# Initial Seismic Vulnerability Assessment of Trashigang District Hospital Trashigang, Bhutan

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Prepared by

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# Executive Summary

The Trashigang District Hospital is the only hospital providing medical care to the residents of Trashigang District, eastern Bhutan's largest and most populous district. The mountain roads that connect Trashigang district to the regional referral hospital at Mongar, to the capital Thimphu, and to India traverse steep, landslide-susceptible terrain. A major earthquake will cause numerous, road-obstructing landslides, cutting off Trashigang and leaving the hospital to face the aftermath of a major earthquake without outside assistance. For this reason, the Ministry of Health (MoH), Royal Government of Bhutan, the World Health Organization Country Office for Bhutan (WHO Bhutan) and Regional Office for South-East Asia (SEARO), and European Commission Humanitarian Aid and Civil Protection (DIPECHO) requested that GeoHazards International (GHI) provide an initial assessment of the hospital's potential earthquake vulnerabilities and level of preparedness.

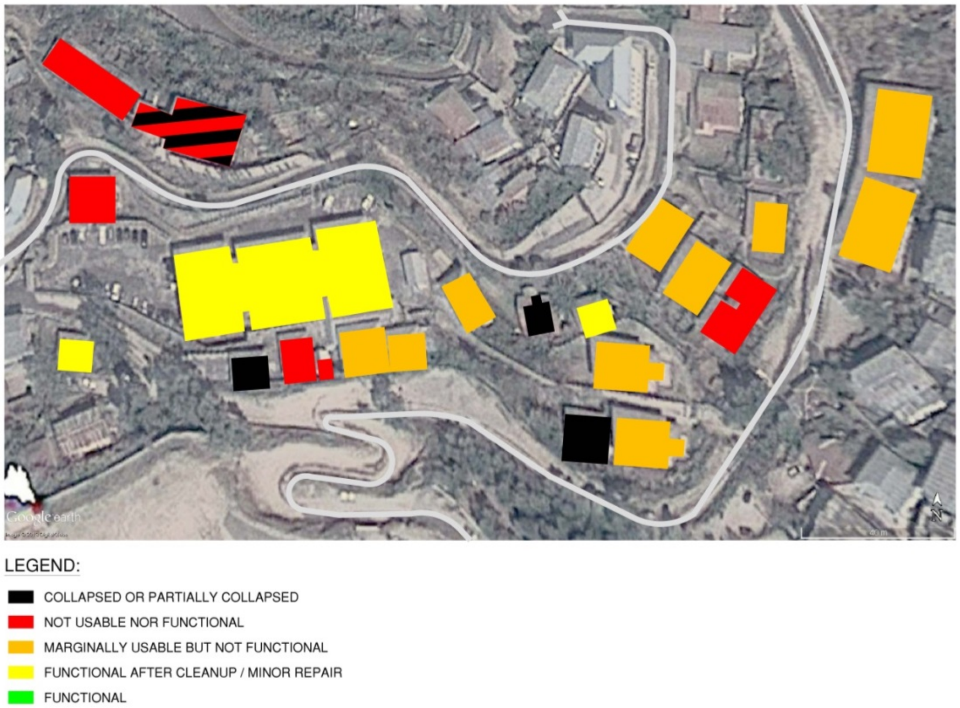
The assessment is intended to provide the hospital, the Ministry of Health, WHO Bhutan and SEARO with an overview of the hospital's seismic vulnerabilities, and to recommend actions to improve the hospital's ability to deliver medical care following a major earthquake. GHI evaluated Trashigang Hospital, along with Trashiyangtse Hospital in a neighboring district, in August to December 2013. This report presents the GHI assessment team's findings and recommendations.

GHI's team obtained the information included in this report through conducting in-person evaluations of buildings and infrastructure over two full days at the hospital site; reviewing available structural and architectural drawings; interviewing or holding discussions with the hospital's administration and key staff; and obtaining supporting technical information from the United States Geological Survey (USGS), Royal Government of Bhutan Department of Health Infrastructure Development Division (HIDD) and Department of Geology and Mines (DGM), as well as relevant technical literature.

The assessment team identified numerous vulnerabilities in the hospital's buildings, on-site backup utility systems, medical equipment and contents, and emergency preparedness. The expected damage resulting from these vulnerabilities will reduce the hospital's capacity to provide life-saving medical care following a major earthquake. The team also identified a potential rockfall hazard that requires further investigation. This report discusses the consequences of the anticipated earthquake damage, and most importantly, presents recommendations to improve post-earthquake medical response and care delivery during the early recovery period. The report presents damage and consequences by introducing three different scenarios. Each scenario is based on a hypothetical earthquake and is intended to illustrate the range of earthquake shaking that the hospital should consider for mitigation and emergency planning purposes. The three hypothetical earthquakes are: (1) a magnitude 7 (M7) earthquake occurring deep beneath Trashigang that creates widespread moderate shaking; (2) a shallow M6 earthquake occurring directly beneath Trashigang that causes very strong but localized shaking, and (3) a massive M8.6 earthquake affecting much of the country.

The figures below show the anticipated performance of the hospital's buildings, in terms of functionality, for each of the hypothetical earthquakes. *Functionality* is the combination of building usability – determined by damage to the building, important equipment and contents from shaking or ground failure – and availability of critical utility services supplied by on-site backup systems. The hospital's ability to function also depends on off-site transportation and utility systems, which are beyond the scope of this report but which should be evaluated for emergency planning purposes, as part of a health-system-wide effort to prepare for the next major earthquake. In a real earthquake, the actual state of functionality might be one level higher or lower than shown here, due to uncertainty in the nature of ground shaking and in the team's existing knowledge of site conditions as well as each building's structure, utility systems, architectural elements and contents. A single expected performance level is shown for illustrative purposes.


**Site plan showing likely performance of hospital buildings in deep M7 hypothetical scenario earthquake**




**Site plan showing likely performance of hospital buildings in shallow M6.1 hypothetical scenario earthquake**


**Site plan showing likely performance of hospital buildings in M8.6 hypothetical scenario earthquake**

The consequences of many of Trashigang hospital's numerous vulnerabilities can be mitigated with reasonable measures, allowing the hospital to remain at least minimally functional following strong but not devastating earthquakes. Much of the hospital was recently built, and most of the newer buildings should withstand moderately strong shaking, up to the design level, without life-threatening damage. More extensive investment in seismic upgrades to buildings and infrastructure would be necessary for the hospital to be able to continue delivering essential medical care following very large earthquakes such as the M8.6 scenario earthquake postulated here.

GHI's highest priority recommendations for improving the hospital's ability to deliver medical care following an earthquake are to:

- Strengthen the hospital's backup water and electrical power systems; this will substantially increase the hospital's ability to remain functional after a strong earthquake;
- Write an emergency plan that provides guidance for hospital operations following a damaging earthquake, and train staff to respond effectively following an earthquake;
- Obtain backup communications to enable contact with Ministry of Health officials in Thimphu;
- Store dangerous chemicals properly so they will not fall and spill during minor shaking; this is simple and costs almost nothing, but the safety impact is large;
- Provide fire suppression capability; and
- Replace or retrofit buildings vulnerable to collapse or life-threatening damage.

The report contains a detailed list of specific recommendations that address the vulnerabilities the team identified in the hospital's site, buildings, utility infrastructure, equipment, contents and level of preparedness. GHI recommends that the hospital begin working immediately to improve the facility's performance; some items, such as storing chemicals properly, are very simple and do not require special budget allocations. The hospital should act on these recommendations immediately. Some mitigation and preparedness measures necessary to help keep the hospital functional will take time to implement and will need to be planned and phased over a number of years. The hospital should be able to make substantial improvements in safety in the current Five Year Plan period by implementing as many of the high priority recommendations as possible. With a safer facility and a more prepared staff, the Trashigang District Hospital will be in a much better position to serve Trashigang's residents following a damaging earthquake.

# Contents

# Introduction

Trashigang is the easternmost district in Bhutan, as well as one of the largest and most densely populated. Trashigang District Hospital is the only hospital providing medical care to more than 57,000 people. The hospital is located in the town of Trashigang, about 550 km east of the capital Thimphu. In this report, "Trashigang" refers to the town area, as opposed to the entire district, unless otherwise noted. The roads connecting Trashigang with the rest of Bhutan and with India, which traverse steep terrain susceptible to landslides, will almost certainly be blocked in a number of places after any strong shaking, leaving the hospital to confront the immediate aftermath of a major earthquake without outside assistance. It is therefore vital that the Trashigang District Hospital be prepared for earthquakes and have the ability to function afterward, when it will be needed the most.

To determine measures that would help the hospital remain functional following a significant earthquake, GeoHazards International conducted an initial seismic vulnerability assessment of the facility in August 2013. The goal of the assessment is to provide the hospital, the Ministry of Health, World Health Organization (WHO) Bhutan and the Regional Office for South-East Asia (SEARO) with an overview of the seismic vulnerabilities of the hospital, and to recommend actions to improve its ability to deliver medical care following a major earthquake. This report summarizes the results of GHI's initial seismic vulnerability assessment.

## Assessment Team and Methods

GHI's on-site evaluation team consisted of Mr. William Holmes, Senior Consultant, Rutherford & Chekene Structural and Geotechnical Engineers of San Francisco, California, USA; Mr. Hari Kumar, GHI South Asia Regional Director; Dr. Janise Rodgers, GHI Chief Operating Officer; Mr. Tshering Dupchu, Engineer, Health Infrastructure Development Division, Ministry of Health; and Ms. Karma Doma Tshering, GHI Bhutan National Director. Mr. Kevin Clahan of Lettis Consultants International, Inc. provided a desk review of potential site hazards. The team has more than 90 combined years of experience in earthquake safety. Prior to its submission to SEARO, this report was reviewed by Health Infrastructure Development Division. Any inaccuracies are the responsibility of the report authors.

The evaluation team visited the hospital site; reviewed satellite imagery, photographs, technical reports, structural drawings and architectural drawings; and interviewed the Medical Superintendent and other key staff members. Team members conducted walk-through assessments of major medical service delivery areas inside the main hospital building, and of services and support functions throughout the site. The team viewed all buildings on the site from the exterior, and went inside many. The team obtained estimates of potential shaking in plausible earthquakes from the United States Geological Survey. Estimates of damage to equipment were obtained using engineering judgment and idealized relationships called *fragility functions* between the level of earthquake shaking and the level of damage; these fragility functions were developed for the United States Federal Emergency Management Agency Report FEMA-58 *Seismic Performance Assessment of Buildings*. The team did not conduct non-destructive testing, remove architectural finishes, conduct destructive evaluations, perform calculations, or carry out on-site assessments of potential site hazards.

## Scope

This report includes an initial seismic assessment of the hospital's medical buildings, support buildings, on-site utility infrastructure, and staff quarters. Some smaller buildings on the hospital campus, such as storage sheds, are excluded from the scope of this report. Evaluations of the site's many retaining walls are outside the scope of this initial assessment. The team identified a potentially significant rockfall hazard to some buildings originating from cliffs uphill from the hospital, but assessing the risk to the hospital requires a more detailed investigation that is outside the scope of this initial assessment.

The scope of the assessment did not include any evaluation of potential earthquake vulnerabilities of the off-site electrical power, water, land-line telephone, mobile telephone, wastewater and solid waste disposal utilities that serve the hospital, nor of the time required to restore service following an earthquake. Similarly, evaluation of transportation systems and access routes to the hospital was beyond the scope of this report.

# Hospital Facility Description

The original 40-bed Trashigang District Hospital was established in 1975. A new 40-bed main hospital building, as well as associated supporting buildings, utility infrastructure and staff quarters, were constructed between 2002 and 2004 with funding and technical assistance from DANIDA, Denmark's development agency. Several of the hospital's original buildings remain, though some buildings were demolished when the new hospital was built.

In addition to inpatient services, the main hospital building has a large outpatient department (OPD) that occupies the entire ground floor. The OPD serves an average of 50 patients per day, with a maximum of 100 patients per day. The hospital averages 90 patients per day in winter and 150 per day in summer. The hospital's services include radiology, laboratory, obstetrics, dental, reproductive health, pharmacy, traditional medicine and immunizations. The hospital has an Operation Theatre, but at the time of the assessment no surgeries were being performed because the hospital did not have an anesthesiologist.

## Buildings

The main hospital is a ground-plus-one-storey building with a partial second storey, built from reinforced concrete frames with brick masonry infill walls and partitions. The hospital was designed by the precursor agency to Bhutan's Health Infrastructure Development Division (HIDD) in 2000-2001 and was constructed in 2002-2004. A number of smaller supporting buildings were also designed and built along with the main hospital building, including a medical store and administration building, physiotherapy building, kitchen, bath house, prayer hall, and some staff quarters. These buildings are predominantly reinforced concrete frame with brick infill walls, though several smaller buildings are unreinforced masonry. The medical store and administration building contains the offices of the District Health Officer, in addition to administrative staff offices.

The old main hospital building is a ground-plus-one-storey concrete frame building built in 1975 by the Government of India (GoI). The building is still in use; the ground floor of the building has been converted to a tuberculosis patients' ward, and the upper floor is occupied by families of support staff working in the hospital. Several other buildings from the original main hospital remain and are being used as staff quarters.

The site plan in Figure 1 below shows the hospital's buildings, color coded by use. Hatching indicates buildings constructed prior to the new hospital complex. Buildings with any medical function, such as the TB ward in the old hospital building that also has staff quarters, are considered medical buildings.


**Figure 1. Site plan with buildings color-coded by use; older buildings constructed prior to the new hospital cross-hatched**

## Infrastructure and Utility Services

The hospital's electric power supply comes from the local grid. The hospital has one 160 kilowatt generator. The diesel generator is housed in a brick masonry generator house amidst the staff quarters. Diesel fuel for the generators is brought in drums by truck and stored in a tank located adjacent to the generator.

Water supply from the city feeds into a 77,000 liter reinforced concrete tank located on a hill above the hospital, in the Trashigang Middle Secondary School premises. The tank appears to supply both the hospital and the staff quarters with domestic water. The hospital has no fire suppression system. There are no boilers or electric hot water generator system in the hospital. However, hot water geysers (hot water heaters) have been installed in the wards, operation theatres and the medical examination rooms. The hospital relies on the city sewer system for waste water disposal and treatment. Medical waste is autoclaved before being sent to the municipal disposal.

Medical gas is supplied via cylinders that are brought in by a supply company truck from Ministry Health's Medical Supply Depot (MSD) in Phuentsholing. About 100-200 cylinders are brought in on a half yearly basis or as required. The hospital does not have a bulk oxygen tank. Most of the hospital's medical supplies are kept in the medical store, and supplies are procured from the MSD in Phuentsholing on a half yearly basis or as required during emergencies.

## Location, Site Conditions and Potential Site Hazards

### Location and Site Conditions

The hospital is located on a northwest-facing slope above and across a stream from Trashigang Dzong, on the same side of the main Dangme Chhu valley, as Figure 2 shows. The terrain near the hospital is quite steep. Figure 3 shows the hospital's general location in map view. Figure 4 shows the location of the hospital's buildings and infrastructure on the site, with respect to access roads and topographic features.


**Figure 2. Topography near the hospital, looking southeast down the Dangme Chhu valley; hospital is in center of image.**

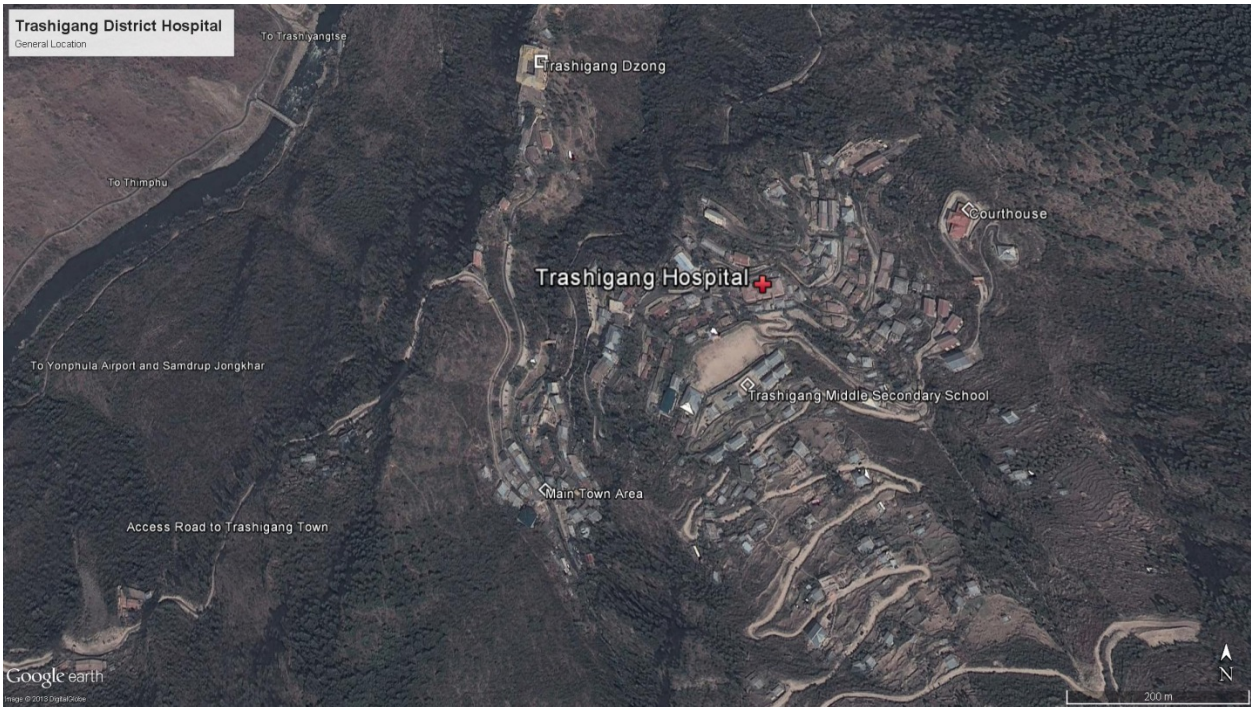



**Figure 3. Hospital location in Trashigang area; upslope is toward the bottom of the image**


**Figure 4. Hospital buildings, local access roads, and on-site utility infrastructure locations; note Middle Secondary School has a large field at lower left that can be used by helicopters during an emergency.**

Geotechnical reports were not available for the hospital site itself, though general information is available in geologic and geotechnical investigation reports for nearby Trashigang Dzong[1], as well as a recently published landslide hazard study of Trashigang town[2]. Because the site slopes significantly, retaining walls exist behind the old hospital building, access road, main hospital building, and service and support buildings just uphill from the main building, plus other locations. An evaluation of the seismic stability of the retaining walls at the site, some of which are shown in Figure 5, requires calculations and is outside the scope of the report. The walls at the front and rear of the hospital must be evaluated, because instability in these walls could threaten the hospital's ability to function.

**Figure 5. Stone masonry retaining wall behind supporting buildings located upslope from the main hospital (left); reinforced concrete retaining wall behind the main hospital building (right)**

Most retaining walls are stone masonry gravity walls, though a large reinforced concrete wall holds up the slope behind the main hospital building. At the time both the original and new hospital buildings were built, common retaining wall design practice considered gravity loads only (albeit for saturated soil conditions), and not seismic loads. As a result, the hospital's retaining walls could be vulnerable to earthquake damage. The large reinforced concrete retaining wall behind the hospital has rotated toward the hospital slightly and is likely to rotate further during earthquake shaking (Figure 5).

Based on discussions with HIDD engineers, the evaluation team understands that no portion of the hospital was built on fill. If portions of any building have been built on fill, then those fills could be susceptible to differential settlement during an earthquake, possibly causing additional damage to that which is described in this report. The evaluation team did not investigate the adequacy of drainage and stormwater management at the site, but these should be assessed. The team recommends that any detailed evaluation include a thorough investigation of the site's geotechnical conditions, drainage conditions, and the seismic stability of major retaining walls.

[1] Van Noord. H. (2013). *Geological and Geotechnical Assessment of Trashigang Dzong*, Report to Department of Culture, bhutan+partners, Netherlands.
Dorji, Y. and Thapa, T.P. (2011). *Report on Preliminary Geological Studies of Trashigang Dzong*, Department of Geology and Mines, Ministry of Economic Affairs, Royal Government of Bhutan.
[2] APECS Consultancy (2013). *Report on the Geotechnical Study for Trashigang Town*, submitted to Ministry of Works and Human Settlements, June 2013.

## Potential Site Hazards

In most mountainous regions of the world, landslides represent a major threat to human life, property and constructed facilities, infrastructure and the natural environment. Landslide hazard is most evident in the slopes above Trashigang Town, where steep slopes, jointed bedrock, and surficial colluvium dominate the topography. The 2009 Mongar earthquake, discussed in more detail in the Earthquake Hazard section reportedly caused rockfalls in the courthouse area of Trashigang. The courthouse is located above the hospital's support staff quarters. There is unmistakable evidence for rockfall deposits in the hospital study area in the form of large, displaced boulders up to approximately 3m diameter (Figure 6). Offsite utilities are out of scope for this study, but in 2012 a landslide near the city water source (some kilometers away) reportedly caused by heavy rain damaged the city water line which also supplies the hospital.

**Figure 6. Hospital staff quarters with courthouse in background (above), steep slope and cliff above the courthouse (below left), large boulder next to staff quarters below court house (below right)**

The landslide hazard for Trashigang is qualitatively described in a recently published geotechnical study of Trashigang town[3]. The Trashigang District Hospital is not specifically addressed in that geotechnical study, however, the report provides some important information for the preliminary evaluation of landslide hazards in the hospital study area. The primary landslide hazard considerations presented in the report include the presence of crystalline bedrock with three primary discontinuity orientations unfavorably dipping subparallel to the north-facing slopes of Trashigang town. This bedrock condition is principally susceptible to rockfalls and rock slides. Numerous rockfall scars are visible in the steep slopes above the hospital.

The geotechnical study of Trashigang town[4] identified areas of relative hazard based on topography, existing and incipient landslide features, water seepages, marshy land, and flooding. As shown on the Hazard Map from this geotechnical study, the Trashigang Hospital buildings are primarily located in an area of low relative hazard (Figure 7). This hazard classification does not consider rockfall runout or deposition (i.e., the distance that falling boulders travel down the slope and where they finally come to rest). The hazard related to boulder impacts with hospital structures from rockfall runout is perhaps equally as high as the hazard in the rockfall initiation areas. Additional studies to determine the rockfall hazard to the hospital, including a rockfall runout assessment using specific specialized software, are recommended.

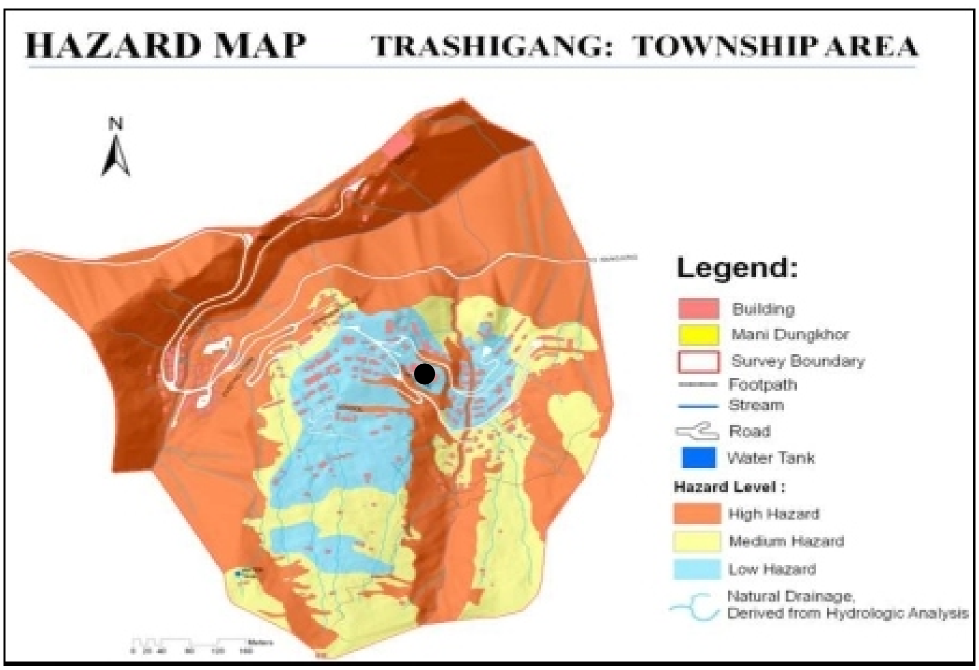



**Figure 7. Hazard Map of Trashigang town. Hospital location indicated by black circle. Credit: APECS Consultancy (2013)**

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[3] *Ibid*.
[4] *Ibid*.

## Earthquake Hazard

Bhutan is located in the Himalayas, where damaging earthquakes occur frequently. While the earthquake hazard has not been well-studied locally, and the historical record is thin, recent studies indicate that Bhutan faces a very high level of earthquake hazard. The main fault that delineates the boundary between the Indian and Eurasian plates approximately parallels Bhutan's southern border. This fault is a thrust fault that dips under Bhutan at a shallow angle, meaning that the fault plane extends underneath the entire country. Bhutan lies in the seismic gap between the 1934 Bihar-Nepal earthquake and the 1950 Assam earthquake. Paleoseismic studies (in which geologists dig trenches across active faults and determine when major fault movements occurred using radio-carbon dating) indicate that a very large earthquake may have last occurred on this section of the plate boundary in approximately 1100 AD[5]. Additional recent evidence suggests a smaller but damaging event occurred in the last several hundred years, possibly in 1713[6]. Scientists estimate that very large earthquake circa 1100 had a magnitude of 8 or greater. If a similarly sized earthquake were to occur today, severe damage would be expected throughout Bhutan. Bhutan recently experienced damage from two much smaller earthquakes: the 2009 M6.1 earthquake centered in Mongar district further south in the Dangme Chhu valley from Trashigang, and the 2011 M6.9 Sikkim-Nepal border earthquake.

While numerous earthquakes of different magnitudes in varied locations could affect Trashigang, the evaluation team selected three hypothetical earthquakes as examples to illustrate the range of shaking, damage and resulting consequences that the hospital is likely to experience in a damaging earthquake:

1. A magnitude 7 (M7) earthquake occurring 35 km deep below Trashigang; and
2. A shallow earthquake of magnitude 6.1 (M6), which is roughly the size of the 2009 Mongar earthquake, but occurring directly beneath Trashigang;
3. A massive earthquake of M8.6 occurring on the plate boundary.

These three earthquakes are ***not*** the same three earthquakes considered in the prior evaluation of the Jigme Dorji Wangchuck National Referral Hospital. In the current assessment, only the hypothetical M6 and M8 earthquakes were assumed to occur on the main plate boundary thrust fault that underlies Bhutan. The M7 event is assumed to occur on a strike-slip fault centered 35 km deep beneath the main plate boundary fault; a number of earthquakes have occurred on similar faults,[7] creating widespread but lower levels of shaking. *The M6 earthquake is much shallower and thus creates stronger shaking at the hospital site than the larger M7 earthquake does*.

These hypothetical earthquakes may not be the three most likely events, nor are they necessarily the three most potentially damaging events. However, although varying in magnitude, they are all located

[5] Kumar, S. Wesnousky, S.G., Jayangondaperumal, R., Nakata, T., Kumahara, Y. and V. Singh (2010). Evidence for surface rupture along the northeastern Himalayan front, India: Timing, size, and spatial extent of great earthquakes. *Journal of Geophysical Research*, 115 (B12422), 1-20.

[6] Ritz, J.-F., Berthet, T., Ferry, M., Pelgay, P., Cattin, R., Drukpa, D., Braucher R., Chophel, J., Thinley, K. and G. Hetényi. Slip rate, magnitudes and ages of surface-rupturing events along the Main Frontal Thrust in Bhutan (Himalaya). *Proceedings, American Geophysical Union Fall Meeting 2013*.

[7] Drukpa, D., A. A. Velasco, and D. I. Doser (2006), Seismicity in the Kingdom of Bhutan (1937–2003): Evidence for crustal transcurrent deformation, *Journal of Geophysical Research*, 111 (B06301).

close to the hospital site, which will produce more intense shaking than similarly-sized events located farther away. The USGS, with collaboration from University of Indiana and DGM, provided preliminary estimates of the median levels of ground shaking that these three hypothetical earthquakes might cause. USGS used its ShakeMap software, with University of Indiana providing input parameters describing the hypothetical fault ruptures, and DGM providing input on the plausibility of the scenario earthquakes.

Please note that the USGS estimates of potential shaking contain large uncertainties, because the scientific community's understanding of Bhutan's earthquake hazard is still emerging. Most of Bhutan's active faults have not been mapped; the first network of local seismometers is being built; scientific relationships called *ground motion prediction equations* that describe how ground shaking may vary with Bhutan's geologic conditions have not been formulated. Ground motion prediction equations developed by Chiou and Youngs (2008)[8] were used to generate the shaking estimates in this report. These estimates of potential shaking are for purposes of illustration only and should not be used for engineering design. The estimates consider only approximate, generalized site conditions; local site effects could further affect the amplitude and nature of ground shaking, and should always be included when developing site-specific estimates of shaking for engineering design. The estimates in this report may be used for emergency planning purposes, with appropriate precautions to account for the uncertainties involved.

A subsequent section of the report, entitled "Hospital Impact Scenarios for Three Hypothetical Earthquakes," provides more details on the hypothetical scenario earthquakes and the hospital facility's postulated response to them.

## Observed Earthquake Vulnerabilities

Buildings that collapse cause the majority of deaths in earthquakes. As a result, vulnerability assessments must determine whether or not buildings are vulnerable to major structural damage or collapse. For hospitals, the ability to remain functional is also critically important, both to preserve the lives of patients and to save the lives of those injured in the earthquake. Vulnerabilities in the hospital's utility systems (especially electrical power, water and medical gas), architectural shell, equipment and contents all affect the hospital's ability to function. The team assessed the hospital facility for all of these vulnerabilities.

The assessment team used engineering judgment and observations of damage to reinforced concrete and masonry buildings in previous earthquakes to estimate the potential levels of damage to the hospital's buildings during the three scenario earthquakes described in the Earthquake Hazard section above. The team classified damage to the building's structure and architectural shell (the exterior walls, roof covering and interior partitions), and to the building's equipment and contents into the damage states listed in Table 1. Please note that building usability does not equal functionality: the hospital will

[8] Chiou, B.S.J. and Youngs, R.R. (2008). An NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra. *Earthquake Spectra* (24) 173-215.

be functional only if critical utility services, such as electrical power, are available. Without utilities, the building could only be used to deliver a very basic level of "austere" care. Because of the importance of utilities, the team has estimated whether or not each of the hospital's major utility systems will be available following the three hypothetical scenario earthquakes.

**Table 1. Damage state classifications**

| **Structure and Architectural Shell**[1] | | |
|---|---|---|
| **Damage State** | **Life Safety Risk** | **Building Usability**[2] |
| S1 Slight | Very slight | Useable based on structural performance |
| S2 Moderate | Isolated falling hazards | Useable with cleanup required, possibly some areas cordoned off. A few partitions may be cracked and/or have fallen pieces |
| S3 Heavy | Significant falling hazards | Widespread masonry falls from partitions and/or bearing walls disrupt function |
| S4 Severe/Collapse | Severe from falling hazards or partial/complete collapse | Usable spaces not maintained, or building is unsafe |
| **Equipment, Pipes and Contents**[3] | | |
| **Damage State** | | **Building Usability**[2] |
| N1 Light | | Useable |
| N2 Moderate disruption | | Generally useable; some areas may be cordoned off, and some medical functionality may be lost |
| N3 Severe disruption | | So disrupted it will be hard to use, without a lot of cleanup and repair |

1 Includes the building's walls, frame (if a reinforced concrete building), masonry partitions, floors, roof, and roof covering.
2 Building usability does not equal functionality. The hospital will be functional only if critical utility services, such as electrical power, are available.
3 Only assessed in main hospital building, generator house, and medical store/administration building

Each damage state for the structure and architectural shell has corresponding implications for both life safety and building usability. Likewise, each damage state for the equipment, pipes, and contents inside the building has implications for building usability. In some cases (i.e. tall and heavy shelving located behind or above staff work areas), each damage state for contents may also have implications for life safety, but these must be evaluated on a case-by-case basis.

## Vulnerability of Buildings to Structural Damage

The hospital's buildings are predominantly of two construction types: reinforced concrete frame with unreinforced masonry infill walls, and masonry bearing wall. Both types of buildings tend to suffer major, life threatening damage in strong earthquakes, unless an engineer has designed them following a modern, earthquake-resistant building code that specifically covers these building types. Based on a review of structural drawings and on discussions with Health Infrastructure Development Division engineers, only the newer, DANIDA-funded reinforced concrete frame buildings were designed using modern earthquake-resistant building codes developed in India, though the codes used were at least one version older than the current version. In addition, the ground motion associated with the M8.6 event is more intense than that provided for in the building code used for design. As a result, the hospital's older buildings can be expected to experience significant damage in moderate to strong earthquakes, and even the newer buildings are expected to be severely damaged in the largest event.

Using the three hypothetical scenario earthquakes as illustrative examples of moderate, strong and violent shaking, this report presents the likely performance for each building in tables in the sub-sections below. The team used engineering judgment, based on experience with buildings of these construction types in other earthquakes, to determine the estimated levels of damage. In addition to the buildings discussed in this section, the hospital has a few smaller unoccupied buildings. These were not considered within the scope of this assessment.

In a few cases, it was difficult to determine the type of masonry used in masonry bearing wall buildings. For the types of buildings at the hospital site, uncertainties regarding the type of masonry do not have a large effect on the building's potential damage level. Unreinforced masonry buildings built without *seismic bands* (horizontal reinforced concrete members embedded in the walls to tie them together) and similar earthquake-resistant features are inherently susceptible to damage in strong earthquakes, whether the masonry is stone, brick or concrete block. Prior to discussing specific buildings in the sub-sections below, several general observations are warranted about the codes and standards used for the structural design of the hospital's buildings.

### Building Codes Used for Design

Bhutan adopted its own seismic design provisions, which incorporate the Indian Standard provisions by reference, in 1996. Prior to this, engineers often used the Indian Standards directly. Engineers from India assisted with or designed a number of health facilities constructed with Government of India funding, and these engineers would have used Indian Standards in effect at the time. The current version of India's earthquake-resistant design code, IS 1893 *Criteria for Earthquake Resistant Design of Structures*, was released in 2002 and includes modifications made after the 2001 Gujarat earthquake. All of the hospital's buildings were designed prior to the 2002 code revision, even if they were built more recently. India also has a standard for ductile detailing in reinforced concrete buildings, IS 13920 *Ductile Detailing of Reinforced Concrete Structures Subjected to Seismic Forces – Code of Practice*, which was released in 1993 and has been reaffirmed (rather than revised) in following years.

Consequently, the team assumed that reinforced concrete buildings designed prior to 1993 do not have the ductile details necessary for earthquake resistance. A very small number of structural drawings were available for the new hospital buildings, for the ramp, and for a few supporting buildings. Architectural drawings were available for most of the newer buildings. No drawings of any kind were available for the original hospital buildings. Reinforced concrete buildings designed prior to 1976, when minimal ductile detailing requirements first appeared in the Indian Standards (in IS 4326:1976, *Code of Practice for Earthquake Resistant Design and Construction of Buildings*), will not have earthquake-resistant detailing. This is the case with the old hospital buildings.

India also has a standard intended to improve the earthquake resistance of masonry bearing wall buildings, IS 4326 *Earthquake Resistant Design and Construction of Buildings —Code of Practice*. This standard was released in 1993 and most recently updated in 2002. The standard mandates that masonry buildings in high seismic hazard zones have vertical bars in the corners and reinforced concrete bands to promote "box" action (where the building's walls act together, like a box, to resist earthquake forces) and to help the walls span horizontally between cross walls. Removing building finishes, which is required to determine definitively whether or not plastered masonry buildings have IS 4326-prescribed earthquake-resistant features, was outside the scope of this assessment. Based on their age, the team assumed that the 1970s masonry buildings at the site did not incorporate the IS 4326-prescribed seismic bands and vertical bars. Of the newer unreinforced masonry buildings, structural drawings were available for only the kitchen building, but architectural plans and sections were available for the other support buildings constructed at the same time. These drawings indicate that the kitchen building and other smaller masonry have a seismic band at the roof line.

## Main Hospital Building and Other Medical Buildings

The hospital provides medical care primarily in the new Main Hospital building, with some services also in the Old Hospital building and the Physiotherapy building. Table 2, at the end of this section, summarizes the likely performance of the hospital buildings at the levels of shaking anticipated in the three hypothetical scenario earthquakes.

### *Main Hospital Building*

The main hospital building, shown in Figure 8 and Figure 9, was built in 2001-2004 with funding from DANIDA. The building was designed by the precursor agency to HIDD, with technical assistance from a DANIDA-supplied engineer. According to HIDD, the Indian standard codes used for design were IS 456 (for general concrete design), IS 13920 (for ductile seismic design of reinforced concrete), IS 1893 (for earthquake loads) and IS 875 (for wind loads).

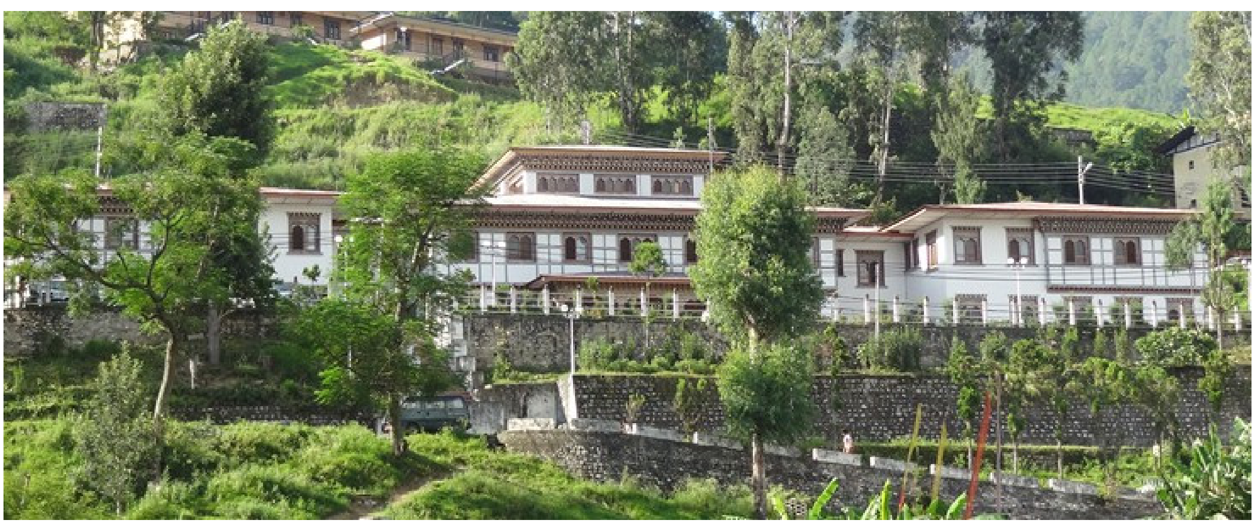


**Figure 8. Front exterior view of Main Hospital building**


**Figure 9. Rear view of Main Hospital building**

Figure 10 shows floor plans for the building. The building is ground-plus-one-storey for most of the plan area, with a small second storey containing a conference room in the central part of the building. The wings at east and west ends are separated from the central portion of the building by what appear to be code compliant seismic joints of 50 mm (25 mm per floor). The building's structural system is reinforced concrete moment-resisting frame with brick masonry infill walls, in which rigid joints between beams and columns resist lateral forces from earthquake and wind. Exterior and interior corridor brick infill walls are double wythe (250 mm), interior brick partitions are single wythe (125 mm). The building is presumed to have a steel tubular truss roof, which is covered with corrugated metal (CGI) sheets.  The ceilings are plywood supported on steel and wood joists.

Structural drawings are not available, but information from HIDD indicates that the building should have ductile details per IS 13920 (*Ductile Detailing of Reinforced Concrete Structures Subjected to Seismic Forces – Code of Practice*). HIDD also indicates that an HIDD engineer would have been present at the site during construction to ensure that the drawings were followed.

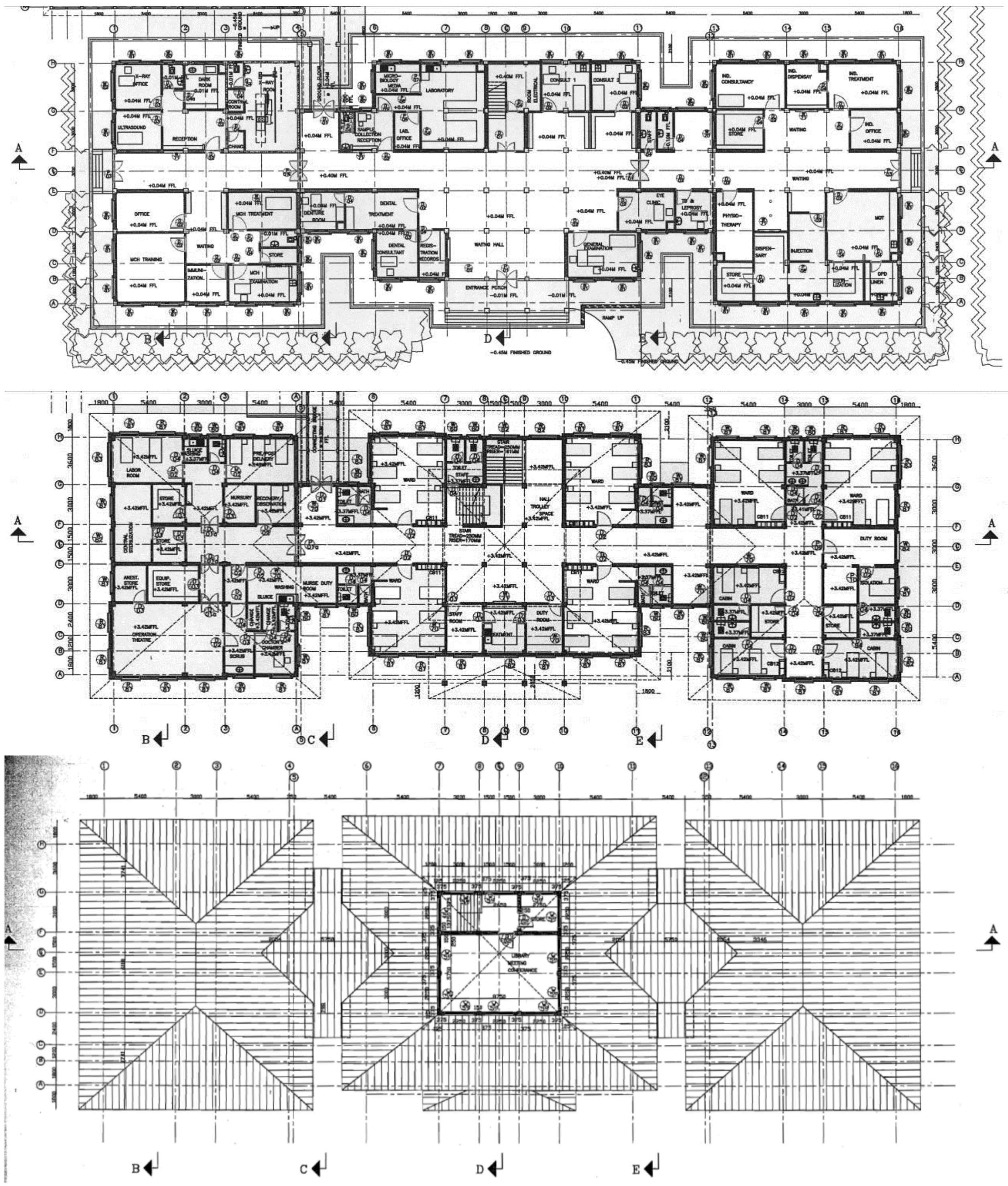


**Figure 10. Ground (top), first (middle) and second (bottom) floor plans of Main Hospital building; note that second floor has very small plan area used as a conference room.**

The building, as a whole, does not have significant vertical irregularities and appears unlikely to collapse or partially collapse in strong shaking. Damage may be greater in the second floor conference room due to dynamic amplification, with partial collapse of this upper structure possible in the very strong shaking anticipated for the M8.6 plate boundary earthquake. The building's brick infill walls and partitions will tend to crack, when any floor in the building moves horizontally more than 1% of the floor-to-floor height, and single-wythe partitions are likely to fail during strong shaking. Falling partitions could cause serious injuries to immobile patients, who are not able to take protective actions during shaking.

The building has some architectural brick projections in the first storey, in which the brick walls are located outside of the column lines on the exterior of the building. Such walls are much more vulnerable to falling outward during shaking than walls confined by the building's frame. Some of these walls are located above the main entrance canopy of the ground floor Outpatient Department (OPD), and could damage the canopy or fall through it and impede the exit. Falling bricks from these walls create a hazard for anyone outside the building near the walls or those trying to exit the OPD during shaking. Though these failures would not affect the frame's ability to carry gravity loads, fallen brick exterior walls and brick partitions may give the impression to building users, many of whom are accustomed to masonry buildings without a frame, that the building is structurally unsafe. Determining the level of earthquake shaking at which infill wall cracking, architectural brick projection failure and partition failure would occur requires a detailed computer analysis, which is beyond the assessment's scope, but is recommended if the Ministry of Health determines that the hospital should be operational following strong to very strong shaking.

### *Other Medical Buildings*

Two other buildings are currently used to provide medical services. These are the Old Hospital building and the Physiotherapy building.

The Old Hospital building, shown in Figure 11, is the original hospital built with Government of India funding in 1975. The ground floor is now used as a tuberculosis ward, while the first floor is being used currently to house hospital support staff and their families. The building is a ground-plus-one-storey reinforced concrete frame building. No structural drawings are available. Based on its age, which predates India's IS 13920, India's ductile reinforced concrete seismic design code, the building is almost certainly a nonductile frame. The building has several additional vulnerabilities. There does not appear to be a beam at the top of the first storey columns in the longitudinal (long dimension) direction, meaning that the frame is incomplete. In the transverse (short dimension) direction, short, thin columns at the top of the first storey at the north end of the building are vulnerable to shear failure. The multiple seismic vulnerabilities of this building put it at risk of collapse during strong shaking.

**Figure 11. Front view (left) and side view (right) of the Old Hospital building**

The Physiotherapy building, shown in Figure 12, was built at the same time as the new hospital building but with funding from Her Royal Highness Ashi Kezang Wangmo Wangchuck. The building is a ground-plus-two-storey building, with the physiotherapy department on the top floor. The assessment team understands that the two lower floors are used for storage. There are no drawings available for the building, but according to HIDD it is a reinforced concrete frame with brick masonry infill walls.

**Figure 12. Front view (left) and side view (right) of the Physiotherapy Building**

**Table 2. Likely Performance of Medical Buildings in Hypothetical Scenario Earthquakes**

| Building Name | Construction Type | Year Built | No. of Storeys (incl. ground) | Likely Performance in Hypothetical Scenario Earthquake[1] (Structure and shell: left columns; equipment, pipes contents: right columns) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Deep M7 | | Shallow M6.1 | | M8.6 | |
| | | | | Light Shaking | | Strong Shaking | | Violent Shaking | |
| | | | | PGA 0.11g | | PGA 0.58g | | PGA 1.18g | |
| | | | | Struct | Equip | Struct | Equip | Struct | Equip |
| | | | | | | | | | |
| Main Hospital building | RC w/brick infill | 2001-4 | 2* | S1 | N1 | S2 | N2 | S3** | N3 |
| Old Hospital building (TB Ward) | Nonductile RC w/infill | 1975 | 2 | S1 | | S3-S4 | | S4 | |
| Physiotherapy building | RC w/brick infill*** | 2004 | 3 | S1 | | S2 | | S3 | |

RC = Reinforced concrete; PGA = peak ground acceleration

1 Damage states (*i.e.*, S1 and N1), are defined in Table 1 on page 18; Equipment, pipes contents only evaluated in main building

* Has partial second floor in *jamthog* that contains conference room.

** Second storey conference room rated S4 due to anticipated dynamic amplification; remainder of building is S3.

*** Assumed RC frame w/infill per HIDD; performance categories will reduce by one category if building is masonry.

## Support Buildings

The hospital has a number of support buildings that house administrative and service functions.

### *Administrative / Medical Store Building*

The Administrative/Medical Store building is a ground-plus-one-storey building, built in 2002-2004 as part of the new hospital. Shown in Figure 13, the building has a reinforced concrete frame structure with brick masonry infill walls. The offices of the District Health Officer and the administrative staff are on the first floor, and the Medical Store (where supplies and medical gas are kept) is on the ground floor. The building does not have an internal stair. An entry bridge from the parking lot above, shown at the left side of Figure 13, provides the only access to the first storey administrative offices. This entry bridge appears to be rigidly fixed to both sides, meaning that it will attract significant earthquake forces as the building tries to sway back and forth. It was probably not designed for these forces and will likely fail as a result, presenting a problem for those trying to exit (or re-enter) the first floor administrative offices.


**Figure 13. Side view showing entry bridge (left) and front view (right) of the Administration/Medical Store building**

### *Prayer Hall, Laundry, Incinerator, Kitchen and Bath*

These smaller support buildings are all small plan brick masonry buildings. Several have significant vulnerabilities. The Prayer Hall has one solid wall and three walls with numerous openings that create narrow piers. Though there is a seismic band at the roof, there is no reinforcing in the narrow piers where damage is likely to occur. The Prayer Hall is likely to be badly damaged in a strong earthquake. The Laundry building has short piers on one side, making it vulnerable to earthquake damage, as Figure 14 shows. The Incinerator building does not appear to have a seismic band; this constructed building is significantly different than the Incinerator building shown on the drawings. The team considered these three buildings to be more seismically vulnerable than the other buildings of the same construction type at the site. The Kitchen and Bath buildings, shown in Figure 15, should have a seismic band according to the drawings.

**Figure 14. Prayer Hall (left), Laundry (center) and Incinerator (right)**


**Figure 15. Back side of the Kitchen and Bath buildings (uphill side)**

### *Generator House*

The Generator House is a single storey brick masonry building that houses the hospital's backup generator and associated equipment. Built as part of the new hospital in 2002-2004, the Generator House has a seismic band at the roof, according to the design drawings. Figure 16 shows a front view of the Generator House.


**Figure 16. Generator House**

Table 3 shows the likely performance of the hospital's support buildings in the hypothetical scenario earthquakes considered in this assessment.

**Table 3. Likely Performance of Support Buildings in Hypothetical Scenario Earthquakes**

| **Building Name** | **Construction Type** | **Year Built** | **No. of Storeys (incl. ground)** | **Likely Performance in Hypothetical Scenario Earthquake**[1] (Structure and shell: left columns; equipment, pipes contents: right columns) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Deep M7 | | Shallow M6.1 | | M8.6 | |
| | | | | Light Shaking | | Strong Shaking | | Violent Shaking | |
| | | | | PGA 0.11g | | PGA 0.58g | | PGA 1.18g | |
| | | | | Struct | Equip | Struct | Equip | Struct | Equip |
| | | | | | | | | | |
| Administration/Medical Store Building | RC w/ brick infill | 2002-4 | 2* | S1 | N2 | S2 | N3 | S3-S4 | N3 |
| Prayer Hall | Unreinforced brick masonry | 2002-4 | 1 | S2 | | S4 | | S4 | |
| Laundry | Brick masonry w/seismic band | 2002-4 | 1 | S2 | | S3 | | S4 | |
| Kitchen/Bath | Brick masonry w/seismic band | 2002-4 | 1 | S1 | | S2 | | S4 | |
| Incinerator | Brick masonry w/seismic band | 2002-4 | 1 | S2 | | S3 | | S4 | |
| Generator House | Brick masonry w/seismic band | 2002-4 | 1 | S1 | N1 | S2 | N2-N3 | S3 | N3 |

RC = Reinforced concrete, PGA = peak ground acceleration

1 Damage states, such as S1 and N1, are defined in Table 1 on page 18

* Has partial second floor in *jamthog* that contains conference room

## Staff Quarters

Trashigang District Hospital has numerous staff quarters of various designs and ages. The hospital needs to provide living accommodations for the entire staff and their families, so many quarters are needed. As a result, some of the families occupy old buildings that were not constructed as living quarters.

### *Staff Quarters - Bungalows*

The hospital has two bungalow type quarters for doctors and senior staff. The District Health Officer (DHO) lives in one of the staff bungalows, shown in Figure 17. The second bungalow, of a different design, is shown in Figure 18. Both of these buildings were built around the time of the original hospital complex or in the 1980s. They are unreinforced masonry, presumably without seismic bands, and as a result are highly vulnerable to earthquake damage and may collapse in strong shaking. These buildings are more vulnerable than the newly built brick masonry buildings with seismic bands. In addition, the bungalow in Figure 18 has an unreinforced masonry gable—a triangular shaped extension of the wall up to the roofline of a peaked roof. (The other bungalow does not have this feature.) Past earthquakes have shown that unreinforced masonry gables are vulnerable to damage, and parts of them can easily fall outward during shaking.

**Figure 17. District Health Officer's quarters, front view (left) and side view (right)**

**Figure 18. Bungalow type staff quarters showing masonry gable (left); view from uphill (right)**

### *Staff Quarters – Duplexes*

Duplex type staff quarters are for doctors and senior staff, and there are two duplex type staff quarters buildings at the hospital. These buildings, shown in Figure 19, are ground-plus-one-storey reinforced concrete frames with brick masonry infill, constructed in 2002-2004 along with the new hospital complex. The architectural drawings identify these buildings as "Type 130" staff quarters.

**Figure 19. Front view (left) and back view (right) of duplex staff quarters**

### *Staff Quarters – Newer Fourplexes*

There are two newer fourplex staff quarters buildings in the Trashigang hospital complex, shown in Figure 20. These buildings are reinforced concrete frame buildings with brick masonry infill walls, and were built in 2002-2004 along with the rest of the new main hospital. The architectural drawings identify these buildings as "Type 60" staff quarters.

**Figure 20. Front (left) and side (right) views of the fourplex staff quarters**

### *Staff Quarters - Older Fourplex*

The hospital has one older fourplex, which appears to be a similar age as the bungalows described earlier. This ground-plus-one-storey building, shown in Figure 21, appears to be unreinforced stone masonry. Staff quarters of similar age with what appears to be the same design are found at the Jigme Dorji Wangchuck National Referral Hospital in Thimphu. A falling tree damaged one unit, and the building is scheduled for demolition.

**Figure 21. Older fourplex staff quarters (left); damage caused by fallen tree (right)**

### *Support Staff Quarters*

The hospital has two large staff quarters for non-medical staff, which are reinforced concrete frame buildings with brick infill constructed along with the new hospital in 2002-2004. These quarters are above the road that runs behind much of the hospital site. The architectural drawings refer to these as "Type 100" staff quarters. Figure 22 shows the very large boulder sitting next to one building, which indicates that rockfalls may be a significant hazard for these buildings. According to local engineers, boulders fell from the cliffs above the courthouse building in the upper right corner of the photo during the 2009 Mongar earthquake.

**Figure 22. Support staff quarters with large boulder (located alongside building); courthouse is building at upper right**

### *Attendant Guest House*

Though originally built as a patient attendant guest house along with the new main hospital complex, this single storey brick building shown in Figure 23 is now being used as staff quarters. The walls are double wythe (250mm) and it has a seismic band, which will help improve its performance during shaking. However, the back side of the building has numerous windows that greatly reduce the wall area and therefore the building's strength to resist shaking. Per the drawings, the interior walls in the building's long direction are very short and cannot resist much load. The narrow brick piers between the back windows are likely to crack in strong shaking.

**Figure 23. Front view (left) and side and back view (right) of the Attendant Guest House**

### *Old OPD Staff Quarters*

The old hospital's outpatient department building, built in the 1970s, has been converted to staff quarters. This building is primarily ekra (timber frame with panels of plastered ekra reed lattice), with one end that is unreinforced brick masonry as Figure 24 shows. The brick portion is not braced by a roof diaphragm, and the ekra walls do not provide adequate support. This portion is likely to be damaged by strong shaking.


**Figure 24. Back view (left) and front view (right) of the old OPD, now staff quarters, showing brick masonry portion on end**

### *Caretaker's Residence*

The caretaker's residence, shown in Figure 25, is located across the road behind the hospital. It is a small single storey brick masonry building with a seismic band at roof level, built in 2002-2004 along with the rest of the new hospital complex. The building is a small box with some interior cross walls and will likely perform better than other buildings of the same type at the site.

**Figure 25. Caretaker's residence**

Table 4 shows the likely performance of various staff quarters in the three hypothetical scenario earthquakes considered in this report. The likely performance of the Old Hospital building, which currently houses staff on one floor and the TB ward on another, is described in the medical buildings section and noted in Table 2. Similarly, the performance of the Physiotherapy building, which also has accommodations, is discussed in the medical buildings section.

**Table 4. Likely performance of staff quarters in hypothetical scenario earthquakes**

| **Building Name** | **Construction Type** | **Year Built** | **No. of Stories (incl. ground)** | **Likely Performance in Hypothetical Scenario Earthquake** | | |
|---|---|---|---|---|---|---|
| | | | | Deep M7 | Shallow M6.1 | M8.6 |
| | | | | Light Shaking | Strong Shaking | Very Strong Shaking |
| | | | | PGA 0.11g | PGA 0.58g | PGA 1.18g |
| Bungalows | URM* | 1970s | 1 | S2 | S4 | S4 |
| Duplexes | RC w/brick infill | 2002-4 | 2 | S1 | S2 | S3 |
| Newer fourplexes | RC w/brick infill | 2002-4 | 2 | S1 | S2 | S3 |
| Older fourplex | Unreinforced stone masonry* | 1980s | 2 | S2 | S3 | S4 |
| Support staff quarters | RC w/brick infill | 2002-4 | 2 | S1 | S2 | S3 |
| Attendant guesthouse | Brick masonry w/seismic band | 2002-4 | 1 | S1 | S3 | S4 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Old OPD staff quarters | Ekra and unreinforced brick | 1970s | 1 | S2 | S3 | S4 |
| Caretaker's residence | Brick masonry w/seismic band | 2002-4 | 1 | S1 | S2 | S3 |

RC = reinforced concrete; URM = unreinforced masonry; PGA = peak ground acceleration
* Exact construction material type and details are not known; assumed type is the most vulnerable of the likely construction material/structural system types.

## Utility System Vulnerability and Backup Capabilities

Hospitals rely on utility systems such as electrical power, water and medical gases to function. Under normal operating conditions, utilities such as electricity and water are supplied by the local grid or city water system, but hospitals require backup supply capabilities in the event that utility service is interrupted. Other utilities, such as medical gas, must be supplied at the hospital. The hospital has on-site supply systems with significant equipment, as well as distribution systems that provide services throughout the main hospital building. Both on-site supply systems and distribution systems can be vulnerable to earthquake damage, which can interrupt utility services and impede or prevent the hospital from delivering essential medical services.

Damage to utility system components in numerous past earthquakes, along with recognition of the essential role that utility services play in functionality, has led earthquake engineering researchers to develop standard estimates, called *fragility functions*, of the levels of ground shaking at which unanchored equipment and utility system components will begin to experience damage or stop working. The assessment team used engineering judgment and fragility functions from the Performance Assessment Calculation Tool (PACT) software, developed as part of the United States Federal Emergency Management Agency (FEMA) Report, FEMA P-58, *Seismic Performance Assessment of Buildings*, to estimate the potential availability of on-site utilities after the three hypothetical scenario earthquakes. The following sections present utility system vulnerabilities observed by the evaluation team, as well as estimates of performance in the three hypothetical scenario earthquakes.

### Electrical Power System

The hospital's most important utility system is the electrical power system. Without power, the hospital's essential medical equipment, life support equipment, lighting and other safety-critical items will not function. Following a moderate earthquake, it is highly likely that the supply from the electrical grid will be disrupted; grid power will certainly be lost for a significant period of time following a major or severe earthquake. Estimates of the time required to restore grid power following the hypothetical scenario earthquakes were outside the scope of this investigation, but Bhutan Power Corporation should be asked to provide such estimates for planning purposes.

The transformer that receives the grid power supply appears not to be bolted to its concrete base (the team could not confirm, as entry was restricted). The entire system that connects to the grid should be checked for seismic vulnerabilities to ensure that the hospital can access grid power, once it is restored.

**Figure 26. Transformer connecting grid power to the hospital (left); close-up of apparently unanchored base (right)**

During the immediate response period following an earthquake, and even for days or weeks afterward, the hospital will need to rely on backup power supplied by emergency generators. However, at the Trashigang hospital there is only one emergency generator of 160 KVa. The unanchored generator is likely to slide off of its small "pot bearing" vibration isolators in strong earthquake shaking. The batteries that enable the generator to start are not anchored and may break or become disconnected.

**Figure 27. Unanchored emergency generator with inadequately braced exhaust system and unsecured batteries (left); non-seismic vibration isolators (right)**

The generator has a tank that holds 160L and uses 10L of fuel per hour. This means the fuel supply will last for at most 16 hours of operation under normal conditions. If power can be supplied to only the most essential functions after an earthquake (i.e., operation theatre, etc.), then the supply of fuel could last longer, perhaps a day in a best-case scenario. The hospital does not store fuel for the generators but procures what is required on a need basis from the nearest Bhutan Oil Distributor in Kheri, approximately 2km away. Areas of active landsliding were observed on this road, which are described in more detail in the section "Dependence on Offsite Lifelines" on page 47.

The Pan American Health Organization (PAHO) recommends that hospitals have a fuel supply sufficient to last five days (120 hours). Given Trashigang's geographic isolation, the hospital should keep fuel on hand for a much longer period of time than PAHO recommends, basing the amount of stored fuel on realistic estimates provided by Bhutan Power Corporation of the potential length of time required to restore grid power after a major earthquake. Currently, the hospital falls far short of meeting the PAHO recommendations.

The team recommends procuring at least one more emergency generator for Trashigang hospital, because overheating of generators during extended use is a common problem. The team was told that the hospital's generator can run for 24 hours but does overheat and has to be shut down. The maximum time that the generator has been run in the past was four days, with cool down breaks in operation. Having one more generator would allow use of generators on a rotational basis to prevent overheating and loss of power to the hospital. Similarly, the team recommends that the hospital store coolant on site for the generators to avoid this problem. The generator is water-cooled, and the water must be added manually.

The electrical cabinets housing switchgear and controls are unanchored and could topple, because they are tall and narrow. The team recommends that the electrical cabinets be anchored appropriately, which is not difficult to do. However, electrical cabinets and other electrical equipment can be very dangerous – one can be seriously injured or even killed by opening an electrical cabinet unsafely. Only trained electricians should open or work on electrical cabinets or equipment.

**Figure 28. Tall and narrow apparently unanchored electrical cabinets sitting on frame in generator house (left) and under stairs in main hospital building (right)**

The team also observed that the support staff responsible for the operation of the generator and its maintenance was living in the Generator House with his family. The family had cooking gas cylinders, stoves and other household items that could pose a fire hazard to the generator house. While the team understands the shortage of staff housing and the need for the staff to be close by to operate the generator in case of emergencies, the team highly recommends shifting the family out of the generator house for their own safety and for the safety of the generator.

**Figure 29. Inside the Generator House, also used for living quarters**

Table 5 shows the likely performance of the onsite electrical power system in the hypothetical scenario earthquakes considered in this report, as well as rough estimates of the availability of off-site grid power. The vulnerabilities in the electrical power system pose the greatest threat to the hospital's functionality, even in moderate and distant earthquakes.

**Table 5. Likely performance of on-site electrical system in hypothetical scenario earthquakes**

| **System** | **Likely Performance in Hypothetical Scenario Earthquake** | | |
|---|---|---|---|
| | Deep M7<br>Light Shaking<br>PGA = 0.11g | Shallow M6.1<br>Strong Shaking<br>PGA = 0.58g | M8.6<br>Violent Shaking<br>PGA = 1.18g |
| **Electric Power from off-site supply** | May have short interruption of power | Interruptions of power are likely to be longer than 24 hours | Long interruptions of power should be expected |
| **Electric Power from on-site generators** | Generator operational; power available while fuel lasts | Generator and associated equipment may be damaged but still operational; fuel will run out before power is restored | Generators and electrical equipment damaged and not operational. Expect that power will not be available until replacement generator from off site is delivered and damaged equipment is repaired in an estimated 3 weeks or more. |

PGA = peak ground acceleration

## Medical Gas System

The medical gas system relies on cylinders that are taken to locations within the hospital as needed; there is no central manifold. Most cylinders are small 180L cylinders; only the OT has large 680L cylinders. Medical gas cylinders are stored inside the Medical Store, and the empty cylinders are piled outside the store to be sent for re-fill. The store procures medical supplies, including medical gas cylinders, every six months and as and when required directly from the Medical Supply Depot in Phuentsholing. The hospital normally keeps 80 to 90 filled oxygen cylinders and 5-10 filled nitrogen cylinders on hand. At the time of the site visit, the hospital had approximately twice as many filled oxygen cylinders. The hospital uses approximately 12 small cylinders per month. Following an earthquake, the usage rate could be significantly higher due to the larger number of badly injured patients.

There is no anchorage system for the stored cylinders. In case of strong earthquake shaking, the cylinders could roll around on the floor and start leaking. The cylinders are stacked in such a way that they are likely to roll down and block the door, so that the staff cannot access the room to retrieve additional cylinders (or put out a fire if one starts). Leaking oxygen is a fire and explosion hazard. PAHO recommends that hospitals maintain a 15-day supply. If the cylinders remain intact and are stored in a seismically secure manner, the hospital's supply should be adequate for moderate to strong local earthquakes.  The hospital's supply may not be sufficient following a very large earthquake, such as the M8.6 hypothetical scenario event, due to greater usage and the difficulty of resupply. Medical gas must be brought all the way from Phuentsholing over roads highly likely to be blocked by landslides caused by the earthquake.

**Figure 30. Medical gas cylinders stored inside the Medical Store (left), cylinders likely to roll down and block the door (right)**

The team was very pleased to note that laboratory technician Mr. Chokey Dorji had installed simple seismic restraints on the large cylinders in the Operation Theatre to prevent them from toppling during shaking. The restraint is a simple strap with a small loop at the end that fits over a nail into the window frame. With staff creativity, such effective seismic restraints can be made out of what is available, without additional budget. Elsewhere in the hospital, cylinders are either on small trolleys or freestanding in rooms and halls. These tall and narrow freestanding cylinders can easily topple, and they need seismic restraints.

**Figure 31. Mr. Chokey Dorji with seismic restraints he installed on OT medical gas cylinders (left); simple restraint attachment (right)**

Table 6 shows the likely performance of the medical gas systems in the three hypothetical scenario earthquakes.

**Table 6. Likely performance of medical gas systems in hypothetical scenario earthquakes**

| System | Likely Performance in Hypothetical Scenario Earthquake | | |
|---|---|---|---|
| | Deep M7<br>Light Shaking<br>PGA = 0.11g | Shallow M6.1<br>Strong Shaking<br>PGA = 0.58g | M8.6<br>Violent Shaking<br>PGA = 1.18g |
| **Medical Gas** | | | |
| Oxygen and Nitrogen | Supply adequate but cylinders likely to roll down and block door. | Supply likely to be adequate but cylinders likely to roll down and block door | Supply likely inadequate. |

PGA = peak ground acceleration

## Domestic and Drinking Water Systems

Under normal operating conditions, the hospital receives water from the city supply, which will most likely be unavailable for some time after a major earthquake. The hospital will need to function using stored water. The hospital's water storage tank is located approximately 150m uphill from the hospital, on the Trashigang Middle Secondary School premises, as Figure 4 shows. From the tank, the water flows down to the hospital through what the team was told are galvanized iron (GI) pipes with threaded couplings. Water storage down at the hospital itself is minimal, consisting of several plastic tanks holding approximately 1000L each.

The hospital's water storage tank has a capacity of 77,000L (accounting for the location of the overflow outlet). PAHO recommends that hospitals have domestic water storage capacity of 300L per bed per day, for at least three days (72 hours). For 40 beds, the hospital should have 12,000L per day of domestic water storage. Because water system repairs and delivery of water by truck will be hampered by landslide-blocked roads following a strong earthquake, the hospital should store additional water beyond the PAHO-recommended amounts. The amount of additional water to store should be determined based on the estimated time required to restore city water service. For normal usage levels, the tank can theoretically supply water to the hospital for approximately 6 days, which might not be long enough to allow for repairs to the city water system. Following an earthquake, rationing could extend the supply to some extent.

Despite the tank's intended multi-day backup capacity, the supply tank was drained in less than a day during a recent city water outage caused by a landslide near the city water source (some kilometers away from the town). This indicates that either staff quarters are also being fed from the storage tank, or that the system has significant leaks. While both problems can be rectified, the hospital currently does not have adequate backup water storage capacity.

The team recommends that the maintenance staff responsible for the tank immediately determine whether the staff quarters are being supplied by the tank. If so, the hospital maintenance staff and HIDD should begin the process of having a separate city line, which bypasses the storage tank, installed to serve the staff quarters. Smaller local tanks can provide an emergency water supply for the staff quarters. If the staff quarters are not being fed from the hospital's water storage tank, then the maintenance staff should begin investigating where leaks are occurring.

**Figure 32. Main water storage tank on Trashigang Middle Secondary School grounds (left); small local tanks behind main hospital building (right)**

Assessment of the seismic vulnerability of the city water system is beyond the scope of this report, but damage requiring significant repair time has affected a number of water systems in past earthquakes elsewhere. The 2012 landslide near the city water source, which interrupted water service, indicates that portions of the city water system may be vulnerable to damage caused by earthquake induced landslides and resulting service interruptions. The hospital should obtain an estimate of the likely time needed to restore city water service.

Drinking water is provided by filtering domestic water using filter units placed in wards and other areas of the hospital. The supply of drinking water is therefore dependent on the availability of domestic water and prevention of earthquake damage to the filter units. Figure 33 shows the tall and narrow filter units, meaning that during shaking they could topple from the edge of the tables where they are placed. The filters units are thin plastic and many have ceramic filters. A fall from the table top could potentially break the filter. If enough filters are damaged, the hospital will not have sufficient safe drinking water for the staff and patients.


**Figure 33. Drinking water filters at the hospital**

Table 7 shows the likely performance of the hospital's water systems in the three hypothetical scenario earthquakes.

**Table 7. Likely performance of water systems in hypothetical scenario earthquakes**

| **System** | **Likely Performance in Hypothetical Scenario Earthquake** | | |
|---|---|---|---|
| | Deep M7<br>Light Shaking<br>PGA = 0.11g | Shallow M6.1<br>Strong Shaking<br>PGA = 0.58g | M8.6<br>Violent Shaking<br>PGA = 1.18g |
| **Water from off-site system** | Water supply may be disrupted, but could be repaired within a few days. | Water supply probably disrupted and could take days to reestablish. | Water supply damaged and not repaired for extensive length of time. |
| **Water from on-site storage** | | | |
| Domestic | Available until tank supply depleted; water rationing could allow supply to last longer.. | Likely insufficient. | Insufficient. |
| Filtered Drinking | Generally available but dependent on supply of domestic water. | Some filters damaged; supply limited by domestic water. | Not sufficient; many filters damaged; domestic supply quickly depleted. |

PGA = peak ground acceleration

Evaluation of the seismic resistance of the reinforced concrete water tank (shown in Figure 23) was outside the scope of this assessment, but it is possible that the tank, or pipes connecting the tank to the hospital, could be damaged in an earthquake and cause leaks. The table above assumes that leaks do not substantially reduce the supply of available water; note that major leaks could cause water loss and reduce the performance of the water system.

### Fire Suppression

Fires often start following earthquakes because ignition sources such as laboratory burners, stoves, and heaters can slide or fall during shaking and come in contact with flammable materials. Sparks from damaged electrical equipment or wiring and reactions between spilled chemicals can also ignite fires.

The team did not observe a fire suppression water system or fire sprinklers. The team did not note the presence of fire extinguishers. In the absence of a fire sprinkler system, the hospital should have an adequate number of fire extinguishers distributed in prominent and easily accessible locations throughout the building.

### Communication Systems

The hospital currently uses both landline and mobile phones as its major communication systems. The hospital does not have separate backup communications. During the 6.1M earthquake in Mongar in 2009, all mobile phone networks were jammed and landline phones were non-functional for at least a few hours. Fortunately there was no major damage to the mobile towers and network.

However, the hospital should expect that mobile communications will be down for a long period of time, perhaps a much longer period, following a stronger earthquake like the shallow M6.1 and M8.6 earthquakes considered in this report's scenarios. Mobile towers, electrical equipment and buildings could be damaged in an earthquake and require repairs. Furthermore, individual mobile phones require electrical power to recharge, and service providers must have electricity to operate their systems. The hospital will not be able to rely on mobile phones. Table 8 shows the team's approximate estimates of disruption to communication systems in the three hypothetical scenario earthquakes. The hospital should obtain estimates from the telecommunications providers for planning purposes.

**Table 8. Assumed performance of communication systems in hypothetical scenario earthquakes**

| **System** | **Assumed Performance in Hypothetical Scenario Earthquake** | | |
|---|---|---|---|
| | Deep M7<br>Light Shaking<br>PGA = 0.11g | Shallow M6.1<br>Strong Shaking<br>PGA = 0.58g | M8.6<br>Violent Shaking<br>PGA = 1.18g |
| **Communications** | | | |
| Landline phones/ switchboard | Probably operational | Service probably interrupted | Not operational for days to weeks, depending on damage and repair time |
| Mobile phones | Network unavailable for several hours | Network unavailable for hours to days | Network unavailable for days to weeks, depending on damage to towers and infrastructure and repair time |

PGA = peak ground acceleration

## Ramps, Stairs and Exit Pathways

The ramp, shown in Figure 34, is on the exterior of the hospital and is separated by a seismic joint. It has reasonably spaced column ties, according to the structural drawings, and appears unlikely to suffer damage that would make it unsafe to use, until perhaps the largest scenario event.


**Figure 34. Ramp behind the Main Hospital building leading to the Operation Theatre and the ward**

During the afternoon and evening hours when the ground floor Outpatient Department (OPD) is closed, all of the ground floor exit doors are kept locked for security reasons. During these hours there is only a single exit for the entire first and second floors of the hospital. The first floor contains the continuously occupied wards. The team noticed that exit doors had many boxes stored behind the door, as Figure 35 shows, which could fall down during shaking and block the exit. This was noted in a number of room and building exit points in the hospital. The team recommends that all exits be open and cleared of stored items that could block the route during emergencies.


**Figure 35. Entry to the general ward in the Main Hospital (left), entry/exit blocked by stored boxes (right)**

## Vulnerability of Medical Equipment, Contents, and Architectural Shell

A hospital's medical equipment, contents such as medicines and supplies, and the building's architectural shell are all important for maintaining essential services and protecting patients. At Trashigang District Hospital, many of these items were apparently not installed with earthquake safety or protection in mind. A systematic survey of medical equipment and contents was outside the scope of this assessment, but the team recommends that the hospital conduct such a survey. The following sections describe the evaluation team's findings.

### Medical and Laboratory Equipment

Trashigang hospital has some specialized and costly medical and laboratory equipment, though not as much as a regional or national referral hospital would have.  Much of the equipment is critical to the ability of the hospital to deliver emergency medical services. However, the equipment is not anchored to prevent damage during shaking, as shown in Figure 36. Mobile equipment does not have provisions for tethering when not in use. The hospital's X-ray machine, which the medical staff will need in order to treat fractures (a common injury caused by earthquakes), is not bolted to the floor and therefore likely to slide. The top rail is not adequately fixed to the walls. The hospital has benchtop laboratory equipment that could slide and fall, as well as tall and narrow free-standing refrigerators, as Figure 37 shows. The team recommends that the hospital assess existing equipment and begin anchoring it to reduce the likelihood of earthquake damage.

**Figure 36. Unanchored medical equipment in Trashigang hospital including incubators, X-ray machine and autoclave**


**Figure 37. Unanchored laboratory equipment**

### Contents and Furnishings

In several areas of the main hospital building and Medical Store, important items such as medicines and sterile surgical instruments are stored on unanchored shelving (Figure 38) that may topple in an earthquake. In the laboratory, dangerous chemicals are stored in glass bottles on open shelving or counters where they can easily fall, break and spill (Figure 39).

**Figure 38. Supplies stacked in Medical Store**

**Figure 39. Potentially dangerous chemicals unrestrained on counter tops open shelving in the laboratory**

The team observed desks and work stations located near heavy shelves that could topple and injure staff members during an earthquake; Figure 40 shows an example. In all of these locations, unrestrained items will fall, become disorganized or ruined, and require time-consuming cleanup or restocking. In some cases heavy cupboards or shelving can block exits. Simple hardware to anchor shelving to walls or floor, combined with shelf restraint systems, can prevent this from happening.


**Figure 40. Heavy shelving and glass partitions by an exit pathway (left) and unsecured cupboards near staff work areas (right)**

### Architectural Shell: Elements and Finishes

The architectural shell consists of the building's partitions, windows, roof covering and exterior architectural elements. The architectural shell defines functional spaces and facilitates infection control and fire protection. The brick partitions, key parts of this shell, are vulnerable to damage during strong earthquake shaking.

### Partitions

The hospital has single wythe (i.e., built from a single row of bricks) brick partitions that extend from floor slab to floor slab, or from floor slab to ceiling joists in the upper floors. The partitions are very slender and tend to buckle and collapse in an earthquake as a result, especially those partitions in upper floors, where the building's motion is amplified. Because such partitions can fail, medical equipment and heavy items such as cupboards should not be anchored to them. Instead, the evaluation team recommends that equipment be anchored to floor-to-ceiling supports called *strongbacks*. The hospital also has wood and glass doors and partitions; the glass in these partitions can break, creating an exit pathway hazard. Figure 41 shows some typical partitions.


**Figure 41. Single wythe brick partition too weak to support large cabinet if it were anchored (left); wood and glass partitions and doors in the nurses station (right)**

The hospital's main medical building also has window glass and decorative elements on the exterior that could potentially be damaged and fall on people nearby in an earthquake.

## Dependence on Off-site Lifelines

Trashigang does not have facilities to manufacture the medical supplies, fuel and medical gas that the hospital needs to provide medical care. The hospital depends on roads for resupply of these items. Diesel fuel from generators comes from a petrol pump at the Bhutan Oil Distributor in Kheri, at the junction of the Samdrup Jongkhar road. The team observed areas of active landsliding between the hospital and Kheri, where strong shaking is likely to cause further landsliding that would block the only road and cut off access. The area shown in Figure 42 is right at the entrance to Trashigang town. Though the area is limited, large rocks that would be time consuming to remove will likely fall onto the road, blocking access. The road between the hospital and the petrol pump in Kheri crosses a large landslide deposit shown in Figure 43. Reactivation of this landslide could affect access along a longer portion of the road for a much greater time period.

**Figure 42. Active landslide area at the entrance to Trashigang town**

**Figure 43. Road between Trashigang and petrol pump at center of photo crosses a large landslide deposit (white outline indicates approximate extent)**

Most other resupply items come from the Medical Supply Depot in Phuentsholing, over a narrow, winding mountain road prone to landslides and rockfalls. Moderate to severe earthquakes such as the three hypothetical scenarios considered here will cause landslides to occur on the roads that connect Trashigang to other parts of the country and to India, especially during the monsoon. Following a major earthquake, it may take days or weeks to reopen the lateral road and the road to Samdrup Jongkhar, depending on the strength of shaking and level of landslide damage to the road. Yonphula airport may be damaged in more severe shaking. Humanitarian relief efforts will be impeded as a result. It will be difficult to refer patients to hospitals either inside or outside the country.

Mobile telephone service will become jammed with calls following a damaging earthquake; in a more severe earthquake, cell towers and infrastructure may be damaged, and the electrical power needed by users and mobile phone infrastructure will not be available.

City water and grid-supplied electrical power systems are likely to be damaged by strong earthquake shaking, and may be unavailable for days or weeks. The city water system could be vulnerable to damage caused by earthquake induced landslides; the 2012 landslide that interrupted water service indicates that some parts of the system are in areas susceptible to landslides. Due to blocked roads, the city solid waste disposal may not be accessible for some time following a strong earthquake. The team did not assess vulnerabilities of these systems, but based these general remarks on past performance of other utility systems in earthquakes. For planning purposes, the hospital should obtain estimates of the time required for each of these utilities to restore service.

## Emergency Planning

The evaluation team interviewed the hospital's Medical Officer and learned that the hospital, at the moment, has no emergency procedures in place and there is no formal emergency plan to deal with natural hazards such as earthquakes. So far, the hospital has not faced any major or recent emergencies that would have tested their abilities and systems in place to deliver emergency medical care. Because the 2009 Mongar earthquake was centered much further south near Narang in Mongar district, the shaking in the Trashigang area was not strong enough to cause significant damage and injuries. The hospital did not face an influx of patients and experienced only minor damage to architectural finishes. The 2009 earthquake did cause damage to health infrastructure, though: 45 health facilities reported damage, and the Narang Basic Health Unit collapsed.  All three district hospitals at Trashigang, Mongar and Lhuentse reported minor, repairable damages[9].  It is evident that in a major earthquake, smaller out-reach facilities built by the communities or by private contractors will fail, forcing people to congregate and seek medical care at the district hospitals. The team also conducted a hospital emergency sensitization session for the hospital's management committee members and senior staff. During the sensitization session, the hospital management committee members and senior staff expressed the importance of having an emergency plan and training for staff in place.

[9] National Recovery and Re-construction Plan, 2009, Department of Disaster Management.

# Hospital Impact Scenarios Based on Three Hypothetical Earthquakes

To help readers envision the impact of potential earthquake damage on the hospital's ability to function and deliver care, the evaluation team has postulated how the facility might respond to three scenario earthquakes. Each scenario is based on a hypothetical earthquake and is intended to illustrate the range of earthquake shaking that the hospital should consider for mitigation and emergency planning purposes. The three hypothetical earthquakes are (1) a deep M7 earthquake occurring near Trashigang; (2) a shallow M6.1 earthquake occurring directly under Trashigang; and (3) a massive M8.6 earthquake occurring on the plate boundary and affecting much of Bhutan. The USGS, with collaboration from University of Indiana and DGM, provided preliminary estimates of the median levels of ground shaking that these three earthquakes might cause.

The USGS estimates of potential shaking presented in this report contain large uncertainties, because the scientific community's understanding of Bhutan's earthquake hazard is still at an early stage. A real earthquake, even if it were to have the same magnitude and to originate in exactly the same location, might cause shaking that is substantially stronger or substantially weaker than the estimates presented in this report. The report presents these estimates for purposes of illustration only. They should not be used for engineering design, both because of the uncertainties involved and because they consider only approximate, generalized site conditions; local site effects could further affect the amplitude and nature of ground shaking. These estimates may be used for emergency planning, with appropriate precautions that account for the uncertainties involved.

While these earthquakes are hypothetical, they represent the types of earthquakes that Bhutan should anticipate. Moreover, they are of reasonable magnitudes and plausible locations, and are not necessarily the worst case scenarios.

The following sections describe for each earthquake scenario:

- possible infrastructure and building damage in the earthquake-affected area; and
- likely damage and consequences that the evaluation team expects at the hospital, as a result of vulnerabilities identified in prior sections.

The scenarios have been kept intentionally simple and are intended to give the reader a snapshot of the hospital's performance following each hypothetical earthquake. Much more detailed scenarios, with an extended timeline – GHI recommends one month – for larger earthquakes would be used for emergency planning purposes. (This would reflect complex interactions with the transportation and utility systems.) In the final section of this report, the team provides recommendations for actions that will reduce the earthquake damage to the hospital and will improve functionality of the hospital.

Postulated levels of earthquake damage determined for the estimated shaking were assigned using the damage states defined in Table 1. The team estimated the likely functionality of each building by combining the damage states with a determination of whether or not critical utilities (electrical power and domestic water) would be available. For residences (i.e., staff quarters), the team estimated whether the buildings are likely to be habitable. Table 9 defines the likely functional states by color codes, which are then used to present a graphical overview of the facility for each scenario. Summary tables in Appendix A provide damage states, functional states and utility performance for all three scenarios.

**Table 9. Functional state color codes**

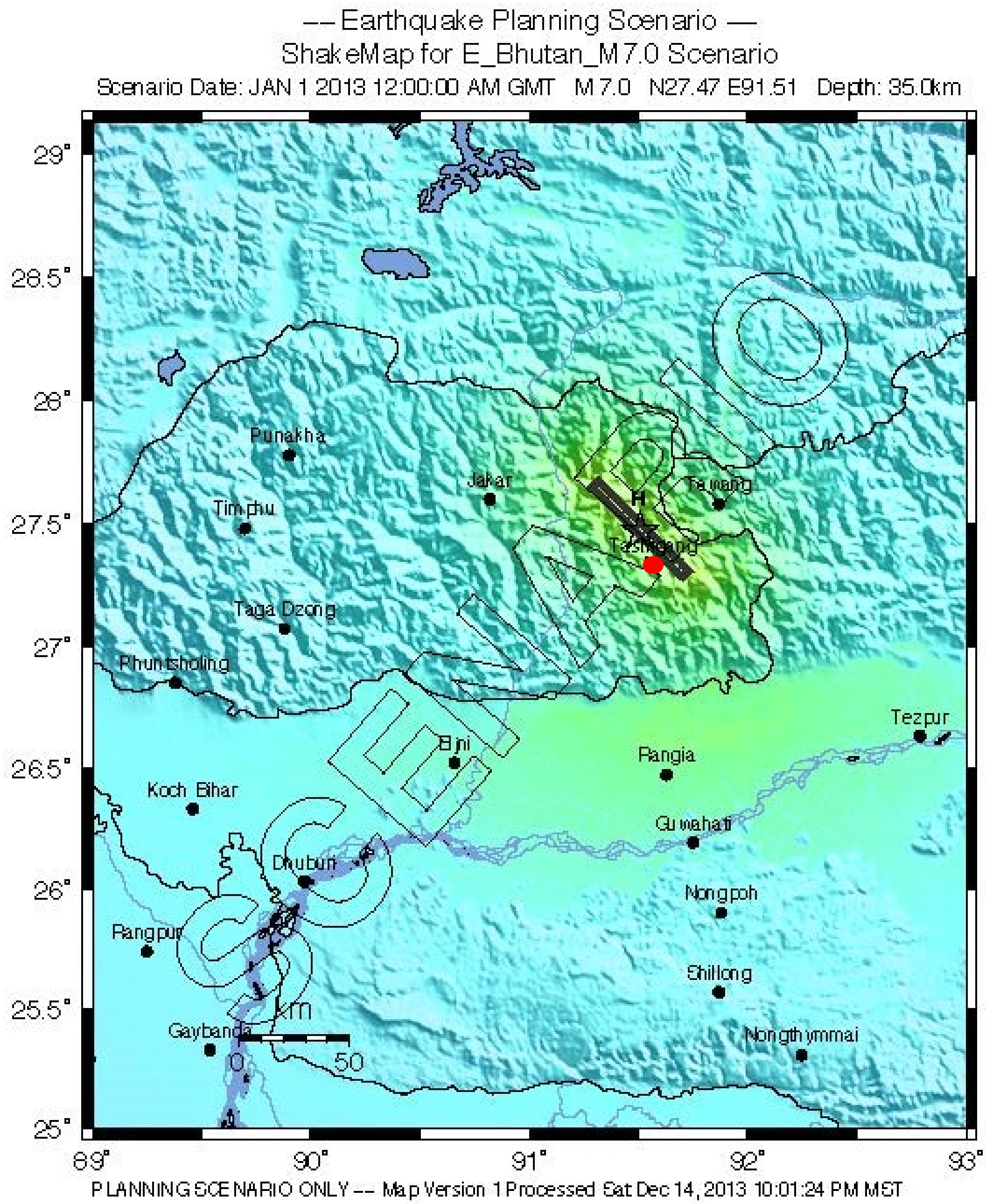
| Color Code | Description of Functional State | Damage states | Critical Utilities |
|---|---|---|---|
| Black | Collapsed or partially collapsed | S4 | N/A |
| Red | Neither useable nor functional | S3 plus N3 (if applicable) | Not available |
| Orange | Marginally useable but not functional<br>For residences: damaged; may not be habitable | S1 / S2 plus N3<br>Or S2 plus N2 | Not available |
| Yellow | Functional after cleanup / minor repair<br>For residences: damaged: habitable with cleanup | S2 plus N1 (if applicable)<br>or S1/S2 plus N2 | Available |
| Green | Functional<br>For residences: habitable | S1 plus N1 (if applicable) | Available |

## Scenario 1: Hypothetical Deep M7 Earthquake Occurring North of Trashigang

Just before 11:00 a.m. on a Saturday morning, eastern Bhutan is shaken by a magnitude 7 (M7) earthquake centered 35 kilometers below northern Trashigang district. Though not especially strong, the shaking is felt throughout most of eastern Bhutan. Figure 44 shows a potential pattern of ground shaking intensity in this earthquake, as estimated by the USGS using their ShakeMap system. A red dot shows the location of Trashigang District Hospital. The star indicates the earthquake's epicenter, and the box shows the portion of the fault that the USGS assumed had ruptured in order to generate this hypothetical earthquake.

There is widespread damage to buildings in both Trashigang and Trashiyangtse districts, both in the main towns and outlying villages. Building damage is reported from Lhuentse, Mongar, Pemagatshel, Bumthang and Samdrup Jongkhar districts. Some people inside of buildings were injured by falling bricks and furniture, or scalded by pots of boiling water kept on stoves. Some traditional stone masonry buildings have collapsed, killing or injuring some occupants; others have been badly damaged and are not safe to occupy. Some small landslides and rockfalls have blocked the road between Trashiyangtse, Trashigang, and Yonphula. Some portions of the Trashigang access road are partially blocked by landslides and fallen bricks and other debris in town.

Inside the hospital, staff and patients feel the earthquake shaking and are unsure of what to do. Some unrestrained supplies fall from carts and shelves. The power fails, but the emergency generator is started within a few minutes and restores power. The Medical Superintendent, and staff living on site who are not already at work, rush to the hospital after checking that their families are all right. They notice some small cracks on the walls of some of their quarters and hope that the district engineers arrive soon to check the buildings. The mobile phone network is overloaded within minutes of the earthquake. Landlines are functioning, so the hospital staff is able to contact the Ministry of Health to report on the situation.




| 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. (2011)

**Figure 44. Median estimate of potential ground shaking intensity from M7 hypothetical scenario earthquake near Trashigang, courtesy USGS. The star indicates the earthquake epicenter and red dot the hospital. The black box indicates the portion of the fault that ruptured during the earthquake.**

The injured begin arriving from the town almost immediately. The main injuries are lacerations from falling objects, including stones. Some have suffered fractures. Over the next several days, more injured people arrive from villages. People have heard that the road to Mongar is blocked in several locations, and aftershocks continue to bring rocks down onto the road, so they feel safer coming to Trashigang rather than risking the longer drive to Mongar Regional Referral Hospital. The widespread shaking and damage cause the patient load at Trashigang hospital to be much higher than normal, and supplies are depleted quickly. The acute shortage of doctors – there is only a single doctor in the hospital – reduces the ability to deliver care, especially for more serious injuries. It takes several days to clear the landslides on the roads to Mongar (and the regional referral hospital there) and Yonphula airport. Several patients critically injured by building collapses are transferred out to the Jigme Dorji Wangchuck National Referral Hospital in Thimphu by helicopter the evening of the earthquake. The Middle Secondary School just uphill from the hospital has a large open area where helicopters can land.

District engineers arrive to inspect the hospital's buildings. The hospital and other medical buildings have not suffered any structural damage, only minor cracking of finishes and partitions. The older unreinforced masonry staff quarters and the Prayer Hall have suffered significant cracking. The other buildings are essentially undamaged except for minor cracking.

Table 10 shows the anticipated damage states (defined in Table 1) for the hospital's buildings for this deep M7 hypothetical scenario earthquake.

**Table 10. Likely damage states for buildings in deep M7 hypothetical scenario earthquake**

| **Building Name** | **Construction Type** | **Year Built** | **No. of Stories (incl. ground)** | **Likely Performance in Deep M7 Scenario Earthquake**, PGA 0.11g | |
|---|---|---|---|---|---|
| | | | | Structure & Shell | Equip & Contents |
| | | | | | |
| Main Hospital building | RC w/brick infill | 2002-4 | 2 | S1 | N1 |
| Old Hospital building | Nonductile RC w/infill | 1975 | 2 | S1 | |
| Physiotherapy Building | RC w/brick infill | 2002-4 | 3 | S1 | |
| Administration/Medical Store building | RC w/ brick infill | 2002-4 | 2 | S1 | N2 |
| Prayer Hall | Unreinforced brick masonry | 2002-4 | 1 | S2 | |
| Laundry | Brick masonry w/seismic band | 2002-4 | 1 | S2 | |
| Kitchen/Bath | Brick masonry w/seismic band | 2002-4 | 1 | S1 | |
| Incinerator | Brick masonry w/seismic band | 2002-4 | 1 | S2 | |
| Generator House | Brick masonry w/seismic band | 2002-4 | 1 | S1 | N1 |
| Bungalows | URM* | 1970s | 1 | S2 | |
| Duplexes | RC w/brick infill | 2002-4 | 2 | S1 | |

| | | | | | |
|---|---|---|---|---|---|
| Newer Fourplexes | RC w/brick infill | 2002-4 | 2 | S1 | |
| Older Fourplex | Unreinforced stone masonry* | 1980s | 2 | S2 | |
| Support Staff Quarters | RC w/brick infill | 2002-4 | 2 | S1 | |
| Attendant Guesthouse | Brick masonry w/seismic band | 2002-4 | 1 | S1 | |
| Old OPD | Ekra and unreinforced brick | 1970s | 1 | S1 | |
| Caretaker's Residence | Brick masonry w/seismic band | 2002-4 | 1 | S1 | |

RC = reinforced concrete; URM = unreinforced masonry; PGA = peak ground acceleration
* Exact construction material type and details are not known; assumed type is the most vulnerable of the likely construction material/structural system types. Vulnerability rating may improve if better, more earthquake-resistant construction can be verified.

The generator remains functional though there is some minor disruption inside the Generator House. Because the Bhutan Power Corporation office is nearby, the hospital has its power restored within the day, so the generator fuel is sufficient. The city water system suffers disruption from ground failure, and the on-site tank is drained in a day. The hospital is without water after the first 24 hours of the response. Because most roads are open, some of the support staff are able to fetch small amounts of water for the most critical functions, such as operating sterilizers, hand washing and drinking. Water service is restored within three days, but the water shortage has caused some difficulties for the hospital. Infection control has suffered, and some patients become ill as a result. Table 11 shows the anticipated performance of key utility systems in the deep M7 hypothetical scenario earthquake.

**Table 11. Likely performance of key utility systems in deep M7 hypothetical scenario earthquake**

| **System** | **Likely Performance in Deep M7 Hypothetical Scenario Earthquake**, PGA = 0.11g |
|---|---|
| **Electric Power from off-site supply** | Possible short interruption of power |
| **Electric Power from on-site generators** | Generator operational; power available while fuel lasts |
| **Water from off-site system** | Water supply may be disrupted but could be repaired within a few days |
| **Water from on-site storage** | |
| Domestic | Available until tank supply depleted; water rationing could allow sufficient water |
| Filtered Drinking | Generally available but dependent on supply of domestic water |
| **Communications** | |
| Landline phones | Probably operational |
| Mobile phones | Network unavailable for several hours |
| **Medical Gas** | |
| Oxygen and Nitrogen | Supply adequate but cylinders likely to roll down and block door |

PGA = peak ground acceleration

Figure 45 shows the anticipated performance of the hospital's buildings, in terms of functionality. The actual state of functionality is highly uncertain, due to uncertainty in the exact nature of ground shaking, and in the evaluation team's existing knowledge of site conditions and structural and nonstructural systems. Each building could be one performance level higher or lower than shown. The hospital is able to maintain most essential functions and treat the injured, but the severe shortage of doctors reduces the quality of care and the ability of the hospital to treat more severe injuries.


**Figure 45. Likely performance of hospital buildings in deep M7 hypothetical scenario earthquake**

## Scenario 2: Hypothetical Shallow M6.1 Earthquake Occurring Beneath Trashigang

On a weekday afternoon, Trashigang is shaken by M6.1 earthquake centered directly beneath the town, 8 kilometers deep within the earth. Because the earthquake is relatively shallow, it creates powerful shaking within Trashigang town and surrounding areas, but the area affected by the strongest shaking is relatively small. Figure 46 shows a potential pattern of ground shaking intensity in this earthquake, as estimated by the USGS using their ShakeMap system. A red dot shows the location of Trashigang District Hospital. The star indicates the earthquake's epicenter, and the box shows the portion of the fault that the USGS assumed had ruptured in order to generate this hypothetical earthquake.

Buildings throughout the town area are badly damaged, and a number of older stone masonry buildings have collapsed. The shaking has caused large boulders to fall from the cliffs behind the court house, damaging more buildings, including one of the support staff quarters. Townspeople begin to congregate at the hospital immediately, bringing injured relatives and neighbors. People dig frantically at the sites of collapsed buildings, trying to rescue those trapped inside. Rescuers bring the injured to the hospital using whatever means they can.

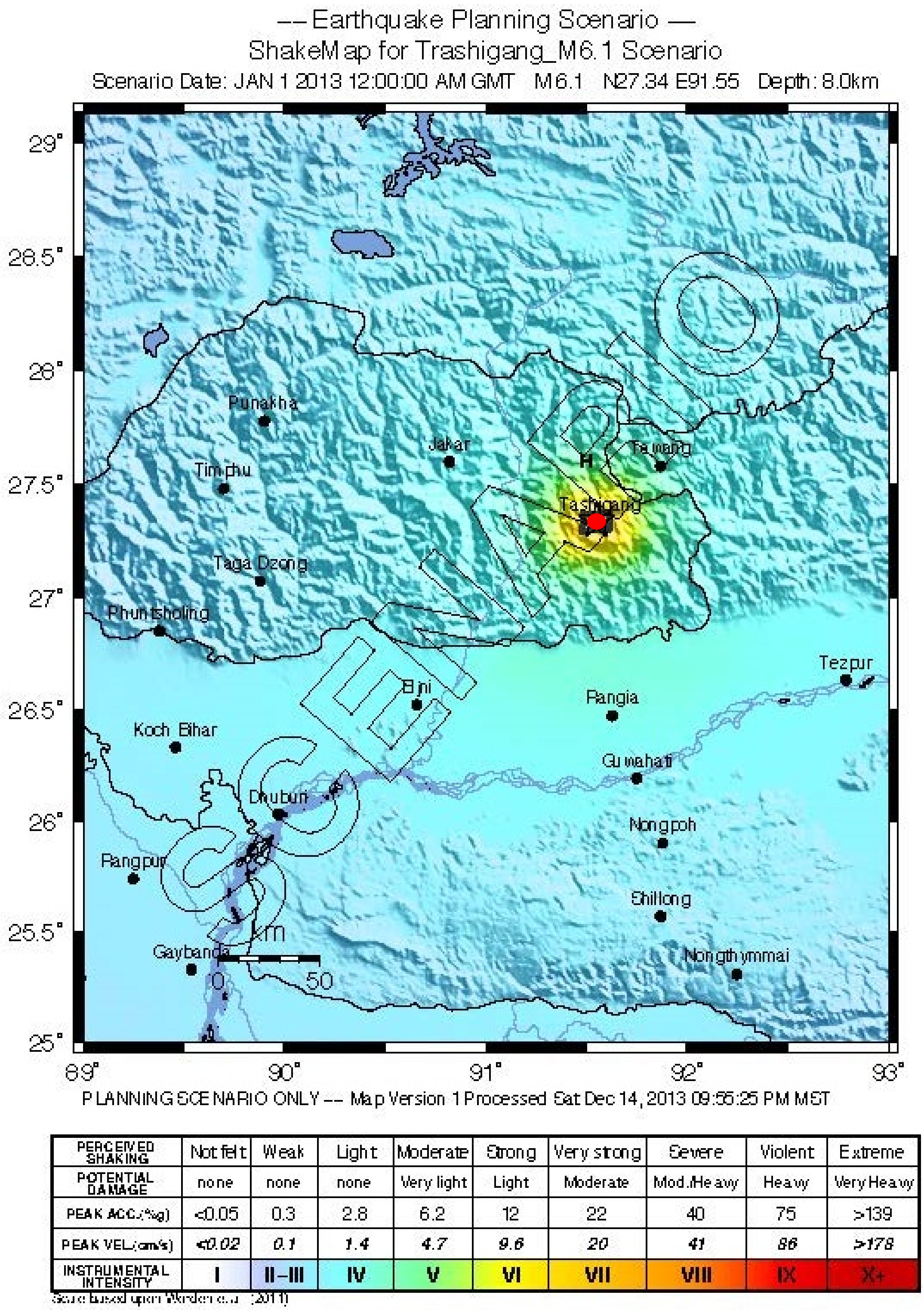



**Figure 46. Median estimate of potential ground shaking intensity from shallow M6.1 hypothetical scenario earthquake near Trashigang, courtesy USGS. The box indicates the portion of the fault that ruptured during the earthquake. The earthquake epicenter as well as the hospital (red dot) are located with the box.**

Table 12 shows the damage states (defined in Table 1) that the team anticipates the M6.1 hypothetical scenario earthquake will cause. Inside the hospital, the strong shaking causes furniture and equipment to slide and overturn, and supplies to fall from shelves. Some glass bottles slide off of laboratory benchtops and shelving and break on the floor, spilling dangerous chemicals. Some water filtration units fall from tables, spilling water everywhere. Glass in doors and partitions breaks as the building moves back and forth and doors swing. Footing is treacherous, with water, glass, medicines and supplies on the floor of rooms and corridors. Because the OPD is closed, the downstairs exit doors are locked. After the shaking stops, people rush downstairs across broken glass, only to find that they cannot get out. In the confusion, people fall and are injured by broken glass.

Unanchored medical equipment slides and moves, including the X-ray machine which dislocates from its rails and is badly damaged. Other major medical equipment, such as the radiant warmers, roll around and crash into the walls. Fortunately there are no babies inside.

The Medical Store is completely disrupted; staff can barely enter the room to retrieve supplies. The medical cylinders have rolled against the door of the room where they are stored, preventing staff from opening it. The older staff quarters and the Old Hospital building are badly damaged and unsafe, as are the Prayer Hall and Laundry. Other staff quarters have suffered damage and the occupants wonder whether they are safe to occupy.

**Table 12. Likely damage states for hospital buildings after shallow M6.1 hypothetical scenario earthquake**

| **Building Name** | **Construction Type** | **Year Built** | **No. of Stories (incl. ground)** | **Likely Performance in Shallow M6.1 Scenario Earthquake**, PGA 0.58g | |
|---|---|---|---|---|---|
| | | | | Structure & Shell | Equip & Contents |
| | | | | | |
| Main Hospital building | RC w/brick infill | 2002-4 | 2 | S2 | N2 |
| Old Hospital building | Nonductile RC w/infill | 1975 | 2 | S3-S4 | |
| Physiotherapy Building | RC w/brick infill | 2002-4 | 3 | S2 | |
| Administration/Medical Store Building | RC w/ brick infill | 2002-4 | 2 | S2 | N3 |
| Prayer Hall | Unreinforced brick masonry | 2002-4 | 1 | S4 | |
| Laundry | Brick masonry w/seismic band | 2002-4 | 1 | S3 | |
| Kitchen/Bath | Brick masonry w/seismic band | 2002-4 | 1 | S2 | |
| Incinerator | Brick masonry w/seismic band | 2002-4 | 1 | S3 | |
| Generator House | Brick masonry w/seismic band | 2002-4 | 1 | S2 | N2 |
| Bungalows | URM* | 1970s | 1 | S4 | |
| Duplexes | RC w/brick infill | 2002-4 | 2 | S2 | |
| Newer Fourplexes | RC w/brick infill | 2002-4 | 2 | S2 | |

| | | | | | |
|---|---|---|---|---|---|
| Older Fourplex | Unreinforced stone masonry* | 1980s | 2 | S3 | |
| Support Staff Quarters | RC w/brick infill | 2002-4 | 2 | S2 | |
| Attendant Guesthouse | Brick masonry w/seismic band | 2002-4 | 1 | S3 | |
| Old OPD | Ekra and unreinforced brick | 1970s | 1 | S3 | |
| Caretaker's Residence | Brick masonry w/seismic band | 2002-4 | 1 | S2 | |

RC = reinforced concrete; URM = unreinforced masonry; PGA = peak ground acceleration
* Exact construction material type and details are not known; assumed type is the most vulnerable of the likely construction material/structural system types. Vulnerability rating may improve if better, more earthquake-resistant construction can be verified.

Table 13 shows the anticipated performance of the most important utility systems in the M6.1 hypothetical scenario earthquake. The shaking damaged the generator and equipment, but an attendant manages to get it running within an hour. The fuel lasts less than a day, so by the following afternoon the hospital is without power again. A landslide between the town and the petrol pump has blocked the road, preventing the attendant from obtaining more fuel until the road reopens. The water runs out the day after the earthquake; despite careful water use, the influx of patients and leaks in the system have drained the tank. The search begins for water, but with roads blocked and the city supply out of service, the hospital must take water from the local stream and boil it (runoff from houses above the hospital has contaminated the stream). Boiling water is a laborious process that requires firewood because there is no diesel fuel. All communications are down, and the hospital cannot inform the Ministry of Health of their dire situation: no power, no water, and many injured.

**Table 13. Likely performance of key utility systems in shallow M6.1 hypothetical scenario earthquake**

| **System** | **Likely Performance in Shallow M6.1 Scenario Earthquake**, PGA = 0.58g |
|---|---|
| **Electric Power from off-site supply** | Interruptions of power are likely to be longer than 24 hours |
| **Electric Power from on-site generator** | Generator and associated equipment may be damaged but still operational; fuel will run out before power is restored |
| **Water from off-site system** | Water supply probably disrupted and could take days to re-establish |
| **Water from on-site storage** | |
| Domestic | Likely insufficient |
| Filtered Drinking | Some filters damaged; supply limited by domestic water |
| **Communications** | |
| Landline phones | Service probably interrupted |
| Mobile phones | Network unavailable for hours to days |
| **Medical Gas** | |
| Oxygen and Nitrogen | Supply likely to be adequate but cylinders likely to roll down and block door. |

PGA = peak ground acceleration

Figure 47 shows the anticipated functional performance of the hospital's buildings. The main hospital building remains functional for a short time, until fuel and water run out; improving backup capabilities would greatly increase the hospital's ability to function following moderately strong earthquakes.

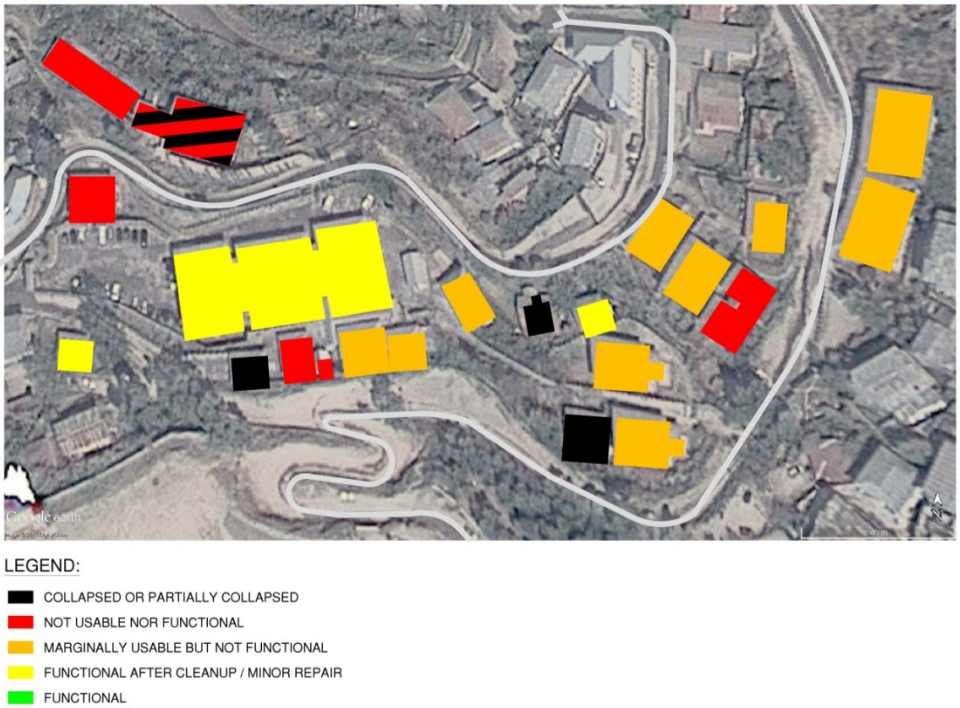
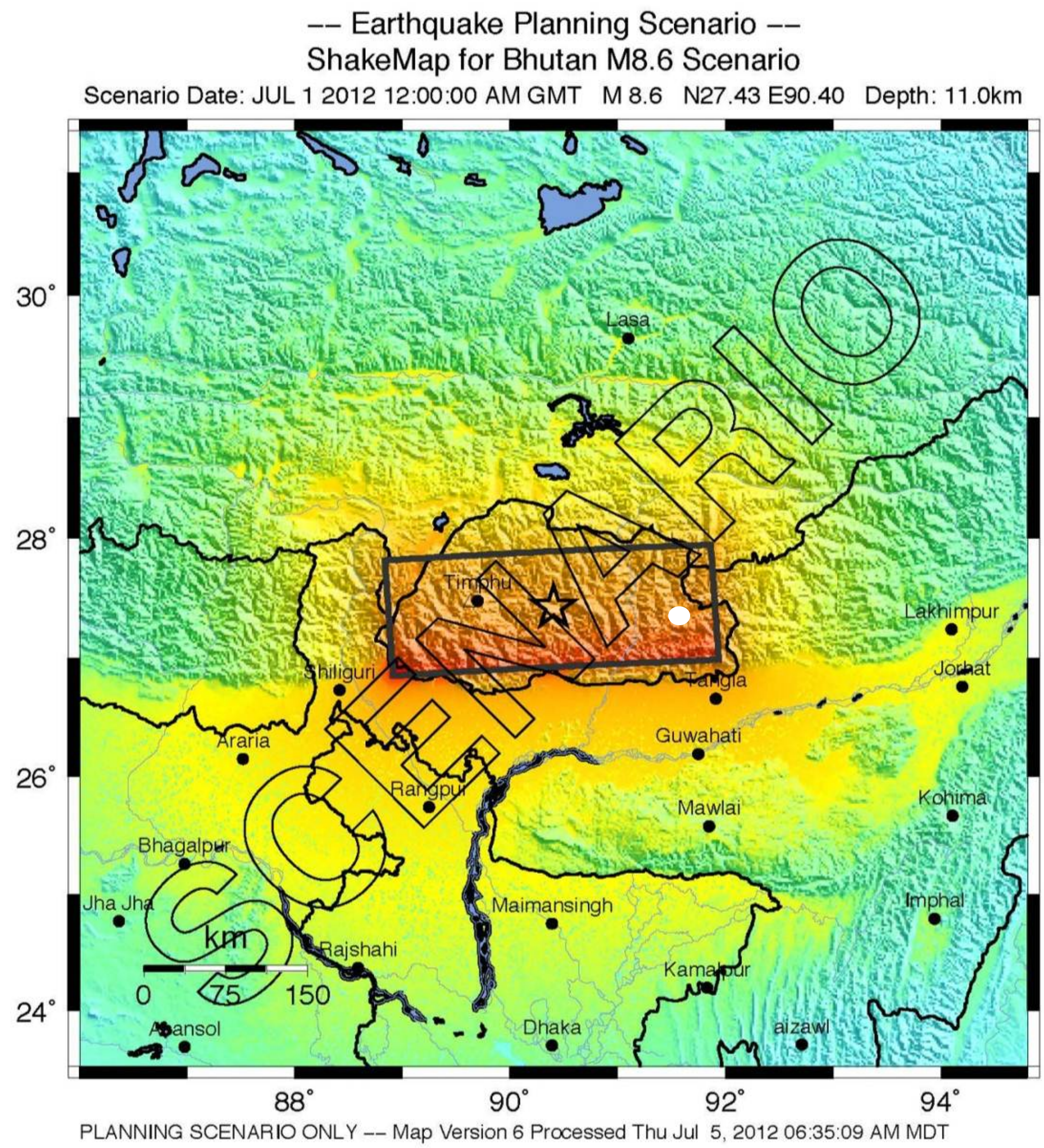



**Figure 47. Site plan showing performance of hospital buildings in shallow M6.1 hypothetical scenario earthquake**

## Scenario 3: Hypothetical M8.6 Earthquake Affecting Most of Bhutan

The worst earthquake to affect Bhutan in approximately 900 years strikes in the middle of a working day. The massive M8.6 earthquake ruptures a segment of the main plate boundary fault that extends nearly the length of the country. The ground shakes strongly for several minutes, causing devastation that stretches from eastern Nepal to western Arunachal Pradesh. In India, the states of Sikkim, Bihar, West Bengal, Assam and Arunachal Pradesh are badly affected. Nepal, China and Bangladesh also report deaths and injuries. One of the largest disaster relief operations in history begins. Figure 48 shows an estimated distribution of median shaking intensity for this hypothetical earthquake, provided by the USGS using their ShakeMap system. Trashigang is indicated by a white dot. The box indicates the portion of the fault that ruptured to generate the earthquake. In Trashigang, the anticipated level of ground acceleration is very strong: it exceeds 1g, the acceleration due to gravity.

Buildings have collapsed across the country, with vulnerable traditional houses suffering some of the worst damage. In Trashigang, the devastation is almost complete. Only the most seismically resistant buildings, built recently to modern codes, survive the earthquake without collapsing.




| 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. (2011)

**Figure 48. Median estimate of potential ground shaking intensity from M8.6 hypothetical scenario earthquake on the main plate boundary fault, courtesy USGS. The black box indicates the portion of the fault that ruptured during the earthquake. The star marks the earthquake epicenter, and a white dot marks the hospital.**

Bhutan's roads across the country have been badly damaged by the earthquake. Massive landslides have buried the roads in multiple locations. These slides will take weeks to clear. The lateral road and the road to Samdrup Jongkhar have been badly affected by multiple large landslides. Smaller landslides and rockfalls have occurred all along the length of Bhutan's highways. Key bridges are out at multiple locations.

Inside the hospital, the strong shaking creates chaos as furniture and equipment slide and overturn, and supplies are thrown from shelves. Partitions break, and bricks fall. The shaking is so violent that people are thrown to the floor and cannot move. All of the hospital's buildings suffer structural damage, and some of them collapse. The main building remains standing but the second floor conference room collapses. The hospital is so badly damaged that everyone evacuates immediately; there is no need to wait for the district engineer to tell them the building is unsafe. The medical staff begins trying to treat the injured in the parking area in front of the main building, retrieving whatever supplies they can from the Main Hospital and the Medical Store, but access is blocked in many places by fallen equipment and contents. Some staff have been injured or are trapped in the staff quarters; fortunately the only doctor is not among them. The entry bridge to the administrative offices above the Medical Store detaches, trapping the staff working there until they can find a piece of furniture to place across the gap.

Table 14 shows the damage states (defined in Table 1) that the evaluation team anticipates the M8.6 hypothetical scenario earthquake to cause.

**Table 14. Likely damage states for hospital buildings in the M8.6 hypothetical scenario earthquake**

| **Building Name** | **Construction Type** | **Year Built** | **No. of Stories (incl. ground)** | **Likely Performance in M8.6 Scenario Earthquake**, PGA 1.18g | |
|---|---|---|---|---|---|
| | | | | Structure & Shell | Equip & Contents |
| | | | | | |
| Main Hospital building | RC w/brick infill | 2002-4 | 2 | S3** | N3 |
| Old Hospital building | Nonductile RC w/infill | 1975 | 2 | S4 | |
| Physiotherapy building | RC w/brick infill | 2002-4 | 3 | S3 | |
| Administration/Medical Store building | RC w/ brick infill | 2002-4 | 2 | S3 | N3 |
| Prayer Hall | Unreinforced brick masonry | 2002-4 | 1 | S4 | |
| Laundry | Brick masonry w/seismic band | 2002-4 | 1 | S4 | |
| Kitchen/Bath | Brick masonry w/seismic band | 2002-4 | 1 | S4 | |
| Incinerator | Brick masonry w/seismic band | 2002-4 | 1 | S4 | |
| Generator House | Brick masonry w/seismic band | 2002-4 | 1 | S4 | N3 |
| Bungalows | URM* | 1970s | 1 | S4 | |
| Duplexes | RC w/brick infill | 2002-4 | 2 | S3 | |
| Newer Fourplexes | RC w/brick infill | 2002-4 | 2 | S3 | |
| Older Fourplex | Unreinforced stone masonry* | 1980s | 2 | S4 | |

| | | | | | |
|---|---|---|---|---|---|
| Support Staff Quarters | RC w/brick infill | 2002-4 | 2 | S3 | |
| Attendant Guesthouse | Brick masonry w/seismic band | 2002-4 | 1 | S4 | |
| Old OPD | Ekra and unreinforced brick | 1970s | 1 | S4 | |
| Caretaker's Residence | Brick masonry w/seismic band | 2002-4 | 1 | S3 | |

RC = reinforced concrete; URM = unreinforced masonry; PGA = peak ground acceleration
* Exact construction material type and details are not known; assumed type is the most vulnerable of the likely construction material/structural system types. Vulnerability rating may improve if better, more earthquake-resistant construction can be verified.
**Second storey conference room is S4 due to anticipated dynamic amplification

Table 15 shows the anticipated performance of the most important utility systems in the M8.6 hypothetical scenario earthquake. Both onsite and offsite utilities are badly damaged. The generator falls from its supports and will not run, and the water supply is quickly depleted by leaks. Mobile telephone towers fail across the country, and landlines are down. Because of the lack of communications, international relief agencies will take days to reach Trashigang with aid.

**Table 15. Likely performance of key utilities in M8.6 hypothetical scenario earthquake**

| **System** | **Likely Performance in M8.6 Scenario Earthquake**, PGA = 1.18g |
|---|---|
| **Electric Power from off-site supply** | Long interruptions of power should be expected |
| **Electric Power from on-site generators** | Generators and electrical equipment damaged and not operational. Expect that power will not be available until replacement generator from off site is delivered and damaged equipment is repaired, an estimated 3 weeks or more |
| **Water from off-site system** | Water supply damaged and not repaired for extensive length of time |
| **Water from on-site storage** | |
| Domestic | Insufficient |
| Filtered Drinking | Not sufficient; many filters damaged; domestic supply quickly depleted |
| **Communications** | |
| Landline phones | Not operational for days to weeks, depending on damage and repair time |
| Mobile phones | Network unavailable for days to weeks, depending on damage to towers and infrastructure and repair time |
| **Medical Gas** | |
| Oxygen and Nitrogen | Supply likely inadequate. |

Figure 49 shows the anticipated performance of the hospital's buildings, in terms of functionality. The main hospital has not collapsed and has protected the lives of most inside, but many other buildings are badly damaged or have collapsed. The hospital is able to provide only a basic level of "austere" care in the immediate post-earthquake period, but the main building is badly damaged and is probably not repairable.


**Figure 49. Likely performance of hospital buildings in M8.6 hypothetical scenario earthquake**

# Recommendations and Conclusions

Given the likely damage and consequences resulting from a strong earthquake such as the shallow M6 or M8.6 hypothetical scenarios described above, GHI strongly recommends that the hospital administration and staff take immediate action to begin improving the hospital's ability to deliver medical services after a major earthquake. Trashigang is a remote district, and in a major earthquake there is a very high possibility that the mountain roads leading toward Thimphu and the nearest southern city, Samdrup Jongkhar, will be blocked by landslides. Cut off from the rest of Bhutan, with limited or no outside assistance or resupply for a significant period of time, the hospital will have to provide medical service to Trashigang district's population. The outreach clinics and Basic Health Units, given their performance in the last 2009 earthquake, may suffer serious structural damages and be unable to deliver services, which would mean people from rural villages would all seek care at the Trashigang hospital. Given this scenario, it would be crucial for the district hospital to enhance its capacities, mitigate its risks, and be prepared to function effectively following a major earthquake.

## Recommendations to Improve Seismic Performance

As the scenarios in prior sections illustrate, a functional hospital must have safe, useable buildings; available utilities and medical equipment; and prepared staff.  Recommendations to help achieve all three "ingredients" for a functional hospital can be grouped in four general areas:

A. Physical safety of buildings
B. Utility systems and backup capabilities

C. Planning and preparedness
D. Medical equipment and supplies to deliver care

The assessment team recommends that the hospital take specific mitigation actions, described in the following subsections, to begin improving the hospital's earthquake performance.

## A. Physical Safety of Buildings

Site and retaining walls:

1. Assess the stability and seismic vulnerability of the site's retaining walls;
2. Conduct a detailed investigation of rockfall hazards to determine the potential affects and likelihood of rockfall runout. Rockfall mitigation techniques including deflection walls, flexible barriers, slope fencing, rock bolting, and anchoring of blocks in place should be considered.

Main Hospital building:

3. If a decision is made that the hospital should remain functional, then a qualified structural engineer should conduct non-linear analyses (meaning computer analyses that include mathematical representations of the ways that the building's structural members become damaged) considering realistic, site specific ground motions, in order to determine the displacements and accelerations that design earthquakes are expected to cause, and to estimate the damage to the building's structural frame, interior partitions and exterior walls. The need, costs and benefits of strengthening could then be estimated. Collapse or heavy damage of infill walls and partitions causes a loss of function in the adjacent spaces, as well as fear among occupants that the building may not be safe.

4. Previous studies have indicated that single wythe brick partitions are likely to crack and fall perpendicular to their length, particularly if they are supporting equipment. A qualified structural engineer should design a partition bracing system that satisfies infection control requirements, or the hospital should replace single-wythe brick partitions in critical areas (such as OT) with lightweight partitions.

Other buildings:

5. Use planned capital improvements over successive five year plans as opportunities to replace older vulnerable buildings with seismically safer new ones;
6. Work with HIDD and MoH to develop a long-term facilities improvement plan;
7. Retrofit or replace the older staff quarters, especially the Bungalows and the Old Hospital building, followed by the Old OPD staff quarters and the older masonry fourplex nurses quarters;
8. Evaluate the rockfall hazard to the Support Staff Quarters and relocate staff if needed;
9. Conduct structural analyses of the reinforced concrete Staff Quarters and Administration / Medical Store building to verify that they provide life safety for the expected level of ground shaking in a major earthquake;

10. If the hospital is to remain functional, replace the current unreinforced brick Generator House with a seismically robust building designed to withstand the design level shaking with minimal damage.

## B. Strengthening Utility Systems and Backup Capabilities

Detailed recommendations for each major utility system are listed below.

Electrical system:

1. Provide additional fuel (adding another, larger tank would be one solution) sufficient to last the number of days deemed necessary: five days minimum;
2. Anchor backup generator that supplies emergency power, including the batteries and muffler;
3. Obtain a second backup generator and ensure it is seismically protected when installed;
4. Request Bhutan Power Corporation to anchor the transformer that supplies grid power to the hospital and ensure that other connection equipment to the grid power system is seismically robust;
5. Anchor all currently unanchored electrical cabinets at the base to prevent overturning;
6. Provide housing for maintenance staff that is separate from the Generator House.

Communications systems:

7. Obtain a backup communications system that does not rely on mobile phones, in order to enable cross country communication with the Ministry of Health and other government agencies;
8. Put in place simple communication procedures for emergencies, especially with responders (who will contact whom, etc.) and district engineers.

Water system:

9. Determine whether the water storage tank supplies the staff quarters. If so, provide additional connection to the main supply for staff quarters, so that the water storage tank supplies medical buildings only. If the tank does not supply water to the staff quarters, check the system for leaks;
10. Based on an estimate of the time required to restore the city water supply, improve the emergency water supply by adding storage capacity, if needed;
11. Ensure that water filtration units in the Main Hospital building are anchored or placed so that they will not fall and become damaged;
12. Provide flexible connectors for any water lines that cross seismic joints or other areas where differential movement is expected;
13. Ensure that hot water geysers are not anchored to single wythe partitions;
14. Request that Department of Engineering Services determine (by experimental testing) whether typical geyser anchorage detail is adequate for design seismic forces;

Medical gas system:

15. Store cylinders in seismically protected racks where they cannot roll or topple, rather than in a stack that can collapse against the access door; and
16. Remove unsecured cylinders from hospital corridors.

Fire suppression:

17. Provide fire suppression capability by placing fire extinguishers in highly visible, easily accessible locations throughout the hospital.

Ramps, stairs and exit pathways:

18. Review adequacy of exit pathways from upper floors, considering current policy of locking ground floor exit doors. One possible solution would be to consider installing new doors with panic bars at ground floor exits.

## C. Planning and Preparedness

1. Form a committee with representatives from all hospital departments, responsible for writing an emergency plan that considers not only earthquakes but all hazards that the hospital faces;
2. Develop an emergency plan that addresses continuity of operations and integration with the Health Sector Disaster Management and Contingency Plan, 2011;
3. Determine the level of performance expected from the facility: should the main hospital be functional following a massive earthquake on the plate boundary, or will it be acceptable to deliver medical care via field hospitals in open spaces near the building?;
4. Obtain estimates of the time required to restore service from offsite utilities following a set of possible earthquakes similar to those presented in this report;
5. Determine the length of time after a major earthquake for which the hospital should plan to be self-sufficient. Given Trashigang's geographic isolation from resupply sources, the period recommended in international standards will not be sufficient;
6. Arrange with the district engineer for an immediate safety inspection of hospital buildings, following an earthquake. Provide training on post-earthquake safety inspection;
7. Coordinate with Trashigang Middle Secondary School to plan for use of their open ground for a heliport in a major emergency to bring in supplies and extra personnel, and to transport patients;
8. Develop an evacuation policy and procedures;
9. Ensure that all staff are familiar with the hospital's emergency plan and know their role in it;
10. Provide earthquake safety training for staff;
11. Help staff members to prepare personally (family emergency plans, anchoring potentially hazardous items in the home, etc.), so they will be better able to work following an earthquake;
12. Establish recurring training, so that new staff members receive emergency preparedness and earthquake safety training;
13. Test specific aspects of the emergency plan with regular drills (i.e., fire);
14. Test the broader emergency plan with simulation exercises.

## D. Medical Equipment and Supplies to Deliver Care

The hospital needs to anchor the most important medical equipment against seismic forces. An exhaustive list of recommendations for protecting the hospital's important medical equipment is outside the scope of this report, but such recommendations should include those below. In addition, the hospital should ensure that medical supplies necessary to deliver care are secured so that they are available to treat the influx of patients expected after the earthquake. Simple, very inexpensive measures to restrain supplies and equipment against toppling and sliding during shaking will go a long way toward reducing interior disruption, cleanup and loss of supplies. If the hospital staff are focused on cleaning up the mess created by the earthquake, it will strain staff resources because this is the time when the injured will begin arriving in significant numbers following the earthquake, seeking care.

1. Anchor X-ray machine to the floor and ceiling joists to prevent damage;
2. Anchor main sterilizer in OT to the floor to prevent toppling;
3. Store dangerous chemicals currently kept on open shelves or benchtops in the laboratory in seismically secure locations, such as on shelves with seismic shelf restraints;
4. Install latches on refrigerator doors and secure them to prevent toppling;
5. Secure laboratory benchtop equipment;
6. Tether radiant warmers to prevent damage caused by rolling into walls or other equipment, or by toppling;
7. Anchor racks and shelves to the walls or floor, and install shelf restraints;
8. When purchasing new equipment, include seismic anchorage as part of the contract.

The assessment team recommends that the hospital implement the mitigation measures discussed above, according to the priorities in Table 16. GHI also suggests that any of the recommended mitigation measures that can be easily accomplished should be done as soon as possible, regardless of the priorities set in the table.

**Table 16. Suggested priorities for mitigation measures to address vulnerabilities**

| Mitigation Measure | Number | Priority Level (1 Highest) |
|---|---|---|
| Increase emergency generator fuel supply | B.1 | 1 |
| Anchor emergency generator | B.2 | 1 |
| Provide backup communications | B.6 | 1 |
| Develop emergency plan | C.1-2 | 1 |
| Train staff | C.9-11 | 1 |
| Restrain medical supplies and unsecured metal racks in medical store | D.7 | 1 |
| Secure hazardous chemicals in laboratory and medical store | D.3 | 1 |
| Provide fire suppression capability | B.17 | 1 |
| Plan to retrofit or replace older, seismically deficient buildings over time | A.5-7 | 1 |
| Obtain engineering geological evaluation of rock fall hazards, including a rockfall runout assessment using specific modeling software | A.1 | 2 |

| **Mitigation Measure** | **Number** | **Priority Level (1 Highest)** |
|---|---|---|
| Assess seismic stability of retaining walls | A.2 | 2 |
| Provide additional connection to main supply for staff quarters so water storage tank supplies medical buildings only; | B.9 | 2 |
| Add water storage capacity | B.10 | 2 |
| Obtain a second, functional emergency generator | B.3 | 3 |
| Have transformer anchored by Bhutan Power Corporation | B.4 | 3 |
| Anchor other parts of electrical system | B.5 | 3 |
| Seismically protect important medical and laboratory equipment such as X-ray machine, autoclave, radiant warmers and medical refrigerators | D.1-2,4-6 | 3 |
| Request that Department of Engineering Services determine (by experimental testing) whether typical geyser anchorage detail is adequate for seismic forces | B.14 | 3 |
| Store medical gas cylinders in seismically protected racks | B.16 | 3 |
| Improve stability of interior partitions and anchor exterior brick walls that project out from frame | A.4 | 4 |
| Anchor cupboards and racks inside main building | D.7 | 4 |
| Provide flexible connectors for services crossing seismic joints and other areas where differential movement is expected | B.13 | 5 |
| If operational performance in a rare event is desirable, analyze main building to determine likely performance and potential measures to improve performance | A.3 | 5 |

The recommended mitigation measures and priorities must be weighed with practicality and costs. The evaluation team does not have complete knowledge of the immediate availability of resources or funding processes, though some consideration is reflected in the priorities of Table 16.

Overall, the team's highest priority recommendations are to:

- Strengthen the hospital's backup water and electrical power systems; this will substantially increase the hospital's ability to remain functional after a strong earthquake;
- Write an emergency plan that provides guidance for hospital operations following a damaging earthquake and train staff to respond effectively following an earthquake;
- Obtain backup communications to enable contact with Ministry of Health officials in Thimphu;
- Store dangerous chemicals properly so they will not fall and spill during minor shaking; this is simple and costs almost nothing, but the safety impact is large;
- Provide fire suppression capability; and
- Replace or retrofit buildings vulnerable to collapse or life-threatening damage.

Furthermore, the team strongly recommends that the Ministry of Health assign more than one doctor to Trashigang District Hospital, and provide the staff necessary to reopen the Operation Theatre. In a disaster such as a major earthquake, the medical response will be severely hampered if the current staffing situation persists. This is a significant emergency response and preparedness issue.

## Conclusions

The consequences of many of Trashigang hospital's numerous vulnerabilities can be mitigated with reasonable measures, allowing the hospital to remain at least minimally functional following strong but not devastating earthquakes. Much of the hospital was recently built, and most of these newer buildings should withstand moderately strong shaking, up to the design level, without life-threatening damage. More extensive investment in seismic upgrades to buildings and infrastructure would be necessary for the hospital to be able to continue delivering essential medical care following very large earthquakes. The hospital's older buildings are of types known to engineers to be vulnerable to life-threatening damage in strong shaking such as that caused by the shallow M6.1 and the massive M8.6 earthquakes; these buildings should be strengthened or replaced to reduce the threats to staff living in them. In addition, several of the masonry support buildings have characteristics that make them vulnerable to life-threatening damage in strong to very strong shaking. While hospital function depends on facilities and infrastructure, it also depends on people to deliver medical care. Medical professionals and the staff who support them must be kept safe so they will be able to carry out their responsibilities following an earthquake.

While this report and the companion report on Trashiyangtse hospital cover two key facilities in eastern Bhutan, these hospitals are part of Bhutan's medical care delivery system, which includes outreach clinics and Basic Health Units, district hospitals in other districts, and the regional and national referral hospitals. Some of these facilities – including the Jigme Dorji Wangchuck National Referral Hospital and some Basic Health Units - have been evaluated for potential earthquake vulnerabilities, but most have not. The medical care system relies on communications as well as transportation, medical professionals, and equipment within the system.

The hospital's ability to function depends on interdependent off-site transportation and utility systems, which are beyond the scope of this report. Trashigang's geographic isolation means that the hospital will keenly feel the effects of disruptions to these systems. Electric power, generator fuel, communication systems, water supply and road transportation are interdependent and critical to the hospital's ability to function. The hospital's ability to provide care depends on restoring grid power quickly and on opening supply routes to bring fuel, additional supplies and medicines in, and to transport referral patients out. To help understand the potential effects of road blockages and utility disruption, GHI recommends that the hospital test its emergency plan (once created) by conducting a "tabletop" scenario exercise with a timeline that extends one month after a major earthquake, and which involves not only the Ministry of Health but also those responsible for roads, municipal water supply and electrical power.

The assessment team also recommends that Ministry of Health conduct a broader, integrated assessment of potential earthquake vulnerabilities in Bhutan's health system, in addition to supporting assessments of individual facilities.

In this report, the team has provided a detailed list of specific recommendations that address the vulnerabilities identified in the Trashigang District Hospital's site, buildings, utility infrastructure, equipment, contents and level of preparedness. GHI recommends that the hospital begin working immediately to implement these recommendations to improve the facility's performance; some items, such as storing chemicals properly, are very simple and do not require special budget allocations. The hospital should act on these recommendations immediately. Some mitigation and preparedness measures necessary to help keep the hospital functional will take time to implement, and will need to be planned and phased over a number of years. The hospital should be able to make substantial improvements in safety in the current Five Year Plan period by implementing as many of the high priority recommendations as possible. With a safer facility and a more prepared staff, the Trashigang District Hospital will be in a much better position to serve Trashigang's residents following a damaging earthquake.

# Appendix A –Performance Summary for Scenario Earthquakes

**Table 17. Performance of buildings in hypothetical scenario earthquakes; damage states defined in Table 1; functional stat color codes defined in Table 9**

| Building Name | Construction Type | Year Built | No. of Stories (incl. ground) | **Likely Performance in Hypothetical Scenario Earthquake** (Structure and shell left; equipment, pipes, & contents center, functional color code right) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Deep M7 Light Shaking | | | Shallow M6.1 Strong Shaking | | | M8.6 Violent Shaking | | |
| | | | | PGA 0.11 g | | | PGA 0.58g | | | PGA 1.18g | | |
| | | | | Utilities available | | | Utilities extremely limited | | | Utilities not available | | |
| | | | | Struct | Equip | Code | Struct | Equip | Code | Struct | Equip | Code |
| Main Hospital building | RC w/brick infill | 2002-4 | 2 | S1 | N1 | | S2 | N2 | | S3** | N3 | |
| Old Hospital building | Nonductile RC w/infill | 1975 | 2 | S1 | | | S3-S4 | | | S4 | | |
| Physiotherapy building | RC w/brick infill | 2002-4 | 3 | S1 | | | S2 | | | S3 | | |
| Admin/Medical Store | RC w/brick infill | 2002-4 | 2 | S1 | N2 | | S2 | N3 | | S3 | N3 | |
| Prayer Hall | Unreinforced brick masonry | 2002-4 | 1 | S2 | | | S4 | | | S4 | | |
| Laundry | Brick masonry w/seismic band | 2002-4 | 1 | S2 | | | S3 | | | S4 | | |
| Kitchen/Bath | Brick masonry w/seismic band | 2002-4 | 1 | S1 | | | S2 | | | S4 | | |
| Incinerator | Brick masonry w/seismic band | 2002-4 | 1 | S2 | | | S3 | | | S4 | | |
| Generator House | Brick masonry w/seismic band | 2002-4 | 1 | S1 | N1 | | S2 | N2 | | S4 | N3 | |
| Bungalows | URM* | 1970s | 1 | S2 | | | S4 | | | S4 | | |
| Duplexes | RC w/brick infill | 2002-4 | 2 | S1 | | | S2 | | | S3 | | |
| Newer Fourplexes | RC w/brick infill | 2002-4 | 2 | S1 | | | S2 | | | S3 | | |
| Older Fourplex | Unreinforced stone masonry* | 1980s | 2 | S2 | | | S3 | | | S4 | | |
| Support Staff Quarters | RC w/brick infill | 2002-4 | 2 | S1 | | | S2 | | | S3 | | |
| Attendant Guesthouse | Brick masonry w/seismic band | 2002-4 | 1 | S1 | | | S3 | | | S4 | | |
| Old OPD | Ekra/brick URM | 1970s | 1 | S1 | | | S3 | | | S4 | | |
| Caretaker's Residence | Brick masonry w/seismic band | 2002-4 | 1 | S1 | | | S2 | | | S3 | | |

RC = reinforced concrete; URM = unreinforced masonry; PGA = peak ground acceleration

* Exact construction material type and details are not known; assumed type is most vulnerable of likely structural system types. Vulnerability rating may improve if better, more earthquake-resistant construction can be verified.

** Second storey conference room is S4 due to anticipated dynamic amplification of earthquake shaking.

**Table 18. Performance of key utilities in hypothetical scenario earthquakes**

| **System** | **Likely Performance in Hypothetical Scenario Earthquake** | | |
|---|---|---|---|
| | Deep M7<br>Light Shaking<br>PGA = 0.11g | Shallow M6.1<br>Strong Shaking<br>PGA = 0.58g | M8.6<br>Violent Shaking<br>PGA = 1.18g |
| **Electric Power from off-site supply** | May be short interruption of power | Interruptions of power are likely to be longer than 24 hours | Long interruptions of power should be expected |
| **Electric Power from on-site generators** | Generator operational; power available while fuel lasts | Generator and associated equipment may be damaged but still operational; fuel will run out before power is restored | Generators and electrical equipment damaged and not operational. Expect that power will not be available until replacement generator from off site is delivered and damaged equipment is repaired in an estimated 3 weeks or more. |
| **Water from off-site system** | Water supply may be disrupted, but could be repaired within a few days. | Water supply probably disrupted and could take days to reestablish. | Water supply damaged and not repaired for extensive length of time. |
| **Water from on-site storage** | | | |
| Domestic | Available until tank supply depleted; water rationing could allow sufficient water. | Likely insufficient. | Insufficient. |
| Filtered Drinking | Generally available but dependent on supply of domestic water. | Some filters damaged; supply limited by domestic water. | Not sufficient; many filters damaged; domestic supply quickly depleted. |
| **Communications** | | | |
| Landline phones/ switchboard | Probably operational | Service probably interrupted | Not operational for days to weeks, depending on damage and repair time |
| Mobile phones | Network unavailable for several hours | Network unavailable for hours to days | Network unavailable for days to weeks, depending on damage to towers and infrastructure and repair time |
| **Medical Gas** | | | |
| Oxygen and Nitrogen | Supply adequate but cylinders likely to roll down and block door. | Supply likely to be adequate but cylinders likely to roll down and block door | Supply likely inadequate. |

PGA = peak ground acceleration