International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:10, No:5, 2016

Surveying Earthquake Vulnerabilities of District 13 of Kabul City, Afghanistan

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Abstract**—**High population and irregular urban development in Kabul city, Afghanistan's capital, are among factors that increase its vulnerability to earthquake disasters (on top of its location in a high seismic region); this can lead to widespread economic loss and casualties. This study aims to evaluate earthquake risks in Kabul's 13th district based on scientific data. The research data, which include hazard curves of Kabul, vulnerability curves, and a questionnaire survey through sampling in district 13, have been incorporated to develop risk curves. To estimate potential casualties, we used a set of M parameters in a model developed by Coburn and Spence. The results indicate that in the worst case scenario, more than 90% of district 13, which comprises mostly residential buildings, is exposed to high risk; this may lead to nearly 1000 million USD economic loss and 120 thousand casualties (equal to 25.88% of the 13th district's population) for a nighttime earthquake. To reduce risks, we present the reconstruction of the most vulnerable buildings, which are primarily adobe and masonry buildings. A comparison of risk reduction between reconstructing adobe and masonry buildings indicates that rebuilding adobe buildings would be more effective.

Keywords**—**Earthquake risk evaluation, Kabul, mitigation, vulnerability.

I. Introduction

AFGHANISTAN is a landlocked country in central Asia with an approximate population of 32 million. It is a country in which various types of disasters such as floods, draughts, earthquakes, and avalanches occur every year, which always lead to casualties and widespread loss of property. Although earthquakes are one of the most life-threatening hazards in Afghanistan, unfortunately, less attention has been paid to them. For over 4000 years, the occurrence of destructive earthquakes in Afghanistan has led to the loss of lives; in the last 10 years, more than 7000 people lost their lives because of earthquakes [1].

Years of war have left the Afghan people burdened with widespread infrastructure damage, especially in the city of Kabul. In recent years, a rapid increase in urbanization after the afghan civil war (1996-2001) has led to an irregular development of the city of Kabul because of the construction of low-strength dwellings; all this was the result of unemployment, concentration of economic activity in Kabul, and finally migration of people to Kabul from surrounding villages. Consequently, because of the absence of relevant research for evaluating earthquake risks in Kabul, the vulnerability of this city to earthquakes has increased. This issue is most visible in the 13th district of Kabul. Besides the poor state of most residential buildings and high population density of the district, a comparison between areas occupied by residential dwellings and other facilities show that urban development in district 13 does not follow a logical process considering its population growth [2].

Research concerning earthquake hazard analysis in Afghanistan was undertaken by the United States Geological Survey (USGS) in cooperation with the United States Agency for International Development (USAID), which resulted in hazard curves being developed for Afghanistan's major cities, including Kabul, as well as the preparation of seismic hazard map of Afghanistan for 2% and 10% probability of exceedance in the next 50 years. According to Fig. 1, the 50%g peak ground acceleration (PGA) is estimated for the city of Kabul at 2% probability of exceedance over the next 50 years, which is equivalent to an intensity of VIII. Consequently, there is likely to be sever shaking and heavy damage to unreinforced masonry buildings [1].

The main objective of this research was to evaluate earthquake risks in terms of economic loss and casualties in Kabul's district 13. We evaluated the current situation in the district to understand to what degree the population and dwellings are currently exposed to potential loss of life and damage from a probable future earthquake. To evaluate this, we used risk curves, which we compiled using the hazard curves for the city of Kabul from the USGS's report and vulnerability curves for residential buildings in Iran (owing to a lack data for residential buildings in Afghanistan). Our risk analysis was scenario based. In each earthquake scenario, an envisaged picture of the incident demonstrates a different level of damage and casualties. The level of damage for different building types is then converted into damage ratios of each building type and following that economic loss is calculated. For the casualties calculation, a model by Coburn and Spence was applied.

To reduce the risk, we applied a hypothetical mitigation policy including replacement of some traditionally constructed dwellings with reinforced concrete buildings. Using risk calculation, it is decided which dwellings are most vulnerable to earthquake exposure. The mitigation policy was subsequently applied to the adobe and masonry buildings, which are the most vulnerable building typologies. Then

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policy cost for each typology was compared with the risk reduction. Section II explains the target area and its current situation. Section III discusses the use of risk curves as a research methodology to obtain research data and calculate risks. Section IV presents the results including the economic loss and casualties risk calculations. Section V adds a discussion on the most vulnerable buildings, which have a direct impact on increasing risk. Section VI compares the replacement of a number of the most vulnerable dwellings as a mitigation policy and its impact on risk reduction. Finally, Section VII presents the conclusion and the effectiveness of the proposed policy.

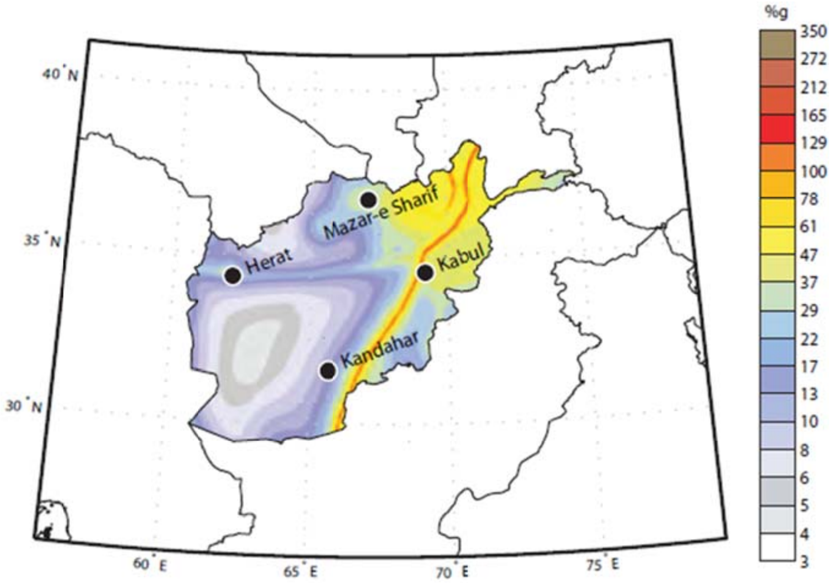

Fig. 1 Afghanistan hazard map showing ground motion for all modeled sources for PGA at 2% probability of exceedance in 50 years [1]

II. Target Area

A. Afghanistan

Afghanistan is a landlocked and mountainous country, which covers a total area of 652,230 square kilometers. It is administratively divided into 34 provinces. Each province has a capital city and is governed by a provincial governor and provincial council.

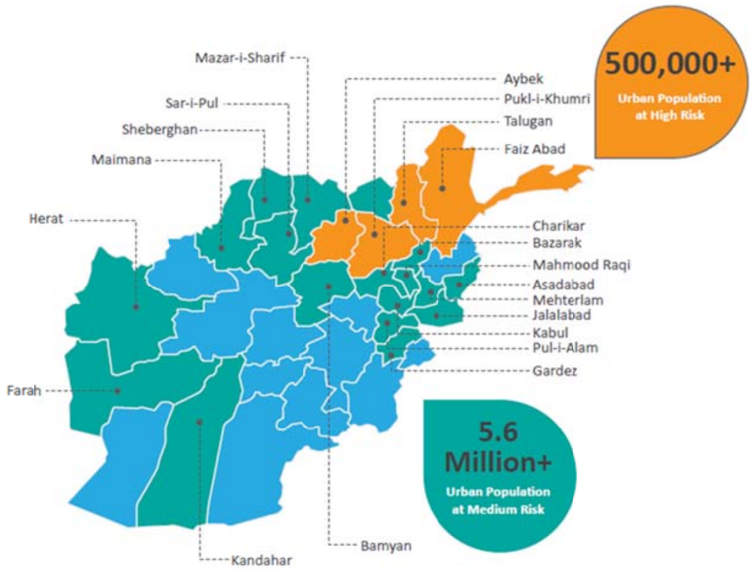

Fig. 2 Urban population in earthquake risk zones [3]

Earthquakes are one of the most frequently occurring disaster risks in Afghanistan's cities. Rupture of the main faults in Afghanistan increases the potential for destructive earthquakes to occur, specifically in east and northeast of Afghanistan. Fig. 2 shows a distribution of the country's cities that are exposed to earthquakes [3].

Fig. 3 Districts of Kabul city [4]

B. Kabul

Kabul, the capital of Afghanistan, is also the largest city in Afghanistan. Kabul city is located in the eastern section in a mountainous region of Afghanistan; it has an approximate area of 275 km². According to an estimate, the population of the city was around 3,543,700 [3]. The city contains 22 districts.

C. District 13

District 13, which is the target area of this research, is located in the western part of old Kabul city. It extends southward towards the mountain area. The district has a large land area of 46.6 km^2 but 40.2% is vacant or bare land since the southern part is occupied by mountains [4].

The population of district 13 (based on the statistics by Kabul Municipality and the Japan International Cooperation Agency's survey team) was 467,440 in 2009. There are 31,447 residential dwellings in the district, which covers 14.97 km^2 of the district's area. Most of the residential areas in the district are unplanned except for the newly constructed areas along the main artery road. Most facilities including trade centers, hospitals, and educational centers have been developed along this one main road, putting a burden on households who live far from this main road since it is hard for them to supply themselves with necessary goods [4].

There are 1093 business centers (81 high rise buildings and 1012 low rise buildings and small shops), which cover 0.458 km^2 of the district area. There are also 40 educational buildings and 20 health care centers including hospitals and clinics. Because of unplanned development of the district, urban density is not controlled by the municipality [4].

Because there are many intersections with community roads, many crossing barriers, lots of cars, an absence of traffic lights and traffic rules mean that this main road is one of the most crowded roads in the city. Most of the community roads are unpaved. Generally, the total land area occupied by roads is 3.262 km^2 (10.2% of the district area), which is less than the necessary area for road development based of most standards [2].

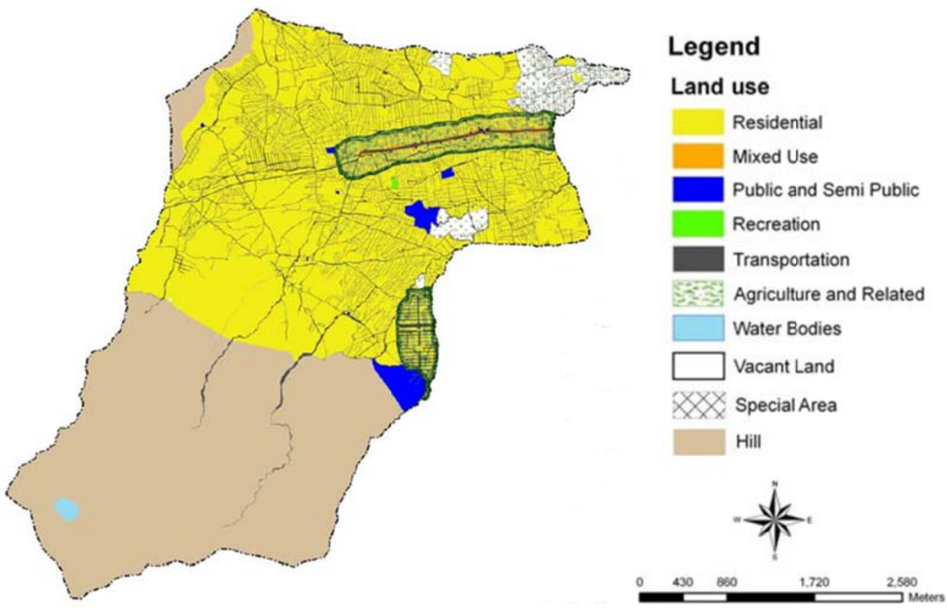

Fig. 4 Map of district 13 [4]

Fig. 5 Photo of district 13

III. Methodology

A. Risk Curve

Risk is evaluated using a "risk curve." A risk curve is a loss exceedance probability (EP) curve that shows a correlation between two variables where the probability of exceedance is represented on the vertical axis and damage to element at risk along the horizontal axis. The risk curves show how often the occurrence of an event such as an earthquake may have consequences such as economic loss and casualties, indicating the level of loss with different return periods. Such risk curves are generally used by decision makers, such as physical planners and civil protection agencies, to make plans for risk countermeasures.

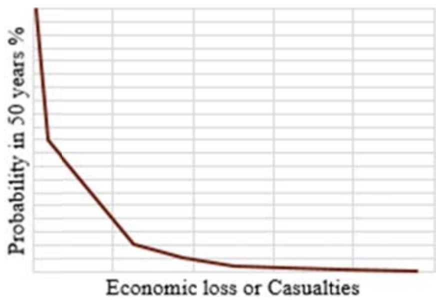

Fig. 6 Conceptual risk curve

Each point on the risk curve stands for a specific level of damage such as economic loss and casualties with a specific probability of exceedance in 50 years, i.e., for the specific scenario of an earthquake. The area under the risk curve shows the expected loss, which might be economic loss or casualties.

To calculate the risk in terms of expected economic loss and number of casualties, we combined sources from the literature containing hazard surveys and vulnerability curves together with our own field survey of district 13.

B. Hazard Curve

Hazard curves are a correlation of probability of occurrence of an incident in a region for a period of time. For example, there is a 10% probability of exceedance in 50 years for 50%g PGA equal to an intensity of a VIII earthquake in the city of Kabul.

The hazard curves for Kabul city were prepared by the USGS in cooperation of the USAID in Afghanistan. They are the result of a major analysis of faults, which are the source of earthquakes.

Fig. 7 shows the hazard curves for Kabul. The solid black line is the seismic hazard curve resulting from a combination of all sources. The dashed-dot curve is the contribution to seismic hazard using the ground motion relation. The solid curve is the Western United States ground motion relation. The red curve is the contribution to seismic hazard from characteristic fault sources. The green curve is Gutenberg Richter. The blue curve is contribution from background seismicity less than 50 km depth. The cyan curve is contribution from seismicity between 50–100 km depth (solid) and 100–150 km depth (dashed-dot) [1].

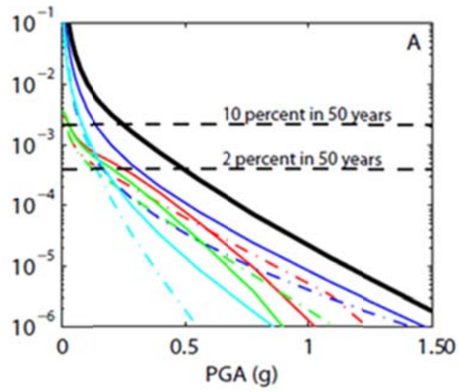

Fig. 7 Hazard Curves of Kabul [1]: See text for figure explanation

The earthquakes scenario is made by interpolating and deriving the value of PGA versus various probabilities of exceedance in 50 years. Table I shows this according to the solid black line hazard curve for the city of Kabul.

C. Vulnerability Curve

Vulnerability curves generally show how much a hazard like an earthquake with a specific intensity may cause damage to the elements that are exposed to that hazard. These elements might be buildings or inhabitants living inside the buildings. Fig. 8 shows some correlations between PGA and intensity based on different sources, and Fig. 9 shows vulnerability curves for residential building typologies in Iran.

TABLE I
PGA Derived from Hazard Curve of Kabul for eight Earthquake Scenarios

Probability of exceedance in 50 years (%)	Value of probability on graph	PGA (g)
100	2×10^{-2}	0.069
50	1×10^{-2}	0.097
10	2×10^{-3}	0.270
5	1×10^{-3}	0.347
2	4×10^{-4}	0.500
1	2×10^{-4}	0.580
0.5	1×10^{-4}	0.722
0.1	2×10^{-5}	1.000

According to Fig. 8, the red line, which is the mid curve, has been used to interpolate and get the intensity value based on the value of PGA that we got from the hazard curves of Kabul. For each intensity, we could then get the value of the mean damage grade for the building typologies that exist in district 13 by referring to Fig. 9. The proposed vulnerability curves in Fig. 9 are derived from an adaptation of European data to buildings in Iran; additionally, data on damage from previous earthquakes in Iran was incorporated. Because of the similarity of the construction materials and methods for buildings in Afghanistan and Iran and also because of the lack of such data for buildings in Afghanistan, the proposed vulnerability curves were used to calculate building damage and economic loss [5]. The damage ratio of buildings, which is the ratio between the costs of building repair to the construction cost, were then calculated based on the mean damage grade of the specific type of building (more explanations about correlation between mean damage grade and damage ratio are available in Appendix 1). We calculated the economic loss using an average of the total cost of each building typology and belongings inside them, which we determined with the results of a questionnaire survey in district 13. To estimate casualties, we used a model developed by [6] (further explanations of the calculations of the casualties are available in Appendix 2).

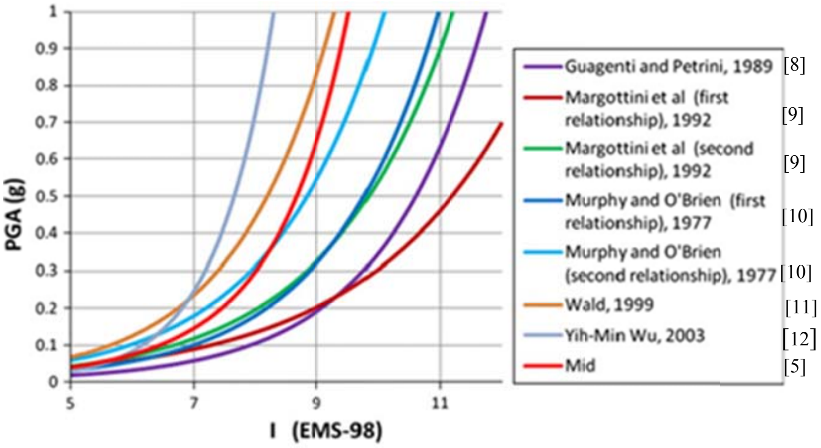

Fig. 8 Different correlations between PGA and intensity [5]

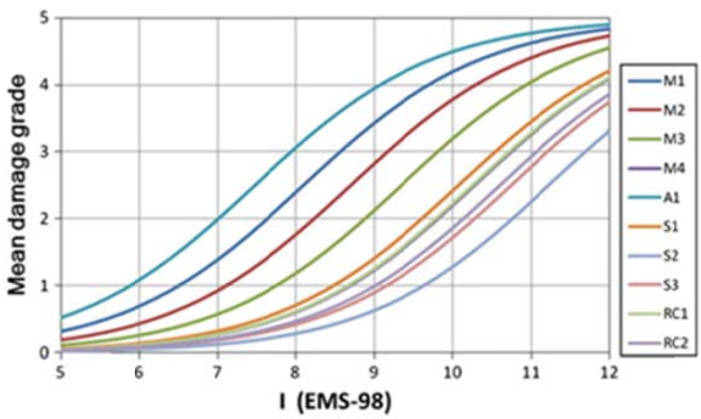

Fig. 9 Experimental vulnerability curves for different building typologies [5]

D.Exposure

Based on the number of residential dwellings and people living in district 13 (these data points were obtained from the literature and public statistics), we sampled buildings to survey in the target area and conducted a questionnaire survey to determine the percentage of each building type, the number of inhabitants in each type of dwelling, the value of the houses, and other necessary data for loss estimation. The sampling was based on a random selection from 10,000 small segments of the 13th district's map using software, as shown in Fig. 10. Generally, most of the points selected in the southern part of the district were omitted since they were located in mountainous region. Therefore, the questionnaire survey was performed more in the northern part. In total 101 buildings were surveyed. A summary of the results of site survey and investigation to distinguish various typologies of buildings are shown in Table II.

Additionally, samples of adobe and masonry buildings are shown in Figs. 11 and 12, respectively.

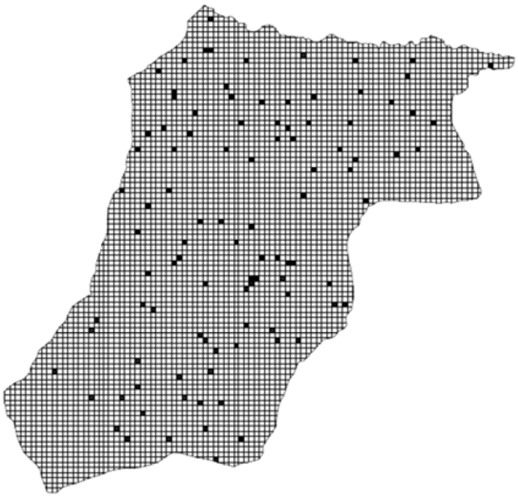

Fig. 10 Sampling points in district 13

TABLE II
SUMMARY OF QUESTIONNAIRE SURVEY IN DISTRICT 13

No.	Building Type	Description	Percentage of buildings
1	Adobe (A1)	Constructed from earth material such as cob and rammed earth	28.75%
2	Masonry (M2)	Constructed from masonry material like brick	41.25%
3	Steel Frame with Masonry wall (S1)	Consisting of a steel frame with brick wall	7.50%
4	Reinforced Concrete (RC1)	Consist of moment frame	18.75%
5	Steel Frame with Bracing (S2)	Braced frame composed of steel members	3.75%

IV. RESULT

Since more than 80% of the buildings in district 13 are residential, most economic losses are associated with these buildings. Figs. 13 and 14 summarize the results of the risk calculation for residential buildings in district 13 in terms of economic loss and casualties, respectively.

Fig. 11 Sample of an adobe building

Fig. 12 Sample of masonry building

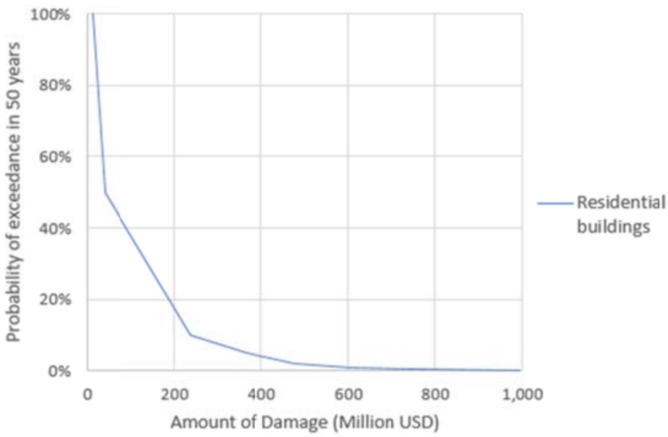

Fig. 13 Calculation of risk in terms of economic loss for all residential buildings in district 13

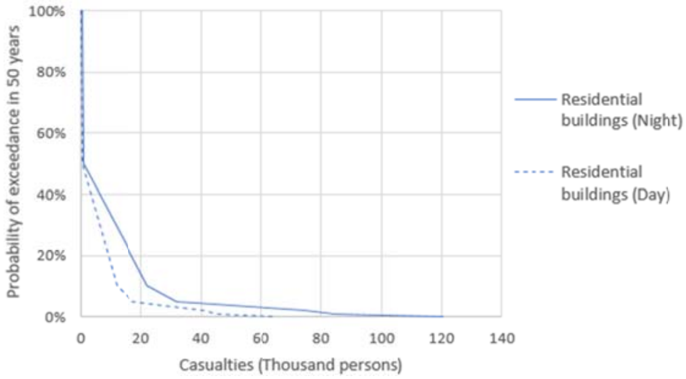

Fig. 14 Calculation of risk in terms of number of casualties for all residential buildings in district 13

Based on Fig. 13 (the risk curve of residential buildings), a great increase in economic loss for the scenario of 50% probability of exceedance in 50 years and lower probabilities form a huge area under the risk curve. This means that economic loss and casualties dramatically increase for M6.3 and greater magnitude earthquakes. The worst case scenario is the 0.1% probability of exceedance in 50 years: An M7.2 earthquake in which economic loss for residential buildings are at their highest value (near to 1000 million USD). Also, as shown in Fig. 14, for that same worst case scenario the number of casualties would be close to 120 and 65 thousand people for nighttime and daytime earthquake, respectively, which is equal to 25.8% and 13.95% of the population of district, respectively. The expected economic loss in 50 years (area under risk curve) is 96.3 million USD and the expected number of lives lost in 50 years is 5,071 and 9,379 persons for the daytime and nighttime earthquake scenarios, respectively.

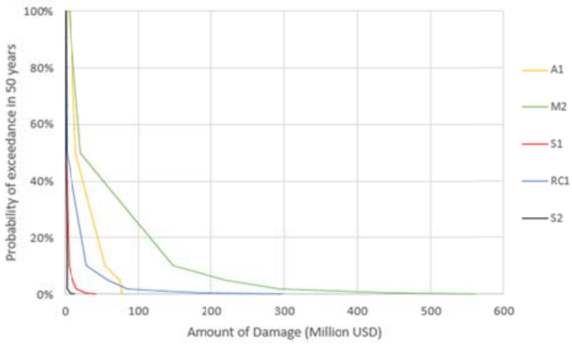

Fig. 15 Calculation of risk in terms of economic loss for each type of residential building in district 13

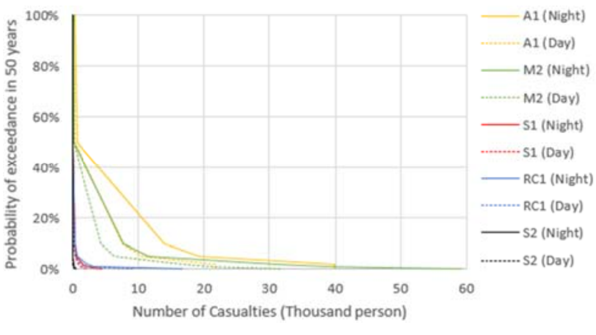

Fig. 16 Calculation of risk in terms of number of casualties for each type of residential building in district 13

V. Discussion

According to the results, residential buildings in district 13 are at high risk. The loss EP curves in terms of economic loss and number of casualties for each building type are shown in Figs. 15 and 16. All calculated risk curves have a concave style, meaning that for smaller probabilities of exceedance there is a large increase in damage. According to Fig. 13, for 10% probability of exceedance in 50 years equal to 90% value at risk the economic loss would be 237.4 million USD, meaning that there is 90% probability for the mentioned amount of damage. In other words, the related organizations need to have at least 237.4 million USD budget for recovery for a case of 90% probability. For 95% and 99.9% value at risk, the economic loss would be 364.5 and 991.6 million USD, respectively. This demonstrates that the increase in the amount of economic loss when the value at risk changes from 95% to 99.9% is more comparing with the situation for the value at risk changing from 90% to 95%.

Based on Fig. 15, in the worst case scenario of an earthquake that has 0.1% probability of exceedance in 50 years (equivalent with M7.2 earthquake), the economic loss for masonry and reinforced concrete buildings are at their highest value, which are approximately 560 and 297 million USD. The economic loss for adobe buildings is near to 78 million USD and has been kept fixed in this value from 2% probability to 0.1% probability exceedance in 50 years. The 2% probability of exceedance in 50 years is equivalent to 50%g PGA (hazard curves of Kabul), which produces an M6.7 earthquake. This issue means that all adobe buildings will be on damage state 5, i.e., complete destruction, in this scenario and scenarios of greater magnitude.

Based on Figs. 15 and 16, most of the casualties of an earthquake are caused by the abundance of adobe and masonry buildings.

VI. Policy Implications

In this section, we simulate a hypothetical mitigation policy for risk reduction for future earthquakes. As indicated in the previous section, the number of adobe and masonry dwellings plays a crucial rule at increasing the risk. Here, a policy constituting replacement of a number of adobe and masonry dwellings with engineering based reinforced concrete buildings (RC1) has been considered. This policy is applied for 10% of adobe and masonry buildings as a sample to study the results. Based on the vulnerability curves in Fig. 9, the damages are calculated once again after replacement of 10% of adobe (A1) and 10% of masonry (M2) buildings with reinforced concrete (RC1) buildings for all earthquake scenarios. The hypothetical policy cost contains either subsiding reconstruction of existing building with reinforced concrete building (RC1) or reconstruction of new buildings by the government. To achieve a very significant degree of risk reduction, i.e., to turn earthquake vulnerabilities into earthquake resiliencies in district 13, full support for construction of new RC1 buildings has been considered. A comparison between replacement of 10% of adobe and 10% of masonry dwellings in two separate scenarios indicates the results of applying of this hypothetical mitigation policy for risk reduction for the mentioned typologies. The total cost of the policy then is compared with the economic loss reduction and number of casualties after the mitigation policy scenarios have been implemented. As shown in Table III, we assumed that 100% of the expense of constructing each RC1 building is subsided by the government (policy cost for each dwelling).

TABLE III
BREAK DOWN OF TOTAL AMOUNT TO BE SUBSIDED FOR ADOBE AND MASONRY BUILDINGS

No.	Building typology	Replaced building	Policy cost for each dwelling (USD)	10% of each typology (nos)	Total amount of policy cost (Million USD)
1	Adobe (A1)	RC1	45,000	904	40.68
2	Masonry (M2)	RC1	45,000	1297	58.37

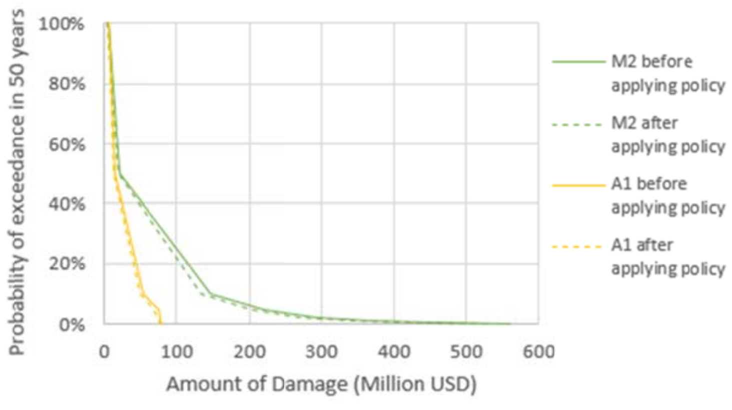

Fig. 17 A comparison of risk calculation in terms of economic loss for adobe and masonry buildings before and after applying policy

By applying the hypothetical policy on replacing 10% of adobe and 10% of masonry buildings with reinforced concrete buildings, the risk in terms of economic loss and number of casualties were calculated again and then compared with the situation with this policy. The calculated risk curves in terms of economic loss for adobe and masonry buildings are shown in Fig. 17.

The area under the risk curve that stands for expected loss in 50 years has been calculated and compared for both typologies before and after applying the policy, as shown in Fig. 18. Based on the calculations, there is 1.42 and 4.88 million USD reduction in expected economic loss for adobe and masonry buildings, respectively. However, these amounts are less than the amount the policies cost. This means that the hypothetical mitigation policy is not cost-effective for economic loss reduction for both typologies.

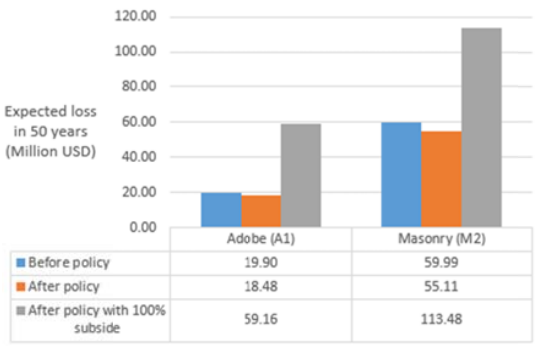

Fig. 18 A comparison of expected economic loss for adobe and masonry buildings before and after applying policy

Figs. 19 and 20 are the results of a comparison of the risk calculation in terms of the number of casualties for daytime and nighttime earthquakes for the current adobe and masonry buildings and for when 10% of each type are reconstructed with reinforced concrete.

Figs. 21 and 22 show a comparison of the expected number of casualties; they indicate that after applying the policy for both adobe and masonry buildings, the expected number of casualties are decreased. The reductions are 279 and 517 persons, respectively, for daytime and nighttime earthquake scenarios for adobe buildings. Also, there are casualty reductions of 170 and 316 people after applying the policy to masonry buildings for daytime and nighttime earthquake scenarios, respectively.

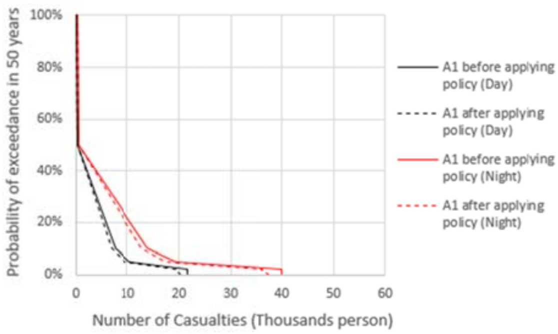

Fig. 19 Risk curves in terms of number of casualties for adobe building before and after applying the policy

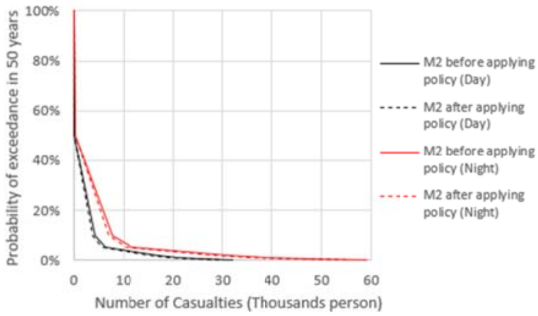

Fig. 20 Risk curves in terms of number of casualties for masonry buildings before and after applying the policy

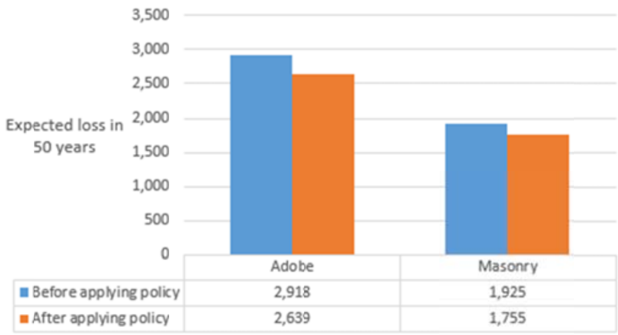

Fig. 21 A comparison of the reduction in expected loss of lives for daytime earthquake scenario

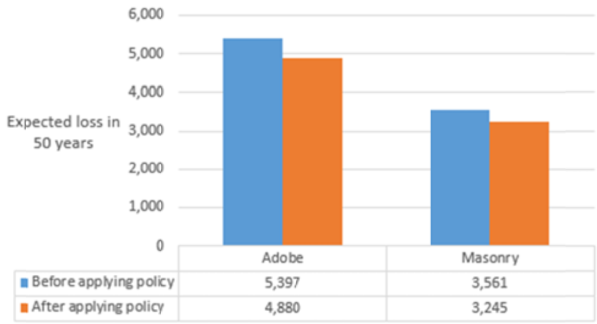

Fig. 22 A comparison of the reduction in expected loss of lives for nighttime earthquake scenario

VII. Conclusion

The research focused on evaluating the earthquake risk in district 13 of Kabul by using a risk curve. Owing to the increasing population in district 13, absence of planned construction, and the poor state of the dwellings, which are not resistant to even moderate ground motion, earthquake vulnerabilities are significant in district 13. Among all buildings in district 13, adobe (A1) and masonry (M2) had a direct effect on increasing risk. To reduce the risk in district 13, we proposed a hypothetical mitigation policy that saw the replacement of 10% of adobe (A1) and 10% of masonry (M2) buildings with reinforced concrete (RC1) buildings. The risk reduction comparison between the two building typologies before and after applying the hypothetical policy shows that although the mentioned policy is not cost-effective from an economic point of view for both typologies, it can reduce the expected number of casualties for both typologies. This reduction for adobe building is greater than that of masonry for both daytime and nighttime earthquake scenarios.

Appendix

A. Mean Damage Grade

Damage grade is a value from 1 to 5 that is given to a building corresponding to its level of damage by an earthquake. Mean damage grade is a parameter that is representative of the damage grade for a set of buildings [7], [14]; it is calculated as:

$$\mu_D = 2.5\left[1 + \tanh\left(\frac{I + 6.25 \cdot V_I - 13.1}{2.3}\right)\right] \quad . \quad (1)$$

In (1), μ_D refers to mean damage grade, parameter I is the intensity of an earthquake, and V_I is the vulnerability index that is adopted based on Iranian building construction data for the current building typologies [5].

Damage ratio is the ratio between the costs of repair of a damaged building to the construction cost of that building. Damage ratio can be calculated using the following formula [5], [13]:

$$D_i = -0.0004\mu_D^3 + 0.0854\mu_D^2 + 0.0085\mu_D \quad . \quad (2)$$

To express the scenarios in terms of magnitude, the following relationship between intensity and magnitude of an earthquake has been used [15]:

$$I = 1.7M_s - 2.8 \quad (3)$$

B. Estimation of Casualties

To estimate the human casualties of different earthquake scenarios, Coburn and others have proposed a set of M parameters through which we can estimate casualties in the following model [6], [7]:

$$K_S = C \cdot \left[M1 \cdot M2 \cdot M3 \cdot \left(M4 + M5 \cdot (1 - M4)\right)\right] \quad . \quad (4)$$

in which K_S is the number of casualties, C is the number of collapsed buildings (which here is assumed to be equivalent with the percentage of the damage ratio), M1 is the occupancy rate obtained based via the questionnaire survey for each type of house, and M2 is the occupancy at the time of the earthquake. For daytime and nighttime, this factor is obtained via the questionnaire survey. Parameters M3, M4, and M5 are chosen from Tables IV-VI [6].

The building typologies adobe, masonry, and steel frame with masonry walls are assumed to be in the category of *Masonry*, reinforced concrete and steel frame with bracing in the category for *RC* for adjusting parameters M3, M4, and M5. For the current scenarios, we have assumed the situation *"community incapacitated by high casualty rate"* for M5.

TABLE IV
M3: Estimated Average Percentage of Occupants Trapped by Collapse [6]

Collapsed masonry buildings (up to three storeys)				
Intensity	VII	VIII	IX	X
	5%	30%	60%	70%
Collapsed RC structures (3–5 storeys)				
Near-field, high frequency ground motion				70%
Distant, long-period ground motion				50%

TABLE V
M4: Estimated Injury Distribution at Collapse [6]

Triage injury category	Masonry	RC
1. Dead or unsaveable	20	40
2. Life-threatening cases needing immediate medical attention	30	10
3. Injury requiring hospital treatment	30	40
4. Light injury not necessitating hospitalization	20	10

TABLE VI
M5: Percentage of Trapped Survivors in Collapsed Buildings that Subsequently Die [6]

Situation	Masonry	RC
Community incapacitated by high casualty rate	95	-
Community capable of organizing rescue activities	60	90
Community + emergency squads after 12 hours	50	80
Community + emergency squads + SAR experts after 36 hours	20	10

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