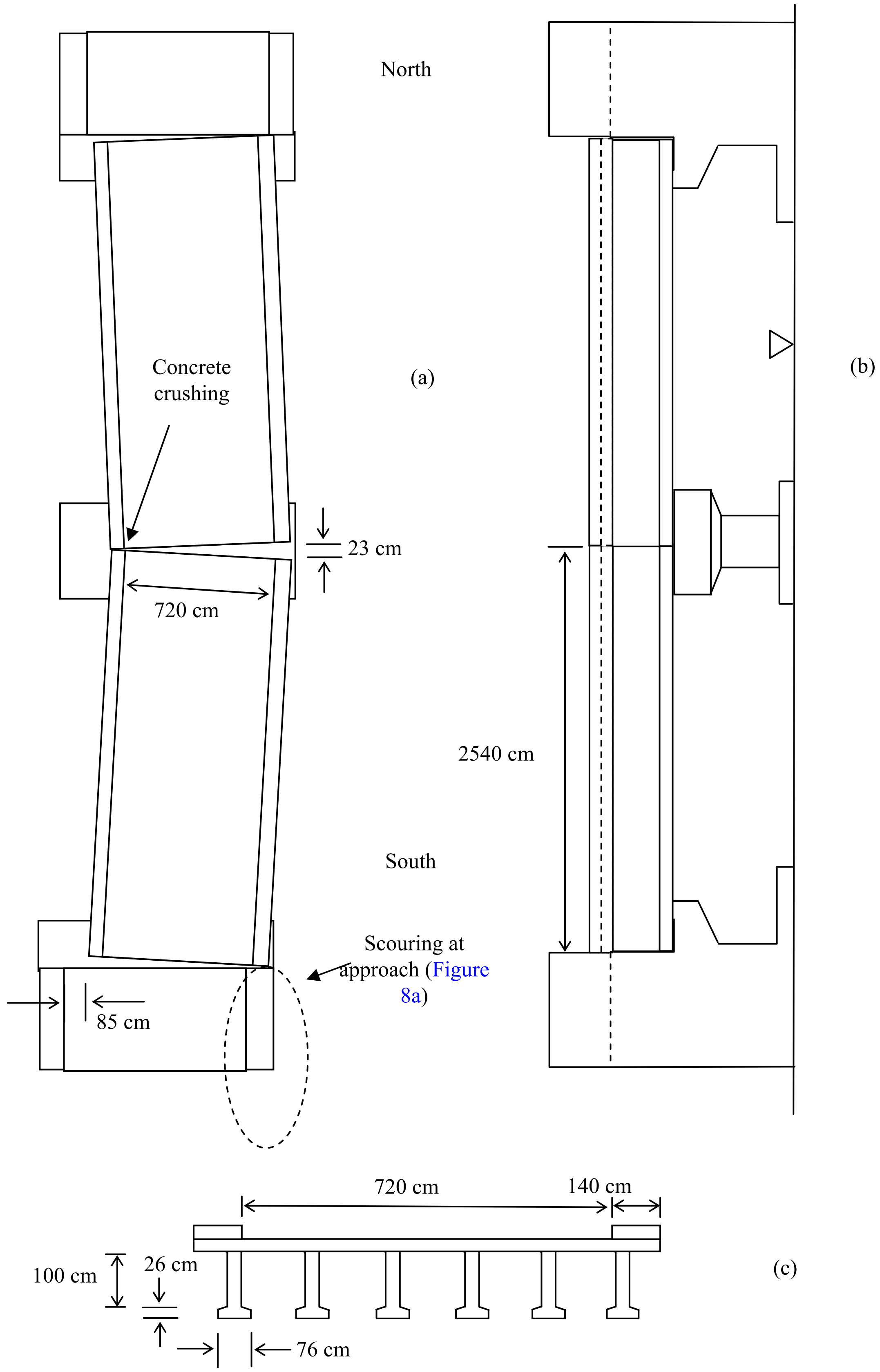

Figure 9. Dimensions and displacements of Asoe Nanggroe Bridge

(3) Peukan Bada Bridge Damages

Figure 10 shows bridge No.20, Peukan Bada Bridge. It is a one-span bridge supported by two abutments. One span consists of a deck supported by three reinforced-concrete girders (Figure 11).

The bridge was displaced to the upstream direction by about 165 cm at the south side and 95 at the north side (Figure 11).

Figure 10. Peukan Bada Bridge, March 04, 2005

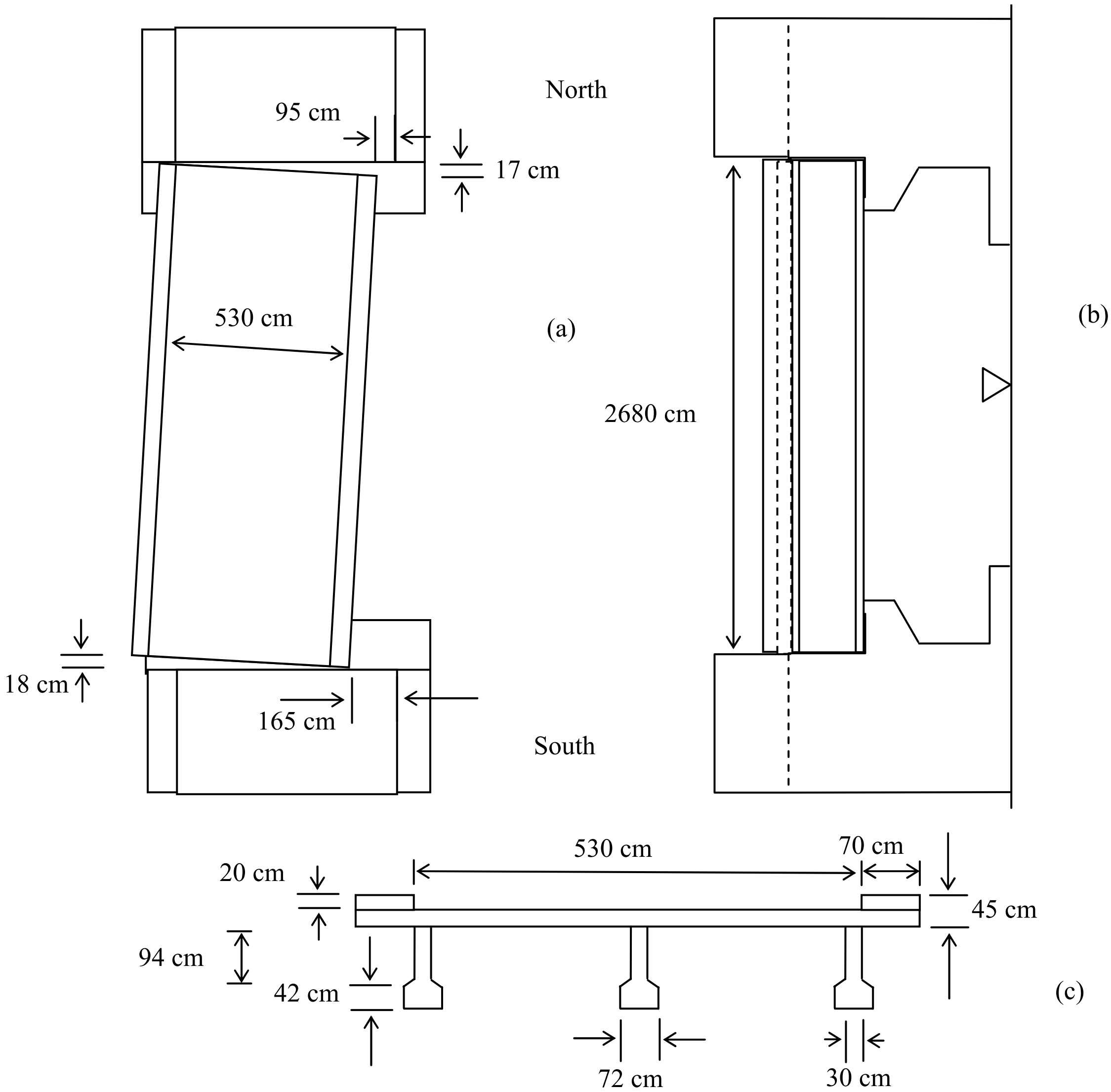

Figure 11. Dimensions and displacements of Peukan Bada Bridge

3. MINIMUM WATER VELOCITY

Minimum water velocity causing the bridge to move is predicted by using fluid drag force formula. The formula is shown in Equation 1, where ρ_{wtr} is the water density (1000 kg/m^3), C_d is the fluid drag coefficient taken as 2.0 for a normal plane, v is the water velocity, and A is the attacked area of the bridge.

$$F_d = \tfrac{1}{2}\rho_{wtr} C_d v^2 A \qquad (1)$$

(1) Minimum water velocity for Peukan Bada Bridge

Minimum tsunami-water velocity capable of displacing the Peukan Bada bridge is calculated as follows. Attacked area A is calculated as 48.51 m^2. The volume V of the bridge containing three girders and one deck is calculated as 90.905 m^3. Therefore, the mass m is $V\times\rho_{con}$ = 90.905 × 2,500 = 227,262 kg. The weight W is $m\times g$ = 227,262 × 9.8 = 2,227,168 Newton.

Resisting force of the bridge is caused by friction, $W\times\mu$ = 2,227,168 × 0.3 = 668,150 Newton. Therefore, the minimum water velocity that give drag force larger than the friction force will make the bridge move.

$$v = \sqrt{\frac{668{,}150\times 2}{1000\times 2.0\times 48.51}} = 3.71\,\text{m/s} \approx 13.36\,\text{km/h} \quad (2)$$

The calculation did not consider water uplift at the bridge. The bridge weight ratio of that which considers uplift and that which neglects uplift is calculated as:

$$\frac{V\times(\rho_{con}-\rho_{wtr})\times g}{V\times\rho_{con}\times g} = \frac{\rho_{con}-\rho_{wtr}}{\rho_{con}} = \frac{2{,}500-1{,}000}{2{,}500} = 0.6 \quad (3)$$

The ratio is applicable to other bridges as well since it is only a function of water and bridge (concrete) densities, respectively. The minimum water velocity considering uplift can then be calculated as:

$$v_{water} = v\times\sqrt{0.6} = 3.71\times 0.775 = 2.87\text{ m/s} \approx 10.34\text{ km/h} \quad (4)$$

which is smaller than that considering no water uptlift.

(2) Minimum water velocity for Asoe Nanggroe Bridge

The attacked area A is calculated as 44.70 m^2 for one span. The volume V of the bridge containing six girders and one deck is calculated as 139.34 m^3. The mass m is calculated as $V\times\rho_{con}$ = 139.34 × 2,500 = 348,350 kg. The weight W is calculated as $m\times g$ = 348,350 × 9.8 = 3,413,830 Newton.

The resisting force of the bridge because of friction is calculated as $W\times\mu$ = 3,413,830 × 0.3 = 1,024,149 Newton. The minimum water drag force is the same as the bridge friction force. Therefore, the minimum water velocity is calculated as:

$$v = \sqrt{\frac{1{,}024{,}149\times 2}{1000\times 2.0\times 44.70}} = 4.787\,\text{m/s} \approx 17.23\,\text{km/h} \quad (5)$$

Considering water uplift at the bridge, the minimum water velocity can be calculated as:

$$v_{water} = v\times\sqrt{0.6} = 4.787\times 0.775 = 3.71\,\text{m/s} \approx 13.36\,\text{km/h} \quad (6)$$

4. DEBRIS IMPACT FORCE

Predicting debris impact forces are not as easy as predicting water drag forces, since it depends on the shape and mass of the debris. Impact forces can be obtained from experimental results. However, for the time being it will be calculated based on some debris properties.

Debris with mass m hits concrete surface of the bridge with a velocity v. The assumptions are: the contact surface between the debris and the bridge is elastic with a Coulomb damping. The elasticity comes from the debris (which is mainly of wooden objects), since the concrete surface is stiffer than that of the debris. The conservation of energy law is shown as in Equation (7), where f_C, k, and x is the assumed Coulomb friction force, stiffness, and deformation of the contact-surface, respectively.

$$\tfrac{1}{2}mv^2 = f_C x + \tfrac{1}{2}kx^2 \quad (7)$$

For the debris to stop after hitting the bridge, a second condition is shown in Equation (8). After substituting this equation to Equation (7), the maximum wood deformation can be calculated as in Equation (9). Friction force f_C is calculated based on Equation (8) and ends up with Equation (10). The maximum force exerted to the bridge from the impact is the total maximum stiffness force plus Coulomb damping force, as shown in Equation (11).

$$0 = -f_C x + \tfrac{1}{2}kx^2 \quad (8)$$

$$x_{\max} = v\sqrt{\frac{m}{2k}} \quad (9)$$

$$f_C = \tfrac{1}{2}kx_{\max} \quad (10)$$

$$F = kx_{\max} + f_C \quad \text{or} \quad F = \tfrac{3}{2}kx_{\max} \quad (11)$$

The stiffness of the contact surface k is assumed to come only from the debris, since the concrete is mainly stiffer than wood. Now assuming the debris is a wooden pole hitting the bridge in a way as shown in Figure 12, the stiffness comes from half part of the wooden pole.

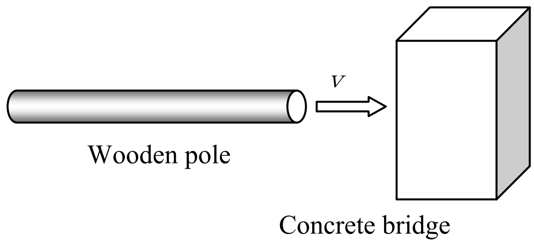

Figure 12. A pole hits a concrete bridge surface

The mass m of the pole can be calculated based on Equation (12), where ρ is the mass density. The stiffness k is estimated from Equation (13), where E is the wood's modulus of elasticity.

$$m = \rho l\pi\left(\frac{d}{2}\right)^2 \quad (12)$$

$$k = \frac{E\pi\left(\frac{d}{2}\right)^2}{0.5l} \quad (13)$$

Wood mass density is about 700 kg/m^3. Assume the pole is 2 meter long, and 10 cm diameter. The flowing speed is 18 km/h. Therefore, the mass of the pole is

$$m = 700\times 2\times\pi\times 0.05^2 = 10.99\,\text{kg} \quad (14)$$

The estimated stiffness of the contact area of the pole if the pole hit the bridge as shown in Figure 12 (the elastic modulus E is assumed to be 11 GPa or 11×10^9 N/m^2) is:

$$k = \frac{11\times10^9 \times \pi \times 0.05^2}{0.5\times 2} = 86.4\ \text{MN/m} \quad (15)$$

$$x_{\max} = \frac{18}{3.6}\sqrt{\frac{10.99}{2\times 86.4\times10^6}} = 0.0013\ \text{m} = 1.3\ \text{mm} \quad (16)$$

The maximum deformation of the wooden pole is calculated in Equation (16). The force exerted to the bridge by the wooden pole is calculated in Equation (17).

$$F = \tfrac{3}{2}\times 86.4\times10^6 \times 0.0013 = 163{,}425\ \text{Newton} \quad (17)$$

This force is about one fourth of the maximum resisting force of the bridge provided by friction force. Therefore, debris impact force is significant during a tsunami attack.

5. POSSIBLE COUNTERMEASURES

(1) Preventing Bridges from Being Washed Away

The bridges above were experiencing non-uniformly lateral displacements, so that the decks were locked to each other, and prevented from further movements. This means, limiting the bridge movements seems appropriate for the bridge to survive the tsunami water.

The maximum water drag force is a little bit higher than seismic force. For example, the drag force is around 1.2 times of the weight of the bridge (using water velocity twice as much as the minimum water velocity). Whereas a severe inter-plate earthquake causes a maximum force of about 1.0 times of the bridge weight (Japan Road Association, 1996).

An estimation by other researchers using video records of the tsunami shows that water-flow velocities in Banda Aceh were between 18 to 21 kilometers per hour (榊山 et al., 2005). These numbers are almost twice as much as the minimum water velocity calculated before. Therefore the water drag forces acting on the bridge should have been almost four times as much as the friction force..

Therefore, the stopper now should resist higher force than earthquake force. Moreover, the pier should be design to resists larger force since the stoppers are attached to the pier.

(2) Reducing Drag Force

Other method is to reduce the drag force and impact force themselves, rather than resisting the force. The methods are shown herein.

To reduce the water drag force, the shape of the bridge plays an important role. Common shapes of bridges, such as those of bridges shown above, are very prone to lateral water force, since they have large areas normal to the water attack direction.

Figure 13 shows a possible modification for reducing water drag force. However, this modification may significantly change the load carrying capacity of the bridge. Therefore, supports at points A must be added, otherwise the bridge will roll sideways. Moreover, the side webs cannot effectively resist vertical load since the web is not vertical anymore. Other aspects should also be considered for guaranteeing the loading capacity.

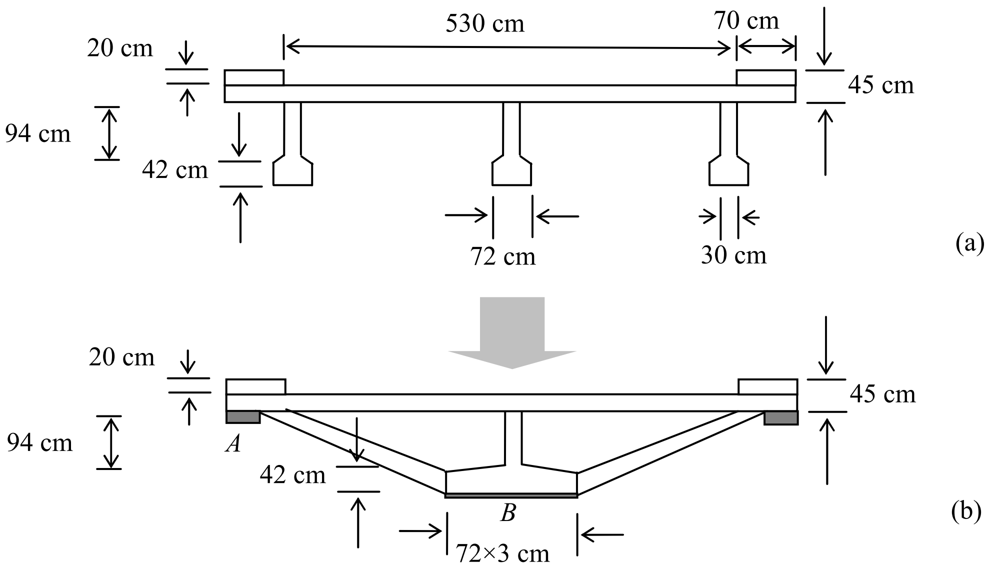

Figure 13. (a) Original cross section of Peukan Bada Bridge (b) Possible modifications for reducing water drag force

Unseating is the problem for a bridge suffering from water drag forces. Meanwhile, in earthquake engineering, unseating is also the problem for bridges under severe ground excitation. Therefore, it is expected that prevention system for the seismic unseating problem would be applicable for those by tsunami water force as well.

There is another possibility by rounding sharp corners of the deck and girders. Cengel and Cimbala (Cengel and Cimbala, 2006) mentioned in their book that by rounding sharp corners, a rectangle-shape object can reduce its drag coefficient significantly. Figure 14 shows the drag coefficients of both shapes.

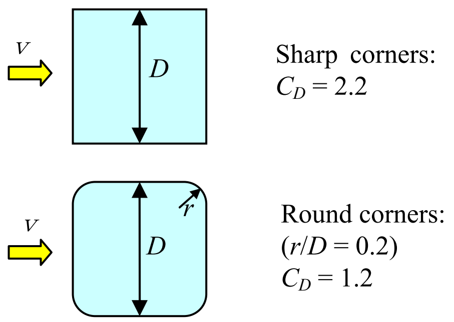

Figure 14. Effect of round corners on drag coefficient

Therefore, by rounding the sharp corners of deck and girders, the drag coefficient is expected to reduce. This expectation needs experimental support to study how much reduction can be expected for the whole bridge.

Additionally, the railing can be made easy to break when it is hit by debris. This will avoid an accumulation of debris on the railing, so that the attack area is not increase; the debris can flow easily over the top of the deck.

(3) Reducing Debris Impact Force

It is shown above when calculating the impact force that the force is a function of the stiffness of the objects. The smaller the stiffness the smaller the impact force. Therefore, by putting some flexible and damped material at locations to be hit by debris, the impact force should be reduced.

Figure 15 shows the potential locations to be hit by debris. The locations is covered with bumpers which are flexible and dampening that are expected to reduce impact force to the bridge.

6. CONCLUDING REMARKS

Survey of the damages is expected to give valuable lessons for better bridge structures in the future that are capable of minimizing tsunami induced damages.

The tsunami water force is well above the lateral resisting force of the bridge, however, the bridges survived just because the deck movement was non-uniformly lateral so that the decks were locked to each other and prevented from falling over.

Unseating prevention system used in earthquake engineering application for bridges is expected to be useful for the tsunami case as well. The tsunami water drag force is a little bit larger than an inter-plate type earthquake, therefore it needs stronger piers to resist the force than those needed by the earthquake.

Debris floating with water is also potential in damaging a bridge. Calculations show that debris impact force is about one fourth of the bridge resisting force. Some kind of soft and dampening bumper systems would be helpful in reducing debris impact forces.

There are also other factors advantageous for reducing water forces: stream-lined shape of the bridge, and weak railing of the bridge. The stream-lined shape may have serious impact on the loading capacity of the bridge, therefore it needs careful investigation. Other possibility is by rounding off sharp corners of the bridge decks and the girders.

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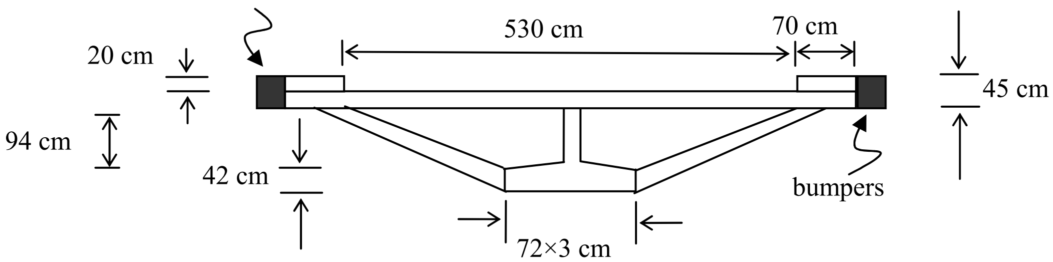

Figure 15. Additional bumpers at potential locations to reduce debris impact force