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Article

Archeoseismic Study of Damage in Medieval Monuments around New Delhi, India: An Approach to Understanding Paleoseismicity in an Intraplate Region

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Abstract: The seismic shaking observed around Delhi and the surrounding region due to near-field and far-field earthquakes is a matter of concern for the seismic safety of the national capital of India, as well as the historical monuments of the region. Historical seismicity indicates that the Delhi region has been affected by several damaging earthquakes originating from the Himalayan region as far-field events, as well as due to near-field earthquakes with epicenters close to Delhi. The historical records, along with recent archeoseismological studies, suggest that Qutab Minar, a UNESCO World Heritage Site, was damaged by the earthquake of 1803 CE. This event represents the only evidence of seismic damage from the region, as there has been no detailed study of other historical monuments in the area or earthquakes that have caused damage. In this context, the earthquake damage to other monuments might have been overlooked to some extent around the Qutab Minar due to the lack of proper earthquake damage surveys and documentation in historical times. The main goal of this study is to identify evidence of earthquake archeological effects around the Qutab Minar and to shed new light on the occurrence and characteristics of ancient earthquakes while providing data to inform seismic risk assessment programs. With this aim, we describe different earthquake-related damage (EAE, earthquake archeological effects) at the Isa Khan Tomb and Humayun's Tomb, built between 1548 CE and 1570 CE, respectively, as well as the older Tomb of Iltutmish (built in 1235 CE) along with the Qutab Minar, which was built between 1199 CE and 1220 CE. The damage was probably caused by seismic events with intensities between VIII and IX on the European Macroseismic Scale (EMS). Based on the methodology of paleo ShakeMaps, it is most likely that the 1803 CE earthquake was the causative earthquake for the observed deformation in the Isa Khan Tomb, Tomb of Iltutmish, and Humayun's Tomb. More detailed regional paleoseismological studies are required to identify the responsible fault. In conclusion, the impressive cultural heritage of Delhi city and the intraplate region is constantly under seismic threats from near-field earthquakes and far-field Himalayan earthquakes.

Keywords: archeoseismology; seismic hazard; Delhi; intraplate deformation; Qutab Minar

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1. Introduction

The documentation of past damaging earthquakes in tectonically active regions, more specifically in the intraplate parts, is a crucial factor for seismic hazard assessment [1–8]. In such regions, archeological earthquake records can contribute to a well-constrained characterization of historical earthquakes, their characteristics, intensity, and a better understanding of the earthquake scenario for a more accurate seismic hazard assessment in future [9–18]. Archeoseismology has the potential to address numerous unresolved questions. These include determining the earthquake's occurrence time and location, ascertaining its magnitude, and assessing the damage it caused. These insights can aid in estimating the macroseismic intensity and shaking scenario [5,7,8,12,18,19]. The recognition or description of historical earthquakes distinguishes archeoseismology as one of the methods well suited to enhancing our understanding of past seismic activity. This, in conjunction with paleoseismology, historical seismology, and instrumental earthquake recordings, forms the essential foundation for any seismic hazard analysis, primarily in intraplate regions facing continuous earthquake shakings from near-field as well as far-field earthquakes such as New Delhi [3,17,20].

The Indian subcontinent is one of the most seismically active areas in the world. Its seismicity is concentrated mainly at the orogen boundaries in the north and west, whereas the stable continental interior of the Indian craton is seismically quiet, besides rare intraplate earthquakes like the 1720 Delhi earthquake (M_w 6.5) [21]; 1967 Koynanagar earthquake (M_w 6.6) [22]; or 2001 Bhuj earthquake (M_w 7.7) [23]. The 1967 Koynanagar event is considered to be associated with a 25 km long surface rupture, and the question of induced seismicity has been raised, as the nearby Koyna dam may have triggered the event [24]. Despite its severe damage and high magnitude, the 2001 Bhuj earthquake did not cause any surface rupture. The 2001 Bhuj earthquake also raised concern about the seismic hazard scenario of the Indian subcontinent [25,26]. The 2001 Bhuj earthquake caused damage to several historical/heritage sites, such as Prag Mahal and Aina Mahal and the historic Swaminarayan temple [27]. Ref. [17] poses several examples of earthquake-induced damage to heritage sites around the Indian subcontinent, suggesting the archeoseismological potential of the Indian subcontinent and deriving earthquake-related information from the damage patterns, such as intensity and source. That information can enhance our knowledge regarding past earthquakes in India, which is not reported in historical chronicles.

The ongoing convergence between the Indian and Eurasian Plates has resulted in several damaging earthquakes of a magnitude $M_W > 7–8$ along the Himalayan region [28,29]. Some of these earthquakes have caused seismic-induced damage along the Indo-Gangetic Plain, including the national capital Delhi [30–37] (Table 1). Apart from these Himalayan earthquakes, several historically damaging earthquakes have hit the Delhi area with epicenters in the vicinity of Delhi (Table 1) [36,38–43].

Moderate to high seismic risk can be inferred from the historical seismic records for the national capital territory (NCT) of Delhi, including local earthquakes as well as from those originating in the Himalayan region [21,44–46]. Earthquakes of intensities up to IX (MMI) and magnitudes between 6 and 7 have occurred in and around Delhi in the past [42,47]. Despite being one of the major capitals of several ancient kingdoms, the historical earthquake data are incomplete for the region, or considerable uncertainty remains with the seismic data [48].

To understand and mitigate the seismic hazards of an area, it is crucial to understand past earthquakes, which can be found in the seismic catalog of the area, which incorporates information about past events according to archeological, historical, and paleoseismological studies. This helps to delineate the seismogenic fault, its location, and socioeconomic effects, along with the recurrence interval [15,49–53]. Unfortunately, in the intraplate region, which generally faces low- to moderate-magnitude ($M_w < 6.5$) earthquakes, the delineation of the timing, local intensity, and spatial distribution of strong ground motions, as well as the location of epicenters and the magnitude of the seismic events, are not easy to determine due to a large recurrence interval, an incomplete seismic catalog, and no evidence of surface ruptures [54–58].

In such cases, the earthquake damage observed in historical or archeological sites can provide crucial information about past seismicity, which is known as archeoseismology. Archeoseismology is a branch of paleoseismology, which focuses on earthquake-related damage to man-made structures to understand the timing and type of past earthquakes [5,59,60]. Several deformation types, such as fallen pillars and blocks, conjugate fracture sets in walls, toppled walls, fallen columns, dropped keystones in arches, displaced arch segments, displaced pillars, penetrative cracks in walls, folded floors, etc., can be used as markers of earthquake-related damage, and the timing of the earthquakes can be determined from the history of the buildings, dating of the features, and historical seismicity records [14,15,59–62]. Archeoseismology can help us to identify specific earthquakes responsible for the destruction of structures and sites or even the abandonment of civilization as it can provide useful information about earthquakes that has not been recorded in the historical records, where this can be used to extend the seismic catalog of the area [17,62–69]. Accurate estimation of the effects of historical earthquakes on heritage buildings can help us determine the recurrence and past impacts for accurately estimating the seismic risk in intraplate regions [68,69].

The Indian subcontinent continuously faced damaging earthquakes in the historical past, but the proper documentation of earthquake-induced damage started after British rule. So, archeoseismology can be used as a tool to solve these issues for destructive earthquakes along the Indian subcontinent. Several researchers have used archeological evidence to understand the earthquake history in India. Kovach et al. [69] reported archeoseismological evidence from the Dholavira site in the Kachchh region, Western Gujarat. Rajendran [70] reported evidence of ancient earthquakes from the Ter region of Maharashtra, whereas Rajendran and Rajendran [34] presented evidence of past earthquakes from stone temples in the Almora region, along with the damages to the Qutab Minar in New Delhi during the 1505 CE and 1803 CE earthquakes. Several studies have suggested the masonry temples in the Kashmir region were repeatedly damaged by the 1555 CE and 1885 CE earthquakes [71,72]. Joshi and Thakur [73] reported archeoseismological evidence of the 1555 CE Kashmir and 1905 CE Kangra earthquakes from Hindu temples of the Chamba region. Kázmér et al. [17] presented several archeoseismological pieces of evidence of past earthquakes spanning from north to south within the Indian subcontinent, suggesting that ancient Indian structures possess great potential for us to use to understand the severity and earthquake hazards in the past. Considering these previous studies, it can be said that the ancient cities and buildings on the Indian subcontinent have great potential in terms of understanding of the seismic history of the country using an archeoseismological approach.

Several attempts have been made to understand the seismic source and hazard potential for the national capital territory (NCT) using archeoseismological evidence [17,34] or recent minor to moderate seismicity [21,35,45–47]. But all of these archeoseismological studies are only focused on the Qutab Minar archeological complex, a UNESCO World Heritage Site, and previous studies have suggested that the Qutab Minar was probably damaged during the 1803 CE earthquake [34,37,42,74]. Numerous other monuments in the vicinity of New Delhi, such as Iltutmish's Tomb (1235 CE), Alai Darwaza (1311 CE), the Tomb of Imam Zamin (16th century), Humayun's Tomb (1558 CE), Barber's Tomb (1556–1605 CE), Bu Halima's Tomb (1500–1600 CE), Firoz Shah Tughlaq's Tomb (1352–1353 CE), the Purana Quila fort (including the Qila-i-Kuhna Mosque, 1541 CE, and Sher Mandal, 16th century), and Safdarjung's Tomb (1754 CE) [75–77], were all constructed either before the 1720 CE Delhi earthquake or the 1803 CE earthquake, which caused damage to the Qutab Minar (Figures 1 and 2). The historical earthquake data indicate that no significant seismic events occurred in the nearby seismic source area between 1500 CE and 1810 CE, except for the 1720 CE Delhi earthquake and the 1803 CE Kumaun–Garhwal earthquake, both of which caused extensive damage in the Indo-Gangetic Plain. In the present study, we have mapped the archeoseismological damage in another quarter of Delhi and covered a different medieval period to understand the earthquake hazard scenario for the heritage sites around New Delhi.

Table 1. Significant earthquake events that caused damage around Delhi with local MM intensity [32,34,44,72–87].

Earthquake Events	Epicentral Location	Magnitude	Intensity	Areas	Effects
6 June 1505	-	M_w = 8.2–8.9			Felt around Delhi and Agra; no major damage to historical monuments
15 July 1720	28.37° N–77.10° E	M_w = 6.5	IX	Delhi	Extensive damages observed in Old Delhi Damaged the old Delhi fortress and many buildings
1 September 1803	27.50° N–77.70° E	M_s = 7.5/M_w = 6.8	IX	Mathura/Kumaun	Felt severely in Delhi and caused extensive damage to buildings and also some loss of life
10 October 1956	28.15° N–77.67° E	M_w = 6.7	VII	Near Bulandshahar	Minor damage in Delhi
27 August 1960	28.20° N–77.40° E	M_w = 6.0	VII	Near Faridabad	Cracks in buildings, old houses collapsed
15 August 1966	28.67° N–78.93° E	M_w = 5.8	V	Near Moradabad	Moderate shaking around Delhi
5 March 2012	28.74° N–76.60° E	M_w = 5.0	VI	Delhi	Cracks in buildings

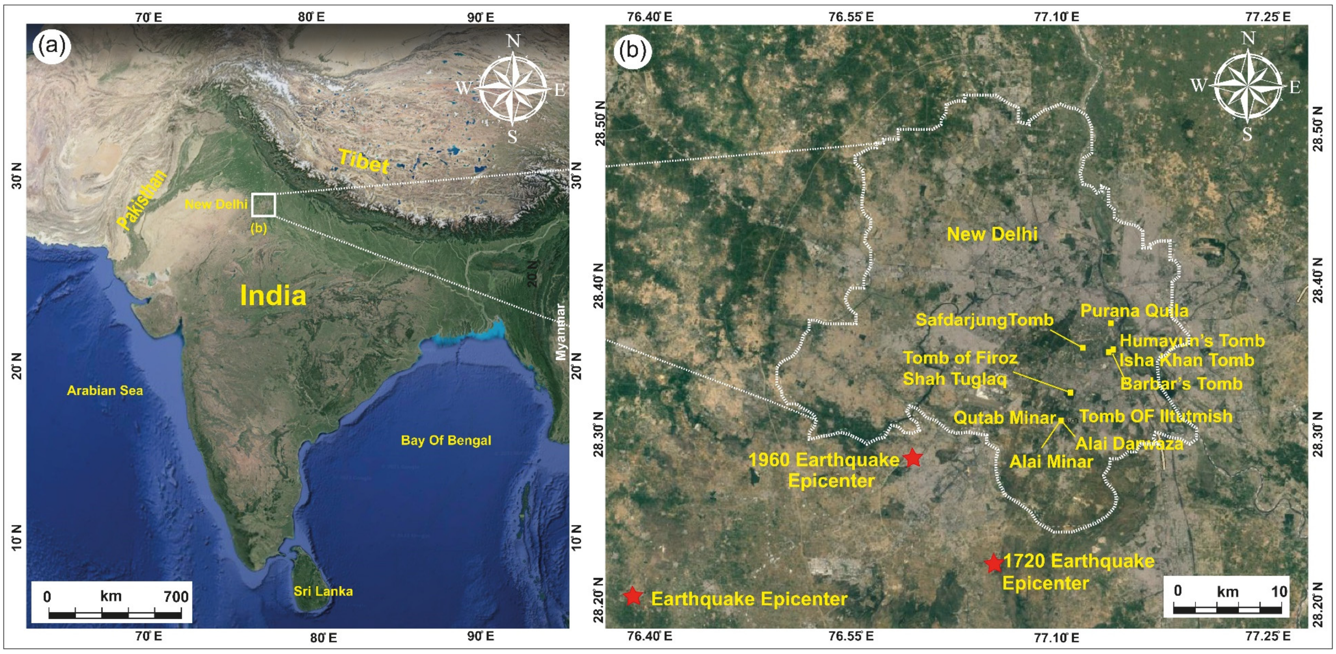

Figure 1. Map (**a**) showing the location of New Delhi as per the Indian context; (**b**) map showing the medieval archeological sites around New Delhi, along with the archeological monuments such as Qutab Minar, Iltutmish's Tomb, Humayun's Tomb, and Isa Khan's Tomb, which are considered for detailed archeoseismological study (Image Source: http://www.earth.google.com (accessed on 30 October 2023).

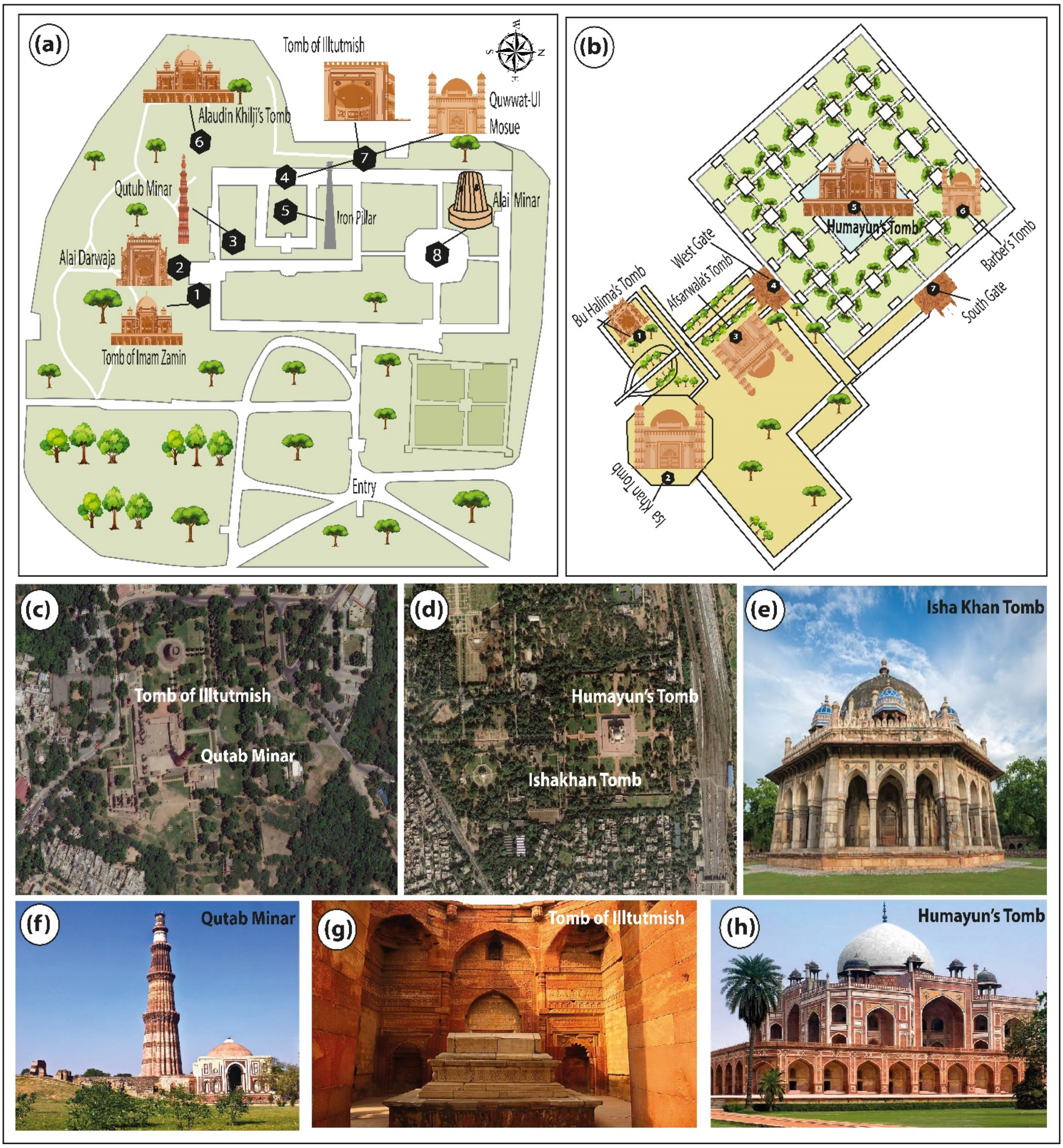

Figure 2. (**a**) A sketch showing the monuments of Qutab Minar complex; (**b**) monuments of Humayun's Tomb complex; (**c**,**d**) aerial view of the Qutab Minar and Iltutmish's Tomb, Humayun's Tomb, Isa Khan's Tomb considered in this present archeoseismic study; photographs showing (**e**) Isa Khan's Tomb, (**f**) Qutab Minar, (**g**) Tomb of Iltutmish, (**h**) Humayun's Tomb. Photographs used for figures (**e**,**f**,**h**) of these monuments were taken from https://www.delhitourism.gov.in/delhitourism/ (accessed on 30 October 2023).

2. Geology and Tectonics of the Study Area

New Delhi is one of the largest cities in India, with a population of approximately 20 million and is located about 250 km SW of the seismically active Himalayan Belt, which is well known for generating large-magnitude earthquakes [21,22,80]. Delhi is part of the Delhi–Aravalli Fold Belt (DAFB), bounded by the Indo-Gangetic Plain in the north and the Aravalli Mountains in the south. The terrain is generally flat except for the low-relief NNE–SSW-trending Delhi–Haridwar Ridge in the southern and central parts of the area [22,80]. New Delhi and its surrounding regions are situated on the Proterozoic folded meta-sedimentary quartzite and metapelite of the Delhi–Aravalli Fold Belt (DAFB) [81–85]. Along the DAFB subsurface, mapping of the geological formations indicates the rocks of DAFB have undergone several folding and metamorphic phases [85–88]. The DAFB is bounded to the east by the strike-slip Great Boundary Fault (GBF) and to the west by the Mahendragarh–Dehradun Fault (MDF) (Figure 3). The region is also surrounded by the NNE–SSW Delhi–Haridwar Ridge and NNW–SSE Delhi–Sargodha Ridge, which are sub-parallel to the Himalayan Fold and Thrust Belts, forming a triple junction around New Delhi (Figure 3) [21,89,90]. The upper part of Delhi and the adjoining area comprise quaternary sediments and floodplain deposits [91]. The site comprises ridges and faults trending NNE–SSW with a few lineaments/faults of N–S trend (Figure 3). The Oil and Natural Gas Corporation (ONGC) and the Geological Survey of India used drilling, a geophysical survey, and an aeromagnetic survey to map the traces of the faults and successfully traced some of them, such as the Mahendragarh–Dehradun Fault (MDF), Sohna Fault (SF), Mathura Fault (MF), and Moradabad Fault (MBF) [79,87,90,92,93]. The Mahendragarh–Dehradun Fault (MDF) is a 295 km NE–SW-trending long fault connecting the Peninsular Craton in the south to the Himalayan Frontal Thrust (HFT) in the north [79]. The New Delhi region also has several subsurface faults identified based on ground-penetrating radar (GPR) and Bouguer gravity anomaly data [93]. Based on this geophysical survey, several NW–SE-trending reverse faults and shallow steep vertical faults were identified close to the Mahendragarh–Dehradun Fault (MDF) around the Delhi region [88,93].

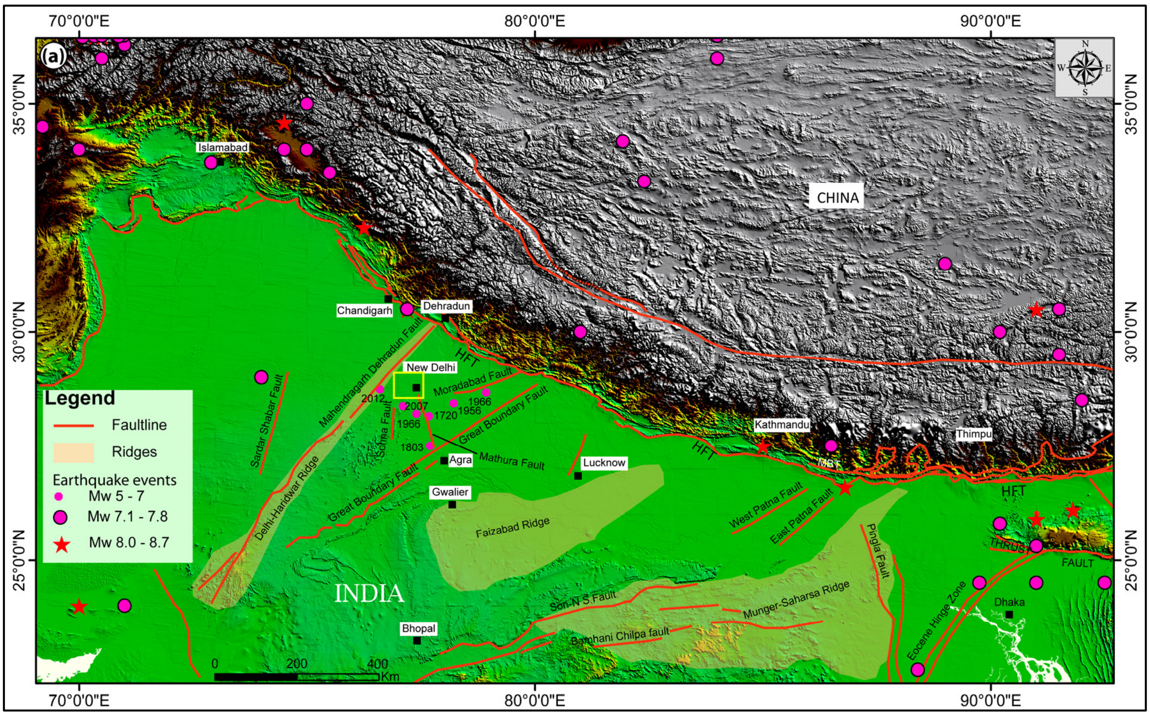

Figure 3. Seismotectonic map showing the major structural features around the Indo-Gangetic Plain, including the major structural features around Delhi. The map also shows the distribution of major earthquakes that were felt around New Delhi from near-field and far-field sources. The year mentioned in the figure indicates the timing of the earthquake [Modified from [37,89]].

The GPS data indicate that Delhi and its surrounding area are moving with a composite velocity of approximately 0.6 to 1.4 ± 1.2 mm/y [94]. According to the IS-1893 code, Delhi is categorized under seismic zone IV, which corresponds to an MSK intensity of VIII and a PGA of 0.24 g [94]. Rare data from the World Stress Map indicate NNW–SSE-directed horizontal shortening in the NCT area [95] associated with strike-slip faulting based on the 10 October 1956 earthquake.

3. Methodology

We have searched for earthquake-related damages to heritage sites around New Delhi. Many characteristic features were recorded, such as conjugate fracture sets in walls, toppled walls, fallen columns, dropped keystones in arches, displaced arch segments, displaced pillars, penetrative cracks in walls, and folded floors. Detailed photographs, drawings, and locations were documented. The history of the heritage sites, such as their construction, damage, and repair history, was analyzed based on our current observations and published chronicles. The damage patterns observed were analyzed based on the earthquake archeological effects to deduce the causes of damage and to determine whether earthquakes were seismic or non-seismic [96–98].

To understand the possible sources of these archeoseismological damages, scenario-based paleo ShakeMaps and intensity distributions were developed considering the historical seismic data around New Delhi. The ShakeMap software developed by the US Geological Survey was used to generate the paleo ShakeMaps, which are representations of the actual ground shaking produced by an earthquake [99–101]. An earthquake is characterized by a single magnitude and epicenter, but it generates a diverse range of ground-shaking intensities, influenced by factors such as the distance from the fault rupture and the geological characteristics of the surrounding rock and soil at each location. In the absence of specific data regarding the earthquake magnitude, intensity, epicentral area, and focal depth—which are typically the standard input parameters for ShakeMap calculations—we conducted an analysis by simulating various scenarios. These scenarios involved adjusting the earthquake magnitude and focal depth to gain insights into the distribution of the intensity levels for historical earthquakes. To perform these calculations, we followed the guidelines outlined in the USGS ShakeMap Manual [101] and utilized a Python script using input parameters such as the earthquake magnitude, depth, fault strike, and coordinates of either the epicentral area or active fault. Using the software, the earthquake-generated shaking distribution and intensity were calculated, originating from a 2D source (scenario hypocenter). The topographic data (slope and elevation) were extracted from Digital Elevation Models (DEMs). Based on the DEMs, data on the magnitude, fault strike and depth of earthquake, shaking intensity, and contours were estimated for several historical earthquakes, such as those in 1720 CE, 1803 AD, and 1960, which have caused damage around New Delhi.

4. Past Damaging Earthquakes around Delhi

New Delhi and its surroundings fall into seismic zone IV, expecting severe shaking of Modified Mercalli (MM) intensity VIII in the future [46,89]. Earthquake hazards in Delhi and the northern capital region (NCR) are mainly caused by their proximity to the Himalayan mountain range and the resulting tectonic activity (Table 1). Historically, there have been several significant earthquakes in the Delhi region, i.e., the 26 July 1720 CE Delhi earthquake, the 1 September 1803 CE earthquake, the 10 October 1956 Khurja earthquake, and the 1960 Gurgaon earthquake, whose epicenters were located in the neighborhood of Delhi [40], including the severe far-field Kangra earthquake on 4 April 1905 [69,70] and the Bihar–Nepal earthquake on 15 January 1934 [37,102,103] (Table 1). Considering the scope of this study, the details of the past historical seismicity causing damage around Delhi will be described to understand whether Delhi has sustained solid and damaging earthquakes and to what extent. It is important to note that smaller earthquakes can also occur in the region and can cause damage.

4.1. The 6 June 1505 CE Earthquake

The 1505 CE earthquake is one of the major earthquakes recorded in the Indian subcontinent [104]. Several historical reports suggest that in 1505, within a span of one month from 6 June to 6 July, two earthquakes were recorded in northern India and Afghanistan close to Kabul [34,37,74]. Due to the close temporal occurrence, the damage associated with these two events remains debatable. Ambraseys and Jackson [104] reported that the 6 June 1505 earthquake was extensively felt in northern India. The earthquake shook areas as far as the Garhwal–Kumaun Himalayas and the Lo Mustang and Kyirong areas in SW Tibet, but also Delhi and Agra in the Indo-Gangetic Plain. A study by Iyengar et al. [32] suggested the earthquake occurred on the 3rd Safar 911 H (6 July 1505). He reported that the earthquake was violent in nature, with significant structural damage to buildings around Agra and Delhi, along with reports of shaking as far as Afghanistan; however, Kabul is c. 1000 km away from Delhi.

The Babarnama (The Letters of Babur) and the Akbarnama (The Book of Akbar) chronicles reported the earthquake in Hindustan on 3rd Safar 911 H (Hijri year, 6 July 1505), with strong shaking in the mountainous regions, large building collapses, liquefaction, and the uprooting of trees [104]. Although the earthquake caused extensive damage to monasteries and houses in the Tibetan region, damage was not observed at major monuments like the Bara Gumbad Mosque in Agra (built in 1484 CE) and the Qutab Minar in Delhi (built in the late 12th century; [33]. From the damage associated all along the region of the Indian subcontinent, it can be suggested that the 6 June 1505 event was a great Himalayan earthquake possibly associated with a surface rupture [37].

4.2. The 26 July 1720 CE Earthquake

This was one of the most damaging earthquakes that occurred close to Delhi. Although the epicentral location is still debatable, some previous studies have suggested that this was a local event with an intensity of IX [84]. Some of the literature mentions that this earthquake caused extensive damage around old Delhi on 22 Ramadan 1132 AH (Hijri Calendar), which corresponds to the Gregorian date of Friday 26 July 1720 [42,43,48,105,106].

4.3. The 1 September 1803 CE Earthquake

The 1803 earthquake was one of the most damaging earthquakes reported in the Garhwal Himalayas area. During this event, extensive shaking was observed in a large area between Punjab in the west and Kolkata in the east, with extensive damage around Garhwal and a few cities located in the Indo-Gangetic Plain. Still, the epicentral location of this earthquake remains debatable, but several researchers have suggested the epicenter was near Uttarkashi considering the damage pattern reported during the earthquake [34,104]. A few earlier documents reported the epicentral location was near Mathura in the Indo-Gangetic Plains based on the damage patterns and extensive liquefaction [30]. In contrast, the Indian Meteorological Department suggested the epicenter was located in the central Himalayas. Extensive damage was observed around Uttarkashi, Srinagar of the Garhwal Himalayas, and near Agra and Mathura along the Indo-Gangetic Plain [34].

All of the 700 to 800 houses located in Garhwal were damaged, whereas extensive liquefaction was reported from Mathura [30]. Around 300 people died during the earthquake. The 1803 earthquake damaged several temples of the 8th–12th century from the Garhwal and Kumaun regions. Some temples were again damaged by the 1999 Chamoli earthquake (M_w 6.6), but less so in comparison with the 1803 destruction. This probably indicates the 1803 earthquake was larger than the 1999 Chamoli earthquake [34,37]. The 1803 earthquake caused damage to the 72.5 m high Qutab Minar, built in the 13th century [33,106]. Observing the damage to this monument and widespread liquefaction around Mathura, Bapat et al. [107] suggested an epicenter close to Mathura. But, taking into account the damage pattern [107–110], it was suggested that the 1803 earthquake was a large seismic event and could have produced a surface rupture of about ~200 km along the Himalayan Frontal Thrust (HFT). The magnitude of the earthquake was assessed as M_w 7.5 ~ 8 [34,35,104,107–111]. Recently, Malik et al. [37] discovered evidence of a surface rupture of 1803 in paleoseismic trenches in the Kumaun Himalayas, which might provide the epicentral location for this earthquake. Considering the surface rupture evidence of the

1803 earthquake there, it can be suggested that the epicenter of the earthquake was in the Kumaun Himalayas instead of Garhwal.

4.4. Recent Earthquakes

Apart from these historical earthquakes, Delhi has also sustained earthquake damage during recent earthquakes whose epicentral locations were in and around Delhi. Some of these damaging earthquakes are the 10 October 1956 Khurja earthquake (Mw 6.7; [39]); 27 August 1960 (Mw 6.0; [48]) earthquake; and 15 August 1966 Moradabad earthquake (Mw 5.8) [39,47]. The 10 October 1956 Khurja earthquake caused 23 fatalities in Bulandshahr and some injuries in Delhi, whereas the 27 August 1960 earthquake injured 50 people in Delhi. On 15 August 1966, the Moradabad earthquake killed 14 people in Delhi [39]. Iyengar [42,43] reported damage to one of the minarets of Delhi's Jama Masjid during the Mw 4.0 earthquake on 28 July 1994. The 5 March 2012 (M_w 5.0) Delhi earthquake caused extensive building damage with minor and major cracks in concrete buildings [29,44]. Recently, during 2020–2021, the NCT region has experienced several low-magnitude earthquakes [44,46,47]. In general, it can be said that earthquakes of an intensity up to IX (MMI) and magnitudes between 6 and 7 have occurred in and around Delhi in the past (Table 1). Therefore, it can be inferred that the city is under threat of seismic risk, not only from local earthquakes but also from those originating in the Himalayan region. There is a need for a seismic damage survey of historical monuments to understand the past seismic damage and for future seismic hazard assessment, as well as to protect from future earthquakes.

5. Archeoseismological Evidence from Delhi

Of the previous studies around Delhi, most focus on the Qutab Minar complex (Figure 2a; [17,33,34,106]). This may be due to the earthquake-related damage reported in the historical records and the delicate and susceptible structure of the minaret. However, there are several other important structures built during the 13th to 15th Century in and around Delhi that have not been studied in terms of archeoseismology. Herein, we present the earthquake-related damage to two historical monuments built during the 15th century in Delhi and model the seismic source of the damage.

5.1. The Qutab Minar Complex

The Qutab Minar complex is a UNESCO World Heritage Site located in South Delhi (Figures 1 and 2). It was completed in 1198 CE.

The complex consists of the Quwwat-ul-Islam mosque, Qutab Minar, Alauddin's Madrasa, Alai Darwaza, and Alai Minar. The Qutab Minar is a 72.5 m high minaret. There are three tombs inside the complex: the Tomb of Iltutmish (1235 CE), Alauddin's Tomb, and Imam Zamin's Tomb (1538 CE). Several authors have reported that the top portion of the Qutab Minar minaret was broken during the 1803 CE earthquake (Figure 4a–d; [17,33,34,106]. Recently, Kázmér et al. [17] reported the earthquake-related damage to the Tomb of Iltutmish. However, there is a lack of detailed studies on the Qutab Minar complex.

This study recorded several earthquake-induced damages around the Quwwat-ul-Islam mosque and the Iltutmish Tomb within the Qutab Minar complex (Figure 4). The Quwwat-ul-Islam mosque was erected between 1192, the conquest of Delhi, and 1198 when the building was completed by Sultan Muizuddin ibn Sam. The mosque was built upon the remains of different Hindu temples. The following ruler, Shamsuddin Iltutmish (1211–1236), doubled the size of the mosque in 1230 by extending its colonnades outside the original enclosure (photos were taken in this later part). The result was that the Qutab Minar fell within the mosque enclosure. A later Delhi sultan, Alauddin Khalji (1296–1316), again extended the mosque substantially by enlarging the enclosure. His major contribution was adding the two massive gateways. During our systematic archeoseismic damage survey around the Quwwat-ul-Islam mosque, we observed that the upper elements of two composite columns (left) bear axial fractures (Figure 4a,b).

These were caused when the block above repeatedly hit the columns during earthquake-induced shaking. The lower elements of the same columns bear deeply fractured oblique edges. These were created when the rectangular block above hit them during shaking. Within the same mosque, the stone beams connecting the three columns were fractured in the middle, right above the central column. Horizontal stone beams are damaged easily, but not when right above a strong supportive pillar. This is a clear indication that the differential vibration of the central column caused the failure (Figure 4a,b). In many places, the edge of the column was fractured parallel with the long axis. This is the typical fracture caused by the repeated hammering of the ashlar above due to strong shaking (Figure 4c,d).

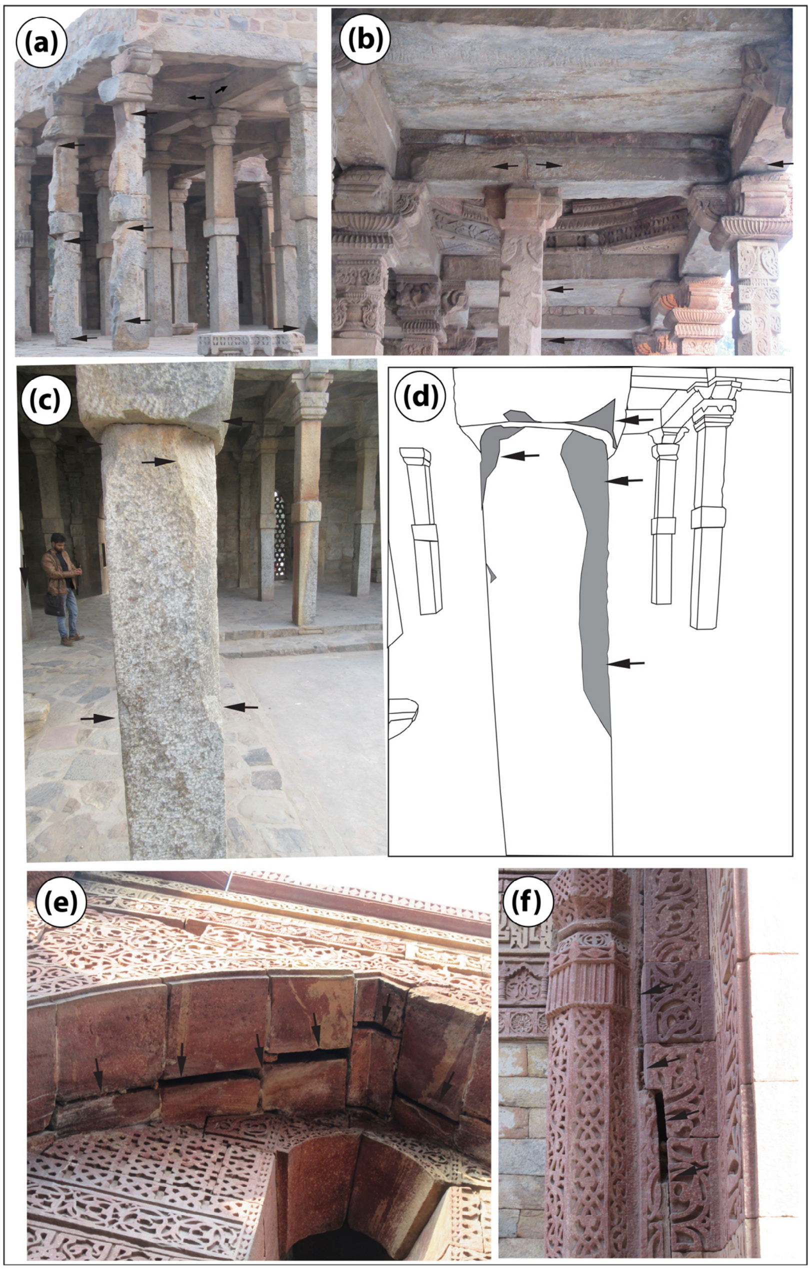

Figure 4. Damage observed around Quwwat-ul-Islam mosque, Qutab Minar complex. (**a**) Upper elements of two composite columns (left) bear axial fractures; (**b**) stone beam connecting three columns was fractured in the middle, right above the central column; (**c**,**d**) photograph and line diagram showing the edge of column fractured parallel with the long axis, typical fracture caused by

repeated hammering of the ashlar above (arrows); (**e**) out-of-plane shift in arch masonry blocks separated by a more than 5 cm wide gap near the top of the entrance arch of the northern gate in the Iltutmish Tomb, Qutab Minar complex in Delhi; (**f**) opening of wall decoration a few centimeters large at north gate in the Iltutmish Tomb, Qutab Minar complex in Delhi.

5.2. Iltutmish's Tomb

Iltutmish's Tomb was built by Shamsuddin Iltutmish for himself in 1235, who ruled during 1211–1236 (Figure 2). Iltutmish's Tomb is a cubic building with dimensions of about 13 × 13 m in plain view and with a height of 9 m in its present state. The walls are 2 m thick and made of light-brown-colored sandstone. The tomb shows evidence of major restoration, which can be observed due to the modification of the original richly carved portions with later undecorated walls. At the top of the tomb, we observed 5 cm wide gaps, which are due to the out-of-plane shift in the masonry blocks (Figure 4e,f). This kind of shifting can be observed during an earthquake of intensity IX [17]. Since both the Qutab Minar and the Tomb of Iltutmish are located within the same archeological complex and are around 500 m apart, it can be inferred that both were damaged during the 1803 CE earthquake. Similar damage features have been documented at various earthquake-hit sites worldwide (Table 2).

5.3. Humayun's Tomb

Humayun's Tomb is a massive stone monument built of reddish sandstone, white marble, and granite, and it is the earliest Islamic garden tomb in the Indian subcontinent (Figures 1, 2h and 5a). Therefore, Humayun's Tomb has been a UNESCO World Heritage site since 1993; it was built from 1562 to 1571 CE.

The area covers c. 27.04 hectares, which includes other Mughal-style 16th century tombs like the Nila Gumbad, Isa Khan, Bu Halima, Afsarwala, and Barber's Tombs situated on the banks of the Yamuna River.

Humayun's Tomb was built on a wide terraced platform with two bay deep-vaulted cells on all four sides. It is an octagonal-shaped monument with four long sides and chamfered edges with a height of c. 42.5 m. It has a double dome clad with marble flanked by pillared kiosks (chhatris), and the domes of the central chhatris are decorated using glazed ceramic tiles. The archeoseismic survey suggests that previous earthquakes have damaged the entrance gate of Humayun's Tomb.

We noticed earthquake-induced damage to the main cupola (Figure 5b–f). The red sandstone of the main copula shows fractures along its corner. The white marble blocks used at the main entrance also show chipped corners. The corner marble pillars of the main structure show fractured edges, whereas the red dotted sandstone blocks used for the artwork on the main complex corners show differential fractures at the centers and corners. The gate artwork was made of alternate white and reddish stones. The reddish stone blocks at the edges fractured along their long axis (Figure 6a,b), which is a typical damage type observed due to the repeated hammering of the blocks during earthquakes. Similar damage features were documented at various earthquake-hit sites worldwide (Table 2).

Table 2. Earthquake-induced damage—worldwide examples.

Damage	Location	Age	Earthquake Date	Reference
Axial Fracture of Column	Basilica Santa Maria di Collemaggio, L'Aquila, Italy	13th Century	2009	Figure 9a in Gattulli et al. [112]
	Ribat entrance, Sousse, Tunisia	8th Century	Probably 859 CE	Figure 3f in Kázmér [113]
	Ribat entrance, Monastir, Tunisia	796 CE	Probably 859 CE	Figure 7c in Kázmér [113]
Chipped Corners	Armenia	Medieval	Repeated	Figure B in Rideaud [114]
	Cusco, Peru	Pre-Spanish	~1400–1533 CE	Figure 5b in Combey et al. [18]
	Havuts Tar Monastery, Armenia	Medieval	Repeated	Figure 10 in Rideaud and Helly [115]
	Kal'at Nimrod	13th Century	1759 CE	Figure 2i in Marco [53]

	Propylaia, Akropolis, Athens, Greece	Antiquity	Repeated earthquakes	Figure 22 in Pampanin [116]
	The Barracks, Umm al-Jimal, Jordan	Byzantine	Repeated	Figure 45a in Al-Tawalbeh [117]
Extensional Gaps	Cusco, Peru	Pre-Spanish	~1400–1533 CE	Figure 5d in Combey et al. [18]
	Basel Münster, Switzerland	12th Century	1356 CE	Figure 4. in Fäh et al. [118]
	Jerade, Anatolia, Turkey	Antiquity	Repeated	Figure 8 in Giuliani [119]

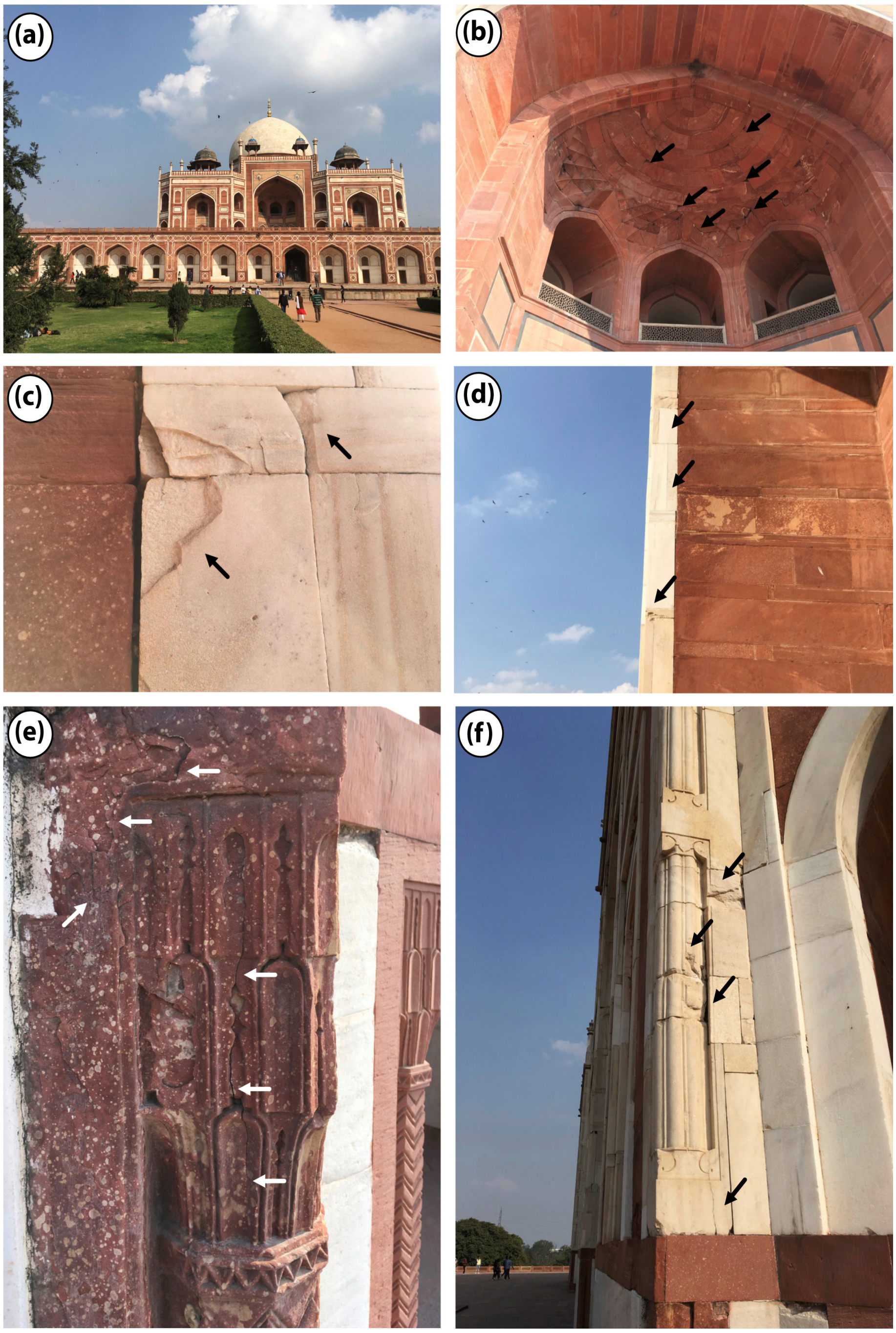

Figure 5. (**a**) Humayun's Tomb (taken from https://www.delhitourism.gov.in/ (accessed on 30 October 2023); (**b**) the red sandstone in the central cupola with corner break-outs indicated by black arrows; (**c**) marble application at main entrance has corner break-outs (black arrows); (**d**) chamfered marble edge on the western corner with corner break-outs (black arrows); (**e**) dotted red sandstone with fractures and deformation (white arrows); (**f**) the western corner with corner break-outs in marble (black arrows).

Figure 6. (**a**) Damage to the entrance gate of Humayun's Tomb; (**b**) the reddish stone block fractured at the corner due to the repeated shaking, detail indicated by black arrow.

5.4. Isa Khan's Tomb

This tomb was built during 1547–1548 for the noble Isa Khan Niazi during the ruling time of Sher Shah Suri and is located within the Humayun's Tomb complex in Delhi. The tomb is made of white–yellowish granitic rocks, with a minor portion also made of red sandstone, and is octagonal in shape (Figure 7). Isa Khan Niazi was an Afghan noble who served Sher Shah Sur, then his son Islam Shah Sur, during the Sur interruption (1540–1555 CE) of the Mughal reign in Delhi. His tomb, domed and octagonal in design, is ringed by a deep veranda and sits at the center of an octagonal complex to the west of Humayun's Tomb [120,121]. It has been observed that the Niazi Tomb contains some of the basic forms and ideas that later influenced Humayun's Tomb, including its position in a walled garden enclosure [122,123]. A mosque at the edge of the complex, known as the Mosque of Isa Khan, is thought to have been built at the same time as the tomb.

The detailed damage survey suggested that several damages to features across the tomb are of seismic origin, such as chipped corners; displaced arches and edges of masonry blocks; tilted, broken steps; collapsed stairs; and extensional gaps (Figure 7a–h). We have interpreted that the dipping broken corners or chipping may indicate vertical or rotational motions associated with seismic waves [14,62]. The fractured walls could be the consequence of repeated shear movements due to intense shaking during an earthquake (Figure 7g). We interpreted that the broken corners of the stone columns not only in Isa Khan's Tomb but also in the Quwwat-ul-Islam mosque, Iltutmish's Tomb, and Humayun's Tomb are the result of maximum compressive stress ($\sigma 1$) changes to the vertical stress at the surface due to seismic waves and repeated shaking during seismic wave amplification or passage through the ground (Figure 7b,e). Similar damage features were documented at various earthquake-hit sites worldwide (Table 2).

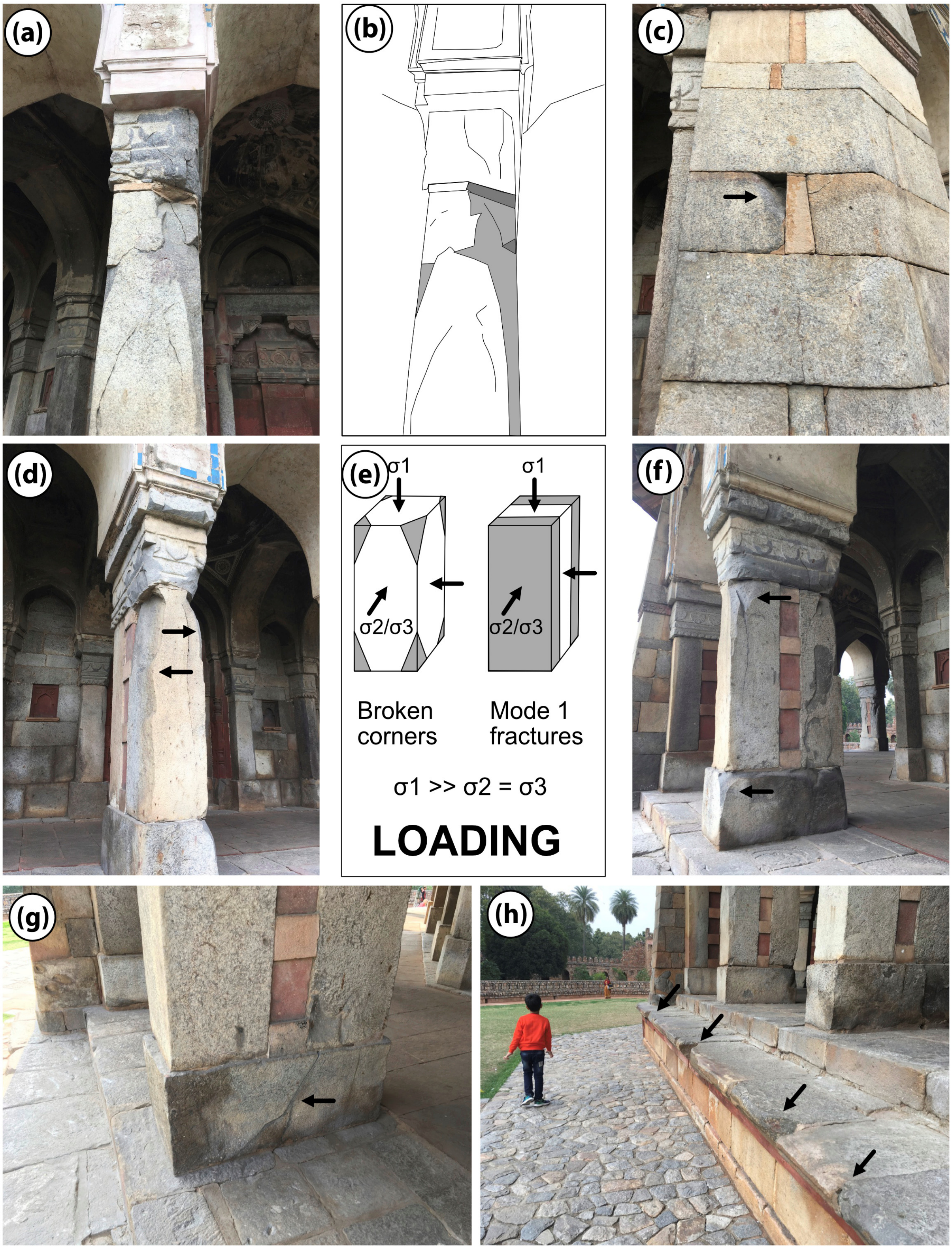

Figure 7. Archeoseismic damage observed around Isa Khan's Tomb; (**a**) classical fracture pattern in a granitic column; (**b**) sketch of photo in (a); (**c**) corner break-out in a granitic block (arrow); (**d**) mode 1 fractures (without confining pressure) in granitic column (arrows); (**e**) center—explanation for the cracks; (**f**) mode 1 fractures in granitic column (arrow) induced by vertical loading forces; (**g**) crack in a granitic foundation block (arrows); (**h**) corner break-out in granitic block tiles (arrows).

6. Generation of Paleo ShakeMaps and Its Implication for the Archeoseismic Damage Observed

From the observed damage around the Qutab Minar complex and Humayun's Tomb complex, it can be inferred that an earthquake of intensity VII-IX hit the area in the past. Beyond the damage observed to the Qutab Minar, the timing of the earthquake which caused damage to the Quwwat-ul-Islam mosque, Isa Khan's Tomb, Iltutmish's Tomb, and Humayun's Tomb is unknown. The historical seismicity (Table 1) suggests New Delhi was affected by two earthquakes of intensity IX (the 1720 CE and 1803 CE earthquakes) and one earthquake of intensity VII (the 1960 Gurgaon earthquake).

The earthquake responsible for causing damage to the monuments in the Qutab Minar complex and Humayun's Tomb complex remains uncertain. To ascertain the potential source earthquake behind the damage, we employed Paleo ShakeMap techniques, taking into account the epicentral location and magnitude of three historically significant earthquakes (1720 CE, 1803 CE, and 1960 Gurgaon earthquakes). Our goal was to identify the earthquakes that could plausibly have been the cause of the observed damage in the vicinity of both complexes.

With the available information on the epicentral locations and magnitudes of these three earthquakes as documented in the literature, we created ShakeMap earthquake scenarios for the years 1720 CE, 1803 CE, and 1960 (Figures 8–10). The paleo ShakeMaps we generated illustrate the shaking intensity at various locations surrounding New Delhi. Specifically, for the 1720 CE earthquake, the ShakeMap indicates intensity values of VIII in the Gurgaon area, while New Delhi experiences intensity VII. Likewise, in the case of the 1803 CE earthquake, Mathura exhibits a higher intensity level of VIII, whereas New Delhi registers an EMS-98 intensity of V–VI. For the 1960 Gurgaon earthquake, both New Delhi and Gurgaon display EMS-98 intensity levels of VII–VIII.

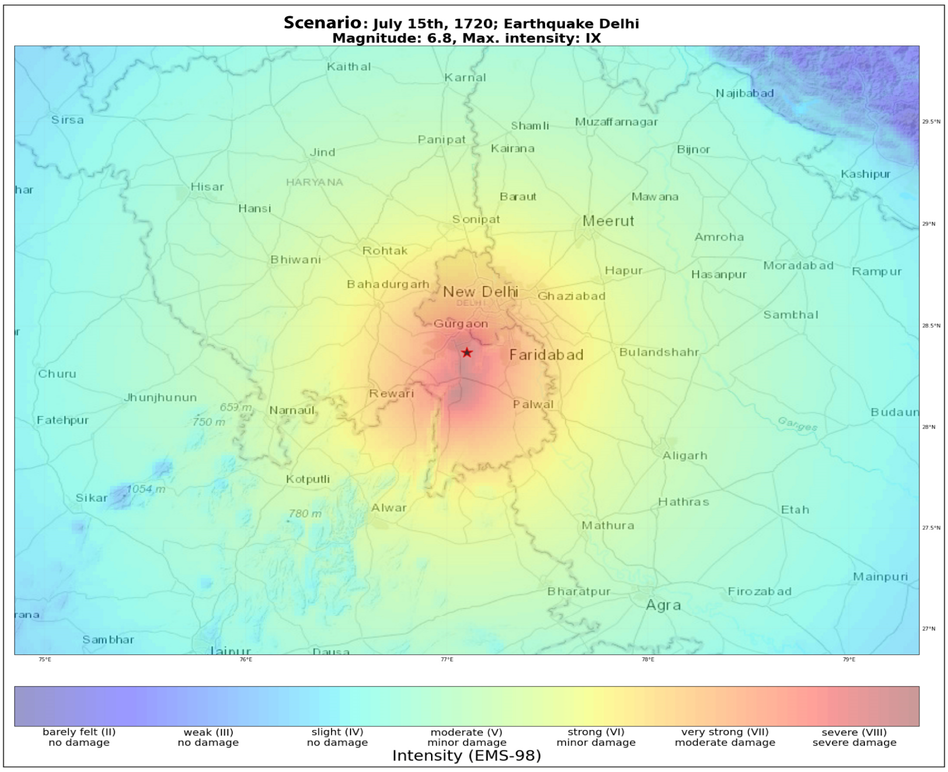

Figure 8. Paleo EMS-98 ShakeMap for the 15 July 1720 Delhi earthquake, which shows higher intensity of VIII around Gurgaon and intensity of VII–VI around Delhi.

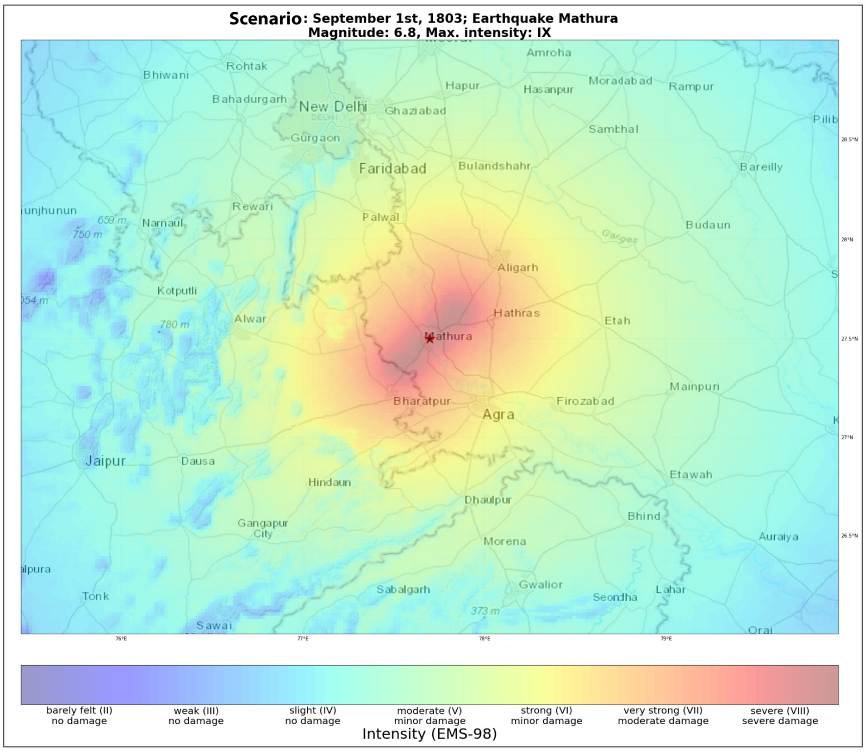

Figure 9. Paleo EMS-98 ShakeMap for the 1 September 1803 Mathura earthquake, which shows higher intensity of VIII around Mathura and Bharatpur and intensity of IV–V around Delhi.

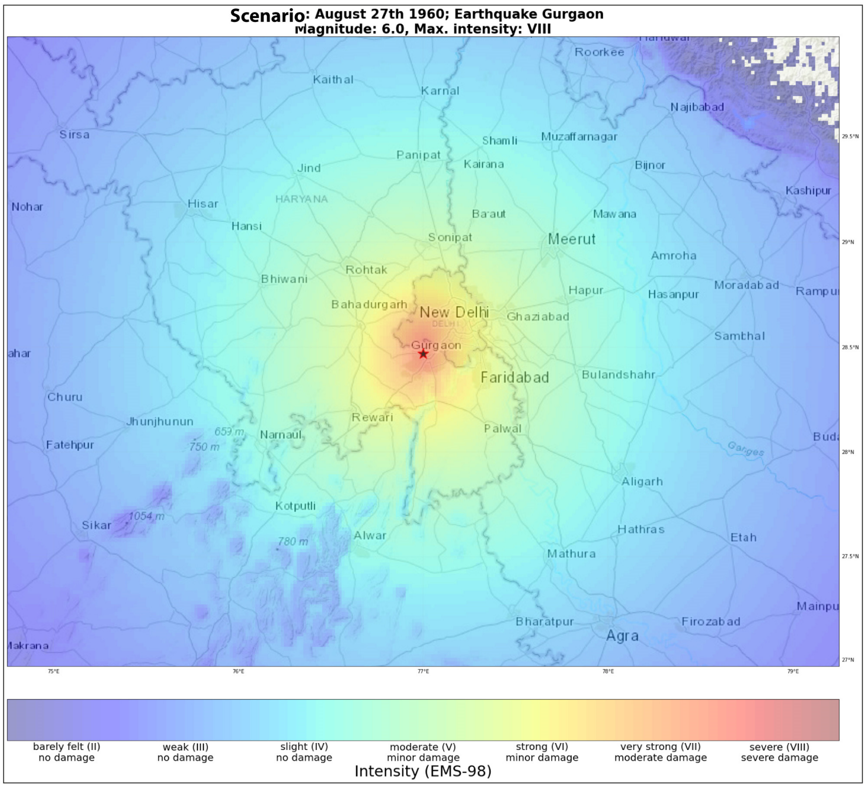

Figure 10. Paleo EMS-98 ShakeMap for the 27 August 1960 Gurgaon earthquake, which shows higher intensity of VIII–VII around Gurgaon and Delhi.

7. Discussion

The damage associated with historical monuments can be seen when seismic waves are transmitted from a seismic focus to structures.

Several studies have reported the several types of damage to historical buildings caused by earthquakes [9,13,14,54,58,63,69,124–133]. The type of damage, such as, for example, displaced tilted walls, is dependent on the orientation of the wall with respect to the horizontal component of the seismic waves [14,62,66]. The orientation of the fallen columns depends on the propagation direction of the seismic waves [14,15,96,129,130]. From past studies, it can be inferred that fractured walls could be the consequence of repeated shear movements due to intense shaking during an earthquake, whereas dipping broken corners or chipping may indicate the vertical or rotational motions associated with seismic waves [14,129].

One could argue that similar damage can be observed during other phenomena such as frost, aging, or ground subsidence, among other things. However, if we consider the temperature during the coldest nights of January—the coldest month—the temperature drops to 3.5 degrees Celsius. Therefore, frost damage can be ruled out. The Little Ice Age is considered to have been significantly colder for Europe than the 20th century. Although there is a lack of records on winter temperatures, there is a consensus that the Little Ice Age in India was characterized by a decrease in precipitation (and a weakening of the monsoon, causing drought and famine) rather than by lower temperatures [132].

The damage associated with the aging of monuments often includes the rounding of sharp edges. Our observations of what is presumed to be seismic damage show particularly sharp edges around the fractured areas, indicating that damage related to weathering or aging can be ruled out.

The damage to heritage sites can often be traced to subsidence phenomena, which is typically indicated by a pattern of differential settlement of the boundary walls, tilting of the walls, and cracks resulting from either the subsidence or tilting of entire monuments. Such damage patterns are observable at heritage sites with shallow foundations and unstable subsoil, as exemplified by the Tower of Pisa, Italy [133]. However, when considering the construction patterns of medieval monuments in India and the lack of observations related to subsidence or the associated damage patterns, it can be deduced that the monuments around the Qutab Minar and Humayun's Tomb complexes were built on deep foundations to sustain the damage related to subsidence.

Therefore, the observed damage, such as dipping broken corners or chipping, broken beams, and out-of-plane shifts in the stone blocks at the Qutab Minar and Humayun's Tomb complexes, are of seismic origin. The Qutab Minar is considered a seismoscope for the Himalayan earthquakes that have affected the Indo-Gangetic Plain region.

However, the damage observed to Humayun's Tomb and Isa Khan's Tomb adds two more pieces of evidence of earthquake-related damage from the NCT region, which is located in the Indo-Gangetic Plain. But the timing of the damage is debatable. Considering the historical seismicity, the seismic intensity observed during the 1720 and 1803 CE earthquakes (Figures 8 and 9), and the build time of the monument, these two earthquakes are candidate earthquakes for examples of damage in our view.

Historical documents recorded a high-intensity seismic event that occurred around Delhi in 1720 with a seismic intensity of IX. However, the damage distribution or the effect of the earthquake is not well documented. Whereas, the damage history of the 1803 CE earthquake is relatively better documented than the 1720 earthquake. During the 1803 CE earthquake, widespread damage was observed in Garhwal and the Indo-Gangetic Plain. During this earthquake, the Qutab Minar was damaged, which is the only monument reportedly damaged during that earthquake. It is debatable why only this monument was damaged while there are several monuments that exist in the same complex. This may be due to its tall nature, which is more vulnerable to seismic damage during strong site amplification. Furthermore, the nearby Jantar Mantar astronomy observatory ("instruments for measuring the harmony of the heavens") was completed in 1724, so after the 1720 earthquake. The Jantar Mantar has no indications of earthquake-related damage from the 1803 CE earthquake; however, its decay started earlier than the riots of the 1857 uprisings. And there are no reports on the massive restoration of the Jantar Mantar after the 1803 CE earthquake.

It has been observed during several recent earthquakes, such as the 2015 Gorkha earthquake, that taller structures sitting in an alluvial basin may face strong shaking due to site amplification and topple from the top or completely collapse depending on the nature of the material used and type of construction [130].

Another possibility is that no detailed study on this aspect was conducted to observe the archeoseismological damage evidence within the Qutab Minar complex. The recent report of the out-of-plane shift in the masonry block with a 5 cm wide gap at the top of the building in Iltutmish's Tomb can justify the second point. The damage history of the Qutab Minar was well documented. The monument was damaged by lightning in 1368 CE, and the topmost part of the monument was completed in 1388 CE [38]. After that, it was again damaged during 1503 CE by lightning [106]. The next report of damage to the Qutab Minar was reported during the 1803 earthquake, where the balustrades, balconies, and entrance were damaged, along with the top cupola (a plain square top on four stone pillars) being toppled during the earthquake [106]. The damage report on the Qutab Minar can be validated by the report of widespread and co-seismic liquefaction in Mathura, ~150 km south of Delhi [30].

The damage observed at Humayun's Tomb and Isa Khan's Tomb, built in the 1560s and 1547–1548 CE, could have been caused by both the 1720 and 1803 CE earthquakes. However, the damage observed in the other two monuments in Delhi is well constrained, and the 1803 CE earthquake is the main candidate earthquake for such damage. The distance between the Qutab Minar complex and Humayun's Tomb is nearly 10 km. So, if the 1720 earthquake caused seismic damage to Humayun's Tomb and Isa Khan's Tomb, why did it not cause damage to the Qutab Minar? The Jantar Mantar had not been constructed yet. Was it a local event, and did the monument face more shaking than a far-field event from the Himalayas? Considering this point, it can be inferred that the reported intensity of the 1720 event is overestimated, and the seismic damage observed at Humayun's Tomb and Isa Khan's Tomb was also caused by the same seismic event as the Qutab Minar and Tomb of Iltutmish, i.e., the 1803 CE earthquake, or has this event been overestimated?

8. Conclusions

The damage patterns observed around the Qutab Minar and Humayun's Tomb complex area of seismic origin are typical damage patterns such as dipping broken corners or chipping, broken beams, and out-of-plane shifts in the stone blocks. In other words, heavy and prestigious buildings tend to self-destruct due to loading during earthquake shaking. Considering the magnitude of the 1720 CE earthquake; recent paleoseismic evidence of the 1803 CE earthquake along the Himalayan Front, which is located around 200 km from the monument; and the timing of the construction of these two monuments, we speculate with the help of ShakeMaps that Humayan's Tomb was damaged by the same event as the Qutab Minar, either by the 1720 Delhi earthquake or the 1803 CE earthquake, where the latter is slightly more well substantiated. A more detailed regional study is required to make conclusions regarding the responsible earthquake. However, it can be concluded that the cultural heritage of the Delhi region is constantly under seismic threats from near-field earthquakes as well as far-field Himalayan earthquakes.

The Indian government has taken measures to minimize the risk of earthquakes in the region. Building standards have been introduced to ensure that new buildings meet the earthquake safety requirements, and there is a network of earthquake warning systems to alert the population. Despite these measures, earthquake risks in New Delhi remain. It is therefore important that the population is aware of the potential risks and takes measures to protect themselves and their families in the event of an earthquake. This includes making an emergency plan, stocking emergency supplies, and understanding what actions to take during an earthquake to avoid injury. In summary, there is archeoseismological evidence of past earthquakes in the Delhi region. These signs are an important indication that the region may continue to be affected by earthquakes in the future and that precautionary measures against earthquakes are still required.

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