

Risk analysis of seismic bridge damage: case study after Lombok and Palu earthquake

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Abstract. Indonesia is known as an earthquake-prone region, lies in the ring of fire zone. This potential hazard can impact several infrastructures, including bridges. Seismic bridge damages could possibly disrupt traffic flow furthermore cut off the regional connectivity. In this study, risk analysis is carried out on several bridges after Lombok and Palu earthquake. Visual inspection has been undertaken on 38 bridges on-site, and several damages identification are reported. Risk analysis was then carried out according to the severity of element damages and the frequency of occurrence. From the analysis, it is concluded that embankment settlement in the approach road is found to be the most potential element with the highest risk of damage due to earthquakes. Besides, the superstructure displacement and crack in the wing wall are at moderate risk. This finding makes the substructure become the most vulnerable element which needs more attention. Therefore, it is recommended to specify a higher design specification for substructure to mitigate seismic bridge damages, especially for bridges located in the high seismic zone area.

1 Introduction

Indonesia is considered as the biggest archipelago, which has a risk of natural disasters (i.e., earthquake). This fact makes bridges have an important key at road network infrastructures. Currently, there are 23.371 bridges in national road networks, with around 100 categorized as individual bridges. According to the BMS database 2017, approximately 43 % of bridges have age more than 50 years old. Therefore, maintenance of existing bridges is a crucial issue, as well as the development of new infrastructures. If the earthquake and landslide are tended to occur frequently, more bridges will be further at risk of damage and disrupt the importance of road connectivity. Indonesia has established some codes, standards, guidelines, and manuals for bridge design, inspection, and maintenance, which are already included in the Bridge Management System 1992 [1].

Geographically and geologically, Indonesia lies in a region that is vulnerable to natural disasters, and therefore it is prone to natural and man-made calamities. Many types of disasters, including earthquakes, tsunami, volcanoes, floods, landslides, river scouring, have frequently occurred in recent times in most of the country. Earthquake and volcanic zones are found in most parts of the country, beginning from the northern tip of Sumatra to the north part of Papua. A series of recent earthquakes have devastated the country. Lack of emergency management leads to financial and moral losses. On the other hand, technological and human-induced disasters are the results of the human impact, negligence, human error, and system failure [2].

Estimating earthquake damage is not an exact science and depends on several factors. An earthquake can be quantified by the probability of ground motion occurring in a particular area. It is also possibly described from the consequences of the ground motion, which are primarily a function of construction type and the level of ground motion and shaking during the actual event [3]. The 12 MMI scales indicate the impact that occurs on the surface of the earthquake-induced earth, as described in Table 1. Those criteria are useful for the description of the severity of the earthquake. Generally, earthquake is related to the energy released produced from a sudden or violent shaking of the ground as a result of the earth's crust movement or volcanic action [4]. The seismic events cause several damaged bridges to require immediate repair. According to the latest data issued by Meteorology Climatology and Geophysics Agency (BMKG) in 2018, there are at least 11.577 times earthquake recorded in Indonesia. One of earthquake event occurred in Lombok and Palu.

One of several methods to mitigate earthquake risk is by performing seismic risk analysis. In this paper, risk analysis is carried out based on the field inspection data on several bridges after Lombok and Palu earthquake, which occurred in 2018. In the first part, the description of Lombok and Palu earthquake are explained briefly. Then, risk assessment is undertaken according to the severity of the bridge damage and the frequency of occurrence. Finally, a recommendation is proposed for seismic bridge mitigation.

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Table 1. Earthquake intensity in MMI and the corresponding description [5].

Intensity	Simple description	Detailed description	MMI Scale	PGA (gal)
I	Not felt	Not felt or felt by a few people but recorded by a tool.	I-II	< 2.9
II	Felt	Feeled by many people but does not cause damage. Light hanging objects moved and the glass vibrating.	III-V	2.9-88
III	Slightly damage	Non-structural parts of the structures experienced minor damage, such as hair cracks in the walls, roof tiles sliding down and some falling element.	VI	89-167
IV	Moderate damage	Many cracks occur in the walls of structures, partial collapse, broken glass. Some of the wall plaster is exfoliated . Most of the tiles shift down or fall. The building structure has mild to moderate damage.	VII-VIII	168-564
V	Heavily damage	Most of the walls of the permanent structures collapsed. The structures experienced heavy damage. Railway become excessive deformation	IX-XII	>564

2 Lombok and Palu earthquake

2.1 Lombok earthquake

Lombok earthquake occurred on August 19, 2018, at a relatively shallow depth of 10 km [6]. The Lombok earthquake consisted of several earthquake peaks, namely M 6.4, M 7.0, and M 6.9, respectively, in different time periods. Some of the damages include the subsidence of embankment near the bridge (Fig.1), cracking in the retaining structures, damage at expansion joint (Fig.2), and the excessive displacement of the bridge superstructure.



Fig. 1. Subsidence of embankment near the Tampes bridge [7]

The settlement causes the access disruption at the bridge location. The truck carrying gasoline and logistics was difficult to reach the affected area. This makes a serious problem to accelerate the recovery process after a seismic event.

2.2 Palu earthquake

The earthquake in Palu was occurred on September 28, 2018, with a magnitude of M 7.7. It was accompanied by a tsunami that swept through the western islands of Sulawesi. Based on BMKG data, the depth of the epicenter is 10 km, with a distance of about 26 km from North Donggala, Central Sulawesi. The observed bridge damage includes landfill subsidence, cracks in the retaining walls, destruction at expansion joint, excessive displacement of the superstructures (Fig.3), and settlement of the foundation (Fig.4).

3 Risk analysis method

The study was conducted by visually inspecting the condition of the existing bridge to see the level of damage caused by the earthquake. Damage that occurs is then evaluated to determine the effect of the earthquake on bridge elements. The number of bridges that were observed was taken by a random sampling method. The objects are the bridge located on the national road section in West Nusa Tenggara and Central Sulawesi, which are two provinces in the Central Region of Indonesia that were affected by a major earthquake in 2018. Based on the results of the field survey, there are 27 bridges damaged in the West Nusa Tenggara. Whereas, for the Central Sulawesi National road, there are 11 damaged bridges. From the visual inspection results, a matrix of damaged bridge elements and the risk of bridge damage due to the earthquake was compiled.



Fig. 2. Damage at the expansion joint in LUK bridge [7]



Fig. 3. Excessive superstructure displacement in Batusuya bridges [8]



Fig. 4. Settlement of pier foundation in Tompe bridge [8]

The level of risk of damage that occurs on the bridge element is dependent on the earthquake scale that occurred in the field. The risk of damage can also be estimated based on historical data. In this study, the level of risk is set to depend on two factors, the frequency of occurrence and the severity of bridge conditions. The rate of existence is the number of occurrences of bridge elements that have been damaged. Such damage can be in the form of an excessive foundation settlement, excessive displacement, corrosion of elements, or other damage. Therefore, it is necessary to determine the

4 Results and discussion

There are 10 (ten) types of damage observed on the existing bridges during the field survey, as shown in Fig. 5. Those include damage of expansion joint, settlement of the landfill, damage of retaining walls, excessive displacement of the upper structure, sliding of the support, cracks in the abutment, damage at seismic restrainers, foundation settlement, and cracks at bridge piers.

According to Fig. 5, damage to the expansion joint is the most often damages that occur on the bridges. This type of damage is caused by the movement of the upper

frequency criteria and condition value criteria to get the risk value. Table 2 shows the criteria for the frequency of events at each inspection. These criteria are determined based on the number of bridges examined in the field. If the frequency of events is close to the number of bridges being examined, it can be inferred that the frequency of events is "very often". Whereas, if the frequency of occurrence is around 50% of the number of bridges examined, it can be considered that the frequency of events is "moderate".

Tabel 2 Frequency criteria

Frequency	Frequency criteria	I ndex
Very rare	<= 5 event/inspection	1
Rare	5 - 10 event/inspection	2
Moderate	10 - 15 event/inspection	3
Often	15 - 20 event/inspection	4
Very often	>20 event/inspection	5

The more event number are observed, the more risk are possible to exist. For the determination of the bridge damage criteria, it is conducted based on the bridge inspection guidelines using Condition Value criteria, as shown in Table 3. Damage criteria for bridge elements are determined following bridge inspection guidelines based on the Bridge Management System, as shown in Table 3. For each type of condition value, it is necessary to determine the follow-up action required. For example, bridges with minor damage, then countermeasures are possible by performing routine maintenance. For bridges with heavy damage, major repairs or bridge strengthening should be undertaken if necessary. After the occurrence frequency and condition value are obtained, the risk level of bridge damage can be determined by multiplying the frequency with the condition value. A risk matrix is then generated for each type of damage that occurs in the bridge elements, as shown in Table 4. The corresponding risk criteria are shown in Table 5. According to the risk matrix, the bridge with a vulnerability rating of less than 3 is considered to have negligible attention. On the contrary, the bridge with a vulnerability rating of more than 20 need to be seriously assessed for seismic performance. structure due to the earthquake, causing damage such as cracks, differential settlement, and gap opening. The effect of damage to the bridge is relatively negligible because the joint expansion act as a complementary element to accommodate bridge deformation and not act as the load-carrying capacity element.

The second frequent damages are the settlement of embankment, which occurs due to the process of soil compaction during an earthquake event. It can also occurred due to the presence of cracking or breaking in the retaining walls. The event probability of embankment settlement is relatively high, and the effect of damage to the embankment on the bridge structure is quite significant.

Table 3. Damage criteria and countermeasure [1]

Condition value (NK)	Remarks	Index	Countermeasure
NK1	Lightly damage	1	Routine Maintenance and Monitoring
NK2	Medium damage	2	Minor Rehabilitation
NK3	Heavy damage	3	Major Rehabilitation/Strengthening
NK4	Critical	4	Bridge Element Replacement
NK5	Collapse	5	Reconstruction

Table 4. Risk matrix

Damage		Index	Condition value				
			N K1	N K2	N K3	N K4	N K5
Frequency	Very rare	1	1	2	3	4	5
	Rare	2	2	4	6	8	10
	Moderate	3	3	6	9	12	15
	Often	4	4	8	12	16	20
	Very often	5	5	10	15	20	25

risk = frequency x condition value

Table 5. Risk criteria

Risk	Vulnerability rating
Low	< 3
Moderate	3 - 9
High	9 - 20
Very high	>20

The earth retaining wall elements that are prone to have damages are those made from masonry or brick elements. The bond strength between the stone or brick are not strong enough to withstand the seismic load. Also, there is a significant movement of soil around the retaining wall, which causes excessive force, which is also one of the causes of damage to the retaining walls.

The superstructures of floor elements, girder, frame, and placement is one of the main structural components of the bridge. These elements can experience movement due to earthquake, especially bridge support. The central issues are to limit the seismic energy entering the structure from the ground in the first place and then to dissipate as much of it as possible by damping devices. The seismic damage impact can be reduced by using a

particular device to absorb seismic forces. By decoupling the structure from seismic ground motions, it is possible to minimize the earthquake-induced forces in it, that can be done in two ways. Firstly, increase the natural period of the structure by base isolation and, secondly, increase the damping of the system by energy-dissipating device as proposed by Tandon [9].

Fig. 6 shows the results of the risk analysis of damaged bridges in Palu and Lombok. It is concluded that the settlement of embankment in the approach road is found to be the most potential element with the highest risk of damage due to earthquakes. In addition, the excessive superstructure displacement and crack in the retaining walls are at moderate risk.

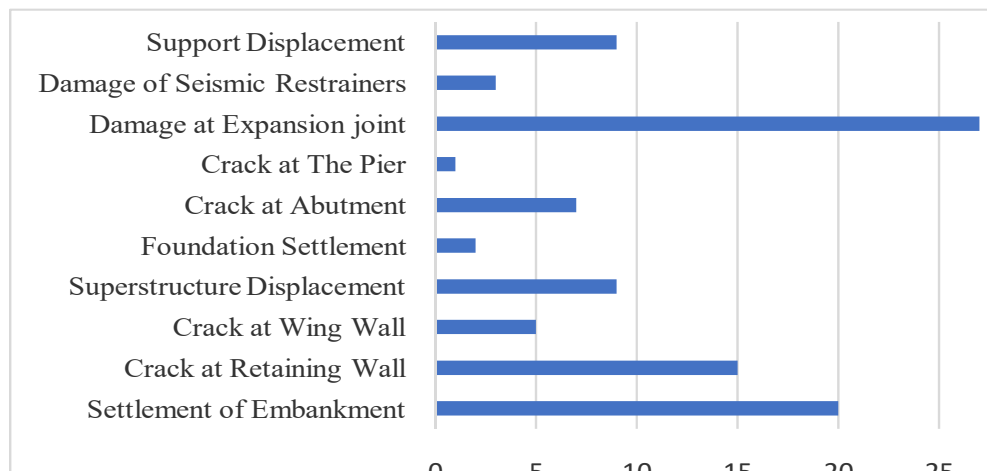


Fig. 5. Statistics of bridge element damage observed after Lombok and Palu earthquake [7,8]

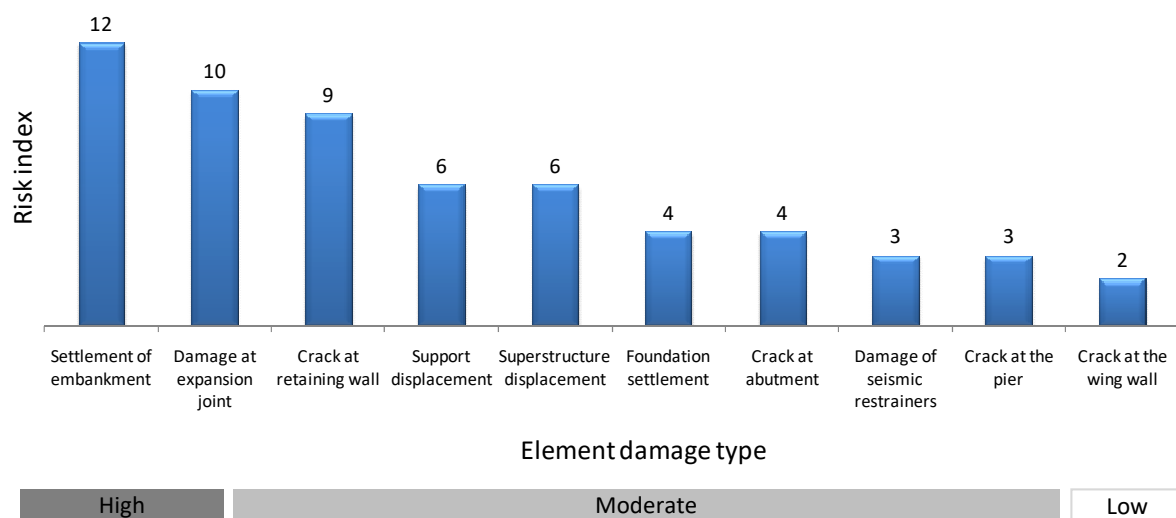


Fig. 6. Risk distribution after Lombok and Palu earthquake

5 Conclusion

Based on the results of the risk analysis, the type of damage of bridge element with the highest risk to earthquake events is the settlement of embankment. While the lowest risk value is the damage of the wing wall. In addition, the excessive superstructure displacement and crack in the retaining walls are at moderate risk. This finding makes the substructure become the most vulnerable element that need more attention. Therefore, it is recommended to specify a higher design specification for sub-structure, particularly in high seismic zone areas like Lombok and Palu.

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