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PERFORMANCE OF STRUCTURES DURING THE KASHMIR (PAKISTAN) EARTHQUAKE OF 8 OCTOBER 2005

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ABSTRACT

An earthquake of magnitude 7.6 struck regions of South Asia on October 8, 2005 and caused enormous loss of life in the north-western region of the subcontinent. A large number of structures collapsed in major city centres in Kashmir and Pakistan. Earthquake caused over 76,000 deaths and affected approximately 3.5 million people of which 2.8 million were made homeless due to the collapse of over 400,000 housing units. The materials of choice for the construction in the region are concrete, masonry and wood. Although some engineered buildings performed reasonably well even in the most seriously affected areas, a number of structures were damaged or collapsed due to the poor design and construction practices. Material properties also played a major role in the response of structures. Of particular interest is the engineered high-rise reinforced concrete apartment buildings that collapsed in an area that was subjected to only moderate ground shake. The paper highlights the structural aspects of this serious seismic event with the aim of helping in the reconstruction efforts in the region.

Introduction

A severe earthquake of Richter Magnitude M_w 7.6 struck areas of Northern Pakistan and parts of Kashmir (Azad Jammu and Kashmir, AJK) at 03:50 GMT 08.50 local time) on Saturday, October 8, 2005. An earthquake in this area was not entirely unexpected. The two tectonic plates that have created the Himalayas collide in this region creating a history of devastating earthquakes. Although a definitive identification of the fault rupture has not been possible thus far, a reasonable estimate of the location of the fault is shown in Figure 1 (http://comet.nerc.ac.uk). The height of Himalayan mountains rapidly increases on the northeast side of the fault line. The southwest movement of the mountains (Asian plate) is blocked by the northeastward movement of the Indian plate. The relative movement of the two plates is estimated at 55 mm per year of which approximately 20mm is concentrated along the Himalayas.

The epicentre of the earthquake was located at a distance of about 100 km from the Pakistani capital city of Islamabad and only 10 km northeast of Muzaffarabad, the capital of AJK (Figure 2) (http://cires.colorado.edu/~bilham/). The focal depth was estimated at 26 km according to USGS. The earthquake resulted on the intra-plate fault in the major Indian Plate where it is subducting under the Asian Plate. The major earthquake was followed by more than 1000 aftershocks, of magnitude M_w up to six, in four to six weeks. A shock of M_w 6.3 was recorded in the first week of December 2005 in the same general area.

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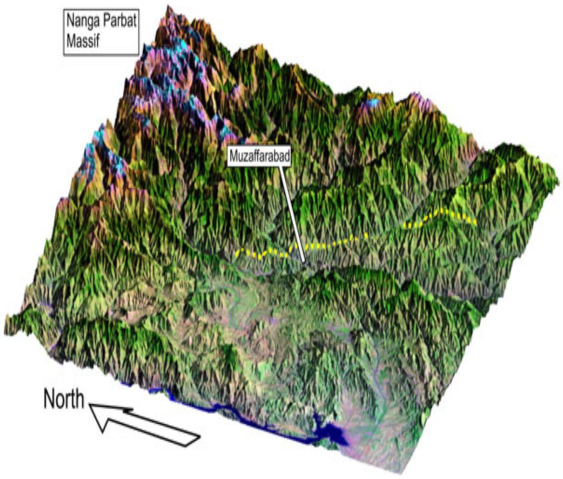

Figure 1. 3D perspective of the Kashmir earthquake Region (http://comet.nerc.ac.uk).

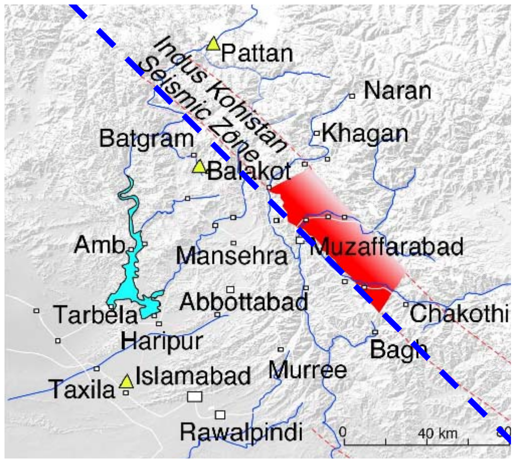

Figure 2. Rupture region (R. Bilham web site, http://cires.colorado.edu/~bilham/).

The earthquake left widespread destruction in its wake. The death toll varies from a low estimate of 76,000 to over 100,000 while in excess of 80,000 people were injured. Approximately 300,000 square kilometer of area was affected by the earthquake. The population of this area is about 3.5 million of which 2.8 million were made homeless. As of November 12, 2005, the Asian development Bank (ADB) and World Bank (WB) estimated that of the 787,583 housing units in the area surveyed, 203,579 units were completely destroyed and 196,574 were damaged (ADB-WB 2005). Later reconnaissance showed that in some areas of Kashmir, almost all the housing units were destroyed or severely damaged. Over 60% of the housing units in AJK were completely destroyed and over 30% were severely damaged leaving only about 15% of the units inhabitable. The Government of Pakistan data shows that about 272,019 structures including housing units, educational institutes, medical facilities and government buildings were completely destroyed and 182,886 were severely damaged. Most of the housing units were un-engineered structures while commercial and government buildings, and high-rise structures were mostly engineered or semi-engineered. Figure 3 shows an aerial view of widespread damage around Muzaffarabad.

Figure 3. Aerial view of damage around Muzaffarabad.

Earthquake Records

The most affected regions were not adequately instrumented for measuring seismic activity. Only three strong-motion acceleration records, each with two horizontal components and one vertical component, are available (Mahmood 2005). These are from areas known as Abbotabad, Nilor and Murree. No record is available from the most heavily damaged regions of Balakot and Muzaffarabad. Of the available records, Abbotabad shows the strongest ground motion while record from Nilor is the weakest (Figure 4). Structures in Abbotabad suffered serious damage but not comparable to the complete destruction that Balakot and Muzaffarabad experienced. Nilor is close to Islamabad where two high-rise condominium building collapsed during the earthquake. Based on the available records, Durrani et al (2005) used selected attenuation relationships of PGA and predicted peak ground accelerations for various sites in Pakistan and Kashmir. The peak ground accelerations for the sites of interest are shown in Table 1.

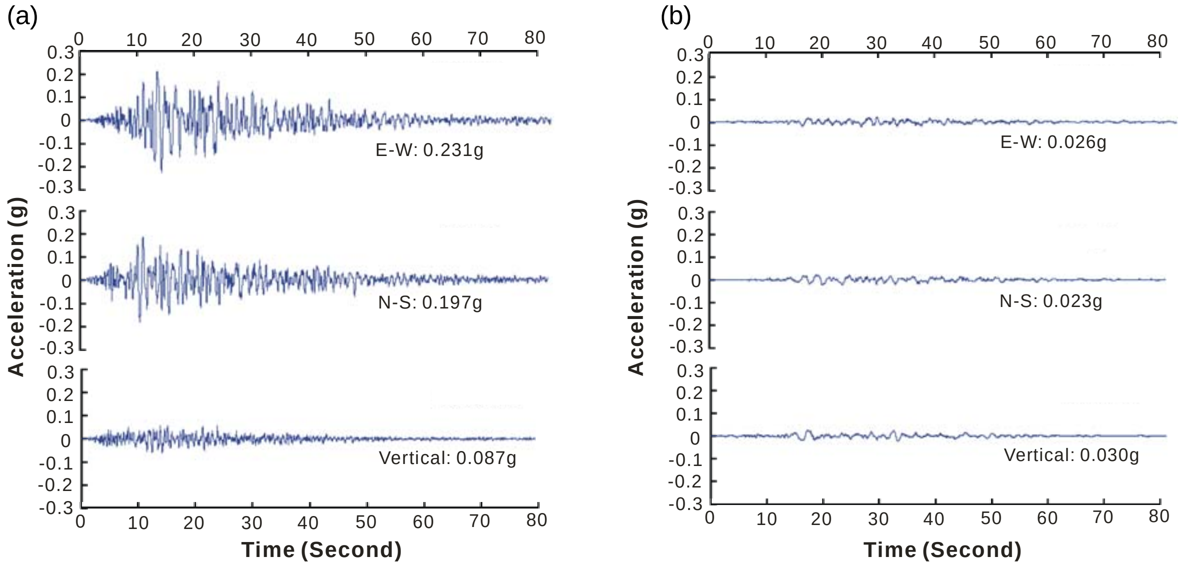

Figure 4. Ground Motion Records: (a) Abbotabad; (b) Nilor.

Table 1. Predicted horizontal peak ground acceleration for attenuation relationships (Kim and Elnashai 2007).

Location (distance from fault)	Krinitzsky et al (1988)		Dahle et al (1995)		Campbell (1997)		Schmidt et al (1997)		Ambraseys et al (2005)	
	Stiff	Soft	Stiff	Soft	Stiff	Soft	Stiff	Soft	Stiff	Soft
Muzaffarabad (4 km)	0.079	0.968	0.458	0.635	0.720	0.800	0.751	0.835	0.659	0.805
Balakot (10 km)	0.078	0.964	0.345	0.478	0.471	0.548	0.531	0.591	0.486	0.594
Abbottabod (39 km)	0.073	0.903	0.16	0.221	0.124	0.155	0.21	0.234	0.194	0.237
Islabamad (98 km)	0.056	0.692	0.079	0.110	0.031	0.04	0.094	0.104	0.094	0.115

Performance of Structures

Most housing units in the area were non-engineered. The materials of choice are the stones, mud and wooden beams that are locally available. A typical older low cost house has load bearing walls made of mud and/or stones and roof consists of a combination of wooden beams, corrugated sheets and mud. Mud roofs, although heavy, provide insulation in the extreme cold winters. The stone walls are generally un-plastered (undressed) and the mortar is mud- or lime- based. A slightly more affluent house may have the reinforced concrete slab supported on similar load bearing walls in which the stones are plastered (dressed). In some cases, bricks are used in place of stones. These types of buildings represent about 15% of the housing units in the affected areas and almost all of them were completely destroyed or severely damaged (NWFP 2005). Figure 5 shows a collapsed stone masonry house in Balakot which was the most severely affected area during this earthquake. The heavy roof dead loads caused large inertia forces that the structures were incapable of carrying. There was minimal connectivity between the roof and the walls. Most of the walls suffered out-of-plane collapse under the roof dead load as soon as the lateral ground motion occurred. It should be noted that in most cases, foundations for these houses primarily consists of bearing of stone walls on a thin (~100 to 150 mm) layer of concrete several centimeters below the ground level.

Figure 5. Collapsed Stone houses in Balakot.

A more modern house construction consisted of un-reinforced concrete block masonry walls and roof made of corrugated sheet or reinforced concrete slab. In general the connectivity between the vertical and horizontal floor elements was poor. The concrete blocks were mostly solid. Foundations of these buildings were mostly in stone masonry and there was minimal anchorage to the ground. In most of these houses cement-sand mortar was used as a binder but with very low cement contents and high water-cement ratio. Approximately 50% of the total buildings in the affected areas were of this type. Although their performance was relatively better than the stone masonry buildings, over half of these structures collapsed or suffered severe damaged. Figure 6 shows a number of un-reinforced concrete masonry structures converted into a heap in Balakot.

Figure 6. Collapsed un-reinforced masonry buildings in Balakot.

About twenty years ago, good quality bricks became readily available in the area and started partially replacing the stone masonry in many structures. Brick masonry buildings constitute approximately 25% of the structures in the area and provide load bearing elements in most of these structures. Although clay mortar has been used in some structures, cement mortar was a common binding material for brick masonry. Because of their regular shape, lighter weight, good quality control and excellent binder, performance of un-reinforced brick masonry was better than stone masonry and un-reinforced concrete block masonry. Approximately 5% of the brick structures were completely destroyed while another 35%

were severely damaged. Foundations in most of these structures were made of stones which contributed to their poor performance. Figure 7 shows three structures one in Balakot and two in Muzaffarabad in which brick masonry was used. The buildings in Muzzafarabad collapsed partially or completely while the house in Balakot survived with only minor damage. A three-storey hotel with reinforced concrete framed structure about 50 m from this house in Balakot collapsed completely as shown in Figure 8a.

(a)

(b)

(c)

Figure 7. (a) A well-built house in Balakot; (b) A collapsed R.C. building with brick masonry in Muzaffarabad; (c) Partially collapsed R.C school building with brick masonry.

A typical reinforced concrete building in Balakot and Muzaffarabad consists of a frame with infill block or brick walls. A great majority of these buildings were not engineered by qualified structural designers. Some can be classified as semi-engineered where little consideration was given to earthquake effects. Survey of the damaged buildings clearly shows a lack of implementation of design codes. Many of these buildings collapsed or experienced severe damage. Figure 8b shows a five-storey reinforced concrete building in which the failure seems to have been caused by a soft storey, lack of connectivity between elements and weak non-ductile columns (see Figure 8c). A building next door avoided complete collapse (Figure 8d) partly because of superior confining reinforcement in circular columns. A similar failure of a hotel in Abbotabad is shown in Figure 8e. Figure 9 shows building failures in Muzaffarabad and Balakot which appear to be caused by the soft storeys at the ground floor level.

A number of deficiencies could be observed in failed buildings in addition to poor quality construction. These included soft storey, weak column-strong beam system, lack of continuity, location of lap splices in the most stressed regions, insufficient lap splice length, insufficient lateral reinforcement for shear and confinement, poor reinforcement detailing, use of smooth steel bars and poor material properties. Figure 10 shows a two story hotel in Balakot that survived the earthquake with relatively minor damage. The structure was symmetric, well-planned and well-designed. It was a reinforced concrete framed building with masonry infill walls. The damage was limited to infill masonry block walls as shown in Figure 10b. Most of the structures around this building were severely damaged or collapsed as shown in Figure 6.

(a)

(b)

(c)

(d)

(e)

Figure 8. (a) A three-storey reinforced concrete structure in Balakot; (b) R.C. building in Muzzafrabad; (c) Lack of confinement in columns; (d) Ductile columns contributed to collapse prevention; (e) A collapsed hotel building in Abbotabad.

Figure 9. Soft storeys in buildings in Muzaffarabad and Balakot (Durrani et al 2005).

Figure 11a shows two adjacent buildings of a military hospital in Muzaffarabad that suffered severe damage. The building on the left had an elevator shaft in which the elevators had not yet been installed.

Shear walls in the elevator core provided a robust lateral load resisting system that minimized the damage. The building on the right only had columns as vertical structural elements which were unable to provide the required strength and ductility to resist the earthquake loads. Almost all the columns of the ground floor sheared off and the building dropped down by up to two meters. Lack of lateral reinforcement in columns is obvious in Figure 10b.

(a) (b)

Figure 10. (a) Reinforced concrete hotel building in Balakot; (b) Shear damage to infill walls.

Figure 11. Hospital in Muzaffarabad.

Failure of high-rise buildings: Islamabad is in a moderate seismic zone. Among the three sites for which the ground motion records are available, Nilore is closest to Islamabad at about 10 km and both places are approximately 100 km from the epicentre. The ground motion experienced by Islamabad thus is not expected to be significantly stronger (see Table 1). Margala Towers in Islamabad is a group of condominium buildings in 5 blocks. Blocks 1 and 5 had two buildings each that had common basement while Blocks 2 to 4 had one building each. During the earthquake, the building of Block 4 and one building of Block 5 (5B) completely collapsed while Building 5A was severely damaged (Figure 12) resulting in the death of approximately 80 people and several injured. A preliminary analysis of the building was carried out to study the causes of failure (ABS 2006). Brief details of the analysis and observations from the site are summarized below.

Buildings 5A (north side) and 5B (south side) had 11 and 8 floors, respectively. The footprint of Building 5B was approximately 17.8 x 16.5 m but at the second and fourth levels there were large setbacks on one side. There were no stairs or elevator core in 5B and access to upper floors was only through building 5A which had a footprint of about 19.4 x 14.6 m. The top floor of 5A was primarily a mechanical room of 15.8 x 6.4 m in plan which also housed a 2.3 m high water tank. Typical floor height was 3.05 m and the basement 4.9 m high in all the buildings. The structural system in Building 5B consisted of beams, columns and two-way slab while Building 5A, in addition, contained an E-shaped elevator core consisting of 300 mm thick reinforced concrete walls and the stairs opening located at east end of the building (below the mechanical room). The slab was 200 mm thick and the typical beams were 910 mm deep with width ranging between 300 and 600 mm in both the buildings. The columns were typically 450 mm square, 600 mm square or 450 x 600 mm in section. A 1.2 m thick raft slab was used as the foundation.

Figure 12. Margala Towers in Islamabad.

Figure 13. Structural and reinforcement details in Margala structures.

Considering the age of the building, the relevant US standards are the 1991 edition of Uniform Building Code (UBC) and ACI-318-89. The buildings are located in an active area that can be classifies as Zone 2. With an R_w of 6, the base shear in the buildings 5A and 5B was about 7.2% and 6.5% of the gravity loads.

A check of demand to capacity ratios of various elements indicated serious deficiencies in the buildings. Although the design capacity of the soil was130 kN/m^2 for dead and live loads, the maximum stress generated under dead load alone was found to be 164 kN/m^2 representing 26% overstress. Considering the combined effects of dead, live and seismic loads, the soil stresses would certainly have exceeded the allowable design values by a wide margin. This would also have contributed to excessive deflections of the buildings. The demand to capacity ratios (DCR) of several beams and columns exceeded unity indicating serious strength deficiency. Table 2 shows flexural and shear DCR values for beams and columns in both the buildings. Only the worst and the best values are shown for each building in the table. In general, Building 5B that collapsed completely, shows a more serious deficiency than Building 5A. All the beams and about half the columns were found to be deficient. It should be noted that the demand and capacity values used were factored. This may explain why Building 5A did not collapse completely.

Table 2. Flexural and Shear Demand to Capacity Ratios (DCR) for Buildings 5A and 5B.

Building	Level	Frame	Station	DCR
Beam Flexure				
5B	2F	B2F70	end-1	7.53
5B	1F	B1F68	end-1	1.17
5A	3F	B3F19	end-1	3.52
5A	6F	B6F09	end-2	1.17
Beam Shear				
5B	2F	B2F67	mid	1.88
5B	GF	BGF66	end-1	1.06
5A	2F	B2F19	mid	2.46
5A	3F	B3F21	mid	1.14
Columns shear				
5B	B	CBF1B	bot	2.06
5B	G	CGB1D	mid	0.62
5A	B	CBH1C	bot	1.53
5A	B	CBH1C	mid	0.48

The separation between the two buildings was only 30 mm wide. The analysis showed that a gap in excess of 750 mm was needed to avoid pounding between them. Figure 13 shows part of Block 3 building in which a lack of continuity between different floor levels is obvious. The figure also shows typical inadequate reinforcement details in a rectangular column. Rectangular columns reinforced with single hoops at small spacing display brittle flexural behaviour even when the shear capacity is not exceeded (Sheikh 1980). Spacing of hoops in potential plastic hinge regions of the columns was found to be in excess of 300 mm.

Conclusions

The Kashmir earthquake of magnitude 7.6 on October 8, 2005 caused an enormous loss of life and damage in the northwestern parts of the subcontinent. Loss of over 76,000 lives, similar number of injured and a heavy toll on the livelihoods for millions in addition to their being homeless were primarily caused by the widespread destruction of housing and other structures. In some affected areas about 90% of the structures either collapsed or suffered serious damage. Although most engineered structures performed reasonably well, there were several examples of engineered or semi-engineered structures that performed very poorly. Poor construction practices were observed in most of the failed structures. The serious deficiencies contributing to this disaster included inadequate lateral load resisting structural systems, presence of soft storey, weak column-strong beam system, lack of continuity between structural elements, location of lap splices in the most stressed regions of concrete structures, insufficient lap splice length, insufficient lateral reinforcement for shear and confinement, poor reinforcement detailing, use of smooth steel bars and poor material properties. Implementation of seismic design codes is very weak in the region which has created a serious safety situation in an active seismic zone. Un-engineered construction appears to proceed without any proper control or supervision. There is an urgent need to develop ways to build new structures and strengthen existing ones that will survive the next strong seismic event expected in this region.

Acknowledgments

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