Inspection and evaluation of bridge structures for earthquakes risk

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Abstract. The 2017 Earthquake Source and Hazard Map Update in 2017 showed a significant change to the previous earthquake map. An increase in the number of active faults and high magnitude earthquake events indicates an increased potential for earthquake risk. The availability of qualified seismic manual is a must to support the direction of government policy in the provision of infrastructure, especially roads and bridges in a sustainable manner. This study aims to determine the value of the vulnerability of existing bridges against earthquakes and alternative reinforcement that can be done. The reinforcement philosophy is based on performance, similar to the philosophy used in the design of new bridges. Performance criteria are examined using earthquakes with a probability of exceeding 7% in 75 years. Performance criteria are determined based on the level of importance and remaining life of the bridge service. An example of a case study was made by examining and evaluating a prestressed girder bridge located in the earthquake zone 4 of the Jakarta area. Analysis and evaluation of bridge capacity is made using the SAP 2000 program. The 3 (three) dimension model is used to calculate the effect of 3 (three) structural dimensions on the dynamic behavior of the bridge. Earthquake input is made in the form of spectra response according to SNI 2833-2016. For earthquake loading in the X and Y direction the g/R scale factor is used (9.81/5), which is 1.96. The basic shear capacity of the column is calculated according to SNI 2833-2016 which consists of the shear capacity of the contribution of the concrete section and reinforcement. Based on the analysis, it was obtained that the column sliding capacity was 1333.3 kN. The value of the capacity is greater than the ultimate shear load of 519.07 kN so it can be concluded that the sliding capacity of the column still meets the earthquake load so that no structural reinforcement is needed.

1. Introduction

1.1. Background

Earthquakes are natural phenomena that are vulnerable to occur in Indonesia. This is due to Indonesia being in the meeting of 3 (three) active tectonic plates (Eurasia, Australia, and Pacific). In addition, Indonesia is also on the path of the world's active volcano (Ring of fire). The earthquake occurred during the last 5 (five) years and caused significant damage. An earthquake of magnitude (Mw = 6.5) occurred in Maluku in 2019, a year after the earthquake accompanied by tsunamis that hit the cities of Palu (Mw = 7.4) and Lombok with Mw ranging from 6.0 to 7.0 [5]. Figure 1 shows the intensity of earthquake events in Indonesia until 2016.
The impact of damage caused by the earthquake on road and bridge infrastructure including cracking on expansion joints, bearing shifts, reduction in bridge oprit, sliding cracks on abutments, until the bridge collapses. To avoid sudden collapse of the bridge, periodic checks are needed to determine the value of the existing capacity. The strength of the existing bridge structure needs to be evaluated based on the strength of the earthquake that occurred with a magnitude scale greater than in previous years. After the release of the latest 2017 Earthquake Map, it is necessary to analyze and evaluate the strength of the existing bridges on the earthquake map. This study aims to determine the size of the existing bridge capacity by referring to the 2017 Earthquake Map. If the evaluation results show that the bridge capacity is smaller than the earthquake load, retrofitting, strengthening, or even replacing a new bridge needs to be done.

Bridge structures must be designed to be earthquake resistant, with an emphasis on aspects of good structural ductility and the ability to participate in good energy, so that structures are earthquake resistant. The design of the bridge structure for earthquake loads refers to SNI 2833: 2016 (Perencanaan Jembatan terhadap Beban Gempa). Existing bridges built in the decade of the 80s need to be evaluated against the latest earthquake loads. Based on SNI 2833: 2016, the bridge structure is planned with a minimum design life of 75 years and the earthquake force probability is exceeded by 7%, so that the bridge structure is planned to be able to bear the earthquake force with a 1000 year return period. In checking and evaluating existing bridges for earthquake loads, a number of things need to be considered are carrying out an inspection process to identify earthquake hazard risks using structural vulnerability and earthquake hazard data, evaluating bridge capacity for earthquake loads, and selecting appropriate reinforcement techniques to increase bridge resistance to earthquake risk.

2. Methodology
The method of checking and evaluating the existing bridge structure for earthquake loads is shown in figure 2.
3. Results and discussion

In this research a case study of the inspection and evaluation of bridge structures in the Jakarta area was made. A bridge consists of 3 (three) spans (13.33 m + 26.82 m + 13.33 m) and has a total width of 15 m. The bridge was built in 1989 and has a type of prestressed concrete girders and with soil classification including soft soil. Bridges are included in other categories of bridge importance. The bridge is supported by 3 columns of 1.2 m diameter in each pillar. The length of the existing placement in the pedestal area is 300 mm. Sketch of the elongated and transverse bridge can be seen in figure 3.

Figure 2. Flowchart for checking and evaluating the structure of existing bridges against earthquake loads
Figure 3. Longitudinal section of bridge

Figure 4. Cross section of bridge
Bridge material data based on figure 3 and figure 4 are shown in table 1.

| Table 1. Bridge material                                      |
|---------------------------------------------------------------|
| Concrete element:                                             |
| Strength (MPa) | Modulus of Elasticity (MPa) | Poisson ratio |
| Girder I        | 60                          | 36000         | 0.2          |
| Head beam       | 30                          | 25000         | 0.2          |
| Column          | 30                          | 25000         | 0.2          |
| Reinforcement element:                                       |
| Strength of yield (MPa)                                       |
| Main bar         | 420                         | 525           | 14 (d < 19 mm)|
| Shear bar        | 420                         | 525           | 12 (22 < d < 36 mm)|

**Determination of seismic strength category [1]:**
The service life of the bridge is 29 years. The assumed service life is 75 years, so the remaining service life (SUL) = 46. Service life categories are between (16-50) years (SUL 2). The level of performance against earthquakes is included in the TK1 performance level. Based on the 2017 Indonesia Earthquake Map (Pusgen) and SNI 2833: 2016, the level of earthquake hazard for the Jakarta area with soft soil is as follows:

\[
P_{GA_{(g)}} = 0.28 \\
A_{S_{(g)}} = P_{GA_{(g)}} \times F_{PGA} = 0.28 \times 1.3 = 0.364 \\
S_{D_{S_{(g)}}} = S_s \times F_a = 0.55 \times 1.6 = 0.88 \\
S_{D_{I_{(g)}}} = S_i \times F_v = 0.23 \times 3.1 = 0.713
\]

In accordance with SNI 2833: 2016, with SD1 = 0.713, the earthquake hazard level is included in the earthquake zone 4. For earthquake zone 4 and TK1 performance level, the retrofitting category is included in KPS C (in vulnerability assessment all components must be checked).

**Structural joint and bearing [3]**
The upper structure is not continuous on the expansion joint, so the bridge is considered not to have good bearing details. The position of continuous bearing in the transverse direction of the bridge is considered not to provide significant damage to the transverse direction of movement of the bridge VT = 5. The minimum length of placement in the longitudinal direction is as follows:

\[
L = 13.33 + \left( \frac{26.82}{2} \right) = 26.74
\]

\[
H = 5 \text{ m} \quad \text{B} = 15 \text{ m} \quad S1 = 0.23 \quad fV = 3.1 \quad (\text{soft soil})
\]

SD1 = 0.71 (earthquake zone 4 based on SNI 2833: 2016)
\[
\alpha = 0^\circ \quad (\text{no skew}).
\]

Minimum length requirements:

\[
N = \left[ 0.2 + 0.0017L + 0.0067H \right] + 0.000125S^2
\]

\[
N = \left[ 0.2 + 0.0017 \times 26.74 \right] + 0.00067(5) + 0.000125(0)^2 = 0.279
\]

For earthquake zone 4, the value of N is modified by increasing the percentage of N by 150%, so the value of N becomes N (d) = 1.5 (0.279) = 0.419.
Therefore \( \frac{N_{(c)}}{N_{(d)}} = \frac{300}{419} = 0.72 \) Therefore \( 0.5 < \frac{N_{(c)}}{N_{(d)}} < 1 \)

Then the value of susceptibility to bearing in the longitudinal direction (VL) is equal to 5. Vulnerability of structure and placement connection (V1).

\[ V1 = \max. \ (VT, VL) = \max. \ (5, 5) = 5 \]

Determine the value of Q in the shortest and heaviest column (column pillar 2) as follows:

\[
Q = 13 - 6 \left( \frac{L_c}{P_3 Fb_{max}} \right) = 13 - 6 \left( \frac{4}{4200} \right) = 10.5
\]

The slope of the skew is less than 20°, the maximum reduction is 2 so the CVR column vulnerability value = 10.5-2 = 8.5 \( \approx \) 9. While the value of vulnerability in the abutment (AVR) is 0. Soil conditions from solid to sandy, unsaturated, very dense and gravel. Therefore, soil has a low susceptibility to liquefaction so that the susceptibility to liquefaction (LVR) is 0. The vulnerabilities of other elements of \( V_2 \) are as follows:

\[ V_2 = CVR + AVR + LVR = 9 + 0 + 0 = 9 \]

The overall vulnerability value is the maximum value between \( V_1 \) and \( V_2 \). \( V_e = \max. \ (V_1, V_2) = \max. \ (5, 9) = 9 \).

Earthquake hazard assessment is determined using earthquake coefficients in a 1 second period \( (S_{D1}) \) so that \( E = 10 S_{D1} = 10(0.71) = 7.1 \). Bridge vulnerability rating \( (R_V = V_c \times E = 9 \times 7.1 = 63.9) \). Based on the vulnerability rating value where 30 <\( R_v < 70 \), then the bridge is included in the medium vulnerability class. The next step is to inspect the bridge capacity quantitatively against earthquake loading. The bridge is then further evaluated for inspection of element capacity and identification of structural deficiencies and their maintenance [2]

Figure 5 shows the 3-dimensional model of the bridge according to the bridge description in figure 3 and figure 4. Beam components, head beams, diaphragms, and columns are modeled with frame elements, then slab are modeled with shell elements. Pile foundations are not modeled specifically because it is assumed that the foundation behaves elastic in an earthquake. In the bridge model, a rigid link is used to connect the upper structure and head beam with different elevations.

Figure 5 3D model of the bridge
The next step is defining the cross section of the girder and column elements. Figure 6 shows the girder cross-section input while figure 7 shows the column cross-section input. Then proceed with the definition of the slab elements as in figure 8.
Figure 8. Defining slab in columns

The shell element was chosen because it was assumed that against earthquake loading, the floor could behave like a plate or membrane simultaneously. Plates have a ratio of thickness to width equal to 0.1 so it is considered a thin shell (thin shell).

Earthquake loading
Earthquake input is made in the form of spectra response in accordance with SNI 2833: 2016. The spectral response coordinate points can be inputted in the definition of the spectral response function as shown in figure 9.

Figure 9. Spectra response of the Jakarta region - soft soil
Based on figure 9, the Jakarta area is a region with a high level of vulnerability to earthquakes, therefore the bridge structure in this region must be designed to withstand earthquakes, with emphasis on aspects of good structural ductility and ability to participate in good energy, so that the structure is able to withstand Jakarta's characteristic earthquake [6].

Figure 10. Definition of X-direction response spectrum

Figure 11. Definition of Y-direction response spectrum

For earthquake loading in the X (Spec-X) and Y (Spec-Y) directions, a scale factor of $g/R$ is used where $g$ is gravity and $R$ is the response modification factor. For compound columns on other bridges
the value of \( R \) is taken equal to 5 according to SNI 2833: 2016[5], so the scale factor is used \( \frac{9.81}{5} = 1.96 \).

The combination of earthquake loading includes:

1. Combination 1 = DL + EQx
2. Combination 2 = DL + EQy
3. Combination 3 = DL + EQx + 0.3EQy

The analysis tool discussed in this paper can provide practising engineers and researchers with the ability to assess detailed behavioural response of structural elements subjected to unforeseen loading conditions such as earthquake. It could also be a useful tool in the assessment of structural elements with unusual detailing, particularly if constructed in seismic prone area.

Check column capacity

Column capacity is checked with the help of column interaction diagrams. In this example, a response is taken in the second column of the first pillar (K2P1). Based on structural analysis, the internal forces are obtained as shown in Table 2.

| Load     | \( M_{13} \) (kNm) | \( M_{22} \) (kNm) | \( V_{33} \) (kN) | \( V_{22} \) (kN) | \( P \) (kN) |
|----------|-------------------|-------------------|-------------------|-------------------|-------------|
| DL       | 463.19            | 0.00              | 0.00              | 233.80            | 1709.00     |
| Eqx      | 879.75            | 0.00              | 0.00              | 285.27            | 0.73        |
| Eqy      | 0.00              | 788.80            | 302.31            | 0.00              | 0.00        |
| Comb-1   | 1342.94           | 0.00              | 0.00              | 519.07            | 1709.73     |
| Comb-2   | 463.19            | 788.80            | 302.31            | 233.80            | 1709.00     |
| Comb-3   | 1342.94           | 236.64            | 90.70             | 519.07            | 1709.73     |
| Comb-4   | 727.12            | 788.80            | 302.31            | 319.38            | 1709.21     |

Based on Figure 12, it can be seen that the internal forces in the column due to earthquake are still within the column capacity area, so that the column meets the capacity against earthquake loading.

Column shear capacity can be calculated in accordance with SNI 2833: 2016 which consists of 2 (two) components, namely the shear capacity of contributions from the cross section of concrete \( V_c \) and shear contributions from reinforcement \( V_s \).
Shear capacity of the concrete column section

\[ V_c = 0.083 \beta f_c' b_d f_v \]  

(1)

with \( b_v \) is the dimension of the column, \( d_v \) is the effective shear depth.

\[ V_c = 0.083(2) 30(1200)(0.75*1200) \]

\[ V_c = 981957 \text{ N} \]

Therefore \( P_u < 0.1A_g f_c' \) then

\[ V_c = \frac{P_u}{0.1A_g f_c'} \]

\[ V_c = \left\{ \frac{1709000}{0.1(1130400)} \right\} = 494858 \text{ N} \]  

(2)

Shear capacity of shear reinforcement

\[ V_s = \frac{\pi}{2} \left[ \frac{nA_{sp} f_y D}{s} \right] \]

(3)

with \( A_{sp} \) is the area of shear reinforcement, \( f_y \) is the yield shear reinforcement, \( D \) is the diameter of the concrete core, and \( s \) is the shear reinforcement.

\[ V_s = \frac{\pi}{2} \left[ \frac{2(132.66)(420)(1200 - 2(50))}{150} \right] = 1282981 \text{ N} \]

\[ \phi V_u = \phi (V_c + V_s) = 0.75(1777839) = 1333379 \text{ N} = 1333.3 \text{ kN} > V_u = 519.07 \text{ kN} \]

So it can be concluded that the column sliding capacity meets the earthquake loading.

4. Conclusion

Based on the results of the structural evaluation it can be concluded that the column capacity still meets the requirements for earthquake loading so that no structural retrofitting is needed. To prevent sudden collapse of existing bridges against earthquake loads, periodic bridge inventory and inspection efforts should be undertaken. From the results of the inspection, if the capacity of the existing bridge is smaller or equal to the earthquake load, it is necessary to take retrofitting or strengthening the bridge.

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