SEISMIC RISK TO ROADS AND BRIDGES IN THE KYRGYZ REPUBLIC, CENTRAL ASIA

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ABSTRACT

The Kyrgyz Republic is located in a highly seismic region subjected to devastating earthquakes that have caused loss of life, destroyed buildings and infrastructure and ruined livelihoods in historical and recent times. In order to better understand the hazard and the risk from earthquakes to critical assets, including transport infrastructure, a national level seismic hazard and risk study was undertaken. Across the Kyrgyz Republic there are around 4,300 km of four-lane primary roads, 43,000 km of two-lane secondary roads and over 1,400 road bridges with an estimated total value of USD 34 billion. The study included a probabilistic seismic hazard assessment for the country as well as twelve (12) representative scenario earthquake events hazard calculations. The mean expected direct economic losses to road transport infrastructure associated with the individual scenario earthquake events was estimated to be in the range of USD 60 million to 1 billion for roads and in the range of USD 2.4 to 22 million for bridges. These findings will allow stakeholders to make informed decisions for upgrades and new investment for transport infrastructure to reduce losses, better plan for emergency response and inform longer term recovery after earthquake disasters.

Keywords: Seismic; Risk; Kyrgyz; Road; Bridge

1. INTRODUCTION

1.1 General

The Kyrgyz Republic is located in a region of high seismic hazard with earthquakes of magnitude Mw≥5 occurring about once per month, and potentially devastating earthquakes of magnitude Mw≥7 occurring with recurrence intervals of several decades. Although earthquakes occur less frequently than other natural hazards such as floods and landslides, they cause the largest proportion of disaster related losses across the country (World Bank, 2008). The country has a population of approximately 6 million people and had a GDP of 6.6 billion USD in 2015 (World Bank, 2016). Due to rapid urbanisation and the developing nature of the economy in the Kyrgyz Republic, there is a strong incentive to invest in a national seismic risk reduction strategy as the most effective way to mitigate the potential impact of disaster related shocks and reduce expected losses. In order to better understand seismic hazard and risk in the country, the World Bank and the Global Facility for Disaster Reduction and Recovery (GFDRR) have commissioned Ove Arup & Partners International Ltd (Arup), Helmholtz Centre Potsdam German Research Centre for Geosciences (GFZ), the Central Asian Institute of Applied Geosciences (CAIAG)
and the Global Earthquake Model Foundation (GEM) to perform the first detailed countrywide quantitative seismic hazard and risk assessment for the Kyrgyz Republic. As part of this study, the seismic risk to transport infrastructure (roads and bridges) from selected earthquake scenario events has been calculated, and is presented in this paper along with related seismic risk management recommendations. The results of the seismic risk to buildings and their occupants in the Kyrgyz Republic is described in a separate paper (Free et al., 2018).

1.2 Earlier Seismic Risk Studies in the Kyrgyz Republic

The Kyrgyz Republic has acknowledged the importance of a comprehensive approach to disaster risk reduction (DRR). In particular, the implementation of the Sendai Framework and the coordination of efforts from several governmental agencies have been listed as strategic goals for the country (UN, 2015). A number of risk projects for the Central Asia region have assessed seismic risk in the Kyrgyz Republic (Bindi et al., 2011; Pittore et al., 2014). However, these studies did not specifically assess the expected damage and losses to transport infrastructure in the country.

2. HAZARD, EXPOSURE AND VULNERABILITY COMPONENTS OF TRANSPORT INFRASTRUCTURE

2.1 Seismic Hazard in the Kyrgyz Republic

In the event of an earthquake, both ground shaking and related ground deformation can cause damage and losses to linear transport infrastructure such as bridges and roads. The computation of ground shaking intensity (in terms of peak ground acceleration (PGA), macroseismic intensity, and spectral ordinates up to a period of 2.0sec.) has been performed as part of a comprehensive seismic hazard assessment for the Kyrgyz Republic (Arup, 2016).

2.1.1 Scenario Earthquake Calculations

The seismic hazard assessment included scenario earthquake calculations for twelve (12) maximum credible scenario earthquake events (selected according to the potential impact on urban centres) (Figure 1) as well as a probabilistic seismic hazard assessment for the entire country. A more detailed discussion of the seismic hazard levels across the country is given in Arup (2016) and Free et al. (2018).
Figure 2 gives an example that shows the distribution of ground shaking (median results) in terms of peak horizontal ground acceleration (PGA) for the Issyk-Ata scenario event near Bishkek, the country’s largest city (population 1 million) (Figure 2). The Issyk Ata Fault is located south of Bishkek and this scenario is associated with a magnitude Mw 7.3 earthquake on the fault.

![Figure 2](image)

Figure 2. Earthquake scenario PGA values (median prediction) for the Issyk Ata Fault using a combination of GMPEs and a USGS Vs30 site soil assumption (Arup, 2016). The red star marks the epicentre.

2.1.2 Permanent Ground Deformations (PGD) as a Result of Seismic Shaking

Damage to roads and bridges is commonly associated with permanent ground deformation (PGD), which is mainly caused by liquefaction, and also by landslides and surface fault ruptures (Pitilakis et al., 2014) (Figure 3). The evaluation of liquefaction-induced PGD is a complex undertaking, and a number of methodologies are available for the assessment of expected this behaviour (Bird et al., 2006). The majority of these methodologies require the input of detailed geotechnical data (e.g. median particle size, fines content) (Kongar et al., 2016). However, it was not possible to retrieve such data at an appropriate resolution for the Kyrgyz Republic, and so alternative methodologies for assessing permanent ground deformations were investigated for this study (as presented in Bird et al, 2006).

![Figure 3](image)

Figure 3. Damage to Kyrgyz roads from surface seismic waves (left) and from seismically-induced rock slides (right) as a result of the Nura earthquake (5 October 2008).
For the present study, the HAZUS models for lateral movement and vertical settlement (FEMA, 2003) were chosen, as they can be applied without the need for geotechnical data. According to the HAZUS methodology, PGD due to lateral spreading can be estimated based on:

- The assignment of a liquefaction susceptibility category (SC);
- The threshold ground acceleration necessary to induce liquefaction for the selected SC;
- The PGA experienced at the site, as determined by probabilistic seismic hazard analysis; and
- A displacement correction factor \( k_\Delta \), as a function of the moment magnitude (Mw) of the event.

The probability of liquefaction was estimated following the procedure set out by Zhu et al. (2015), who proposed empirical functions to predict the liquefaction probability conditional on a specific level of PGA. The functions were developed using logistic regression on data from the earthquakes that occurred in Kobe, Japan, on 17 January 1995 and in Christchurch, New Zealand, on 22 February 2011. The functions were further tested on observations from the 12 January 2010 Haiti earthquake.

A number of limitations are associated with the methodology used in this study:

- PGD predictions estimated using this methodology are due only to the possible effects of liquefaction and shakedown settlement. Other causes of PGD are therefore not considered;
- The selected simplified methodology (HAZUS) has been developed on the basis of empirical data from California and Japan. Given the lack of post-earthquake damage data, it was not possible to assess the applicability of this model to the Kyrgyz Republic;
- Additional input data for the HAZUS model (e.g. groundwater depth, liquefaction susceptibility defining parameters) were only approximately known for the territory of the Kyrgyz Republic; and
- The aforementioned approximations were used under the assumption that they introduce additional uncertainty without biasing the results towards clearly lower or higher estimates.

To account for site response effects, estimates of ground motion amplification are computed as a function of \( V_{S30} \), considering the following alternatives:

- A scenario in which a uniform shear-wave velocity \( V_{S30} = 250 \text{m/s} \) was considered at all asset locations; and
- A non-uniform site amplification based on the estimation of \( V_{S30} \) from topographic data (Wald and Allen, 2007).

### 2.2 Exposure Model for Roads and Bridges

No data on roads or bridges were received from official Kyrgyz sources as input to this study. Therefore, open source data was used. The exposure models for roads were derived from the OpenStreetMap database of primary and secondary roads in the Kyrgyz Republic and validated with high resolution remote-sensing imagery provided by Bing and Google Maps. Figure 4 presents the spatial distribution of primary and secondary roads in the Kyrgyz Republic. The replacement value of the road network was developed on the basis of replacement costs (USD/m²) that were available from local construction cost data sources, and assuming a total width of 7.0m for the secondary roads and 12.0m for the primary roads. Across the Kyrgyz Republic there are around 4,300 km of four-lane primary roads and around 43,000 km of two-lane secondary roads. The total value of secondary roads is estimated to be 30 billion USD, while the primary roads amount to a value of approximately 3.3 billion USD.

Bridge properties and locations were extracted from OpenStreetMap. In addition, a small number of bridge visual inspections were performed, where the structural characteristics of the bridges were recorded. Figure 5 presents examples of the inspected bridges. A total of around 1,400 bridges were extracted from OpenStreetMap, and assigned the relevant typologies using broad categories (concrete, steel or other). Bridges were classified according to their replacement value (in USD), which was obtained from international construction cost data sources for bridges of this type and scale (on average, 40m span). The total value of the bridge portfolio is approximately 500 million USD.
Figure 4. Primary and secondary roads in the Kyrgyz Republic (the inset shows the region around Bishkek).

2.3 Fragility and Vulnerability of Roads and Bridges

Simple typology descriptions were defined specifically for each road and bridge typology. Damage states and fragility functions for the road and bridge typologies were obtained from the SYNER-G project (JRC, 2013) and combined into the final fragility model.

2.3.1 Fragility and Vulnerability of Roads

Fragility functions for roads are defined for minor, moderate and extensive/complete damage states, as presented in Table 1 and Figure 6. The damage-to-loss ratios (ratio between attained loss for a specific damage state and total value of the road segment) proposed by FEMA (2003) (Table 2) were combined with the corresponding fragility curves (shown in Figure 6), resulting in the vulnerability model illustrated in Figure 7.

Table 1. Lognormal parameters for fragility functions for roads in terms of PGD (JRC, 2013).

<table>
<thead>
<tr>
<th>Typology</th>
<th>Damage state</th>
<th>μ (m)</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 traffic lanes (secondary roads)</td>
<td>Minor</td>
<td>0.15</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>0.30</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>Extensive/complete</td>
<td>0.60</td>
<td>0.70</td>
</tr>
<tr>
<td>≥ 4 traffic lanes (primary roads)</td>
<td>Minor</td>
<td>0.30</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>0.60</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>Extensive/complete</td>
<td>1.50</td>
<td>0.70</td>
</tr>
</tbody>
</table>
Figure 5. Examples of Kyrgyz bridges that were inspected in May 2015.

Figure 6. Fragility functions for primary and secondary roads for minor, moderate and complete damage.

Table 2. Damage-to-loss model proposed by FEMA (2003) for roads.

<table>
<thead>
<tr>
<th>Typology</th>
<th>Damage state</th>
<th>Damage Ratio*</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 traffic lanes (secondary roads)</td>
<td>Minor</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Extensive/complete</td>
<td>0.70</td>
</tr>
<tr>
<td>≥ 4 traffic lanes (primary roads)</td>
<td>Minor</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Extensive/complete</td>
<td>0.70</td>
</tr>
</tbody>
</table>

* Ratio between attained loss for a specific damage state and the total value of the affected road segment.
Figure 7. Vulnerability functions for primary and secondary roads.

2.3.2 Fragility and Vulnerability of Bridges

Bridge vulnerability is dependent on construction material, complexity of the structure, the interaction with the bridge abutments, and the local ground conditions. In this study, fragility functions for road bridges were defined for three bridge types: concrete, steel and “other”. Damage thresholds were defined by two damage states: (i) minor damage (or yielding) and (ii) extensive/complete damage. The fragility functions developed as part of the SYNER-G project (JRC, 2013) were harmonised in terms of intensity measure, damage state definition and bridge properties. In the case of concrete bridges, fragility curves were computed as a weighted combination of curves defined for each of different combinations of two sets of attributes: isolated/non-isolated and irregular/regular. Fragility functions for steel road bridges were obtained through a similar approach, whereby curves proposed for multi-span simply-supported, multi-span continuous, and continuous steel bridges were combined. In the case of “other” bridges, fragility functions reflect the weighted combination of the concrete and steel fragility curves, in accordance with the proportion of steel or concrete bridges in the exposure dataset.

Table 3 and Figure 8 present the bridge fragility model, and Figure 9 illustrates the vulnerability curves computed for the different bridge typologies, based on the damage-to-loss model proposed by FEMA (2003) (Table 4).

<table>
<thead>
<tr>
<th>Typology</th>
<th>Damage State</th>
<th>$\mu$ (g)</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>Minor</td>
<td>0.19</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>Complete</td>
<td>0.96</td>
<td>0.54</td>
</tr>
<tr>
<td>Steel</td>
<td>Minor</td>
<td>0.23</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>Complete</td>
<td>0.76</td>
<td>0.46</td>
</tr>
<tr>
<td>Other</td>
<td>Minor</td>
<td>0.21</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>Complete</td>
<td>0.88</td>
<td>0.52</td>
</tr>
</tbody>
</table>
Table 4. Damage-to-loss model proposed by FEMA (2003) for bridges (“n” is the number of spans. If n≤2, a damage ratio of 1.00 was applied).

<table>
<thead>
<tr>
<th>Bridge type</th>
<th>Damage state</th>
<th>Damage Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel, concrete or “other”</td>
<td>Minor damage</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Extensive/complete</td>
<td>2/n</td>
</tr>
</tbody>
</table>

3. SCENARIO EARTHQUAKES RISK RESULTS

This section presents a summary of the range of scenario earthquake-based risk results in terms of economic losses estimated for transport infrastructure for all scenarios. Economic losses are presented in absolute values and as percent of GDP. The mean results are presented for assumed site conditions of $V_{S30} = 250$ m/s (soft soil) and for the USGS $V_{S30}$ values. The losses reported correspond to the mean plus/minus one standard deviation.

3.1 Scenario Earthquake Risk Results for Roads and Bridges

Figure 10 and Figure 11 provide a summary of the expected losses to transport infrastructure (bridges and roads respectively) when subjected to scenario earthquake ground shaking. The mean expected economic losses for the range of earthquake scenarios are in the order of 2.3 to 22 million USD for bridges and 60 million to 1.0 billion for roads but could be up to three times higher than these mean values when accounting for the associated standard deviation. These results indicate that the level of
damage to many roads and bridges in the event of these selected scenario earthquakes could seriously hamper emergency response and longer term economic recovery.

Figure 10. Summary of mean economic losses for bridges across the Kyrgyz Republic. Error bars represent the mean plus and minus one standard deviation.

Figure 11. Summary of mean economic losses for roads across the Kyrgyz Republic. Error bars represent the mean plus and minus one standard deviation.

3.2 Example Scenario Earthquake Risk Results: Issyk Ata Fault Scenario

This section presents the risk results for the Issyk Ata Fault scenario earthquake (refer to Section 2.1 for a description of this scenario). Figure 12 presents the spatial distribution of mean loss ratios for roads and bridges, while Figure 13 presents the mean losses for roads and bridges aggregated by district. Note
the very high bridge loss ratios and road loss ratios in the area of the scenario earthquake (an area of about 200km x 125km).

Figure 12. Issyk Ata Fault scenario. Spatial distribution of mean loss ratios (ratio between attained loss and total value of the road or bridge segment), considering a non-uniform V_{S30} distribution obtained from USGS.

Figure 13. Issyk Ata Fault scenario. Spatial distribution of mean absolute losses (USD) per district, considering a non-uniform V_{S30} distribution obtained from USGS.

4. RISK MANAGEMENT STRATEGY FOR ROADS AND BRIDGES

The seismic hazard and risk study for the country informed an overall seismic risk reduction strategy. This strategy included recommendations tailored by sector, asset category and key stakeholders and was framed according to the Sendai Framework (UN, 2015). Selected risk reduction recommendations for transport infrastructure (roads and bridges) as presented in Table 5 include:
### Table 5 Risk Reduction Recommendations for Roads and Bridges in the Kyrgyz Republic

<table>
<thead>
<tr>
<th>Risk Reduction Recommendations</th>
<th>Key Stakeholders</th>
<th>Timeframe</th>
<th>Sendai Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use the results of this study to inform emergency response planning and initial prioritization of critical bridges for assessment and upgrading.</td>
<td>Ministry of Transport (MoT), Ministry of Emergency Services (MoES), National Government</td>
<td>3 to 6 months</td>
<td>3, 4</td>
</tr>
<tr>
<td>Establish a countrywide database of roads and bridges.</td>
<td>MoT, MoES, National Government</td>
<td>6 to 12 months</td>
<td>1, 3</td>
</tr>
<tr>
<td>Perform selected assessments for critical bridges.</td>
<td>MoT, Ministry of Construction (GOSSTROY)</td>
<td>1 to 4 years</td>
<td>1, 3</td>
</tr>
<tr>
<td>Perform an updated seismic risk assessment for transport infrastructure and cost benefit analyses for bridge retrofits and replacements.</td>
<td>MoT, GOSSTROY, World Bank</td>
<td>1 to 4 years</td>
<td>1, 3</td>
</tr>
<tr>
<td>Based on the results of the risk assessment, perform prioritized upgrades (retrofits or replacements) for critical bridges.</td>
<td>MoT, GOSSTROY</td>
<td>1 to 4 years</td>
<td>3</td>
</tr>
</tbody>
</table>

Based on the risk results for each scenario earthquake event, potentially heavily damaged critical roads and bridges for primary routes were identified. Recommendations were given for prioritizing upgrades and/or replacements of critical bridges as well as highlighting damaged roads in areas that lack multiple access routes and redundancy for emergency planning and/or supplies. For example, for the Issyk Ata scenario, remote communities in mountainous areas south of Bishkek may be cut off if certain secondary roads are heavily damaged.

### 5. CONCLUSIONS

The seismic risk assessment described in this paper includes the probabilistic assessment of the effect of twelve (12) scenario earthquakes with magnitudes (Mw) ranging from 6.7 to 8.3 occurring on mapped geological faults located throughout the country. This study has shown that large losses are expected for transport infrastructure (roads and bridges) when these assets are subjected to the simulated scenario earthquake ground shaking. The expected direct economic losses to roads from the individual scenario earthquakes were estimated to be in the range of USD 60 million to 1 billion and damage to bridges in the range of USD 2.4 to 22 million depending on the proximity of the scenario earthquake events to the infrastructure assets. The risk results for transport infrastructure identified the extent and geographic concentration of expected damage and direct economic losses near major urban centres for the selected scenario events. The findings have been used to prepare risk management strategy options for transport infrastructure to allow stakeholders to make informed investments and decisions to reduce losses, better plan for emergency response and inform longer term recovery after earthquake disasters.

The significance of the seismic risk facing the Kyrgyz Republic has been communicated to a wide range of Kyrgyz stakeholders (e.g. the Office of the Prime Minister, the Ministry of Emergency Situations, the Ministry of Transport, etc.), and multilateral donor organisations (e.g. the World Bank) over a number of meetings and workshops held in the Kyrgyz Republic.

#### 5.1 Limitations of Seismic Risk Calculations

The quality of the seismic risk assessment results that are described in this paper are dependent on the accuracy and detail of the spatial input information that was made available for this assessment. The main sources of information for the present risk assessment came from a combination of literature...
review, from public domain sources and from field surveys. Uncertainties still remain, however, in terms of the location of the assets, their structural characteristics and structural condition, and their replacement costs. Engineering judgement, statistical data treatment and the input of local experts were used to overcome the limitations in the available information for the various infrastructure asset classes for the current project. It should also be noted that there are inherent uncertainties in seismic risk calculations when using estimated infrastructure characteristics and estimated ground conditions and seismic ground motions. These uncertainties have been treated in a systematic way, and sensitivity analyses have been undertaken. Despite these limitations, it is important to emphasize that this study has provided a meaningful set of risk results to inform a seismic risk reduction strategy for the transport infrastructure assets of the country.

6. ACKNOWLEDGMENTS

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7. REFERENCES


The reports and digital datasets produced for this project are available on (http://geonode.mes.kg/).