

April 25, 2015 – GORKHA EARTHQUAKE, NEPAL

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Build Change Post-Disaster Reconnaissance Report

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1. Overview

On April 25, 2015, at 11:56 am local time, a M7.8 earthquake occurred in Nepal, centered 34 km ESE of Lamjung. This earthquake is referred to as the Gorkha Earthquake, named for the Gorkha district of Nepal where it was centered. Seventeen days later, on May 12th at 12:50 pm local time, an earthquake of M7.3, this one centered 19 km SE of Kodari, again shook Nepal, although this second large earthquake is considered an aftershock of the April 25th event. The earthquake and aftershocks were the result of thrust faulting between the subducting India plate and the overriding Eurasia plate to the north. The plates are converging at a rate of 45 mm/year towards the north-northeast.

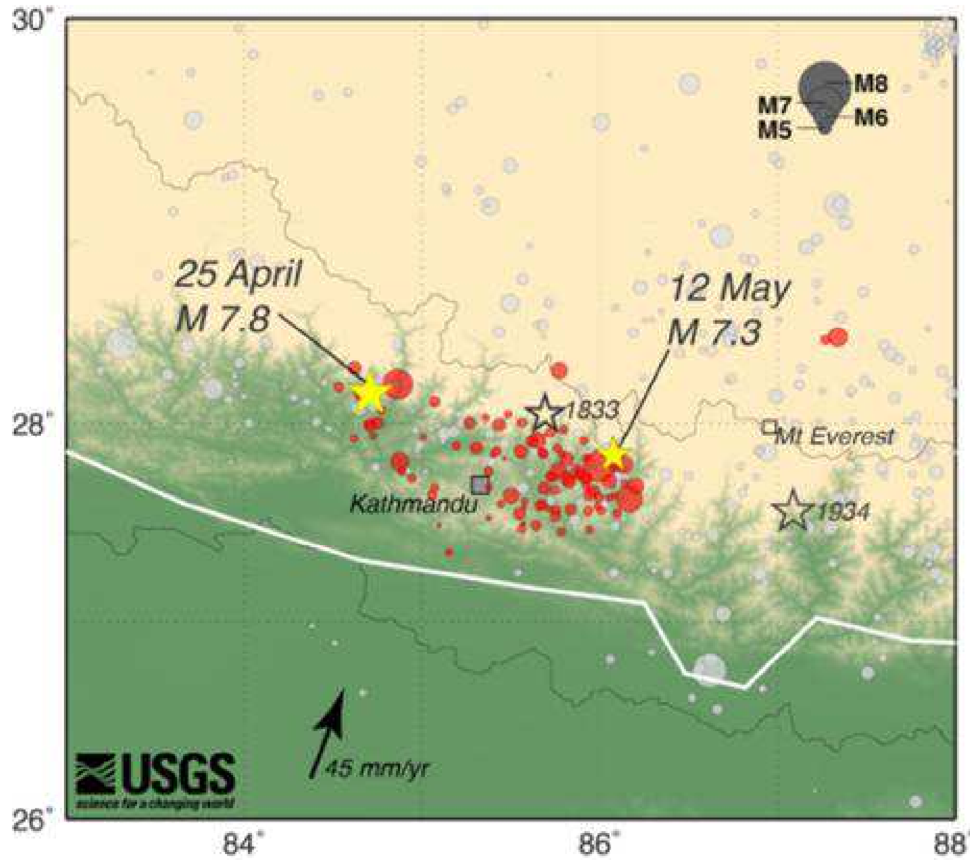


Figure 1. April 25, 2015 Gorkha Earthquake aftershock map, also showing the epicenters of the 1833 and 1934 Nepal earthquakes (USGS, 2015)

Although final numbers are not yet available, it is estimated that the earthquake and the ensuing aftershocks killed nearly 8,700 people and injured over 16,800. One month after the earthquake, the National Society for Earthquake Technology - Nepal (NSET) was reporting that over 500,000 houses were considered completely destroyed and over 269,000 houses were partially damaged. Of government buildings, nearly 1,000 were completely destroyed and over to 3,000 were partially damaged.

The Nepal government is evaluating damage to the public schools, but field observations have indicated that many public school buildings have been destroyed or damaged beyond repair. The government was trying to have detailed assessments done on all public school buildings as quickly as possible, to post all school buildings with either a green "safe" or red "unsafe" tag, with no intermediate yellow tags. Some reports have indicated that nearly 7,000 public schools have been destroyed. Unfortunately, this effort and these numbers do not include the many private schools in Nepal.

Figure 2. Housing damage in Bungamati.

Figure 3. Damaged school in Mahakal, Sindhupalchok.

Seven UNESCO World Heritage Sites existing in the affected regions of Kathmandu, Patan, and Bhaktapur suffered varying degrees of damage. The iconic Dharahara tower, while not a UNESCO site, was a nine-story, 61.88 meter (203 foot) tower, originally built in 1832 and rebuilt twice after the 1833 and 1934 earthquakes. The tower was reduced to a pile of rubble, killing an estimated 200 people inside.

Figure 4. Destruction at UNESCO site in Kathmandu Durbar Square.

Figure 5. Destruction at UNESCO site in Kathmandu Durbar Square.

Build Change staff Karin Kuffel, Lead Engineer - Philippines, Paolo Zorzoli, consulting engineer, and Ulina Shakya, an engineering graduate student intern also acting as translator, made field observations during reconnaissance visits in the Central Region of Nepal around the Kathmandu area on May 5-6, 2015, and in the surrounding districts of Kavrepalanchok and Sindhupalchok on May 12-14, 2015. Additional observations were made when on May 31st, 2015, Ulina Shakya and Daniel Chavez, structural engineer, returned to the area of Sindhupalchok. This report reflects the observations made during these visits.

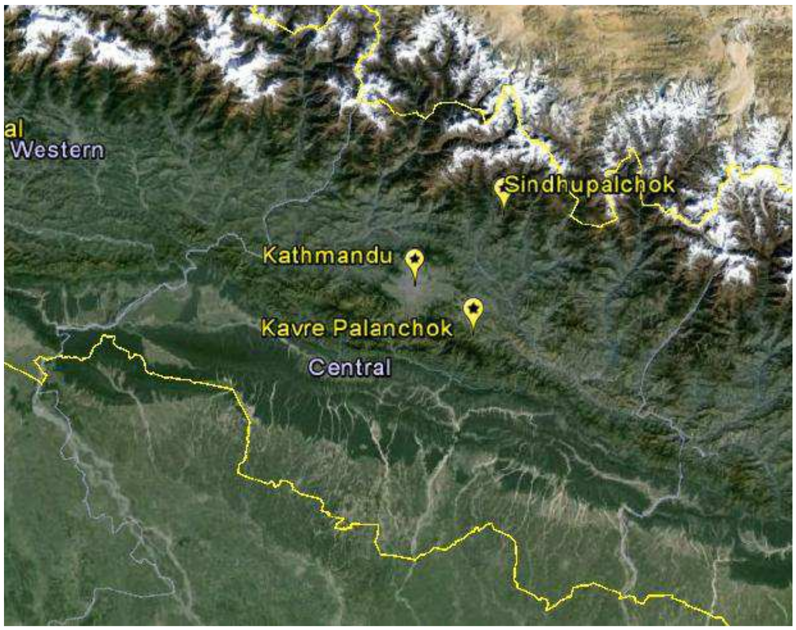


Figure 6. Map of the Central Region of Nepal, with field visit areas indicated (Google Earth)

This report has been amended to also include subsequent visits made to the following areas through the end of August 2015. This amendment has been prepared by Danial Chavez, Tim Hart, Liva Shrestha and Lizzie Blaisdell based on their observations at these locations.

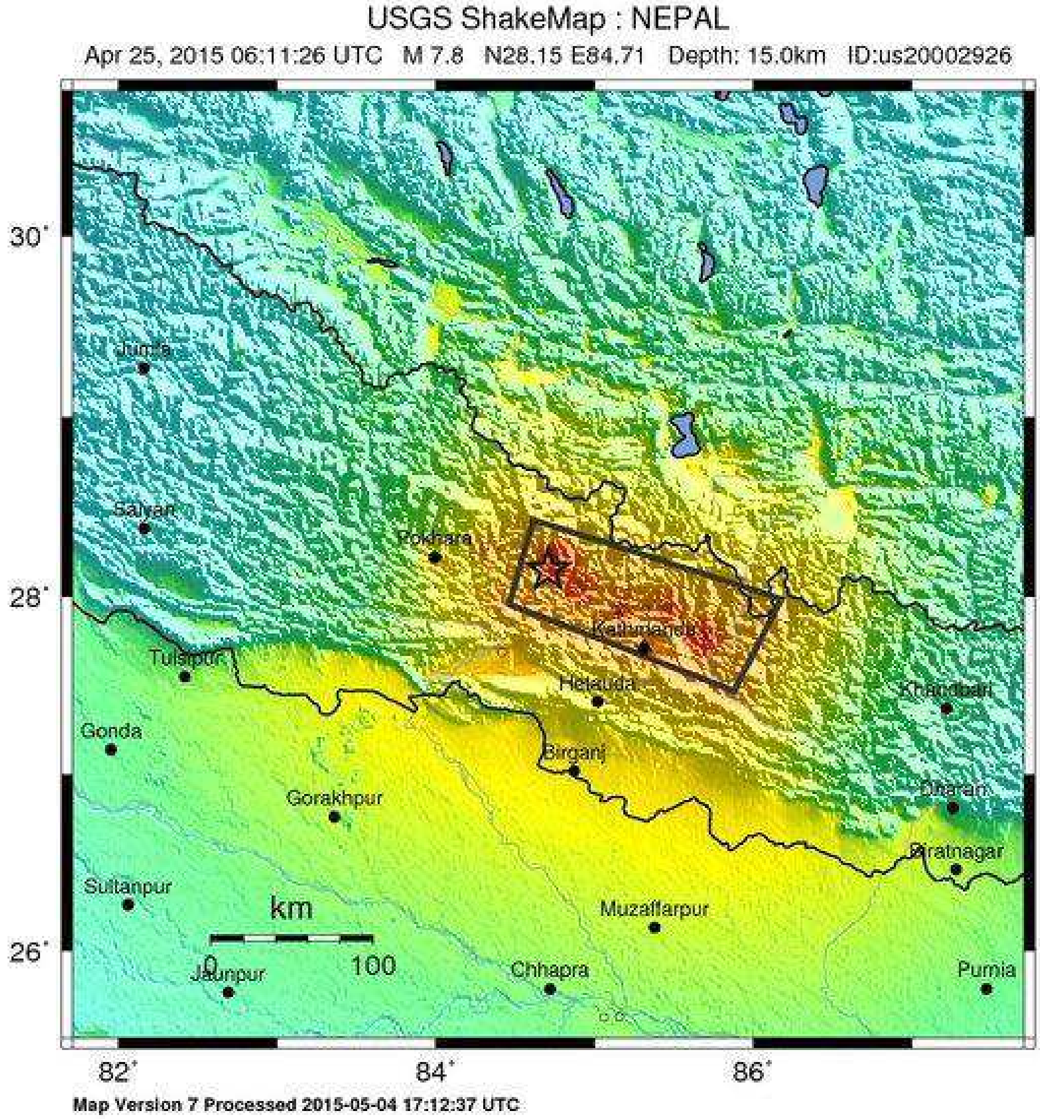
VDC or Municipality	District
Dhungkharka, Chyasingkharka, Mahankal Chaur, Chalal Ganeshthan and Tukucha Nala	Kavrepalanchok
Ramche and Maneshwor	Sindhupalchok
Sankhu	Kathmandu
Ragani	Okhaldhunga
Chaulakharka	Solukhumbu
Lachyang, Manakamana, and Kaule	Nuwakot
Devi Chaur	Lalitpur

The damage suffered in Nepal from the primary earthquake and subsequent aftershocks was severe and wide-spread. Unconfined and partially confined masonry failure was the cause of a majority of the damage observed. While the people of Nepal are committed to building back better, with safer, earthquake-resistant structures, the construction practices commonly used will require change to accomplish this.

2. Earthquake Details

According to the USGS, shaking intensities varied from VI (strong) to IX (violent) in the Central Region of Nepal in the April 25th event and from V (moderate) to VIII (severe) in the May 12th event (See Figures 7 and 8 for the USGS Shake Intensity maps). The corresponding peak ground accelerations reached as high as approximately 0.8g and 0.6g in the April 25th and May 12th events, respectively (See Figures 9 and 10).

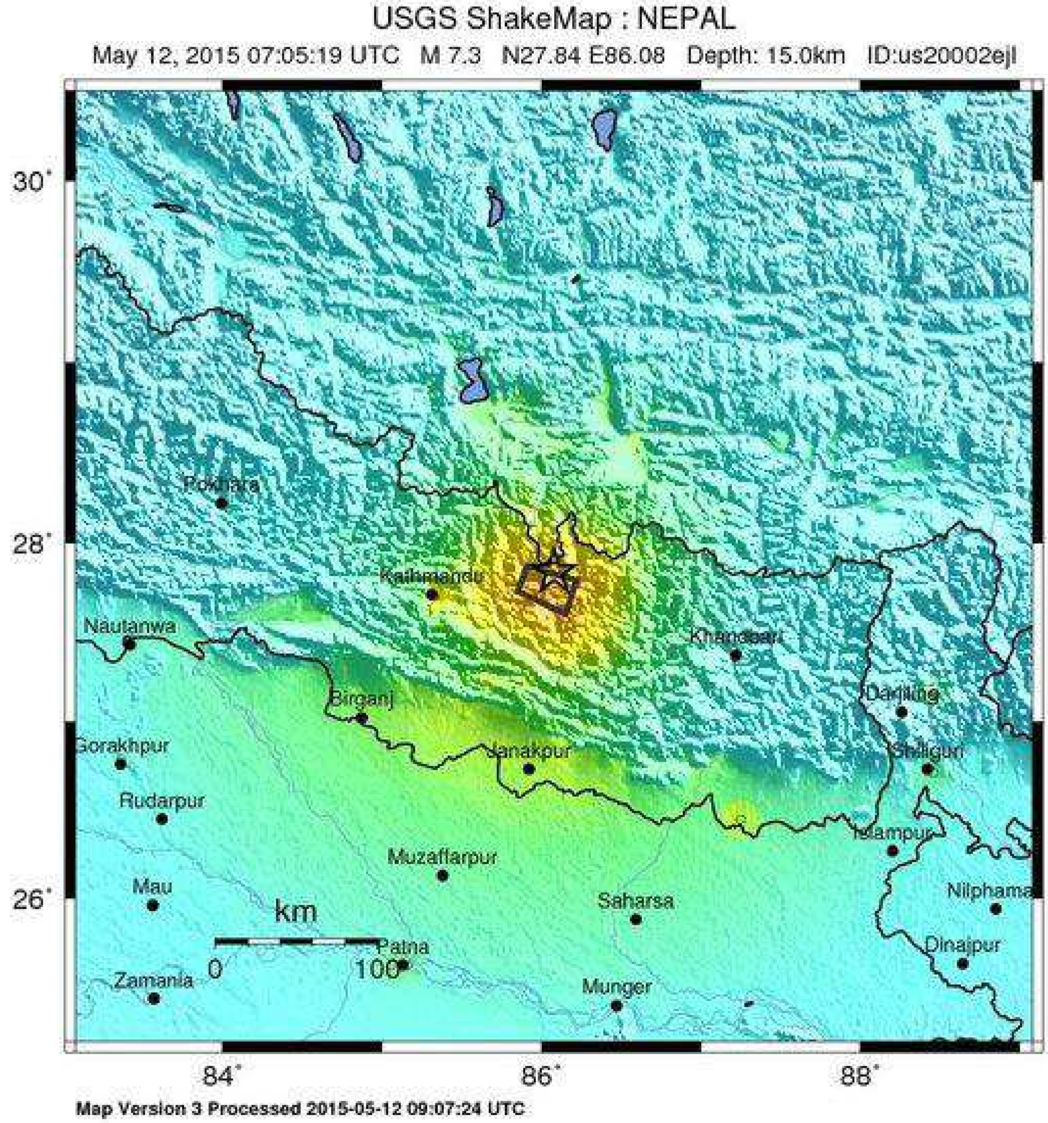
Based on the USGS shake and peak ground acceleration maps, the ground accelerations experienced in the two largest Nepal events were significantly larger than the design forces based on the current Nepal code. A section of the Nepal National Building Code, *NBC 105 : 1994, Seismic Design of Buildings in Nepal*, in conjunction with IS 4326 – 1976, contains design requirements for design lateral force coefficients. The maximum design base shear by the Nepal code, estimated using the Seismic Coefficient Method, is 0.32g, which is much lower than the ground accelerations experienced during the events.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	***<0.02***	***0.1***	***1.4***	***4.7***	***9.6***	***20***	***41***	***86***	***>178***
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2012)

Figure 7. April 25, 2015, Shake Intensity map (USGS, 2015).



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
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INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2012)

Figure 8. May 12, 2015, Shake Intensity map (USGS, 2015).

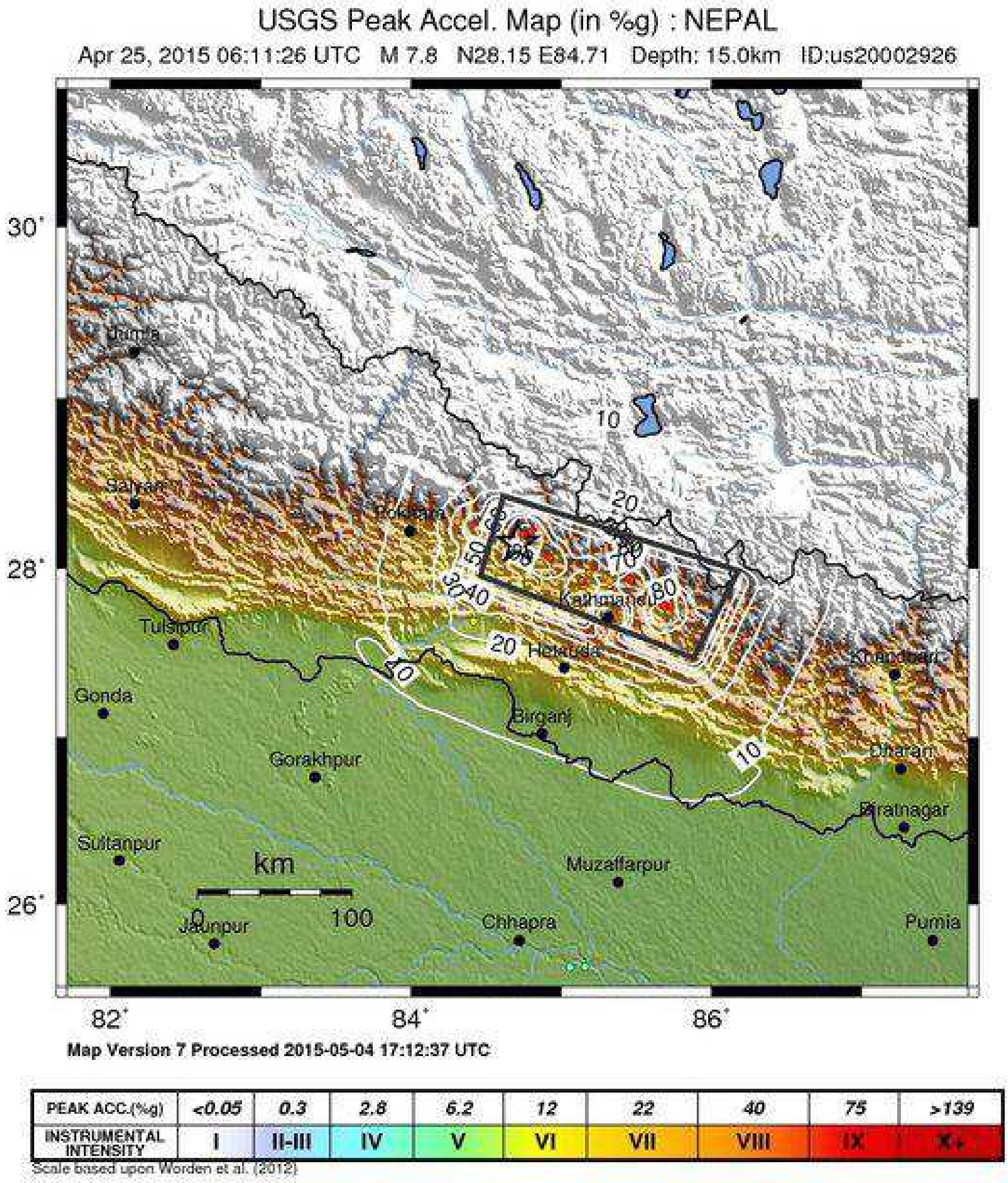

Figure 9. April 25, 2015, PGA (peak ground acceleration) map (USGS, 2015).

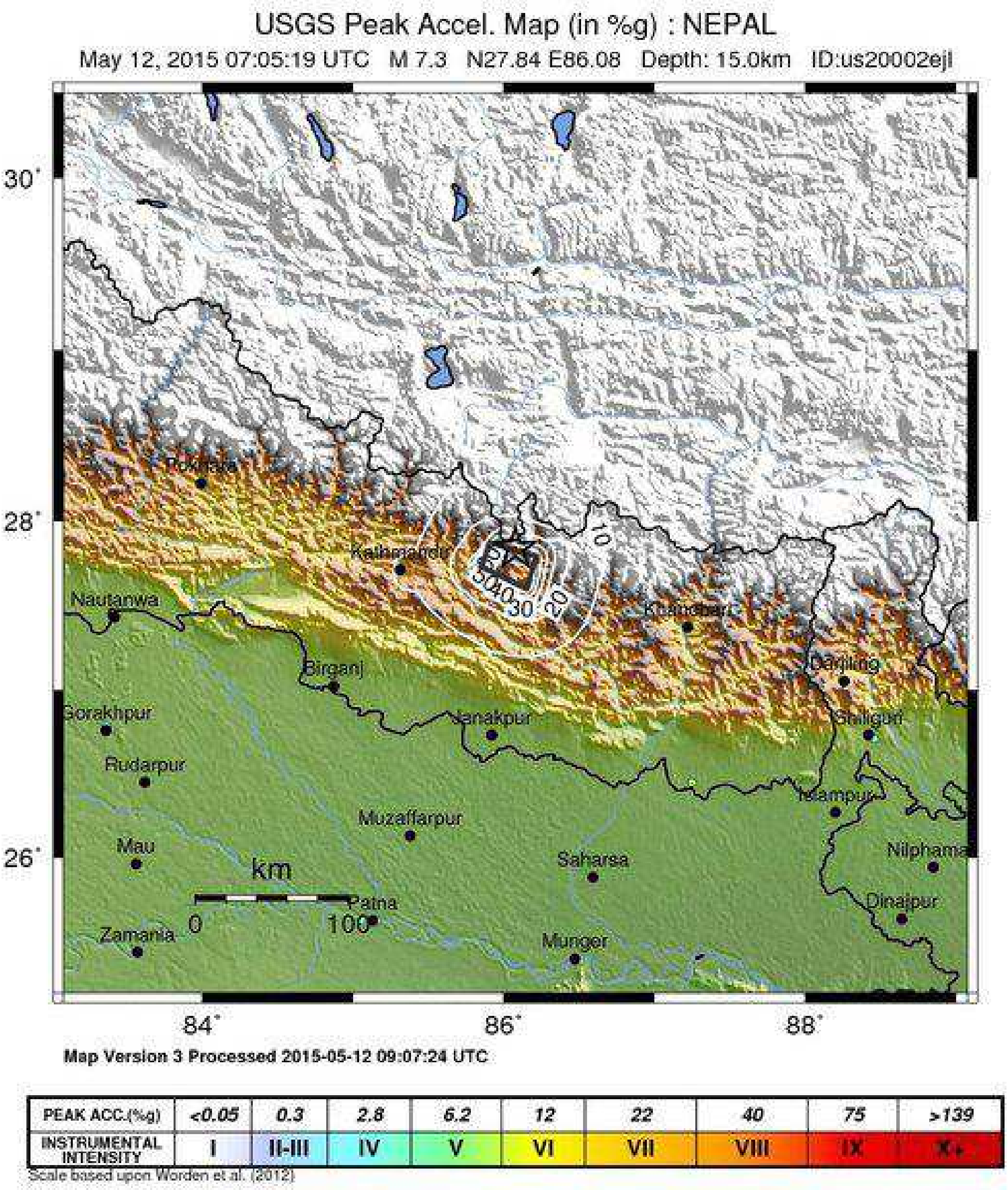

Figure 10. May 12, 2015 PGA (peak ground acceleration) map (USGS, 2015)

3. Nepali Building Construction and Materials

3.1 Building Types

3.1.1 Reinforced Concrete Frame with Infill

In the more urban city areas, the newer house structures are frequently constructed with reinforced concrete column and beam frames (RC frames), concrete floors and roofs, and unreinforced masonry infill (See Figures 11 and 12). For buildings which line the roads serving as main arteries to a city, the exterior elevations along the road tend to consist of open bays at the ground floor level to accommodate the storefronts of local businesses. Building height varied, typically in the range from 3-4 stories and up to 6-7 stories.

The infill thickness is typically 12” to 15” or more, and the concrete column and beam widths match the infill thickness. The majority of the infill in newer urban construction is solid clay brick. Occasional use of concrete block infill for frames was observed, particularly in areas outside of Kathmandu (See Figure 14). There is typically no concrete plinth beam at the ground level between the masonry walls and foundations. The mortar used in these buildings is most often a cement mortar. Exposed brick wall surfaces are usually plastered over.

The concrete reinforcement is primarily limited to four deformed longitudinal bars in columns and beams, with widely spaced ties. There was no indication of reinforcing in any of the brick work, nor of any ties between the brick infill and the concrete columns and beams.

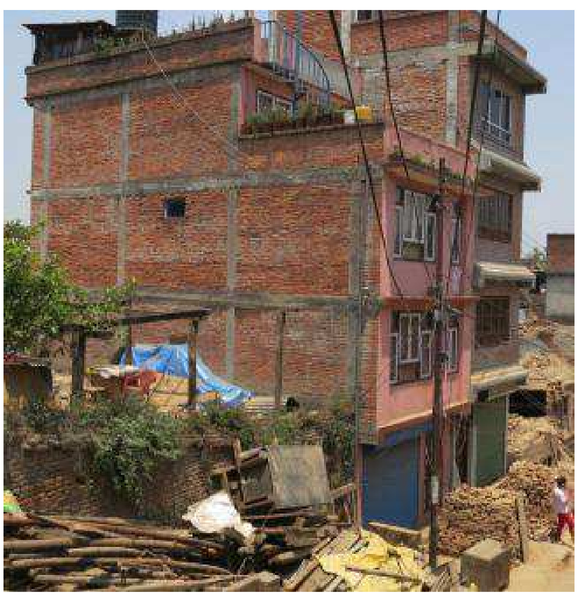

Figure 11. Reinforced concrete frames with masonry infill.

Figure 12. Reinforced concrete frames with masonry infill.

Figure 13. Note mortar finishing on exposed side wall versus mortar finish on “out of sight” back wall, Chautara.

Figure 14. Concrete block infill, Chautara.

3.1.2 Unconfined, Unreinforced Masonry

The majority of construction in Nepal utilizes various forms of unreinforced masonry consisting of solid brick, concrete block, or stone, with either cement or mud mortar, with styles varying based on location and building age. For load bearing masonry walls, the Nepal National Building Code specifies minimum wall thicknesses based on type of masonry and mortar used, but it was not clear whether the buildings observed comply with the “Rules of Thumb” (See Table 1.1 : Building Size Limitations, from *NBC 202 :1994, Mandatory Rules of Thumb, Load Bearing Masonry*).

Urban

Older urban house structures utilize unconfined, unreinforced brick masonry with either wood or masonry lintels at door and window openings and wood-framed floors supporting heavy mud floor and roof slabs, or sloped wood-framed roofs or canopies with corrugated galvanized iron (CGI) or clay/stone tile finishes. The masonry wall thicknesses range from 12” to 18”. A mud mortar is found in the older buildings, and the brick walls are most often exposed, and not plastered over (See Figure 15).

Figure 15. Urban area unconfined, unreinforced masonry buildings,

TABLE 1.1 : BUILDING SIZE LIMITATIONS

	Floor	Min. Wall Thickness (mm)	Max. Height (m)	Max. Short Span of Floor (m)	Canti-lever (m)
Load-Bearing Brick Masonry in Cement Mortar	2nd	230	2.8	3.5	1.0
	1st	230	3.0	3.5	1.0
	Ground	350	3.2	3.5	No
Load-Bearing Stone Masonry in Cement Mortar, or	1st	350	3.0	3.2	No
Load-Bearing Brick Masonry in Mud Mortar	Ground	400	3.2	3.2	No
Load Bearing Brick Masonry in Mud Mortar	1st	350	3.0	3.2	No
	Ground	350	3.2	3.2	No

Table 1.1, Excerpt from Nepal National Building Code, NBC 202 : 1994, Mandatory Rules of Thumb, Load Bearing Masonry.

Semi-Urban

As the sites become more rural, there are areas where more use of hollow concrete block walls occurs. In the intermediate areas between urban and hillside rural, houses constructed with stone masonry foundations and stone masonry ground level walls are frequently found with hollow concrete block and/or brick walls above the stone walls.

A common theme seems to be that a single level home is first built, with additional stories added as more money for further construction becomes available. Figure 16 is an example of this with mud mortar used throughout, at both the stone and brick masonry, occurring in a hilly remote area accessible only by a narrow dirt road. Figure 17 illustrates similar mixed materials, but in the town of Zero Kilo, on a paved highway route where access is not difficult. Here, cement masonry was used at the brick walls, with a combination of cement or mud mortar at the stone masonry. Figure 18 illustrates combined brick and stone infill used at the ground floor level of a concrete frame school building. The infill at the upper levels was solely brick masonry.

As with the confined brick walls, there was no indication that concrete block walls are reinforced.

Figure 16. Brick above stone masonry, Balthali VDC.

Figure 17. Brick above stone masonry, Zero Kilo.

Figure 18. Use of mixed brick and stone for infill construction, to economize costs School in Mahankal.

Rural

In the more remote, rural areas, the construction is almost entirely unreinforced stone masonry. As village locations become more remote and climb into the hillsides, and access is via narrow dirt roads along cliff sides, house construction consists almost exclusively of stone masonry with mud mortar. The type of stone used and quality of the mortar work varies greatly from village to village, although the type of construction and materials and quality of work is relatively consistent within a village itself.

A typical house in the areas that were visited consisted of two floors with an attic. The ground floor usually had a kitchen area, but some homeowners used part of their ground floor space to house farm animals such as cows, buffaloes and goats. Almost all of the houses observed had bedrooms on the first floor. New houses that were closer to towns typically had plywood partition walls separating the bedrooms on the first floor level, whereas old houses, and houses that were a farther distance from the town center, were more likely to have wooden plank partition walls. Since the main occupation of the homeowners living in villages is agriculture, a decent amount of space is required for them to store agricultural harvests and tools. The preferred area of storage for such items was the homeowners' attic space. The exterior wall finishes for the houses were primarily mud based plaster. Cement based plaster was also encountered in the field but it was not common. Figure below provides floor plans and elevations that are representative of the typical houses encountered in Mahankal Chaur, Kavrepalanchok and the surrounding VDCs.

Concrete frame with unreinforced brick infill was also used in some of the villages for both housing and school construction. The use of framed infill appeared to be more prevalent the closer the village was to a larger municipality. There were also scattered examples of unreinforced brick masonry construction throughout the areas that were observed.

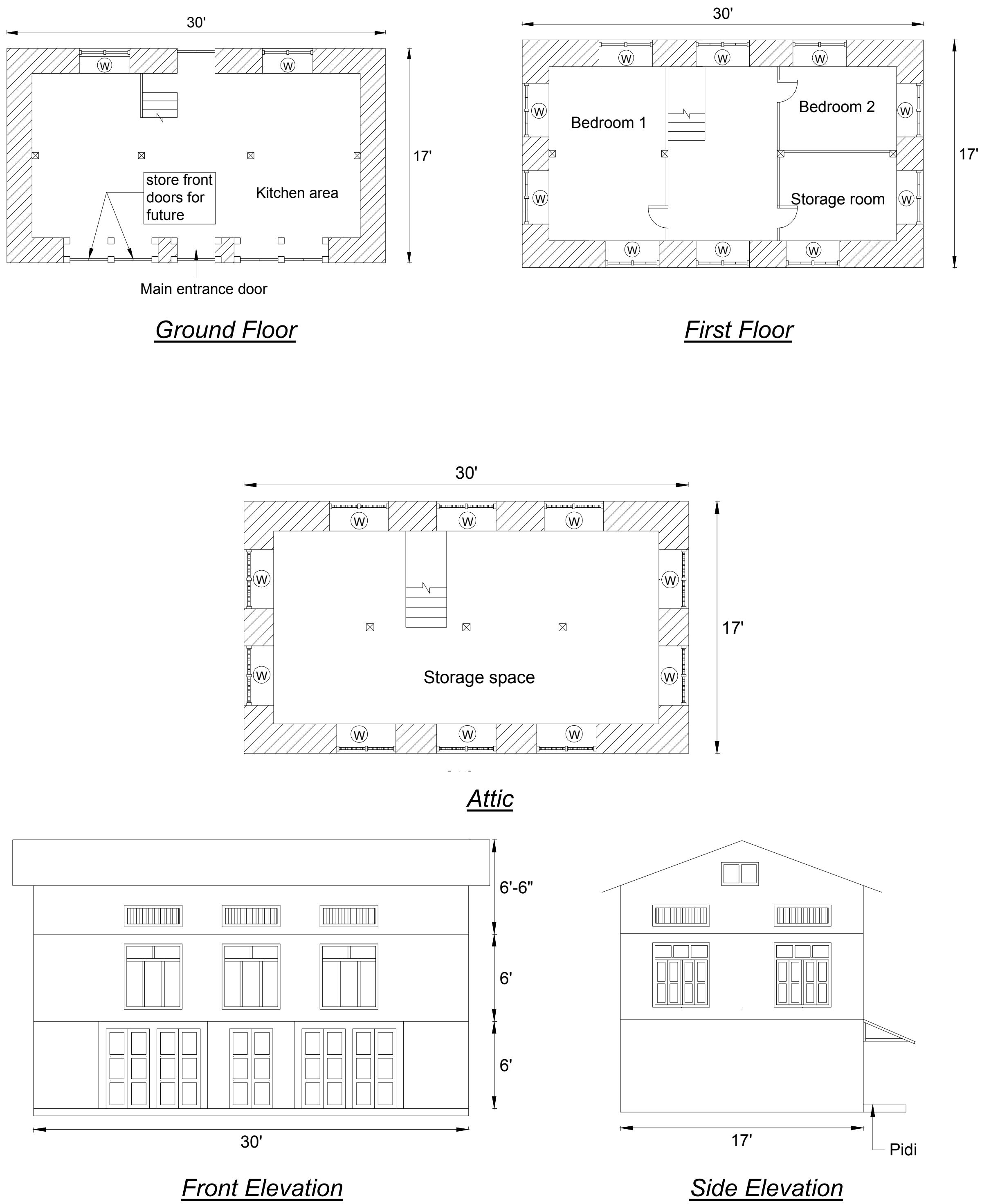

Figure 19. Plans and elevations for a typical house located in Mahankal Chaur, Kavrepalanchok.

The arduous nature of travel to and from the remote villages visited largely drives the type of material used to build the homes there. These mountainous regions, prone to landslides due to earthquakes or the rain-heavy monsoon season, make delivery of brick, concrete block, or cement difficult. But access to stone in these terraced farming regions is easy; the stone is part of the landscape. Dirt from these same hillsides is used to create the mud mortar. There is often a local builder in the village, taught in the trade by a master builder before him, who builds most of the homes in the village. Otherwise, the villagers build their homes themselves, using the same type of materials and construction methods as their neighbors. The primary difference from village to village was the size and shape of the stones used. In some villages, the stones consisted of randomly shaped rocks of various size. In other villages, the stones were cut from the mountainside, but the typical size of the cut stone varied from village to village.

Figure 20 is an example of stone masonry. A near constant with stone masonry is the use of a mud mortar. The soil used for the mortar appears to be a clay material, reddish in color, and predominant in the local geologic landscape. Figure 21 shows a piece of mud mortar from a stone masonry wall.

Figure 20. Random shaped stone masonry, Thula Gaun.

Figure 21. Piece of mud mortar, Thula Gaun.

3.2 Masonry Materials

3.2.1 Bricks

There is a noticeable difference between the brick used in newer versus older construction, which could contribute to the difference in earthquake performance. The newer bricks are taller in height, narrower in width, and longer in length than bricks from older construction. Additionally, the newer bricks usually have deformations with a brick maker's logo embossed on at least one side of the brick. Bricks from older construction tend to be flatter in shape and smooth on all sides. Figure 22 shows a side-by-side comparison of bricks from newer and older construction.

The newer bricks appear to be uniform in size and shape, regardless of manufacturer, suggesting a mechanized manufacturing process. The Nepal National Building Code (NBC) specifies a standard brick size of 240 mm x 115 mm x 57 mm. Based on bricks observed in rubble piles, where many individual bricks were still intact or clearly fractured due to overall building failure, it can be surmised that brick strength and quality of the newer bricks is not a significant contributing factor in building damage due to seismic forces. Due to the differences in types of bricks used, there does not appear to be a typical number of brick wythes in a wall.

Figure 22. Older brick, above, compared to newer brick, below. Note brick maker's embossment on newer brick.

In some areas, unfired brick was used for construction, see Figure 23 and 24. As observed in Sankhu, unfired brick is typically paired with mud mortar, like adobe construction, creating a weak wall in comparison to fired brick with cement mortar.


Figure 23 Unfired brick compared to fired brick


Figure 24 Damaged unfired brick and mud house in Sankhu

There are brick plants located in all three districts of Kathmandu valley (Kathmandu, Lalitpur and Bhaktapur). Brick plants are also located in various districts in the Terai Region. Along with housing, brick plants were also affected by earthquake. Many brick plant chimneys partially collapsed in the 25th April Gorkha earthquake. Even though the kilns were damaged, they appear to be in operating mode to meet the construction demand. The price of brick has remained at around Rs 13.5 per piece after the earthquake as it was before. However, some anticipate that the price of brick will rise due to the widespread damage to the kilns, the shortage of workers at the plants, and the increase in demand. Many homeowners might choose to re-use bricks from collapsed buildings instead of purchasing new ones to avoid paying higher prices.

There were no brick manufacturing facilities in any of the surveyed rural villages; bricks are instead brought in from the valleys. For example, clay bricks used in the villages of Kavrepalanchok are transported from Bhaktapur and are purchased from either an intermediary seller or directly from a brick manufacturing plant. This appears to discourage homeowners from using bricks, since they typically need to pay extra to cover the transportation costs. Meanwhile, stones are usually locally sourced from local quarries so their cost is significantly less then brick. Despite the difference in cost, based on discussions with homeowners, most of the people who live in stone houses aspire to constructing a house with bricks instead. Many homeowners and builders indicated that they would prefer to rebuild their homes with bricks rather than stones if they could afford to do so.

3.2.2 Concrete Blocks

A number of small, handmade, concrete block facilities were observed at roadsides when leaving the urban environment of Kathmandu. In Bahunepati, the block maker was not present, but the landowners where the block making operation was located were present and shared their knowledge of the block making process, as learned from watching the block maker at work, and occasionally helping him.

As related by the landowners, the block maker makes two types of blocks. One is a cheap block, made from 4 parts gravel/ 4 parts sand/ 1 part cement, and sold for RS 35 (Nepalese rupees) per block. The better block is made from 2.5 parts gravel/ 2.5 parts sand/ 1 part cement and sells for RS 40 per block. The concrete mixture is consolidated in a press-like machine around a form, then released and set aside. The blocks cure for two days in the sun. After the first two days, the blocks are watered at random (or unknown) intervals. One bag of cement generally yields about 60 blocks. The usual production level of this particular block maker entailed the use of about 7 bags of cement/day, yielding about 420 blocks/day.

A home close to the block maker's facility in Bahunepati was recently built, using the "better" blocks. The house was said to have suffered no damage in either the main April 25th earthquake or the large May 12th aftershock. Although the block walls of the house had been plastered over, no cracking was visible in the exterior walls.

Figure 25. Handmade concrete blocks, Bahunepati.

Figure 26. Concrete block hand press, Bahunepati.

Figure 27. Handmade concrete block, curing, Bahunepati.

3.2.3 Stones

The stone work varies from randomly shaped loose stones of varying sizes, likely dug out of the hillsides, to formed stones cut from the mountainsides. Depending on location, some of the cut stonework is of small and thinner rectangular shapes, closer to brick sizes, while other cut stones are much larger and taller, approaching concrete block size. Figure 28 illustrates the variety in stone shapes and sizes used even within the same house.

Figure 28. Example of flat cut stone with random stone shapes, Thula Gaun.

The type of stones used to build houses were either round in nature or generally flat and rectangular, see Figures 29 - 32. The technique used to construct the stone walls appeared to vary by district. For example, in the villages surveyed in the Kavrepalanchok district it was common to use uncut stones for the walls with cut stones only at the building corners. Mud mortar was typically used throughout. In the Sindhupalchok district villages, however, cut stones were typically used for the walls. Mud mortar was commonly used but there were houses where no mortar was used to bind the stones together. This was not found in the Kavrepalanchok villages. Cement mortar was not commonly used for the stone masonry buildings in either district.

Figure 29. Stones used for wall construction, Dhungkharka, Kavrepalanchok

Figure 30. Stones used for wall construction, Maneshwor, Sindhupalchok

Figure 31. Stone wall construction, Chalal Ganeshthan, Kavrepalanchok

Figure 32. Stone wall construction, Ramche, Sindhupalchok

3.3 Floor and Roof Systems

For all types of masonry where wood framed floors and roofs were used, the wood framing typically is extended into the masonry, and often through the masonry wall thickness. Unless a concrete beam-column frame was present, in which case a concrete floor or roof slab was used, the floors and roofs were typically built using wood-framed joists and rafters. At floors, a wood subfloor is placed over closely spaced floor joists. The subfloor is often bamboo or twigs, primarily serving as support for a mud slab floor layer above. These floors are typically 3”-4” thick above the subfloor. In newer construction, the subfloor is a straight-sheathed timber floor. Figures 33-36 show variations of support framing for mud floor slabs. Figure 39 shows a section at the edge of a typical mud floor installed over a more recent straight sheathed floor. There was evidence of pegs installed at overhanging roof rafters, used to anchor the sloped rafter in the masonry wall (See Figures 37 and 38). Figure 40 shows a sloped CGI (corrugated galvanized iron) roof over sloped wood roof framing.

Figure 33. Example of subfloor framing, Bungamati.

Figure 34. Example of subfloor framing, Bungamati.

Figure 35. Herringbone subfloor layout, Thula Gaun.

Figure 36.Straight sheathed subfloor, Thula Gaun.

Figure 37. Pegged roof rafters in wall, Thula Gaun.

Figure 38. Pegged rafter in rubble pile, Thula Gaun.

Figure 39. Mud floor over straight sheathed subfloor.

Figure 40. CGI over sloped timber roof framing,Thula Gaun.

4. Housing Structural Damage Assessment

4.1 Kathmandu and Urban Areas - Kuleswor, Balkhu, Bungamati, Khokana, and Sankhu

4.1.1 Reinforced Concrete Frame with Infill

Store front/soft story failures were more common at recent construction where the concrete columns at the ground level would fail at the column top or bottom joints. Often, after a failure of one or more ground story concrete columns, the upper portion of the structure would remain intact as the building fell over to one side (See Figures 41 – 43 for examples of this failure).

Due to the height-to-thickness ratio of the masonry infill walls, which run from about 12” to 15”, there was not much of out-of-plane failure of infill masonry walls observed except at gable roof ends, where the unsupported height of the walls increased. Despite not being physically tied to the concrete frames, the thick brick masonry infill does appear to be a major contributor to lateral resistance.

Buildings that did not fail tended to be newer construction with reinforced concrete frames. The ground level concrete columns appeared to avoid damage if there was either some amount of infill in the store front line, or if the building was abutted directly against another structure, without an alley, road, or open lot adjacent to either side. The presence of immediately adjacent buildings may have caused some pounding damage, but at the same time would brace the building against side sway, limiting damage to the concrete columns.

Figure 41. Soft story failure, Kuleswor.

Figure 42. First story column failure, Balkhu.

Figure 43. Close up of Figure 35 column failure, Balkhu.

4.1.2 Unconfined, Unreinforced Masonry

At older construction that did not utilize concrete frames, there was a substantially higher rate of failure and collapse, particularly at the wall corners and gable roof ends. There is no reinforcement tying perpendicular walls together at the corners. While the low ends of the roofs are supported by masonry walls, and the timber roof framing often runs into the wall, the gable wall ends had no ties or bracing back to the roof framing, and were frequently a source of initial collapse.

Figure 44. Gable wall failure & corner separation, Khokana.

Figure 45. End wall collapse, Bungamati.

Figure 46. Collapsed end wall at gable, Bungamati.

Figure 47. Unconfined masonry collapse. Note undamaged infilled frame in background, Khokana.

In Sankhu, many of the buildings were constructed of unreinforced masonry. Some buildings were constructed with brick and mud mortar, while others were constructed with brick and cement-based mortar. The buildings utilizing cement-based mortar clearly performed better than those with mud. This could be observed in relatively similar (with the exception of the mortar type) side-by-side buildings with different performance, such as those shown below in Figures 48 and 49.

Figure 48. Sankhu - Both buildings are 3-4 stories, with wood floors and fired brick walls. The building on the left utilized mud mortar and sustained significant damage, while on the right the building used cement mortar and had no observable damages.

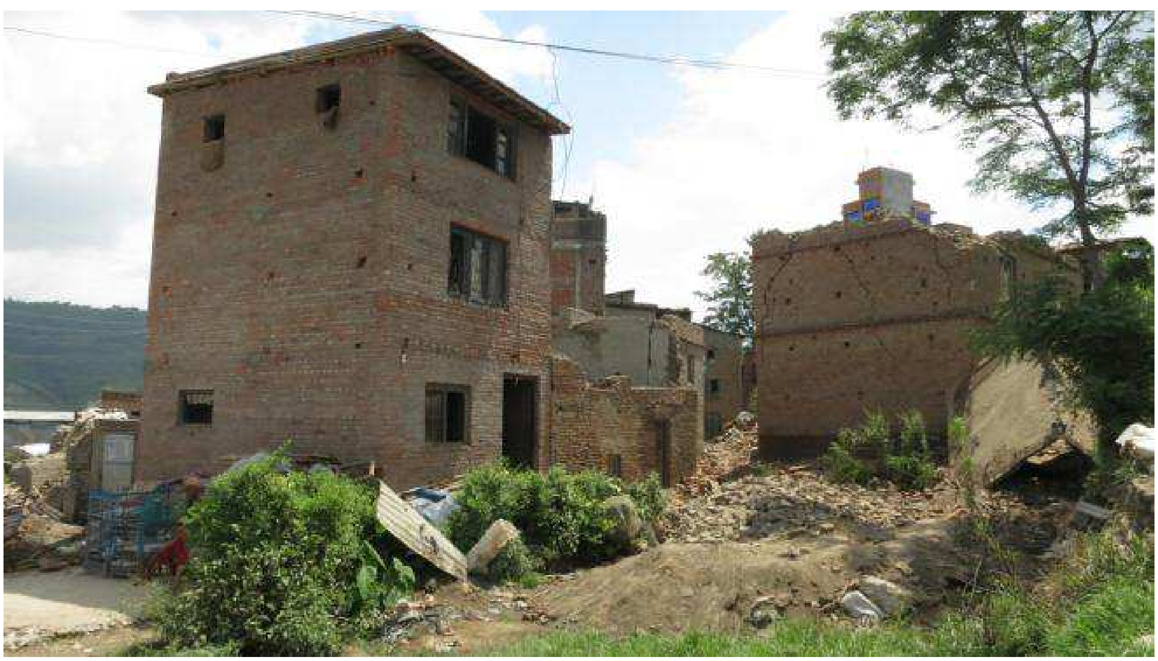

Figure 49. Sankhu – Left side three-story building used cement mortar and had minimal damage, center one-story and right two-story used mud mortar and suffered significant damage.

4.2 Sindhupalchok District Urban Hillside Area – Chautara, Lamosanghu, and Khadichaur

While Chautara was already heavily damaged in the April 25th earthquake, it was learned that there was extensive additional damage and collapse as a result of the May 12th aftershock event. During the visit, there was no way to discern if the damage observed occurred as a result of the first or the second M7+ event.

4.2.1 Foundation Failures

In more urban hillside areas, such as Chautara, in the Sindhupalchok district, landslides due to earthquake ground motion combined with inadequate foundation systems appeared to be the major cause of building failure and collapse. The age of construction varies greatly, with materials ranging from unconfined stone masonry with mud mortar at older buildings to concrete frame with brick infill and cement masonry. But regardless of construction type and age, a lack of adequate foundations for the steep hillside sites contributed to many of the collapsed and damaged structures.

Cracking along entire front side at the base of buildings located above the steep hillsides was often clearly evident even where no other building damage was noted. Where hillside building failures did occur, it often appeared to be due to inadequate ties to a foundation or partial lower level, or a lack of a solid foundation – such as the use of stone rubble for foundations. The presence of buildings lower on the hillside, below the upper buildings, prevented closer observation to try to determine whether the damage observed was actually due to foundation slippage or failure, or damage to lower hillside columns or walls.

Figure 50. Evidence of foundation shifting at front of building (bottom of stair), Chautara.

Figure 51. Foundation/lower level failure on hillside, Chautara (See Figures 52 & 53 for column failure details).

Figure 52. Foundation column failure, Chautara.

Figure 53. Foundation column failure, Chautara.

Figure 54. Foundation failure, Chautara.

Figure 55. Foundation failure, Chautara.

4.2.2 Reinforced Concrete Frame with Infill

Other causes of damage and/or collapse observed in Chautara, Lamosanghu, and Khadichaur, were related to masonry wall failure, pounding by adjacent buildings, and collapse of adjacent structures onto a building (See Figures 56 – 60 below).

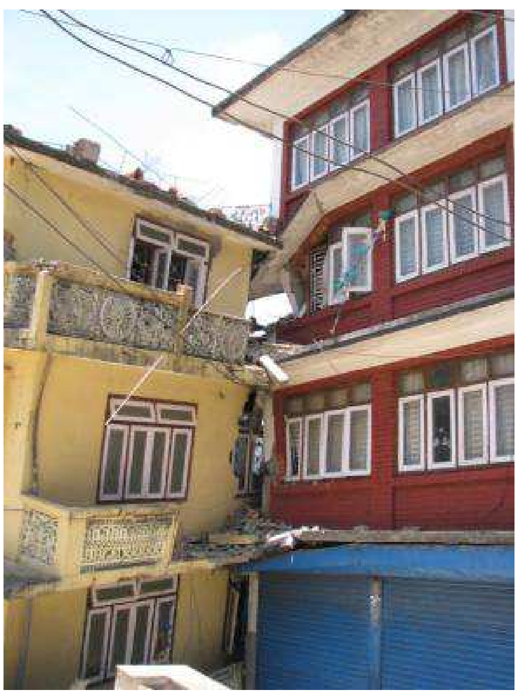

Figure 56. Damage due to adjacent building collapse, Chautara.

Figure 57. Pounding damage, Chautara.

Figure 58. Damage due to pounding and collapse of adjacent building, Chautara.

Figure 59. Damage due to collapse of adjacent building, Lamosanghu.

Figure 60. Demolition of collapsed building. Note damage to adjacent building caused by building collapse, Khadichaur.

4.2.3 Damage Assessment Evaluation and Posting

In Chautara, engineers from the Nepal Department of Urban Development and Building Construction (DUDBC) had been performing post-earthquake assessments and posting buildings with red, yellow, and green "tags" for entry. Most tagging observed was in the form of open circles spray-painted on the front walls of the buildings, usually near doorways. In one instance, a red placard was posted adjacent to the red circle. Figures 61-63 show the assessment posting circular "tags".

Figure 61. Green tagged structure, Chautara.

Figure 62. Red tagged structure with placard, Chautara.

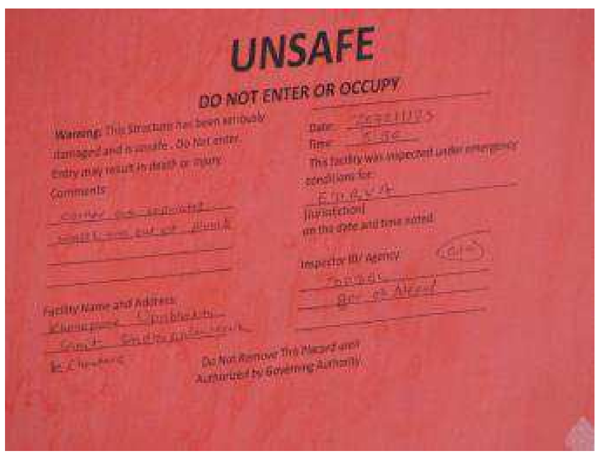

Figure 63. Placard on red tagged building, Chautara.

4.3 Kavrepalanchok and Sindhupalchok District Rural Areas - Thulo Gaun, Mahankal, Ichok, Dhungkharka, Chyasingkharka, Mahankal Chaur, Chalal Ganeshthan, Ramche, and Maneshwor

There was extensive damage to unreinforced stone masonry buildings in all of the villages that were observed. There was also extensive damage to the unreinforced brick masonry buildings. The damage ranged from localized damage to individual walls to complete collapse of the building structure. Concrete frame with brick infill buildings generally performed better than the unreinforced masonry structures in the Kavrepalanchok District, similar to what was seen in Kathmandu. However, in the Sindhupalchok District there was extensive damage to concrete frame buildings, likely because the villages in this district are located much closer to the epicenter of each of the two earthquakes.

Figure 64. Damaged two story house in Mahankal Chaur

Figure 65. Complete collapse of house, Dhungkharka

Figure 66. One of the houses in Chalal Ganeshthan Ward 9 where the upper floors were demolished and the ground floor level covered with CGI sheets.

Figure 67. Collapsed houses in Ramche

Figure 68. Collapsed house in Ramche

In the remote, rural hillside areas, most of house construction consists of stone masonry with mud mortar. These homes suffered the greatest amount of damage. Like unconfined brick masonry, wall corners and gable walls collapsed first. Without having even header courses to tie the width of the wall masonry together, and dried mud mortar that can be crushed to dust between fingers, the stone masonry walls disintegrated easily when subjected to the lateral earthquake forces. With the random layout nature and varying shapes and sizes of stone masonry, X-cracking was not frequently observed, or clearly visible, in these buildings.

Figure 69. Severely damaged stone masonry home with randomly shaped rocks, Thula Gaun.

Figure 70. Damaged stone masonry with small cut stones, Mahankal, Sindhupalchok.

Figure 71. Large cut stones in damaged stone masonry, with plaster over stonework, Ichok.

Figure 72. House with major damage at the corners, Mahankal Chaur VDC

There were many cases of out of plane stone wall failures in the rural villages, likely due to a number of deficiencies in the configuration and construction of the walls. The typical floor plan had masonry exterior walls but with limited internal cross walls. Internal cross walls can provide important out-of-plane support to the exterior walls and also increase the lateral strength of the house. The wood-framed floors are not specifically built stiff enough or well-connected enough to provide adequate resistance for bracing two-story walls out-of-plane. Therefore walls may have been effectively unbraced over the full two-story height, leading to slender walls that are more likely to collapse. The masonry walls were commonly missing ties and bands that help the unreinforced stone masonry span out-of-plane and transfer loads to the foundation in-plane. The absence of bands can lead to early failure of the wall in-plane and especially out-of-plane.

Figure 73. Out of plane wall failure, Ramche VDC

Figure 74. Out of plane wall failure, Dhungkharka VDC

One of the primary failure modes for the walls was the delamination of the interior or exterior wall faces. This failure mode is due to the typical construction technique of building the walls with stone masonry on the inside and outside faces and filling the void between the two faces with rubble or debris. Through stones that would tie together the inside and outside faces and prevent delamination were not used in any of the houses that were observed.

Figure 75. Delaminated wall failure, Chalal Ganeshthan VDC

Figure 76. Delaminated wall failure, Mahankal Chaur VDC

It was common for stone walled houses to have small holes in the walls. The homeowners explained that the holes were created when the walls were built to support temporary scaffolding used by the builders to construct the walls. It is standard practice for the holes to left in place, in part to allow for scaffolding to be installed to build vertical additions to the house or to make repairs to the wall. There were cases where cracks in the walls either formed in or propagated through these holes, especially at holes that were adjacent to building corners.

Figure 77. Cracks through holes in walls, Dhungkharka VDC

Figure 78. Cracks through holes in walls, Chalal Ganeshthan VDC

In many cases, houses built on slopes did not have the appropriate configuration required to support the house during the earthquake. There were many houses built on hillsides that suffered major damage or collapse because the foundation was undermined by the soil underneath them sliding away. In Maneshwor, for example, the houses that were on the slope suffered significantly more damage than those built just across the street but away from the slope.

Figure 79. Collapsed house on a hillside, Maneshwor VDC

Figure 80. Undermined foundation slab in school, Chyasingkharka VDC

There were many houses in Maneshwor constructed with concrete frames with brick infill and there was a significant amount of damage to those houses. In addition to the collapses due to undermined foundations, weak story collapses and damage to brick infill walls were common. There was much less damage to concrete frame houses in the Kavrepalanchok villages. However, there was relatively fewer concrete frame houses in these villages compared to Maneshwor. In Chalal Ganeshthan, for example, concrete frame and brick housing was mostly limited to a cluster of houses at the center of the village. These houses sustained little to no visible damage.

Figure 81. Collapsed concrete frame house, Maneshwor VDC

Figure 82. Concrete frame housing, Chalal Ganeshthan VDC

A majority of stone masonry houses in the remote, rural areas of Nepal suffered damage significant enough that the homes will not be able to be repaired. The aftershock also caused further damage and collapse to those homes already partially damaged. The very few houses that only exhibited minimal damage appeared to be more recently built, possibly utilizing more straight sheathed flooring below the mud slabs and CGI roof diaphragms, providing better horizontal diaphragms and out-of-plane bracing of the stone walls. Newer homes were also less likely to have had alterations or additions made to the original construction. A common theme heard from the affected people was that they wished to be told how to rebuild safer, earthquake-resistant homes, regardless of the age or amount of damage their homes had, or had not, suffered.

The Build Change team was in Thula Gaun, in the Balthali VDC, Ward No. 5, at the time of the M7.3 aftershock. Many homes in the village had already sustained considerable damage from the primary earthquake. During the aftershock, out-of-plane movement of the upper story stone masonry front wall was observed in one house that had sustained very little damage in the April 25th event. Given an estimated thickness of 12”, observing this movement was very interesting. The house had a few small cracks in the stone masonry from the first event, but exhibited no additional damage or increase in the initial crack sizes or widths. The house had been built only 6-7 years earlier by a local builder. The upper floor had straight sheathing below the mud slab, which likely aided the house’s lateral resistance by providing a resilient diaphragm at mid-height of the walls. However, prior to the aftershock, the owner had said that he wanted to tear the house down and rebuild a better, safer house.

Figure 83. Largely undamaged house as seen in the final moments of May 12th M7.3 aftershock, Thula Gaun.

4.4 Nuwakot District Rural Areas – Lachyang, Manakamana, and Kaule

The typical construction types observed in the Lachyang, Manakamana, and Kaule VDCs were similar to those encountered in the rural areas of Sindhupalchok. Structures built with reinforced concrete frames with masonry infill typically lined the main roads, and stone and mud construction topped with slate tile roofing were typically found either upslope or downslope from the main roads. When questioned, homeowners and masons located in Lachyang, Manakamana, and Kaule acknowledged that alternative building materials such as fired clay brick, steel reinforcement, and cement were theoretically accessible. However, the additional cost associated with the transportation of these materials generally made them too expensive for homeowners to afford.

Figure 84. Truck transporting construction material in the rural areas of Nuwakot.

Figure 85. Example of a typical damaged stone and mud house with slate tile roof, Lachyang.

Figure 86. Example of slate roofing that has been cut into smaller tiles, Lachyang.

Figure 87. Reinforced concrete frame with stone and mud infill encountered in the rural area of Nuwakot.

Figure 88. Wall section of a collapsed stone and mud structure, Kaule.

4.5 Okhaldhunga and Solukhumbu District Remote Rural Area – Ragani and Chaulakharka

Okhaldhunga and Solukhumbu districts have received little intervention relative to Sindhupalchok, Kavrepalanchok, and Nuwakot districts. In acknowledgment of this a reconnaissance helicopter trip was performed to engage the rural inhabitants in these two districts in order to gain a better understanding of the actual conditions on the ground. During the reconnaissance mission two stops were made, one in the Ragani VDC of Okhaldhunga, and a second in the Chaulakharka VDC of Solukhumbu. Additional stops to more isolated areas within these two districts were also scheduled, however bad weather on the day of the trip limited access to these areas.

In general, the construction type prevalent in both VDCs consisted of the same stone and mud construction type typically found in the rural areas of Sindhupalchok and Nuwakot. However, the inclusion of wood banding in stone and mud construction was more prevalent in Chaulakharka and Ragani than what was observed in the rural areas of Sindhupalchok and Nuwakot. Also, several structures in Chaulakharka displayed exceptional stonework, which is an aspect of good quality construction that is severely lacking throughout most rural areas.

While not prevalent, the use of cement in construction in Ragani and Chaulakharka is worth noting. In Ragani a medical center built from stone masonry with cement mortar was observed and appeared to behave well during the earthquakes. Also, even though none of the stone masonry observed in Chaulakharka included cement mortar, a reinforced concrete frame building was being constructed in the village center during the time of our site visit. Encountering cement based construction in either of these VDC's was unexpected given access to the main market areas requires several hours of hiking, however these two examples of encounters with cement based construction in rural areas reinforces the notion that using construction materials other than stone and mud should not be ruled out entirely.


Figure 89. Typical house in Ragani constructed from stone and mud, damaged

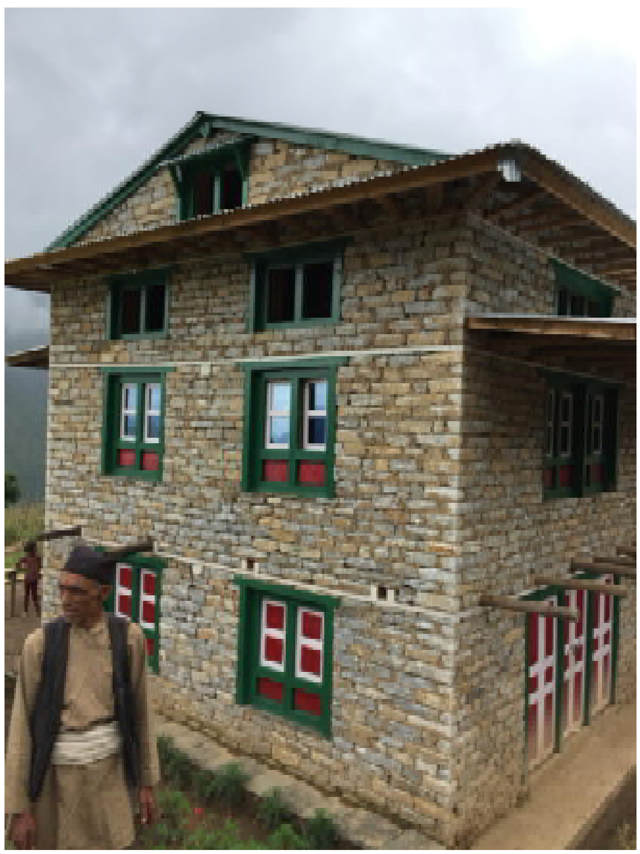
Figure 90. Exceptional stone work for stone and mud mortar building found in Chaulakharka, minimal damage

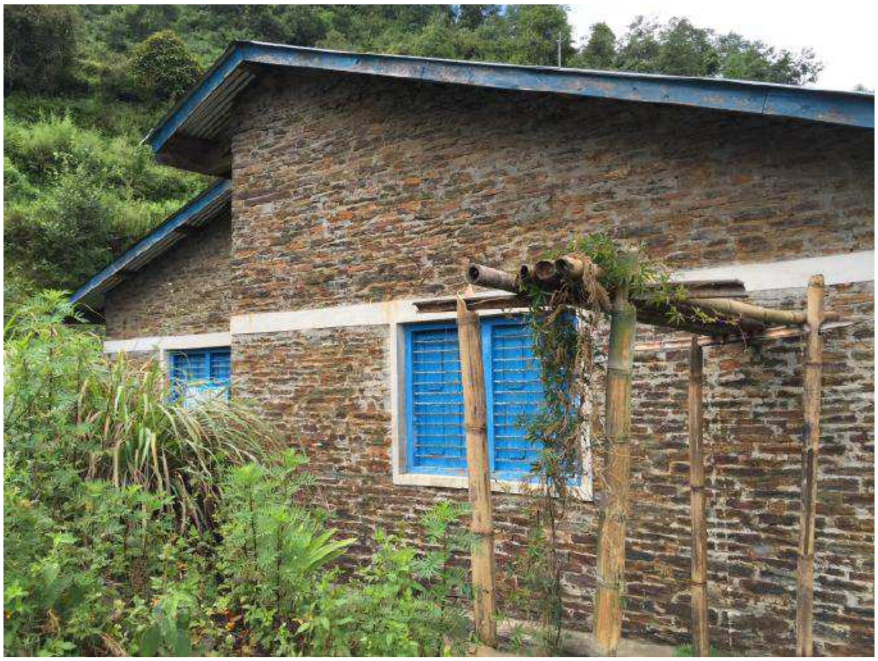

Figure 91. Medical center in Ragani built with stone, cement mortar, and a concrete band at the lintel level.

Figure 92. Stone with cement mortar and concrete band at medical center in Ragani

Figure 93. Reinforced concrete frame structure being constructed in Chaulakharka

5. School Structural Damage Assessment

Several government (i.e., public) schools were observed during Build Change's field visits. Most schools consisted of several separate structures built at different times over many years. It is unfortunate to note that all of the schools observed suffered damage, from mild to severe, and all would require either significant repairs, partial demolition, or complete rebuilding before a safe, earthquake-resistant structure could be provided for the students.

A report on school performance and the effectiveness of community-based interventions was performed and issued by RiskRED, who did detailed studies of the technical and social aspects of previous school construction or strengthening projects. They found that retrofitted schools generally performed better than non-retrofitted schools, that schools designed to be disaster-resistant may have still performed poorly when construction quality oversight and skill-improvements in builders was not performed as part of the construction, that collapses of unreinforced stone and brick masonry infill walls were the primary failure in the schools, and that when communities were engaged in the construction process lasting impacts of safe construction knowledge were observed in the communities. The full report, "Safer Schools, Resilient Communities: A Comparative Assessment of School Safety after the 2015 Nepal Earthquakes" by Rebekah Paci-Green, Bishnu Pandey, and Robert Friedman can be found at this website: http://riskred.wix.com/riskrednepal#!reports/c1qbl.

5.1 Shree Saraswati Higher Secondary School – Mahankal, Sindhupalchok

The Shree Saraswati Higher Secondary School in Mahankal has only one structure that may be able to be retrofit and repaired for use again. This was a 3-story concrete frame structure, consistent with the type of building being constructed in recent years at most other school sites. The structure is about 3 years old and took about 3-4 years to build, being built one story at a time as funding was available. The infill at the first, ground level story is a combination of stone and brick. The upper 2 stories both have brick infill. There is evidence of significant lateral movement – shear cracking of the infill and wracking of doorframes (See Figure 94). There was severe concrete spalling at the interior stairs, with cracking at the stair to floor landing joints that left exposed, making the stairs to the upper levels unsafe (See Figures 95 and 96).

Figure 94. 3-story concrete frame Shree Saraswati School structure with shear cracking at infill walls, Mahankal.

Figure 95. Concrete cracking at stair floor landing.

Figure 96. Close-up of stair landing spalling, Mahankal.

Figure 97. Heavily damaged structures, 50 and 35 years old (left to right), at Shree Saraswati School, Mahankal.

5.2 School in Ichok

A multi-structure school in the remote village of Ichok also suffered similar damage as the Mahankal school. The older stone masonry structures had severe damage with most walls partially collapsed in the single story structures, although the steel supported and framed roof structures were still standing. Collapse of the walls appeared to be primarily due to out-of-plane failure of the unreinforced stone masonry. A newer two-story concrete frame structure was damaged primarily at the unfinished upper story. If the upper story were removed, the two lower story classrooms could be used again (See Figures 99 and 100).

Figure 98.Damaged single-story structures at school, Ichok.

Figure 99. Unfinished second story of school, Ichok.

Figure 100. Beam-column connection damage, Ichok.

5.3 Schools in Sindhupalchok and Kavrepalanchok

The schools that were observed in the rural villages were built with either stone masonry walls or concrete frames with brick infill. Many of the older school buildings that were observed consisted of stone masonry walls with steel truss roof framing. There was also one recently built school in Dhungkharka with this same system that was constructed by builders from the village. Steel trusses observed in the field were made from either cold formed steel sections or structural steel tubing/HSS sections. In some instances the trusses were supported by steel pipe columns that were embedded inside stone masonry pilasters. Most of the school buildings that had this type of construction had damage to the stone walls, typically out of plane failures and/or delamination of the wall faces. However, in every case the roof framing remained standing.

The school building in Dhungkharka was constructed with a horizontal concrete band running over the top of the window and door openings. Horizontal bands are recommended in several stone masonry guidelines but this building was one of the few buildings the Build Change team found in the rural villages that had them. This building sustained no visible structural damage.

Figure 101. Delaminated stone masonry wall in school, Chalal Ganeshthan VDC

Figure 102. School with steel framed roof and stone masonry walls, Ramche VDC

Figure 103. School in Dhungkharka with a horizontal band over the windows and doors

School builders constructed with concrete frames were typically built by outside builders brought in by the government or by outside non-government aid organizations. The building in Mahankal Chaur was under construction at the time of the earthquake and did not appear to sustain damage. The fully constructed concrete frame school building in Chalal Ganeshthan also did not sustain any visible structural damage. An interesting feature of this building was that the concrete beams were poured on top of the constructed masonry walls, similar to confined masonry construction. In addition, one of the walls was infilled with stone instead of brick.

Figure 104. Concrete frame school, Chalal Ganeshthan VDC

Figure 105. School with concrete frame and infill with brick and stone, with a beam poured on top, Chalal Ganeshthan VDC

Figure 106. Concrete frame school building under construction in Mahankal Chaur

5.4 School in Devi Chaur VDC

A school, in Devi Chaur VDC, of fired brick in mud mortar was retrofitted a few months before the April 25th disaster. The retrofitting was done using reinforced concrete (RC) splint and bandage. RC splint was provided at the corners and at either side of the openings and bandage was provided at the floor levels and at sill and lintel levels. The building had corrugated galvanized iron sheets with timber understructure. There were no visible cracks in the retrofitted building whereas the building adjoining to this retrofitted structure, which was not retrofitted, was found to sustain damages to some of its walls. See Figures 107 and 108.

Figure 107. Retrofitted part of the school

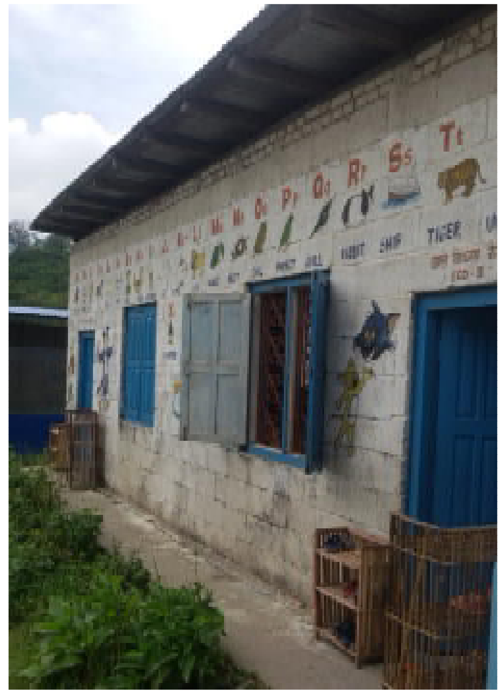

Figure 108. School building that was not retrofitted

The adjoining building was of concrete hollow blocks load bearing system with light CGI roof with timber framing. As concrete blocks are not commonly used in building construction in Nepal, the school authorities were under the impression that concrete hollow block masonry buildings could not be retrofitted. However, from other locations internationally where concrete blocks are used more commonly, there are established techniques for retrofitting this type of building.

Figure 109. Partially collapsed mud in stone house

Figure 110. Partially collapsed adobe house in Devi Chaur

All of the buildings in the surrounding area, predominantly of stone in mud or adobe walls with timber flooring and roofing, were found to be damaged. See Figures 109 and 110.

5.5 Observations of school in Baruwa, Sindhupalchok

A two-story reinforced concrete frame with CMU block infill situated on the hillside of Baruwa, a VDC located in the Sindhupalchok district, endured total collapse, see Figure 111. Unfortunately this school could only be quickly observed given there was not sufficient time to assess its damage to determine the cause of failure. However siting issues, in addition to poor detailing within the concrete moment frame, were likely contributors to its overall failure.


Figure 111. Completely collapsed two-story concrete frame with infill school, Baruwa

5.6 General Observations on Schools

Most schools observed had similar damage types. Typically, the more recent concrete frame buildings showed evidence of shear cracking in the infill and damage at beam-column joints, while older stone masonry structures typically had wall failure and collapse, for the same reasons as previously discussed for other buildings. A school observed in Chautara had been entirely reduced to piles of rubble. The only discernable sign of a building was a door still standing in the middle of a rubble pile, as seen in Figure 112.

Figure 112. Collapsed school buildings, Chautara.

6. Nepal Building Code Provisions and Enforcement

After a 1988 earthquake in Nepal, the Ministry of Physical Planning and Works, Department of Urban Development and Building Construction (DUDBC) prepared a Nepal National Building Code (NBC), published in 1994, which is comprised of a series of guidelines and “mandatory rules of thumb”, rather than one single, cohesive document. The NBC is in English with metric units, and is largely based on the Indian Standard IS Codes dating to the 1970s and 1980s. Prior to that time, there had been no regulations setting out either requirements or good practice for building construction.

There is no indication however, that the building code guidelines are enforced in any practical manner. Many buildings, particularly houses, are not engineered. For the buildings that are engineered, and detailed in drawings, there is no effective system of ensuring that the structures are built in accordance with the drawings, such as by construction inspection or supervision by a qualified engineer. Unless an owner is willing to pay the designing engineer for construction supervision, the builder is free to modify detailing as he wishes.

Conversations with building owners and Nepali civil engineers revealed that, while new buildings in urban areas may be designed by a qualified engineer, who will produce construction drawings, often there is no oversight on the construction process itself to ensure that the building is built in accordance with the engineered drawings. Some municipalities require drawing approval by government engineers, but again, there is no oversight during the construction itself.

In rural areas, homeowners either have built their homes themselves, or hire local builders for the work. Aside from school construction, there seems to be little acknowledgement of a building code or guidelines for safer home construction.

Figure 113. Construction of non-continuous, non-code complying beam at stairway of hotel structure in rural area, Thula Gaun.

6.1 National Society for Earthquake Technology

NSET, National Society for Earthquake Technology-Nepal, often collaborates with DUDBC on building construction issues, and also has published guidelines for earthquake-resistant construction, which are largely accessible online. As with the building code guidelines though, there is little evidence that NSET'S guidelines are implemented in practice. Figure 114 is an example of a NSET one-page guideline for safer, earthquake-resistant building construction. There are efforts by these organizations to make compliance with the guidelines and rules of thumb part of the national law.

Figure 114. NSET Stone Masonry Construction Guideline (NSET).

7. Discussion

The unfortunate coincidence of two earthquakes of magnitudes greater than M7.0 in the same geographical region, taking place within less than three weeks of each other, presents a unique opportunity to examine the residual strength of damaged buildings to resist further strong earthquake loads. It also reinforces the fact that a damaged structure can still be subject to further damage and potential collapse when subjected to additional ground motion forces, even at a lower level than previously experienced. Some minimally damaged and undamaged buildings maintained their structural integrity during the second large earthquake event, while other structures suffered further damage or collapsed.

7.1 Addressing Damaged Buildings

The type of materials and construction practices commonly utilized in Nepal are unlikely to make attempts at retrofitting most damaged buildings economically feasible, however in some cases it may be possible. Unreinforced masonry walls with significant cracks, where movement between the masonry units has occurred causing deformations or failure, would be more cost effective to replace. However, the materials – stones, bricks and blocks can be salvaged and, if in good condition, reused in reconstruction. Confining elements may be introduced to the reconstructed wall to increase the resistance in future events.

For concrete frame buildings, where the frames have sustained minimal or no damage, it could be possible to replace damaged masonry wall panels, and infill more bays (or introduce other lateral-force-resisting elements) as needed to improve the strength of the building in future earthquakes. In cases where the frame joints, beams or columns, have been significantly damaged and deformed, replacement may be necessary.

7.2 Reconstruction Considerations

It will be important to coordinate construction improvement and training efforts with the Nepal government agencies, as they have produced guidelines and training sessions in the past which will provide valid starting points for improvements to current building practices.

Access challenges in remote and rural areas can also make introducing new construction materials problematic. Working with the commonly used materials and developing improved detailing and construction practices would likely be the most effective way to create positive changes in earthquake-resistant building construction that would reach the greatest number of the Nepali people.