IUSS
Scuola Universitaria Superiore Pavia

TOWARDS A SEISMIC VULNERABILITY DATABASE FOR BENEFIT-COST ANALYSIS CONSIDERING RETROFITTING INTERVENTIONS - AN EXAMPLE FROM ISTANBUL

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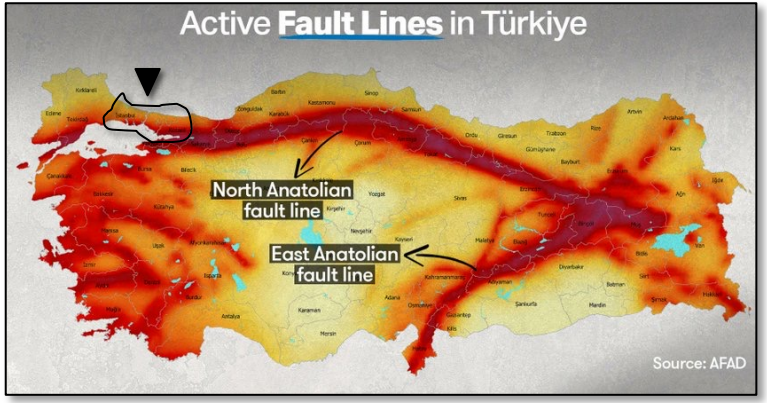
17/06/2025
Rhoades, Greece

GEM
GLOBAL EARTHQUAKE MODEL working together to assess risk

Why Istanbul?

- **Istanbul** is the most critical metropolitan area of Türkiye, located **close to the North Anatolian Fault**—one of Türkiye's two critical fault lines with a significant potential for generating destructive earthquakes.

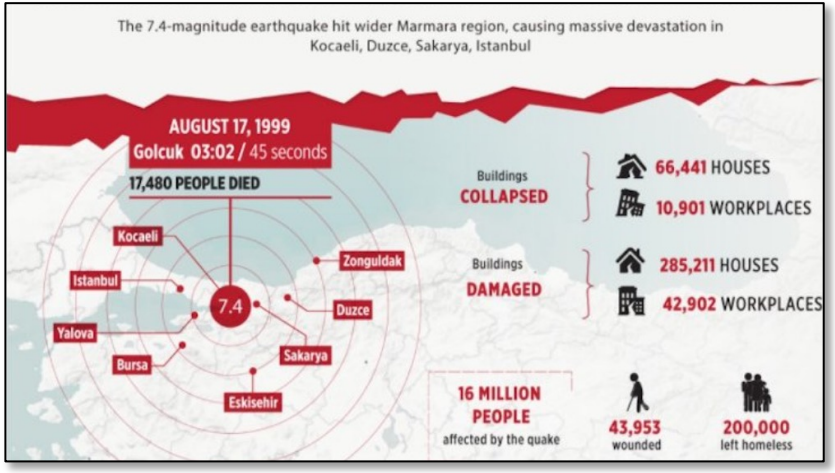
- A substantial portion of **Istanbul's building stock** consists of reinforced concrete **(RC) frame buildings** with 83% of total number of buildings. Moreover, 65% of RC frame buildings were **constructed before the year 2000.**





Why Istanbul?

- 1999 M7.4 Kocaeli Earthquake:
  - Demonstrates the **activity of the North Anatolian Fault** in the Marmara region.
  - Serves as **a reminder** of the catastrophic seismic risks facing the Marmara region, including Istanbul.

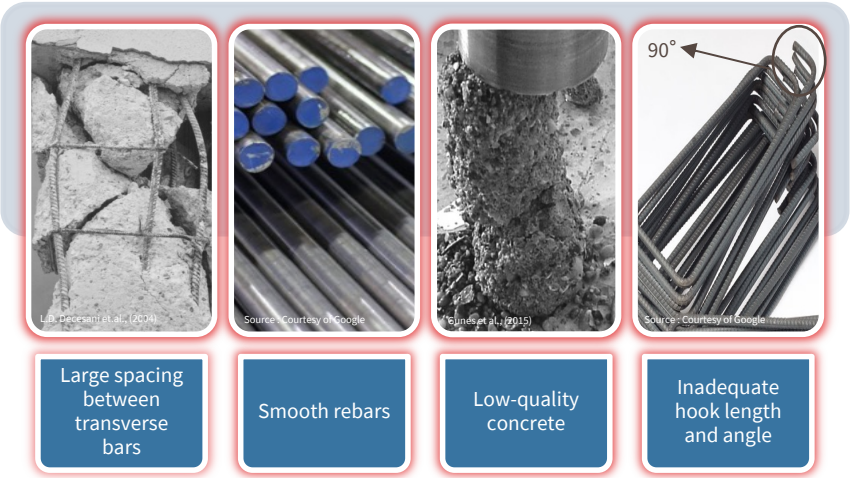






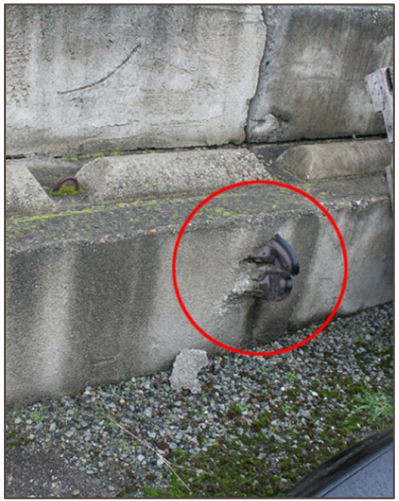
Why Istanbul?

- The common deficiencies observed in the vulnerable buildings in Istanbul, referred to **as substandard buildings**:



- Another key factor led to an insufficient construction: **the improper in-situ inspection**







Aim and Methodology

- To evaluate the benefits of seismic retrofitting **of RC frame buildings** in Istanbul, which is the economic and cultural capital of Türkiye and constitutes 30 percent of the country's GDP.

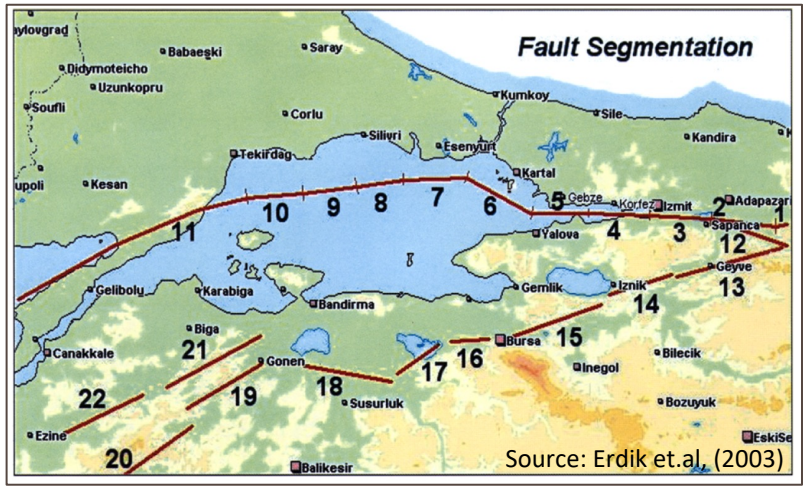
- This study performs **a scenario-based impact analysis** for the city of Istanbul. The work identifies the most vulnerable building classes, focusing on non-ductile reinforced concrete structures.

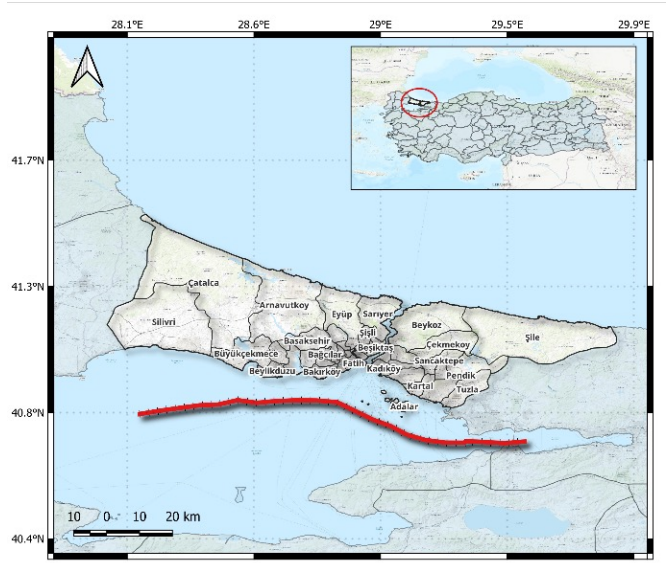
- Next, new vulnerability models are developed to capture **different retrofitting scenarios** featuring **selected increments of ductility**.

- A comparison is made between the original and retrofitted scenarios to investigate the effectiveness and economic benefits of the retrofitting for the city of Istanbul.

Data & Modeling (Rupture Scenario)

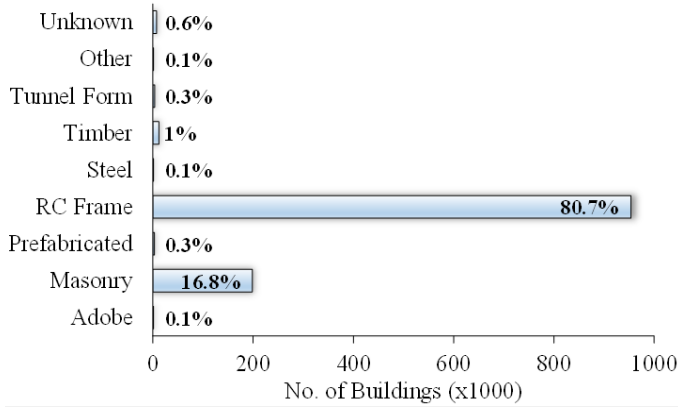
- **A strike-slip earthquake with M_w = 7.5**, associated with the rupturing of segments **5, 6, 7 and 8** was selected as the **"Credible Worst Case"** scenario earthquake.
- The source parameters of the scenario earthquake are similar to the M_w = 7.5 Kocaeli earthquake (1999).

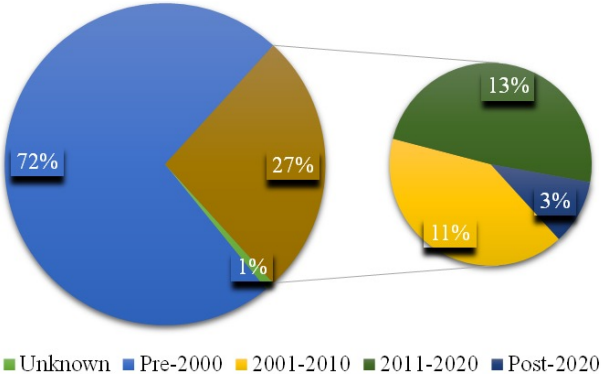




Data & Modeling (Exposure)

- The exposure model of Türkiye was used developed by Narlitepe et al. (2024), with the scope of a World Bank project.
- The building exposure characteristic in Istanbul is presented based on two key parameters: construction period (1), structural system (2).







Typical RC Frame Building



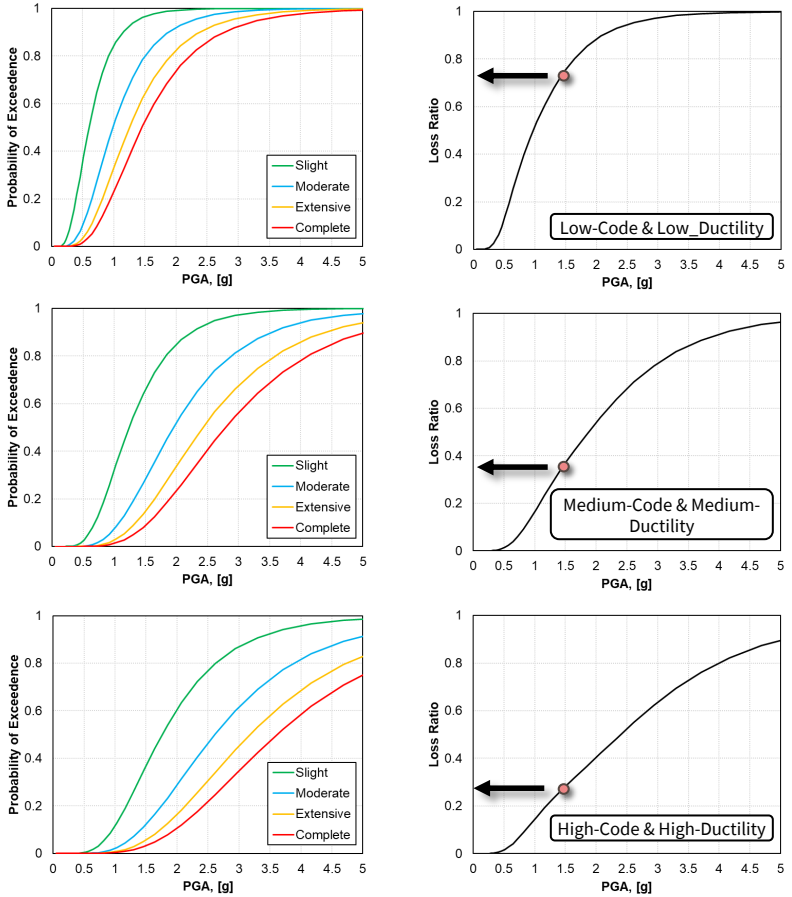
Typical Masonry Building

Data & Modeling (Vulnerability)

- To describe the fragility and vulnerability functions for each building class into the exposure model, **the GEM Building Taxonomy v3.0** was followed.

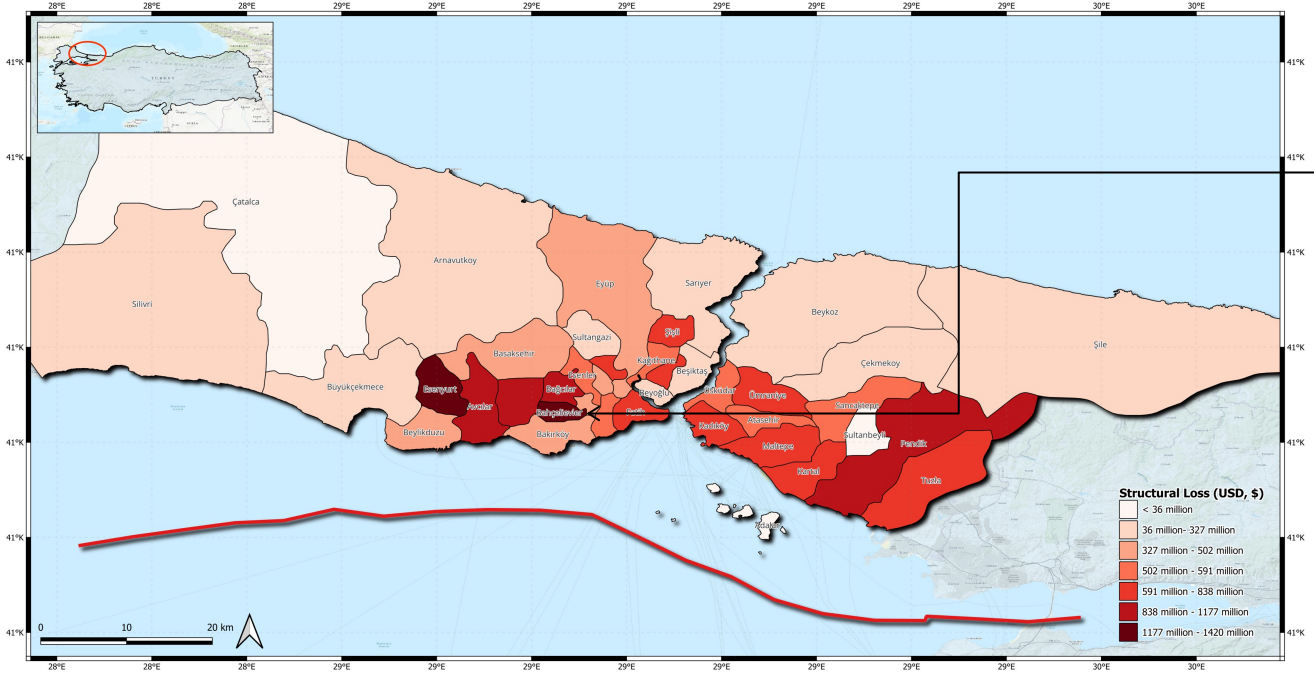
- The vulnerability model proposed **by Martins and Silva (2021)** was used and is publicly available in the GitHub repository featured in the associated publication.

- As an example, the fragility and vulnerability functions are presented for RC frame buildings corresponding to **the different codes and ductility levels**.



Scenario-based Impact Analysis

- Using the **OpenQuake Engine**, a scenario-based seismic impact analysis was performed using vulnerability and exposure models along with the identified rupture.



District	Total Structural Loss (USD)	Structural Loss for RC Frame (USD)	
		Pre-2000	Post-2000
BAHCELİEVLER	1,420.4 million	1,025.9 million	256.2 million
ESENYURT	1,346.1 million	990.9 million	229.3 million
KÜÇÜKÇEKMECE	1,177.3 million	866.8 million	206.3 million
PENDİK	1,016.1 million	747.2 million	177.5 million
BAĞCILAR	955.8 million	701.3 million	174.7 million
AVCILAR	927.5 million	672.3 million	173.2 million
KARTAL	837.9 million	605.0 million	151.0 million
ÜMRANİYE	813.7 million	601.7 million	143.0 million
TUZLA	804.0 million	577.9 million	143.9 million
MALTEPE	743.5 million	543.8 million	132.8 million
KADIKÖY	737.2 million	537.3 million	131.9 million
GAZİOSMANPAŞA	700.8 million	521.0 million	124.2 million
SULTANGAZİ	676.0 million	503.6 million	118.7 million
FATİH	657.9 million	473.8 million	114.6 million
ESENLER	591.5 million	429.4 million	111.7 million
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TOTAL	**21,535.0 million**	**15,742.3 million**	**3,838.3 million**

Retrofitting Options

- Based on the literature review, different retrofitting methods are suggested for RC buildings.
  1) RC jacketing
  2) Adding shear walls to the existing RC frame
  3) Wrapping with fiber-reinforced polymer (FRP) fabrics.

- Here are the **potential improvements** from these **retrofitting** techniques based on **experimental** and **analytical** studies conducted on buildings or structural frame **representative of the Turkish building stock**.



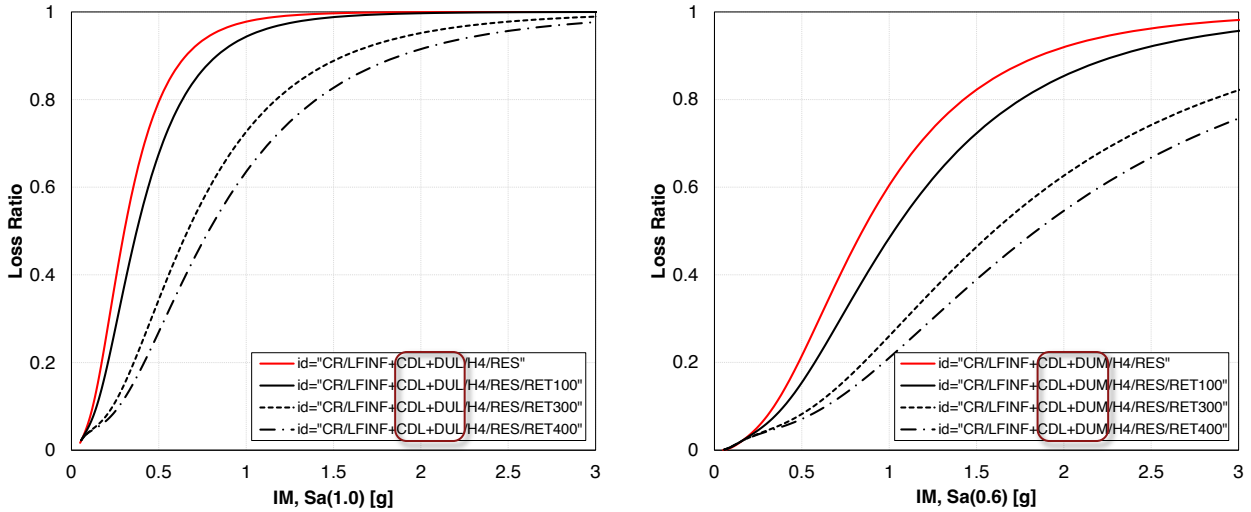




Refrofitting Method	Study	Type of Study	Test Specimen	Enhancement		
				Strength	Ductility	Stiffness
Addition of RC Walls	Erdem et al. (2006)	Experimental	Two Story - Three Bay RC Frame	5.2	-	12.9
	Anil and Altin (2007)	Experimental	One Story - One Bay RC Frame	9.7 5.9	-	35.5 12.0
	Anil et al. (2008)	Experimental	Two Story - One Bay RC Frame	5.6	-	29.0
	Kaltakci et al. (2010a)	Experimental	Two Story - Two Bay RC Frame	3.4 2.4	-	7.0 14.4
	Kaltakci et al. (2010b)	Experimental	Two Story - Two Bay RC Frame	3.8 5.8	-	6.1 6.6
	Kaplan et. Al. (2011)	Experimental	Two Story - Three Bay RC Building	3.3	-	7.2
	Dere Y. (2016)	Analytical	Six-Story RC Building	3.5 2.6	-	12.7 6.8
	Akif et al. (2019)	Analytical	Four-Story RC Building	4.0	-	5.0
RC Jacketing	Goksu et al. (2006)	Analytical	Six-Story RC Building	3.5	4.8	4.0
	Symrou et al. (2012)	Analytical	Four-Story RC Building	1.4	1.8	1.3
	Akif et al. (2019)	Analytical	Four-Story RC Building	2.5	2.4	2.0
FRP	Goksu et al. (2006)	Analytical	Six-Story RC Building	1.1	3.0	-
	Symrou et al. (2012)	Analytical	Four-Story RC Building	1.0	1.6	-
	Inci et al. (2021)	Experimental	Three-Story RC Building	1.3	4.1	-

Retrofitting Options

- The retrofitted vulnerability functions corresponding to distinct ductility enhancements (100%, 300% and 400%) are presented below.
- These functions are assigned based on the seismic hazard of the asset in the region of interest.
  - (RET100 for low-hazard, RET300 is for medium-hazard and RET400 is for high-hazard)



Target Building Classes for Retrofitting: Low Code (CDL) | Residential (RES) | RC-Frame (CR/LFINF) | Low Ductility (DUL) OR Medium Ductility (DUM)

Retrofitting Options

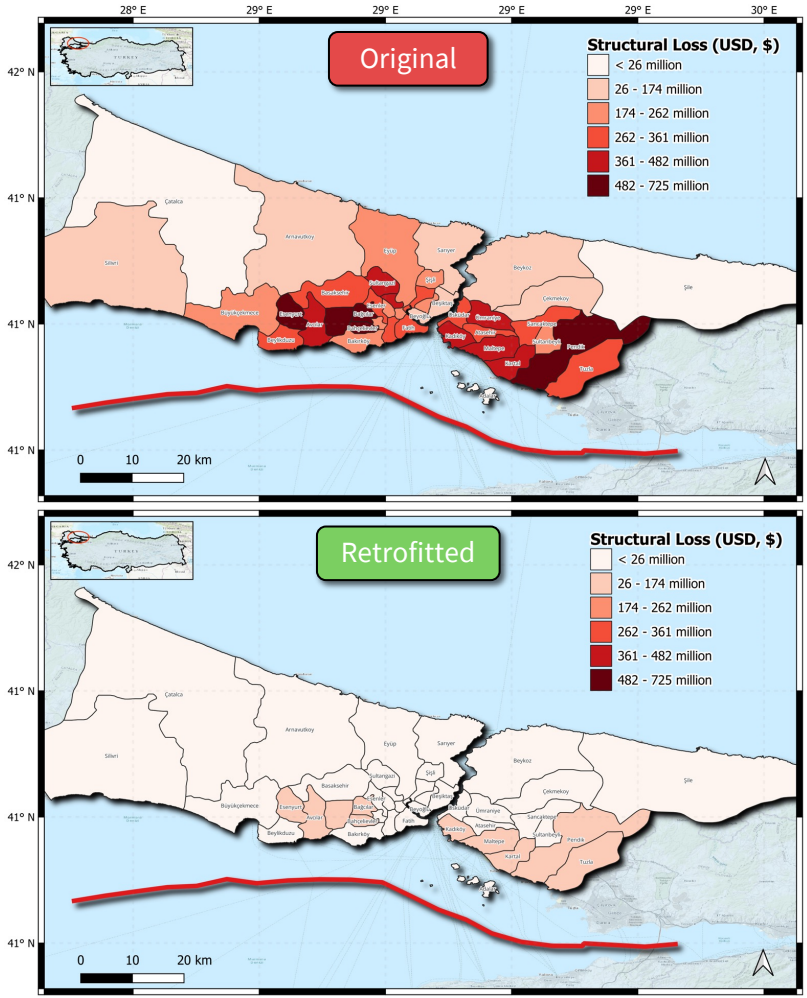
- For a city-scale analysis, the determination of retrofit costs employs **standardized cost coefficients** where specific factors are applied based on the interaction between **building code&ductility level** and **regional hazard**.
- It should be noted that the retrofitting scope of this study is only for **Low_Code (CDL)** residential RC Frame buildings.

CODE DUCTILITY	SEISMIC ZONE		
	H	M	L
CDH+DUH	No Retrofit	-	-
CDH+DUM	-	No Retrofit	No Retrofit
CDM+DUM	0.29	0.26	-
CDM+DUL	-	-	0.26
CDL+DUM	0.32	0.29	-
CDL+DUL	0.38*	0.32	0.29
DNO	0.14	0.12	0.10

*All rates are a percentage of the total replacement cost.

Impact Analysis

- We performed an impact analysis for the retrofitting scenario corresponding to the **different ductility targets** based on the **assets' seismic hazard**.
- Retrofitting significantly reduces structural losses. For example:
  - In total, the losses up to $12 billion drop to $760 million post-retrofit.
  - **Regional Impact**: Dark-colored (high-loss) areas in the original map become lighter, especially in densely urbanized zones, **proving retrofit effectiveness.**



Impact Analysis

Here are some key observations:

1. Cost-Effectiveness

All districts show a cost ratio > 1, indicating that the reduction in the loss is greater than the retrofitting cost across Istanbul.

2. Performance Variation

✓ High-impact areas **(proximity to the rupture)**

✓ Building exposure density

3. Top Performers (CR*> 4.0)

Beylikdüzü (CR = 6.48)

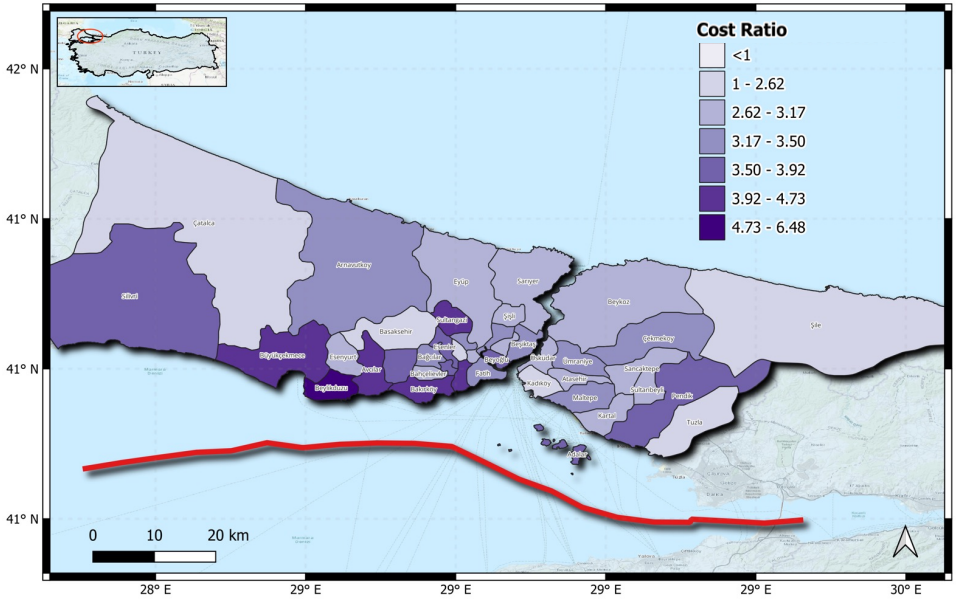
- Notable for extremely effective mitigation (74% cost-to-loss reduction ratio)

Bakırköy (CR = 4.26) & Zeytinburnu (CR = 4.50)

Coastal districts showing high loss reduction

Retrofit costs <25% of original structural losses

***CR= Cost Ratio**



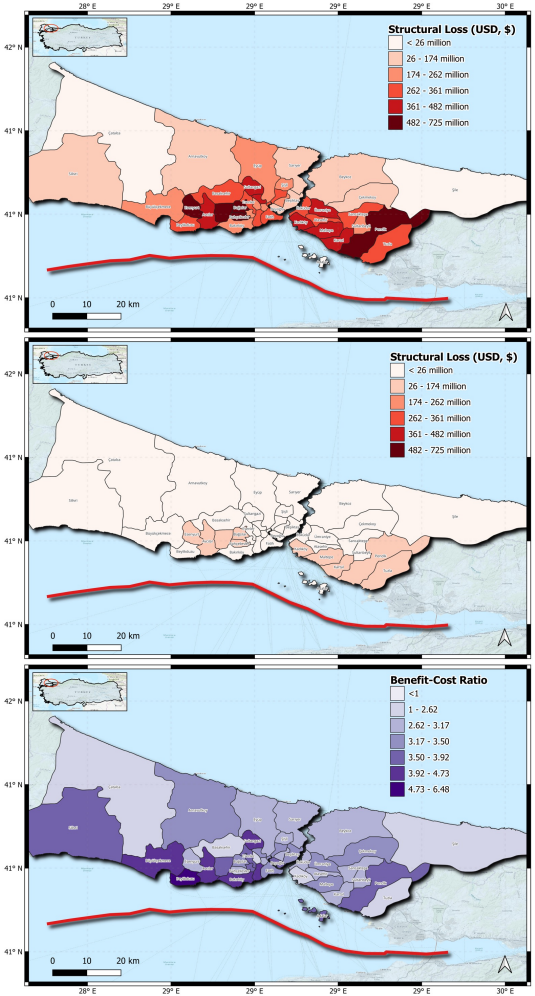
Conclusions

- The impact analysis effectively demonstrates that **retrofitting** in Istanbul is **economically viable**, particularly **in high-risk urbanized areas**.

- **Districts with cost ratio >3.5** should be prioritized for immediate action, as they offer the highest return per retrofitting.

- While **event-based risk assessments** better capture the long-term effectiveness of retrofitting strategies, **this scenario-based analysis** remains highly valuable for urgent preparedness against **Istanbul's impending earthquake**.

- The results for a single rupture provide actionable insights for **worst-case rupture scenarios**, which are critical for **near-term risk mitigation and emergency planning**.





Please attribute to the GEM Foundation with a link to:
https://www.globalquakemodel.org

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