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DEVELOPMENT OF FRAGILITY FUNCTIONS FOR BRICK MASONRY STRUCTURES USING DAMAGE DATA FROM 24 SEPTEMBER 2019 EARTHQUAKE IN MIRPUR, AZAD KASHMIR

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Abstract

This paper presents fragility functions for clay brick unreinforced masonry (URM) buildings which were developed using the data of damage and earthquake intensity by the 24 September 2019 Mirpur, Azad Jammu and Kashmir earthquake. These data were collected through reconnaissance surveys in the affected region. The intensity of the earthquake ranged from V-VII on the Modified Mercalli Intensity scale in the surveyed areas. The damage to clay brick piers of bridges was caused by compression or shear-compression forces applied by the vertical seismic forces. Most of the damaged URM buildings showed in-plane wall cracking with very few cases of out-of-plane wall failure. The damage in these buildings was influenced by both the ground motion's horizontal component and ground motion amplification due to site conditions. The damage types to the URM buildings in the surveyed areas were classified into five damage grades and these data were employed to propose fragility curves for clay brick URM buildings.

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1. Introduction

The bending and compressive stresses caused by the subduction of the Indian plate under the Eurasian plate have created the Himalayan mountain ranges whose western part spreads over northern Pakistan and Kashmir. The convergence of these plates in the middle and northern parts of Pakistan has also been translated into several fault systems in northern Pakistan. It does not come as a surprise that the seismicity of this region is relatively higher compared to other parts of the country. This is also reflected in the presence of several peaks in this region such as Hindu Kush, K2, Pamir, Rakaposhi, Nanga Parbat, Tirich Mir and Karakoram. Northern Pakistan has suffered extensive damage from time to time by earthquakes.

A shallow earthquake of Mw = 5.4 (depth = 10 km) (USGS 2019) struck Azad Jammu and Kashmir (AJK) on 24 September 2019 which is situated in the northeast of Pakistan. The epicentre of this earthquake was on the east-west trending Bong Canal thrust fault which is nearly 20.5 km in length (Fig. 1). The Mirpur district in AJK was badly devastated by the earthquake where extensive building and infrastructure damage was reported. The affected region is situated on the Indian plate (Fig. 1).

A two-member team from the Department of Earthquake Engineering at NED University of Engineering and Technology, Pakistan visited the affected region from 27-30 September 2019 and conducted reconnaissance surveys to record the damage based on visual inspection. Apart from the main city area of Mirpur, damage data were also collected from a few remote rural settlements which are shown shaded in Fig. 1. It is seen in Fig. 1 that the visited areas are widely scattered which were selected based on the news of damage disseminated in the local media.

Table 1 provides details of the visited areas and their distances from the epicentre. Note that the building count given in Table 1 was obtained by employing high-resolution satellite imagery from Google Earth of the area before 24 September 2019 which was digitized using ArcMap (ESRI 2011). The team documented the damage by taking photographs of the damaged built infrastructure along with their coordinates to geographically locate their positions.

The observed damage data were analysed to study seismological aspects of the earthquake (Rafi et al. 2022) and the seismic performance of different common components of the built environment. The data on the performance of reinforced concrete (RC) buildings in the affected region were reported by Rafi et al. (2022). The visiting team also collected and analysed the data for estimating earthquake intensity in the affected areas by interviewing local people and recording their responses on a questionnaire. The data on building damage and earthquake intensity were employed to develop fragility curves. This paper presents the results obtained from the aforementioned studies.

2. Results and Discussion

2.1 Seismology and Ground Motion Characteristics

Rafi et al. (2022) reported that the ground motion data due to the 24 September 2019 Mirpur earthquake were influenced by forward rupture directivity effects. These data were recorded at two stations named Kass and Mangla Dam (Fig. 1). Higher effects of rupture directivity were observed on the former station as it was close to the epicentre (Fig. 1). Note that these effects are typical of near-fault earthquakes (Somerville et al. 1997, Archuleta and Hartzell 1981). Fig. 2 illustrates the response spectrum at 5 percent critical damping of the recorded acceleration at both the abovementioned recording stations in all three directions (E-W, N-S and vertical) while the recorded ground acceleration plots are given in Appendix. It is noted that the N-S component of the spectral ordinate is significantly higher for the ground motion record at the

Mangla Dam station as compared to its E-W component. This type of behaviour resulted due to a lower fundamental period of the input seismic acceleration in the N-S direction as compared to the E-W direction which is caused by the resonance in the former direction due to heterogeneity of the soil layer along its depth (Badaoui et al. 2009). This behaviour, however, was not observed at the Kass station (Fig. 2). This is noted that the Mirpur district can be regarded as an inter-mountainous valley that is situated on an alluvial soil deposit (Planning & Development Department Muzaffarabad 2014).

It is seen in Fig. 2 that the vertical component of the spectral acceleration is significantly higher at the Kass station as compared to the Mangla Dam station owing to its location in the close vicinity of the epicentre of the earthquake (Fig. 1). Higher vertical accelerations due to the near-field earthquakes are caused by the conversion of S waves into P waves within the zone between bedrock and the overlying sedimentary layers (Silva 1997, Amirbekian and Bolt 1998). Further, SV shear waves strongly influence the vertical component for spectral periods greater than 0.1 sec whereas a mixture of P and SV waves contributes to the ground motion for periods less than 0.1 sec (Beresnev et al. 2002). It is noted in Fig. 2 that the corner period for the vertical spectra at the Kass station is 0.12 sec which is close to the recommended value of 0.15 sec in the available literature (Elnashai 1997, Elnashai and Papazoglou 1997, Bozorgnia and Campbell 2004). This short-period characteristic of vertical ground motion requires due consideration in structural design, as structural components and systems are generally stiff in the vertical direction (Bozorgnia et al. 1998, Bozorgnia and Campbell 2016).

Fig. 2 also compares the design spectra suggested by Eurocode 8 (EC8 2004) and NEHRP (2020). The former code has suggested Type 1 and Type 2 spectra which vary in accordance with the seismic hazard of a particular site. The design ground acceleration for Mirpur was taken as 0.2g (MoHW 2007) for determining the Eurocode 8 (EC8 2004) design spectra. A soil with a shear wave velocity of less than 180 m/sec was used for all the design spectra shown in Fig. 2, as recommended by Rafi et al. (2022). The 5% damped maximum considered earthquake (MCE) spectral response acceleration at short periods and a period of 1 sec were taken as 1.29g and 0.53g, respectively (Ahmed 2021) for the NEHRP (2020) design spectrum. It is seen in Fig. 2 that although the Type 2 spectrum (EC8 2004) provides a reasonable correlation with the observed spectrum in the E-W direction at the Kass station (followed by the design spectrum proposed by NEHRP (2000)), all design spectra underestimated peak spectral acceleration in the N-S direction at the Mangla Dam station. In addition, all design spectra under-estimated peak spectral acceleration in the vertical direction as compared to the observed ordinate. The underestimation is highest and lowest for the Type 2 (EC8 2004) and NEHRP (2020) design spectra, respectively. Finally, the Type 1 spectrum (EC8 2004) correlates well with the observed spectrum in the vertical direction at the Mangla Dam station. Note that the recently revised Pakistan Building Code (BCP 2021) has suggested MCE spectral acceleration at short periods and a period of 1 sec as 1.19g and 0.39g, respectively, for 5% damped response spectra for Mirpur. It is clear in Fig. 2 that these values underestimate the seismicity of this region.

Fig. 3 illustrates plots of the vertical-to-horizontal spectrum (V/H) ratio for both recording stations. A geometric mean of spectral accelerations [$(S_a)_H$] [Eq. (1)] (Albarello and Lunedei 2013) of the horizontal components ($(S_a)_{N\text{-}S}$ in N-S direction and $(S_a)_{E\text{-}W}$ in E-W direction) was used to determine V/H ratios.

$$(S_a)_H = \sqrt{(S_a)_{E-W} \times (S_a)_{N-S}} \tag{1}$$

It is seen in Fig. 3 that peak V/H at the Kass station occurred at a shorter period (0.06 sec) as compared to the Mangla Dam station (0.18 sec) which can be attributed to the shorter distance of the former station from the epicentre. This distance influenced the time of strong motion segments in the accelerograms recorded at both of these sites (Rafi et al. 2022). The aforementioned periods correspond to fundamental resonance frequencies of the respective recording sites (Tokimatsu, 1997, Bard 1999, Bonnefoy-Claudet et al. 2006). Gülerce and Abrahamson (2011) indicated that a peak in the V/H ratio could be observed close to the spectral period of 0.05 sec, which is close to that observed at the Kass station. In addition, the peak V/H at the Kass station (2.47) is larger compared to the Mangla Dam station (1.66) (Fig. 3). Apart from source-to-site distance, this peak at a short period is also influenced by the stronger site amplification effects for P waves which are higher for the soil sites as compared to the rock sites (Gülerce and Abrahamson 2011, Bozorgnia and Campbell 2016). Ramadan et al. (2021) also reported V/H ratios in the range of 3-8 at short periods for earthquakes of magnitude 6.5 and 6.0 in Central and Northern Italy, respectively.

Fig. 3 illustrates a comparison of the data of the observed V/H ratio with the predictive model proposed by Bozorgnia and Campbell (2004) for thrust fault and firm soil. It is seen that although the period corresponding to the peak ordinate is close to that observed at the Kass station, the peak value of V/H is significantly underestimated by the ground motion prediction model proposed by Bozorgnia and Campbell (2004).

Gülerce and Abrahamson (2011) proposed theoretical models for determining V/H ratios for strike-slip fault for earthquake magnitudes M5-M8 for a 5 km rupture distance and shear wave velocity of 270 m/sec. These authors also reported negligible differences in the plots of V/H for different faulting mechanisms for M7 earthquakes. In view of this, a comparison of predicted V/H for M5 and M8 earthquakes (Gülerce and Abrahamson 2011) is made in Fig. 3 with the observed data. A good correlation is seen for the period corresponding to the peak ordinate. On the other hand, the peak V/H is significantly underestimated for an M5 earthquake and is close to the observed peak for an M8 earthquake. All the above comparisons further strengthen the observation made by Rafi et al. (2022) that the design of important structures should be based on a site-specific design spectrum for this region.

2.2 Building Typology

The buildings in the surveyed areas (Table 1) mainly consisted of low-rise (one or two storeys) unreinforced masonry (URM) residential dwellings made of clay brick load-bearing walls which are constructed in English bond. These structures typically follow a similar pattern with an open front of the house which is used as a veranda (Fig. 4). The rooms are constructed at the back of this open veranda. The roof over the veranda is supported by slender circular columns which are cast within a hollow cylindrical shell made of cement sand mortar with nominal 4 mm diameter steel bars used as a cage of this shell. This shell is also used as permanent formwork and the column reinforcement is inserted inside the shell before pouring the concrete. These are generally very luxurious and expensive houses. The construction of these houses follows the traditional construction practices by the masons without any engineering input. The floor and roof in these buildings are made of RC or precast cement concrete planks which are supported on steel purlins of Tee shape. RC roof and floor slabs are generally used in expensive houses especially when these are more than one storey high and are directly rested on the walls without a bond beam. Although cement mortar is generally used in the construction of the wall, mud mortar is employed in some single-storey structures to save money. The walls, however, are plastered with cement-sand mortar irrespective of the mortar used in the wall construction.

2.3 Observed Damage

Typical damage patterns of bridges and URM buildings have been discussed in the forthcoming sections based on the observations recorded during the site surveys and photographic data. A discussion is also made on the possible failure mechanism under the lateral seismic forces, where possible.

2.3.1 Damage to Bridges

A number of bridges have been constructed over the upper Jhelum canal to connect the villages on both of its banks (Fig. 1). Some of these bridges are more than 150 years old and were constructed at that time by the British government. These are multiple-span bridges supported on clay brick piers. The deck of these bridges is a composite structure comprising structural steel girders and an RC slab. The piers of a bridge are the main force-resistant components that resist the forces applied on the bridge due to the gravity and lateral loads. A number of these bridges were damaged during the ground shaking caused by the 2019 Mirpur earthquake. Fig. 5 shows the failure of piers in shear in the Afzalpur bridge (33.06119°N 073.77611°E) which was a result of the low length-to-width aspect ratio of the piers (stout piers). This bridge was located 5 km from the epicentre in the south-west direction (Fig. 1). It is seen in Fig. 5 that the damage pattern of all the piers in the series for this bridge is identical: a circumferential crack in the bottom, and crushing of masonry corner on the top on one side of the pier. Some of the internal piers are also tilted in the longitudinal direction of the bridge. This damage pattern indicates that the shear capacity of the pier was exhausted due to the fluctuation in the axial load which was caused by the vertical component of the ground motion. Rafi et al. (2022) reported a strong influence of vertical ground motion on the damage of columns in RC buildings in Mirpur due to the 24 September 2019 earthquake. Elnashai and Papazoglou (1997) have also indicated that the axial members may be subjected to axial tensile forces caused by the vertical component of an earthquake if they carry lesser pre-load axial compression. In some cases, the bridge abutment collapsed leading to the collapse of the bridge span as seen in Fig. 6 for Pul Manda bridge (33.05425°N 073.78983°E). This bridge was 6 km away from the epicentre in the southeast direction (Fig. 1).

2.3.2 Performance of Mosques

Some of the mosques in the surveyed areas (Table 1) were visited owing to their importance as large gathering places. The visited mosques are mostly single-storey URM structures which (in general) performed well, as the damage in the mosques comprised thin diagonal cracks in the walls. The observed crack patterns in the mosques were similar to other URM structures in the affected region, as discussed later. One of the mosques in the village named Sumwal Shareef (Table 1) (33.08102°N 073.79541°E) was constructed in 1730. A complete walk-through survey of this mosque was specially conducted owing to its historic nature to observe and document types of damage. It was found that a slender minaret of the mosque fell down as shown in Fig. 7. Some cracks on the internal faces of the walls were also observed in this mosque (Fig. 7), which were insignificant to affect the stability of the structure.

2.3.3 Performance of URM Structures

URM structures have been generally used for private housing in the visited areas. An exception to this was a two-storey Radio Station building in Mirpur city (33.13726N 073.77855E) and a single-storey building of the Department of Home Economics at Mirpur University of Science and Technology (33.14939°N 073.72953°E) which were also URM structures. This indicates the possibility of the existence of other URM commercial buildings in the region. The common element in all these buildings is that their construction is based on traditional practices without any engineering input. Walls in URM structures act both as load-bearing structural elements (to transfer the load from the roof to the foundation) and non-structural partition walls. The damage observed in the URM buildings ranged from cracking in the wall to the complete collapse of the structure. Although the cracks varied from thin cracks to very wide cracks (which caused a physical separation of pieces of walls at the crack), these cracks were found to be concentrated only on the ground storey, except for a very few buildings where cracks were also seen in the first storey (Fig. 8). These were mostly in the form of diagonal cracks which were caused by the in-plane seismic forces. In only a very few instances, walls collapsed out-of-plane. Fig. 9 illustrates the out-of-plane failure of the façade walls of some of the shops which were constructed in a series next to each other. The bricks in the walls of these shops were laid in mud mortar and the wall collapse resulted from a combination of wall slenderness and weak connection at the joint. Rafi et al. (2015) also reported similar out-of-plane wall failures in adobe structures in the Mashkel region in Pakistan after the 16 April 2013 Iran earthquake. Excessive wall out-of-plane deflection was observed in a few walls due to their cantilever action; these walls were supported by temporary inclined wooden props by the occupants after the earthquake to avoid their collapse.

The highest proportion of collapsed URM buildings was found in Mohra Kikeri village. It was followed by the collapsed building proportion in Mohra Roshan village, as discussed in detail in the forthcoming sections. These observations are a little surprising as both these areas were located in the backward directivity region of fault rupture (Fig. 1) as compared to the other surveyed areas (Table 1) which were in close vicinity of the epicentre. A possible explanation of this lies in the fact that these are hilly regions that create different site conditions for seismic ground motion due to the concentration of seismic waves (Dorbani et al. 2013).

Fig. 4 illustrates the damage to a URM residential building in Mohra Kikeri village due to the diagonal cracking in the wall and the crushing of slender columns of the veranda. Although most of the collapsed URM structures included poorly constructed residential dwellings in the visited areas, a few better quality houses also collapsed at these locations (Fig. 10). In some cases, only the part of the building in the front collapsed (Fig. 11). Similarly, in few cases the circular stair tower roof slid off the walls of the tower to fall down in the front of the house (Fig. 12), as the roof was directly supported by the tower walls.

The influence of a particular component of the ground motion on the building damage can be understood by comparing the structural and natural periods. The structural period (T) can be approximated by Eq. (2) (ICBO 1997)

$$T = 0.0488(H)^{3/4} \qquad (2)$$

where H is building height above the base level

The estimate T from Eq. (1) can vary from 0.12 sec to 0.24 sec for single-storey and two-storey masonry buildings, respectively. These periods are close to the peak natural period of 0.14 sec and 0.28 sec in the E-W and N-S directions for the ground motion recorded at the Kass station. As a result, it is likely that the observed damage pattern in the URM structures mainly resulted from resonance because of the horizontal ground motion and was not significantly influenced by the vertical response amplification. This is contrary to the damage to low to medium-rise reinforced concrete buildings reported by Rafi et al. (2022) which was severely influenced by the vertical component of the ground motion. A possible explanation for this matter is the short building heights for the URM structures. On the contrary, an increase in the axial compression on the wall due to the vertical seismic forces may have helped in avoiding out-of-plane wall failures by increasing the overturning moment capacity of the masonry walls.

2.4 Earthquake Intensity

The data to estimate the earthquake intensity in the surveyed areas were collected using a questionnaire which was also employed by Rafi et al. (2015). The questionnaire has been designed to collect information on people's responses during the earthquake, and the structural and non-structural damage observed. The questionnaire is divided into three parts. The first part is related to the situation of the reporting person at the time of the earthquake. The second part deals with their experiences with the level of shaking during the earthquake. The third part of the questionnaire focuses on the observed effects of ground motion on surrounding objects and buildings. Each section contains several multiple-choice questions for the respondents. These choices were assigned intensity levels between II and IX on the Mercalli Modified Intensity (MMI) scale.

The data collected through the questionnaires were analysed, and the intensity results in different surveyed areas are given in Table 1. The observed earthquake intensities in Table 1 are based on the majority of responses. It is noted in Table 1 that the earthquake intensity varied between V and VII on the MMI scale based on the distance of the location from the epicentre, although the intensity level V was observed only at a single visited location. Note that the intensity of VI was found for the Mirpur city area from the data analysis.

2.5 Damage Grades

The majority of buildings in rural areas consisted of URM structures made with fired clay brick load-bearing walls. The damage data collected for these buildings through the aforementioned questionnaires and site surveys were employed to determine damage grades for this particular type of building typology in the region. Note that the typical construction practices for different types of buildings are the same in Pakistan and AJK. As a result, the obtained results also apply to the clay brick URM structures in Pakistan.

The damage grades defined by the European Macroseismic Scale 98 (EMS-98) (Grünthal 1998) for the European buildings were employed in this paper to categorize the observed damage. The building damage types are classified into 5 grades (D1-D5) based on the severity of damage defined by EMS-98 (Grünthal 1998) which is determined based on the visual inspection of the damaged structures.

The damage grades were first determined for the sample of buildings from the photographic record and the responses of people gathered in the relevant section of the questionnaires. The results of damage grades obtained from these data were extrapolated for the total buildings in a particular area given in Table 1. The obtained results from this work are summarized in Table 2. It is noted in Table 2 that all the buildings in Mohra Hill, New Suniyan, Pul Manada and Samwal Shareef suffered some level of damage as none of the buildings was found to be in D0 (no damage) category. The highest number of collapsed (or near collapsed) buildings (D5) was recorded in Mohra Kikeri and Mohra Roshan which came out to be nearly 33% and 32%, respectively. This was closely followed by the village named New Suniyan where the damage proportion of buildings in the D5 category came out to be 29%. The earthquake intensities in all three aforementioned areas were also the same (Table 1). No collapsed URM building was observed in Pul Manada where the least earthquake intensity was observed (Table 1). Similarly, more than 85% of buildings fall in damage grade D3-D5 (damage ranging from substantial damage to building collapse) in Mohra Hill and Mohra Roshan.

The data of earthquake intensity (Table 1) and building damage (Table 2) were employed to determine fragility curves for the clay brick URM buildings using the macroseismic method proposed by Giovinazzi (2005), called the Vulnerability Index method. A damage probability matrix (DPM) is developed in this method with the help of data on building damage with corresponding earthquake intensity (I) expressed on the EMS-98 (Grünthal 1998) intensity scale. The mean damage grade (μ_D) of the damaged buildings can be related to the vulnerability index (V) and the ductility index (Q) as given by Eq. (2). Note that V and Q provide a measure of the ability of a building/building stock to resist lateral earthquake loading and ductility of a building/building stock, respectively. The higher the value of V the less the building resistance and vice versa. Giovinazzi (2005) suggested Q equal to 2.3 which was employed in the presented paper.

$$\mu_D = 2.5\left[1 + \tanh\left(\frac{I + 6.25V - 13.1}{Q}\right)\right] \tag{2}$$

The distribution of damage can be determined with the help of Eqs. (3)-(7) using beta distribution (Rafi et al. 2015).

$$PDF : p_\beta(x) = \frac{\Gamma_{(t)}}{\Gamma_{(r)}\Gamma_{(t-r)}} \frac{(x-a)^{r-1}(b-x)^{t-r-1}}{(b-a)^{t-1}} \, a \le x \le b \tag{3}$$

$$CDF : P_\beta(x) = \int_a^x p_\beta(y)dy \tag{4}$$

$$r = t\left(0.007\mu_D^3 - 0.0525\mu_D^2 + 0.287\mu_D\right) \tag{5}$$

$$p_k = P_\beta(k+1) - P_\beta(k) \tag{6}$$

$$P(D \geq D_k) = 1 - P_\beta(k) \tag{7}$$

where t is equivalent mean (equals to 4.2); r is equivalent variance; $a = 0$; $b = 6$; Γ is the gamma function; k is the damage grade; p_k is the discrete beta density probability; and $P(D \geq D_k)$ is the cumulative probability beta distribution

The values of μ_D [Eq. (2)] were calculated at each MMI intensity level (V-XII) for a set of V values ranging from 0.8-1.2. These were compared with the observed mean damage grades. The value of μ_D [Eq. (2)] at $V = 1.1$ correlated well with the observed damage grades which was subsequently employed for the development of fragility functions. Complete details of this method are available in Rafi et al. (2015). The beta distribution function was used to develop DPM for the clay brick buildings corresponding to different intensity levels on the MMI scale. Note Giovinazzi (2005) reported $-0.2 < V < 1.0$ for the European buildings. In addition, Giovinazzi (2005) found $V = 0.74$ for the European URM brick masonry buildings. On the contrary, the value of V found for the damaged buildings in Mirpur is significantly large ($V = 1.1$) which indicates a higher vulnerability of these clay brick URM buildings in Mirpur as compared to similar European buildings.

Fig. 13 compares the data of μ_D [Eq. (2)] for the adobe (Rafi et al. 2015) and brick masonry structures in Pakistan at different MMI intensity levels. It is seen that μ_D increases with the intensity level for both types of structures. A higher value of μ_D for brick buildings at lower earthquake intensity values indicates their higher vulnerability compared to the adobe structures which appears to be counterintuitive. However, this may be partly explained considering that the adobe structures were single-storeyed while the brick masonry buildings were mostly two-storeyed.

Fig. 14 illustrates the fragility curves [Eq. (7)] for the clay brick URM buildings in Mirpur which also apply in other parts of AJK and Pakistan due to similar construction practices, as mentioned earlier. The value of I = V and above have been employed in Fig. 14, as the intensity levels less than V are not associated with any building damage. Similarly, damage state D0 was not considered as it is a ‘no damage’ state.

3. Conclusions

This paper presented the data analysis results gathered during the surveys of areas affected by the 24 September 2019 earthquake in Mirpur, Azad Jammu and Kashmir. These data were collected by a team from the Department of Earthquake Engineering at NED University of Engineering and Technology, Pakistan which visited the affected areas from 27-30 September 2019. The following conclusions can be drawn from the study presented in this paper.

1) The soil heterogeneity created directional effects on the strong motion data related to the fault orientation. This increased ground motion in the N-S direction as compared to the E-W direction at a recording station. The design spectra proposed in some of the international codes of practice underestimated the observed peak spectral acceleration. The peak V/H values at the recording stations were 2.47 and 1.66. The former value was higher compared to the value obtained by the predictive models suggested by the researchers in the existing literature. The obtained results from the analysis of ground motion characteristics indicated the need to develop a site-specific design spectrum for this region.
2) The majority of the buildings in the visited areas comprised clay brick unreinforced masonry (URM) buildings. A significantly large number of these buildings were damaged by the earthquake. The damage to these buildings was caused by the horizontal component of the ground motion and amplified seismic motion due to their location in hilly regions. Conversely, damage to the clay masonry piers of the bridges was influenced by the vertical seismic ground motion.
3) The observed building damage was categorised into five damage grades using the existing literature. These data were employed to determine the fragility curves for the clay brick URM buildings in Pakistan and Azad Jammu and Kashmir. A comparison of the

vulnerability index of the URM buildings in the visited areas with similar European buildings indicated that the former were more vulnerable compared to the latter.

Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

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TABLES AND FIGURES

List of Tables

Table 1. Details of visited areas and earthquake intensity

Table 2. Damage statistics for clay brick URM structures

List of Figures

Fig. 1 Location of earthquake epicentre and surveyed areas in Mirpur district

Fig. 2 Response spectra of 2019 Mirpur earthquake: (a) E-W component; (b) N-S component; (c) vertical component

Fig. 3 Spectral ratio of ground motion acceleration

Fig. 4 Typical URM private housing structure

Fig. 5 Damage of piers in Afzulpur bridge

Fig. 6 Collapse of Pul Manda bridge deck due to abutment failure

Fig. 7 Damages in historic mosque in Sumwal Shareef: (a) collapsed minaret; (b) minor cracking in internal walls

Fig. 8 Typical pattern of diagonal cracks: (a) classroom on ground storey at Mirpur University of Science and Technology; (b) residential building with diagonal wall cracks on first storey

Fig. 9 Out-of-plane failure of façade wall panel by overturning

Fig. 10 Collapse of a good quality URM residential building

Fig. 11 Partially collapsed housing unit

Fig. 12 View of fallen circular roof of stair tower

Fig. 13 Mean damage grade versus earthquake intensity

Fig. 14 Fragility curves for brick masonry buildings