Safety Prioritization of School Buildings for Seismic Retrofit using Performance-Based Risk Assessment in the Kyrgyz Republic

– Executive Summary –

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GFDRR
Global Facility for Disaster Reduction and Recovery

Japan World Bank Program for Mainstreaming Disaster Risk Management in Developing Countries

Overview

The technical assistance (TA) supported by the World Bank's Global Program for Safer Schools (GPSS) and the Global Facility for Disaster Reduction and Recovery (GFDRR) under the Component 2 ("Improving the Safety of School Infrastructure (US$ 12M)") of Enhancing Resilience in Kyrgyzstan (ERIK) project, is aiming to support the Government of the Kyrgyz Republic to efficiently improve the safety and functional conditions of schools in areas of highest seismic hazard in the country. The work under this TA is to provide analytical support to the government in preparation of a long-term national risk reduction strategy for school infrastructure.

With the analytical work conducted by the Applied Technology Council (ATC), three typical school building types in the country with high seismic risk are identified, their seismic performance is assessed, and performance-based retrofitting options in terms of increments are proposed. Building upon the analytical results, a risk-based prioritization framework is developed using a benefit-cost ratio integrating seismic hazard, structural performance, and school occupancy. As a result, a prioritization rank of schools eligible for ERIK project is established to support the selection of the most cost-efficient intervention strategy and investment plan. The work enables informed decisions of the Government of the Kyrgyz Republic to optimize the investment plan for seismic risk reduction of school infrastructure at scale.

Path to Achieving the Most Good for the Most Kids

The work under this TA aims to "Do the Most Good for the Most Kids". Specifically, the objective is to develop a solid analytical framework to inform the investment decision to maximize the safety benefit through efficiently reducing the seismic risk for students with limited funds. Meanwhile, improvement on education environment is also considered in terms of Energy Efficiency (EE), and Water, Sanitation and Hygiene (WASH).

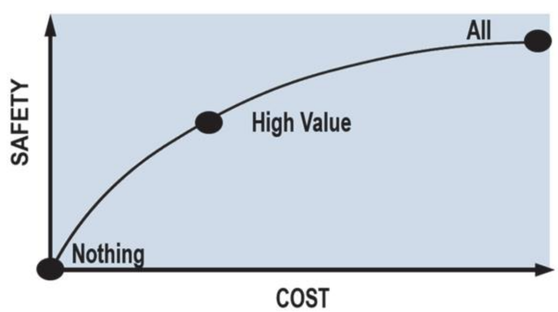


Figure 1: Illustration depicting concept of identifying high value risk reduction strategies to maximize benefit efficiently.

To achieve this objective, it is necessary to understand that the cost of interventions to reduce seismic risk and improvement of safety do not linearly related, which makes it a complex optimization problem. This is because of the complexity of the factors influencing the school safety investment efficiency, including the seismic resisting capacity of the school building, the seismic hazard level at the school location, and the amount of occupancy in the school building. For example, smaller earthquakes are expected to occur at a much higher frequency than larger earthquakes, leading to the fact that retrofit to resist smaller earthquakes with lower cost may save more lives than retrofit to resist larger earthquakes with much higher cost, statistically. Therefore, the analytical framework developed in this work is to find the most efficient solution with the balance on the trade-offs between safety improvement and intervention cost. Figure 1 shows the concept in developing this analytical framework to reach the most efficient optimal solution balancing the intervention cost and the safety improvement – the "High Value".

Under ERIK, to practically implement the concept to maximize the safety improvement for school infrastructure in the country with the limited funds (US$ 12-13M), the overall process is as Figure 2 shows. From the national school portfolio, a group of approximately 300 eligible schools was shortlisted. The eligible schools were considered based upon the following:

- State schools
- Constructed after 1970 (to avoid buildings near the end of their useful life)
- Larger schools to maximize the social benefits (schools with more than 500 students in urban area, with more than 100 students in rural area)
- Fully or near fully occupied schools to maximize the social benefits (more than 70% of school capacity is occupied)
- Located in the areas of high seismic risk (with higher estimated expected fatality number under potential earthquakes)
- Engineered school buildings to be more cost-effective to retrofit (at least 70% of school buildings are engineered)
- Avoid schools already approved for other retrofit funding

Figure 2: Overall process to identify the final list of "selected" schools to be financed under Component 2 of the ERIK project.

Further to support the selection of schools to be intervened under ERIK for maximized safety improvement, a robust analytical framework with quantitative prioritization criteria was developed. The framework consists of three main steps as summarized below with corresponding major findings.

➢ **Step 1: Representative Index Building** – Vulnerability Assessment and Intervention Solution at Scale

To assess the vulnerability of all the school buildings one by one is an expensive task, in terms of both data collection and seismic analysis. Considering that school buildings can usually be classified into several typical building types with similar seismic vulnerability in a country, a subset of the building inventory from 78 eligible schools were inspected and 3 most common building types in the country were identified as Figure 3 suggested. These 3 typical school building types are complex masonry (CM), complex masonry with concrete framing (CMCF), and precast concrete frame and walls (PC). Note that all the minor building types are grouped into "Other", such as unconfined/unreinforced masonry and non-engineered concrete frame, etc. Based on the identified 3 common building types, 3 representative index buildings are developed accordingly from available structural drawings collected during field inspection. These index buildings provide the numerical models for the seismic analysis to assess their vulnerability and develop corresponding retrofit solutions in the next step.

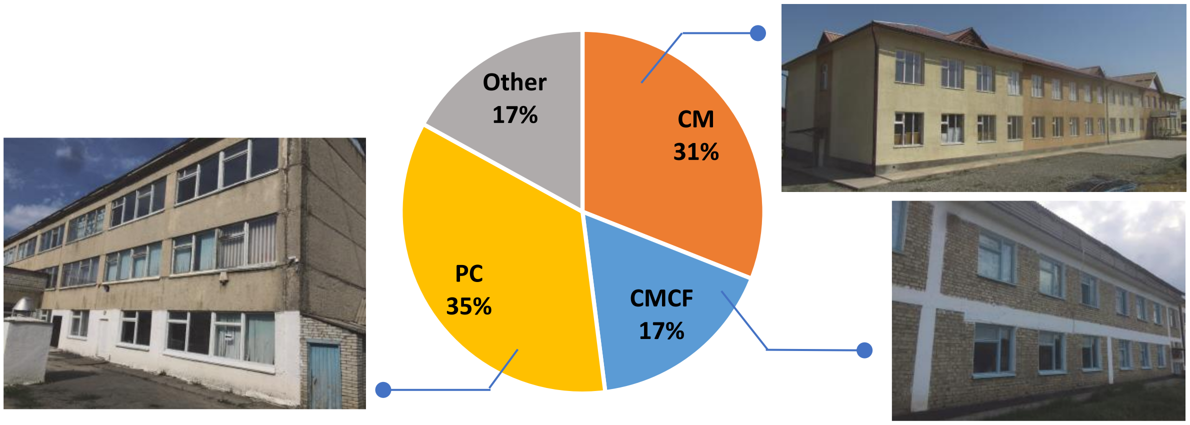


Figure 3: Distribution of common building types (long axis of the building) from field inspection of a subset of 78 eligible schools

Due to the representativeness of the 3 index buildings for the whole school building portfolio, the assessment results and proposed retrofit solutions is widely applicable to the school buildings in the country. For the schools have not been inspected, the building structure information is from a relatively comprehensive database compiled by United Nations Children's Fund (UNICEF) in 2013. However, it is noted that not all the school buildings perfectly fit into the index buildings. Therefore, to differentiate any variation of expected vulnerability from index buildings, the assessment results for each building were extrapolated from the vulnerability of index buildings with proportional adjustments when needed, based on existing vulnerability information of varies building types from literature. Such extrapolation process considers varies factors influencing the seismic vulnerability of the building, such as differences in detailed structural typology, building height, plan/elevation irregularity, foundation type, and structural deficiencies (e.g. short column, soft story, etc.).

➢ **Step 2: Performance-Based Assessment and Retrofit Solution** – Efficient Vulnerability Reduction

To set the base for the vulnerability assessment and the design of vulnerability reduction retrofits applicable for the whole school portfolio in the country, performance-based assessments were conducted for the 3 index buildings and incremental retrofit solutions were developed. The key values of these two tasks performed are discussed below.

- *Performance-based assessment*: It is to evaluate whether the building structure is able to meet the selected performance objectives for improved safety, life safety (LS) and collapse prevention (CP), under probable earthquakes. Further, it is to understand the critical deficiencies of the building structure and therefore support tailored retrofit solutions to efficiently solve these critical deficiencies. Specifically, nonlinear pushover analyses were carried out to understand the lateral resistance capacity and failure mechanism of different index buildings. In general, structural deficiencies can be categorized in terms of lack of strength and lack of flexibility to resist earthquake load.
- *Incremental retrofit solution*: For different type of structural deficiencies, tailored incremental retrofit solutions were developed targeting different design objectives. To provide varies cost-efficient options, retrofit increments were designed progressively for different elements/locations of the building using the most locally available technique (e.g. reinforced concrete jacketing) to improve seismic capacity through different design strategies. Figure 4

illustrates the general concept of two main design strategies targeting the improvement of strength and/or flexibility, which in details include adding displacement capacity, strength, resistance to collapse, and resistance to falling hazards. Note that the amount of retrofit work and associated cost increases with higher retrofit increment.

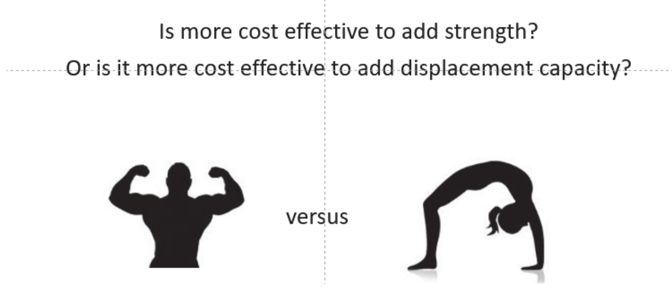


Figure 4: Graphic illustration depicting retrofit design for strength vs. flexibility.

The deficiencies of the as-is condition of the index buildings can be observed through their analytical results (Figure 5). It can be seen from Figure 5 that all three building types exhibit a dangerous brittle failure mechanism, which loses strength without appreciable deformation. Out of the three building types, PC is the most vulnerable building type with lowest seismic capacity in both strength and flexibility. As a result, the retrofit costs for PC is the highest among the 3 index buildings (Table 1). Retrofit increments (summarized in Table 1, with estimated cost, including EE and WASH cost) were developed to progressively eliminate different key deficiencies found for the 3 common school building types. The improvements on seismic capacity (strength and/or flexibility) of different retrofit increments are demonstrated in Figure 6. The developed increments are served as retrofit options to be selected for the most cost-efficient solution in the next step.

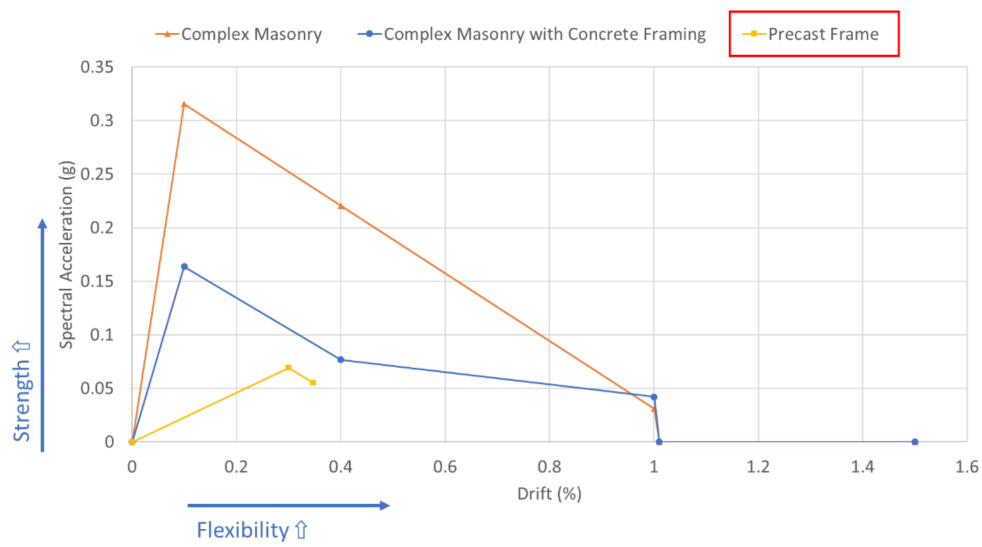
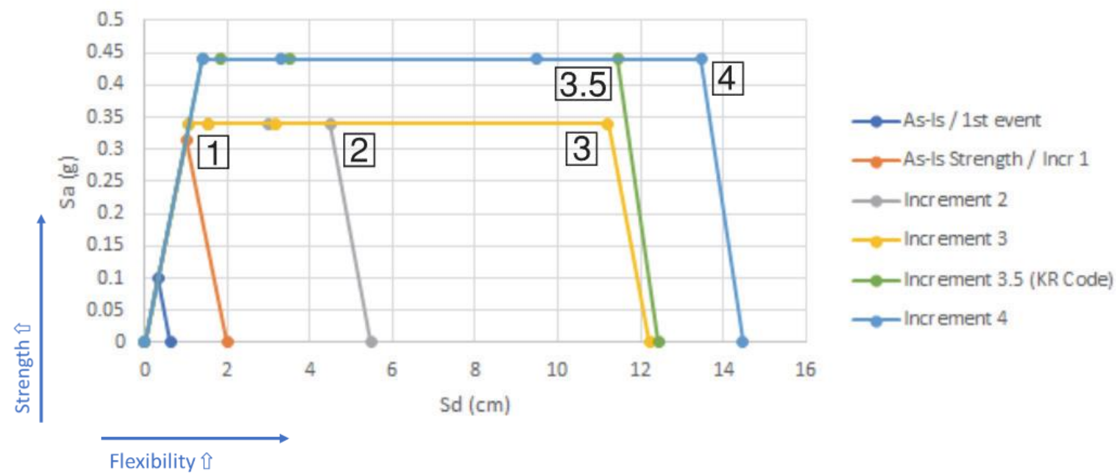


Figure 5: Representative pushover curve of the index buildings showing their original seismic capacity

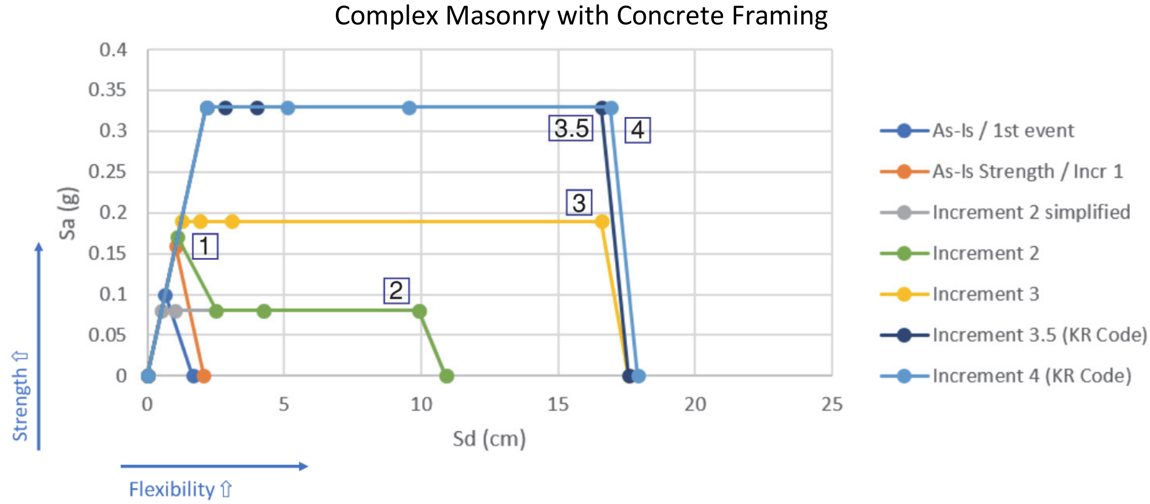
Table 1: Strategic improvements of different retrofit increments for index buildings

Index Building	Increment 1	Increment 2	Increment 3	Increment 3.5	Increment 4
CM	Strength ⇧, $\$105/\text{m}^2$	Flexibility ⇧, $\$171/\text{m}^2$	Flexibility ⇧, $\$217/\text{m}^2$	Strength ⇧, $\$232/\text{m}^2$	Flexibility ⇧, $\$242/\text{m}^2$
CMCF	Strength ⇧, $\$124/\text{m}^2$	Flexibility ⇧, $\$171/\text{m}^2$	Strength and Flexibility ⇧, $\$175/\text{m}^2$	Strength ⇧, $\$205/\text{m}^2$	Flexibility ⇧, $\$208/\text{m}^2$
PC	-	Strength and Flexibility ⇧, $\$240/\text{m}^2$	Strength ⇧, $\$329/\text{m}^2$	-	Flexibility ⇧, $\$349/\text{m}^2$

Complex Masonry



Complex Masonry with Concrete Framing



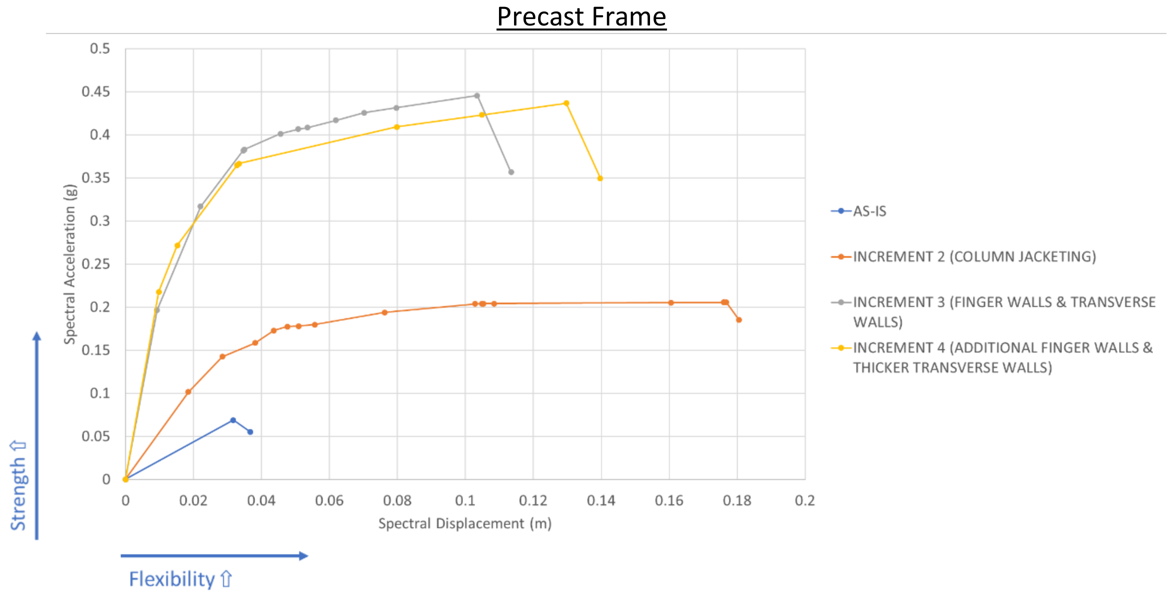


Figure 6: Capacity curves showing seismic capacity improvements for typical school building types

- **Step 3: Risk-Based Prioritization** – Cost-Efficient Intervention Strategy and Investment Plan

To find the most cost-efficient retrofit option for each school building, as well as the optimal investment plan for the eligible schools, a risk-based prioritization framework was developed as Figure 7 shows. The benefit-cost ratio to evaluate the safety improvement from retrofit investment for a school is based on both the reduction in the seismic vulnerability (safety index: expected avoided fatality under probable earthquake scenarios, in a statistical sense) and the efficiency of the investment (efficiency index: students benefited per intervention cost). Additional criteria were enforced to ensure the selected retrofit increment at least satisfy CP performance objective and the current design code in the country, and is altered to replacement if retrofit cost is more than 50% of replacement cost for practical efficiency. The resulting prioritized list of schools are then following a decreasing benefit-cost ratio, informing the priorities of schools to be intervened to most efficiently reduce seismic risk at scale for the schools in the country. The most efficient intervention option for each school building is also suggested.

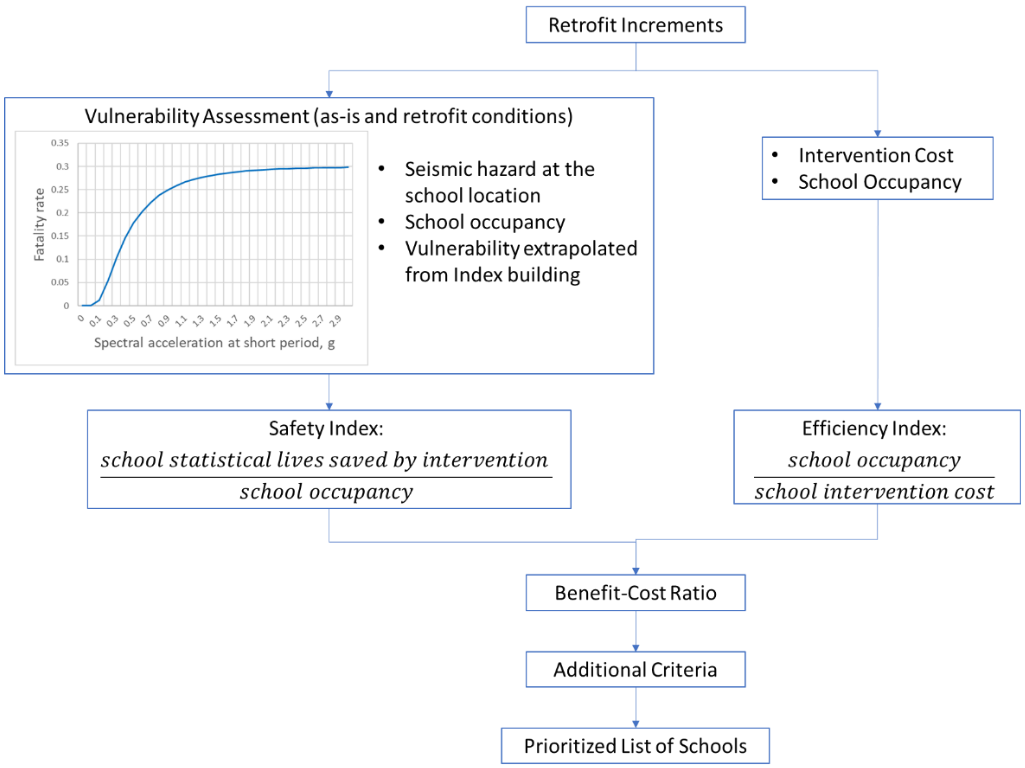


Figure 7: Flowchart of the risk-based prioritization framework

Evidence-Based Recommendations

- In general, precast frame buildings are much more vulnerable than other building types (Figure 6). In addition, they are also more expensive to retrofit (Table 1) and more practical and efficient to be replaced.
- Increment 2 has the highest benefit-cost ratio for all 3 building types as suggested in Figure 8. However, at least increment 3.5 or 3 is required to satisfy the current design code requirement in the Kyrgyz Republic.

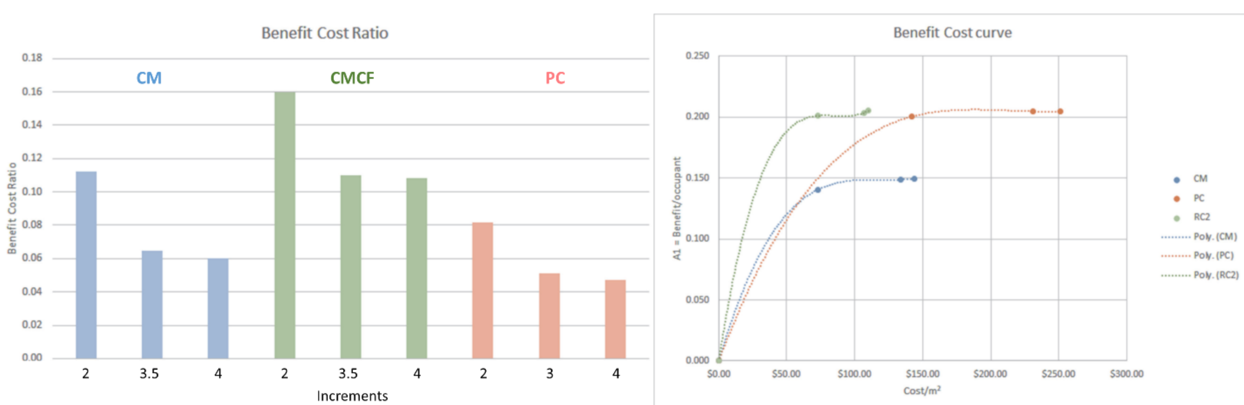


Figure 8: Benefit-cost of considered retrofit increments for 3 building types (left: benefit-cost ratio per increment; right: fitted curves demonstrating the relationship between the safety/benefit index and cost for seismic retrofit.)

- The developed risk-based prioritization framework can be used to provide prioritization ranking of schools with recommended efficient incremental retrofits and associated cost. As demonstrated in Figure 9, this ranking could inform national investment plan towards maximized fatalities avoided with limited funds.

Figure 9: Intervention lines, investment, and estimated fatalities avoided of the prioritization ranking of schools