Seismic fragility of concrete box girder bridges in Malaysia

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Abstract. In Malaysia, the majority of structures and infrastructures have not been designed for seismic actions. Recent earthquakes in the country, however, has raised the attention of authorities toward the seismic vulnerability of these structures. Bridges are among the crucial infrastructures that their functionality during ground motions is of great importance. In this study, three bridges with different pier heights of 10 m, 20 m, and 30 m were selected and their nonlinear response was determined through pushover and incremental dynamic analysis. By using 15 far-field earthquake records the seismic fragility curves of the bridges were derived. Peak ground acceleration was considered as the ground motion intensity measure and the drift ratio was selected as the engineering demand parameter. The obtained fragility curves revealed different patterns for the probability of exceeding light to severe damage for the studied bridges. While the difference between the probabilities of exceeding light and severe damage in the shortest bridge was significant, in the tallest bridge it was negligible. The bridge with the pier height of 20 m had the largest probability of exceeding light and severe damage when compared to other bridges. The tallest bridge, on the other hand, showed the lowest seismic vulnerability when compared with other bridges. Comparison between Malaysia national annex to Eurocode 8 and the obtained fragility curves revealed that for the estimated PGA in Kuala Lumpur, all studied bridges could remain functional.

1. Introduction
Seismic performance of bridges can be affected by various uncertain parameters, therefore, a probabilistic assessment approach is required to address their vulnerability against seismic actions [1]. Seismic fragility curves have been widely employed as an efficient tool for probabilistic seismic risk assessment of structures [2]. Fragility curves can be obtained by empirical, analytical and hybrid methods[3]. However, a review of literature shows that the analytically obtained fragility curves have been frequently used for the seismic vulnerability assessment of bridges and other type of structures[4-12]. The fragility curves enable national authorities to prepare retrofitting scheme, seismic risk map and emergency measures. It is worth noting that experience from past earthquakes have shown that many bridges have suffered substantial damages during ground motions[13,14]. It should be also mentioned that seismic induce damage to bridges can impede emergency response operations during earthquakes. Moreover, the repair cost of damaged bridges are often high and time consuming.
Most of the bridges constructed in Malaysia have not been designed for seismic actions because seismic design has not been compulsory in the country and no local seismic code has been established for seismic design of structures. During past decades, seismic activity in Malaysia has been considered to be very low mostly because of being far from strong active faults and the lack of historical data that shows seismic damage to structures. However, in 2015, an earthquake with the magnitude of 6.0 hit Ranau in Sabah and imposed significant damage to the structures. The Ranau earthquake raised the attention of authorities toward the vulnerability of existing structures and infrastructures. However, seismic vulnerability studies on buildings and bridges are limited in Malaysia and existing studies have mostly concentrated on buildings[15].

In this study, three concrete box girder bridges were selected from the current practice in Malaysia for the seismic vulnerability study. These three bridges have different pier heights of 10 m, 20 m, and 30 m but they share a similar concert deck. The finite element models of the concrete box girder bridges were established using CSI Bridge software [16]. Pushover analysis which has been widely used for seismic assessment of structures [17,18] was employed to estimate the drift capacities of the bridges. For the development of seismic fragility curves, incremental dynamic analysis (IDA) was applied on 15 far-field earthquake records. Three structural performance levels of immediate occupancy (IO), life safety (LS), and collapse prevention (CP) recommended by FEMA 356 [19] were employed as the limit states in the development of fragility curves.

2. Selected structures
The selected bridges in this study are similar to those used in the line 2 of the Mass Rapid Transit (MRT) project in Kuala Lumpur, Malaysia. Figure 1 shows a sample of the 3D finite element model of bridges which is established in CSI Bridge software[16]. All simulated bridges have five similar spans with the length of 39.8 m. As it is shown in figure 2, the width of the bridge deck in all investigated bridges is 9.8 m and its thickness is 0.24 m. The deck of bridges is not continuous and sits on two rubber bearings at both ends of each span. The deck is post-tensioned by 16 tendons each of which having the jacking force of 4082 kN. The yield stress, ultimate stress, and the modulus of elasticity of tendons are 169 MPa, 186 MPa, and 196 MPa, respectively. The yield and ultimate stress of reinforcing bars in piers and the bridge deck are 485 MPa and 600 MPa, respectively. The compressive strength of concrete for all of the structural element in the bridges is 40 MPa. As it is shown in figure 3 the cross section of piers is tapered along their height such that the bottom and upper parts are larger than the middle part. In the finite element models, piers are divide into six sections along their height. Table 1 shows the size of cross section and reinforcing bars of each section for the pier with the total height of 30 m. In all piers a reinforcement ratio of 2.5% was considered. The effective stiffness of structural elements were calculated based on the recommendation of ASCE 41-13 [20]as shown in Table 2. It should be mentioned that, in the nonlinear analysis, in order to consider the inelastic behavior of piers the lumped plasticity model that has been widely used by other researchers [21,22]is adopted. Plastic hinges are assigned to the both end of each section of piers. The modeling parameters of plastic hinges and their corresponding acceptance criteria are determined based on the recommendation of ASCE 41-13 [20]. The deck of the bridge was simulated using shell elements. The deck was meshed using the auto mesh option of the software. The deck to pier connection was simulated using link elements suggested by the software. The piers connection to the ground was assumed to be fixed. In order to validate finite element models the fundamental natural frequencies of the simulated bridges were compared with those obtained from analytical calculations. As can be seen from table 3 the obtained values from both methods are close to each other indicating a good agreement between the finite element models and analytical results.
Figure 1. Finite element model of a concrete box girder bridge.

Figure 2. Cross section of the bridges’ deck (all dimension in mm).

Figure 3. Pier with six sections and the height of 30 m simulated in the software.
### Table 1. Dimension and reinforcing bars inside the 30 m height pier.

| Section | Length (mm) | Width (mm) | No. of 50 mm bar in 3-dir. | No. of 50 mm bar in 2-dir. |
|---------|-------------|------------|----------------------------|---------------------------|
| Section 1 | 2800        | 3000       | 26                         | 28                        |
| Section 2 | 2640        | 2840       | 23                         | 25                        |
| Section 3 | 2480        | 2680       | 21                         | 22                        |
| Section 4 | 2320        | 2520       | 18                         | 20                        |
| Section 5 | 2160        | 2360       | 16                         | 17                        |
| Section 6 | 2000        | 2200       | 14                         | 15                        |

### Table 2. Effective stiffness considered for the bridges.

| Component | Flexural rigidity | Shear rigidity |
|-----------|-------------------|----------------|
| Column with compression caused by design gravity load \( \leq 0.5A_g f'_c \) | \( 0.3E_c I_g \) | \( 0.4E_c A_w \) |
| Deck (pre-stressed) | \( E_c I_g \) | \( 0.4E_c A_w \) |

### Table 3. Comparison of natural frequency.

| Pier height | Pier height 10 m | Pier height 20 m | Pier height 30 m |
|-------------|------------------|------------------|------------------|
| Direction   | Analytical | CSI Bridge | Analytical | CSI Bridge | Analytical | CSI Bridge |
| Longitudinal | 0.30 sec | 0.39 sec | 0.90 sec | 1.01 sec | 1.70 sec | 1.80 sec |
| Transverse  | 0.28 sec | 0.44 sec | 0.83 sec | 0.94 sec | 1.54 sec | 1.57 sec |

### 3. Derivation of fragility curves

The probability of exceeding the damage state (i.e. IO, LS and CP) was calculated by using equation (1)[23]:

\[
P(DS/\text{SI})=1-\Phi\left(\frac{\lambda_c-\lambda_{D/\text{SI}}}{\sqrt{\beta_{D/\text{SI}}^2+\beta_C^2+\beta_{\mu}^2}}\right)
\]

where, \( S_E^2 \) is the standard error of demand drift; \( DS \) is damage state; \( SI \) is seismic intensity; \( \Phi \) is standard normal distribution; \( \lambda_{D/\text{SI}} \) is natural logarithm of the median demand drift given the seismic intensity from the best fit power law; \( \lambda_c \) is natural logarithm of the median of drift capacities for particular damage state; \( \beta_C \) and \( \beta_{\mu} \) are uncertainties related to capacity and modelling, respectively.

The uncertainties of capacities were calculated from the results of Incremental Dynamic Analysis (IDA) and that of the modelling was taken as 0.3[23]. The drift capacities of bridges were calculated...
by using both the pushover analysis and IDA. However, for the calculation of fragility curves conservative values were selected for the drift capacities by comparing the results of pushover analysis and IDA. Table 4 shows the employed drift capacities for the derivation of fragility curves. It is evident from this table that the drift capacities related to the LS and CP performance levels of the bridge with the 30 m height pier are close to each other. This indicates a limited reserved displacement ductility in the bridge. It can also be seen that the taller piers have larger drift capacities when compared with the shorter piers. In this study, the drift ratio was selected as the engineering demand parameter and Peak Ground Acceleration (PGA) was considered as the seismic intensity measure. The fragility curves were derived for PGAs varying from 0.1g to 0.5g as shown in figure 4, figure 5, and figure 6 for 10 m, 20 m, and 30 m height piers, respectively. Figure 4 shows that the probability of a light damage (i.e. IO) to the bridge with the 10 m height pier is significantly larger than severe damage (CP). It can also be seen that the probability of exceeding a moderate damage (LS) is close to the probability of exceeding a severe damage. On the other hand, the bridge with the 20 m height pier shows a significant difference between the probabilities of exceeding a moderate and a severe damage. For this bridge, the probability of exceeding a light damage compared to a moderate damage is not as much as it is for the bridge with the 10 m height pier. Similar to the bridge with the 10 m height pier, increase in the PGA significantly raises the probability of exceeding the light damage. However, unlike the first bridge, increase in the PGAs also significantly raises the probability of moderate and severe damage. This implies that the bridge with the 20 m height pier has a larger chance of collapse during strong earthquakes when compared with the bridge having the 10 m height pier. Figure 6 shows that in the bridge with the 30 m height pier the probability of exceeding light damage is slightly larger than moderate and severe damage indicating a limited reserved ductility in the bridge to sustain large deformations. The probability of exciting light, moderate and severe damage in the bridge with the 30 m height pier is smaller than the other two bridges. This implies that, for an identical intensity of PGA, this bridge will experience less damage when compared with other bridges. The main reason for such observation relies on the fundamental natural period of the bridges and the frequency content of the selected records. In addition, the cross-sectional size of piers in the tallest bridge is larger than the other two bridges.

In accordance to the seismic hazard map given in the Malaysian national annex to Eurocode 8[24], the peak acceleration on the bed rock in Kuala Lumpur is 0.09g. Considering a maximum soil amplification of 1.4, as given in the national annex, the value of PGA is 0.13g for this city. Therefore, as can be seen from figure 4, figure 5, and figure 6, the probability of exceeding light damage for bridges with the 10 m, 20 m, and 30 m height piers are all below 10%. This implies that the studied bridges will remain almost intact when the intensity of PGA is 0.13g. It can also be seen that, for a strong earthquake with the PGA of 0.5g, only the bridge with 20 m height pier is expected to experience a light damage.

**Table 4. Drift Capacities of the studied bridges.**

| Pier height | IO (%) | LS (%) | CP (%) |
|-------------|--------|--------|--------|
| 10 m        | 1.10   | 1.96   | 2.62   |
| 20 m        | 2.22   | 2.82   | 3.38   |
| 30 m        | 2.88   | 3.46   | 3.89   |
Figure 4. Seismic fragility curve of the bridge with the 10 m height pier.

Figure 5. Seismic fragility curve of the bridge with the 20 m height pier.

Figure 6. Seismic fragility curve of the bridge with the 30 m height pier.
4. Conclusions
This study investigated the seismic vulnerability of concrete box girder bridges in Malaysia through the framework of fragility curves. Three bridges with different pier heights of 10 m, 20 m, and 30 m were simulated in the CSI Bridge software. A 2.5% reinforcement ratio was considered for all piers. Nonlinear static and nonlinear incremental dynamic analyses were applied on the simulated bridges. Totally, 15 far-field natural earthquake records which were scaled to the PGAs of 0.1g to 0.5g were employed for the derivation of seismic fragility curves. Results indicated that the bridge with the pier height of 20 m is more vulnerable compared to the other studied bridges. However, for a PGA of 0.13g, which is the estimated peak ground acceleration in Kuala Lumpur, all studied bridges were able to maintain their functionality during low to medium intensity earthquakes.

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