Measuring Seismic Risk in the Kyrgyz Republic
Development of Fragility Functions – November 2017

About the Project

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 return periods of several decades. The Government of the Kyrgyz Republic is aware of this issue and has been making efforts to understand the seismic hazard that affects the country. In order to better understand the hazard and the risk from earthquakes, the Government of the Kyrgyz Republic, with support from the World Bank and the Global Facility for Disaster Risk Reduction, is funding the project “Measuring Seismic Risk in the Kyrgyz Republic”. The project consists of five components:

Component 1. Undertaking a seismic hazard assessment which identifies where earthquakes occur and how strong is the ground shaking and other hazards.

Definition and Use of Fragility Functions

In seismic risk assessment, expected losses and damage to buildings are described by fragility functions. Fragility functions describe the probability of exceeding different damage or injury levels with increasing levels of ground shaking. These functions represent the resilience of building typologies that share common features such as construction material. Figure 1 shows example fragility functions for reinforced concrete buildings in the Kyrgyz Republic. On the horizontal axis of the fragility function is a measure of the intensity of the ground shaking, which is typically defined in terms of:

• Macroseismic intensity: based on post-earthquake data, felt intensity of ground shaking and effects on buildings.
• Instrumental intensity: based on seismic shaking measured by recording instruments. Peak ground acceleration (PGA) and permanent ground displacement (PGD) are commonly used for buildings and transport infrastructure, respectively.

The vertical axis represents the probability that a building of a given typology would be damaged to a particular degree. Degrees of damage are measured in terms of discrete thresholds, referred to as “damage states”. The adopted damage scale (as per European Macroseismic Scale, EMS) is based on five damage states, ranging from 1 (for negligible to slight damage) to 5 (destruction or collapse).

A specific fragility function provides the probability of a building exceeding the associated damage state for each value of intensity. Figure 1 shows that a reinforced concrete building subjected to ground shaking of 0.2g PGA is approximately 4% likely to collapse or be very heavily damaged, 40% likely to sustain heavy damage, 47% likely to sustain moderate damage and 9% likely to sustain no or negligible damage.

Damage levels provide a relationship between damage and the financial or human losses that an asset may incur. Different damage scales are used for buildings, roads and bridges. Damage states for masonry buildings are illustrated and described in Figure 2, according to EMS.

Fragility Function Development

Methods for developing fragility functions include:

1. Empirical: Damage observations from previous earthquakes are plotted against seismic intensity, and regression is used to fit a function form to the data.
2. Analytical: Building response to different levels of ground shaking is simulated through numerical modelling of buildings of each typology;
3. Expert judgement: Experts with experience in assessing building damage data provide estimates of the probabilities of damage for different building typologies as a function of ground motion intensity.
4. Hybrid methods: A combination of the above methods (e.g. using observational data to calibrate analytical models).
Fragility Functions for Kyrgyz Buildings

The vulnerability index approach was used to develop fragility functions in this project. This is a hybrid approach combining empirical data with expert judgement. The empirical component is based on the performance of buildings in previous earthquakes. Expert judgement is then used to adjust the baseline values based on specific characteristics of the buildings (e.g. the level of earthquake resistant design). The benefits of this approach are the following:

- It offers a consistent approach that can be applied across all building typologies.
- It allows characteristics of the building construction to be considered without significant analytical effort.
- It allows all typologies to be considered, not just those which have experienced earthquake damage in the past.

The method works by assigning a vulnerability index ($V_i$) to each building typology. Values for the vulnerability indices range typically between 0 and 1, although higher values, which correspond to more fragile structures, are also possible. Fragility functions for each damage state are then developed on the basis of this index.

Average vulnerability indices assigned to the building typologies commonly encountered in the Kyrgyz Republic are shown in Table 1. The most vulnerable building typology ($V_i = 1.06$) was considered to be the adobe buildings. The least vulnerable building typology ($V_i = 0.28$) was considered to be steel buildings.

It is possible that a given steel building may be more vulnerable than a given adobe building, but on the average, adobe buildings are significantly more vulnerable than steel buildings.

Vulnerability indices were converted to fragility functions through equivalent normal distribution functions in terms of EMS-98 macroseismic intensity, and equivalent lognormal distribution functions in terms of peak ground acceleration. Fragility functions for the most common building typologies in the Kyrgyz Republic are shown in Figure 3 to Figure 10.

Table 1: Vulnerability indices assigned to Kyrgyz building typologies (higher $V_i$ means higher vulnerability).

<table>
<thead>
<tr>
<th>Type</th>
<th>EMCA Class</th>
<th>EMCA Description</th>
<th>$V_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masonry buildings</td>
<td>c1.1</td>
<td>Unreinforced masonry with wooden floors</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>c1.2</td>
<td>Unreinforced masonry with concrete floors</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>c1.3-1.4</td>
<td>Reinforced or confined masonry</td>
<td>0.56</td>
</tr>
<tr>
<td>Cast-in-situ concrete</td>
<td>c2.1</td>
<td>Monolithic concrete frames</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>c2.2</td>
<td>Dual frame and wall system</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>c2.3</td>
<td>Monolithic frames with brick infill walls</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>c2.4</td>
<td>Monolithic concrete walls with flat slabs</td>
<td>0.50</td>
</tr>
<tr>
<td>Precast concrete</td>
<td>c3.1</td>
<td>Large panel walls with monolithic joints</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>c3.2</td>
<td>Large panel walls with welded plate connections</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>c3.3</td>
<td>Flat slab</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>c3.4</td>
<td>Frame with cruciform and linear-beams</td>
<td>0.56</td>
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<tr>
<td>Adobe</td>
<td>c4</td>
<td>Adobe structures</td>
<td>1.06</td>
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<tr>
<td>Timber</td>
<td>c5.1</td>
<td>Wooden structures</td>
<td>0.72</td>
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<tr>
<td>Steel</td>
<td>c6</td>
<td>Steel structures</td>
<td>0.28</td>
</tr>
</tbody>
</table>
Figure 3: Fragility functions for unreinforced masonry buildings with wooden floors (c1.1) in EMS-98 macroseismic intensity.

Figure 4: Fragility functions for in-situ monolithic concrete frame buildings (c2.1) in EMS-98 macroseismic intensity.

Figure 5: Fragility functions for large precast panel wall buildings with monolithic panel joints (c3.1) in EMS-98 macroseismic intensity.

Figure 6: Fragility functions for adobe buildings (c4) in EMS-98 macroseismic intensity.

Figure 7: Fragility functions for unreinforced masonry buildings with wooden floors (c1.1) in peak ground acceleration.

Figure 8: Fragility functions for in-situ monolithic concrete frame buildings (c2.1) in peak ground acceleration.

Figure 9: Fragility functions for large precast panel wall buildings with monolithic panel joints (c3.1) in peak ground acceleration.

Figure 10: Fragility functions for adobe buildings (c4) in peak ground acceleration.
Fragility Functions for Transport Infrastructure

In the case of transport infrastructure (roads and bridges), available and validated fragility functions were compiled and further corrected through a regional modification factor. In the event of an earthquake, ground shaking has a direct impact on bridges and the corresponding fragility functions are given in terms of peak ground acceleration. Damage to roads, however, is mainly caused by lateral ground movement induced by earthquake action (e.g. through liquefaction), and as a result, fragility functions for roads are given in terms of permanent ground deformation (PGD).

The damage state description for roads includes “minor”, “moderate” and “extensive/collapse” limit states. These are associated with serviceability constraints identified as “reduced speed or partially closed” to “completely closed for weeks”. Fragility functions are defined according to the type of road (Figure 11), which is assumed as either “major” or “urban”, depending on the number of traffic lanes (equal or greater than four lanes in the case of “major” roads; and urban otherwise).

Bridge vulnerability is dependent on material type, complexity of the structure, the interaction with the bridge abutments, and the local ground conditions. In this project, fragility functions for road bridges were defined for two bridge types: concrete and steel. Damage state descriptions were given using two states: (i) minor damage (or yielding) and (ii) extensive/complete damage.

In this project, fragility functions were determined as a weighted combination of curves proposed for various bridge configurations in Europe. In the case of concrete bridges, these include the combination of two sets of attributes: isolated / non-isolated, and regular / irregular (Figure 12). Fragility functions for steel road bridges were obtained through a similar approach, whereby curves proposed for multi-span simply-supported (MSSS), multi-span continuous (MSC), and continuous steel (CS) bridges in Europe were combined.

![Figure 11: Fragility functions for urban roads.](image1)

![Figure 12: Fragility functions for concrete bridges.](image2)

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The reports and digital datasets produced as part of this project are available on the Kyrgyz Geonode (http://geonode.mes.kg/).