Initial Seismic Vulnerability Assessment of Trashiyangtse District Hospital Trashiyangtse, Bhutan

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Prepared by

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Executive Summary

Trashiyangtse is one of Bhutan's most remote districts. The 20-bed Trashiyangtse District Hospital, located in Trashiyangtse town is the only hospital in the district. The closest facility outside the district is Trashigang District hospital, more than two hours' drive over steep mountain roads that traverse landslide-susceptible terrain. The nearest regional referral hospital, at Mongar, is a further several hours over similarly mountainous roads. A major earthquake will trigger numerous landslides that will block these roads and take days to weeks to clear. With road access cut off, Trashiyangtse Hospital will be the only source of hospital-level medical care in the district in the critical period following a major earthquake. 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. Due to concerns about medical care delivery following an eastern Bhutan earthquake, the assessment program also included Trashigang District Hospital in the adjacent Trashigang District.

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 Trashiyangtse District Hospital and Trashigang District Hospital in August to December 2013. This report presents the GHI assessment team's findings and recommendations.

Evaluation team members obtained the information included in this report through conducting in-person evaluations of buildings and infrastructure over two days at the hospital site; reviewing available structural and architectural drawings, satellite imagery and photographs; interviewing or holding discussions with the hospital's administrators; 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) and relevant literature. 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, and as part of a health-system-wide effort to prepare for the next major earthquake.

The assessment team identified a number of seismic vulnerabilities in the hospital's buildings, on-site backup utility systems, medical equipment and contents, and emergency preparedness. Earthquake damage resulting from these vulnerabilities will reduce the hospital's ability to continue providing essential medical care after a major earthquake. In addition, the team observed a potential debris flow hazard that warrants further investigation.

This report discusses the consequences of the anticipated earthquake damage, and most importantly, presents recommendations to improve medical response and care delivery during the early recovery period. The report introduces three hospital impact scenarios, or postulated responses to earthquake events. Each scenario is based on a hypothetical earthquake and is intended to illustrate the range of earthquake shaking – and ensuing damage and consequences – that the hospital should consider for risk mitigation and emergency planning purposes. The three hypothetical earthquakes are: (1) a magnitude 7 (M7) earthquake occurring deep beneath and to the south of Trashiyangtse that creates widespread moderate shaking; (2) a shallow M6 earthquake occurring directly beneath Trashiyangtse 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. This report defines *functionality* as the combination of building usability – determined by damage to the building, important equipment and contents – and availability of critical utility services supplied by on-site backup systems. 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 all contribute to uncertainty in the performance level. In a real earthquake, each building could be one performance level higher or lower than shown here; a single expected performance level is shown for illustrative purposes.

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

LEGEND:

- COLLAPSED OR PARTIALLY COLLAPSED
- NOT USABLE NOR FUNCTIONAL
- MARGINALLY USABLE BUT NOT FUNCTIONAL
- FUNCTIONAL AFTER CLEANUP / MINOR REPAIR
- FUNCTIONAL

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

LEGEND:

- COLLAPSED OR PARTIALLY COLLAPSED
- NOT USABLE NOR FUNCTIONAL
- MARGINALLY USABLE BUT NOT FUNCTIONAL
- FUNCTIONAL AFTER CLEANUP / MINOR REPAIR
- FUNCTIONAL

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

Many of Trashiyangtse District Hospital's seismic vulnerabilities can be mitigated with reasonable measures, allowing the hospital to remain at least minimally functional following strong but not devastating earthquakes. Because the hospital was recently built, its 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 postulated here.

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

- Provide emergency water storage;
- Strengthen the hospital's backup electrical power system; this will 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; and
- 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.

The report contains detailed, specific recommendations that address 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 safety and performance; some items, such as storing chemicals properly or anchoring shelving, are very simple and do not require special budget allocations. The hospital should implement such recommendations immediately. Some mitigation and preparedness measures necessary to help keep the hospital functional will require planning and several years to implement. The hospital should be able to make substantial improvements in safety in several years, though, by implementing as many of the high priority recommendations as possible. Making the facility safer, and better preparing the staff, will help Trashiyangtse District Hospital continue to deliver medical care to Trashiyangtse residents following a damaging earthquake.

Contents

Introduction

Trashiyangtse district was a sub-division under the Trashigang District until 1992, when it became a separate, full -fledged district. Trashiyangtse has eight blocks—Bumdeling, Jamkhar, Khamdang, Ramjar, Tongzhang, Yangtse, Toetsho, and Yalang—and 3645 households. Trashiyangtse is 54 kilometers from Trashigang, from which Thimphu, the capital of Bhutan, is another 550 kilometers. Trashiyangtse is one of the most remote districts in Bhutan. The roads connecting Trashiyangtse to Trashigang and to the rest of Bhutan cross high mountain passes, span major rivers, and in many places are cut into steeply sloping terrain that experiences many landslides during each monsoon. Strong earthquake shaking would trigger numerous landslides that will block these roads, which are Trashiyangtse's lifeline to the outside world. Days or weeks could pass before outside help reaches Trashiyangtse, meaning the hospital staff would face the demands created by a major earthquake alone and without assistance. Trashiyangtse District Hospital's staff and facility must be prepared in order to serve their community at their time of greatest need.

In August, 2013, Geohazards International (GHI) performed an initial seismic vulnerability assessment of the Trashiyangtse District Hospital, along with a companion assessment of the next nearest district hospital, Trashigang District Hospital in Trashigang. The goal of the Trashiyangtse hospital assessment is to provide the hospital, the Ministry of Health, World Health Organization (WHO) Bhutan and Regional Office for South-East Asia (SEARO) with an overview of the seismic vulnerabilities of the hospital and recommend actions to improve its ability to deliver medical care following a major earthquake affecting Trashiyangtse. 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 and Project Manager; 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, relevant 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 Applied Technology Council's Report ATC-58-1 *Guidelines for 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 (which comprise the Hospital building, the kitchen/store building, and the medical store building), on-site utility infrastructure, and staff quarters. Some smaller buildings on the hospital campus, such as storage sheds and toilet blocks, are likewise excluded from the scope of this report. Evaluations of the site's several retaining walls are outside the scope of this initial assessment. The team observed evidence of a potential flash flood and debris flow hazard, and was told that a flash flood had occurred near the site, but assessing the risk such events may pose to the hospital 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 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 20-bed Trashiyangtse District Hospital was constructed between 1996 and 1998 with funding from the Government of India. The hospital was designed in the offices of the precursor agency to the current Health Infrastructure Development Division (HIDD) by engineers on deputation from the Central Public Works Department (CPWD) of the Government of India. Gaseb Construction built the hospital, and the team was informed by HIDD that that an engineer would have been posted to the site full time to oversee all construction work.

Buildings

The hospital campus includes a main hospital building, a medical store building, combination kitchen and non-drug medical store building, and three staff quarters. 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. All the hospital's buildings were built at the same time as the main building with Government of India funding. The medical store building and the kitchen/ store building are also a ground-plus-one-storey reinforced concrete frame buildings. The ground floor of the medical store building was built as a garage, and one side of it now houses an autoclave used for sterilizing medical waste. The kitchen/store has the kitchen on the ground floor, and the upper floor serves as store rooms for the hospital and the administration.

The site contains three staff residences, ranging from ground-plus-one-storey to ground-plus-two-storey buildings. The staff quarters are standard designs created by the same CPWD engineering group.

Identical staff quarters can be found at the Jigme Dorji Wangchuck National Referral Hospital in Thimphu. The site plan in Figure 1 below shows the hospital's buildings, color coded by use.

Figure 1. Site plan with buildings color-coded by use

Infrastructure and Utility Services

The hospital's electric power supply comes from the local grid. The hospital has two generators but only one, which has a capacity of 63 KVA, is functioning. The diesel generator is housed in a stone masonry building on a hill above the main hospital building. Diesel fuel for the generators is brought in drums by truck and stored in barrels located adjacent to the generator in the generator house, and the hospital can store up to 375 L of fuel. The generator consumes approximately 20 L of diesel fuel per hour.

Water supply is from the municipal source and feeds into a 500L plastic (Sintex) tank. The supply line serves both the hospital and the staff quarters. This is also the source of water for fire suppression, if required. There are no boilers and no 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. 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 of Health's Medical Supply Depot (MSD) in Phuentsholing. The hospital stores around 40 cylinders, and about 20-30 cylinders are brought per shift every six months or as and when required. The hospital does not have a bulk oxygen tank. Most of the hospital's medical supplies are kept in the two medical store buildings. Supplies are procured from the MSD in Phuentsholing on a half yearly basis and also as and when required. The hospital also provides supplies to at least one nearby Basic Health Unit (BHU).

Location, Site Conditions and Potential Site Hazards

Location and Site Conditions

The Trashiyangtse District Hospital is located on a hill reached just before entering the Trashiyangtse town. The hospital sits on alluvial fan deposits on the east bank of the Kulung Chhu valley, south of Chorten Kora as Figure 2 and 3 show. Figure 4 shows the location of the hospital's buildings and infrastructure, with respect to access roads and topographic features.

Figure 2. Hospital location in Trashiyangtse area

Figure 3. Topography near the hospital, looking south from a hill near the new Trashiyangtse Dzong

Figure 4. Hospital buildings, local access road, and on-site utility infrastructure locations

Geotechnical reports were not available for the hospital. The site has large stone masonry retaining walls below the main building and between the main building and the staff quarters as Figure 5 shows. According to HIDD, at the time the hospital was 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.

Figure 5. Retaining walls between main building and doctor's quarters (left); below main building (right)

From discussions with HIDD engineers, the evaluation team understands that no portion of the hospital building was built on fill, though fill might underlie parking areas. 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 storm water 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 and geologic conditions, drainage conditions and the major retaining walls.

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. This threat of landslides is evident in the mountains above Trashiyangtse, where steep west-facing slopes and drainages provide source material and conduits for channelized debris flows. Debris flows are moving masses of mud and rock containing an abundance of coarse-grained material. Debris flows often initiate on steep slopes as rock slides triggered by heavy rainfall, snowmelt, or earthquake ground shaking that then enter a rapidly flowing drainage channel. These turbulent masses of fluidized material entrain additional material as the debris flow continues downslope. The zone of deposition for debris flows depends on the velocity of the debris flow, sinuosity of the channel, and slope gradient.

Intermittent debris flows originating in the mountains above Trashiyangtse over the last many thousands of years have deposited a large alluvial fan complex upon which the hospital and Trashiyangtse Town are located. Debris flows continue to be active on the landscape with historical reports of debris flows depositing large boulders and material on the fan slopes just north of the hospital (Figure 6).

Figure 6. Boulders in rice terraces north of hospital that may have been deposited by debris flow

The relative age of deposits on the fan surface can be estimated by geomorphic analysis. Older fan surfaces are higher in elevation and more heavily dissected than younger fan surfaces. Older fan surfaces are often more heavily vegetated and expose fewer coarse deposits such as boulders than younger fan surfaces. Preliminary interpretations of Google Earth imagery and site photographs indicate that the Trashiyangtse Hospital is located on a relatively older fan surface, labeled Qf4 (Quaternary fan 4, where Quaternary refers to the current geologic time period) in Figure 7. The active drainage channel is bounded by the youngest and most active fan deposits (Qf1) with successively older fan surfaces stepping away from the active channel. The potential for a large debris flow to affect Trashiyangtse hospital is considered low due to the relative age of the Qf4; however, a detailed debris flow hazard study is recommended for this site.

Figure 7. Oblique view of the west facing hill slope and fan surfaces at Trashiyangtse. Preliminary interpretation of fan surfaces shown as Qf1 – Qf5 (youngest to oldest) are outlined in white, debris flow paths are shown in light blue, and active stream channels are shown in dark blue.

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, and 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[1]. Additional recent evidence suggests a smaller but damaging event occurred in the last several hundred years, possibly in 1713[2]. 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, and the 2011 M6.9 Sikkim-Nepal border earthquake.

While numerous earthquakes of different magnitudes in varied locations could affect Trashiyangtse, 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 between Trashiyangtse and Trashigang;
2. A shallow earthquake of magnitude 6.1 (M6), which is roughly the size of the 2009 Mongar earthquake, but occurring directly beneath Trashiyangtse; and
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 M6.1 and M8.6 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 some distance beneath the main plate boundary fault; a number of earthquakes have occurred on similar faults[3]. The M7 earthquake is centered 35 km deep beneath the main plate boundary fault, creating widespread but lower levels of shaking. The M6.1 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 close to the hospital site and 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.

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[1] 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.

[2] 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*.

[3] 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).

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)[4] 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

Collapsing buildings cause the majority of deaths in most earthquakes. As a result, the first and most important task in a vulnerability assessment is to 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 states listed in Table 1. Please note that building usability does not equal functionality: the hospital will 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 (basic medical care delivered under conditions of duress, or when supplies or equipment are insufficient for normal emergency medical 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.

[4] 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.

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 condoned off. A few partitions may be cracked and/or have pieces fallen
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	Useable spaces not maintained, or building is unsafe
Equipment, Pipes and Contents[3]		
Damage State		**Building Usability[2]**
N1 Light		Building is 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 building, and medical store buildings

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 conduits, 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 contains buildings 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 limited architectural drawings and on discussions with Health Infrastructure Development Division engineers, it appears that only the hospital's reinforced concrete frame buildings were likely designed using modern earthquake-resistant building codes developed in India, albeit at least one version older than the current version. However, this should be verified. The unreinforced stone masonry generator building does not have seismic bands or other earthquake resistant features. As a result, the generator building is expected to experience more damage than will the concrete frame buildings.

Using the three hypothetical scenario earthquakes as illustrative examples of moderate, major and severe earthquakes, 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.

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.

The hospital's buildings were designed by Government of India Central Public Works Department engineers in 1994-1995. These engineers should have been aware that IS 13920 was published in 1993, but it is possible that due to posting in Bhutan they were not aware of the new code. **For this reason, field verification of earthquake-resistant details is necessary to confirm the performance levels assumed in this document.** A very small number of structural drawings were available for the main building, for the roof trusses and stairs. These drawings do not provide any information about whether the reinforced concrete members have ductile detailing or not. Architectural drawings were available for the main building, and should be available for the standard plan staff quarters, though the team did not have access to all of them.

India also has a standard, IS 4326 *Earthquake Resistant Design and Construction of Buildings —Code of Practice*, intended to improve the earthquake resistance of masonry bearing wall buildings. This standard was released in 1993 and was 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, but the generator building does not appear to have the IS 4326-prescribed seismic bands and vertical bars.

Main Hospital Building and Support Buildings

The main hospital building, shown in Figure 8, was built in 1996-1998 with funding from the Government of India. The Lhuentse District Hospital was also built with this same design. The building is a reinforced concrete frame building with masonry infill walls. Most of the building is ground-plus-one-storey, with a small ground-plus-two-storey central portion containing offices, including the District Medical Officer's (DMO) office; this portion of the building will encounter more damage in severe shaking, as will be noted in the hospital impact scenarios. On the front side of the building, the first storey has architectural brick walls that project out beyond the columns to mimic the rabsey (window assemblies) in traditional Bhutanese buildings. These brick walls are not in line with the frame, and as a result they are more likely to topple outward. Normal infill walls in line with the frame are surrounded and confined by the beams and columns, and are less likely to fall out . Bricks from projecting infill walls can fall and create a hazard for people down below.

Figure 8. Exterior view of Trashiyangtse District Hospital

The building steps back at each end; Figure 9 shows the configuration of the ground storey with a terrace above. The back side of the main building is structurally and architecturally simpler, as the right photo in Figure 9shows; note that plumbing runs on the outside of the buildings. Figure 10 shows an architectural ground floor plan, one of the few drawings available for the hospital.

Figure 9. Side view (left) and back view (right) of Hospital building

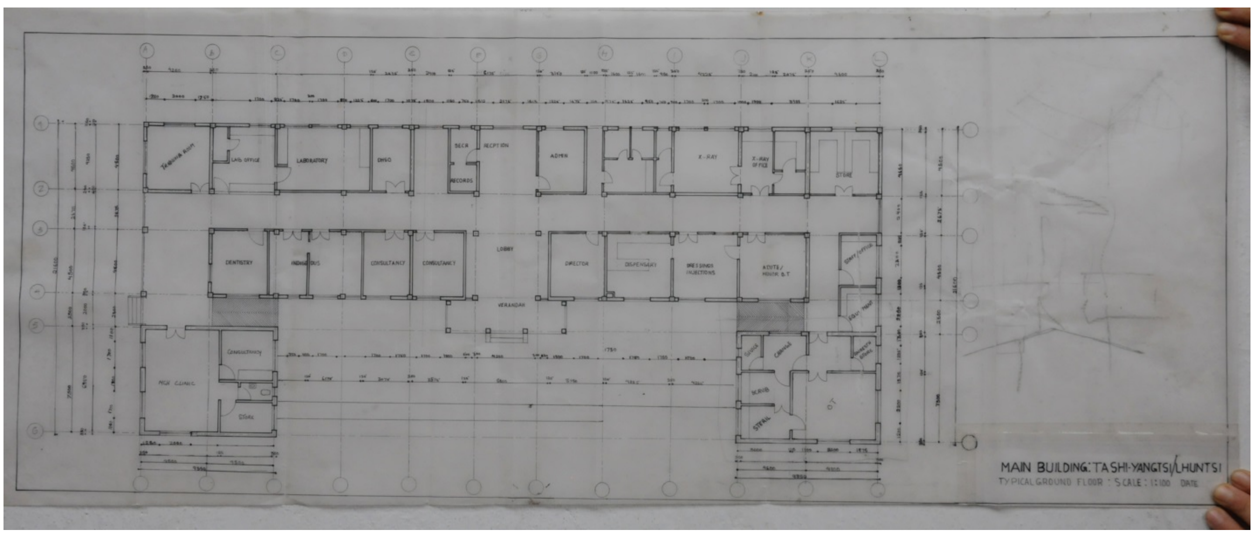


Figure 10. Architectural ground floor plan of main hospital building

The medical store building, shown in Figure 11, was built at the same time as the main hospital building, also with funding from the Government of India. The building is a ground-plus-one-storey reinforced concrete frame building. The ground floor was built as a car garage, but one side was closed in with stone masonry walls and now houses an autoclave machine for sterilizing medical waste before it goes to the municipal disposal. Because of the garage, the building has a relatively open ground storey with fewer walls than the storey above. In past earthquakes elsewhere, buildings with open ground storeys have performed poorly, with many collapsing. Though there are some solid walls in the transverse (short plan dimension) direction, the ground storey in the longitudinal (long plan dimension) direction is open and appears much weaker than the storey above.

Figure 11. Front (left) and side (right) views of the medical store building

The kitchen and non-drug medical store building, shown in Figure 12, is a ground-plus-one-storey building constructed together with the main hospital building. It is a reinforced concrete frame building with masonry infill walls. The building also has architectural brick walls that project out beyond the frame, similar to those on the main building.

Figure 12. Side view of the kitchen and non-drug medical store building (left); brick walls projecting beyond frame (right)

The generator building is a stone masonry bearing wall building housing the hospital's backup generators and associated equipment and fuel. The stone walls are 440mm thick including finishes, and appear to be double wythe. According to HIDD, the walls are not reinforced, and the building does not have earthquake resistant features such as a seismic band. It is not clear whether the stone walls have "through stones" (long stones that connect the inner and outer wythes together). The walls are quite tall, there is no roof diaphragm, and there is no seismic band, meaning that the stone walls are quite vulnerable to earthquake damage.

Figure 13. Generator 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 0.12g		PGA 0.44g		PGA 1.02g	
				Struct	Equip	Struct	Equip	Struct	Equip
Main Hospital Building	RC w/ brick infill	1998	2*	S1	N1	S2	N2	S3**	N3
Medical Store Building	RC w/ brick infill	1998	2	S1	N2	S3	N2	S4	n/a
Kitchen and Non-drug Medical Store Building	RC w/ brick infill	1998	2	S1	N2	S2	N2	S2	N3
Generator Building	Unreinforced stone masonry	1998	1	S2	N1	S3	N2	S4	n/a

1 Damage states are defined in Table 1
RC = reinforced concrete, PGA = peak ground acceleration
* Has partial second storey in *jamthog* that contains offices and storage
** S4 for partial second storey containing offices

Staff Quarters

Trashiyangtse District Hospital has three staff quarters within the hospital area, built from three separate standard plans at the same time as the main hospital building. Structural drawings were not available for any of the staff quarters. The team understands from HIDD that the buildings were designed in the mid-1990s. The quarters house hospital staff and their families.

Type I Fourplex Doctors' Quarters

The hospital has a building with four quarters for doctors and senior staff, shown in Figure 14. These reinforced concrete ground-plus-one-storey buildings were designed by HIDD and constructed from 1997-1998. HIDD refers to these buildings as "Type I" quarters. Buildings constructed from this same plan are present at Jigme Dorji Wangchuck National Referral Hospital (JDWNRH). The building has double wythe brick exterior walls and single wythe interior brick partitions. The front of the building has architectural brick projections in the first storey, which can fall from the frame much more easily than normal infill walls that are in line with and therefore restrained by the frame. Bricks from these walls create a falling hazard for anyone who happens to be down below.

Figure 14. Type I Fourplex Doctor's Quarters

Type II Nurses' Quarters

The hospital has one building that is a Type II nurses' quarters building constructed at the same time as the main hospital building. The "Type II" is a standard plan building, and there are a number of identical buildings at JDWNRH. It is a reinforced concrete frame building with masonry infill walls, with a very large step in elevation – almost a half storey - at the center of the building. The top storey has brick architectural projections that can fall during strong shaking.

Figure 15. Type II Nurses' quarters

Type III Nurses Quarters

There is one Type III ground-plus-two-storey building housing staff working at the hospital. The building was built in 1997-1998 from standard plans designed in HIDD. As is the case with the Type I and Type II staff quarters, buildings constructed from the same standard plans are also located at the Jigme Dorji Wangchuck National Referral hospital. The building has a reinforced concrete frame, presumably with ductile seismic detailing per the Indian Standard IS 13920, and brick masonry infill walls. Like the other staff quarters at the site, the building has architectural brick projections in the top storey, which can fall from the frame much more easily than normal infill walls.

Figure 16. The ground-plus-two storey staff quarters front view (left) and side view (right, with generator building in front)

Table 3 shows the likely performance of various staff quarters in the three hypothetical scenario earthquakes considered in this report.

Table 3. Likely performance of staff quarters in hypothetical scenario earthquakes

Building Name	**Construction Type**	**Year Built**	**No. of Storeys (incl. ground)**	**Likely Performance in Hypothetical Scenario Earthquake[1]**		
				Deep M7	Shallow M6.1	M8.6
				Light Shaking	Strong Shaking	Violent Shaking
				PGA 0.12g	PGA 0.44g	PGA 1.02g
Type I Fourplex Doctors Quarters	RC w/ brick infill	1998	2	S1	S2	S3
Type II Nurses Quarters	RC w/ brick infill	1998	3	S1	S2	S3-S4*
Type III Nurses Quarters	RC w/ brick infill	1998	3	S1	S2	S3-S4*

1 Damage states are defined in Table 1

RC = reinforced concrete, PGA = peak ground acceleration

* Anticipated performance depends to a large extent on presence or absence of ductile seismic detailing; better performance is anticipated if ductile detailing exists.

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 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 each of 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 hospital does not have its own transformer on site to receive grid power; the nearest transformer is a 10-minute walk away. The team was unable to observe this transformer. It is essential for the transformer to be appropriately and adequately bolted, and 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.

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. Trashiyangtse District Hospital has two generators, but only one generator with 63 KVa capacity is functional at present. Figure 17 shows the functional generator, which sits unrestrained on rubber shoe isolators, and is likely to slide off of its base during earthquake shaking. The muffler is not braced, and can be damaged by shaking, which may prevent the generator from operating. The batteries that enable the generator to start are not anchored (see Figure 18) and may break or become disconnected. The diesel fuel storage tank is likewise unanchored and may slide during shaking, breaking the fuel lines. Moreover, the generator is in an unreinforced stone masonry building that is likely to be badly damaged or even collapse in strong shaking.


Figure 17. Emergency generator (left); non-seismic generator vibration isolators that cannot prevent the generator from sliding (right)

Figure 18. Unanchored generator batteries (left) and unanchored diesel fuel tank (right)

The generator has a tank that holds 225L, and 150L of additional fuel is stored in barrels in the generator house. The generator uses 20L of fuel per hour. This means the fuel supply will last for at most 18 hours of operation at full capacity. If power can be used only for lighting after an earthquake, then the supply of fuel could last longer, perhaps 50 hours in a best-case scenario.

The Pan American Health Organization (PAHO) recommends that hospitals have a fuel supply sufficient to last five days (120 hours). Given Trashiyangtse'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.

The team recommends procuring at least one more emergency generator for Trashiyangtse hospital, as overheating of generators during extended use is a common problem. The hospital maintenance staff reported that Trashiyangtse's generator had overheated after four hours of continuous use. Having one more generator would allow use of generators on a rotational basis to prevent overheating. Similarly, the team recommends that the hospital store coolant on site for the generators to avoid this overheating problem.

The team observed a small electrical cabinet that may not have the necessary anchorage to prevent overturning. The team recommends that an electrician determine whether the electrical cabinet is anchored, and if it is not, to then work with an engineer to anchor it properly.

Table 4 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 4. Likely performance of on-site electrical system in hypothetical scenario earthquakes

System	Likely Performance in Hypothetical Scenario Earthquake		
	Deep M7 Light Shaking PGA = 0.12g	Shallow M6.1 Strong Shaking PGA = 0.44g	M8.6 Violent Shaking PGA = 1.02g
Electric Power from off-site supply	Possible 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	Emergency generator may still function. Fuel not stored in large supply at site, and coolant not stored at all, so may be inadequate.	Generator and associated equipment may be damaged. Coolant not available.	Generator will not be operational, as battery and electrical equipment will be damaged. Power will not be available until generators from off-site are delivered and/or damaged equipment repaired in 3-4 weeks or more.

PGA = peak ground acceleration

Medical Gas System

The medical gas system relies on cylinders that are taken to the locations within the hospital where they are needed. The hospital does not have piped oxygen supply, a central manifold for cylinders, or a bulk oxygen tank. Medical gas cylinders are stored inside the medical store and the empty cylinders are stacked under the stairs going up to the store. The hospital stores around 40 cylinders and procures 20-30 cylinders from the Medical Supply Depot in Phuentsholing on a half yearly basis and as required. The hospital uses an average of 3-4 cylinders per month, with a maximum usage of 5-6 cylinders per month. PAHO recommends that hospitals maintain a 15-day supply of medical gas, so the supply maintained by the hospital should be adequate, even with a higher usage rate following an earthquake due to the influx of patients. Due to landslides blocking the roads to Phuentsholing after a major earthquake, resupply would not be available for weeks, if the hospital happened to need more medical gas. However, there is no anchorage system for the cylinders, and in case of strong earthquake shaking the cylinders could roll around on the floor and start leaking. Leaking oxygen is a fire and explosion hazard.

Figure 19. Empty medical gas cylinders stored under the medical store stairway (left), cylinders stored in the hospital dressing room (right)

Table 5 shows the likely performance of the medical gas system in the three hypothetical scenario earthquakes.

Table 5. Likely performance of medical gas systems in hypothetical scenario earthquakes

System	Likely Performance in Hypothetical Scenario Earthquake		
	Deep M7 Light Shaking PGA = 0.12g	Shallow M6.1 Strong Shaking PGA = 0.44g	M8.6 Violent Shaking PGA = 1.02g
Medical Gas			
Oxygen and Nitrogen	Supply adequate.	Cylinders are stored in a heap in medical store and could roll around and leak, a fire and explosion hazard. Supply adequate.	Supply probably adequate. Resupply not available for weeks at minimum.

PGA = peak ground acceleration

Domestic and Drinking Water Systems

Under normal operating conditions, the hospital receives water from the municipal 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 current water storage capacity consists of a single 500L plastic (Sintex) tank. The hospital does not have any additional tank. PAHO recommends that hospitals have domestic water storage capacity of 300L per bed per day, for at least three days (72 hours). For 20 beds, the hospital should have 6000L per day of domestic water per the PAHO recommendation. The staff quarters do not appear to have any emergency water supply.

Given Trashiyangtse's geographic isolation, the hospital should have water storage for an additional period of time that should be determined based on the estimated time required to restore city water service. For normal usage levels, the tank has a supply adequate for less than a day; the hospital staff reports that the backup supply is adequate for only about four hours. The staff quarters should have a water supply and backup water storage capacity that is separate from that serving the main hospital.

Figure 20. Trashiyangtse Hospital water tank (left) and drinking water filter in front of the medical ward (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 hospital should obtain an estimate of the likely time needed to restore city water service.

The present tank has a capacity of only 500L and the quantity of water is not at all sufficient, even for daily hospital usage and for the staff living on the premises during normal times. The present tank is also not anchored and in case of strong earthquake shaking the tank could fall off and disrupt what little supply is available. There is need to establish a water tank of at least 18,000L capacity to ensure 300L of water per bed per day as per the PAHO recommendations.

Drinking water is provided by filtering domestic water using filter units. However, the team noticed only one such filter available in the OPD and ward floor of the hospital. The filter is not anchored sufficiently and may fall and break during strong shaking. Therefore, the team recommends installing more filter units and anchoring them appropriately to ensure some supply of drinking water after a major earthquake. Otherwise water will need to be treated or boiled. The supply of drinking water is also dependent on the availability of domestic water.

Table 6 shows the likely performance of the hospital’s water systems in the three hypothetical scenario earthquakes.

Table 6. Likely performance of water systems in hypothetical scenario earthquakes

System	Likely Performance in Hypothetical Scenario Earthquake		
	Deep M7 Light Shaking PGA = 0.12g	Shallow M6.1 Strong Shaking PGA = 0.44g	M8.6 Violent Shaking PGA = 1.02g
Water from off-site system	Water supply may be disrupted, but could be repaired prior to exhaustion of on-site tank.	Water supply probably disrupted and could take days to re-establish.	Water supply damaged and not repaired for extensive length of time.
Water from on-site storage			
Domestic	Supply from tank and distribution system inadequate if city water supply disrupted.	Supply from tank and distribution system inadequate.	Supply from tank and distribution system inadequate.
Filtered Drinking	Inadequate supply due to disruption in domestic supply and few number of filtration units, which may be damaged by earthquake shaking.	Supply limit as per domestic water. The few filter units available may break due to poor or no anchoring.	Filters will not be functional. Water will need to be boiled or treated, and availability will be limited by domestic supply.

PGA = peak ground acceleration

Communication Systems

The hospital currently uses both landline and mobile phones as its major communication systems. The hospital does not have other backup communications. During the 6.1M Narang 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 were no major damages to the mobile towers and the communication 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 larger earthquake like the M7 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 and should obtain a backup communications system. Having the means to communicate with Trashigang and Thimphu is especially important given the likelihood of lengthy road blockages caused by landslides after a major earthquake. . Table 7 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 7. Assumed performance of communication systems in hypothetical scenario earthquakes

System	Assumed Performance in Hypothetical Scenario Earthquake		
	Deep M7 Light Shaking PGA = 0.12g	Shallow M6.1 Strong Shaking PGA = 0.44g	M8.6 Violent Shaking PGA = 1.02g
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

Wastewater System

The hospital depends on a municipal system for wastewater disposal. An assessment of the city system to following strong earthquake shaking was outside the scope of this report, but this information should be obtained. The evaluation team understands that the hospital is planning to install its own soak pit because the current toilet block overflows and backs up. The soak pit originally built with the hospital seems to have been constructed on private land, and the new private owner of the land disconnected the soak pit. The hospital's wastewater system has cast iron (CI) pipes.

Ramps, Stairs and Exit Pathways

The main hospital building has a reinforced concrete ramp structure at the back, which is separated from the main building by a seismic joint. The ramp seems to have been designed for seismic resistance but may warrant further investigation; it is the only exit (and entrance) to the first floor wards and would be essential in any evacuation. The hospital should also consider installing a second exit from one of the terraces at the ends of the building.

Figure 21. Ramp behind the main hospital building leading to the operation theatre and the ward

The team noticed that many doors and exits were partially blocked by boxes, cupboards, racks or old equipment and furniture. The team recommends that all exits be open and cleared of stored items that could block the exit route during emergencies.

Figure 22. Large cupboards near entry into consultation rooms (above and below left), large TV stand by main entry into the hospital (above right); items stored in hallway leading to the operation theater (below 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 Trashiyangtse 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

Trashiyangtse Hospital has several pieces of specialized and costly medical equipment, shown in Figures 23-25. The equipment used most often is the laboratory equipment, X-ray equipment, and radiant warmers for newborn babies (there are 10-12 deliveries per month at the hospital). Most of the equipment is critical to the ability of the hospital to deliver essential medical services, but it is not properly anchored or tethered. The team recommends that the hospital assess existing equipment and begin anchoring it to help prevent earthquake damage.

Figure 23. Various unanchored medical equipment in Trashiyangtse Hospital

Figure 24. X-ray machine (left) with ceiling rail inadequately anchored to resist shaking (right)

Figure 25. Unrestrained benchtop laboratory equipment

Contents and Furnishings

In several areas of the hospital building and medical store, important items such as medicines and sterile surgical instruments are stored on unanchored shelving that may topple in an earthquake or on countertops where they can slide off (Figure 26). In both the medical store and non-drug medical store, glass bottles were near the edge of shelves without any shelf restraints. In the non-drug medical store, some of these bottles contained poisonous or flammable chemicals. In the case of strong shaking, the bottles could fall and break, which could cause a chemical hazard to staff trying to enter and retrieve supplies.

Figure 26. Sterile instruments unsecured on counter in dressing room (left); toxic, flammable and other potential harmful chemicals in glass bottles unrestrained on shelf in non-drug medical store (right)

Figure 27. Medicines stocked in medical store above garage (left); glass bottles on racks near entrance (right)

Figure 28. Supplies stacked above a staff desk in the medical store (left); potential ignition sources (stove and geyser) in laboratory may cause a fire following an earthquake (right)

The team observed desks and work stations located near heavy shelves that could topple and injure staff members during an earthquake (see Figure 27). In all of these locations, unrestrained items will fall, become disorganized or ruined, and require time-consuming cleanup or restocking. Simple and inexpensive hardware to anchor shelving to walls or floor, combined with shelf restraint systems, can prevent this from happening.

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.

Brick Partitions

As mentioned earlier in the buildings section, the hospital has single wythe (i.e., one brick thick) brick partitions, double wythe (two bricks thick) infill walls, and brick walls that create architectural projections in the upper stories. These latter walls are on the outside of the frame line and are therefore not confined by the frame. The single wythe partitions and the walls outside the frame are especially vulnerable to earthquake damage. Because such partitions can fail, medical equipment should not be anchored to them. Instead, the evaluation team recommends that equipment be anchored to floor-to-ceiling supports called *strongbacks*.

The hospital should anchor or otherwise mitigate the falling hazard created by the walls outside the frame line directly above the main OPD entrance shown in Figure 29.

Figure 29. Brick architectural projection walls, a falling hazard, above the main OPD entrance.

Ceilings

The hospital has pre-laminated particle board ceiling that is 10-12 mm thick and appears to be firmly attached to ceiling joists. These ceilings are much less vulnerable than other suspended ceiling types such as lay-in acoustical tile.

The hospital 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

Trashiyangtse 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. Most resupply items come from the Medical Supply Depot in Phuenstholing, 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 Trashiyangtse to Trashigang and to other parts of the country. Following a major earthquake, it may take days or weeks to reopen the lateral road and the road to Samdrup Jongkhar. 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 from Trashiyangtse 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 sewer system and solid waste disposal may suffer significant interruptions in regular service 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.

In the 2009 earthquake in Narang, Mongar, in eastern Bhutan, the health sector infrastructure suffered major damages, with 45 health facilities reporting damages, including one Basic Health Unit that collapsed. Three district hospitals—Trashigang, Mongar and Lhuentse—reported minor repairable damages[5]. It is evident that in a major earthquake the smaller out-reach facilities (built by the communities or private contractors) will fail, forcing people to congregate and seek medical care at the district hospitals.

Emergency Planning

The evaluation team discussed with the hospital's Medical Officer the importance of risk reduction and emergency preparedness in hospitals to ensure functionality during emergencies. 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

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

that have tested its abilities and systems in place to deliver emergency medical care. Shaking from the 2009 Mongar earthquake was not strong in Trashiyangtse, so the hospital's capacity was not tested.

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 between Trashiyangtse and Trashigang; (2) a shallow M6.1 earthquake occurring directly beneath Trashiyangtse; 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 the worst case scenarios.

The following sections describe for each scenario that the evaluation team considered:

- an overview of possible infrastructure and building damage in the earthquake-affected area; and
- a description of the earthquake damage and consequences likely to occur at the hospital, as a result of the vulnerabilities identified in prior sections.

The scenarios have intentionally been kept simple and are intended to give the reader a snapshot of the hospital's performance following each hypothetical earthquake. Much more detailed scenarios—with a longer timeline for larger earthquakes, due to disruptions in the transportation and utility systems—would be used for emergency planning purposes. In the final section of this report, the team provides recommendations for actions that will reduce earthquake damage to the hospital and lessen protect hospital functionality post-earthquake.

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. Table 8 defines the likely functional states by color codes used to present a graphical overview for each scenario. Summary tables in Appendix A provide damage states, functional states and utility performance for all three scenarios.

Table 8. 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 For residences: damaged; may not be habitable	S1 / S2 plus N3 Or S2 plus N2	Not available
Yellow	Functional after cleanup / minor repair For residences: damaged: habitable with cleanup	S2 plus N1 (if applicable) or S1/S2 plus N2	Available
Green	Functional For residences: habitable	S1 plus N1 (if applicable)	Available

Scenario 1: Hypothetical Deep M7 Earthquake Occurring Near Trashiyangtse

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 and southern Trashiyangtse district. Though not especially strong, the shaking is felt throughout most of eastern Bhutan. Figure 30shows 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 Trashiyangtse 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 Trashiyangtse and Trashigang 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 and Trashigang as well as the roads continuing to Yonphula Airport and Mongar.

Inside the hospital, staff and patients feel the earthquake shaking and are unsure of what to do. A few unrestrained supplies fall from carts and shelves. Dangerous chemicals fall from shelves in the medical store and non-drug store, preventing staff from entering to retrieve additional supplies for more than a day. 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 safe. They notice some small cracks on the walls of some of their quarters. 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 in Thimphu to report what has happened and the situation at the hospital.

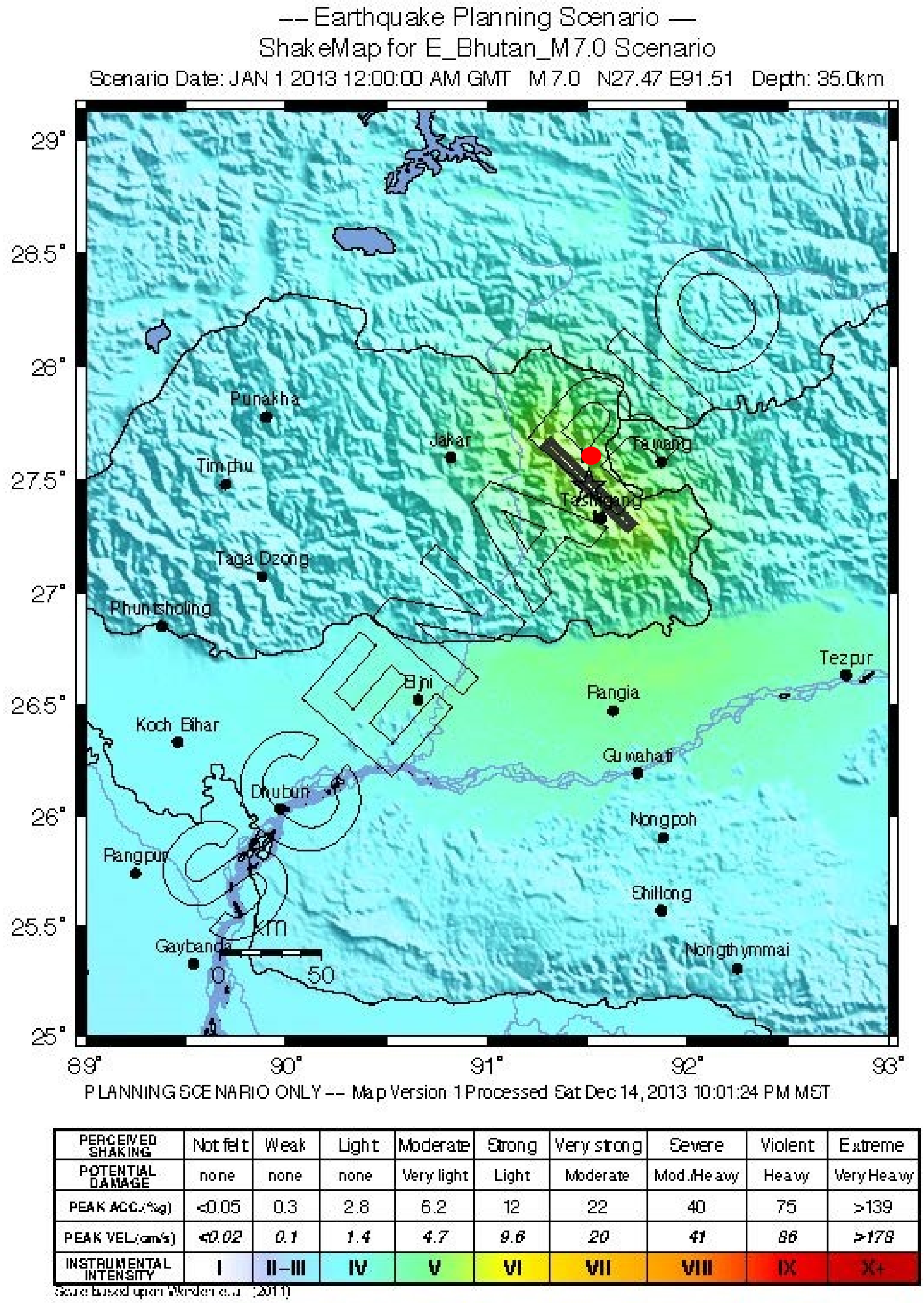


Figure 30. Median estimate of potential ground shaking intensity from deep M7 hypothetical scenario earthquake between Trashiyangtse and Trashigang, courtesy USGS. A red dot indicates Trashiyangtse hospital. The black box indicates the portion of the fault that ruptured during the earthquake.

The injured begin arriving from the town almost immediately. The main injuries people have suffered are lacerations from falling objects, including stones. Several people have suffered fractures and other more serious injuries. Over the next several days, additional injured people arrive from villages. The widespread nature of the shaking and damage cause the patient load at Trashiyangtse hospital to be much higher than normal, and supplies are depleted quickly. It takes several days to clear the landslides on the roads to Trashigang Hospital and onward to Yonphula airport and Mongar Regional Referral Hospital. Several patients have been badly injured by building collapses and are transferred out to the Jigme Dorji Wangchuck National Referral Hospital in Thimphu by helicopter, with some difficulty because the hospital does not have a helipad and the nearest large open ground is at the school near the main town area, a little more than a kilometer and a half away. The road between the hospital and the school crosses gentle slopes, and it has not been affected by landslides.

District engineers arrive to inspect the hospital's buildings. The only building that has suffered structural damage is the unreinforced stone masonry generator building. All the other buildings only have minor cracking of finishes and partitions. Table 9 shows the anticipated damage states (defined in Table 1) for the hospital's buildings for this deep M7 hypothetical scenario earthquake.

Table 9. Likely damage states for buildings in deep M7 hypothetical scenario earthquake

Building Name	**Construction Type**	**Year Built**	**No. of Storeys (incl. ground)**	**Likely Performance in deep M7 Hypothetical Scenario Earthquake** PGA 0.12 g	
				Structure & Shell	Equip & Contents
Medical and Support Buildings					
Main Hospital Building	RC w/ brick infill	1998	2	S1	N1
Medical Store Building	RC w/ brick infill	1998	2	S1	N2
Kitchen and Non-drug Medical Store Building	RC w/ brick infill	1998	2	S1	N2
Generator Building	Unreinforced stone masonry	Post 1998	1	S2	N1
Staff Quarters					
Type I Fourplex Doctors Quarters	RC w/ brick infill	1998	2	S1	
Type II Nurses Quarters	RC w/ brick infill	1998	3	S1	
Type III Nurses Quarters	RC w/ brick infill	1998	3	S1	

RC = reinforced concrete; PGA = peak ground acceleration

The generator remains functional though there is some minor disruption inside the generator building. The hospital has its power restored quickly, so the generator fuel lasts long enough. The city water system suffers minor disruption, and because the hospital has no appreciable water storage capacity, the water in the single small Sintex tank quickly runs out. The hospital is without water after the first four hours of the response. Because most roads are open, some of the support staff are able to secure water from other sources, such as streams, but it must be boiled first. Water service is restored within a day, but the water shortage has caused some difficulties for the hospital. Table 10 shows the anticipated performance of key utility systems in the deep M7 hypothetical scenario earthquake.

Table 10. Likely performance of key utility systems in deep M7 hypothetical scenario earthquake

System	**Likely Performance in deep M7 Hypothetical Scenario Earthquake**, PGA = 0.12g
Electric Power from off-site supply	May experience short interruption of power
Electric Power from on-site generators	Emergency generator may still function. Fuel and coolant not stored at site, so supply may be inadequate.
Water from off-site system	Water supply may be disrupted, but could be repaired within a few days.
Water from on-site storage	
Domestic	Supply from tank and distribution system inadequate if city water supply disrupted
Filtered Drinking	Inadequate supply due to disruption in domestic supply and few number of filtration units, which may be damaged by earthquake shaking
Communications	
Landline phones	Probably operational
Mobile phones	Network unavailable for several hours
Medical Gas	
Oxygen and Nitrogen	Supply adequate.

PGA = peak ground acceleration

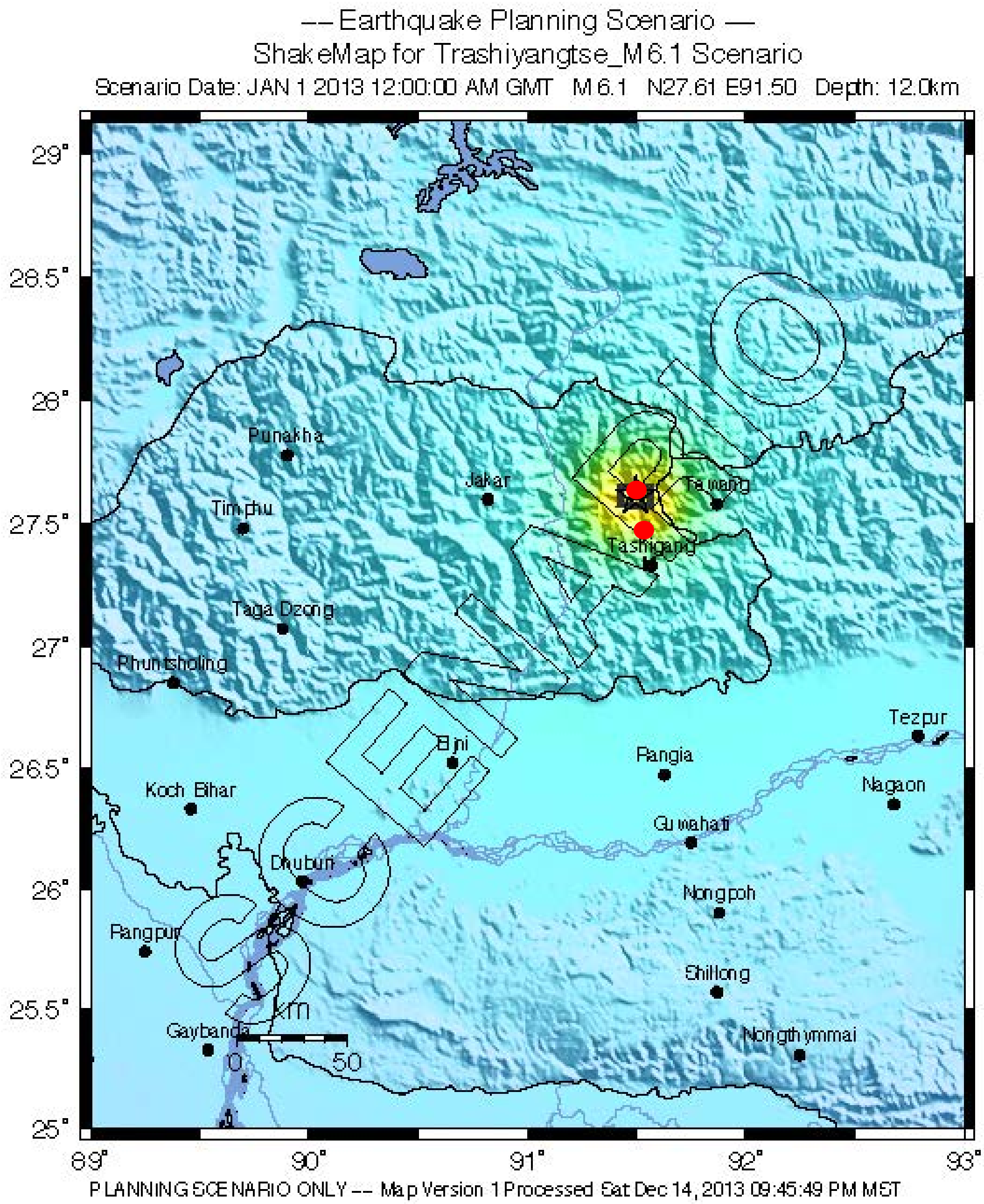
Figure 31 shows the anticipated performance of the hospital's buildings, in terms of functionality. Each building could be one performance level higher or lower than shown due to uncertainty in the nature of ground shaking, and in the team's existing knowledge of site conditions and building systems. One performance level is shown for illustrative purposes. The hospital keeps staff and patients safe, but the loss of water and supplies reduces the quality of care and the ability of the hospital to treat the injured.

Figure 31. Likely performance of hospital buildings in deep M7 hypothetical scenario earthquake

Scenario 2: Hypothetical Shallow M6.1 Earthquake Occurring Directly Beneath Trashiyangtse

Early on a weekday morning, a moderately sized but shallow M6.1 earthquake occurs directly beneath Trashiyangtse. The shaking in the town area is quite strong, but the most intense shaking does not affect a large area. The shaking is strong enough to badly damage a number of unreinforced stone masonry buildings in the town area, and a number of buildings collapse. Several landslides completely block the road to Trashigang, and rocks fall onto the road in many locations. People from Trashiyangtse town begin to arrive at the hospital with injured relatives and neighbors almost immediately. Figure 32 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 hospital's location. 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.

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 shelves in the medical stores and break on the floor, spilling dangerous chemicals. Staff cannot go in to retrieve the extra supplies they desperately need to treat the many people who are injured. As the injured begin to arrive, the staff tries to clean up the mess, wondering whether the building is safe with the many cracks in the brick walls. The X-ray machine dislocates from its rails and is badly damaged, which hinders efforts to treat those with fractures. The small sterilizers fall from countertops and are damaged. Sterile instruments fall to the ground and are no longer sterile. The lack of interior stairwells creates difficulties for staff trying to move within the building.



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 32. Median estimate of potential ground shaking intensity from shallow M6.1 hypothetical scenario earthquake near Trashiyangtse courtesy USGS. A red dot indicates the hospital location. The black box indicates the portion of the fault that ruptured during the earthquake.

The main building has suffered significant cracking to partitions and to brick walls that project outside the concrete frame. Parts of the walls over the entrance canopy (surrounding the nurses station) have fallen out; people arriving with the injured question the safety of the building. The district engineer arrives and notes that there is no significant structural damage, except to the offices on the second floor. He helps assure people that they can use the building. The other buildings also suffer damage to their brick infill walls, and some bricks fall from the upper storey brick walls that project outside the frame. The generator building experiences major cracking.

Table 11 shows the damage states (defined in Table 1) that the team anticipates the shallow M6.1 hypothetical scenario earthquake will cause.

Table 11. Likely damage states for hospital buildings after shallow M6.1 hypothetical scenario earthquake

Building Name	**Construction Type**	**Year Built**	**No. of Storeys (incl. ground)**	**Likely Performance in M6.1 Hypothetical Scenario Earthquake**, PGA 0.25g	
				Structure & Shell	Equip & Contents
Medical and Support Buildings					
Main Hospital Building	RC w/ brick infill	1998	2	S2	N2
Medical Store Building	RC w/ brick infill	1998	2	S3	N2
Kitchen and Non-drug Medical Store Building	RC w/ brick infill	1998	2	S2	N2
Generator Building	Unreinforced stone masonry	Post 1998	1	S3	N2
Staff Quarters					
Type I Fourplex Doctors Quarters	RC w/ brick infill	1998	2	S2	
Type II Nurses Quarters	RC w/ brick infill	1998	3	S2	
Type III Nurses Quarters	RC w/ brick infill	1998	3	S2	

RC = reinforced concrete; PGA = peak ground acceleration

Table 12 shows the anticipated performance of the most important utility systems in the shallow M6.1 hypothetical scenario earthquake. The loss of water after 4 hours impairs the hospital's ability to function and consumes scarce staff time, as staff members must locate a source of water and arrange to have it brought to the hospital and boiled. Community members can help, but many are busy with injured family members and damage to their own homes. The power goes out, and it takes some effort to get the generator going, because the batteries have fallen down and become disconnected. The maintenance staff is able to repair the damage but the hospital is without power for a crucial hour or more. The generator has to be shut down every four hours to prevent overheating, creating difficulties for the medical staff, who are trying to treat the many injured people. Mobile phone service is down, and landline service is interrupted. For a time, there is no way to get word to either Trashigang or Thimphu about the situation in Trashiyangtse.

Table 12. Likely performance of key utility systems in shallow M6.1 hypothetical scenario earthquake

System	**Likely Performance in Hypothetical M6.1 Scenario Earthquake**, PGA = 0.44g
Electric Power from off-site	Interruptions of power are likely to be longer than 24 hours

supply	
Electric Power from on-site generator	Generator and associated equipment may be damaged. Coolant not available.
Water from off-site system	Water supply probably disrupted and could take days to reestablish.
Water from on-site storage	
Domestic	Supply from tank and distribution system inadequate.
Filtered Drinking	Supply limit as per domestic water. The few filter units available may break due to poor or no anchoring.
Communications	
Landline phones	Service probably interrupted.
Mobile phones	Network unavailable for hours to days
Medical Gas	
Oxygen and Nitrogen	Cylinders are stored in a heap in medical store and could roll around and leak, and lead to fire and explosion hazard. Supply adequate.

PGA = peak ground acceleration

Figure 33 shows the anticipated performance of the hospital's buildings, in terms of functionality. Without a backup water supply, the hospital's functionality suffers due to the off-site water system outage. The main building is damaged but useable, but with only 20 beds, a small medical staff, and the loss of equipment and supplies, the hospital's capacity is severely taxed.

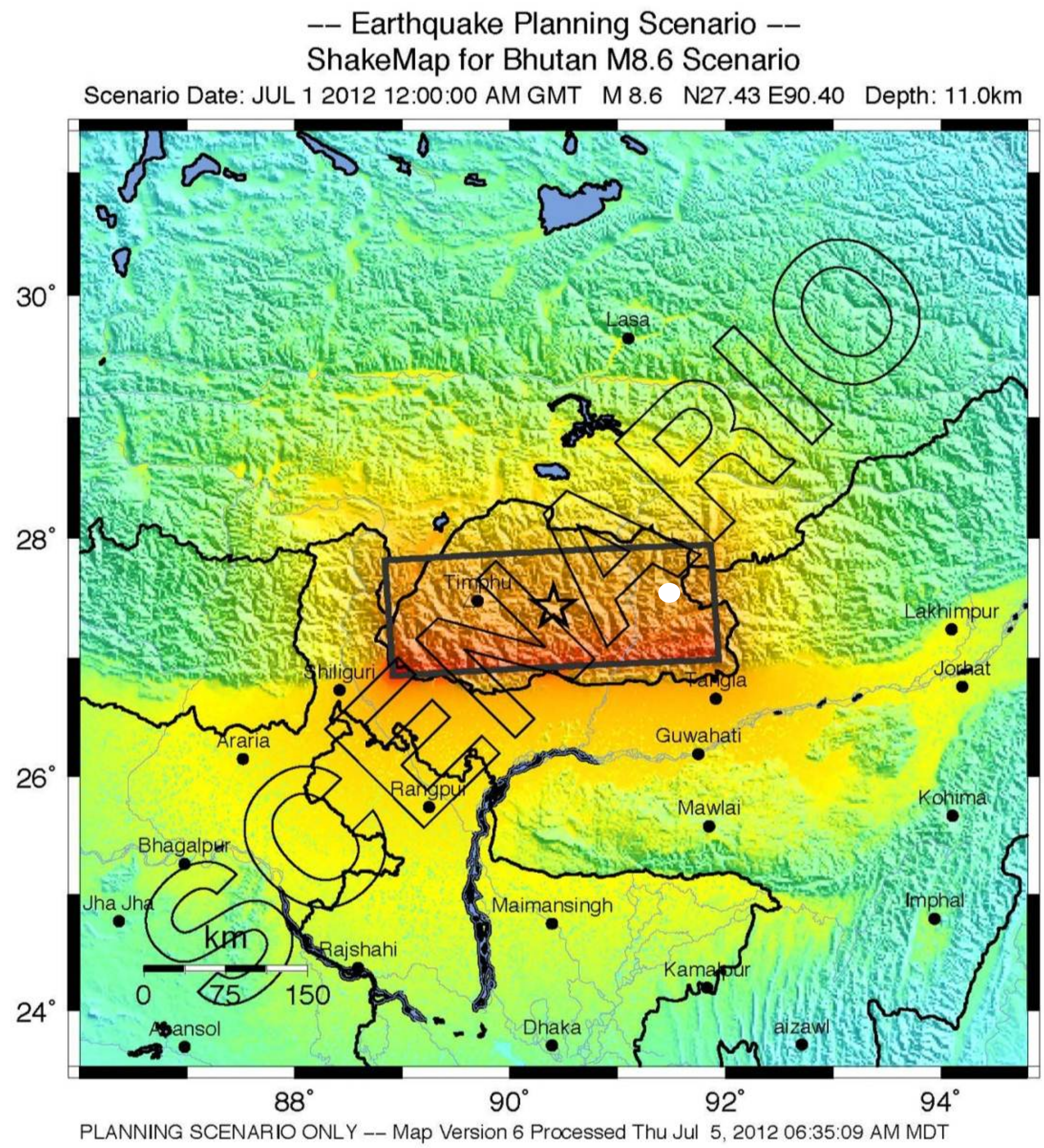
Figure 33. Site plan showing performance of hospital buildings in M6.1 hypothetical scenario earthquake

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 34 shows an estimated distribution of median shaking intensity for this hypothetical earthquake, provided by the USGS using their ShakeMap system. The box indicates the portion of the fault that ruptured to generate the earthquake. In Trashiyangtse, 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. Most of the stone masonry buildings in Trashiyangtse have at least partially collapsed. The road to Trashigang is blocked by a number of large landslides, and some sections of the road have simply disappeared down into the river valley below. The roads that connect eastern Bhutan to the outside world have suffered severe landslide damage, and most will be blocked for weeks. Key bridges have collapsed in multiple locations. Road clearing proceeds slowly across the country, hampered by a shortage of equipment and workers, as Dantak (part of India’s Border Roads Organisation) is stretched very thin.

Inside the hospital, the strong shaking tosses furniture, equipment and supplies about, creating chaos. Partitions break, and entire walls in the upper stories of buildings fall down to the ground below. The shaking is so strong that people cannot walk or stand. All of the hospital’s buildings suffer structural damage, and the generator building collapses. The open storey in the medical store collapses. The main building remains standing, but the second floor conference room partially collapses. The hospital is too badly damaged to use, and everyone evacuates.



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 34. Median estimate of potential ground shaking intensity from M8.6 hypothetical scenario earthquake on the main plate boundary fault, courtesy USGS. A white dot indicates the location of Trashiyangtse hospital. The black box indicates the portion of the fault that ruptured during the earthquake.

The medical staff begins trying to treat the injured in the parking area in front of the main building, but some have been injured themselves. They retrieve whatever supplies they can from the main hospital building. They cannot enter the non-drug medical store because of the toxic vapors from spilled chemicals. Staff members must take risks to retrieve supplies from the partially collapsed medical store. With few supplies, no power, no water, and no communications, the staff can provide only austere care. Many of the badly injured will die before outside help arrives many days later. With most of Bhutan and a large swath of northeast India devastated, the remote district of Trashiyangtse is not even on the radar of international relief agencies.

Table 13 shows the damage states (defined in Table 1) that the evaluation team anticipates the M8.6 hypothetical scenario earthquake will cause.

Table 13. 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 Hypothetical Scenario Earthquake** PGA 1.02g	
				Structure & Shell	Equip & Contents
Medical and Support Buildings					
Main Hospital Building	RC w/ brick infill	1998	2	S3*	N3
Medical Store Building	RC w/ brick infill	1998	2	S4	n/a
Kitchen and Non-drug Medical Store Building	RC w/ brick infill	1998	2	S2	N3
Generator Building	Unreinforced stone masonry	Post 1998	1	S4	n/a
Staff Quarters					
Type I Fourplex Doctors Quarters	RC w/ brick infill	1998	2	S3	
Type II Nurses Quarters	RC w/ brick infill	1998	3	S3-S4**	
Type III Nurses Quarters	RC w/ brick infill	1998	3	S3-S4**	

RC = reinforced concrete; URM = unreinforced masonry, PGA = peak ground acceleration
* S4 for partial second floor containing offices
** Anticipated performance depends to a large extent on presence or absence of ductile seismic detailing; better performance is anticipated if ductile detailing exists.

Table 14 shows the anticipated performance of the most important utility systems in the M8.6 hypothetical scenario earthquake. The offsite utility systems are badly damaged by earthquakes and landslides. At the hospital, the generator slides from its supports, and the day tank overturns before the generator building collapses on top of them. The backup electrical power system will have to be completely replaced; it might take months to get a new generator delivered. The water tank slides off its platform, breaking the pipes, but it would have only provided four hours of water anyway. City water service will be out for much longer –likely weeks to months.

Table 14. Likely performance of key utilities in M8.6 hypothetical scenario earthquake

System	Likely Performance in M8.6 Hypothetical Scenario Earthquake, PGA = 1.02g
Electric Power from off-site supply	Long interruptions of power should be expected
Electric Power from on-site generators	Generator will not be operational, as battery and electrical equipment will be damaged. Power will not be available until generators from off-site are delivered and/or damaged equipment repaired in 3-4 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	Supply from tank and distribution system inadequate
Filtered Drinking	Filters will not be functional. Water will need to be boiled or treated, and availability will be limited by domestic supply
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 probably adequate. Resupply not available for weeks at minimum.

PGA = peak ground acceleration

Figure 35 below shows the anticipated performance of the hospital's buildings, in terms of functionality. The hospital remains standing but is too badly damaged to be useable.

Figure 35. 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 M7 or M8.6 hypothetical scenarios described above, GHI strongly recommends that the hospital take immediate action to begin improving the hospital's ability to deliver medical services after a major earthquake. Trashiyangtse is a remote district, and in a major earthquake there is a high possibility of its fragile road network leading toward Trashigang and Thimphu being 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 serve the district's population alone. The outreach clinics and Basic Health Units, given their performance in the last 2009 earthquake, may suffer structural damages and be unable to deliver services, which would mean people from rural villages in northern Trashiyangtse district would need to walk to Trashiyangtse 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 during emergencies.

Recommendations to Improve Seismic Performance

A functional hospital must have safe, usable 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 Trashiyangtse District 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 debris flow hazard study of the Trashiyangtse area to model the potential for debris flows to affect the hospital site. This study should include detailed geologic and geomorphic mapping, quantification of debris flow volumes, calculated velocities, modeling of deposition areas, and mitigation recommendations. If age and timing of past debris flows can be obtained, a probabilistic hazard assessment can be calculated to assist selection of potential mitigation recommendations.

Main hospital building:

3. Verify that the building has ductile seismic detailing per Indian Standard 13920, through either non-destructive testing or limited destructive evaluation.

4. A qualified structural engineer should conduct nonlinear analyses (meaning computer analyses that include mathematical representations of the ways that the building's structural members

become damaged), if a decision is made that the hospital should remain functional even after severe shaking. The analyses should consider 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. 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. Such an analysis would make possible an estimate of the he need, costs and benefits of strengthening the building, or of parts like the second floor offices that may suffer greater damage.

5. Have a qualified structural engineer design a partition bracing system that satisfies infection control requirements, or replace single-wythe brick partitions in critical areas (such as OT) with lightweight partitions. 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.

6. Tie the walls that present a falling hazard back into the building frame. The front side of the main building has exterior architectural brick walls that are not confined by the frame ("outfill" as opposed to infill walls). The walls over the main OPD entrance are particularly important to address right away.

Other buildings:

7. Retrofit or replace the generator building.
8. If the hospital is to remain functional, Retrofit or replace the medical store
9. Verify the presence of ductile seismic detailing per Indian Standard 13920, and conduct structural analyses of the reinforced concrete staff quarters and kitchen / non-drug medical store buildings, to verify that they provide life safety for the expected level of ground shaking in a major earthquake.
10. Restrain the exterior architectural brick walls that are not confined by the frame ("outfill" as opposed to infill walls) in the kitchen / non-drug medical store.

B. Strengthening Utility Systems and Backup Capabilities

Detailed recommendations for each major utility system are listed below.

Electrical system:

1. Provide additional fuel sufficient to last the number of days deemed necessary, but five days minimum.
2. Anchor the backup generator that supplies emergency power, including the batteries, fuel tank and muffler.
3. Obtain a second, functional backup generator and ensure it is seismically protected when installed.
4. Request Bhutan Power Corporation to ensure that the connection to the grid power system is seismically robust.

5. Anchor unanchored electrical cabinets at the base to prevent overturning.

Communications systems:

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

Water system:

8. Provide emergency water storage tank with sufficient capacity to last until city water supply is restored, but provide 300L per bed per day for 3 days (18,000L) minimum.
9. Provide emergency water storage for staff quarters, separate from hospital water storage and supply.
10. Ensure that water filtration units in the main hospital building are anchored or placed so they will not fall and become damaged.
11. Ensure that geysers are not anchored to single wythe partitions;
12. Request that Department of Engineering Services determine (by experimental testing) whether typical geyser anchorage detail is adequate for design seismic forces.

Medical gas system:

13. Store cylinders in seismically protected racks, where they cannot roll or topple.
14. Restrain unsecured cylinders in medical care areas.

Ramps, stairs and exit pathways:

15. Provide a second exit from the first storey ward area; there is currently only one exit, via the ramp at the back of the building.

C. Planning and Preparedness

1. Form a committee, with representatives from all 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, from utility service providers, 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 Trashiyangtse's geographic isolation from resupply sources, the length of time recommended in international standards likely will not be sufficient.
6. Arrange with district engineer for immediate safety inspection of hospital buildings, following an earthquake. Provide training on post-earthquake safety inspection.
7. Develop an evacuation policy and procedures.
8. Ensure that all staff are familiar with the hospital's emergency plan and know their role in it.
9. Provide earthquake safety training for staff.
10. 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.
11. Establish recurring training, so that new staff members receive emergency preparedness and earthquake safety training.
12. Test specific aspects of the emergency plan with regular drills (i.e., fire).
13. 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 to ceiling joists to prevent damage.
2. Store dangerous chemicals currently kept on open shelves in the medical stores and laboratory in seismically secure locations, such as on shelves with seismic shelf restraints.
3. Install latches on refrigerator doors and secure the appliances to prevent toppling.
4. Secure laboratory bench-top equipment.
5. Tether radiant warmers to prevent damage caused by rolling into walls or other equipment, or by toppling.
6. Anchor unsecured racks and shelves to the walls or floor, and install shelf restraints.
7. 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 15. 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 15. Suggested priorities for mitigation measures to address earthquake vulnerabilities

Mitigation Measure	Number	Priority Level (1 Highest)
Provide emergency water storage capacity	B.8	1
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.8-10	1
Restrain medical supplies and unsecured metal racks in both medical stores	D.6	1
Secure hazardous chemicals in laboratory and non-drug medical store	D.2	1
Replace or retrofit generator building	A.7	2
Verify that main hospital building and other reinforced concrete buildings contain ductile seismic detailing per Indian Standard 13920	A.3,9	2
Seismically protect important medical and laboratory equipment such as X-ray machine, radiant warmers and medical refrigerators	D.1,4-5	2
Assess seismic stability of retaining walls	A.1	2
Perform debris flow hazard study	A.2	3
Obtain a second, functional emergency generator	B.3	3
Anchor other parts of electrical system	B.4,5	3
Request that Department of Engineering Services determine (by experimental testing) whether typical geyser anchorage detail is adequate for seismic forces	B.11	3
Store medical gas cylinders in seismically protected racks	B.12	3
Improve stability of interior partitions and anchor exterior brick walls that project out from frame	A.5,6	4
Anchor cupboards and racks inside main building	D.6	4
Provide a second exit from the first floor ward	B.14	5
If operational performance in a massive earthquake event is desirable, analyze main building to determine likely performance and potential measures to improve performance	A.4	5

The recommended mitigation measures and priorities must be weighed with practicality and costs. Although these are considerations in Table 15, the evaluation team does not have complete knowledge of the immediate availability of resources or funding processes.

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

- Provide emergency water storage;
- Strengthen the hospital's backup electrical power system; 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; and
- 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.

Conclusions

Many of Trashiyangtse District Hospital's seismic vulnerabilities can be mitigated with reasonable measures, allowing the hospital to remain at least minimally functional following strong but not devastating earthquakes. Because the hospital was recently built, its buildings should withstand moderately strong shaking, up to the design level, without collapse. Most buildings have upper story architectural walls projecting outside the building frame, which are more easily damaged than ordinary infill walls and can fall and injure or kill people below; these should be addressed promptly at the front of the main hospital. Providing emergency water storage would require a modest investment but would greatly enhance post-earthquake functionality. 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 and to prevent potential loss of life from falling brick walls.

The evaluation team also observed evidence of past debris flows near the hospital site, indicating a potential debris flow hazard that should be investigated. Because debris flows are often caused by heavy rainfall events, the debris flow hazard may not be predominately earthquake-related. It is also worth noting that other important public buildings, such as the school (which also has a large open ground that can be used by helicopters and for emergency response) are in areas that appear to have a debris flow hazard. The recommended debris flow hazard study could benefit the users of these buildings as well.

This report and the companion report on Trashigang District Hospital cover two key facilities in eastern Bhutan. Both of these hospitals make up a small 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 Trashiyangtse District Hospital's ability to function depends on interdependent off-site transportation and utility systems, which are beyond the scope of this report. In particular, the hospital depends on the offsite water system because it has essentially no emergency water storage capacity. Trashiyangtse's geographic isolation means disruptions to these systems may take a very long time to fix. 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 such as the Trashiyangtse District Hospital.

The report contains detailed, specific recommendations that address 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 safety and performance; some items, such as storing chemicals properly or anchoring shelving, are very simple and do not require special budget allocations. The hospital should implement such recommendations immediately. Some mitigation and preparedness measures necessary to help keep the hospital functional will require planning and several years to implement. The hospital should be able to make substantial improvements in safety in several years, though, by implementing as many of the high priority recommendations as possible. Making the facility safer, and better preparing the staff, will help Trashiyangtse District Hospital continue to deliver medical care to Trashiyangtse residents following a damaging earthquake.

Appendix A – Tables Summarizing Performance States for Hypothetical Scenario Earthquakes

Table 16. Performance of buildings in three hypothetical scenario earthquakes

Building Name	**Construction Type**	**Year Built**	**No. of Storeys (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 0.12 g			PGA 0.44g			PGA 1.02g		
				Utilities available			Utilities extremely limited			Utilities not available		
				Struct	Equip	Code	Struct	Equip	Code	Struct	Equip	Code
Medical and Support Buildings												
Main Hospital Building	RC w/ brick infill	1998	2	S1	N1		S2	N2		S3*	N3	
Medical Store Building	RC w/ brick infill	1998	2	S1	N2		S3	N2		S4	n/a	
Kitchen and Non-drug Medical Store Building	RC w/ brick infill	1998	2	S1	N2		S2	N2		S2	N3	
Generator Building	Unreinforced stone masonry	Post 1998	1	S2	N1		S3	N2		S4	n/a	
Staff Quarters												
Type I Fourplex Doctors Quarters	RC w/ brick infill	1998	2	S1			S2			S3		
Type II Nurses Quarters	RC w/ brick infill	1998	3	S1			S2			S3-S4**		
Type III Nurses Quarters	RC w/ brick infill	1998	3	S1			S2			S3-S4**		

RC = reinforced concrete; PGA = peak ground acceleration
* S4 for partial second floor containing offices
** Anticipated performance depends to a large extent on presence or absence of ductile seismic detailing; better performance is anticipated if ductile detailing can be verified.

Table 17. Performance of key utilities in hypothetical scenario earthquakes

System	**Likely Performance in Hypothetical Scenario Earthquake**		
	Deep M7 Light Shaking PGA = 0.12g	Shallow M6.1 Strong Shaking PGA = 0.44g	M8.6 Violent Shaking PGA = 1.02g
Electric Power from off-site supply	May experience 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	Emergency generator may still function. Fuel minimal and coolant not stored at site, so may be inadequate.	Generator and associated equipment may be damaged. Coolant not available.	Generator will not be operational, as battery and electrical equipment will be damaged. Power will not be available until generators from off-site are delivered and/or damaged equipment repaired in 3-4 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 re-establish	Water supply damaged and not repaired for extensive length of time
Water from on-site storage			
Domestic	Supply from tank and distribution system inadequate if city water supply disrupted	Supply from tank and distribution system inadequate	Supply from tank and distribution system inadequate
Filtered Drinking	Inadequate supply due to disruption in domestic supply and few filtration units, which may be damaged by earthquake shaking	Supply limit as per domestic water. The few filter units available may break due to poor or no anchoring	Filters will not be functional. Water will need to be boiled or treated and availability will be limited by domestic supply
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	Cylinders are stored in a heap in medical store and could roll around and leak, causing fire and explosion hazard. Supply adequate	Supply probably adequate. Resupply not available for weeks at minimum

PGA = peak ground acceleration