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Municipal resilience bonds for earthquake risk reduction: a financing model for Istanbul's infrastructure

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Abstract

Earthquakes lead to significant economic and social risks. As one of the world's most densely populated cities, Istanbul faces both high earthquake risk and ageing infrastructure, while municipal budgets and conventional (re)insurance continue to prioritise post-disaster recovery over preparedness. This study proposes the innovative application of a Municipal Resilience Bond (MRB) to finance pre-disaster preparedness and evaluates its potential value for Istanbul, Turkey. The study integrates three objectives: (i) a compound Poisson loss process for earthquake frequency and severity calibrated to Turkish Catastrophe Insurance Pool records (1141 events, 2000–2024) and indemnity data; (ii) a Vasicek interest rate model to simulate the dynamic interest rate; and (iii) a payoff structure that links resilience bond triggers to magnitude bands with an effectiveness parameter (ξ). The framework quantifies how an upfront "rebate" generated by modelled risk reductions can be recycled into priority retrofits and lifeline infrastructure, thereby aligning the incentives of municipality, (re)insurer, and investor incentives while expanding Istanbul's capacity for pre-disaster mitigation. This approach can be generalised to other catastrophic events and cities, offering a data-driven bridge between catastrophe risks and resilience finance to accelerate adaptation while maintaining capital market discipline.

Keywords: *resilience bonds, earthquake resilience, infrastructure investment, risk modelling, bond valuation*

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1. Introduction

As one of the largest and most populous cities in Europe, Istanbul is widely recognised as Turkey's primary financial, commercial, cultural, and educational centre. However, the location of the city on prominent active fault lines places it in a significant earthquake zone, making it one of the world's most earthquake-prone urban areas [1, 2]. Cities along active faults typically face double exposure: (1) co-seismic effects of extreme shaking (surface rupture, near-fault directivity pulses, liquefaction, and landslides) and (2) systemic fragility arising from dense, highly interdependent concentrations of people, buildings, and infrastructure. Such events can simultaneously damage structures and disrupt power, water, fuel, telecommunications, transportation, and healthcare [3]. Among nearly 300 devastating earthquakes worldwide over the last decade, 21 occurred in Turkey, resulting in 18,234 deaths and approximately USD 21.23 billion in economic damages [4]. As home to around one-eighth of Turkey's population and 40% of the nation's industrial infrastructure, Istanbul is particularly vulnerable. Despite forecasts of a major earthquake in the near future, public interest in preparedness remains low. Erdik and Aydinoglu [5] identified several factors that have increased the earthquake risk in Istanbul, including excessive rate of urbanisation, inadequate planning of land-use and construction, insufficient infrastructure and services, and environmental degradation.

A variety of strategies have been discussed to mitigate the risks. For instance, Erdik and Durukal [6] proposed three strategies: properly planning future construction to avoid escalating risks, strengthening existing infrastructure to minimise damage, and applying adequate insurance tools to redistribute the risks. This study focused on infrastructure as a complex, interdependent system which can be improved through prevention and mitigation measures, including targeted retrofits and upgrades to reduce the consequences of failure. According to [7], prevention refers to ex-ante measures that reduce the probability of damage or infrastructure failure, such as infrastructure retrofits, base isolation, and network redundancy. In contrast, ref. [8] shows that mitigation refers to actions that reduce the negative economic impacts or severity of loss conditional on a shock, such as emergency planning, insurance, and risk transfer. Despite the technical maturity of many prevention and mitigation strategies, financing remains a constraint for Istanbul's local authorities. Most governments worldwide struggle to secure sufficient and affordable capital for large-scale retrofit and upgrade infrastructure projects; therefore, these constraints are issues of high priority that need to be addressed by the governments of developing countries around the world [9]. According to Kamiya and Zhang [10], the availability of revenue from the local government is the key determinant for the ability of a city to provide necessary services to citizens and fulfil the requirements of the expenditures. Since mitigation and preparedness of infrastructure projects for catastrophes have traditionally been recognised as government responsibilities, the lack of public funds fosters the growth of the involvement of private sectors in the investment of infrastructure projects [11].

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Fixed-income financial instruments present an alternative way to raise capital through the private sectors in the debt capital market for infrastructure-related projects. As García-Lamarca and Ullström [12] state, the lack of upfront investment funds has elevated bonds to having an essential long-term role as debt instruments to raise capital for financing infrastructure projects. Bonds not only provide low-cost debt capital sources in the long term but also connect a diverse base of investors by pooling global capital. Thus method bridges the gap between investment needs and the latent demand for resilient and sustainable investments from institutional investors [13]. Bonds enable governments to finance infrastructure projects with low-cost debt and offer low fixed interest rates to act as a safe investment for potential investors, with an example being pension funds. Mathews and Kidney [14] define bonds as suitable financial instruments for both public and private investment in major infrastructure projects. Resilience bonds are one such instrument, linking infrastructure investments with disaster-risk reduction by monetising expected savings from future losses and reduced insurance costs. In recent years, the increasing urgency of climate-resilient and sustainable infrastructure projects has fostered the growth of new assets class, which are specifically aimed at financing resilient infrastructure projects. Resilience bonds emerged in 2015 as a mechanism to raise upfront capital for resilient infrastructure projects, improving systems' ability to withstand and adapt to sudden catastrophes, while reducing risk and losses and generating broader development benefits [15]. By widening the investor base across public and private sectors, resilience bonds expand access to capital and encourage cross-sector cooperation. To adapt resilience bonds within the broader toolkit for Turkey, the design of the municipal resilience bonds (MRB) valuation model and the development of the market mechanism in Turkey will be proposed in this paper. MRB can efficiently finance resilient infrastructure, lower borrowing costs for individuals, firms, municipalities, and governments and support Turkey with insurance gaps.

This study aims to establish and test the valuation framework for municipal resilience bonds (MRBs) as an innovative mechanism to finance Istanbul's earthquake preparedness. The framework integrates earthquake risk modelling based on TCIP data, stochastic interest rate simulation via the Vasicek model, and a payoff structure that incorporates resilience effectiveness. It further assesses the influence of mitigation on bond pricing through sensitivity analysis and explores the broader potential of MRBs to expand municipal capacity for financing resilient infrastructure. This paper is divided into five sections. Section 2 provides a review of resilience bonds. Section 3 presents the valuation model and analysis for a municipal resilience bond, utilising a dataset from Turkey. In Section 4, the paper explores the potential development of the municipal resilience bond market in Turkey. Finally, Section 5 concludes this study.

2. Literature review

High-density and economically vital countries face escalated catastrophe risk, which has resulted in severe human and financial losses. Traditional (re)insurance may only provide valuable post-catastrophe reimbursement when pre-defined triggers are met [16]. For example, non-life insurance can protect business operations when critical assets fail. However, low-probability but high-impact "mega-catastrophes" may overwhelm insurers' capital and generate excess claims and potential solvency risks. Proactively building resilience into infrastructure ahead of time is more effective than reacting after catastrophic events, as it supports risk prevention and loss mitigation. Prevention means avoiding new risks, steering growth and critical assets away from disaster-prone zones, enhancing modern building, and relocating essential facilities may reduce the impact of catastrophes on society and infrastructure. For example, early preparedness measures, such as rank suppliers, optimised pre-disaster orders, and re-optimised post-disruption with extended capacity and shortage caps, may reduce risks and post-disaster impacts [17]. Mitigation reduces the severity of losses from risks that already exist. Infrastructure retrofits and base isolation for hospital and schools, seawalls, and surge barriers that limit cascading blackouts, may strengthen assets and build redundancy to enable quicker service recovery [18]. Although most countries rely on government investment for infrastructure, the high opportunity cost of public funds has prompted a shift toward capital market financing [19]. Consequently, Insurance-Linked Securities (ILS) have appeared in the market as popular alternative tools to transfer the catastrophic risks to the capital market, such as catastrophe bonds and resilience bonds.

2.1. Catastrophe risk transfer instruments

Catastrophe risk transfer comprises financial arrangements, such as reinsurance and insurance-linked securities, which may shift disaster losses from exposed entities to specialised risk bearing capital in exchange for a risk adjusted premium. However, tail events can breach reinsurance layers and exhaust risk capital, creating solvency pressure and leading to insurer failure. Resilience bonds are considered as a variation of conventional catastrophe (CAT) bonds, which are insurance-linked securities with the focused on the development of resilient projects, such as flood defences and seawalls. According to Cummins [20] and Vaugirard [21], CAT bonds are widely applied by (re)insurers as a complementary tool to traditional markets, efficiently transferring catastrophe risks to capital market investors to hedge potential default risks. Canabarro and Finkemeier [22] describe the CAT bonds as Insurance-Linked Securities (ILS), offering exposure to catastrophe risks through bond issuance with coupon payments contingent on disasters. The first catastrophe-linked securities emerged in the market after the Hurricane Andrew, with CAT bonds soon introduced to the market in 1994 and experiencing rapid expansion in 1997 [23]. One example is the American Strategic Insurance Group, which has issued a catastrophe bond via Bonanza Re Ltd. on February 2020, offering USD 100 million in coverage for named storms, wildfires, and earthquakes across the US over four years. With an initial attachment probability and expected loss of 1.15% and 1.03%, the bond will be priced in the range from 4.25% to 4.75% [24]. As per Cummins [20], entities seek financial protection from the sponsors against the unpredictable losses; sponsors will issue CAT bonds via an issuer to raise collateral funds invested in highly rated market-like Treasury Bonds (T-Bill). SwissRe [25] state that CAT bonds specify coverage for catastrophic events in the pre-defined insurance contract, ensuring that investors receive the principal and coupon payment if no covered events happen during the bond's maturity period. If the specific pre-defined catastrophe event occurs, investors may lose part or all of their principal, which will be reimbursed to the insured entities through sponsor. While CAT bonds primarily deliver post-catastrophe reimbursement rather than provide support to the pre-catastrophe preparedness [15]. The newly published resilience bonds have been defined as a new insurance-linked financial instrument to support the public sector with physical and financial protections to against catastrophes [26]. According to Vaijhala and Rhodes [27], resilience bonds build on the same securitisation framework as CAT bonds, which convert modelled reduced losses into upfront funding for pre-catastrophe preparedness and resilience projects. The resilience bond has three main functions: (i) an insurance service designed similarly to the conventional CAT bond; (ii) a rebate mechanism that provides upfront funds based on forecast risk mitigation across the whole system; and (iii) a resilient project investments function, whereby loan proceeds are used to support the development of resilient infrastructure. The aim of a resilience bond is to connect the insurance coverage to the public-sector entities (which have already purchased insurance policies or a CAT bond) with the capital investments in resilience projects. Re:Focus [15] reported that the integration of CAT bonds with infrastructure investments brings impact because CAT bonds primarily address the financial recovery and post-disaster reimbursement, rather than strengthening physical resilience within society. Given that climate change has become a pressing global issue, which is marked by changing weather patterns and a rise in disaster risks, financial support from the innovative resilience bonds is increasingly important. The European Bank for Reconstruction and Development (EBRD) has launched the world's first climate resilience bond successfully, which has raised USD 700 million to support climate resilient projects, such as climate-resilient infrastructure, climate business and operations, or agriculture and ecological systems [28]. In addition, the interest in bonds has grown significantly, now including almost 40 investors from 15 countries [29].

2.2. From CAT bonds to resilience bonds

For earthquake-exposed cities like Istanbul, catastrophe risk transfer can be paired with resilience investments to both finance mitigation pre-catastrophe and secure contingent liquidity post-catastrophe. Resilience bonds are uncorrelated with financial markets and event-driven payoff investors like in CAT bonds, but extended a pre-catastrophe value engine; the verified mitigation lowers expected losses and risks over the bond maturity [30].

As shown in **Figure 1**, the CAT bonds (left) transfer a defined catastrophe risk from a sponsor to capital market investors through an issuer. The issuer is normally a bankruptcy remote special purpose vehicle (SPV). Investors' principals will be held in a collateral account which can only invest in high-quality products, such as US T-bills. Sponsor pays a coupon and if a pre-defined trigger is met, the trust releases some or all of the principal to the sponsor for post-catastrophe recovery; otherwise, investors receive their principal back at maturity plus the coupon. The resilience bond (right) applies the same securitisation foundation as CAT bonds, including the issuer, collateral trust, and established trigger types. To distinguish it from a CAT bond, resilience bonds generate upfront "rebates" to fund resilient infrastructure projects. The rebates represent the quantified reductions in risks and associated costs, which will be re-invested into resilience initiatives, thereby offering direct support rather than aftermath reimbursement or on-hold projects due to insufficient funding [15]. In the mechanism of resilience bonds, proposed infrastructure-strengthening projects will be evaluated by a third-party assessor, who estimates the risk reduction and translates it into premium and principal discounts, where the difference is the created rebates. This rebate supports the initial project cost or ongoing maintenance and operational expenses. The sponsor of the resilience bonds can be the entities interested in resilience investment, such as insurance companies seeking to safeguard projects during construction [30]. In the next section, the modelling and valuation framework for resilience bonds will be examined. The model enables investors, public–private entities, decision-makers, and governments to understand the value proposition of resilience bonds in resilient infrastructure investment; make informed decisions; and plan to develop the resilience bond market by aligning incentives across shareholders.

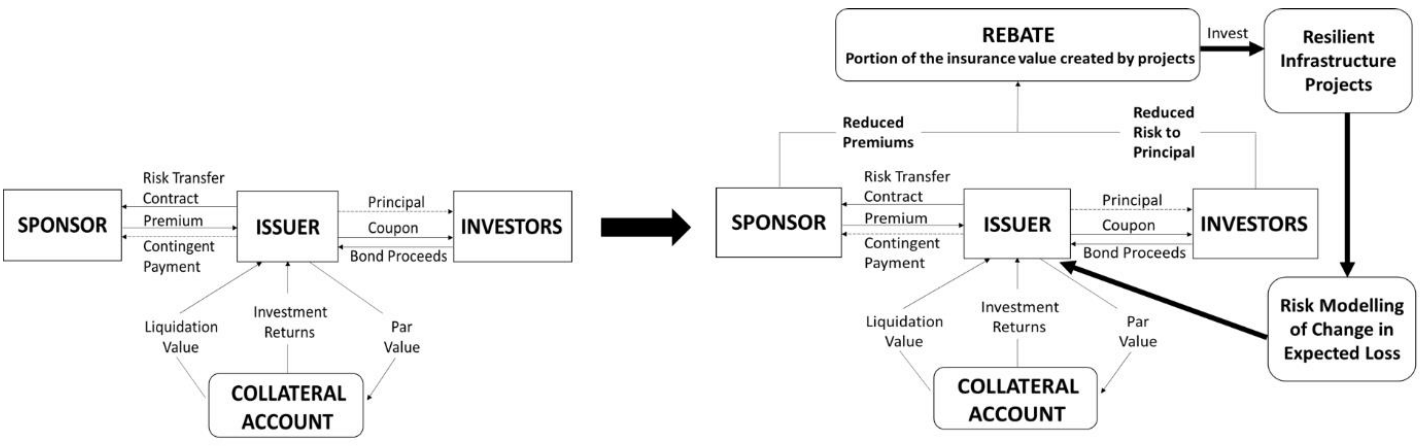

Figure 1 • Mechanisms of catastrophe bonds and resilience bonds [15].

3. Materials and methods

3.1. Data description

To reflect the real financial and earthquake dynamics in Turkey, this study applied two primary datasets. First, daily historical data from the Turkish Government Bond from 2024 to 2025 are used to simulate the dynamic interest rate environment. Second, the Turkish Catastrophe Insurance Pool (TCIP) historical dataset provides records of earthquake location, magnitude and claims from 2000 to 2024, which enable the calibration of the earthquake loss model, enhancing the accuracy of the loss projections. As an alternative financial instrument, this rational valuation model serves as a useful tool for decision-makers, guiding the fair market price for the municipal resilience bonds, and potentially increasing the attractiveness to investors by providing a clearer understanding of the risk and return.

Table 1 shows the 20 largest earthquake events recorded by the Turkish Catastrophe Insurance Pool (TCIP) from 2000 to 2024. For each event, it lists the date and time, location, moment magnitude (Mw), and total insurance claims. This study will use this historical record to calibrate the municipal resilience bond (MRB) valuation model. The claims series informs the frequency and severity parameters and the magnitude-loss mapping, from which we derive expected loss and tail metrics. These risk metrics are then translated into a fair spread over the risk-free zero-coupon yield curve used to price the MRB. The municipal resilience bonds valuation model involves several components. Initially, a stochastic model is employed to analyse time-series data, simulate the dynamic interest rate, and assess random earthquake events. Then, a compound Poisson process is utilised to represent the economic losses resulting from earthquake occurrences, for instance, the economic losses caused by high-magnitude earthquake events impacting vulnerable urban infrastructure in Turkey. Furthermore, it is assumed that the strengthening infrastructure projects can effectively mitigate the potential losses in Istanbul, Turkey. To quantitatively evaluate the value of municipal resilience bonds, different components are translated into modelling framework.

3.2. Methodology

Municipal resilience bonds (MRB) focus on enhancing infrastructure resilience through proactive investment to resilient projects that reduce economic losses from catastrophic events, such as earthquakes. The proposed municipal resilience bond (MRB) valuation model integrates several key components: stochastic loss modelling, earthquake magnitude, dynamic interest rate simulation, and effectiveness of resilient infrastructure projects resulting from reinvestments. These components will be used to construct the payoff function to capture a distinct dimension of risk and valuation for the bond.

Table 1 • Top 20 insurance claims from TCIP, 2000–2024 (currency in Turkish lira) [31].

Date	Time/location/magnitude	Claim (TRY)
2023/2/6	04:17:34/KAHRAMANMARAÅž/PAZARCIK/7.7	38,135,944,075
2023/2/6	13:24:47/KAHRAMANMARAÅž/ELBISTAN/7.6	762,317,417.5
2020/10/30	14:51:24 SEFERÄ° HÄ°SAR/6.6	558,176,266.9
2020/1/24	20:55:15/ELAZIG/SIVRICE/6.8	384,359,145.5
2024/10/16	10:46:31/MALATYA-KALE/5.9	376,712,708.7
2023/8/10	20:48:00/MALATYA/YEÅžILYURT/5.3	319,376,353.2
2022/11/23	04:08:15/DÃœZCE-GÃ–LYAKA/5.9	183,399,033.7
2011/10/23	13:41:00/VAN/MERKEZ/MERKEZ/6.6	116,809,749.2
2024/1/25	16:04:04/MALATYA/BATTALGAZI/5.2	107,068,775.1
2020/12/27	09:37:32/ELAZIÄž/MERKEZ/5.3	82,494,852.53
2019/9/26	13:59:24/MARMARA DENIZI/5.8	77,577,222.31
2023/7/25	08:44:49/ADANA/KOZAN/5.5	58,255,981.88
2021/2/1	08:46:53/EGE DENÄ°ZÄ°/KARABURUN/5.1	22,850,634.98
2020/3/19	20:53:31/ELAZIÄž/SÄ°VRÄ°CE/5.0	20,731,804.14
2011/11/9	21:23:00/VAN/EDREMÄ°T/EDREMÄ°T/5.6	12,756,844.23
2022/11/4	03:29:21/Ä°ZMÄ°R/BUCA 4.9	11,848,190.94
2011/5/19	23:15:00/KÃœTAHYA/SÄ°MAV/SÄ°MAV/5.9	9,782,567.99
2024/9/7	09:31:10/KAHMANMARAÅž/PAZARCIK/5.0	7,002,338.2
2017/7/21	01:31:12/GOKOVA KORFEZI/6.3	5,231,414.03
2020/6/5	21:06:20/MALATYA/PÃœTÃœRGE/5.0	5,230,068.56

3.2.1. Stochastic modelling of earthquake events and dynamic loss

This study models earthquake risk by adapting the approach from Shao, Pantelous, and Papaioannou [32] and Ma and Ma [33] to apply a stochastic time-series framework that simulates dynamic losses with the randomness of catastrophic event occurrences under different earthquake magnitudes. Specifically, earthquake occurrences and their severity over the period will be modelled as a compound Poisson process, which captures both the severity and frequency of earthquake events.

$$L(t) = E[e^{\beta \cdot M_j}] \cdot \sum_{j=1}^{N_t} \alpha \cdot e^{\beta \cdot M_j} \tag{1}$$

where

$L(t)$ is the expected loss; $L(t) = 0$ when $N_t = 0$;

N_t is the counting process follows Poisson process with event frequency λ;

M_j represents the magnitude of the *j-th* earthquake event;

α is the baseline loss for a unit-magnitude event, which $\alpha > 0$;

β is the growth parameter which controls the speed of damage escalates with magnitude ($\beta > 0$);

$E[e^{\beta \cdot M_j}]$ is the scaling factor.

By establishing the baseline for expected earthquake losses, the foundation of the financial valuation can be built. Since bond pricing also depends on the future cash flows, the next step will be to work on the dynamic of the interest rate.

3.2.2. Modelling the dynamic interest rate

The dynamic fluctuations of the interest rate are essential in the pricing of bonds; the effects are directly related to the discounting of future cash flows and losses. The Vasicek short-rate model is a pragmatic choice for simulating the dynamic interest rate in this study. It is simple, fast, and transparent, while capturing the key features of interest rates of the mean reversion [34]. The model delivers close-form zero-coupon prices, so discount factors drop straight out without heavy numeric, which is ideal when interest rates are only one part of a larger Monte Carlo engine. The Vasicek model handles low and negative rates and avoids over-parameterisation and over-fitting, reducing noise in scenarios and speeding runtime. The Vasicek model offers the best balance of realism, tractability, and explainability for bond valuation where rate risk is not the dominant driver [21]. Therefore, this study applies the Vasicek model to simulate the short-term interest rate r_t:

$$dr_t = k(\theta - r_t)\, dt + \sigma r_t dW_t \tag{2}$$

where

r_t is dynamic interest rate at time t (in years);

dW_t is a Wiener process (Brownian motion);

$k(\theta - r_t)$ is the drift factor, where k is the speed of reverting to the average rate θ, σ is volatility, and k, θ, σ are all positive constants.

With both earthquake losses and interest rate fluctuations, the framework can turn to defining the payoff mechanism that links the resilience measures to the bondholder's returns. The next section defines the payoff function of the Municipal Resilience Bond; it states the coupon payments, principal fractions, and resilience rebate under the chosen trigger. Combining that payoff function with the Vasicek discount factors converts physical risk into price.

3.3. Payoff function of municipal resilience bonds

Strengthening urban infrastructure projects is expected to enhance resilience and mitigate future unexpected losses, denoted by L_T. Following the methodology of [26], we introduce the parameter of effectiveness ($\check{\mathfrak{z}}$) to quantify the impact of the resilience measures. The effectiveness (resilience) parameter is introduced to make the payoff function reflect the real risk changes when the investor's capital is re-invested in prevention and mitigation. The parameter summarises how much the retrofit and redundancy programme lowers expected losses across the infrastructure system; higher values indicate greater risk reduction and feed directly into the bond's valuation. The pre-defined contract for the payment mechanism is determined by the payoff function below, which considers whether the probability of aggregate losses after the deduction of resilience from the strengthening project have exceed the predefined threshold D_M in the municipal resilience bond contract.

$$P_{RB}(T) = \begin{cases} F\rho & \text{if } L_T - \check{\mathfrak{z}} L_T > D_M \quad (bondistriggered), \\ F & \text{if } L_T - \check{\mathfrak{z}} L_T \le D_M \quad (otherwise), \end{cases} \tag{3}$$

where

P_{RB} is the payoff function of resilience bond at maturity;

ρ represents the proportion of the face value repaid to investors;

F is the face value of the resilience bond;

L_T is aggregate losses;

D_M represents trigger value based on the earthquake magnitude;

$\check{\mathfrak{z}}$ is the impact of the resilient infrastructure project, where $0 < \check{\mathfrak{z}} < 1$.

To summarise the final municipal resilience bond valuation model, the study integrates the three core components: the dynamic loss estimation mode, the dynamic interest rate model, and the municipal resilience bond payoff structure. These models work together to capture the impact of earthquake risks, the time value of money, and the effectiveness of resilience investments.

$$V_t = B_{Vasicek}(t, T) \cdot P_{L_{im}} \cdot \sum_{i=4}^{8} 1_{M \in (\mu_i, \mu_{i+1})} \cdot \left[\rho F \cdot 1_{(1-\check{\mathfrak{z}})L_{im > D_M}} + F \cdot 1_{(1-\check{\mathfrak{z}})L_{im \le D_M}} \right] \tag{4}$$

where

V_t is the value of the municipal resilience bond at time t;

$B_{Vasicek}(t, T)$ is the simulation of dynamic interest rate with an application of Vasicek model;

$P_{L_{im}}$ is the probability of the level of loss occurring;

$\sum_{i=4}^{8} 1_{M \in (\mu_i, \mu_{i+1})}$ is the sum of four indicator functions, considering that the earthquake magnitude M falls inside (4,5), (5,6), (6,7), and (7,8) levels;

$\left[\rho F \cdot 1_{(1-\check{\mathfrak{z}})L_{im>D_M}} + F \cdot 1_{(1-\check{\mathfrak{z}})L_{im\leq D_M}}\right]$ represents the expected payoff of cash flow;

ρF is the proportion of the face value repaid to investors if the bond triggered;

L_{im} is the economic loss associated with the specific earthquake intensity interval;

D_M represents trigger value based on the earthquake magnitude, where $4 < M < 8$.

The payoff function links the physical risk reduction, earthquake modelling, financial dynamics, and resilience incentives. Having established the data sources and methodology, the following section details how they are incorporated into the modelling process and the empirical results of the modelling.

4. Results

4.1. Empirical results

To evaluate the municipal resilience bond (MRB), the model was calibrated using the TCIP record of 1141 earthquake events from December 2000 to November 2024, including the date, location, moment magnitude, and indemnity payment in Turkish lira (TRY). As expressed in **Equation (1)**, the calibration was carried out in three steps. Firstly, the annual frequency of events was estimated as the total number of earthquakes divided by the observation years to obtain 47.74 events per year. Secondly, the indemnity claims data was fitted in several heavy-tailed distributions, such as log-logistic (Fisk), lognormal, and generalised extreme value (GEV). Thirdly, the study applied the Akaike Information Criterion (AIC) and the Kolmogorov–Smirnov (K-S) test to compare the goodness-of-fit for the distributions. The results showed that the log-logistic (Fisk) distribution best captures the heavy-tailed nature of earthquake losses. Most claims data are modest; the median is about TRY 10,232 and half of the claims fall between TRY 3103 and TRY 52,516. However, the data are extremely right-skewed. For instance, the 95th percentile is around TRY 1,304,635 and the largest claim reaches TRY 38,135,944,074, which pulls the average up to roughly TRY 36,308,452. Consequently, many small-to-medium claims are accompanied by a few very large ones that dominate the tail. By fitting the dataset in log-logistic distribution, the result obtained with shape $c \approx 0.771$ and scale $s \approx 12,478$, indicating a heavy tail and medians, are more reliable than average since $c < 1$. Lognormal is the next best distribution for describing the heavy-tailed pattern of the claims dataset. The study assumed that earthquake magnitude and indemnity claims in the TCIP dataset follow a log-linear relationship. The baseline loss (α) is obtained from the intercept of a regression of the natural logarithm of claims (ln[claim]) on earthquake magnitude (M). In addition, the growth parameter (β) is obtained from the slope of the log-linear regression to measure how quickly claims increase with magnitude. As the functional form systematically underestimates the actual TCIP claim, the scaling factor—severity multiplier ($E[e^{\beta \cdot M_j}]$)—was introduced. The severity multiplier was calculated as the ratio of the observed mean claim to the model-implied mean claim, which equals 270.3. This scaling factor is constant and ensures that the calibrated model reproduces the empirical loss levels while preserving the magnitude–loss relationship. Then, we can obtain the following summary.

As shown in **Table 2**, the calibrated parameters define the annual loss distribution that drives the MRB's expected loss and tail risk. The pricing model of the bond also depends on the time value of money, where simulated event-contingent cash flow needs to be converted to the present values to derive a fair spread over the zero-coupon yield curve. In this way, the next section will introduce the Vasicek dynamic interest rate model which is used to describe the current term structure.

Table 2 • Parameters of dynamic loss model.

Parameter	Value
Sample size—earthquake events	1141 times/24 years
Observation window	24 years (Dec 2000 to Nov 2024)
Magnitude range (M)	2.4 to 7.8
Baseline loss (α)	3,922.7421 TRY
Growth parameter (β)	0.307921
Event frequency (λ)	47.74 earthquakes/year (over 24 years)
Severity multiplier ($E[e^{\beta \cdot M_j}]$)	270.3118
Expected loss	1,060,364 TRY
Expected annual loss	50,625,130 TRY

To ensure that the Vasicek interest rate model reflects the actual dynamics of the Turkish financial market, we validate the model (**Equation (2)**) by calibrating daily yield data from Turkish Government Bonds over a two-year period (2024–2025).

Figure 2 shows 50 simulated short rate paths in different colours generated with the calibrated Vasicek parameters for Turkey. Each coloured line is one Monte Carlo simulation representing a possible time path of the short term interest rate, showing how the rate could move over time under different random shocks. The horizontal blue line marks the long-run mean. The paths fluctuate with shocks but quickly revert toward the mean and the dispersion around the level reflects the estimated volatility. The simulated interest rate paths reproduced the mean-reverting dynamics observed in the market, and these paths generate the scenario-specific discount rates used in valuation and robustness analysis. The calibration obtained the following parameters: $k\,(speed) = 2.4751$; $\theta\,(mean) = 34.3909\%$; $\sigma\,(volatility) = 6.5311\%$; and $r_0 = 0.3103$.

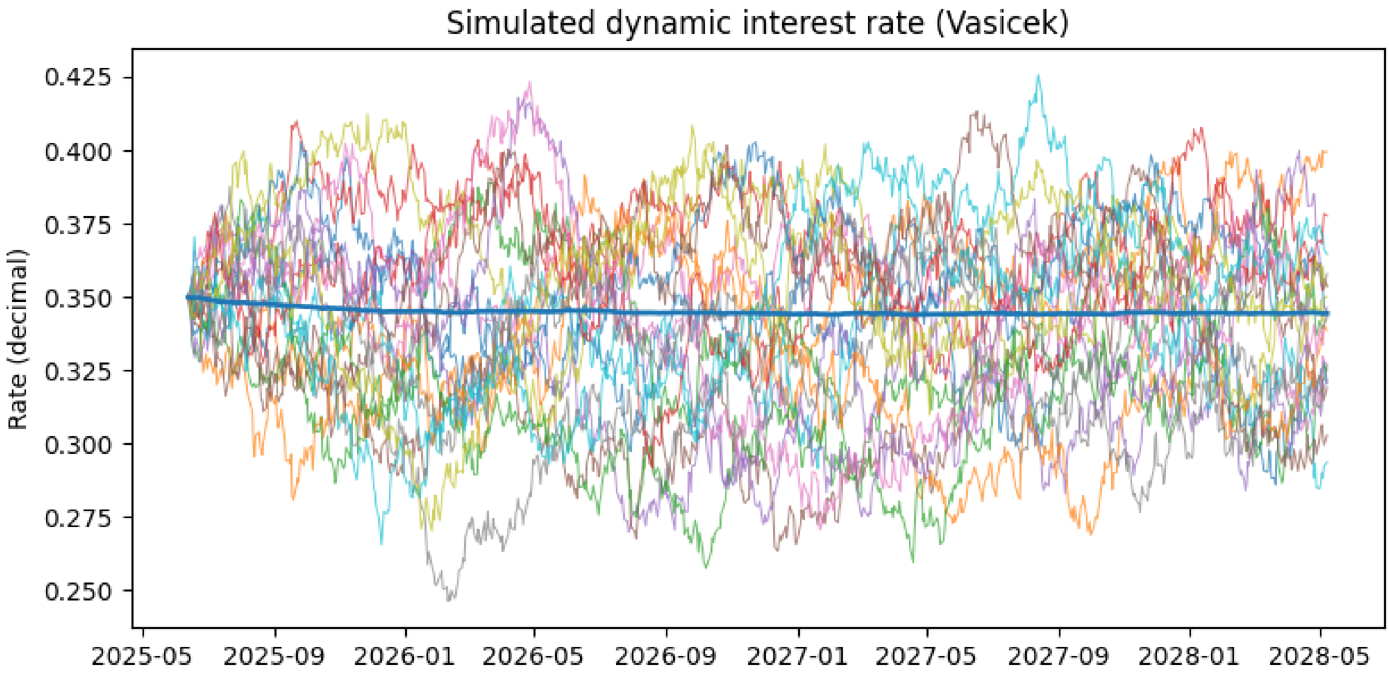

Figure 2 • Dynamic interest rate simulation via Vasicek model. Each coloured line represents one Monte Carlo scenario showing a possible path of the short term interest rate over time. The horizontal blue line indicates the long run mean rate.

The payoff function of the MRB determines how much investors receive at maturity, depending on the severity of earthquake losses and the effect of resilience measures, as shown in **Equation (3)**. Aggregate earthquake losses are compared against the trigger threshold linked to earthquake magnitude, where the trigger is defined as the product of the mean expected loss within a given earthquake magnitude band, adjusted for the resilience effectiveness parameter (ǯ) and the empirical probability of an event occurring in that band. If losses remain below the threshold, investors receive repayment proportional to the bond's face value. Otherwise, if losses exceed the trigger, the payout is reduced as an assumed proportion ($\rho = 60\%$) of the face value repaid to investors, reflecting the transfer of risk to investors. From the dynamic loss estimation model, we categorised the earthquake into four magnitude bands from levels 4 to 8. To account for the expected earthquake risk mitigation from the resilience investment, we assume the infrastructure-strengthening generates a 20% loss reduction (ǯ = 20%). The framework simulates the realistic and data-driven assessment of the resilience bond's risk-adjusted performance, while supporting strategic planning for Istanbul with earthquake risk mitigation and sustainable urban finance.

The final valuation framework for the MRB is constructed by integrating three complementary components. The combination in **Equation (4)** ensures that resilience benefits are explicitly quantified and reflected in the bond's value. By considering a 20% deduction in expected losses through infrastructure strengthening and considering that the municipal bond will pay 80% per 100 par value at maturity to investors, and with consideration of the discounted factor via the interest rate model, the yield of the municipal resilience bond is 31.73. This final estimated price of TRY 31.73 per 100 par shows the risk adjusted market value of the proposed Turkish municipal resilience bonds, considering both the probability of earthquake losses and the time value of the money under dynamic interest rate conditions. For investors who are interested in resilience investment, the price implies that investors are only expected to recover about 37.31% of their principal plus a high coupon returns if any earthquake occurs. However, this price also reflects the level of earthquake risks being mitigated by preparing the urban infrastructure in advance. An application of this bond may attract governments and municipalities since it offers cost-effective protection to hedge the future unexpected earthquakes. Resilience bonds can be extended to cover floods, hurricanes, wildfires, and earthquakes. It may benefit different cities and regions suffering from infrastructure investment deficit and growing catastrophe risk exposure. The valuation of the municipal resilience bond is not just a numerical price but also reflects the transition of how public sectors measure, finance, and reward resilience. This model provides a bridge between risk science and financial markets, providing opportunities for private and public investors to make data-backed decisions that lead to safer and more sustainable cities.

4.2. Sensitivity analysis: resilience effectiveness (ǯ)

In order to assess the impact of resilience investments on the municipal resilience bond's valuation, the study conducted a sensitivity analysis on the resilience effectiveness parameter (ǯ). The parameter represents the percentage reduction in expected losses due to the performance of infrastructure retrofit projects. By varying ǯ from 0% (no reduction) to 80% (highly effective reduction), the results show the influence of resilience performance to both the expected payoff and the fair price of the bond. This sensitivity analysis shows the financial value of resilience, highlighting the positive correlation between the investment in infrastructure retrofit projects and bond attractiveness to investors.

Table 3 demonstrate the results of the financial value of resilience investments in the municipal resilience bond issuance. As the resilience effectiveness of risk mitigation measures increase, the fair price of the Turkey Resilience Bond rises significantly. In the scenario of no mitigation (0% resilience), the bond is valued at just TRY 25.38 per 100 par, which reflects the high risk of loss in the event of an earthquake. However, with the moderation of 20% resilience, the fair price improves to TRY 31.73 and continues to climb with higher mitigation levels of 80% resilience at TRY 44.65. In this sensitivity analysis, a 60–80% resilience effectiveness is used solely as an assumed upper-bound scenario to explore the maximum potential impact; such a high mitigation in losses is rarely achieved in practice due to the scale, cost, and complexity of implementation. The improvements can be translated as the direct additional capital that municipalities can raise. For example, to estimate the additional capital that can be gained through higher resilience effectiveness levels, the study assumes that the municipal authority issues TRY 1 billion (par value) in municipal resilience bonds; the table below shows how the capital gains changes with different level of mitigations:

As shown in **Table 4**, the resilience effectiveness and capital gain tables show the quantifiable relationship between the level of disaster risk reduction and the financial performance of municipal resilience bonds (MRB). The investments in earthquake retrofitting or infrastructure enhancement projects will improve investors' expected payoff and the fair market price of the bond will rise. The MRB's price increase from TRY 25.38 in the absence of mitigation to TRY 44.65 when the resilience level is 80%, reflects a 76% increase in the bond value. With 20% resilience effectiveness, the municipality can raise TRY 317.3 million, which is TRY 63.5 million over the no-mitigation scenario. Furthermore, the total capital raised reaches TRY 446.5 million at 80% resilience effectiveness, which is TRY 192.7 million higher than the no mitigation scenario. These findings not only show the economic benefits of resilience investment in MRB but also demonstrate a strategic pathway for municipalities to increase the financing capacity for infrastructure projects. This sensitivity analysis provides a foundation for understanding the financial value of resilience, which directly informs the next section on developing the municipal resilience bond market. These insights can be applied to enhance the mechanism and market design, investor engagement, and policy frameworks.

Table 3 • Impact of resilience effectiveness on expected payoff and bond fair price.

Resilience effectiveness ξ	Loss reduction	Expected payoff E[P(T)]	Discounted price (per 100 par)
0% (no mitigation)	0%	64.00	25.38
10%	10%	72.00	28.56
20% (base case)	20%	80.00	31.73
30%	30%	87.50	34.70
40%	40%	94.00	37.27
60% (rare)	60%	105.00	41.65
80% (rare)	80%	112.50	44.65

Table 4 • Projected capital gains from varying levels of mitigation effectiveness.

Resilience effectiveness	Fair price (TRY) per 100 par	Total capital raised (TRY million)	Capital gain vs. no mitigation (TRY million)
0%	25.38	253.8	–
20%	31.73	317.3	+63.5
40%	37.27	372.7	+118.9
60%	41.65	416.5	+162.7
80%	44.65	446.5	+192.7

5. Discussion: developing municipal resilience bond mechanism in Istanbul, Turkey

Istanbul holds almost 18.3% of the population of Turkey and approximately 30.4% of national GDP [35, 36]. The city faces a high medium-term earthquake risk, where the earthquake probability is 62%, with strong shaking in Istanbul within 30 days and 64% probability of magnitude greater than 7 within 7 years. However, there is only 65% earthquake insurance coverage for residences.

Catastrophic events, such as earthquakes, floods, and hurricanes are High-Impact Low-Probability (HILP) events, which are unlikely to occur, with low probability, but once they happen, will bring significant consequences. According to Görmez, Köksalan, and Salman [37], the Istanbul Metropolitan Municipality has pre-positioned relief strategies for post-catastrophe operations in anticipation of a potentially destructive earthquake in the near future. In order to strengthen urban resilience and expand the insurance coverage, the Turkish government and private sector have taken actions in advance to hedge a destructive earthquake event; for example, the issuance of second catastrophe bonds from the Turkish Catastrophe Insurance Pool [38]. However, a key limitation of catastrophe bonds is that they only reimburse post-disaster economic losses rather than help with preparing the city against unpredictable catastrophes. The study therefore proposes a municipal resilience bond for Istanbul to foster public–private cooperation and fund pre-catastrophe measures that make the city more robust. As Üstün [1] suggests, Istanbul should examine and adapt good disaster resilience management examples from developed countries; the local and central administrations should learn from historical experiences and promote pre-catastrophe efforts, such as allocating financial resources efficiently, strengthening and retrofitting infrastructures and buildings, and updating information on the condition of infrastructure and public facilities. Globally, governments are typically responsible for investing in the development of infrastructure projects; however, restricted public funding, which comes mainly from tax and tolls, often struggle to cover the high costs of various development projects. The OECD [9] show that there are plenty of opportunities for infrastructure investment in developing countries, though investors may not be fully aware of these opportunities because of barriers in this context. In this way, a municipal resilience bond could act as the bridge and bring the opportunities for the Istanbul Municipality to raise sufficient funds from capital market investors, especially for resilient infrastructure projects, as well as gaining insurance services to hedge the potential economic losses from unpredictable catastrophes.

Figure 3 illustrates the mechanism of applying municipal resilience bonds (MRBs) in Istanbul, Turkey. An insurer issues the MRB to public and private investors; then, the principal from investors will be saved in a fully collateralised account and invested in high-quality assets only. The Istanbul Metropolitan Municipality (IMM) signs a risk transfer contract with the insurer and pays the insurance premium. If the pre-defined trigger events (earthquakes) is met, the insurer uses the collateral fund to make a contingent payment to IMM, covering emergency liquidity and early recovery. Meanwhile, an independent third party will estimate and quantify the risk reduction generated by the resilience infrastructure projects, which is captured by the Resilience Effectiveness parameter (ǯ). The change in expected losses will be monetised as a rebate and reinvested in the infrastructure retrofit/enhancement projects. The following section identifies the key entities, explains how risk reduction is measured and converted into a rebate, and defines eligible resilience projects for Istanbul, Turkey.

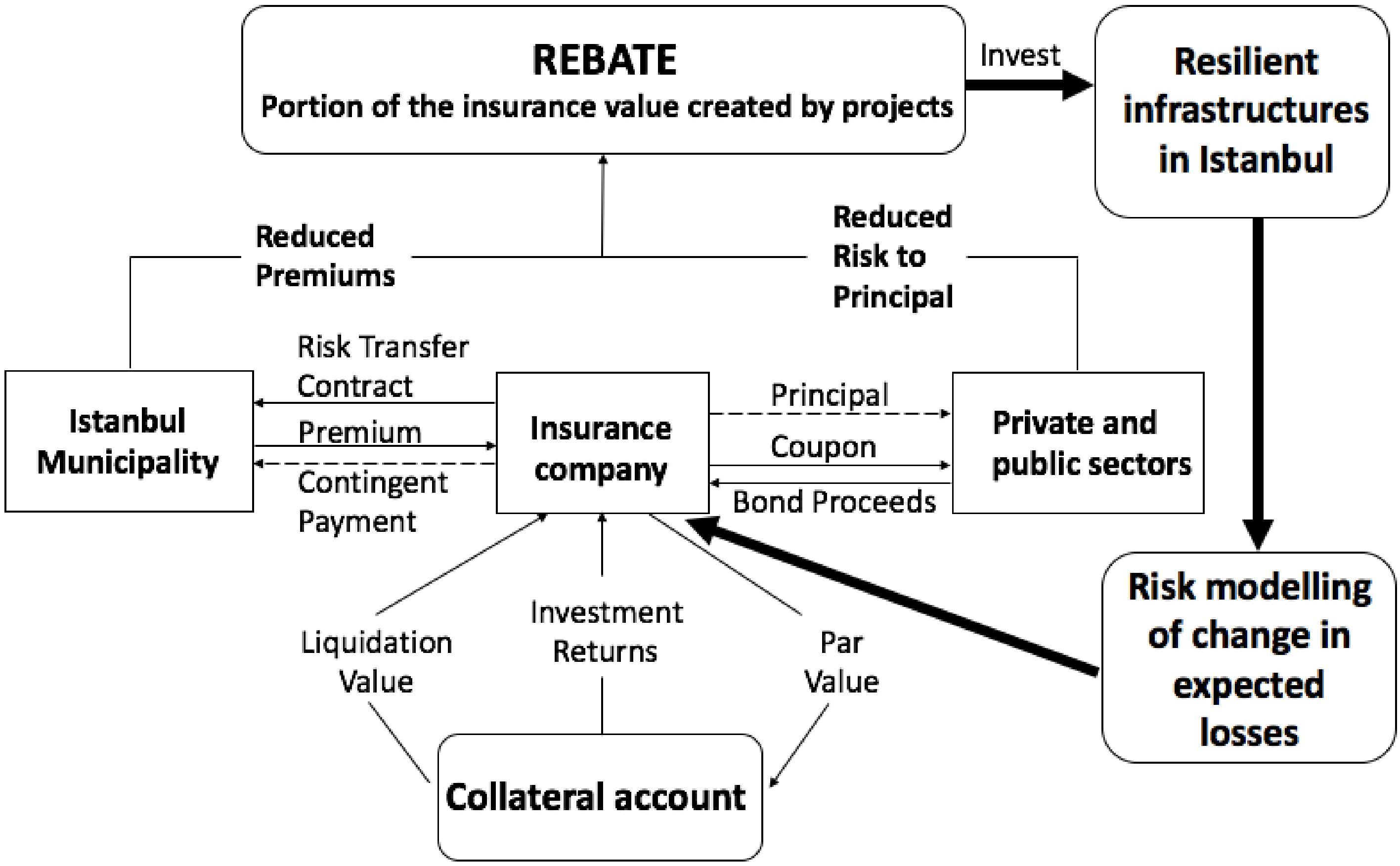

Figure 3 • Istanbul municipal resilience bonds mechanism [15].

5.1. Entities involved in municipal resilience bonds

The resilience bond is modelled based on the mechanism of CAT bonds, maintaining a similar insurance function that is designed to protect sponsors from unforeseen catastrophe risks [39]. The Istanbul Metropolitan Municipality is the sponsor seeking contingent protection and lower financing costs for infrastructure projects. Issuance can be executed via an SPV arranged with a (re)insurer or bank. The potential investors of the municipal resilience bonds could be investors who are interested in high-yield bonds, including pension funds, mutual funds, hedge funds, and commercial banks. Investor funds flow into the collateral account, coupons are paid from investment returns, and principal is returned at maturity in the absence of a qualifying catastrophic event.

5.2. Risk reduction and rebate mechanism

Climate change is one of the most serious long-term issues that challenges countries around the world. Adger, Agrawala, and Mirza [40] show that countries globally should pay significant attention to the continued challenges of climate change; the consideration of enhancing resilience or reducing vulnerability should be put into adaptation practices. MRB finances pre-catastrophe resilience and transfers post-catastrophe risk. Istanbul could implement a portfolio of upgrades to the existing infrastructure (retrofits, lifeline redundancy, early warning). An independent model estimates the change in expected loss from these measures, which is reflected by the resilience effectiveness parameter ($\check{\zeta}$). If the trigger is met, the MRB will pay out the reimbursement, but verified risk reduction from the infrastructure projects lowers both the probability and severity of any principal loss for investors.

5.3. Eligible projects and the market in Istanbul, Turkey

The Istanbul Climate Change report [41] highlights that as the most populated city in Europe, Istanbul is ranked highest in the assessment of potential economic losses from extreme weather events among 15 European coastal cities. For instance, Turkey faced extreme weather conditions in 2017, experiencing both severe droughts and floods, which significantly impacted different infrastructure sectors, e.g., transportation and housing. Building resilience in Istanbul involves strengthening infrastructure to withstand, manage, absorb, and adapt to climate change threats. For example, earthquake engineering prioritises maintaining functionality and speed of recovery from earthquake events, aiming to mitigate fatalities and infrastructure damages [42]. Projects eligible for applying MRB to generate rebates to be reinvested to infrastructure projects include earthquake retrofits and base isolation for schools and hospitals, the strengthening of critical infrastructure, and upgrades to the infrastructure network.

With Istanbul's growing population, strengthening its resilience to infrastructure will create eligible infrastructure projects in the market, which may create opportunities for the expansion of municipal resilience bonds. Istanbul can issue TRY tranches through an SPV to tap global insurance-linked securities investors while also engaging domestic institutions. The MRB's verified loss reduction and ring-fenced use of proceeds align naturally with ESG. As Environmental, Social and Governance (ESG) investing is gaining popularity among different investing philosophies nowadays, evaluating performance through ESG criteria and metrics brings more opportunities for resilience investing [43]. According to Boffo and Patalano [44], ESG scoring and reporting presents opportunities for companies to participant in investing resilience to create long-term value. Hachenberg and Schiereck [45] show one advantage to be that financial instruments employing ESG criteria typically outperform those that do not consider ESG. Integrating ESG evaluation into the municipal resilience bonds could broaden investor interest, attracting private finance from resilience and ESG investments and improving market opportunities. Future research could explore methods for incorporating ESG performance metrics, particularly with a focus on municipal resilience bonds, assessing its potential to improve investor engagement, enhancing bond performance and support sustainable resilience practices. The MRB creates a practical bridge between Istanbul's resilience pipeline and deep capital market capital with the strengthening of the preparedness to unexpected catastrophes.

5.4. Limitations

This study has several constraints. The characterisation of Istanbul's catastrophes may not fully capture site effects or compounding perils. Exposure and vulnerability inventories have gaps and some fragility functions are adapted from non-local studies. While Monte Carlo propagates parameter uncertainty, structural model uncertainty, spatial correlation and event clustering are only partially represented. We mitigate these issues by documenting data provenance, reporting sensitivity to key parameters, and applying conservative assumptions. Future work will extend site-response and multi-catastrophes modules, calibrate fragilities with local data, model network recovery, and test alternative rate/spread processes.

6. Conclusions

This study proposes a novel framework for the valuation of municipal resilience bonds in the Turkish market and explores the potential to develop the bond market. The proposed municipal resilience bond provides a targeted solution to the significant funding gap between the Istanbul Municipality and financial markets. The bonds attract private investors who are interested in resilient infrastructure investments. The application of a municipal resilience bond not only provides funding for infrastructure development but also incentivises pre-catastrophe preparedness. The paper develops a tractable valuation mechanism that links verified risk reduction to municipal resilience bond pricing for Istanbul's earthquake exposure. By integrating a compound Poisson loss process, the Vasicek short-rate model and a magnitude-banded payoff function with an explicit resilience effectiveness parameter, the framework quantifies how pre-catastrophe mitigation translates into fair value for municipal resilience bonds (MRBs). The empirical application of the MRB demonstrates that resilience has measurable financial value. In the base case, a 20% reduction in expected losses yields a discounted fair price of TRY 31.73 per 100 par, while stronger mitigation ($\check{\zeta}$ up to 80%) increases the price to TRY 44.65, significantly expanding feasible proceeds for infrastructure retrofit or upgrades projects. These results show that MRBs can recycle modelled risk reductions into upfront "rebates" that align with the incentives of municipalities, (re)insurers, and investors and shift the balance from post-catastrophe relief to pre-catastrophe preparedness in Istanbul.

This paper contributes both a valuation framework and a strategic rationale for applying resilience bonds in Istanbul. By integrating real Turkish data and quantifying the value of earthquake risk mitigation into the municipal resilience bond pricing model, it provides data-driven insights to help entities understand how cities like Istanbul can adopt this innovative instrument not only for earthquake recovery, but also to improve resilience through advance preparation. Municipal resilience bonds can attract growing numbers of institutions' investments, which increasingly follow ESG investments. Most ESG investors show interest in financial instruments that deliver social impact and align with global sustainability goals. Introducing resilience bonds to Turkey's disaster risk market could foster the development of a financial ecosystem for resilience investment. This study can serve as a blueprint for municipalities globally to create opportunities to apply the valuation model to price bonds in the local context, raise funds for municipal budgets, and plan catastrophe preparedness in advance. Resilience bonds represent more than just a financial instrument; the bond provides an innovative financial strategy for climate adaptation. Adopting such an innovative financial instrument in Istanbul is essential to ensure public safety and to build a sustainable future for its economy.

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Conflict of interest

The authors declare that they have no competing interests.

Data availability statement

The data supporting the findings of this publication can be made available upon request.

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References

1. Üstün AK. Evaluating İstanbul's disaster resilience capacity by data envelopment analysis. Nat Hazards. 2016;80(3):1603–23. doi: 10.1007/s11069-015-2041-y
2. Ay D, Demires Ozkul B. The strange case of earthquake risk mitigation in Istanbul. City. 2021;25:1–21. doi: 10.1080/13604813.2021.1885917
3. El Ezz AA, Smirnoff A, Nastev M, Nollet M-J, McGrath H. ER2-earthquake: Interactive web-application for urban seismic risk assessment. Int J Disaster Risk Reduct. 2019;34:326–36. doi: 10.1016/j.ijdrr.2018.12.022
4. Tekeli-Yeşil S, Dedeoğlu N, Braun-Fahrlaender C, Tanner M. Factors motivating individuals to take precautionary action for an expected earthquake in Istanbul. Risk Anal Int J. 2010;30(8):1181–95. doi: 10.1111/j.1539-6924.2010.01424.x
5. Erdik M, Aydinoglu N, Fahjan Y, Sesetyan K, Demircioglu M, Siyahi B, et al. Earthquake risk assessment for Istanbul metropolitan area. Earthq Eng Eng Vib. 2003;2(1):1–23. doi: 10.1007/BF02857534
6. Erdik M, Durukal E. Earthquake risk and its mitigation in Istanbul. Nat Hazards. 2008;44(2):181–97. doi: 10.1007/s11069-007-9110-9
7. Izumi T, Shaw R, Djalante R, Ishiwatari M, Komino T. Disaster risk reduction and innovations. Prog Disaster Sci. 2019;2:100033. doi: 10.1016/j.pdisas.2019.100033
8. Kim J-M, Yum S-G, Park H, Bae J. Strategic framework for natural disaster risk mitigation using deep learning and cost-benefit analysis. Nat Hazards Earth Syst Sci. 2022;22(6):2131–44. doi: 10.5194/nhess-22-2131-2022
9. OECD. Fostering investment in infrastructure: lessons learned from OECD investment policy reviews. OECD investment policy reviews. 2015 [accessed on 2025 Oct 1]. Available from: https://ppp.worldbank.org/sites/default/files/2022-04/Fostering-Investment-in-Infrastructure.pdf

10. Kamiya M, Zhang L-Y. Finance for city leaders handbook—improving municipal finance to deliver better services. Nairobi: United Nations Human Settlements Programme; 2016.

11. Koppenjan JF, Enserink B. Public–private partnerships in urban infrastructures: reconciling private sector participation and sustainability. Public Adm Rev. 2009;69(2):284–96. doi: 10.1111/j.1540-6210.2008.01974.x

12. García-Lamarca M, Ullström S. "Everyone wants this market to grow": the affective post-politics of municipal green bonds. Environ Plan E Nat Space. 2020;2020:2514848620973708. doi: 10.1177/2514848620973708

13. OECD. Green bond: mobilising the debt capital markets for a low-carbon transition. 2015 [accessed on 2025 Oct 1]. Available from: http://web-archive.oecd.org/2016-03-03/389765-Green%20bonds%20PP%20[f3]%20[lr].pdf

14. Mathews JA, Kidney S. Financing climate-friendly energy development through bonds. Dev South Afr. 2012;29(2):337–49. doi: 10.1080/0376835X.2012.675702

15. Re:Focus. Leveraging catastrophe bonds: as a mechanism for resilient infrastructure project finance. RE bound insurance report. 2015 [accessed on 2025 Sep 27]. Available from: https://www.refocuspartners.com/wp-content/uploads/2017/02/RE.bound-Program-Report-December-2015.pdf

16. Spry J. Non-life insurance securitization: market overview, background and evolution. In: The handbook of insurance-linked securities. Hoboken (NJ): John Wiley & Sons; 2012. p. 7–18. doi: 10.1002/9781119206545.ch2

17. Kaur H, Singh SP. Disaster resilient proactive and reactive procurement models for humanitarian supply chain. Prod Plan Control. 2022;33(6–7):576–89. doi: 10.1080/09537287.2020.1834124

18. Kong J, Simonovic SP, Zhang C. Resilience assessment of interdependent infrastructure systems: a case study based on different response strategies. Sustainability. 2019;11(23):6552. doi: 10.3390/su11236552

19. Gichoya D. Factors affecting the successful implementation of ICT projects in government. Electron J e-Gov. 2005;3(4):175–84 [accessed on 2025 Sep 27]. Available from: https://academic-publishing.org/index.php/ejeg/article/view/440

20. Cummins JD. CAT bonds and other risk-linked securities: state of the market and recent developments. Risk Manag Insur Rev. 2008;11(1):23–47. doi: 10.1111/j.1540-6296.2008.00127.x

21. Vaugirard VE. Pricing catastrophe bonds by an arbitrage approach. Q Rev Econ Financ. 2003;43(1):119–32. doi: 10.1016/S1062-9769(02)00158-8

22. Canabarro E, Finkemeier M, Anderson RR, Bendimerad F. Analyzing insurance-linked securities. J Risk Financ. 2000;1(2):49–75. doi: 10.1108/eb043445

23. Bouriaux S, MacMinn R. Securitization of catastrophe risk: new developments in insurance-linked securities and derivatives. J Insur Issues. 2009;32:1–34 [accessed on 2025 Oct 1]. Available from: https://www.jstor.org/stable/41946289

24. Evans S. American strategic owner's Bonanza Re 2020-2 cat bond fixed at $295m. ARTEMIS. 2020 [accessed on 2025 Sep 26]. Available from: https://www.artemis.bm/news/american-strategic-owners-bonanza-re-2020-2-cat-bond-fixed-at-295m/

25. SwissRe. SCF forum: disaster risk finance insurance incl. cat and resilience bonds. Swiss Re global partnerships. 2016 [accessed on 2025 Sep 27]. Available from: https://unfccc.int/files/adaptation/application/pdf/kessler_-_2016_scf_forum_-_drfi_solutions_incl_cat_bonds.pdf

26. Song Y, Medda F, Wang M. The value of resilience bond in financing flood resilient infrastructures: a case study of Towyn. J Sustain Financ Invest. 2024;14(4):889–912. doi: 10.1080/20430795.2024.2366200

27. Vaijhala S, Rhodes J. Resilience bonds: a business-model for resilient infrastructure. Field actions science reports the journal of field actions. 2018 (Suppl. 18):58–63 [accessed on 2025 Sep 27]. Available from: http://journals.openedition.org/factsreports/4910

28. Bennett V. World's first dedicated climate resilience bond, for US$ 700m, is issued by EBRD. European bank for reconstruction and development. 2019 [accessed on 2025 Oct 1]. Available from: https://www.ebrd.com/home/news-and-events/news/2019/worlds-first-dedicated-climate-resilience-bond-for-us-700m-is-issued-by-ebrd.html

29. Bigoni M. Climate bonds standard version 3.0. Climate bonds initiative. 2019 [accessed on 2025 Oct 1]. Available from: https://www.climatebonds.net/files/documents/Climate-Bonds_Climate-Bonds-Standard_V3_Dec-2019.pdf

30. Song Y. Resilience bonds and the financing of resilient infrastructure [PhD thesis]. London: UCL (University College London); 2022.

31. TCIP NDII. 2025 [accessed on 2025 Oct 1]. Available from: https://www.dask.gov.tr/en/about-the-tcip

32. Shao J, Pantelous A, Papaioannou AD. Catastrophe risk bonds with applications to earthquakes. Eur Actuar J. 2015;5(1):113–38. doi: 10.1007/s13385-015-0104-9

33. Ma Z-G, Ma C-Q. Pricing catastrophe risk bonds: A mixed approximation method. Insur Math Econ. 2013;52(2):243–54. doi: 10.1016/j.insmatheco.2012.12.007

34. Vasicek O. An equilibrium characterization of the term structure. J Financ Econ. 1977;5(2):177–88. doi: 10.1016/0304-405X(77)90016-2

35. TUIK. Gross domestic product by provinces. Ankara: Turkish Statistical Institute; 2024.

36. TUIK. The results of address-based population registration system. Ankara: Turkish Statistical Institute; 2025.

37. Görmez N, Köksalan M, Salman FS. Locating disaster response facilities in Istanbul. J Oper Res Soc. 2011;62(7):1239–52. doi: 10.1057/jors.2010.67

38. SwissRe. Risky cities: earthquake resilience in Istanbul. Mitigating climate risk. 2018 [accessed on 2025 Oct 1]. Available from: https://www.swissre.com/dam/jcr:b75ffe6a-eff9-415e-b822-ba3bae71b316/risky_cities_istanbul.pdf

39. Götze T, Gürtler M. Sponsor-and trigger-specific determinants of CAT bond premia: a summary. Z Gesamte Versicherungswissenschaft. 2018;107(5):531–46. doi: 10.1007/s12297-018-0411-8

40. Adger WN, Agrawala S, Mirza MMQ. Assessment of adaptation practices, options, constraints and capacity. In: Climate change 2007: impacts, adaptation and vulnerability contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge: Cambridge University Press; 2007.

41. Istanbul. Istanbul climate change action plan summary report. 2018 [accessed on 2025 Sep 29]. Available from: https://cevre.ibb.istanbul/wp-content/uploads/2022/05/Ozet_Rapor_Ingilizce.pdf

42. Gernay T, Selamet S, Tondini N, Khorasani NE. Urban infrastructure resilience to fire disaster: An overview. Procedia Eng. 2016;161:1801–5. doi: 10.1016/j.proeng.2016.08.782

43. Capelle-Blancard G, Crifo P, Diaye MA, Scholtens B, Oueghlissi R. Environmental, Social and Governance (ESG) performance and sovereign bond spreads: an empirical analysis of OECD countries. SSRN 2874262. 2016 [accessed on 2025 Sep 29]. Available from: https://pure.rug.nl/ws/portalfiles/portal/41714247/WP_EcoX_2017_07.pdf

44. Boffo R, Patalano R. ESG investing: practices, progress and challenges. Paris: OECD; 2020.

45. Hachenberg B, Schiereck D. Are green bonds priced differently from conventional bonds? J Asset Manag. 2018;19(6):371–83. doi: 10.1057/s41260-018-0088-5