



A Safer Tomorrow?

Effects of a Magnitude 7 Earthquake on Aizawl,
Mizoram and Recommendations to Reduce Losses



GeoHazards Society
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Disclaimer

The scenario described in this document is not a prediction. Rather, it is a hypothetical narrative describing what could happen in the event of an earthquake in Aizawl. A real event may be significantly different.

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As part of our partnership with the Mizoram Department of Disaster Management and Rehabilitation (DM&R), GeoHazards International (GHI) and GeoHazards Society (GHS) wrote this scenario and facilitated a process of consultation with local professionals to develop the recommendations in this document. We are grateful for the support of Mr. P. C. Lallawmsanga, Principal Secretary, DM&R, and his staff, and for the assistance provided by dedicated professionals from Aizawl Municipal Council, Aizawl Development Authority and numerous agencies of Government of Mizoram (GoM), including Public Works (PWD), Public Health Engineering (PHED), Power and Electricity, Mizoram Remote Sensing Application Center (MIRSAC), and Directorate of Geology and Mineral Resources (DGMR), who are too numerous to mention by name. They worked together with us for more than a year, and continually inspire us with their dedication and passion for a safer Aizawl.

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What is an Earthquake Scenario?

In the pages that follow, we present an *earthquake scenario* for Aizawl. A scenario tells the story of a realistic, but hypothetical, earthquake and its estimated impacts. It is not a prediction. It will help you visualize specific impacts and decide what to do. We want to help you, and all the people of Aizawl, plan for safe outcomes. As you read, we encourage you to imagine yourself living the scenario, and ask:

- Where will I be?
- Where are my children, my spouse, my parents?
- What are my responsibilities? Can I fulfill them?

Picture What Might Happen to You in this Scenario

It is 2 PM on a weekday when a magnitude 7.0 earthquake strikes Aizawl. Centered on a fault 10 km northwest of Aizawl and 30 km deep, the earthquake is not the largest that could happen, but it is large enough to do tremendous damage. The shaking lasts about 30 seconds. In that brief period of time, it changes Aizawl forever.

The shaking collapses thousands of buildings, sends hundreds of landslides thundering down slopes, and throws brick walls, water tanks and pieces of buildings down onto streets and paths. The noise is deafening. Where can you find safety? Everything is moving; everything is falling. You slide under a table and hold on. Fortunately your building remains standing, but many do not. When the shaking stops, a thick, choking cloud of dust created by collapsed buildings rises over the city. More than 19,000 Aizawl residents have been killed immediately by building collapses, landslides and falling bricks. You have made choices about the safety of your home or workplace that have helped you survive: your house was designed and built to resist earthquakes, is not in a zone of very high landslide hazard, and you have taken care not to destabilize the slope.

As the dust begins to clear, you emerge from your home or workplace to a changed city. Debris from more than 14,000 collapsed buildings blocks streets and paths. Older reinforced concrete buildings, constructed before Aizawl Development Authority (ADA) and Aizawl Municipal Council (AMC) building regulations went into effect, have collapsed and killed the most people. Some buildings have fallen downhill and caused those below to fall as well. Landslides triggered by the earthquake have severed roads and water mains, and have swept away electrical poles. There is no power, no water, and no mobile phone service. Though you don't know it yet, most of Aizawl's communications and transportation links with the rest of India and the world are cut off.

Your elderly neighbor is seriously injured, and you and a family member decide to take her to the hospital. Though the shaking has made a mess of your kitchen, you quickly locate a bag and fill it with a few bottles of water, snacks, and blankets, knowing that these will be in short supply. After an arduous 3-hour journey on foot around piles of debris and crushed cars you reach the hospital, only to find chaos. Though the main building still stands, the interior of the hospital is badly damaged, and people are crammed into the parking areas outside. Doctors and nurses are trying to treat the injured with whatever supplies and equipment they could pull out of the hospital, but supplies are completely inadequate for the number of injured. Nurses are dividing patients into three categories: those who will not be treated because their injuries though painful are not severe; those who will not be treated because their injury is so severe

that they will die regardless; and those who will be treated as help becomes available. Decisions are difficult and upsetting to all involved. Family members of those not treated find it hard to accept these decisions, and police must move them away so the nurses can continue to work. Your neighbor survives the trip to the hospital and is placed in the third group that eventually receives care, but many do not. Six thousand more people will die from a lack of timely medical care, bringing the total number of deaths to more than 25,000. It is now dark and the journey home is completely impossible without light, so you sleep outside the hospital in the only empty space you can find.

In the meantime, your spouse has made a similarly difficult journey to your children's school as planned in your family's preparedness plan. There is chaos outside as parents try to find their children. The government school building, designed by an engineer and built to resist earthquakes, withstood the shaking without collapsing. Long before the earthquake, the teachers prepared and trained the students on what to do. Because the engineer, the builder, and the teachers chose to prepare for an earthquake, your children survived. Your spouse finds them, frightened but safe.

In the days that follow the earthquake, the situation becomes increasingly dire. Food and cooking gas begin to run out. Helicopters—the only way in and out of the city—are busy bringing rescuers in and taking the badly injured out. You have a family emergency kit with stored water and food, which helps somewhat. You and your family—finally reunited—help neighbors in any way you can, but if more aid does not arrive soon, your children will not have enough to eat. You begin to consider how you and your family might leave the city and return on foot to your parents' home village, but due to the lack of communication you do not know whether that village also suffered damage. Because of badly damaged and collapsed buildings, more than half of the city's residents do not have a safe place to live. It takes months just to clear the debris. Recovery will be so long and painful that the majority of residents will leave over the course of the coming weeks and months. Aizawl will never be the same.

Aizawl's Choice

The choices you have made and will make—regarding whether your home is resistant to earthquakes, whether your home is on stable land, and how you have prepared your family—in large part determine your chance of survival when an earthquake strikes Aizawl.

Today, Aizawl stands at the threshold of major growth, with a master plan that sees the population doubling in the next 20 years. The choice the Aizawl community faces is a serious one. Your city can choose to build safely, to avoid destabilizing the land, and to reduce the risk presented in this scenario. Or it can let development proceed with building practices that increase risk. If Aizawl makes only marginal improvements, your capital city will face devastation when a major earthquake strikes. We urge you to choose for the future and invest now in a safe, thriving city.



Contents

What is an Earthquake Scenario?	iii
Picture What Might Happen to You in this Scenario	iii
Aizawl's Choice	iv
Introduction.....	1
How Earthquakes and Landslides Occur in Aizawl	1
How Experts Forecast Earthquakes.....	2
How this Scenario Can Help Aizawl Plan for the Future	2
High Level Recommendations.....	3
Scenario Contents	4
The Scenario Event.....	5
The Earthquake	5
Earthquake Shaking.....	6
Hazards Triggered by Earthquakes.....	8
Earthquakes Trigger Landslides.....	8
Earthquakes Ignite Fires.....	11
Earthquakes Create Hazards from Falling Objects Inside and Outside of Buildings	11
Damage to the City of Aizawl.....	12
Building Damage Caused by Shaking and Landslides.....	12
Individual Building Damage Caused by Shaking.....	12
Individual Building Damage Caused by Landslides	13
Important Buildings.....	13
Multiple-building Collapses	14
Total Expected Damage to Buildings	14
Damage to, Utilities, Communications and Transportation Systems Caused by Shaking and Landslides.....	15
Water System.....	17
Wastewater	18
Electrical System	18
Communications Systems	19
Transportation Systems.....	21
Fuel Delivery	23
Consequences of Damage and Impacts on the Community	24
Human Casualties	24
Disruptions from Building Damage.....	26

Utility Breaks and Interruptions	26
Disruption to Critical Medical Care	26
A Local Example of Earthquake Impacts: Case Study of Electric Veng Locality	28
Emergency Response and Recovery	31
Emergency Response following the Scenario Earthquake	31
Day One	32
Day Two	35
One Week	36
Two Weeks	37
Recovery and Economic Impact	37
One Month.....	38
Three Months	38
Six Months.....	38
One Year.....	38
Actions to Improve Earthquake Safety and Resilience	39
What Can Aizawl's Leaders Do to Prepare?	39
What Can I Do?	40
Detailed Recommendations	41
Appendices	57
A: Earthquake Sources and Shaking	
B: Landslides	
C: Buildings	
D: Infrastructure	

Introduction

When most Mizo people lived in traditional timber homes on the tops of ridges, earthquakes could do little harm. The lack of reports about past earthquake disasters may be incorrectly interpreted as implying that earthquakes are infrequent in Aizawl. Actually, the city is located in an area of high seismic hazard, meaning that a damaging earthquake might soon strike this young city. How will it affect Aizawl's known landslide risk? How will it impact buildings and infrastructure? How will it impact people? How can the community lessen the consequences of such an earthquake? This scenario and report, developed by a team of local and international experts, explains the consequences of a plausible, medium intensity earthquake and how the city can reduce future earthquake and landslide damage and its consequences.

The scenario describes the foreseeable damage and consequences of a plausible but hypothetical magnitude 7 (M7) earthquake on Aizawl. It also shows impacts to certain roads, villages and the Lengpui airport, which fall outside the Aizawl Municipal Council boundary in the State of Mizoram's jurisdiction. The report describes specific actions that will help the people of Aizawl reduce the damage caused by earthquakes and landslides and its consequences. Recommendations include improvements to infrastructure, development policies and plans, building design and construction, emergency planning and preparedness, and response capabilities.

How Earthquakes and Landslides Occur in Aizawl

Aizawl will always face a risk of earthquakes. The scenario earthquake originates on a fault approximately 10 kilometers northwest of the city. There are many fault segments near Aizawl— even some under the city—that could cause damaging earthquakes of M7 or greater. Earthquakes can occur on faults lying to the north, south, west or east. They can be of smaller or greater magnitude, on faults that lie deeper or near to the ground surface, farther away or closer. It is possible for a huge plate boundary fault that underlies parts of Bangladesh and northeast India to rupture, as it is inferred to have done numerous times in the past. While earthquakes on this fault would be huge and devastating, the chance of a great earthquake occurring is much less than the chance of moderate earthquakes striking nearby.

Hills and valleys provide evidence of on-going geologic processes that bend and buckle the layers of rock beneath the city, shaping the landscape, and also causing earthquakes. The steeply sloping beds of sandstone and shale that underlie Aizawl, which are exposed throughout the city, were once horizontal layers of sediment on the ocean floor. The tremendous forces necessary to uplift Aizawl's high ridges result from the Indian subcontinent colliding with the rest of Asia and squeezing northeast India against Myanmar and China. Instruments that monitor the relative movement of the ground surface using satellites show that the Indian subcontinent continues to move northward into the rest of Asia at several centimeters per year (about as fast as fingernails grow). This process places tremendous pressure on the underlying rock, which deforms elastically and stores the pent-up energy until it is released by sudden shifts along weak shear surfaces called *faults*. These *fault ruptures* cause violent jolts that radiate seismic waves through the solid earth and shake the surface in what is known as an earthquake.

The size (magnitude) of the earthquakes in northeast India varies over a wide range. Most are small earthquakes that are detected only by instruments. Occasionally a larger earthquake causes perceptible ground shaking and damage. Some earthquakes are huge and cause widespread damages. In geologically active areas such as the Burma Ranges where Aizawl is located, small earthquakes are common, and some large damaging earthquakes are described in the historic record. After each earthquake, elastic strain starts building up, and the cycle leading to the next earthquake begins anew. Throughout the region, this process has been repeated countless times to build mountain ranges and will continue far beyond our grandchildren's lifetimes to gradually transform the shape of the land surface.

Aizawl also experiences frequent landslides on its many slopes. Heavy rainfall can trigger them, as can excavations that undermine slope stability. Earthquakes, however, present the most dangerous landslide risk: even moderate earth shaking can trigger hundreds of landslides all at once.

How Experts Forecast Earthquakes

Since producing the last damaging earthquake, a fault may have built up energy to the point where a similar damaging earthquake could occur again at any time. While the precise location, time and size of future earthquakes cannot be predicted, earthquakes occur in predictable locations and at intervals that can be estimated from the size of the maximum magnitude or the size of the fault and from the long-term rate of slip. Aizawl is affected by several different faults, so that the probability of damage from earthquakes must combine the contributions from each of these fault systems. Earthquakes also affect buildings, infrastructure and people in foreseeable ways. Scientists, engineers and emergency management professionals can anticipate the location of faults, what size earthquakes such faults can generate, how strong the shaking may be, how earthquakes trigger landslides, and how buildings, roads, pipelines and utility systems perform. These professionals can describe potential losses and consequences.

To develop the scenario M7 earthquake in Aizawl, a team of earth scientists, engineers and planners from Mizoram and from elsewhere in India and the United States, local government officials and leaders contributed professional knowledge as well as experience gained during earthquakes and landslides. Earth scientists described the geologic forces that cause earthquakes, the nature of faulting, and the strength of shaking. Geologists reviewed geologic structure, geomorphology, and existing landslides, and then estimated amount of landsliding likely to occur. Engineers, relying on analysis and experience from observing earthquake damage in India and elsewhere, estimated how buildings would shake and fail. The team determined how landslides and building damage would harm people; damage water, electricity and communications utilities; and block roads. The team estimated casualties, based on observations from other earthquakes and professional judgment. The consequences derive from past earthquakes experiences and knowledge of local participants. For brevity in this report, "we" means the team members who contributed data and wrote the scenario, and who made recommendations to minimize damage.

How this Scenario Can Help Aizawl Plan for the Future

This report, *A Safer Tomorrow? Effects of a Magnitude 7 Earthquake on Aizawl, Mizoram and Recommendations to Reduce Losses*, presents foreseeable losses and consequences from a hypothetical earthquake near Aizawl. We determined that a plausible M7 earthquake would cause extensive damage, destroy buildings, render useless utility systems and roads, cause

thousands of casualties, interrupt lives, and set back Mizoram's economic development. The shaking would trigger hundreds of landslides, causing new slides and reactivating existing ones. The recovery process would take years. Some families and businesses would never recover. Mizoram and Aizawl would change drastically. The scenario reflects what would happen if the M7 earthquake were to strike today.

Aizawl *can* avoid the dire consequences presented in this scenario. By implementing the recommendations presented here, Aizawl can considerably reduce the damage and consequences from such an earthquake. This scenario provides insights into the needs following an earthquake and informs plans to prepare and respond effectively to an earthquake disaster. More important, the report describes measures that people, organizations, and the government can take to reduce existing risk and plan for a more robust, more resilient Aizawl. Damage and casualties create unprecedented demands for medical care, rescue operations, food and water. Understanding losses, their implications and what can be done to reduce them provides homeowners, businesses and government agencies with the information and motivation to take action. This scenario and recommendations, and the planning that follows, will provide a roadmap to safety.

Aizawl is located in an earthquake zone, but being a very young city it has not yet experienced a destructive earthquake. Nevertheless, knowledge about the threat exists and will improve over time.

Read this scenario and consider how an earthquake would affect you, your family and your community, your responsibilities to care for them, and your livelihood. Use the information to think about what *you* will do to improve the situation. Discuss this report with your family and friends, with your co-workers and colleagues in offices, schools, community organizations and church groups. Decide together what you can do, because even small measures can save lives. Aizawl is in a race with time. How much can we accomplish, together, before a damaging earthquake strikes?

High Level Recommendations

Working with local agencies, we developed a set of recommendations to help make Aizawl safer and reduce the tremendous damage and loss of life that will occur if nothing is done. The highest priority city-wide recommendations include:

- regulate slope cutting that makes slopes unstable;
- provide a comprehensive rainwater and wastewater drainage system to help prevent rain-triggered landslides;
- enforce and encourage the public to follow the AMC building regulations to help prevent building collapses in an earthquake;
- prevent land allocation and development in areas of high landslide hazard; and
- obtain and use more detailed geologic maps to better define and manage hazardous areas.

In the sections following the scenario, we provide a detailed description of our recommendations, outlining a number of specific steps to improve earthquake and landslide safety in Aizawl.

Together, Aizawl's residents and technical professionals can make meaningful improvements in safety in the coming years. We hope that this scenario will help you to better understand the risks Aizawl faces, and to identify what *you* can do to help.

Scenario Contents

The scenario that follows describes the hypothetical earthquake, the intensity of shaking in Aizawl, the effect of shaking on buildings and infrastructure, the landslides triggered by the shaking and their effects on infrastructure and buildings, the effects of damage on people, and the implications for emergency response and for long-term recovery. In each section, the scenario's immediate effects are described in italics. Recommendations to help Aizawl avert the disastrous consequences the scenario describes comprise a separate section following the scenario description. Four appendices provide additional technical information and describe the assumptions and methods we used.

The Scenario Event

The Earthquake

At 2 PM on a weekday, a magnitude 7.0 earthquake occurs on an unnamed strike-slip fault centered approximately 10 kilometers northwest of the city, and 30 km below the surface. Figure 1 shows the earthquake's source – the portion of the fault that breaks, called a rupture plane – with respect to Aizawl. At 2 PM children are at school, people are at work, roads are busy, and government officers are at their desks. Four hours of daylight remain.

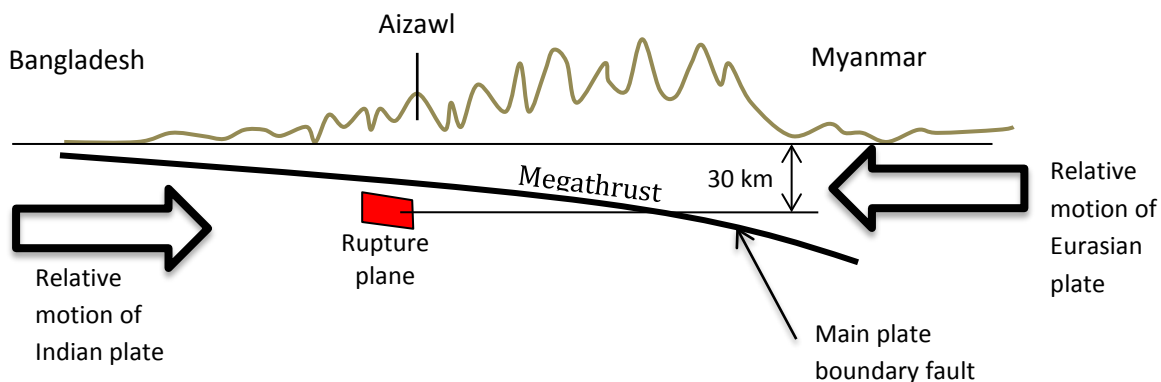


Figure 1. Schematic East-West cross section through the Earth's crust showing the location of the rupture plane (in red) that is the source of the M7 scenario earthquake. Topography is exaggerated. (After Seeber)

While hypothetical, this scenario earthquake is in a zone where smaller earthquakes occur frequently. The hypothetical M7 source is realistic, reasonable, and based on current scientific knowledge. Seismologists have observed earthquakes of this type in other parts of northeast India with similar geology. Earthquakes that would have far more damaging effects in Aizawl are possible from other fault sources. Earthquakes affecting Aizawl can be much larger or closer to the surface, and can occur directly under the city. [Appendix A: Earthquake Sources and Shaking](#) describes the source of the scenario earthquake as well as other faults that can generate damaging earthquakes affecting Aizawl.

This scenario describes a reasonable set of consequences from a plausible moderately large earthquake. The effects of a real earthquake, however, which could occur on any of these faults at any time of day, may be more severe or less severe than what we present in this scenario. Though the scenario describes a daytime earthquake, an earthquake could happen at night when people, including government officials, are at home, or on Sunday while most are attending church services.

A large damaging earthquake is usually the “mainshock” of an earthquake sequence that includes many smaller aftershocks. They will occur both on the same fault that produced the mainshock and on other related faults, as the earth adjusts to changed conditions. Several aftershocks with damaging magnitudes are likely within the first few weeks. The frequency of aftershocks would gradually diminish with time but an enhanced likelihood of a large nearby earthquake would persist for years after the mainshock.

Earthquake Shaking

The earthquake shaking—and the landslides triggered by shaking—cause the majority of the expected damage in Aizawl. The back-and-forth ground motion caused by the earthquake generates large forces and displacements in buildings, bridges, pipes, tanks, retaining walls, and communication towers. Many of these structures fail because they were not designed to withstand such forces and displacements.

The scenario earthquake causes ground accelerations in Aizawl of approximately 35 percent of the acceleration due to gravity (0.35g). The scenario ground acceleration is similar to that prescribed by the building code (Indian Standard 1893) for engineering design in Seismic Zone V, and is also similar to the levels anticipated by several recent studies¹. This level of shaking is strong enough to cause severe damage to buildings. The level of damage varies from building to building, but can be generalized for the types of buildings common in Aizawl.

The scenario's duration of strong shaking is 10 seconds. "Strong shaking" is greater than 0.1g, the level at which landsliding is expected to begin. Figure 2 shows ground shaking, expressed in terms of peak ground acceleration, estimated using a simulation of the event by the United States Geological Survey using its ShakeMap software. Figure 3 was also produced using USGS ShakeMap software and shows the expected intensity of shaking from this scenario earthquake.

The computed level of shaking in the Aizawl area for the scenario earthquake would be described by people who feel it as "very strong" to "severe", and is assigned an intensity of VII to VIII on a scale with a maximum of XII. This intensity scale measures the strength of shaking from an earthquake in a particular place. People in neighboring states and in Bangladesh would feel weaker but perceptible shaking, as Figure 3 shows.

In every earthquake, the shaking varies somewhat from place to place, due to local soil conditions and other factors. Some areas would feel much stronger shaking, other areas lighter. For the purpose of analysis, however, this scenario considers a uniform level of ground shaking within the city. Though no studies have been done in Aizawl, evidence from past earthquakes elsewhere indicates that ridges and other topographic features can amplify ground shaking.

¹ Iyengar R.N. et al. (2010) *Development of Probabilistic Seismic Hazard Map of India*, Final Report to the National Disaster Management Authority, and MIRSAC (2005). *Hazard Risk and Vulnerability Analysis of Aizawl District*, Mizoram Remote Sensing Application Centre, Aizawl, Mizoram.

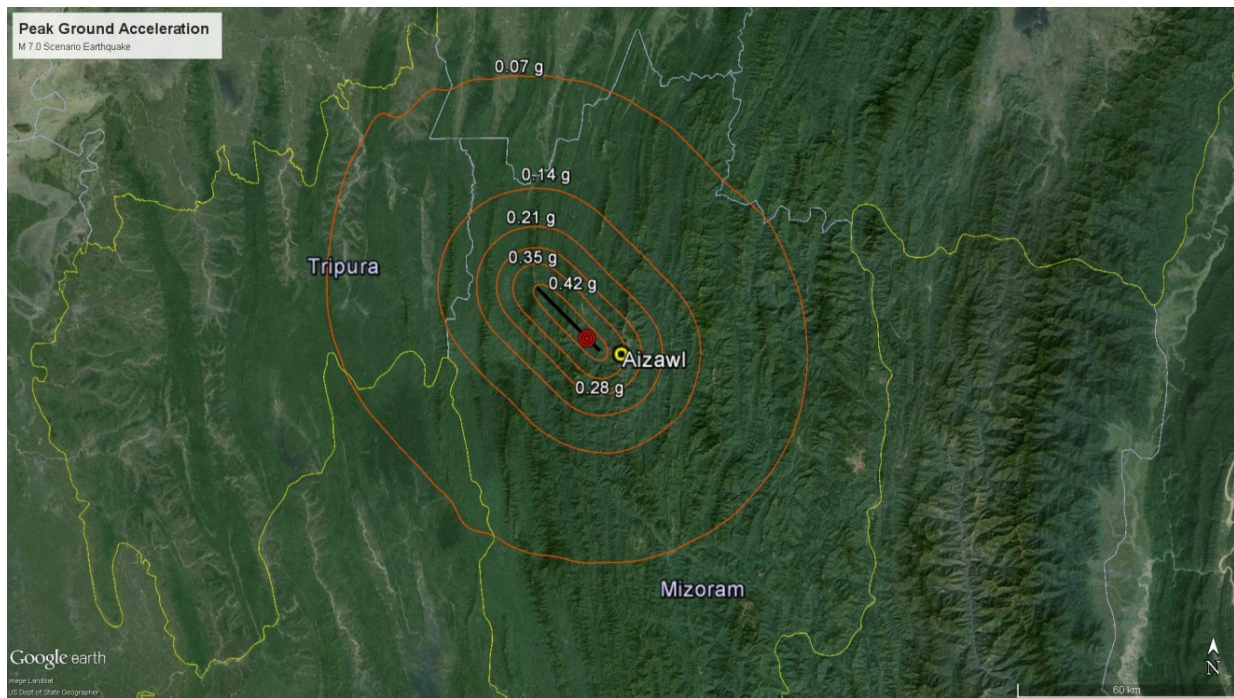
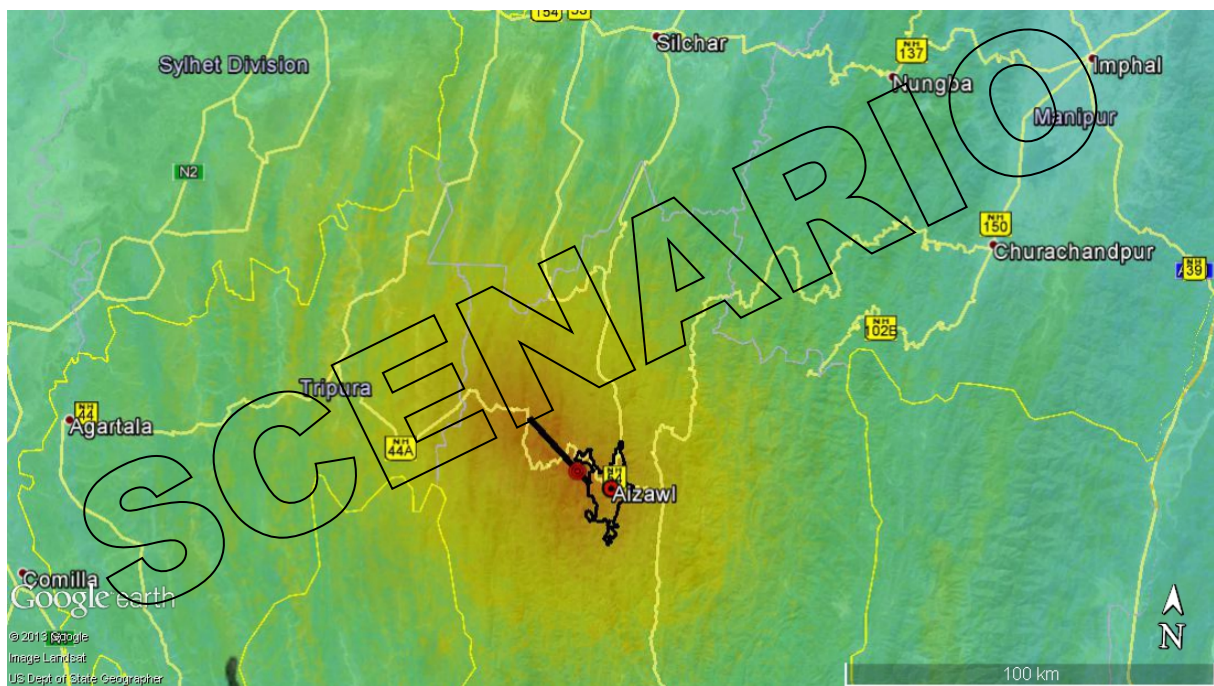


Figure 2. Peak ground acceleration (courtesy US Geological Survey)



Fault	Aizawl Urban Area Boundary						Epicenter		
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
PEAK ACC.(%g)	<0.1	0.5	2.4	6.7	13	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	11	22	43	83	>160
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Wald, et al.; 1999

Figure 3. Shaking intensity (courtesy US Geological Survey) showing the regional extent of shaking; the event would be felt in neighboring states in India as well as in Bangladesh.

Hazards Triggered by Earthquakes

The shaking from the scenario earthquake causes several hundred landslides throughout the city and surrounding countryside. Fires start from various sources. Falling objects, both inside and outside of buildings, injure thousands of residents.

Earthquakes Trigger Landslides

Many new landslides occur in the scenario earthquake, especially on large areas of the eastern side of the main ridge, where landslide hazard is relatively higher because of bedrock geologic conditions. In addition to new landslides occurring, many existing landslides reactivate and move further down the slope. Rocks and large boulders tumble down steep cliffs.

The amount of movement as well as the size of landslides triggered by the scenario event will vary greatly between the dry season and the monsoon season, when slopes are saturated. More than 18 square kilometers of Aizawl's surface area will be affected during the monsoon season, compared to approximately 3.6 square kilometers during the dry season. Figure 4 shows landslide hazard zones for a portion of Aizawl; red and gold areas that make up approximately 88 percent of the mapped area show where more landsliding is likely to occur. In these areas, existing landslides are likely to move, and new landslides would occur. However, it is not possible to predict specific locations of the approximately 1100 landslides that we estimate the scenario event would trigger within the Aizawl urban area. Landslides triggered during the monsoon would be larger and more destructive.

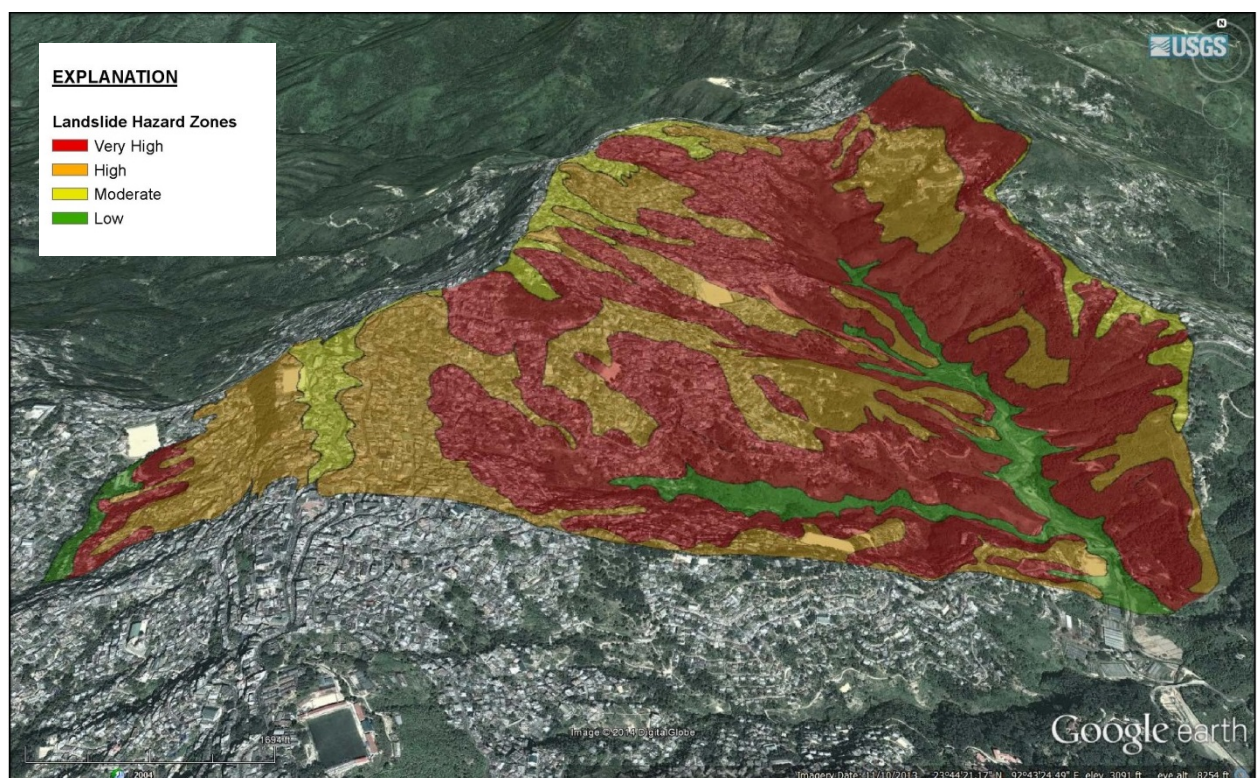


Figure 4. Landslide hazard zones for natural terrain in a portion of Aizawl; slope modifications made by people for building and road construction, quarrying, and similar activities may increase the hazard (Image credit: Lettis Consultants International)

If the earthquake occurs during the monsoon, 16 percent of the red areas and 9 percent of the gold areas are expected to slide. If the earthquake occurs during the dry season, 3 percent of the red areas and 2 percent of the gold areas are likely to slide. The landslide hazard zones in Figure 4 are for natural terrain, meaning the landscape without significant human modification. If people modify slopes without properly considering geologic conditions, and thereby reduce the slope stability as apparently happened in Laipuitlang (triggering the May 2013 landslide), the level of hazard may increase beyond what is shown on this map. [Appendix B: Landslides](#) contains larger and more detailed maps and figures describing Aizawl's landslide hazard, including a grayscale version for black and white printouts.

Aizawl is built on a ridge in which the rock layers (primarily sandstones and shales) are bent in the shape of an inverted "U". The soil cover is generally thin, but the rock may be intrinsically incompetent (for example, shale is very weak) or may be compromised by weathering. The Aizawl area experiences three primary types of landslides, shown in Figure 5: translational rock slides, rotational rock slides, and rock falls.

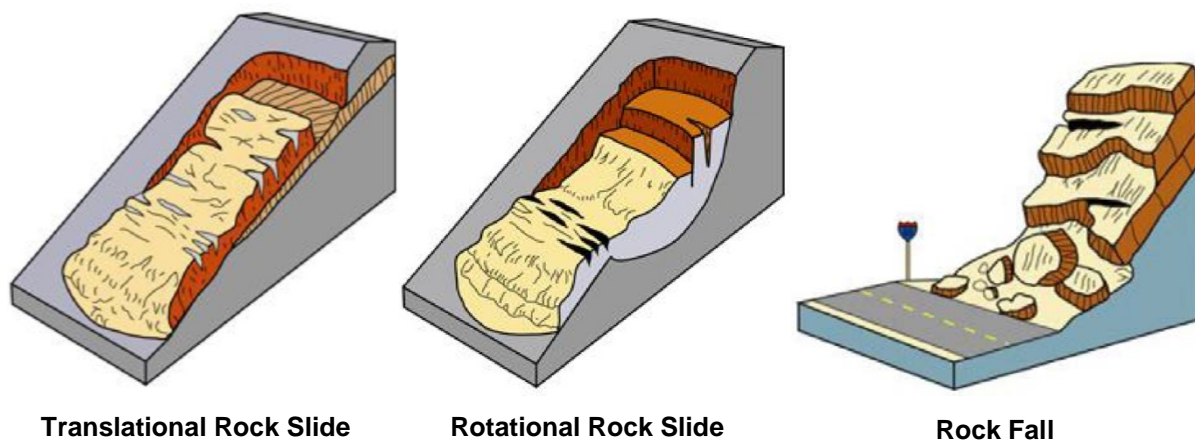


Figure 5. Common types of landslides in Aizawl (Image credit: Geology.com)

The May 11, 2013 Laipuitlang landslide that killed 17 people was a translational rock slide, meaning that the rock broke along a planar surface (visible in the center of the slide area in Figure 6). During the scenario earthquake, similar slides would occur on east-facing slopes with similar geologic conditions. In these locations, the rock layers dip in the same direction and at about the same angle as the slope, with weak layers of shale often hidden underneath stronger sandstone. In many places the shale is not strong enough to resist the scenario shaking, and the slope would fail in a translational rock slide.

A rotational rock slide has a failure surface that is curved instead of planar, as Figure 7 shows. The scenario earthquake would cause slides of this type as well.



Figure 6. May 11, 2013 translational rockslide in Laipuitlang (Photo credit: Lalrinpuii Tlau, GHI)



Figure 7. Rotational rockslide in south Aizawl (Photo credit: Kevin Clahan, Lettis Consultants International)

Rock falls, in which rocks detach from the slope and fall, roll or bounce down the slope, would occur in Aizawl's steep cliff areas. Loose rocks lying below slopes indicate previous rock falls, and are a sign that other rocks may fall. [Appendix B: Landslides](#) contains a detailed explanation of landslide hazards in Aizawl, as well as a description of the methods used to estimate the amount of landsliding during the earthquake.



Figure 8. Rock falls in steep cliff area in Aizawl (Photo credit: Kevin Clahan, Lettis Consultants International)

Earthquakes Ignite Fires

At the time of the earthquake, people may be boiling water for tea. Stoves tip and start fires. Pots fall and cause scalding. Following the earthquake, fires start from several sources.

The number and severity of fires depend on the time of day and weather conditions. Fires would be ignited by cooking stoves that tip over, gas leaks from cylinders, damaged electrical wiring, and heating equipment. Though fires occur in all building types, more fires start in buildings with wood floors and in collapsed buildings. The spreading of fire depends on building density, vegetation and wind conditions, so some fires spread to neighboring buildings and some do not. Under dry, warm and windy conditions, small fires can lead to a conflagration. In areas on the periphery of the city, some of the fires would spread into the nearby forest. If the earthquake occurs during the dry season, fires at the wildland-urban interface can threaten nearby localities.

Earthquakes Create Hazards from Falling Objects Inside and Outside of Buildings

Earthquake shaking causes damage to buildings and their contents, and this damage can harm people, increasing the number and severity of casualties. Buildings amplify shaking, so the accelerations near the top of some buildings could be more than twice as strong as at the base. This level of shaking is strong enough for thin masonry walls to crack and fall from buildings, and for furnishings, equipment and contents to slide or topple. Inside buildings, falling contents like cupboards and building elements such as brick infill walls endanger people, as do hot stoves, boiling water and cooking oil.

Outside, people face dangers from falling buildings or parts of the façade, including exterior architectural features, bricks used to infill between reinforced concrete columns, and water tanks. Downed, but still live, electrical wires can electrocute people. Moving vehicles threaten those who run into the street. After the earthquake, aftershocks dislodge bricks and pieces of concrete from damaged buildings, endangering anyone below.

Damage to the City of Aizawl

Building Damage Caused by Shaking and Landslides

Buildings in Aizawl suffer extensive damage due to the shaking that the scenario earthquake causes. We estimate that nearly 13,000 buildings collapse due to shaking alone—approximately 26 percent of Aizawl's approximately 50,000 buildings—and at least as many others suffer structural damage so severe that they are unsafe to use and must be demolished. Brick partitions inside buildings crack and topple. Thin brick walls in the upper stories of many concrete buildings fall onto the streets and pathways below, killing and injuring people outside of buildings. Landslides triggered by the scenario earthquake cause collapse of an additional 1200 buildings during the dry season, bringing total collapses to about 14,000, or 29% of buildings. Larger and more destructive landslides during the monsoon season collapse more than 6500 buildings, bringing total collapses to approximately 18,000, or 37% of buildings. (During the monsoon, some buildings that would otherwise collapse during shaking are collapsed by landslides.)

The dry season collapsed buildings include more than 18,000 housing units, and the monsoon season collapsed buildings include more than 23,000 housing units. In both the dry season and the monsoon season, at least as many housing units are badly damaged and uninhabitable as collapse, leaving more than half of Aizawl's residents without safe shelter.

In the hours and days following the earthquake, aftershocks endanger those who rescue victims trapped in badly damaged or collapsed buildings, because such buildings are unstable. The Civil Hospital is damaged, which impacts medical care for the community's emergency and long term needs.

Individual Building Damage Caused by Shaking

Most buildings provide housing and have been built by owners during the past fifty years. Aizawl's buildings consist of three major types: traditional timber (Assam-type; classified as Ordinary buildings by Aizawl Municipal Council AMC), concrete frame with lightweight walls and timber floors (classified as Semi-pucca or Semi-permanent buildings by AMC); and reinforced concrete frames, usually with brick infill and partition walls (classified as Permanent buildings by AMC). [Appendix C: Buildings](#) contains photographs and more detailed descriptions of the three building types. All three types of buildings are vulnerable to earthquake damage. Buildings constructed after 2007, when the Aizawl Development Authority (ADA) and AMC began to regulate building construction, are likely to be better designed and to survive the earthquake with less damage.

Buildings constructed on Aizawl's steep slopes are much more vulnerable to earthquake damage than buildings on flat ground. The short, stiff supports on the uphill side must resist large forces as the earthquake pushes the building out from the hill. Because these supports are short and stiff, they do not bend as easily as taller supports, and they must hold the building back by themselves rather than share the load with the taller supports. The long and flexible supports on the downhill side must move a long way as the building twists and sways. Both uphill and downhill supports can fail, and if either fails the buildings could collapse. This is particularly true of older buildings of all three types. However, even new, regulated buildings are more susceptible to damage when located on slopes.

Traditional timber Assam-type buildings are most vulnerable to damage in the under-building stilt supports, which tend to be poorly braced and have weak connections. Semi-pucca buildings often have weak, slender frames that may not be properly reinforced for earthquake resistance. Brick walls added later increase the weight and the danger. Reinforced concrete buildings have many vulnerabilities, but most fundamental is the lack of proper reinforcing for earthquake resistance. Improper reinforcing weakens buildings so they are unable to withstand the extra earthquake demands from hillside foundation configurations, open stories at road level, and large cantilevers used to increase room sizes in upper stories.

In many localities, buildings are closely spaced and can pound against one another as they shake. Heavy floor slabs in one building may repeatedly slam into the outermost columns in the adjacent building, breaking the columns and collapsing part or all of the neighboring building.

Appendix C: Buildings provides more information about building vulnerabilities and expected damage, and explains the methods used to estimate the number of building collapses and casualties.

Individual Building Damage Caused by Landslides

Landslides are often catastrophic to buildings caught in their path. Figure 6 shows debris from collapsed buildings that were atop the May 2013 Laipuitlang landslide. Buildings at the toe of the landslide were consequently buried by debris. During the scenario earthquake, we expect that all of the buildings directly and entirely atop landslides would collapse, as happened in the Laipuitlang landslide and in many other landslides in Aizawl. In densely built up areas, 50 percent more buildings would collapse from being crushed by landslide debris. A few slides might not fail catastrophically (and thus rapidly) during or immediately after the earthquake, but would likely move enough to badly damage buildings atop the slide and render them uninhabitable, or even cause them to eventually collapse.

Important Buildings

Hospitals, fire stations, government offices, schools, churches and Young Mizo Association halls provide essential community services. Most government buildings have been designed by trained engineers and built to Indian Standard codes by professional construction contractors, so they would have better earthquake performance, generally, than similar private buildings. Vulnerabilities of important buildings span a large range, from low-rise Assam-type schools constructed on flat ground (rather than stilts) that are expected to suffer minimal damage, to large older churches and institutional buildings that may suffer severe damage.

The Civil Hospital is likely to be damaged and would have a reduced capacity to treat patients. The main hospital building is likely to suffer damage that could make people inside question its safety. Interior damage to contents, brick partitions and building utilities system such as electrical power and water would disrupt operations. Damage to the hospital's other buildings could be worse. A landslide occurred on the slope below the hospital's west side in 2007. Further landsliding caused by earthquake shaking is possible and could threaten the hospital building if it occurs. Other hospitals would suffer similar structural damage and interior damage, disrupting their operations. Government buildings, YMA halls, and churches would suffer varying degrees of damage, according to their age and level of earthquake resistance. A number of older buildings would collapse.

Multiple-building Collapses

Steep slopes in densely built localities create a situation where vulnerable buildings are perched above other buildings, as Figure 9 shows. The configuration of many concrete buildings on steep slopes increases the chances that multiple floors of the building will fall downhill of the original building footprint during a collapse—crushing, damaging or collapsing the next building below.

During the scenario earthquake, we estimate that one-third of all building collapses would cause collapse of a building downhill. On a few steep slopes packed with vulnerable buildings, a collapse near the top would initiate a catastrophic cascading collapse that would destroy multiple buildings on the slope directly below.

Total Expected Damage to Buildings

Figure 10 shows the proportion of collapses by building type. The total of these collapsed buildings would represent 29 percent and 37 percent of all buildings in Aizawl, during the dry or monsoon season, respectively. Older reinforced concrete buildings would suffer the majority of the building collapses, with those on stepped sites faring the worst. Newer buildings designed and built to the AMC Building Regulations would be less likely to collapse due to shaking, though some buildings might still be affected by a landslide. It is clear that if owners insist that their buildings be built according to the AMC Building Regulations, they would greatly reduce their risk of being killed by a building collapse.



Figure 9. Vulnerable buildings on a steep slope where a collapse would endanger buildings below (Photo credit: Janise Rodgers, GHI)

During the dry season more than 18,000 units of housing would be lost due to collapse, and many more would be so badly damaged that they would be unsafe and need to be demolished. During the monsoon, more than 23,000 housing units would collapse. Assuming an average household size of 5 (Census of India, 2011), more than 90,000 people would lose their housing, if they survive the earthquake during the dry season. The number displaced by collapsed buildings would rise to more than 115,000 during the monsoon season. With the additional

people displaced from badly damaged buildings, more than half of Aizawl's population would lack safe shelter.

It is possible to greatly reduce these sobering numbers over time: by continuing, as AMC and ADA have done, to require earthquake resistant new buildings; by better enforcing the building regulations; and by putting policies in place that encourage and enable owners to strengthen older buildings.

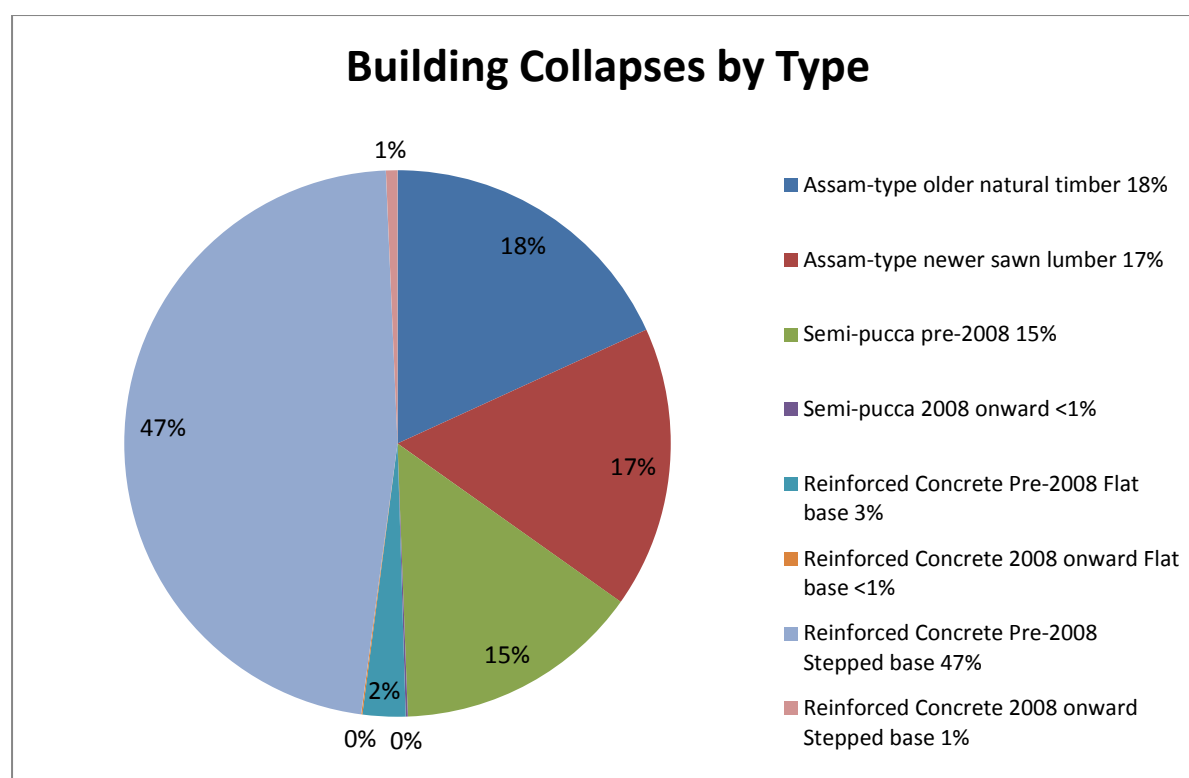


Figure 10. Proportion of the total collapsed buildings by building construction type and age for dry conditions; results are similar for monsoon conditions. Note that post-2008 buildings are assumed built to AMC Building Regulations; see Appendix C for subtype definitions.

Damage to, Utilities, Communications and Transportation Systems Caused by Shaking and Landslides

Damage to the electrical transmission system causes power to go out throughout Aizawl. Water lines broken by landslides and ground shaking leak precious water into the streets, and the damaged water supply system cannot provide more water to the city. In the immediate aftermath, residents do not fully comprehend that Aizawl is completely isolated. Communication options are severed. Landslides and building collapses block access roads. It may take days or weeks to bring in emergency water and power—and much longer to fully restore systems.

Water, electric, and communication systems and roads are the basic infrastructure systems that serve Aizawl's residents. They are called *lifelines* because people depend on them for life-sustaining services; this is especially true in Aizawl, where loss of transportation systems and clean water in particular are life-threatening.

Aizawl's water, electrical power, communications systems and roads are all vulnerable to earthquakes. When earthquakes strike, ground shaking can stretch and compress buried pipelines, conduits, and bridges, and can damage unsecured equipment. Landslides rip through pipelines, topple electrical poles, undermine and bury roads, and could block rivers. Bridge decks can be pulled off their abutments, and sandy saturated soils can liquefy and settle or move, damaging cables, pipelines, dams and equipment. Ground shaking and ground failure affect infrastructure, water mains, electrical transmission and distribution systems, and roads. This damage can be minimized by actions taken ahead of time to make pipelines, bridges and roads more robust.

Earthquake damage to infrastructure systems has consequences, which we discuss in this and later sections, measured in terms of the time needed to restore services, and the extent of repairs. [Appendix D: Infrastructure](#) contains technical information on how we determined consequences for the electrical power and water systems, as well as a description of each major infrastructure system.

Each of Aizawl's infrastructure systems depends on other systems. Water pumps rely on electricity; electric systems depend on roads for delivery of replacement equipment and workers. Emergency generators rely on lorries for fuel. Lorries depend on open roads. Communication systems—landline, cellular, mobile radio, Internet, broadcast radio and television and the print media—are needed to direct repairs and communicate emergency information. These systems rely on electric power, fuel for emergency generators, towers, lorries for supplies and buildings that house switches and controls.

Understanding the vulnerability of interdependent systems is necessary to improve their resilience and to provide life-sustaining aid following an earthquake. Each system relies on all of its elements. A single landslide can render the entire road useless, and loss of a single electrical transformer affects an entire distribution network. Systems depend on systems. Like chains, systems are as vulnerable as the weakest link. The interdependencies between systems, and their complexity, make post-earthquake restoration of service both urgent and intricate.

Aizawl is particularly affected by infrastructure damage from earthquakes for four reasons:

1. It is remote, and roads leading to it lack capacity and are subject to blockage by landslides and debris from collapsed buildings;
2. Many of its slopes are unstable during earthquake shaking, and the resulting landslides will damage utility systems, roads and streets;
3. Hillside construction is exceptionally vulnerable to damage from shaking, and collapsing buildings will damage electrical and communications systems and block streets; and
4. Its dense, urban population is uniquely dependent on infrastructure for food, water and medical care.

Investments can be made to make Aizawl much less vulnerable than it is today. The recommendations section that begins on page 39 of this document explains what can be done.

Water System

After the scenario earthquake, pipelines break in 50 or more locations due to transient movements in the ground and in about 50 locations due to landslides. A landslide could damage a pipeline between the treatment plants and the main reservoir. Damage to the treatment plants prevents the treatment of raw water that is critical to ensuring clean drinking water. Pumping stations and the associated electrical substations are damaged and out of service. Access for repairs stalls, because of road blockage within Aizawl and on the highways leading to other cities.

Emergency water supply is critical to survival for many weeks. The loss of the water supply leaves residents of Aizawl dependent on outside help to deliver potable water to distribution points for months. Because landslides, building damage, and traffic jam streets, most people and the supply lorries have difficulty reaching the delivery stations. Water is in short supply.

The municipal water system consists of two raw water intakes and treatment plants—Phase I and II of the Greater Aizawl Water Supply system—at Reiek Kai on the Tlawng River. Raw water is treated and then pumped 8 kilometers to the main reservoir at Tuikhuahtlang, about 1,100 meters above the treatment plant. A network of distribution mains supplies water to 29 zonal tanks throughout Aizawl. Homes and businesses maintain on-site storage tanks, supplied by periodic municipal deliveries, rainwater harvesting, and deliveries from private lorry tankers. The system is subject to earthquake damage and serious disruption in many ways.

The treatment structures and equipment can be damaged or dislodged by earthquake shaking, rendering them useless until repairs are made or replacements installed. The components comprising the electrical substations at the Phase I and II treatment plants and at the booster pump location are not currently anchored for earthquake motions.

Even if the pipelines remain intact, electric system failures, and failures at the treatment plant substations, would cripple the municipal water system. There would be no electricity to power pumps, chemical processes, flow controls and communications. Because the first set of raw water pumps are not connected to emergency generators or diesel pumps, the water supply is limited to the amount already in the system. The electric pumps that move treated potable water to the Tuikhuahtlang main reservoir through two separate pipelines are backed up by reserve pumps with diesel motors, but these diesel pumps can only pump a quarter of the total Phase II capacity. The stored diesel fuel varies from amounts that can last from a few days to three weeks. However, because diesel motors and fuel tanks are vulnerable to shaking damage if not anchored to resist earthquake forces, they would not be operable without repairs. However, chemicals needed to disinfect the water supply (salt and alum) are stored in ample amounts, so water treatment could resume as soon as any damage to the treatment equipment is repaired.

The treated water pipelines traverse a slope with active landslides. Distribution mains and local distribution lines cross numerous areas where landslides could occur or have occurred.

The two primary reservoir tanks at Tuikhuahtlang and the other major tank at Laipuitlang feed water mains linking sub tanks and distribution pipelines. Most of the tanks are reinforced concrete; the few steel tanks still in service are in the process of being replaced with reinforced concrete tanks. During the scenario earthquake, water would slosh against the tank walls causing the tanks to rock on their foundation. Tank walls can crack, but more often the tank movement will break their connection to pipes that lead to the distribution system. Broken connections and tank wall leaks can drain the tanks, causing localized flooding in addition to the

loss of precious water. Unless joints are designed to be flexible, water distribution systems are subject to failure both at the point where pipelines connect to the tank and along the distribution system.

Private lorry tankers deliver water mostly from perennial spring sources around the city. Lorries depend on passable roads and fuel. Depending on the water source, disinfection might be needed. Road access between the supply points and the urban area would be blocked by landslides.

Residential tanks generally are not anchored, and can slide and potentially fall from their supports during shaking. Falling tanks become a hazard to persons below, and water stored in them will leak out due to broken connections and damage to the tanks themselves. If anchored, these tanks could provide critical drinking water.

Wastewater

Landslides and debris blocks the system of street-side wastewater channels. Ground movement breaks drains, culverts and sewer pipes, and debris from collapsed buildings and landslides blocks them.

Interruption of the drainage system would divert waste and surface runoff from rainfall onto the streets, into low-lying areas and natural channels, and onto potential slides. Uncontrolled waste would contaminate drinking water supplies.

Electrical System

The electrical distribution system within Aizawl is damaged extensively. Repairs of transmission lines and major substations take several weeks, after which power could be delivered only to a few select customers.

Most of the power for Aizawl is generated outside the state and comes from the North East Grid by way of transmission lines from Jiribam, Manipur; Badarpur, Assam; and Kumarghat, Tripura. The Mizoram State Power and Electricity Department operates the electrical system. Power is distributed to 35 substations throughout Aizawl, which have equipment such as transformers, circuit breakers, and switches.

Substations would suffer extensive damage, and distribution circuits would suffer moderate to extensive damage. Extensive substation damage means that as many as 70 percent of the disconnect switches, transformers, circuit breakers are damaged. Given the expected damage rate, two 132/33 KV transformers would be dislodged, with one damaged beyond repair. Because the design of substation control buildings and transmission towers follows the Indian code for seismic provisions, these structures will experience less damage than other parts of the substation.

Key substation equipment, such as switches, circuit breakers and transformers, use brittle porcelain insulators, and transformers are supported on rails. Earthquake shaking would dislodge transformers from their rails, rendering them inoperable. Shaking forces would snap the brittle insulator stacks throughout the substation. Substation transformers that receive transmission voltages weigh from 16 to 18 metric tons, and special multi-wheel lorries and heavy cranes must transport and place them. Replacements might have to be transported from great distances over roads damaged by landslides and congested by vehicles serving other

critical recovery needs. Delivery could take up to one month and cannot occur until roads are cleared.

Hundreds of power poles would topple and break power lines. Transmission towers and poles supporting distribution lines pass through potential landslide areas. Individual towers might be damaged by slides and cause cascading failure of other towers. Re-energizing the distribution lines would take months; because it must be done zone by zone only after isolating damaged connections. If power is restored too hastily, there is a danger of energizing damaged lines, creating unsafe conditions and igniting fires.

The Zuangtui substation, a major substation where power is transformed from 132 KV to 33KV, would be damaged by movement of an existing landslide that underlies a portion of the station. Because work is underway to replace this substation with new facilities at Melriat, it would be easier to complete a new substation than repair the damaged one.

Damage to the electrical system would interrupt critical functions at hospitals, disrupt communication systems, and prevent pumping water from the Tlawng River. While many systems have backup batteries and emergency generators, these backups can be short-lived. These critical uses would require the use of backup generators for at least a month and regular delivery of fuel. However, unless properly installed to resist earthquake forces, backup generators, their switches and circuits, and their fuel supply systems can be damaged by shaking, so they will not function when needed most. Even when functioning, emergency fuel supplies are limited and quickly become dependent on fuel deliveries. Roads to Aizawl and within the urban area would be blocked for weeks while debris and slides are cleared.

Communications Systems

Earthquake damage to communications infrastructure, and the loss of electrical power, sever almost all of Aizawl's communications links to the rest of India and beyond. The Assam Rifles have the only functioning system that can be used to request outside assistance. Within the city, police, fire and traffic police radios are virtually the only functioning communication systems. With mobile and landline telephones, internet, television and radio all out of service for days to weeks, communicating within the city to coordinate relief efforts and reunite families becomes a major challenge.

Communications after an earthquake are essential to saving lives by directing emergency services, advising the affected population and coordinating repairs. These systems would be damaged and lose power. Systems that survive the earthquake on backup power would be overloaded and not operate effectively. Communications systems include landline and mobile telephone systems, broadcast radio and television, mobile radios, police and military satellite communication systems, satellite phones, internet and newspapers. (Appendix D: Infrastructure describes these systems in further detail). Most of these systems would be damaged from shaking and ground failure, and all depend on electricity. Backup battery life is limited. Some back up and emergency electric generators would operate but would quickly run out of fuel. Resupply would depend on fuel delivery. Solar power sources would continue to operate.

Landline Telephone Systems

Earthquake shaking, landslides and falling buildings would snap lines and topple poles. Damage to the control buildings, or internal damage, can topple backup battery racks and dislodge emergency generators needed for electrical power. Even without damage, congestion and open

circuits would jam telephone lines. If the system remains partially functional, system operators can use control switches to connect phones having emergency priority, but not others. Emergency generators have limited fuel supplies. Additional fuel supply for backup power would be critical for weeks.

Cellular Telephone Systems

A large number of cell towers and building-supported transmitter/repeaters would fail, reducing coverage and limiting system capacity. Backup batteries would be drained in hours. Large numbers of emergency generators or solar panels would be needed to restore minimal coverage, and to charge individual phones. The system would not function reliably during the immediate emergency period due to these failures and to call congestion. Call congestion would impede emergency communications and compromise system operations for months.

Mobile Radios

Emergency responders and public works officials rely on mobile radios for essential communications. These systems include radios, towers with receivers, transmitters and repeaters, microwave antennas and electricity. Personnel from the Police, Fire, Traffic Police, Public Health Engineering, Power and Electricity, and Public Works departments have radio systems. Initially, if the central receiving/transmitting equipment remains functional, these personnel could provide critical situation intelligence to decision makers and allow for some coordination.

Earthquake damage to antennas and loss of electrical power would limit the effectiveness and range of hand-held radio systems used by police, fire, electric and water department employees. For this scenario, the hand-held radios used by the traffic police, police, and fire employees would work, but other radio systems would not work. Communications between those conducting damage reconnaissance, directing repairs, coordinating resources would be compromised for at least one week, until adequate equipment is delivered and operating.

Radio systems are similar to cellular systems in that antennas are vulnerable to shaking damage, they need microwave antennas to align, and they need electricity to function. The central receiver/transmitter equipment needs to survive undamaged and have electrical power. Rechargeable hand-held radio batteries require electricity.

Satellite Phones

Satellite phones are not currently available to municipal and state authorities in Aizawl. Satellite phones are among the most reliable communication systems, because they do not rely on receivers and transmitters, on switching systems supported by towers and buildings, or on electricity to power the system. However, satellite phones are expensive to purchase and operate, so they are in limited supply. Satellite phones could be brought in after earthquakes for emergency use.

Satellite phones rely on batteries for power. Without reserve batteries and a charging system, the duration of use will be limited. In this scenario, no satellite phones would be available for two days until equipment is delivered.

Police and Military Satellite Communication Systems

Following the earthquake, these communication systems would be the only links to the rest of India. As such, they will be critical in the initial response phase to communicate the on-ground

situation and request outside help. POLNET, the satellite-based police data and voice communication system, would be a critical link as long as hardware is not damaged and backup power exists. The Assam Rifles in Aizawl, and at every one of their several outposts in various parts of Mizoram, have independent satellite based communications systems to contact the rest of the country. Each outpost has backup generators and stored fuel.

Broadcast Radio and Television

Radio and television are dependent on functioning equipment as well as power and a signal. Satellite dishes can be damaged by building and tower failures and knocked out of alignment. Television would not function following the scenario earthquake due to loss of power to individual sets. Cables from ZONET and LPS would be damaged by toppling poles and landslides. Also, televisions are likely to fall and break during shaking. Radios are more robust, and residents can even access radios in their cars and phones. Radios could serve as an effective communication system as long as transmitting facilities and radio sets have power. Mass communications are needed to provide vital directions and information to people. Without such official communications, misinformation and rumors can circulate.

Young Mizo Association Public Address Systems

In the scenario earthquake, some neighborhood systems would not function because of building damage and loss of power. The YMA maintains public address systems in many Aizawl neighborhoods. These systems provide a valuable resource for transmitting critical information. These systems also require electricity and functioning backup batteries or generators to work. Some neighborhood systems are linked—allowing for a single general message—but some are dispersed and independent. Receiving accurate information and messages from central authorities would be difficult.

Newspapers

In the scenario earthquake, we assume only one newspaper would remain viable. Newspaper production requires electricity for typesetting and printing. Because printing presses are in a building, the building must withstand shaking well enough to be occupied. Loss of the ability to print newspapers locally would mean that Aizawl officials would not have the ability to distribute information using existing resources. Distributing newspapers printed elsewhere would face the problem of road blockage and would be difficult for many weeks.

Internet

Internet connectivity is vulnerable to broken fiber optic cables and loss of electricity. Internet connectivity, except that which relies on satellite dishes (e.g., POLNET) would be lost. These systems require backup power, provided by generators, as well as stored fuel.

Transportation Systems

After an earthquake, roads would be the most critical lifeline, because the city depends on deliveries from the outside. Sustenance depends on delivery of food, water, fuel and emergency shelter; recovery depends on repair equipment and materials, and medical transportation.

Roads

In the scenario earthquake, road access to Aizawl, and circulation within Aizawl, would be lost. Multiple slides would sever the national highways and the road from Lengpui airport, requiring heavy equipment and construction of temporary bridges. Repairing slides and bridge damage to

establish even minimal access could take weeks, even with measures to speed repairs by allowing work at multiple locations, such as by transporting earthmoving equipment to intermediate points. Collapsed buildings with trapped victims would not be removed from streets until search and rescue operations are complete. Emergency vehicles, and lorries with critical equipment and supplies, would not be able to move within or through Aizawl for weeks. Search and rescue and life-saving medical care would be impeded. The Tlawng River bridge on the road to Lengpui could be damaged. A replacement bridge could be constructed within a few days as long as it could be delivered by helicopter.

Aizawl depends on two-lane roads for supplies and services needed for day-to-day survival. The most important roads are national highways linking Aizawl to the other cities, especially NH54 from Silchar, State of Assam. These roads traverse steep slopes where landslides frequently occur, blocking the way. These roads have several major bridges. The system of urban streets within Aizawl city is also critical to circulation of supplies and people. Aizawl's relatively few major urban roads and streets are narrow and congested on weekdays by automobiles, motorbikes, pedestrians, and parked vehicles. Circulation within Aizawl is vulnerable to landslides and blockage by collapsed buildings. Debris from damaged and collapsed buildings would smash cars and block streets, connecting walkways and stairs. It could take several weeks to open major urban roads and streets to allow lorry distribution of critical equipment and relief supplies brought in by helicopter. It would take much longer for street clearing operations to reach some areas of the city.

Airports

Lengpui Airport, located 32 kilometers from the city, connects Aizawl by air to the rest of India. Landslides would block the road connection between Lengpui, Aizawl and other damaged villages. The Tlawng River bridge between Aizawl city center and the airport could fail.

Strong ground shaking during the scenario earthquake would damage the terminal building. Even if damage does not jeopardize the safety of the building, occupants might evacuate the building after observing concrete spalling and cracking. The runway appears to be built on solid ground excavated from the ridge top and should survive strong shaking, except for differential settlement in any fill areas. Airport operations rely on the tower, communications, electricity, and emergency generators. Any runway damage could be repaired quickly with equipment and supplies available locally or brought in by helicopter. Fuel supplies needed to provide electricity for the landing system, lights and communications would be delivered by air.

Lengpui would serve as an important staging area and connection for receiving emergency resources and evacuating severely injured survivors. It would support incoming fixed wing aircraft as well as helicopters. Establishing communications capability, electrical supply and aviation fuel needed to support helicopter operations can be accomplished within a few days. Helicopters would be needed especially during the time the road to Aizawl is blocked. Transporting people, material and equipment from Lengpui to and from Aizawl by helicopter would be a logistical bottleneck until roads are repaired. The old airfield at Tuirial would be used as a staging area especially for helicopters delivering supplies and evacuating injured people. The Thuampui helipad in Aizawl would provide a location for helicopters to take off and land, as would other large open spaces in the city. Helicopters can also hover and winch down supplies in other areas.

Railroad

Aizawl is not served directly by rail. The nearest rail station is located at Bairabi, 120 kilometers to the north on NH 54 and NH 154. Bairabi is located beyond the area affected by strong shaking and should remain operational in the scenario earthquake. The rail system is vital for delivering heavy equipment, electrical transformers and construction materials to the region. Delivery of rail-borne supplies from the rail station to Aizawl depends on road conditions along NH 154, which could be compromised for weeks.

Fuel Delivery

Fuel supplies depend on regular deliveries from long distances. Deliveries rely on tankers and lorries driving from outside the city to depots and filling stations within Aizawl—and they require open roads.

Petrol and Diesel

Damage to roads and congestion would limit supplies severely for weeks. A lack of fuel would limit local generators' capacity to deliver electricity and would hamper repairs dependent on the generators and heavy equipment. Fuel for emergency generators and diesel pumps at the water treatment plant must be delivered by helicopter until access roads are reopened. Automobiles, lorries and equipment require petrol or diesel to operate, and backup generators require diesel. Fuel delivery depends on lorry tankers driving from Silchar to reach depot areas at Aizawl.

Cooking Gas

In the scenario, cooking gas supplies would diminish quickly because of road closures. The lack of gas to cook food and boil water would have health implications. Residents use liquefied petroleum gas (LPG) from individual high-pressure cylinders for cooking fuel. These cylinders are replenished at 25 filling stations throughout the city. The filling stations depend on bulk gas deliveries from lorries.

Consequences of Damage and Impacts on the Community

Human Casualties

The scenario earthquake kills approximately 25,000 people. During the monsoon season, the larger number of landslides and resulting building collapses increase the total number of fatalities to about 31,000 people. Certain building types and specific slope characteristics are more lethal than others.

Figures 11 and 12 break down the fatalities by cause. Building collapses due to shaking would cause the majority of deaths, and building collapses due to landslides and falling bricks would cause most of the remaining deaths. These numbers include 6400 people (nearly 8000 during the monsoon) who would die of serious injuries because they are unable to be rescued from collapsed buildings or cannot obtain medical care quickly enough. Figure 13 shows the fatalities caused by the collapse of each type of building. Older and poorly built reinforced concrete buildings are the main killers, both because more of them collapse and because these buildings are more lethal when they collapse. [Appendix C: Buildings](#) describes the methodology used to estimate the number of casualties. The number of people with injuries requiring hospital treatment is difficult to estimate, but generally ranges from between two to four times the number of immediate deaths. Life-threatening conditions would persist for weeks because of dangerous buildings, inadequate and contaminated water, lack of shelter, lack of medical treatment, and lack of food.

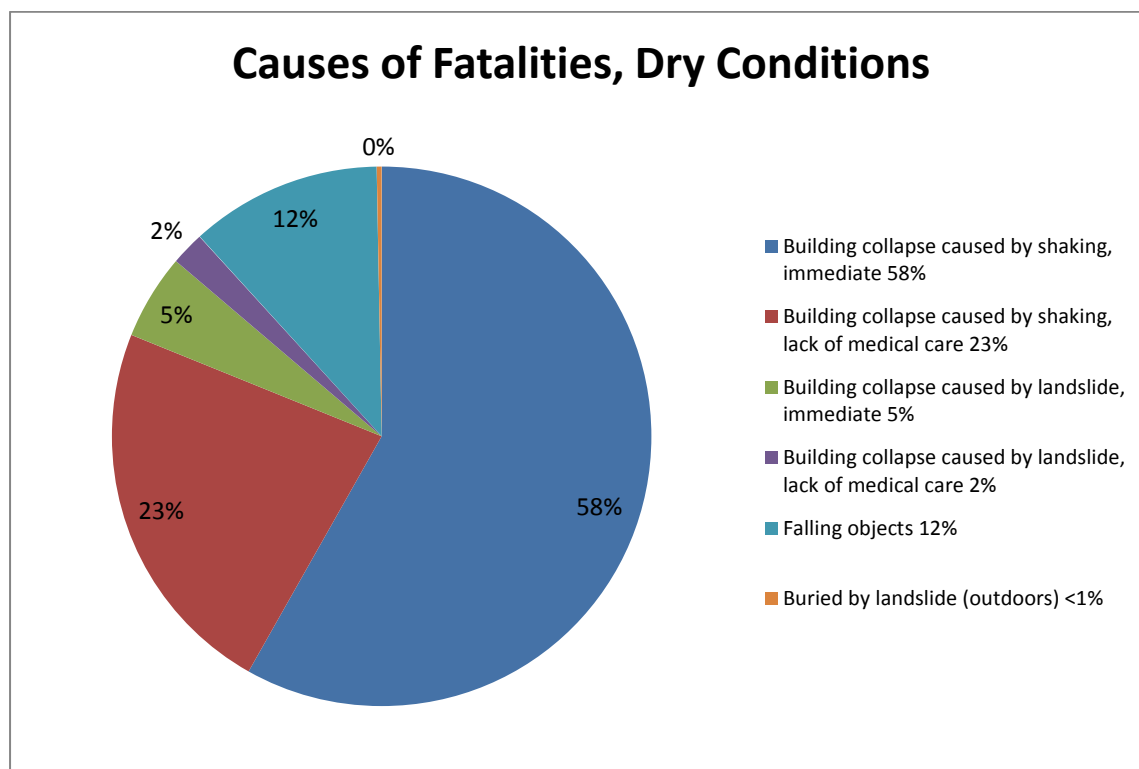


Figure 11. Causes of fatalities for dry conditions

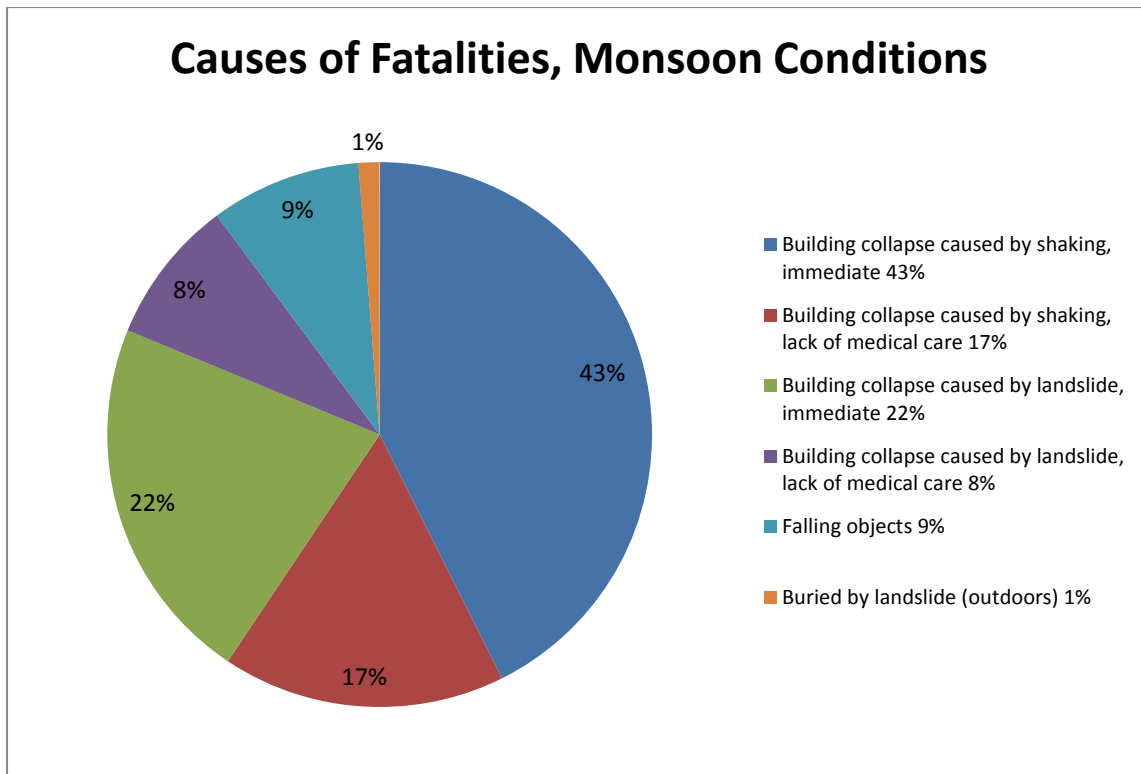


Figure 12. Causes of fatalities for monsoon conditions

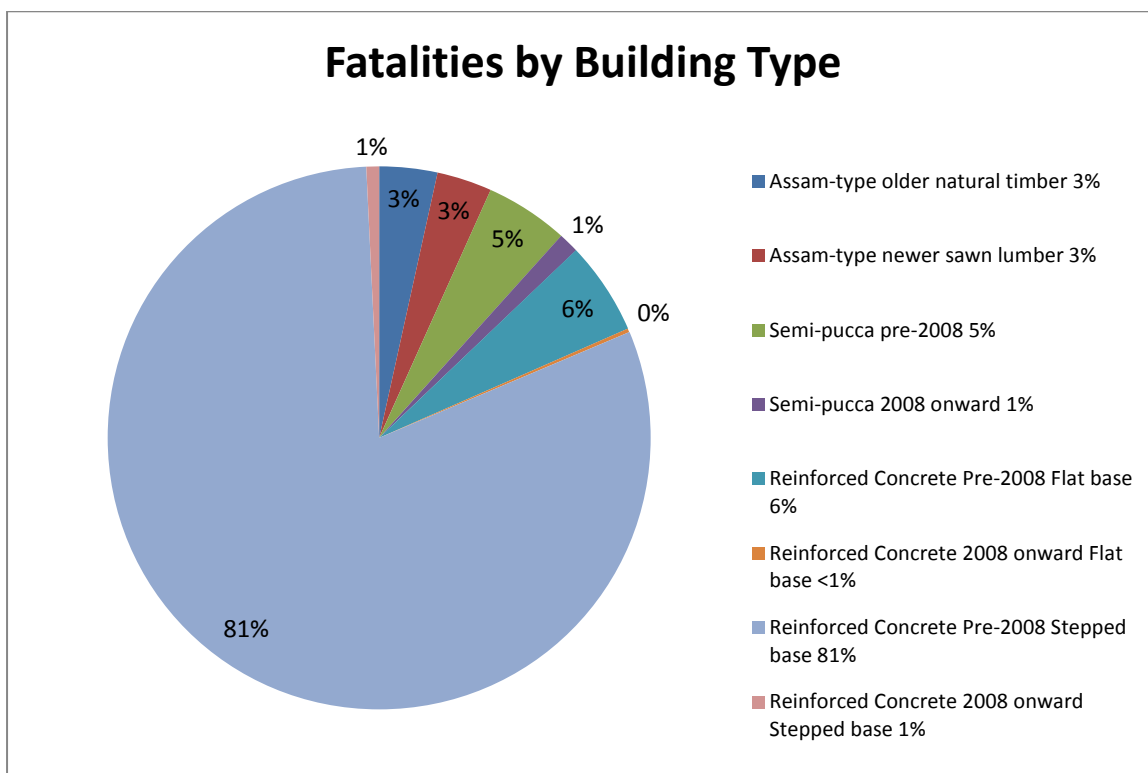


Figure 13. Fatalities due to building collapse presented by building type

Disruptions from Building Damage

Building damage, in addition to causing casualties, has immediate and severe impacts on the city's ability to function. Debris from collapsed buildings and fallen bricks block many of Aizawl's streets and pathways. Many survivors have no place to live. Destruction of shops, offices and commercial property causes people to lose their livelihoods. Market areas where people purchase food and basic necessities are destroyed or filled with debris. Hospitals suffer damage, and their backup power systems fail, leaving them unable to provide many essential medical services. Banks and ATMs are not functional, and few residents have cash on hand. Some government offices and staff quarters are badly damaged or collapsed, disrupting government services. About 14,000 collapsed buildings and many badly damaged buildings must be replaced.

Determining which buildings are safe to occupy based both on structural damage and slope stability, and deciding which can be shored and/or repaired are public safety decisions with life-threatening implications. These decisions can be difficult and require time spent by trained engineers to assess the damage and design repairs. Owners of buildings that collapse or must be demolished would lose everything saved and invested for decades. Replacing this large number of buildings would take decades and would proceed slowly given financing limitations, limited transportation infrastructure, limited work space, and a lack of skilled workers, materials, engineering expertise, and government regulators. The number of buildings lost to collapse or irreparable damage represents many decades of construction. Aizawl—indeed, Mizoram—would be changed forever.

Utility Breaks and Interruptions

Broken water pipes quickly drain water from Aizawl's zonal tanks and distribution system. Residents whose household water tanks have not fallen from supports have water for up to a week, but the tanks soon run dry. With the water system out of service, the water shortage becomes acute. Some people trek downhill to the river and streams to fetch water, but springs, wells and river sources have been contaminated. Without treatment, water from these sources could lead to the outbreak of disease. The loss of water impedes fighting the fires ignited by earthquake shaking and building failures. Loss of electrical power also disrupts critical public services and hinders response efforts. Backup generators, and the fuel to keep them running, become critical for the round-the-clock response effort.

People would begin searching for water wherever they can during the dry season, obtaining water from questionable or polluted sources. Waterborne disease can spread this way. During the monsoon, people would harvest rainwater, so the shortage would not be as acute.

Disruption to Critical Medical Care

Hospitals lack water for drinking or for sanitation and sterilization. The loss of transportation links prevents re-supply of critical medicines, medical supplies, medical gases and fuel for generators. Key equipment is damaged; the staff does the best they can, but it is almost impossible to treat the tens of thousands of badly injured with no water, no power, no sterilized instruments, and scarce supplies.

Aizawl Civil Hospital, along with several smaller private hospitals including the Presbyterian Hospital in Durtlang, provides critical medical services for Aizawl residents. The recently opened State Referral Hospital in Falkawn is far from the main populated areas and is currently lightly used. Earthquake damage in hospitals, and to the transportation networks that access

them, can interrupt medical care delivery in several ways. Structural damage to the building or slope instability can compromise the facility's safety. Interior damage to equipment, contents and the architectural finishes such as suspended ceilings and partitions can render the hospital unusable. Loss of electrical power, water and communications can cripple important hospital functions. Blocked roads and paths would make it difficult for patients, relief supplies and additional medical workers to access any of the hospitals, and would make it difficult to transfer out severely injured patients. The Presbyterian Hospital in Durtlang and the State Referral Hospital in Falkawn would be cut off from the rest of the city by landslides and collapsed buildings that block the road.

A Local Example of Earthquake Impacts: Case Study of Electric Veng Locality

To provide an example of the scenario earthquake's consequences and impacts on a more local level, we estimate the potential impacts on one of Aizawl's 92 localities (local council areas), Electric Veng. Many localities in Aizawl share at least some similarities with Electric Veng and might experience some similar impacts. Situated on the east side of the main ridge, Electric Veng is in the central portion of Aizawl. Its slopes are densely packed with many commercial buildings in addition to residences. Figure 14 shows most of the locality, viewed from the east.



Figure 14. Electric Veng, viewed from east (Photo credit: Janise Rodgers, GHI)

According to the Aizawl Municipal Council's 2009 houselist survey, Electric Veng has approximately 450 buildings and more than 1220 households. Assuming Aizawl's average household size of five people, the estimated residential population is about 6100 people. Buildings are mostly reinforced concrete, built prior to the introduction of building regulations in 2007, and Assam-type. Our field inventory shows that buildings are approximately 63% reinforced concrete (57% older buildings with stepped bases, 1% newer buildings with stepped bases, 4% older buildings with flat bases, 1% newer buildings with flat bases), 32% Assam type (10% older and 22% newer), and 5% semi-pucca (4% older, 1% newer).

Important buildings in Electric Veng include the YMA Hall, the Mizoram Power and Electricity Department headquarters, and several large churches. The locality has an electric substation but does not have a zonal water tank. Like most localities on the ridge's sides, Electric Veng has a number of streets running north-south, parallel to the ridge line. No streets run east-west (up and down the hill), meaning that travel uphill or downhill must be on foot via numerous stairs, or by traveling a north-south road to the end of the locality or beyond and back again.

Electric Veng sits almost entirely on an east-facing slope, which is approximately parallel to the bedding planes of the rock formation below, making the slope particularly susceptible to

landslides. As a result, the entire locality is either in the zone of high landslide hazard (62% of the locality area) or very high landslide hazard (38% of the locality area) as defined in Figure 5 of [Appendix B: Landslides](#). These zones represent hazard in undisturbed, natural terrain; human modifications to the slopes, such as cutting the slope to build roads or buildings, may increase the hazard further. Figure 15 shows the approximate Electric Veng boundary (in blue), locations of important buildings and roads, and the landslide hazard zones.

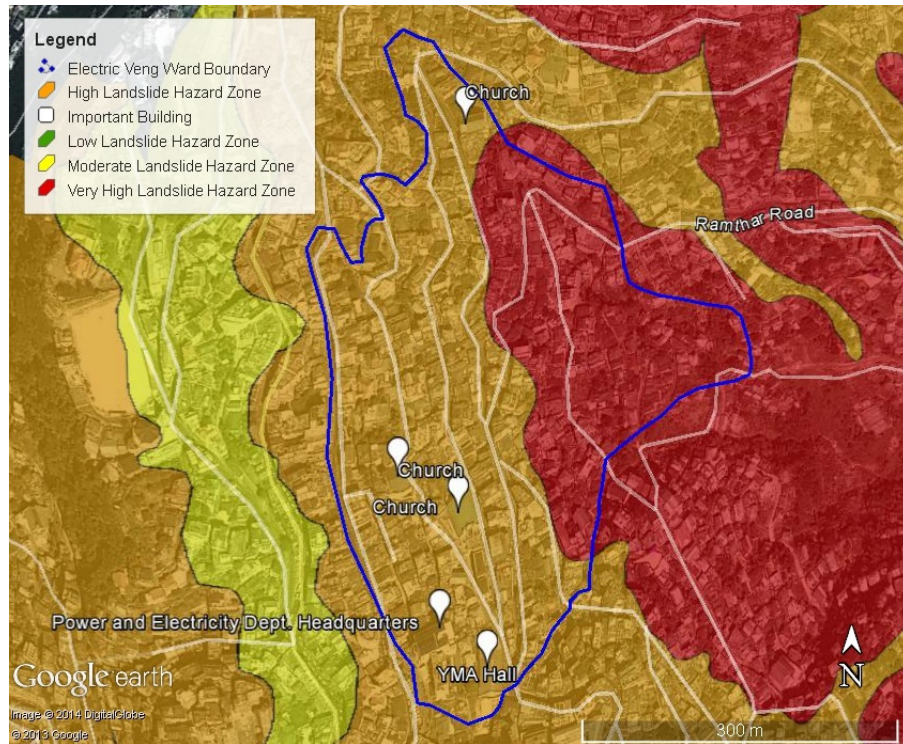


Figure 15. Electric Veng (boundary in blue) with landslide hazard zones, roads and important buildings

If the scenario event occurs during the dry season, 3 percent of the red area and 2 percent of the gold area in Electric Veng (shown in Figure 15) is expected to slide. The resulting landslides would collapse approximately 10 buildings during the dry season and 60 during the monsoon; shaking alone would collapse another 110 buildings during the dry season and 100 buildings during the monsoon. (Shaking collapses fewer buildings during the monsoon, because buildings that would otherwise collapse during shaking are collapsed by landslides instead.) In the dry season, more than 25 percent of Electric Veng's buildings would collapse; during the monsoon more than 35 percent could fail. During the dry season, these collapses along with falling bricks would kill approximately 500 people immediately; another 150 people could die from lack of medical care, bringing total deaths to more than 650—more than a tenth of the locality's residential population. During the monsoon, 650 people would die immediately, and another 200 would die from lack of medical care, bringing the total deaths to more than 850. The power would go out due to damage to the substation. Numerous water distribution lines would break, and household water tanks would topple and break their connections. Debris from collapsed buildings would block roads and stairs, trapping people in the neighborhood and impeding access for rescuers.

In addition, the occurrence of a large, catastrophic landslide during the strong shaking produced by the scenario earthquake cannot be ruled out. Large landslides, such as the 1992 Hlimen

Quarry landslide, are known to occur in the Aizawl area. In northeast Aizawl, we found geomorphological evidence of a number of large landslide complexes (see Figure 2 of [Appendix B: Landslides](#)), indicating that large landslides occurred prior to Aizawl's written history. These pre-historic landslides may have initiated from extreme monsoon rainfall events or as the result of strong ground shaking.

For illustration purposes, we examine what might happen if a catastrophic landslide were to occur in Electric Veng. Other localities with similarly adverse geologic conditions could possibly experience a catastrophic landslide; it is **not** more likely to occur in Electric Veng. Both the Hlmen quarry landslide and the much smaller May 2013 Laipuitlang landslide occurred in areas with similar geology to that underlying Electric Veng. Furthermore, slope stability calculations carried out for a cross section through Electric Veng (shown in Figure 4 of [Appendix B: Landslides](#)) indicate that a large landslide could occur at 0.35 g shaking under both dry and monsoon conditions, and at a much lower level of shaking (0.1g) during the monsoon.

Figure 16 shows the devastating effects that a large landslide would have on Electric Veng. In this example we have drawn a landslide of the size our slope stability calculations indicate is possible in a hypothetical but reasonable location in Electric Veng. Fortunately, a landslide in this location would not collapse any important community buildings, but two large churches would sit near the head scarp and could be at risk from subsequent landsliding. This hypothetical landslide would sever all but one of the locality's north-south roads, impeding travel. The landslide would collapse approximately 80 buildings. These collapses would kill a number of additional people not included in the overall total for Electric Veng mentioned above. We assume that the total fatalities caused by the scenario earthquake remains unchanged, because the method used to estimate the total area of landsliding (and its consequences) uses an average percentage of landsliding over the entire city. We assume that concentrated damage from larger landslides, which cannot be ruled out, is offset by fewer landslides elsewhere.

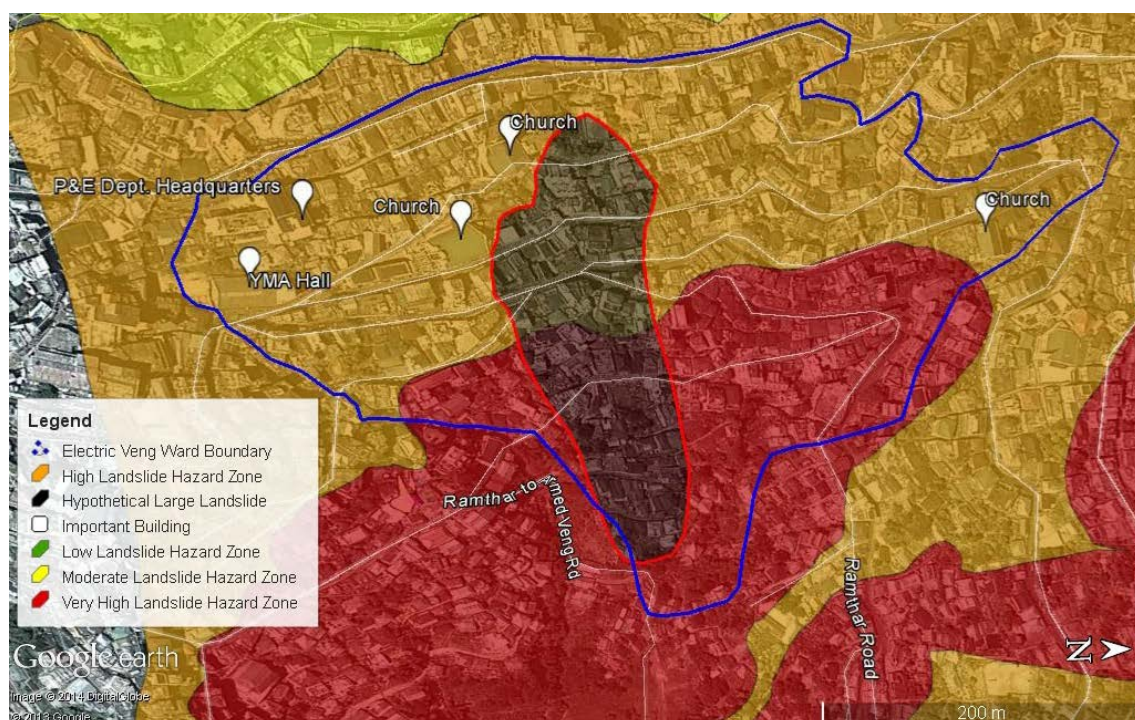


Figure 16. Hypothetical large landslide superimposed on Electric Veng

Emergency Response and Recovery

Emergency Response following the Scenario Earthquake

Earthquakes, like other rapid onset hazard events, are initially dramatic and frightening, but in reality the danger extends for some time. Aftershocks that damage or destroy buildings and infrastructure continue for weeks, or perhaps months. Both the main shock and aftershocks trigger landslides and fires. The consequences evolve and the number of casualties grows. Neighbors, first responders from the community, and state and national government responders carry out rescues, provide medical treatment, transport those needing higher level medical care, and provide the food, water, medicine and shelter needed to sustain victims until early recovery begins. In Aizawl, response is made much more challenging by geographic isolation and the lack of access due to blocked roads and streets. Also, the very dense urban environment has few flat open spaces in which to stage relief and shelter survivors, as Figure 17 shows.

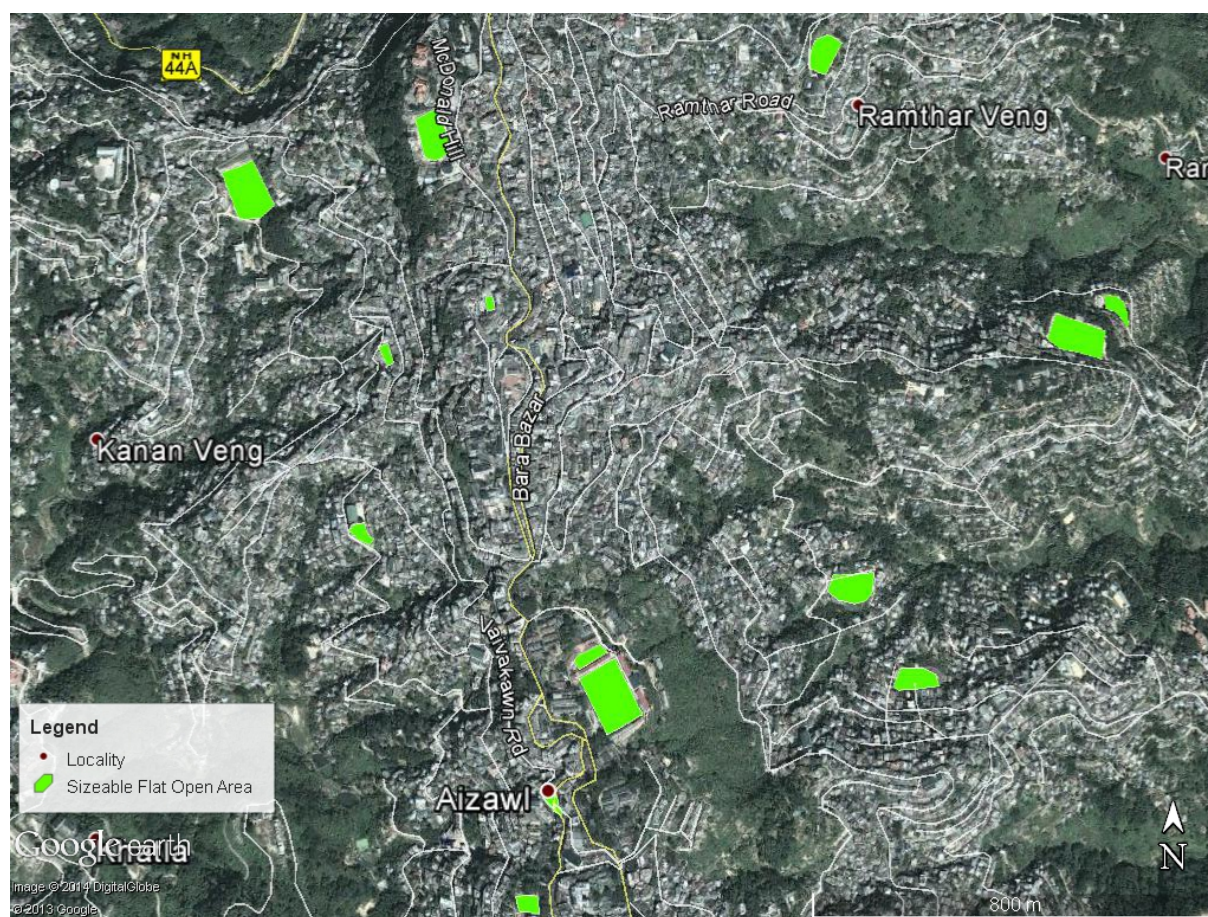


Figure 17. Sizeable flat open spaces in the central part of Aizawl city (in green)

This section provides a situation report-style description of the emergency response activities that would take place following the scenario earthquake. Organized using a timeline, it is intended to highlight issues and problems that emergency/disaster managers would face at different times during the response and early recovery period. Understanding these issues will help emergency managers improve plans, increase coordination between agencies, and bolster response capacity. Such improvements are feasible in the near-to-medium term, and can be cost effective when integrated into ongoing planning processes and preparedness programs.

Day One

The city is rocked by the 7.0 magnitude earthquake at 2:00 PM. A large dust cloud created by collapsed buildings rises over the city. The response begins almost as soon as the shaking stops. Initial reports of the event are shared with the Government of India by the Assam Rifles via their military communications network, which is the only functioning communications link between Aizawl and the rest of India; all other communication links are out of service.

The staff in the Disaster Management and Rehabilitation Department (DM&R) activates the State Disaster Management Committee (SDMC), and the staff in the office of the Deputy Commissioner (DC) similarly activates the City Disaster Management Committee (CDMC). There is damage in both the DM&R and DC's office buildings, and all communication systems are down. Some members of the staffs and state and city disaster management committees are unaccounted for. Members of both committees are spread across Aizawl when the earthquake strikes, and with roads blocked and all telephone service down, there is no way to quickly determine whether the members have been injured or have even survived, and who will be in charge of the response effort. Without communications capability and the ability to move quickly within the city, the SDMC and CDMC have no way to quickly assess the extent of the damage, which areas have been hardest hit, and how many people may have been injured or killed. They are unable to meet in person. Nonetheless, it is clear this is a major disaster and the State Government declares an emergency. In the localities, Locality Disaster Management Committees (LDMCs) are activated by whichever members happen to be present in the locality at the time of the earthquake. They are able to obtain information more quickly, but streets and pathways blocked with debris make it difficult to move within localities. They must communicate through direct conversation.

With no other way to communicate and no knowledge of how the Assam Rifles were affected, DM&R sends a staff member on foot to the nearby Assam Rifles headquarters in central Aizawl to ask them to use their communications systems to contact the Ministry of Home Affairs (MHA) and NDMA and to request deployment of National Disaster Response Force (NDRF) teams. The SDMC sends a runner to contact and coordinate with the CDMC. The Emergency Operations Center (EOC) in the DC's office would be activated, but because of substantial damage to the DC's office compound, a temporary EOC is established nearby.

The Incident Commander (DC or person in-charge in the DC's absence) and the EOC immediately send runners to all line departments and LDMCs to give and get information. With landline and mobile phones out of service, and other wireless radio systems not functioning due to the loss of power and inadequate backup, the only functioning local government communications system is the wireless police radio. Where communication is not possible, (such as with LDMCs), messengers are sent, but travel is slow, on foot and dangerous. Every member of the teams sending and receiving messages is at that moment also concerned about the safety of family members who may be in different parts of the city at the time of the earthquake.

At sites of collapsed buildings, the survivors and neighbors pull as many people from the debris as they can, but these community members do not have heavy equipment or training and cannot free a number of people trapped by heavy concrete slabs. Local YMA branches begin to organize groups of searchers in each locality, but these teams do not have heavy equipment. Survivability in earthquake-collapsed buildings in the first hour is 90%, but then it drops rapidly. The

number of severely injured needing immediate medical care for crushing injuries, for broken bones and arterial bleeding is not known. Neighbors, family and local YMA teams will rescue the most people, simply because they are nearby and can respond immediately. Some of these informal rescuers take risks going into damaged and collapsed buildings, and some are injured and killed by further collapse and shifting of debris caused by aftershocks.

Professional rescuers, such as the State Disaster Response Force (SDRF) units, also begin rescue efforts, but they are too few in number, given that there are over 14,000 collapsed buildings and they are hampered by communications and travel difficulties. SDRF units are attached to three Mizoram Police battalions in Aizawl, so the surviving members of these teams were within their own battalions executing normal duties when the earthquake struck; they must regroup at the pre-appointed place before deployment. It takes them hours to assemble, and many members are missing, either because they cannot travel to the appointed site or because they are helping to rescue people in the location where they were at the time of the earthquake. The first members to arrive begin searching nearby buildings, but there are so many collapses that it is clear the number of SDRF search teams is completely inadequate. Roads are blocked by fallen buildings, so these teams move on foot. They must carry electrical generators to operate search and rescue equipment at building collapse sites. Progress is slow, with entreaties from neighbors and family members to search each of the many collapsed buildings along their route. Teams may be redeployed when news arrives of many people trapped by collapses of large buildings. Deciding which buildings to search is controversial—and emotional—because survivors call out for help at thousands of locations. The task at hand is overwhelming.

Assam Rifles teams swing into action as well, despite some damage to their own buildings and loss of equipment. In addition to helping search damaged buildings, they help maintain order and begin the daunting task of trying to clear roads of debris. As more news comes in of localities affected by earthquake-triggered landslides, the SDRF teams are further deployed with assistance from untrained police personnel and local YMA teams.

Friends and family immediately bring people with minor and major injuries to all of the hospitals. Each hospital activates its response plan and makes arrangements to receive many times their normal daily handling capacity. The number of victims overwhelms the facilities and staffs. Most hospital buildings are damaged, so in-patients and earthquake victims are treated in the few nearby open areas. Many people have suffered heart attacks. Hospital staff must use triage to separate those who need immediate treatment from those who do not, and to determine which of the badly injured are beyond saving. These are difficult decisions complicated by the fact that families find many decisions and priorities hard to accept. Crowd control and security are needed. A few injured staff members and in-patients are evacuated and treated. The skeleton security staff available at the hospitals tries to control crowds. Everyone wants his or her loved one treated immediately. Hospitals use Public Address systems to give out information. Staff members are worried as news—and rumors—comes in of some collapses in staff quarters and damages to school buildings, but they bravely continue treating the injured.

Schools activate their disaster management plans and evacuate children to safe locations. Some children and staff were injured by damage to buildings and falling contents. Many schools located in rented buildings have suffered damage and casualties. Many schools have lost their 'safe' evacuation locations due to collapse of other buildings around them; teachers and students have to assemble in different, possibly unsafe locations. Many teachers rush home to

look after elderly parents and infants left with family members or domestic help. School children are traumatized by the losses in their schools and the injuries around them. School search and rescue, trauma counseling, and first aid teams formed as part of the disaster management plan are overwhelmed by the number of children requiring assistance. Some children attempt to walk home on their own, but they are discouraged by alert teachers. Most schools have not involved parents in their mock drills and do not have arrangements in place for releasing children to their parents or other relatives.

In the 92 Aizawl localities, many of the response team members or their families are victims. Many families have been separated by the event, and surviving members are worried about the safety of their loved ones. The local search and rescue teams organized by YMA swing into action and begin searching collapsed buildings for survivors. Some of their equipment is lost in collapsed structures, but the teams manage with whatever they can get. Members of local first aid teams, who are not injured and who are in their own locality when the earthquake strikes, begin to provide first aid for injured survivors after checking on their families. Some members of these teams join with the local search and rescue teams. No rescues are painless; there is immediate need for specialist medical attention that local first aid teams are not able to provide. They send team members to the DC's office to inform of the grim situation and request for deployment of SDRF teams. Some downed power lines are still live, and community members try to turn off electricity on their own. Some people report LPG leaks from under collapsed structures and warn people not to light cigarettes, fearing a fire or explosion. The sounds are unnerving. Damaged buildings creak and groan during aftershocks and as landslides continue to move. Sirens from emergency vehicles wail. Terrified dogs bark outside collapsed structures, probably looking for lost people. Dust causes respiratory problems for many persons, especially the elderly.

Some seriously injured persons extricated by the search and rescue team are given first aid and carried to the nearby hospitals in makeshift stretchers. Some women in an advanced state of pregnancy are assisted to nearby hospitals by members of the first aid team. Many ask for water, but the teams tasked with preparing food are not able to provide water due to damage to the water system.

Fires break out and are fought by residents using water, sand buckets, etc. However, broken water lines and toppled residential water tanks decimate water supplies.

LDMC information dissemination and damage assessment teams in localities close to the DC's office send runners to provide initial estimates of the number of casualties and building damages, and to ask for help and facilities to store dead bodies. In localities far from the DC's office, the LDMC members quickly realize that travel to the DC's office on foot will not be possible before night falls, and too dangerous in the dark, so they search for police with functioning radios, their only other means of communicating with those coordinating the response.

Churches are designated safe shelters for victims, but many church buildings are badly damaged. The community converges at churches that appear to have only slight damage, offering to help in whatever way they can. Many come seeking prayer as well as the comfort and support of their church family. Shelter management team members, helped by volunteers, try to arrange lighting before night falls, so that search and rescue efforts can continue.

Most generators have less than a few hours of fuel backup and will cease to operate during the night. Very few petrol pumps can operate or have functional generators, and access is limited by building collapses and landslides. The generators of the SDRF teams are running out of fuel and need to be replenished immediately. Some generators are heating up due to continuous usage. Radio handset batteries are running low, and where generator backup is not available, these stand the risk of running out. Teams from telephone service provider BSNL are trying to get their systems to work again with limited success. A strong aftershock rocks the remains of the city, bringing down previously damaged buildings, triggering additional landslides, and creating fear and chaos.

At the DC's office, a team is sent on foot to inspect the Thuampui Helipad to see if it can be used for relief operations. Because the helipad is far from the city center, the NRDF teams that should come in by helicopter by morning will need to land at the Assam Rifles' parade ground. Assam Rifles begins to move people who have congregated on the parade ground elsewhere to make room. People also assemble at Rajiv Gandhi stadium, and the Chite Mini Sports complex, where helicopters are able to land. Rumors begin to circulate, fueling fear.

As night falls, many people remain at the site of their collapsed houses, trying to salvage items, aware of the risk of more aftershocks. Many people burn whatever they can get to keep warm and for light. Families that have not yet fully reunited become more anxious regarding the safety and location of remaining family members. The locality food teams start preparing to cook and serve food from the few items they collected locally. As night falls, churches hold prayer meetings of those assembled and sing hymns to bring peace and comfort. Surviving church leaders prepare to work through the night to comfort and support those in their congregations who have lost homes and loved ones.

By the end of the day, local government and medical officials fully understand that they are dealing with a major disaster. The formal assessment has not begun, but everyone knows the city is isolated, and the demand for life-saving help exceeds what is possible. The number of casualties and their severity, the extent of building damage, and the number and location of road blockages clearly exceed all expectations. Local officials have not had meaningful communications with officials outside of the area, and they are just beginning to know which officials, government and medical workers are among the casualties. The Assam Rifles have established limited communications with outside resources.

Day Two

NDRF teams from Kolkata and Guwahati arrive at Lengpui Airport and are transported to the Assam Rifles parade ground by helicopter. They bring in much needed emergency communications, including satellite phones. The team is debriefed by the CDMC and they send immediate needs requests to the NDMA. A team also lands at Thuampui helipad bringing in search and rescue and medical teams. Some medical teams are taken to the Civil Hospital, and some remain at the parade ground, which is one of the few open areas in Aizawl where field hospitals can be set up. The search and rescue teams are escorted to several nearby areas where many people are thought to be trapped alive under collapsed buildings. With so many collapses, a still-unclear picture of the location of the most heavily damaged areas, and most streets blocked by debris, the CDMC decides that the teams should focus on the closest locations of major collapses and work their way outward as new information comes in and some progress is

made in clearing major streets. The number of collapsed buildings overwhelms the few professional teams. Untrained volunteers conduct most search and rescue efforts.

The CDMC calls for construction teams to establish road access by clearing landslides on NH 54 to Silchar and the road to the Lengpui airport. Crews begin removing building debris and abandoned automobiles along the spine road. Debris clearance is slowed at collapse sites with trapped persons inside. There is very little space to use as a staging area for the relief materials coming in by helicopter. The Indian Army comes in with additional reinforcements and starts providing relief, assisting in the rescue efforts and establishing communications and road access. They provide mobile hospitals. The first badly injured victims are evacuated to Lengpui Airport on return helicopter flights, and are then sent onward for medical treatment.

The Central Government declares assistance to the Government of Mizoram. The Prime Minister appeals to the public to contribute to the PM's relief fund to help the Mizo community through the crisis. Indian and India-based international television, radio and print media make their way toward Aizawl as the government allows a limited number of journalists to board flights to Lengpui Airport carrying relief. A very few journalists are able to fly into the city in Indian Army helicopters. The story quickly goes global, raising worldwide concern.

LDMC first aid teams make their way to hospitals to assist, after providing whatever help they could in their own locality. Some members of these teams join search and rescue teams.

Beginning on the second day, shelter teams organized by local YMA branches clear some areas to accommodate the survivors. Many survivors are elderly citizens who had been alone at home and are now worried about their family members and in need of water and food. The trauma counseling team members counsel them, but they themselves are traumatized by the losses of family members and the scenes around them. They carry on with their duties. Shelter team members begin to set up shelters in the cleared areas. They also create temporary toilets near the shelter area, taking care to construct temporary soak pits for onsite disposal of wastewater, because any leakage could affect communities living downhill. The Food and Water team in the LDMCs start collecting more food supplies, and many shopkeepers give away food items to these teams. By the end of the day, the implications of failed infrastructure—loss of roads, electricity, communications, water supply—become clear, and the need for strategic decisions and resource allocation becomes evident. As on day one, the number of collapsed buildings overwhelms the few professional teams, so untrained volunteers conduct most search and rescue efforts. Members of the LDMCs are assigned to photograph and document dead bodies.

CDMC recognizes the need to provide information to victims regarding safety measures, location of medical services, food and water, and to counter rumors. Only FM radio provides connections, though limited, to the community.

One Week

An exodus from Aizawl starts as significant numbers of residents begin long treks to ancestral villages. Many people cannot get automobiles and motorbikes out of Aizawl because of damage to the urban streets and rural roads. Lorries carrying relief supplies and emergency vehicles congest all open roads. Many families remain because of uncertainty regarding the fate of family members. Able bodied family members will remain, trying to salvage materials for later use. Residents take risks to remove belongings from damaged buildings. The mood changes, as some of those staying behind become angry because of the losses and the lack of resources. Disaster

workers and government decision makers show the strain from the pressures, long work hours, and personal losses. Work to remove landslides and re-establish roadbeds continues. Heavy-lift helicopters deliver earthmoving equipment and temporary bridge structures to damaged sites. Decision-makers grapple with where to put all the debris, created by collapsed buildings and landslides, once it is removed from the streets and pathways. People prevent clearance of building debris from the spine road because they hold out hope that family members trapped in collapsed buildings blocking the road are still alive and can be rescued.

Providing potable water becomes critical as home tanks that survived the shaking begin to run dry. Desperate search and rescue efforts are at full force, with Indian and foreign teams who find and rescue several trapped survivors one week after the event. Funerals and burials for several hundred victims are held each day.

Two Weeks

Debris clearance has opened limited access along the spine road, but most roads remain closed by building debris and landslides. Continued aftershocks unnerve those remaining in the city, cause additional landslides, and exacerbate building damage.

The SDMA must make decisions about damaged structures: which can be used, which can be repaired, and which must be pulled down. Adding to the difficulty, there are no standards to evaluate badly damaged buildings regarding the risk of collapse in an aftershock, so the government must rely on the judgment of individual engineers. There are too few qualified engineers with training regarding the safety of damaged buildings and whether they can be repaired. At the end of the week, only a few damaged buildings are evaluated for safety.

The national news media and citizens of Aizawl begin asking why did this happen? Why were so many buildings damaged? Why did so many die?

Recovery and Economic Impact

With the response phase still ongoing, early recovery begins. This section describes anticipated challenges and timelines for recovery. The pace of recovery depends to a great extent on the resilience of those affected and on outside support. The objective is for individuals, institutions, government agencies, businesses and communities to resume increased levels of activity and to establish a new normal somewhere near the level of activity before the earthquake struck.

Aizawl's recovery would take years, probably longer than a decade. With so many buildings destroyed, many families' major assets would be gone, and a number of families, having lost family members, have lost the ability to earn an income. Students drop out of school to work on reconstruction to provide an income for their family. Residents would expect the government to provide large amounts of financial assistance just to get people back in minimal housing. Large sections of the commercial core, which contains vulnerable, older concrete buildings, would be decimated by building collapses and badly damaged, non-repairable buildings. Many shops and businesses would close due to a loss of their buildings, records and inventory. Economic development would be set back significantly.

Despite Aizawl's tremendous civil society and tight-knit communities, recovery would be very challenging. The devastation would be so severe, and the lack of water and power would persist for so long, that many would leave for villages where they have relatives and roots.

The timeline below highlights some key points in Aizawl's recovery from the scenario event.

One Month

Limited amounts of electricity from the grid would be available at substations, and dedicated lines would restore power to critical lifelines, such as the hospital and key government offices. A few schools would reopen, in an effort to provide children and families with some sense of normal life. Access to and within Aizawl is still severely limited. Aftershocks would increase damage and unsettle residents; damage and safety evaluations would need to be repeated for buildings that suffered substantial additional damage.

Three Months

Debris would be removed from key roads, and some road traffic would be possible within the urban area. Petrol for private use would still be in limited supply. Assessment of damaged buildings to determine whether they can be repaired would be ongoing. Electricity would reach distribution substations, and treated water would reach zonal tanks. However, electrical and water service would not yet reach most homes.

Six Months

Roads would still have limited capacity as repairs continue. Some damaged buildings would have been demolished, and construction of a few new buildings would begin. The geography, small spaces, limited supply routes, and lack of materials and workers restrict the pace of construction.

One Year

Though a significant amount of debris would have been removed, and many irreparably damaged buildings would have been demolished, damaged buildings and piles of debris would still dominate the cityscape. The population would be about one-third of the pre-event population. The city and state governments would have agreed on a rebuilding plan that prioritizes earthquake and landslide safety.

Actions to Improve Earthquake Safety and Resilience

As you have read in the scenario, widespread damage to buildings from shaking and landslides leads to casualties and to demands for rescue, medical care and shelter. But such extensive damage and consequences do not have to happen. New buildings can be located away from hazardous areas and constructed to resist shaking. The electrical and water systems can be made more robust and redundant. Key equipment can be secured, and backup systems installed at key facilities. New pipelines can be located away from areas of high landslide hazard and made flexible to help accommodate movement during an earthquake. Emergency response capacity can be enhanced, and plans can be made and tested to improve response capacity and the efficacy of coordination with outside assistance. Families can safeguard their homes and prepare each person for a role in responding to an earthquake.

Unacceptably risky situations can be rectified over time. For example, communities in hazardous landslide zones can be moved, active slides shored up, and vulnerable hospitals and emergency facilities retrofitted or replaced. Obsolete buildings can be replaced with safe new ones to improve safety and resilience over time. Hazardous landslide zones can be identified and measures taken to stabilize slopes. The city can install an effective surface and wastewater conveyance and drainage system to reduce the risk of landslides.

These are only a few of the many things that Aizawl's leaders and people can do together. Dedicated professionals in Aizawl have invested their careers to create a safer city, and they have already saved many lives. They need support—from you, from neighborhoods, from government agencies.

What Can Aizawl's Leaders Do to Prepare?

We recommend that the Government of Mizoram create a standing Geologic Hazards Commission to plan, coordinate and oversee measures to improve earthquake and landslide safety, including the following highest priority recommendations:

- Develop a better understanding of geology, topography and landslides by mapping and monitoring; as well as a better understanding of the effects of drainage and of constructing roads, buildings and infrastructure on landslide hazard areas.
- Identify and evaluate areas of high landslide hazard, beginning with those that affect large numbers of people and critical facilities, and determine appropriate risk reduction measures.
- Implement a comprehensive program to improve the system for surface water drainage and disposal of wastewater and sewage.
- Regulate slope cutting and slope modifications, and enforce the regulations.
- Enforce the building regulations.
- Encourage people to willingly comply with the site development regulations and building regulations, and provide standard building, foundation and site preparation plans and guidelines.
- Create local amendments to the National Building Code (in the building regulations) to address slopes.
- Require a seismic retrofit of buildings when significant additions/alterations are made.

- Prevent land allocation for building construction in geologically hazardous areas (“no build” areas).
- Review development plans, including the current Master Plan, with respect to this earthquake scenario and new geologic information.
- Utilize the current Master Plan and future revisions to expand Aizawl in a planned manner that properly accounts for geologic hazards. Discontinue incremental, unplanned development practices.
- Provide technical capacity within agencies to understand and properly use information related to earthquake and landslide hazards.
- Build the capacity of local geology, geotechnical engineering, structural engineering, architecture and planning communities.
- Modify one major ground transportation link– for example, NH 54 to Silchar– and the road between Lengpui Airport and Aizawl to remain functional after a damaging earthquake, by installing engineering measures to prevent landslides and strengthening bridges, in order to allow relief supplies to get in and people to get out.
- Identify, assess and reduce vulnerabilities of important buildings such as hospitals through replacement, change of use, strengthening, or land stabilization.
- Test state, district, Aizawl city, and locality disaster management plans with tabletop exercises, and strengthen them based on findings.
- Prepare a long term (i.e., until 2030) action plan that describes mitigation measures for Aizawl city and identifies responsible agencies and resources.
- Conduct outreach and awareness programs to promote family earthquake and landslide preparedness, and encourage families to prepare.

Several additional recommendations were identified as very important but as having slightly lower priority or potential impact on Aizawl’s overall level of risk. These additional important recommendations are:

- Assess utility systems, and increase the robustness of the systems to provide continuous service for critical facilities.
- Conduct school earthquake and landslide safety programs.
- Develop a post-earthquake reconstruction and recovery plan.
- Provide local heavy search and rescue capability; possibilities include a National Disaster Response Force battalion or enhanced State Disaster Response Force battalions.
- Increase the number of local first responders with adequate basic training in light search and rescue, first aid, and other immediate response tasks.

What Can I Do?

You can play an important role in helping to make your family and your community safer. You can begin making choices—today—that will increase your safety and bring peace of mind. You can do many things, most of which are simple. Here are some of them:

- Create a family emergency plan. Discuss with the entire family what you will do following an earthquake, major landslide, or other hazard event and how you will reunite. Determine a meeting place and an alternate location. See the sample plan online: <http://www.geohaz.in/upload/files/important/familypreparedness.pdf>
- Create a family emergency kit that contains emergency food, water, medicine and other essential items. See the State Disaster Management Authority website for a list of items to include: <http://dmr.mizoram.gov.in/page/disaster-survival-tips.html>
- Take the advice of qualified professional geologists before modifying any slopes on your land. Cutting slopes can be dangerous: slope cutting led to two of Aizawl's deadliest landslides, at Hlmen Quarry and Laipuitlang.
- Don't undermine your neighbor's house when building your own. Their house could slide down into yours!
- Install proper drainage and sewerage systems so that rainfall runoff, wastewater and sewage will enter drains or pipes, rather than soak into the ground. Keeping the slopes on your land as dry as possible will reduce the landslide hazard.
- If you build a semi-pucca or reinforced concrete (RCC) building, hire a qualified engineer to design it according to the Aizawl Building Regulations, and hire skilled, experienced masons to build it. Ensure that the masons follow the approved drawings. Buildings designed and built to the regulations typically cost about 5% more than those that are not, if anything, and they are much safer.
- If you build an Assam-type house, hire skilled carpenters and ensure that the support posts below the floor have plenty of X-shaped cross braces.
- Ask a structural engineer whether your home has the support to withstand a moderate earthquake, and find out what you can do to strengthen the structure.
- Obtain training in basic first aid. You just might save someone's life, maybe in your own family!
- Support government programs to reduce earthquake and landslide hazard; see the recommendations in the previous section.
- Learn more about earthquakes and landslides, and teach your children, friends and relatives. The more you know, the easier it will be to make your family and yourself safer.

Detailed Recommendations

The scenario highlights many issues that contribute to earthquake and landslide risk in Aizawl. Working together, Aizawl's people and colleagues throughout India and beyond can begin to address them. The tables in subsequent sections present concrete recommendations to address each separate issue identified during the course of developing the scenario and through consultations with local professionals and community members. Recommendations and the issues they address are organized by major topics:

- Systemic concerns
- Landslide risk
- Building vulnerability
- Infrastructure vulnerability
- Scientific data needed to characterize hazard
- Land use planning

- Public education and awareness
- Response and preparedness

Within some of these major topics, recommendations to address issues are organized into separate sub-sections for policy, technical, and professional community development issues.

Aizawl's people and their leaders must set the priorities and determine which issues to address first. We recommend that the first task of the recommended Geologic Hazards Commission should be to set priorities through an inclusive action planning process.

<i>Systemic Concerns</i>	
Issue	Recommendation
Limited policies, regulations and incentives to address hazardous areas	Create a standing Geologic Hazards Commission to develop land use policies, regulations and incentives. This advisory body should be independent of government control, transparent, and have members from multiple technical disciplines and organizations. (A separate Landslide Policy Committee will address some items related to landslides.)
No coordinated program or plan to address earthquake and landslide risk in Aizawl	Develop a long-term action plan for a safer Aizawl (i.e., until 2030), which describes mitigation actions, responsible agencies, and resources. The plan would work in parallel with the Master Plan, to coordinate initiatives and programs. The Geologic Hazards Commission would develop and oversee implementation of the action plan.
	Design and implement comprehensive earthquake and landslide risk reduction programs, which the Geologic Hazards Commission would oversee.
Lack of drainage systems and wastewater systems contributes to landslides, poor sanitation, and contamination of groundwater, streams and rivers	Implement a comprehensive program to improve the limited system for surface water drainage and disposal of wastewater and sewage; to provide a sewage treatment system; and to eliminate septic systems and soak pits that saturate slopes with contaminated water. The Asian Development Bank funded improvements will make significant progress toward achieving these goals.
Geographic isolation and lack of transportation infrastructure greatly impedes post-earthquake relief and early recovery	Modify the road to Lengpui Airport plus one major road link, perhaps NH 54 from Silchar, to remain functional after a damaging earthquake, by mitigating landslide risk with engineering measures (for example, installing reinforced concrete retaining walls) and strengthening bridges. This will enable relief supplies to get in and people to get out immediately following earthquakes or major storms. Focus on making major improvements to these two roads rather than

	distributed, incremental improvements to several.
	After one road link is modified to remain functional (see above), improve quality—and eventually number—of other road links with neighboring states.
	Increase the number of open spaces in and near the city that can be used for helicopter access for relief efforts.
	Create “pods,” sections of the city that can be self-reliant after earthquakes for about one month, by storing food, water, tools and medical supplies locally and training residents in basic first aid and light search and rescue.

<i>Landslide Risk</i>	
Policy Issue	Policy Recommendation
Landslide hazard maps are not currently used to create regulatory zones that directly link to landslide risk reduction policy actions, and policies have not been adopted	Create landslide risk zoning and regulatory zoning maps from landslide hazard maps at a scale of 1 to 10,000.
	Adopt and implement policies that use information on landslide zoning maps to restrict development and to mitigate the hazard and risk in already developed areas.
	Develop a culturally—and economically—sensitive way to relocate persons out of hazard areas.
	Put a program in place for review and enforcement of policies.
No regulations on surface modification or slope cutting; many instances observed in which people cut land and undermine their neighbor’s property	Enact a site development ordinance to regulate earthmoving/disturbance of land surface.
	Use the site development ordinance to prescribe setbacks from neighbors, to prevent adverse effects of slope cutting such as undercutting adjacent buildings.
	Develop a program for review and enforcement, including sufficient AMC enforcement staff.
Land Revenue and Settlement does not have access to appropriate landslide hazard maps when giving land settlement certificates that allocate land for building, leading to allocation of house sites in areas of	Strengthen Mizoram Land Revenue Act to better consider landslide hazard when giving land settlement certificates and allocating house sites.
	Develop regulations for dividing parcels of land that consider landslide hazard.
	Define no-development zones using technically robust

high landslide hazard	geologic information, and enforce them.
	Provide international-standard geologic hazard maps at a scale of 1:10,000 and information on landslide hazards to Land Revenue and Settlement.
AMC does not have appropriate scale and quality landslide hazard maps for issuing building permits	Strengthen existing permitting system and use landslide hazard maps at a scale of 1:10,000 or better that conform to international standards.
	Require measures to address local and neighborhood-wide hazards.
AMC notification (approval of building permit) requires geologist to inspect certain building sites and issue no objection certificate, but this is a difficult judgment to make without better information and clear public policy	Add an AMC geologist/geotechnical engineer to review plans when issuing building permits
	Create a Geologic Review Board of three to five geologists and geotechnical engineers to review EVERY geologic report, map, and ruling to improve credibility and consistency, provide support for difficult decisions (one geologist is not enough; a team is needed to face upset owners and to raise the professional standard-of-care).
Geologists asked to make recommendations on safety of sites without sufficient geological information or sufficient policy direction.	Increase funding for geological and geotechnical data collection at sites through increased permit fees (perhaps fees can vary with landslide hazard zones or other regulatory zones defined using improved landslide susceptibility maps).
Due to lack of policy or legal grounds, courts have overturned AMC's and geologists' recommendations not to allow development in areas of high landslide hazard	Educate courts on the public safety impacts of allowing buildings to be constructed in areas of high landslide hazard. Articulate the rationale in terms convincing to the court. If necessary, seek changes to relevant laws.
Limited policy mechanisms to carry out mitigation measures affecting multiple parcels, utilities and roads	Develop policy options such as: <ul style="list-style-type: none"> • Government purchases land in very high/high landslide hazard areas and relocates the people living there • Create a geologic hazard abatement district / Block/ Ward (administrative district in landslide hazard areas to create area-wide action).
No mechanism to bring policymakers and geologists together to develop coordinated policies based on sound geologic information	Short-term: Use the multi-departmental, multidisciplinary Landslide Policy Committee for Aizawl City to address policy issues and laws identified in this section (AMC has already formed this committee, which is not the same as the Geologic Review Board recommended above.)
Quarrying operations can	Increase oversight of quarries and limit quarry locations.

destabilize slopes	Provide training for quarry workers and owners in safe operations and safer methods for quarrying.
	Prohibit house site allocation, new residential construction or quarry worker housing in areas that professional geologists determine could be affected by quarrying activity.
Technical Issue	Technical Recommendation
Very limited and incomplete landslide inventory information	Create a landslide inventory categorized by landslide type and bedrock structure. To do this, obtain historical information, collect field data and obtain maps at a scale of 1:10,000 or better.
Landslide susceptibility maps and hazard maps for Aizawl could be significantly improved by including more information on local geologic structure and existing landslides	Improve landslide susceptibility maps by providing maps at 1:10,000 scale or better and including geologic structure and existing landslides. Maps should be made to international standards (i.e., Fell et al. 2008 ²). Maps at 1:1000 scale or better, to facilitate regulatory use, should be the eventual goal.
	Create landslide hazard maps to international standards (i.e., Fell et al., 2008), based on susceptibility maps, at a scale of 1 to 10,000 or better. Maps at 1:1000 scale or better, to facilitate regulatory use, should be the eventual goal.
No landslide hazard maps for critical infrastructure, such as roads to the airport, water pipelines, high voltage transmission lines and substations	Develop strip maps at 1:10,000 scale or better for critical infrastructure outside main city (i.e., water pipelines down to raw water intake and treatment works, road to Lengpui Airport).
Limited capability to interpret and apply geologic maps and conditions that are precursors to rapid onset slides, and limited capability to take action	Build the technical capacity of local geologists. The Geologic Review Board recommended above and the “landslide hazard circle” in Department of Public Works (see below) would help achieve this.
	Develop an early warning system for elevated landslide hazard conditions.
Limited local capacity to design mitigation measures	Create a “landslide hazard circle” within the Department of Public Works to provide consistent, state-of-the-art engineering for mitigation projects carried out by the government. These projects would be reviewed by the Geologic Review Board recommended above.

² Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., Savage, W.Z., and on behalf of the JTC-1 Joint Technical Committee on Landslides and Engineered Slopes (2008): Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. *Engineering Geology*, Vol. 102, Issues 3-4, 1 Dec., pp 85-98.

	Require government and private engineers to obtain training on landslide hazards and mitigation measures.
No mitigation measures in place for most known existing landslides that endanger people	<p>Where appropriate, implement specific mitigation measures that may include:</p> <ul style="list-style-type: none"> • Flexible barriers • Reinforced concrete retaining walls • Excavation, grading, compaction, shear keys • Subsurface and surface drainage systems • Check dams • Geotextile and reinforced earth systems • Soil nailing • Rock bolting • Bridge over failure zones • Replanting cleared areas • And many more locally appropriate solutions
Portions of water system, electrical system and roads have been damaged by landslides or are in areas highly susceptible to landsliding	Institute a program to make infrastructure more robust in locations at high risk of landslide damage
Important buildings threatened by landslides	Assess landslide hazard at important buildings (i.e., hospitals, fire stations and key government response agency offices); stabilize slopes or relocate critical functions to safer buildings.
Professional Community Issue	Professional Community Recommendation
Lack of organized engineering geology and geotechnical professional organizations results in individuals taking sole responsibility for their judgments without peers to develop a standard-of-practice or collaborative bodies to discuss technical information and judgment	Build a professional community of professional geologists and geotechnical engineers; build capacity by supplying information and encouraging professional interaction. The Geologic Review Board and required training recommended above will contribute to this.
Limited or no engineering geology or geotechnical engineering higher education available locally	Provide civil engineering, geotechnical engineering and engineering geology undergraduate and graduate education at local universities; National Information Centre for Earthquake Engineering (NICEE) outreach would be one way to do this.
Few professional geotechnical engineers practicing in Aizawl	Develop an incentive program to attract geotechnical engineers to Aizawl.
	Encourage higher secondary students in Aizawl, who plan to pursue civil engineering studies, to consider geotechnical engineering.

Building Vulnerability	
Policy Issue	Policy Recommendation
AMC has limited ability to demolish unsafe or illegal buildings; current mechanism for government to remove dangerous buildings is via Deputy Commissioner's office	Develop policies and/or regulations necessary to provide AMC with authority to remove dangerous buildings, or to coordinate with the Deputy Commissioner's office to remove them.
No guidance or process for determining when buildings in the area of a landslide may be unsafe, and for preventing occupancy of unsafe buildings	Develop policy and process by which AMC determines under what conditions buildings are unsafe to occupy.
	Enact regulations necessary to authorize AMC to declare buildings unsafe and to force occupants and owners to comply with placards.
AMC building regulations do not include consideration of slope	Revise building regulations to consider slope, by adding special provisions that supplement the National Building Code.
	Consolidate development regulations in a single integrated process that considers landslide hazards and that encompasses land allocation, land division, site development and building permit approval.
Many owners dismiss architect or engineer after receiving AMC approval, due to AMC lack of building code enforcement	Require architect/engineer to observe construction and sign off on as-built conditions prior to occupancy (i.e., completion certificate), and enforce requirement.
Lack of policy options for addressing dangerous buildings and buildings that project into set back areas.	In addition to demolition, provide policy support for options such as: <ul style="list-style-type: none"> • Prevent additions • Encourage replacement • Buy out owners • Encourage appropriate retrofit measures
Lack of policy options to address very large number of seismically vulnerable buildings	Require seismic retrofit when significant additions are made to existing buildings.
	Develop additional policy measures that encourage replacement or appropriate retrofit measures.
Technical Issue	Technical Recommendation
Structurally safer buildings are surrounded by structurally unsafe buildings, which jeopardize the safer buildings	Restrict new building construction on landslide-susceptible slopes, as part of development plans. (Partially implemented in Master Plan.)
	Enact laws that require hazard abatement through either strengthening or removal of hazardous buildings.
Characterizing building	Government of India agencies should support and continue

vulnerabilities is difficult due to lack of data and analysis	research begun after the 2011 Sikkim earthquake on hillside building seismic behavior, which would also be applicable to many hill areas in India, not just Aizawl. Support work by researchers throughout India, including those outside the northeast.
	Install instruments at two or more local buildings to measure seismic shaking to learn more about response characteristics of local building types, including hillside buildings and traditional timber “Assam-type” buildings.
Many important buildings are seismically vulnerable	Conduct a program to assess and replace or retrofit important buildings, beginning with critically important buildings such as Aizawl Civil Hospital.
	Conduct a program to assess and replace, retrofit, relocate or stabilize slopes at vulnerable school buildings; include private schools by enacting laws that require the above actions.
Pounding together of adjacent buildings with floors that do not align, which can cause collapse	Enforce setback regulations for new construction or renovation.
	Educate owner-builders about the dangers of building too closely to neighboring buildings.
	Enact laws mandating owners to address pounding (tying buildings together, armoring weak-mid column areas, adding energy absorbing material, etc.).
Code does not provide adequate guidance for constructing buildings on slopes common in Aizawl	Develop special provisions for design of hillside buildings to address slope issues.
Owner-builders may not be able to afford to hire a qualified engineer, architect or geologist	Develop and provide standard building, foundation and site preparation plans and guidelines.
Limited ability to conduct geotechnical laboratory testing necessary for proper design of building foundations	Promote the geotechnical engineering and engineering geology professional good practice of collecting and testing geotechnical material samples.
	Augment the capacity of PWD’s current laboratory to create a fully equipped geotechnical materials testing laboratory, and provide necessary equipment to sample materials and run in situ tests.
	Develop a pilot program at government level to sample and perform testing at numerous representative or “test” sites from which data could be used for projects at geologically similar sites.

No specific retrofit guidance for buildings on slopes	Develop retrofit guidance and prescriptive measures for commonly encountered building configurations.
No specific retrofit guidance for Assam-type buildings	Develop retrofit guidance and standard “pre-engineered” retrofit plans.
Poor quality re-rolled reinforcing steel from Silchar is widely used	Set standards for reinforcing steel material properties.
	Ban import and use of steel that does not meet these standards.
	Educate owner-builders about deficiencies in re-rolled steel, possibly teaming with Tata or other reliable brands in a marketing campaign.
Professional Community Issue	Professional Community Recommendation
Lack of a professional organization for engineers and architects to speak as one voice, support learning, develop a standard-of-practice, or support each other in carrying out improved practices	Provide a platform for architects and engineers to stand together on quality construction.
	Strengthen local engineers’ and architects’ associations.
Owners, city officials, contractors and workers do not understand earthquake behavior or value measures needed to resist earthquakes	<p>Educate homeowner/builders about:</p> <ul style="list-style-type: none"> • earthquake risk • construction practices that minimize earthquake and landslide risk • the need to employ professional architects and engineers
Many local engineers lack specialized earthquake engineering training	Build capacity of local architects and engineers to design, analyze and retrofit buildings to improve seismic performance.
Uneducated non-local masons from neighboring states construct most buildings in the city	Educate employers and foremen; have requirements for oversight.
	Provide training for non-Mizo masons.
	Develop a more professional network of builders and contractors for building construction.
Local carpenters do not necessarily employ earthquake resistant features in Assam-type houses	Provide training for Mizo carpenters.
AMC does not have enough staff or the training needed to inspect buildings under construction	Improve AMC and ADA enforcement of building regulations. Find a source of income to support the additional effort and training.

Infrastructure Vulnerability	
Technical Issue	Technical Recommendation
Road to airport has several areas of ongoing landsliding	Implement mitigation measures in problem areas.
Damage to the transportation system and need to prioritize life-saving actions will delay delivery of fuel, and repairs	Plan for transportation disruptions by keeping an adequate supply of fuel on hand. Establish a strategy, and build the capacity, to remove multiple landslides after hazard events. Build on existing PWD experience and strategies for clearing roads after heavy monsoon rains.
Aizawl lacks comprehensive storm water, wastewater and sewerage systems, creating multiple problems	See Systemic Concerns section.
Understanding of earthquake and landslide vulnerabilities of critical utility systems is limited and fragmentary, and mitigation options have not been developed in most cases	Identify, prioritize and complete full walkdowns of critical infrastructure for earthquake and landslide vulnerability.
	Develop, prioritize and implement mitigation options to improve service delivery and reduce interruptions.
	Increase the robustness of critical utility systems to provide continuous service for one or more critical facilities.
Water system relies on electrical power for pumping up to ridgetop main reservoir for distribution	Provide backup diesel pumps for raw water pumps.
	Provide sufficient diesel storage to power all backup water pumps for predicted length of electrical power outage caused by earthquake.
	Provide backup water source for critical facilities such as hospitals.
Water system is not redundant: there is one source and one main ridgetop reservoir through which all water passes	Add redundancy as the water system expands.
	Anchor individual family water tanks to prevent toppling during an earthquake to protect distributed water supply.
	Develop additional rainwater harvesting capacity at existing public buildings; mandate for all new public buildings.
	Promote rainwater harvesting at private buildings and homes.
	Develop water rationing plan as part of post-earthquake response plan.
	Develop an emergency water delivery plan that considers blocked roads and streets following earthquakes.
Rigid pipe connections can break	Install valves to control stored water when pipes and

and drain water from the system	connections break.
	Install flexible connections.
	Install flow monitoring systems.
Generators, electrical equipment and fuel tanks not anchored to resist earthquake shaking	Seismically protect water system's electrical equipment (generators, motor service centers, etc.) used for pumping and treatment.
Electrical equipment in substations not seismically protected and prone to damage that may cause lengthy service interruptions	Seismically protect electrical power system equipment in substations.
Communication systems will not work because of convergence, damage, loss of electrical power to transmitters, switches, towers, etc., and to individual battery powered devices	Set up backup communication systems. Prepare a Communications Plan for the State.
Loss of broadcast media hampers ability to disseminate information following an earthquake	Designate one station as an emergency public communication system. Locate it in an earthquake-resistant building, and provide robust emergency power and adequate fuel.
Loss of grid power will prevent mobile phone users from recharging phone batteries even if mobile service is restored quickly	Encourage people to keep small solar chargers to provide power for mobile phones (National Solar Mission of the Government of India could be a good partner).
Lack of solid waste/refuse disposal	Implement Master Plan recommendations on solid waste.
Lack of understanding of infrastructure vulnerabilities and interdependencies	Develop a detailed scenario to anticipate problems and interdependencies and to clarify expectations of each infrastructure system.
	Create an inter infrastructure committee to consider infrastructure interdependencies and write a report on shared vulnerabilities and a long-term mitigation/post-earthquake operations plan.
	Sensitize and train those persons responsible for infrastructure to identify and mitigate earthquake vulnerabilities.

Scientific Data Needed to Characterize Hazard

Issue	Recommendation
No detailed geologic maps of Aizawl district or urban area	Carry out detailed geologic mapping in Aizawl urban area, including bedrock lithostratigraphy, joint structure and formation attitude, as well as Quaternary deposits, at a scale of 1:10,000 or better.
No topographic base map data at sufficient scale for detailed mapping	Obtain 3 meter or better digital elevation model data
Faults in the area have not been mapped in detail or characterized for seismic hazard potential	Because most the faults that contribute to Aizawl's seismic hazard are deeply buried, the Government of Mizoram should request that the Oil and Gas Commission make any subsurface data gathered in the State available to scientific researchers in India for hazard characterization purposes.
	Characterize faults that have been identified or inferred in previous studies.
	Contribute information to a Quaternary fault database for Mizoram and the region.
No array of seismic instruments to give insight into local ground motion attenuation characteristics, topographic amplification effects, and tectonic structures.	Install four to five instruments in Aizawl city to measure ground shaking and to gather data on topographic amplification effects. Department of Science & Technology or Indian Meteorological Department (IMD) could be potential supporters of this effort.
No array of GPS stations to record the direction and speed of ongoing tectonic movements	Install additional continuous GPS stations in Mizoram, including on Aizawl's main ridge and in the next valley to the east, to measure anticline growth and to reconcile regional tectonic movements.
	Tie these new instruments in with existing regional GPS networks. Provide additional staff resources for data compilation and interpretation at institutions operating existing networks.

Land Use Planning

(Most land use planning solutions are located in the landslide hazard and building vulnerability sections.)

Issue	Recommendation
The capacity of Aizawl as a urban area to survive the effects of an earthquake need to be evaluated in terms of both public safety and emergency transportation and circulation, and the effects of building and infrastructure damage and landslides	This scenario document begins to address this issue; other, more detailed scenarios can be developed to assist planners in determining the viability of the city, and the possibility for safe rebuilding in its current location, following a major earthquake. Based on the results of this evaluation, if necessary planners could begin to encourage development in more sustainable locations, including other cities.
	The action plan mentioned previously should include items identified as a result of this evaluation.
Landslide susceptibility map in Master Plan is strictly slope-based (the Master Plan does not use technically adequate maps), leading to zoning for proposed development in areas of presumed high landslide hazard	Review Master Plan versus scenario and newly available geologic information.
	Incorporate recently and newly developed, detailed hazard information and maps into Master Plan.
	Augment Master Plan to directly address building and land development practices and infrastructure vulnerability based on recently and newly developed hazard information and maps.
Past land use practices have allowed building construction in areas of high or very high landslide risk	Identify areas of active landslides or very high landslide risk that need to be addressed right away with planning and mitigation measures.
Master Plan does not adequately control risk over time	Develop measures (incentives, allowable uses and density, transfer of rights, re-subdivision, etc.) to expand the city in ways that will abate vulnerability. Infill projects that replace vulnerable buildings or stabilize unstable areas can reduce the risk.
Incremental unplanned development leads to slope destabilization, crowding and substandard infrastructure	Allow only planned development and discontinue incremental development by following Master Plan (amended to consider current geologic information) fastidiously.

Public Awareness and Education	
Issue	Recommendation
Public not aware of actions they can take to improve safety and reduce risk; not enough training and awareness at community level	Use shake tables to demonstrate earthquake effects on buildings.
	Use mass media such as television to present basic information on risk and preparedness.
	Create a credible scenario to: <ul style="list-style-type: none"> Promote education and awareness generate popular support for enforcement (the scenario in this document is a good start)
Few organized awareness activities in churches, especially social front and existing committees	See above
Effective family preparedness measures are lacking	Develop strategy to encourage and diffuse family preparedness measures.
	Develop incentives to promote family preparedness.
Women and children are not well prepared to manage on their own	Preparedness materials should take gender and age considerations into account.
	Conduct awareness and preparedness programs in schools.
Some government officials not aware of the level of earthquake and landslide risk or of options for reducing it	Raise awareness of government officials through individual meetings and formal awareness programs if necessary
People lack awareness of the earthquake hazard and risks posed by the geologic and built environments, and what they can do to make themselves safer	Install signs and “monuments” both marking and explaining key geologic features and major landslides.
	Open a store-front Hazard Center that can provide public information, classes, meeting space, etc.
	Engage civil society (YMA, Mizo Women’s Association, Mizo Elders Association, church groups, etc.) to explain hazards and protective measures and to provide assistance to their members in need.
	Find a way to reach private businesses and business leaders by providing information, involving them in other mitigation efforts, explaining impacts on businesses, identifying flagship businesses to provide leadership, engage service organizations (Rotary, chamber of commerce, etc.).

Response and Preparedness	
Issue	Recommendation
Current rescue teams may not be well coordinated to incorporate and manage influx of community members and volunteers trying to help	Create an emergency preparedness and response plan that fully engages the private sector and civil society, or augment existing plans.
Local rescue teams are not equipped with heavy lifesaving equipment, and post-earthquake isolation by landslides will restrict the ability to bring in outside equipment	Develop well-equipped local search and rescue teams by strengthening the State Disaster Response Force with more advanced training and equipment.
Professional responders are too few in number to respond to the large number of building collapses expected in even a moderate earthquake	Increase the number of local first responders with adequate basic training in light search and rescue, first aid, and other immediate response tasks.
Determining realistic ability to implement response plans given potential damage to key local infrastructure and resulting consequences	Review and assess dependencies of response plans on roads and local utility infrastructure, and develop contingency plans to deal with anticipated infrastructure damage.
Lack of open space in the city greatly restricts areas that response planners can designate for relief operations	Set aside additional open space in Aizawl Urban Area that can be used for relief operations.
	Preserve and expand open space in current Assam Rifles area when Assam Rifles relocate.
Water borne diseases due to water pipe and sewer pipe breakage are possible	Plan to provide water from sources other than piped supply.
Emergency shelters may not be earthquake resistant	Assess identified emergency shelters for earthquake resistance and seismically strengthen if needed.
Key response agencies, such as the Divisional Commissioner's office, operate out of buildings not designed to remain operational following a major earthquake and therefore building damage is likely to impair the response	Build an Emergency Operations Centre designed to remain operational following a major earthquake.

State, District and Local Disaster Management Plans are new and not well tested	Conduct tabletop and simulation exercises to test and refine the State, District and Locality Disaster Management Plans.
State, District and Local Disaster Management Plans do not address recovery or reconstruction	Develop recovery and reconstruction plans that coordinate with Disaster Management Plans and Master Plan; use plan as opportunity to prevent reconstruction in hazardous areas, improve access, and reduce congestion.
Damaged buildings and landslides will block streets, inhibiting transportation and relief efforts within the city	Consider developing self-reliant “pods” within the each locality where emergency supplies can be stored, so neighbor can help neighbor.

Appendices

A: Earthquake Sources and Shaking

B: Landslides

C: Buildings

D: Infrastructure



Appendix A

Earthquake Sources and Shaking

Despite the paucity of earthquakes in Aizawl's short recorded history, all available scientific evidence shows that a strong, damaging earthquake will affect Aizawl in the future. This appendix describes the source faults capable of generating earthquakes that can affect Aizawl, the rationale for selecting the scenario earthquake, and the method used to estimate the level of shaking that the scenario event would cause.

Regional Tectonic Setting

The Indian plate moves northward relative to Asia and thrusts underneath it along the Himalayan thrust front. This arc-shaped plate boundary ends at hair-pin structural bends, or *syntaxes*, where the Himalayan collision transitions to *transpressional* boundaries. Beyond the eastern Syntaxis, along the eastern flank of the Indian continental "indenter", the relative motion is both right-lateral and shortening. This tectonic system, or *orogen*, has been operative for at least 30 million years and has resulted in the penetration of India into Asia, the lifting of the Tibetan Plateau, and the fragmentation and eastward flight of Southeast Asia, moving out of the way of continental India. Figure 1 shows the plate boundaries and other major structures in the region.

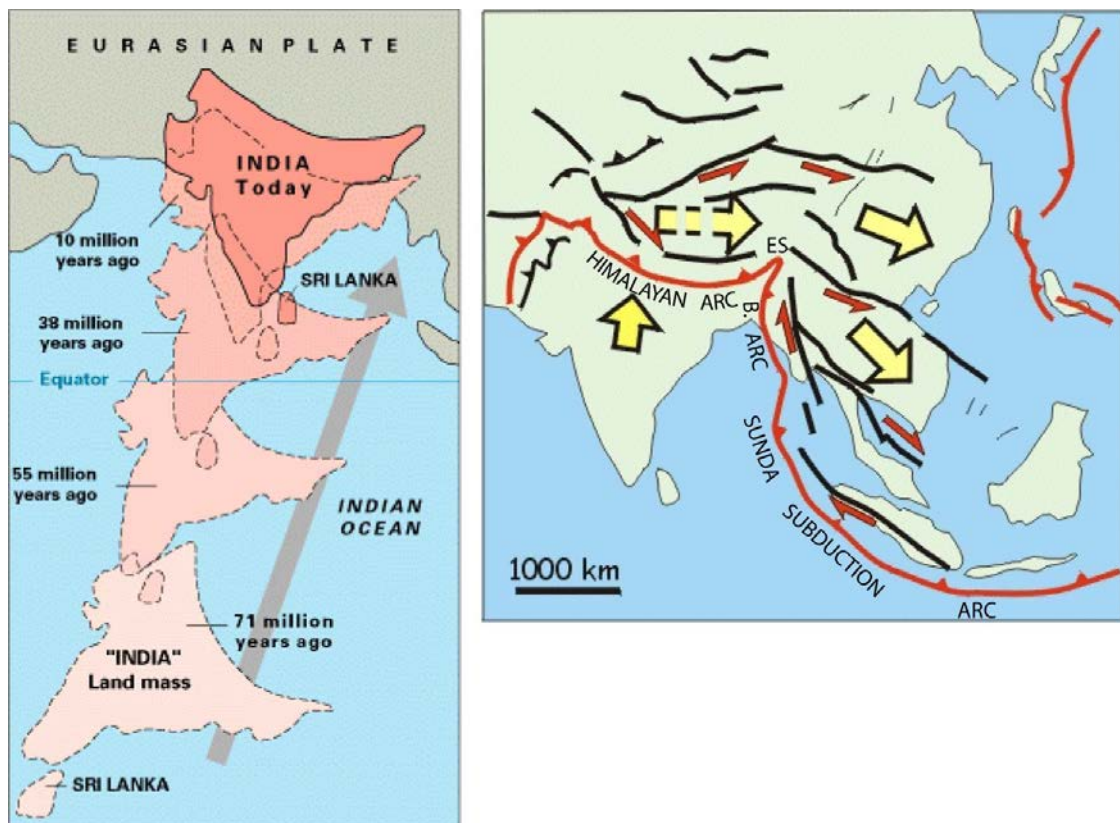


Figure 1. *Left:* Motion of the Indian "land mass" relative to the Asian plate during the last 71 million years. The Indian plate includes this continental portion plus surrounding oceanic lithosphere. The large amount of convergence was first entirely accommodated by subduction of Indian oceanic lithosphere under the Asian plate. By tucking lithosphere into the Earth's mantle, subduction can accommodate convergence without major deformation of the plates on either side. Starting about 38 million years ago, continental parts of the Indian plate began to collide with continental parts of the Asian plate. Continental lithosphere is light and cannot subduct. This collision slowed down the convergence and caused the rise of the Himalayas, the Tibetan Plateau, and the eastward "escape" of Southeast Asia. Subduction, however, continued on the flanks of the Himalayan arc, the contact zone between the continents. *Right:* The India-Asia collision is ongoing, as shown by current tectonic regime in south and Southeast Asia. The continued northward motion of India and the Himalayas relative to the flanking parts of Southeast Asia has warped the boundary forming the Eastern Syntaxis (ES). Subduction along the Sunda Arc continues north into the Burma (B.) Arc, including parts that

flank the Ganges-Brahmaputra delta and are now entirely on land. Plate boundaries are in red, while black lines are major active faults within Asia.

Himalayan tectonics is a dramatic manifestation of the buoyancy of continental masses and of the space problems that arise when continental portions of the plates collide and converge. In contrast, convergence occurs easily where cold and dense oceanic lithosphere of the Indian plate subducts into the mantle along the Sunda Arc. The eastern Himalayan Syntaxis marks the transitions between collision and subduction. This sharp bend of the plate boundary manifests protracted differential velocity: continental India kept pushing the Himalayan collision front northward relative to Asia while the subduction boundary lagged behind, gradually closing in toward India and eventually developing an arc-continent collision, which is currently progressing southward from the syntaxis. The transition from subduction to collision is gradual, involving progressively deeper and more competent parts of the plates.

Aizawl is situated on a ridge of the Burma Ranges, the vast fold belt associated with subduction of the Indian plate along the Burma segment of the Sunda Arc, south of the eastern Himalayan Syntaxis. The Burma fold belt is the surface manifestation of contraction and thrust faulting in the wedge of sediment scraped, or *accreted*, off the Indian plate as it subducted eastward under the Sunda plate (Figure 2). The process of accretion involves the transfer of sediment from the lower subducting plate to the upper plate and implies tectonic shortening of this sediment in the direction of subduction. Shortening is accomplished primarily by folding driven by blind, i.e., buried, thrust faults. Wedges of accreted sediment are typical of subduction boundaries, but the Burma wedge is extreme in having accreted the huge amount of sediment eroded from the Himalayas. As a result of this extraordinary sediment supply, the Burma accretion belt is very wide and thick, and is thus mostly above sea level, while most accretion belts are submerged. In the northern part of the belt, at the latitude of Aizawl, the belt is 350 km wide and completely on land.

Structurally, accretion wedges, including the Burma fold belt, are floored by a shallow-dipping plate boundary fault called a *megathrust*. These megathrusts are typical of subduction boundaries and are responsible for the largest known earthquakes (e.g., Sumatra 2004; Japan 2011). These faults separate the subducting lithosphere below from the accreted sediments above. In the Burma fold belt, tectonic compression and sediment accretion occur simultaneously. Tectonic stress and gravity reach equilibrium when the shape of the accretion wedge attains a critical taper angle between the landward-dipping megathrust and the seaward-dipping upper surface. As continuing accretion makes the wedge wider, internal shortening of the wedge by thrust-folding makes it thicker, thus maintaining critical taper. Additional shortening is required to counteract the effect of erosion. Thus all parts of an accretion wedge tend to be tectonically active (Davis et al., 1983).

Located approximately 150 km north of Aizawl, the Shillong Massif is a huge east-west striking *anticline* (a structure in which the rock layers are bent into an inverted 'U') involving ancient rocks of the Indian crust. The anticline is rooted on a north dipping thrust fault, which is mostly blind, meaning that it does not break the surface, and is the likely source of the 1897 Shillong earthquake. This regional thrust fault retains the name Dauki fault, although it is blind and differs from the structure identified with that name in some of the literature. Paired with the massif-anticline and on the footwall side of the Dauki fault is a very prominent and rapidly subsiding trough called a *foredeep*, identified as the Sylhet basin. The Dauki contractional orogen continues beyond the massif, both to the east buried under the Burma accretion belt,

and to the west-northwest beyond the Brahmaputra River, which bevels the edge of the structure through erosion. This orogen is developing obliquely across the continental margin of India and may eventually reach from the Himalayan collision to the Burma subduction, thus shunting across the Eastern Himalayan Syntaxis. Tectonic and geomorphic processes on the Shillong anticline are clearly not in equilibrium, and the Sylhet foredeep contains only Quaternary sediment. This regional structure is surprisingly young, but is already accommodating some of the shortening previously taken solely by the eastern Himalayas, possibly initiating a profound re-organization of the Eastern Syntaxis. A consequence of tectonics in transition is that major structures capable of generating huge earthquakes, such as the Dauki fault, are so young that they may have accumulated relatively little deformation and thus have only a modest geomorphic expression.

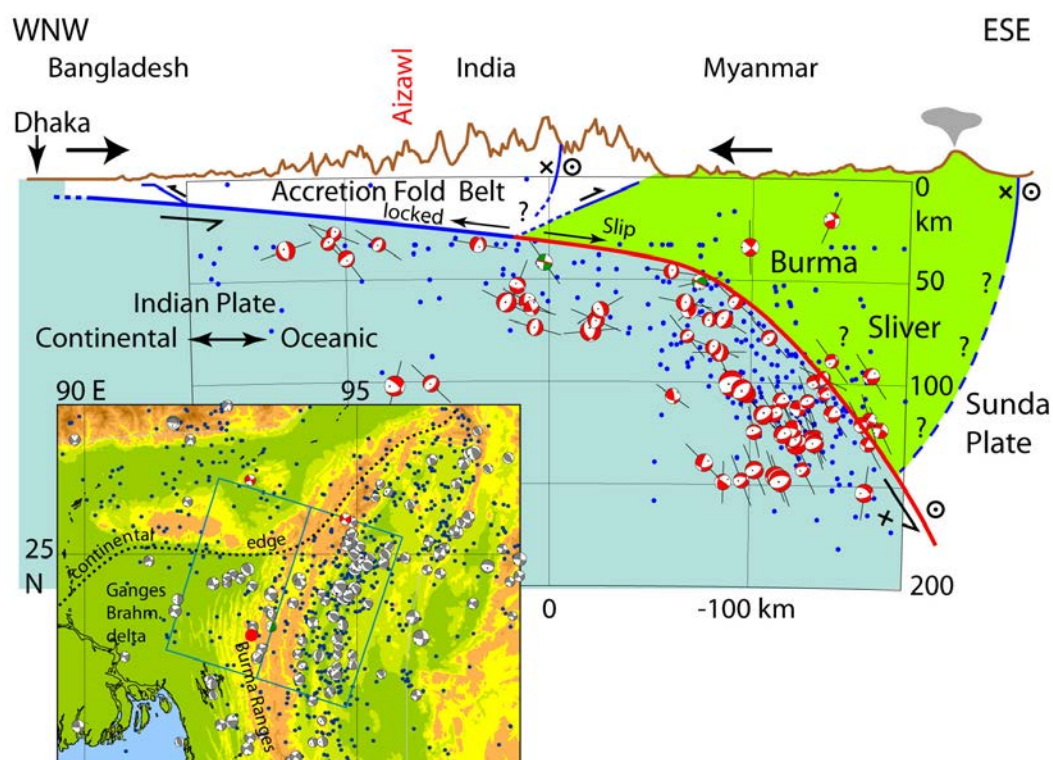


Figure 2. Profile showing seismicity and tectonics across the Burma fold belt. This wide zone of active folding is the result of accretion of the light sedimentary cover above the megathrust (blue), the shallow part of the boundary allowing subduction of the oceanic Indian plate to the east under Burma. Hypocenters from the last 40 years are black dots and, for the larger earthquakes, balloons representing the faulting that generated the earthquakes, as deduced from the seismic waves. Hypocenters from the box in the inset map are projected in the profile. Most current seismicity is diffused within the Indian plate below the megathrust. The faults responsible for this seismicity tend to be normal to this boundary; fault motion tends to be parallel to the boundary such that the subducting Indian plate is stretched in the direction of subduction (thin black lines show the extension direction for each earthquake). Where the boundary is shallow-dipping as below Aizawl, these earthquake sources can be described as sub-vertical strike-slip faults, either oriented northwest and right lateral, or oriented southeast and left-lateral. In contrast, geodetic data show ongoing shortening across the belt, which occurs in the accretion wedge above the megathrust and is structurally manifested by the fold belt. Models of the geodetic data suggest that the megathrust is locked and the motion is currently absorbed elastically for the most part. If so, a large megathrust earthquake rupture is expected (redrawn from Howe et al., AGU, 2013).

Earthquake Sources Relevant to Earthquake Hazard in Aizawl

Earthquake magnitude and distance are obvious parameters affecting whether damage occurs, but many other factors contribute as well, such as the direction the earthquake rupture propagates, the absorption of seismic energy as the seismic waves pass through rock and soil, called *attenuation*, and seismic response at the location in question. Technically, the term *hazard* describes the probability of a given shaking irrespective of what is being shaken. The probability of damage, or the *risk*, involves also the presence and vulnerability of people, buildings and infrastructure exposed to the hazard. As a result, the maximum distance at which a given magnitude earthquake can cause damage varies greatly. Conversely, the area where earthquake sources are pertinent to the hazard at any specific site is large. Poorly constrained parameters make this area larger. Following is a preliminary list of tectonically distinct classes of earthquake sources likely to be pertinent to earthquake risk in Aizawl. Figure 3 shows major faults and regional structures.

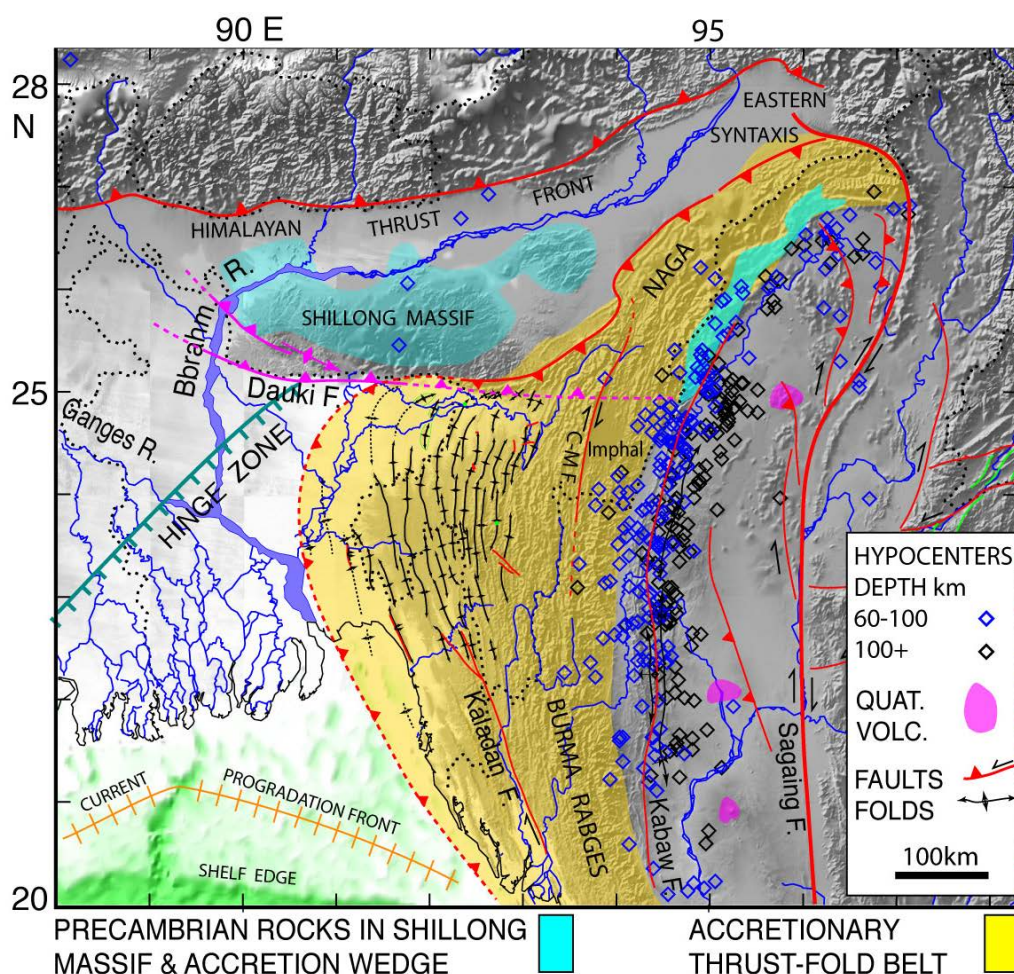


Figure 3. Tectonic map of the India-Burma collision/subduction boundary south of the Eastern Himalayan Syntaxis. Earthquakes deeper than 60 km illuminate the Indian lithosphere subducted below Burma. Shallower events are omitted to avoid clutter. C-M F = Churachandpur Mao fault (Seeber et al., AGU 2013).

Several research teams are independently combining GPS data from Bangladesh, India, Tibet and Myanmar to resolve motions of the Indian, Asian, and Burma plates near the 'triple junction' between these plates, which is centered at the Eastern Himalayan Syntaxis, north of Aizawl. All rates of relative motion mentioned here are preliminary and some of the conclusions are being

debated. As expected, the motion across the India-Burma subduction boundary is oblique convergence. At approximately the latitude of Aizawl, we measure 18mm/y of convergence normal to the boundary and 45mm/y of dextral motion parallel to the boundary (Steckler et al., AGU 2013). We also find 8mm/y of shortening across the Dauki fault, with little or no boundary-parallel motion. We believe that seismicity and GPS velocity profiles pertinent to the structures listed below generally point to elastic deformation within the seismogenic depth range that will eventually be released by earthquake ruptures. Different conclusions have been published. Probabilistic hazard analysis, a type of analysis in which concepts from probability and statistics account for uncertainty, can formally incorporate contrary hypotheses in the calculations.

The sources responsible for the largest earthquakes relevant to hazard in Aizawl are very large thrust faults, or megathrusts, that are responsible for most of the convergence. These faults are shallow-dipping and thus separate lower and upper plates. Near the main faults, these plates tend to deform internally and to contain secondary *intraplate* faults that also generate earthquakes. Maximum magnitudes from these secondary sources tend to be smaller, nevertheless they are important for hazard because these faults are numerous and widely distributed and thus their earthquakes tend to be more frequent and can generally occur closer to population centers.

The India-Burma Subduction Megathrust

The Burma Ranges are the topographic expressions of the active fold-thrust belt of an accretion wedge riding above the megathrust of the active subduction of the Indian plate under the Burma plate. This megathrust accounts for most of the India-Burma shortening and for some of the dextral motion as well. In our interpretation of the GPS data, much of this fault is now locked, from approximately the longitude of Aizawl west, and about 13 mm/y is loading elastically this part of the fault. Much convergence can likely be absorbed before reaching failure, given the large size of the fault and the high compliance of sedimentary rock in the accretion wedge above the megathrust.

Maximum displacements greater than 10 m are typical of large megathrust ruptures; for example, displacements from the M9.0, 2011 megathrust rupture in Japan reached 50 m. Given the GPS results, a characteristic rupture with 13 m of east-west shortening would recur after 1000 years. Total motion on these ruptures would probably be greater than 13 m because the slip would likely be oblique to the boundary to accommodate some of the dextral motion as well. Consequently, it is understandable that such a rupture has not been recorded in several hundred years of written and oral history. On the other hand, no megathrust rupture in the last five centuries implies at least 6.5 m of shortening has been absorbed elastically since the last rupture. A complete single-earthquake rupture of the seismic 'gap' between the 1762 rupture on the south and the Dauki fault to the north would be approximately 250 km along strike and 150 km along dip, which may be expected to deliver an earthquake with magnitude greater than 8.5.

The effects of such a megathrust rupture are conjectural, with no local historic precedent and mostly submarine analogs. But, such an event can be expected to cause damage from strong and prolonged shaking, landsliding, sediment liquefaction and ground failure, river course changes and flooding, and years of damaging aftershocks. Effects may be considerably worse if the earthquake happens during the rainy season. The regional and widespread nature of the damage is likely to compound the negative effects and slow down the recovery. This megathrust

is a relatively low probability earthquake source, but with very high-stakes, potentially directly affecting more people than any other prior earthquake in history. More research is urgently needed to better understand and constrain the seismogenic behavior and effects of this source.

Dauki Thrust Fault

The Dauki fault is a deeply rooted thrust fault responsible for the uplift of the Shillong Massif. This fault is most likely the source of the 1897 Assam earthquake. This earthquake was centered on the western Shillong massif, approximately 250 km from Aizawl, but according to Oldham, the “area of extensive damage to masonry buildings” reached into the fold belt as close as 70 km northwest of Aizawl. Several lines of evidence suggest that the Dauki fault continues eastward below the Burma fold belt and the megathrust that floors them (Seeber et al., AGU 2013). It is conceivable that the 1897 earthquake only ruptured the west segment of the Dauki fault and that another segment of this fault to the east has continued to accumulate elastic strain for a rupture. This eastern segment is 150 km from Aizawl, close enough for Aizawl to be included in the “area of extensive damage to masonry buildings” of an 1897-like earthquake on the Dauki fault’s eastern segment.

Thrust fault(s) Responsible for Anticlines Either Below or Near Aizawl

Like most anticlines, the one hosting Aizawl city is likely to be constructed above one or more thrust faults. Fold-related faults in a fold belt are typically a series of ramps rooted into the same shallow angle detachment, or “flat”. Each of these ramps absorbs some displacement from this basal fault. The megathrust is the master fault postulated to spawn the steeper ramps below each anticline in the Burma belt. Seismicity weakly constrains the megathrust to be 20 km deep below Aizawl (Howe et al., AGU 2013). North and south of Aizawl city, the anticline axis can be traced continuously for 30 km, but at the city the axis is offset to the left 3.5 km. This suggests distinct thrust faults north and south of the city, each about 30 km long.

No direct subsurface evidence is available for the Aizawl anticline, but the dip-dimension of the ramps can be postulated from surface structural data combined with examples of younger and less developed anticlines closer to the deformation front in Bangladesh. Counting from the first exposed anticline (Lalmaj), Aizawl is the 13th. If each of these share equally the total shortening, slip-rate on each ramp would be ~1 mm/y. Several ramp earthquakes in the M5-6 range have recently occurred in the fold belt in Bangladesh. The maximum earthquake magnitude these ramps can generate is expected to increase as the ramps and folds grow in age and in structural relief east of the deformation front and may be in the M6-7 range for Aizawl. These estimates imply recurrence times for such a maximum earthquake of several thousand years. Several such faults are close enough to contribute to the hazard in Aizawl, however. At least some of these ramp earthquakes are likely to be clustered as aftershocks of megathrust ruptures. These ramp earthquakes are shallow, and as a result we expect damage at lower magnitudes. This translates into many more damaging earthquakes, given the typical ten-fold increase in number of earthquakes for each one-unit decrease in magnitude.

Earthquakes within the Indian (lower) Plate

Most of the current seismicity in the area of the fold belt originates in the lower plate below the megathrust (Figure 2). We have no structural information about the faults generating these earthquakes, but we can learn about these sources from seismology. Lower-plate seismicity is known from subduction zones worldwide. Based on such data, maximum magnitudes are likely to be less than or equal to M7, which is higher than from the ramps above the megathrust. But

lower-plate sources are deeper and seismic wave attenuation is expected to be higher, not only for the longer path to the surface, but also because attenuation may be particularly high across the megathrust, which the waves have to traverse. From observed seismicity, these lower-plate earthquakes below the megathrust are generated by quasi vertical strike-slip faults, which either strike SW-NE and have left-lateral motion (meaning that when facing the fault, the opposite side of the fault moves to your left), or they strike NW-SE and have right lateral motion.

Strike-slip Faults Parallel to Fold Belt

Of the 45 mm/y of dextral shear measured by GPS across the India-Burma boundary, 21 mm/y are taken up by the Sagaing fault (Vigny et al., 2003; Maurin et al., 2010), which is 330 km from Aizawl and thus too far to affect Aizawl's hazard. A substantial portion, possibly more than half, of the remaining 20 mm/y is in part taken up by the Churachandpur Mao fault (Gahalaut et al., 2013), whose southern continuation along the belt may reach as close as 75 km to Aizawl. Little is known about this fault, but until proven otherwise, this fault needs to be considered a significant source of hazard for Aizawl. Some dextral motion may be widely distributed and absorbed by thrust folds.

Kabaw Fault

The Kabaw regional fault bounds the Burma Ranges to the east at a minimum distance of about 150 km from Aizawl. It is thought to be active, based on the young sediments being deformed. This fault is likely to contribute to the shortening unaccounted for by the megathrust, but little is known about it. This fault is mostly expressed by folds verging to west and is clearly dipping to east where exposed along its northern segment. This geometry places the high land of the axial zone of the Burma Ranges on the footwall side and the Central Valley on the hanging wall side of the fault. The structure is thus opposite to the one expected from the morphology. It is possible that the Kabaw fault is an antithetic roof thrust of a deeper thrust fault dipping to west (e.g., Figure 2).

Rationale for Selecting the Scenario Event

After evaluating the sources described above, we selected a M7 right-lateral strike-slip event occurring within the lower Indian plate below the megathrust. At Aizawl, we estimate the depth to the megathrust to be 20 km. The rupture plane is vertically oriented, centered at 30 km depth, and is 10 km wide and 25 km long. We arbitrarily selected a NW-SE striking rupture; the rupture could also strike SW-NE. Because most current seismicity occurs below the megathrust, such an event is plausible and least controversial.

We selected this scenario event based on the potential strength of shaking and the general likelihood of occurrence. The strength of shaking at Aizawl anticipated from the above sources varies from relatively weak shaking from more distant events, to very strong shaking from shallow thrust fault earthquakes beneath the city. With many possible levels of shaking, and the relative likelihood of each event poorly constrained by available data, we exercised scientific judgment to select the most appropriate event for the purpose of this scenario. We selected an event that is quite plausible, based on the observed seismicity and world-wide analogs. This event causes shaking strong enough to affect the city and to demonstrate vulnerabilities, but is far from being a less likely "worst case" scenario. Based on observed seismicity, the selected scenario earthquake seems more likely than some of the other events considered.

Shaking Caused by the Scenario Event

The level of shaking for the scenario event was determined by the United States Geological Survey using their ShakeMap software. This software models the shaking from a defined earthquake source using relationships based on data from past earthquakes, called ground motion prediction equations. For this scenario, ground motion prediction equations are from Akkar and Bommer (2010) and generally apply to a tectonically active environment; published ground motion prediction equations specifically for northeast India did not exist when we created this scenario. The ground motions that result are for rock sites, which can be used without significant modification in Aizawl, where rock is either at the surface or very close to it. The estimated maximum value of peak ground acceleration is 0.42g and the peak ground velocity is 50 cm/s. For the main part of Aizawl city, the peak ground acceleration is 0.35g, and the peak ground velocity is 40 cm/s.

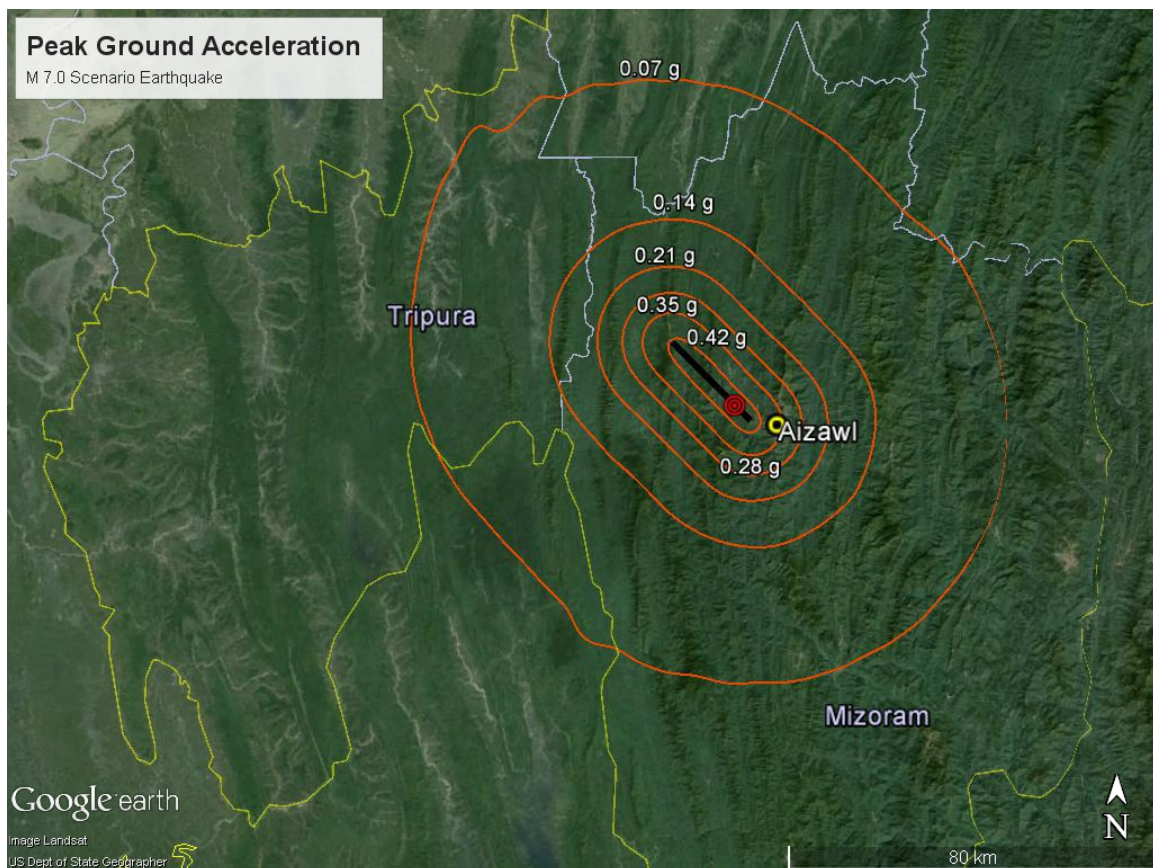


Figure 4. Scenario earthquake peak ground acceleration contours created using USGS ShakeMap software (see [usgs.gov](https://www.usgs.gov) for details). The black line shows the location of the rupture plane's top edge, if projected to the ground surface. The red circle is the epicenter, the location on the ground surface directly above the point where the rupture initiated.

This level of ground shaking is similar to what the Indian Standard IS 1893 (BIS, 2002) prescribes for Seismic Zone V, and is in the range of shaking anticipated by recent probabilistic seismic hazard analyses. The peak ground acceleration (PGA) value at Aizawl from Iyengar et al. (2010) is 0.35g for a 2500 year return period (~2% probability of exceedance in 50 years). The peak ground acceleration value from MIRSAC (2005) is 0.4g for 950 year return period (10% probability of exceedance in 100 yrs). As described in the scenario, we expect this level of shaking to cause considerable damage throughout the city.

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Appendix B

Landslides

1.0 Introduction

Landslides represent a major threat to human life, property, constructed facilities, infrastructure and the natural environment in most mountainous and hilly regions of the world. Aizawl faces an elevated threat of landslides due to specific geologic, seismic, climate, and development conditions that exacerbate landslide hazard conditions. Ongoing geologic processes have created the narrow, steep-sided ridges comprised of weak rock layers that underlie Aizawl City. The unfavorable geologic conditions and steep slopes are subject to devastating failure in the form of pervasive landsliding, often triggered by heavy monsoon rains. As a result, destructive landslides dominate the historical geologic hazard record in the region. The most recent demonstration of this active and ongoing geologic process occurred on May 11, 2013 when a catastrophic landslide occurred in the Laipuitlang locality, causing the deaths of 17 people and destroying several buildings.

This appendix describes the types of landslides that occur in Aizawl and their underlying causes, as well as the process Lettis Consultants International (LCI) followed to estimate the amount of landsliding likely to occur during the scenario earthquake. We investigated potential sliding in a Study Area in north-central Aizawl with representative slopes and development, shown in Figure 1 following the text of this appendix, and extended the results to the remainder of the urban area. The Study Area includes the northern portion of the central Aizawl ridgeline with the highest density of urban development, as well as the valley to the east and limited slope areas to the west. It has an area of approximately 4 km² and comprises large areas of developed hillslopes as well as undeveloped, natural terrain hillside. The Study Area includes all or part of approximately 19 Aizawl localities.

Subsequent sections describe the geologic context, engineering geologic mapping, slope stability analyses, hazard zone definition, and method of estimating the area likely to slide during the scenario. Please note that the analyses and results in this section are based on limited site specific subsurface information including geotechnical laboratory analyses, as well as empirical data from published earthquake induced landslide hazard reports. Ground deformations under static and seismic conditions can result from a variety of sources, and reasonable assumptions have been made to model conditions, including material strength, groundwater conditions, and expected seismic shaking. The information presented represents an attempt to characterize the slope stability hazard of a specified study area in Aizawl under assumed conditions; maps and analyses should be updated as new information becomes available.

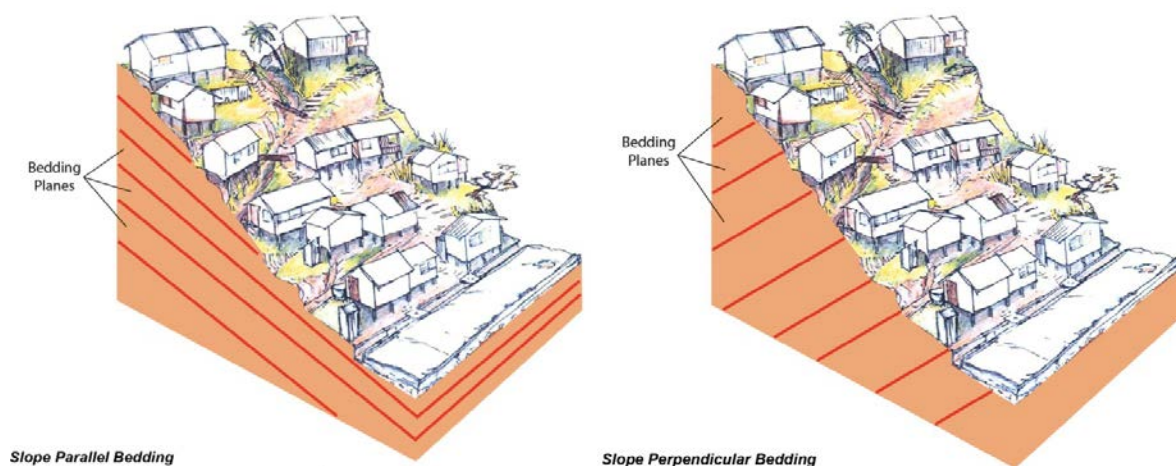
2.0 Regional Geology

Aizawl is located within the hills of the Western Burmese ranges, which extend from Mizoram's borders with Tripura and Bangladesh across the state and into Myanmar. The altitude of the city varies between 800 and 1188 meters above mean sea level. The area is characterized by dramatic north-trending ridges and valleys and steeply dipping hillslopes. These nearly parallel, repeated, linear ridgelines—spaced approximately 25 km apart—are part of the larger Burmese fold and thrust belt formed by the collision of the Indian and Asian crustal plates along the Burma segment of the Sunda Arc. (Appendix A: Earthquake Sources and Shaking contains a detailed description of the regional tectonic setting). Aizawl City is located along the topographic crest and steep limbs of one of these anticlinal folds.

The folding and related compressional faulting that has created the Burmese fold and thrust belt has resulted in the uplift and deformation of late-Tertiary (approximately 5 to 20 million years old) marine sedimentary rocks consisting of sandstone and siltstone-shale flysch deposits. Flysch is a sequence of sedimentary rocks deposited in a marine environment in an active tectonic environment. These flysch deposits include repeating, well bedded, clastic sandstone and siltstone-shale units that comprise approximately 70 and 29 percent of the Aizawl area, respectively (Aizawl Development Authority, 2013). These weak to moderately cemented units were deposited in a deep to shallow marine or deltaic environment and are now exposed along a series of narrow, N-S trending ridges and valleys.

The geologic units in the central part of northern Mizoram are mapped as part of the Surma group with further lithostratigraphic classification that includes the Bhuban and Bokabil subgroups in the Aizawl area (Evans, 1964; Jaggi and others, 1986). The Bokabil subgroup consists primarily of alternating beds of argillaceous siltstone-shale and thinly bedded, medium grained sandstone interbeds. The Bhuban subgroup consists of mainly arenaceous, fine to medium grained, thinly to moderately bedded sandstone with inter laminations of shale.

The folded stratigraphy and steeply incised terrain produces two types of slopes that are of particular interest when assessing landslide hazard, shown below. The first and most susceptible to landsliding are slopes where the bedding of the rock layers is parallel to the direction of the slope, a condition called *slope parallel bedding* or *adverse bedding*. The second type are slopes with bedding perpendicular to the slope, called *slope perpendicular bedding* or *slope normal bedding*. Slopes in the Aizawl area with adverse bedding have a higher prevalence of landslides. Steep slopes with perpendicular bedding are also prone to failure, as they are susceptible to landsliding along intersecting discontinuities, such as joints and fractures.



Slope parallel (adverse) bedding and slope perpendicular bedding (Image credit: MOSSAIC w/LCI additions)

3.0 Landslides in Aizawl

The geologic conditions in Aizawl that contribute to elevated landslide hazard include: 1) steep slopes; 2) weak rock strengths; 3) pervasive discontinuities (i.e., joints, fractures, and faults); and 4) slope parallel sub-surface bedding. These geologic conditions, in conjunction with poorly regulated building practices, heavy monsoonal rain, and the potential for strong seismic ground shaking, produce a high risk environment with potential for significant loss of life and property.

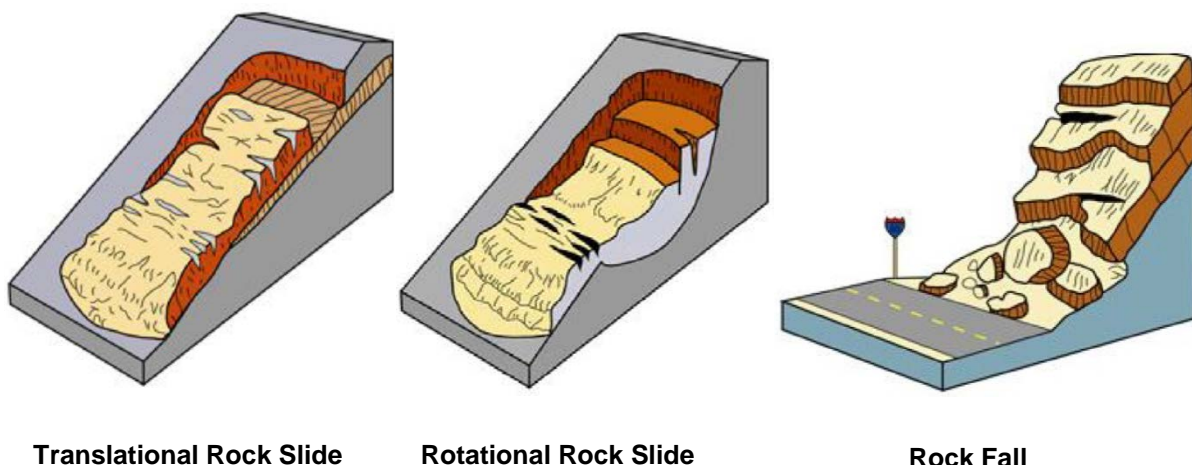
The following sections summarize landslide characteristics for Aizawl City.

3.1 Landslide Types

The term landslide encompasses the downward lateral movement of earth materials due to gravity (Keefer, 1984). We classify landslides with a two-part designation based on Varnes (1978) and Cruden and Varnes (1996). The designation captures both the type of material that failed and the type of movement that the failed material exhibited.

Many different landslide classifications exist that describe failures in both rock and surficial soil materials. Most landsliding in Aizawl is located in rock. Therefore we only modeled rock failures or landslides that occurred in hard or firm bedrock that was intact and in place prior to slope movement. Landslide movements are interpreted from the geomorphic expression of the landslide deposit and source area. Falls and slides are the two most recognized types of landslide movement in Aizawl. Falls are masses of soil or rock that dislodge from steep slopes and free-fall, bounce, or roll downslope. Slides displace masses of material along one or more discrete planes. In rotational sliding, the slide plane is curved and the mass rotates backwards around an axis parallel to the slope; in translational sliding, the failure surface is more or less planar and the mass moves parallel to the ground surface.

The figure below shows the specific types of landslides that most commonly occur in the Aizawl area: deep and shallow seated translational and rotational rock slides; and rock falls.



Common types of landslides in Aizawl (Image credit: Geology.com)

Rock slides are landslides involving bedrock in which the rock that moves remains largely intact for at least a portion of the movement. Rock slides can range in size from small and thin to very large and thick, and are subject to a wide range of triggering mechanisms. The sliding occurs at the base of the rock mass along one to several relatively thin zones of weakness, which are variably referred to as “slide planes,” “shear surfaces,” “slip surfaces,” “rupture surfaces,” or

“failure surfaces.” The sliding surface may be curved or planar in shape. Rock slides with curved sliding surfaces are commonly called “slumps” or “rotational slides,” (or locally, referred to as “sinking areas”). Those with planar failure surfaces are commonly called “translational slides,” “block slides,” or “block glides.” Rock slides that occur on intersecting planar surfaces are commonly called “wedge failures.”

Rock falls are landslides where a mass of rock detaches from a steep slope by sliding, spreading or toppling and descends mainly through the air by falling, bouncing or rolling. Intense rain, earthquakes or freeze-thaw wedging may trigger this type of failure. Rock falls occur on steep slopes of hard, fractured rock. The scar left by a rock fall on the slope may be no more apparent than an area of rock that is less weathered than the surrounding rocks. Rock fall deposits are loose piles of rubble that may be easily removed by erosion. Because neither the scar nor the deposit are distinctive, and because the most frequently occurring rock falls are typically small, individual rock falls are usually not shown on regional-scale (1:24,000 and smaller) landslide maps.

3.2 Landslide Triggering Mechanisms

Landslides occur when the destabilizing forces acting on the earth of a hillside are greater than the stabilizing forces, meaning that one force overrides the other. Rock slides and rock falls are primarily triggered by intense rain (precipitation-induced landslides), earthquakes, or human activity. These triggering mechanisms are summarized below.

3.2.1 Precipitation-induced landsliding

Aizawl has a sub-tropical climate that includes annual monsoonal rains typical starting in May and continuing through August or later. These heavy rains can create saturated conditions especially in areas with poor surface drainage. Monsoonal rain infiltrates the ground surface through the natural porosity of the soil and rock as well as through fractures or other discontinuities in the rock that increase permeability. This infiltration elevates ground water levels already present at depth until the ground cannot hold any more water. This is referred to as saturated conditions. Saturated conditions result in the reduction of shear strength and the increase of pore water pressures that decrease the ability of the slope to resist gravitational influence. By directing surface drainage away from slopes, or by containing runoff within drainage systems, it is possible to prevent saturated conditions and prevent a decrease in slope strengths. Uncontrolled surface water runoff (or overland flow) can also act as an erosional agent that increases landslide hazard by modifying surface conditions through gullying and sheetwash erosion.

3.2.2 Earthquake-induced landsliding

Earthquakes are one of the main triggers of landslides. The effects of earthquake-induced ground shaking are often sufficient to cause failure of slopes that were marginally to moderately stable before the earthquake. Seismic accelerations cause short-lived disturbances to the balance of forces contributing to slope stability. Seismic shaking may cause loss of cohesion and/or reduction of the frictional strength of the material, by shattering the rock mass or increasing the pore pressure of natural ground water within slopes when subjected to cyclic loading.

Topographic relief also influences the intensity of earthquake ground motion. Seismic waves can be amplified as they enter the base of a topographic ridge, are partially reflected back into the rock mass, and diffracted along the free surface. Seismic waves are then focused upward,

and the interference of their reflections and the associated diffractions increases toward the ridge crest, giving rise to higher ground accelerations on topographic high points (Meunier, et al., 2008). For example, landslides induced by the 1994 Northridge earthquake and the 1999 Chi Chi earthquake were strongly clustered near ridge crests (Harp and Jibson, 2002; Meunier, et al., 2008). Though we do not include the effects of topographic amplification in the analyses for this scenario, Aizawl's ridge tops could experience similar effects during a strong earthquake.

3.2.3 Human-induced Landsliding

Recent studies have shown that landsliding has increased in many regions due to human activity such as highway construction, deforestation, terracing, and agricultural activities. However, changes in the magnitude and frequency of landsliding due to human activity are widely debated. Barnard and others (2001) estimate that approximately two-thirds of the landslides that occurred following the 1999 Chamoli earthquake in the Garhwal Himalaya of Northern India were initiated or accelerated by human activity. In areas of high landslide hazard, relatively minor amounts of human modification to the ground surface may adversely affect the stabilizing forces on the slope. These types of modifications often include slope grading activities, fill deposits and construction atop slopes, and poorly designed or unaccounted for surface drainage.

4.0 Engineering Geomorphological Mapping

Given the size of the Study Area (4.3 km²) and the limited amount of field reconnaissance, the engineering geomorphological mapping was undertaken based on topographic interpretation and Google Earth imagery. The morphology (shape) of the land surface has been recorded in accordance with the system proposed by Savigear (1965). This technique is based on the assumption that the plane and curved surfaces of the ground adjoin in discontinuities (breaks of slope and inflections) that can be recognized, measured and mapped. The legend of symbols used to record the morphological features identified during the mapping is presented on the Geomorphological/Terrain Maps (Figure 2, following the text of this appendix). This system comprises the most broadly accepted international standard for the mapping of morphological features. The mapping was performed at a scale of 1:5000.

Surficial geologic units such as colluvium or alluvium were not mapped due to the limited aerial imagery and field reconnaissance. However, our evaluation of landslide processes and types described above indicate that most landsliding in Aizawl is bedrock related.

4.1 Landform Mapping

Critical landform components such as landslide complexes, debris fans, and overly steep (or distressed) slopes were interpreted and are shown on Figure 2.

- Landslide complexes are large scale features involving the downslope movement of large areas of the ground surface. They are likely the result of multiple landslide events, often involving multiple landsliding processes and are identified geomorphologically as containing rounded headscarps, hummocky topography, and deeply incised toe. Typically these features are located in the mid-slope terrain with their heads located at the boundary of the upper terrain. It is considered that these landslide complexes were probably formed in the geological past, possibly in a different climatic regime or resulting from pre-historic earthquake ground motion. Subsequent erosion and

anthropogenic activity has resulted in the removal of many of the landforms associated with the original landslide complex.

- Debris fans are located at the base of cliff terrains and are conical accumulations of rockfall and landslide complex deposits. Debris fans are located primarily along west facing slopes in the Study Area, where geologic bedding is normal to slope.
- Distressed slopes are steep areas associated with active drainage incision and accelerated erosion. They also contain significant concentrations of landslide features.

4.2 Terrain Unit Mapping

Terrain units are areas within which certain predictable combinations of surface forms and their associated soils and processes are likely to be found. Terrain units have been defined as a distinct and relatively unique group of geologic materials and landforms assemblages, typically occurring within a set range of altitude. The distribution of the terrain unit across the Study Area is shown on Figure 2 and provides spatial relationships from which landslide hazard can be evaluated. The lower boundaries of these units are often associated with abrupt changes in slope angle as well as depositional and erosional environments. Based on the engineering geomorphological mapping, seven distinct terrain units were identified within the study area:

- Cliff terrain;
- Incising terrain;
- Mid-slope fan terrain;
- Mid-slope bedding parallel terrain;
- Mid-slope bedding perpendicular terrain;
- Upper terrain; and
- Valley terrain.

We used these terrain units to develop a landform evolutionary model for the Study Area that describes how the current landscape formed as well as the geologic processes at work. The landform evolutionary model in the Aizawl region is characterized by a period of rapid uplift and deformation followed by drainage incision and downcutting. The incising terrain is the area most affected by drainage incision and continues to erode up-slope into the mid-slope terrains throughout the Study Area. The mid-slope terrains differentiate between slope parallel and slope perpendicular terrains by their underlying bedding structure. The mid-slope bedding perpendicular terrain is characterized by steeper slopes that are likely the result of erosional processes controlled by rock falls and topples along joints from more resistant bedrock units. The mid-slope bedding parallel terrain has moderately steep slopes controlled by the dip of resistant underlying bedrock units. Many large landslide complexes within this terrain do not appear to be related to the current period of incision. These landslide complexes may be a result of an earlier period of incision or, most likely, earthquake ground shaking. The mid-slope fan terrain is an accumulation of debris from the up-slope cliff terrain. The upper terrain is defined as the gently to moderately sloping ridge tops as well as the upper portions of spur-ridges between incising mid-slope bedding parallel terrain.

The landscape evolution of the Study Area does not simply reflect differing periods of incision alone but instead appears to be controlled by a complex interplay of erosional processes and geological (i.e. lithological and structural) control.

5.0 Slope Stability Analysis and Results

In geotechnical engineering practice, slope stability is usually expressed in terms of an index, most commonly the Factor of Safety (FS). The FS is the ratio of the shear strength of the soil to the shear stress induced on the potential failure surface. In concept, any slope with a FS above 1.0 should be stable. In practice, however, the level of stability is seldom considered acceptable unless the FS is significantly greater than 1.0 (Kramer, 1996). For our analyses, and part of the accepted standard of practice, we considered any slope with a FS of less than 1.5 to be unstable.

We performed slope stability analyses on two cross sections through the main ridge in the localities of Dawrpui Vengthar, Zarkawt, and Electric Veng (Figures 3 and 4, located following the text of this appendix). The two profiles represent slopes within differing terrain units and bedrock structure, and are representative of the geologic conditions of the region.

- Cross section A-A' located on the western side of the city's main ridge in the Dawrpui and partially the Zarkawt council areas where bedding is not parallel to slope (i.e. bedding dips into slope).
- Cross section A'-A'' located on the eastern side of the city's main ridge in the Zarkawt and Electric Veng council areas where bedding is parallel to slope.

Topographic profiles along the cross section lines were extracted from 8 m Digital Elevation Model (DEM) data distilled from the Aizawl Master Plan. Slope stability analyses were performed using Galena Slope Stability Analysis System. We modeled the stratigraphy as alternating 23 m thick, east dipping sandstone and shale beds, with shale material properties from Mizoram Public Works Department laboratory test data and sandstone properties from Hoek and Brown (1988, 1997). A dip of 25° east was chosen as the closest approximation for the regional bedding orientation, but we also analyzed dips of 15°, 20°, 25° and 30° for cross section A'-A'' to investigate the effect of dip on the stability of the bedding parallel slopes. We considered two scenario groundwater conditions: (a) monsoonal conditions with a phreatic surface 1 m beneath the ground surface (b.g.s.); and (b) dry conditions with the groundwater phreatic surface at a depth well beneath the modeled failure surfaces (50–100 m b.g.s).

We chose circular failure surfaces at various positions along the profiles and at several failure depths to estimate a range of plausible slope failure scenarios. Galena automatically calculates the failure surface with the lowest factor of safety within a pre-defined range of variation, termed the *critical surface*. We modeled two failure scenarios along the west-facing slopes of cross section A-A': a shallow landslide (~18 m deep) and a deep landslide (~40 m deep). Both modeled failure surfaces are located along the steep (25°-30°) upper slopes of the hillside near the head of a gully within the mid-slope bedding perpendicular terrain unit. We modeled two failure scenarios along the east-facing slopes of cross section A'-A'': a shallow landslide (~16 m deep) near the ridge crest on a moderately steep slope (15°-25°) within the mid-slope bedding parallel terrain unit, and a deep landslide (~23 m deep) on the steeper (20°-35°) section of slope straddling the mid-slope bedding parallel and incising terrain units. Figures 3 and 4 (located following the text for this appendix) show critical failure surfaces for each scenario.

We used the Bishop Simplified method of analysis because it is best suited for analyses of circular failure surfaces in homogenous and isotropic materials (Galena, 2013). We analyzed three pseudostatic seismic conditions: static (no earthquake force), 0.1 g peak ground acceleration (PGA), and 0.35 g PGA (scenario level shaking).

For the west facing slopes of cross section A-A', instability (i.e., FS value below 1.5) occurs for the deep and shallow failure surfaces for only one combination of conditions: monsoonal groundwater conditions and a 0.35 PGA earthquake load. All other analyses produced FS values greater than 1.5. Intersecting discontinuities were not considered in the analyses of either the west or east dipping slopes, though field reconnaissance indicates that discontinuities affect slope stability by providing a weak failure surface.

Results for the east-facing bedding parallel slopes show significantly higher potential instability. For the shallow upper failure surface, 0.35 PGA earthquake load produces instability (FS values below 1.5) for both monsoonal and dry groundwater conditions with bedding orientation modeled at 20° and 25°; stable conditions (FS values above 1.5) result from either groundwater condition when the bedding orientation is modeled at 15° and 30°. For the deep lower failure surface, 0.35 PGA earthquake load creates instability for monsoonal groundwater conditions at all modeled bedding orientations. With dry groundwater conditions, instability occurs for bedding orientations of 15°, 20° and 25°. Instability results under static, monsoonal groundwater conditions at bedding orientations of 25° to the east for the upper surface, and 15°, 20° and 25° for the lower surface. An example of the relationship between bedding dip and ground surface dip can be seen from the recent 2013 Laipuitlang landslide. The ground surface in the area of the recent Laipuitlang landslide slopes between 29 and 35 degrees to the east. The bedding in the area dips approximately 25 degrees to the east. The slightly shallower-dipping bedding is daylighting on the steeper slope, creating an adverse slope condition that is prone to failure. The stability of these adverse slope conditions is further exacerbated by grading for building or road construction on the slope.

Slope stability analyses demonstrate the detrimental influence of groundwater and earthquake shaking on the stability of typical Aizawl hillslopes. Key results include:

- East facing bedding parallel slopes (A'-A'') are significantly less stable (i.e., FS values are significantly lower) than the west facing slopes (A-A') where bedding dips into the slope.
- East facing bedding parallel slopes (A'-A'') are marginally stable under monsoonal static conditions. Relatively minor modifications of the ground surface on these slopes, such as slope grading for building or road construction, can reduce the stability of these slopes.
- On the east facing bedding parallel slopes (A'-A'') bedding dips of 20° and 25° had significantly lower factors of safety than bedding dips of 15° and 30°. This is likely the result of the slope/ bedding parallelism with a 20°-25° dip and the increased likelihood of the failure surface being primarily in the modeled weak shale material.
- In the majority of the analyses the critical failure surface (failure surface calculated to have the lowest FS during the multiple analyses) was the deepest surface geometrically permissible within the weak shale material. This implies that large, deep seated, rotational rock slides are more likely than more shallow failures.

7.0 Landslide Hazard

For the purposes of the earthquake scenario, we define landslide hazards as physical situations where ground movement could result in human injury or damage to facilities and transportation routes within the Study Area (Van Dine et al., 2004). The landslide hazard map (Figures 5a and 5b, following the text of this appendix) sub-divides the study area into zones of similar landslide hazards. Landslide hazards have been assessed by extracting relevant components recorded within the Engineering Geomorphological Maps, including the slope morphology, type and extent of landforms and landslide features, drainage line characteristics, and the overall location of the hillslope within the landscape as a whole (i.e. its Terrain Unit). The landslide hazard map considers the level of hazard for natural terrain; human activities that modify slopes and reduce their stability may increase the hazard.

Landslide hazard severity is assigned using the landslide hazard matrix shown in Table 1, which evaluates the terrain units and secondary classifiers such as landslide complexes. The landslide hazard zones have been cross-checked by quantitative analyses of available landslide data (Table 2). For the purpose of this study, landslide hazard has been assessed independent and irrespective of the down slope consequence; effects on buildings downslope are considered separately. Figure 6 (following the text of this appendix) shows an oblique 3-dimensional image of the landslide hazard zone map draped onto Google Earth satellite photography of Aizawl. The high percentage (88%) of the Study Area in the “very high” and “high” landslide hazard zones is a reflection of the geologic conditions.

Table 1 – Landslide Hazard Matrix

	Landslide Hazard			
	Very High	High	Moderate	Low
Primary Classifier	Incising and Cliff Terrains	Mid-Slope Terrains	Upper Terrain	Valley Terrain
Secondary Classifier	Landslide Complex			

While the approach described above primarily identifies hazards arising from rock slides (the most commonly occurring type of mass earth movement in Aizawl), the mapping of cliff terrain shows possible source areas for rock falls. Additional mapping of surface deposits including colluvium, alluvial fans, and areas of thick residual soils would assist in the evaluation of potential hazards from debris slides and debris flows.

8.0 Estimates of Landsliding Due to the Scenario Earthquake

To determine potential landslide damage to buildings and infrastructure, we estimated a percentage of the total area that will fail under the scenario earthquake. The landslide hazard map allows us to estimate the percentage of failure as a function of hazard zone. This estimation is based on theoretical and empirical landslide inventory data as well as from site specific data collected from the Study Area and the results of our slope hazard calculations.

Rock slides and rock falls are the most common type of landslide in Aizawl and are the most likely to occur in response to earthquake ground motions (Keefer, 1984). The radius of the area affected by landslides, and the intensity of landsliding within this area, increase with the magnitude of an earthquake (Youd and Perkins, 1978; Keefer, 1984, 2000). Where sufficient data are available, the density of earthquake induced landslides is linearly and highly correlated with measured peak ground accelerations (Meunier et al., 2007). Aizawl is located within a few tenths of a kilometer of the scenario event, and estimated ground motions are on the order of $PGA = 0.35$ g, so we expect significant landsliding to occur (Table 2).

Most of the material displaced during an earthquake is produced by a small number of large landslides. Statistical methods for estimating the size of landsliding are available and utilize probability density functions and empirical landslide distribution equations derived from landslide inventories (i.e., Malamud *et al.* 2004). These equations are derived from global datasets that include rainfall and rapid snowmelt landslide inventories as well as earthquake-induced landslide inventories, but produce comparable results for use in estimating landslide failure percentages in terms of spatial area.

We used both quantitative (Malamud et al., 2004) and qualitative methods to estimate the total maximum landslide area (A_{Lmax}) that might fail during a M 7.0 earthquake with $PGA = 0.35$ g in close proximity to Aizawl. We do not attempt to model topographic amplification of ground motions, which may significantly increase the total landslide failure area. A brief description of each method and results are provided below:

Quantitative Landslide Model

Malamud et al. (2004) presents a statistical distribution of landslide areas and landslide volumes by defining a probability density function using three complete landslide inventories. These include landslide inventories from 1) the earthquake-induced 1994 Northridge earthquake; 2) the 1997 rapid snowmelt event in Umbria Italy; and 3) the heavy rainfall event in Guatemala from Hurricane Mitch in 1998. Based on the agreement between these three sets of probability densities, a distribution equation is presented from which landslide areas and volumes can be predicted for scenario events (Malamud et al., 2004). The quantitative landslide model is combined with empirical relations of landslide density to calculate a percentage of area expected to fail during the seismic shaking. The results of this analysis represent the minimum total failure percentage for the Study Area (Table 2, following page).

Qualitative Landslide Model

The qualitative model uses slope specific hazard data derived from our slope stability calculations and reconnaissance mapping of the study area in Aizawl. The failure model with the lowest factor of safety is used to estimate an average landslide volume for the Study Area. This landslide area is combined with empirical relations of landslide density to also calculate a percentage of area expected to fail during seismic shaking. The results of this analysis represent the maximum total failure percentage for the Study Area (Table 2).

Table 2 - Estimates of Total Failure Percentage in the Study Area

Hazard Zone ⁽¹⁾	Hazard Zone Area (km ²)	Percent of Study Area (%)	No. of Landslides/ Hazard Zone from existing inventory	Landslides per sq. km	Calculated No. of Landslides/ Hazard Zone ⁽⁴⁾	Landslide Area (m ²) ⁽⁵⁾	Total Landslide Area (m ²)	Percent Landslide Area (%)
						Global Average	Min	Min
						Modeled	Max	Max
Very High	2.40	56	20	9.9 ⁽²⁾	24	3,070	73,680	3
						16,000	384,000	16
High	1.35	32	15	5.4 ⁽³⁾	8	3,070	24,560	2
						16,000	128,000	9
Moderate	0.27	6	1	2.1 ⁽³⁾	1	3,070	3,070	1
						16,000	16,000	6
Low	0.24	6	0	0	0	3,070	0	0
						16,000	0	0

- Notes: 1. See Landslide Hazard Map (Figure 3, following the appendix text)
2. Landslide concentration in San Gabriel Mountains from 1994 Northridge earthquake (Harp and Jibson, 2002)
3. Landslide concentration in Santa Cruz Mountains from the 1989 Loma Prieta earthquake; 5.4 = maximum, 2.1 = minimum (Keefer, 1997)
4. Landslides per sq. km] x Hazard Zone Area (rounded up)
5. Global average from Malamud et. al. (2004); Modeled area uses approximate credible dimensions of the deep landslide modeled along section A'-A'' (see Section 6.2)

The minimum and maximum estimates of percent landslide area in Table 2 correspond to dry and monsoonal conditions, respectively. Because the Study Area's slopes are representative of slopes throughout the city, we can extend these estimates to the remainder of the Aizawl urban area by direct extrapolation. Because the total Aizawl Urban Area is 152.8 sq. km (Aizawl Development Authority, 2013), for the scenario earthquake we can expect a total landslide area of 3.6 sq. km for dry conditions and 18.1 sq. km for monsoonal conditions. The area of landsliding we estimate will create an enormous amount of debris that in many cases will need to be cleared to reopen streets and repair infrastructure and building damage. These area estimates do not include the runout zone, which is the area affected by the slide mass as it moves down slope. For the purposes of estimating the number of building collapses, the percent landslide area for the generally densely developed high hazard zone has been increased by 50% over the values in Table 2 to account for the damage to buildings in the runout zone. For the other zones (including the very high hazard zone), we have not applied an amplification factor to the values in Table 2 because development is less dense. Also, we used the empirical relations for landslide density and the average landslide areas in Table 2 to estimate, approximately, the number of landslides that the scenario level of shaking would cause throughout the Aizawl urban area. Based on the slope stability calculations discussed previously, we expect that earthquake induced landslides occurring during the monsoon would be larger and more destructive.

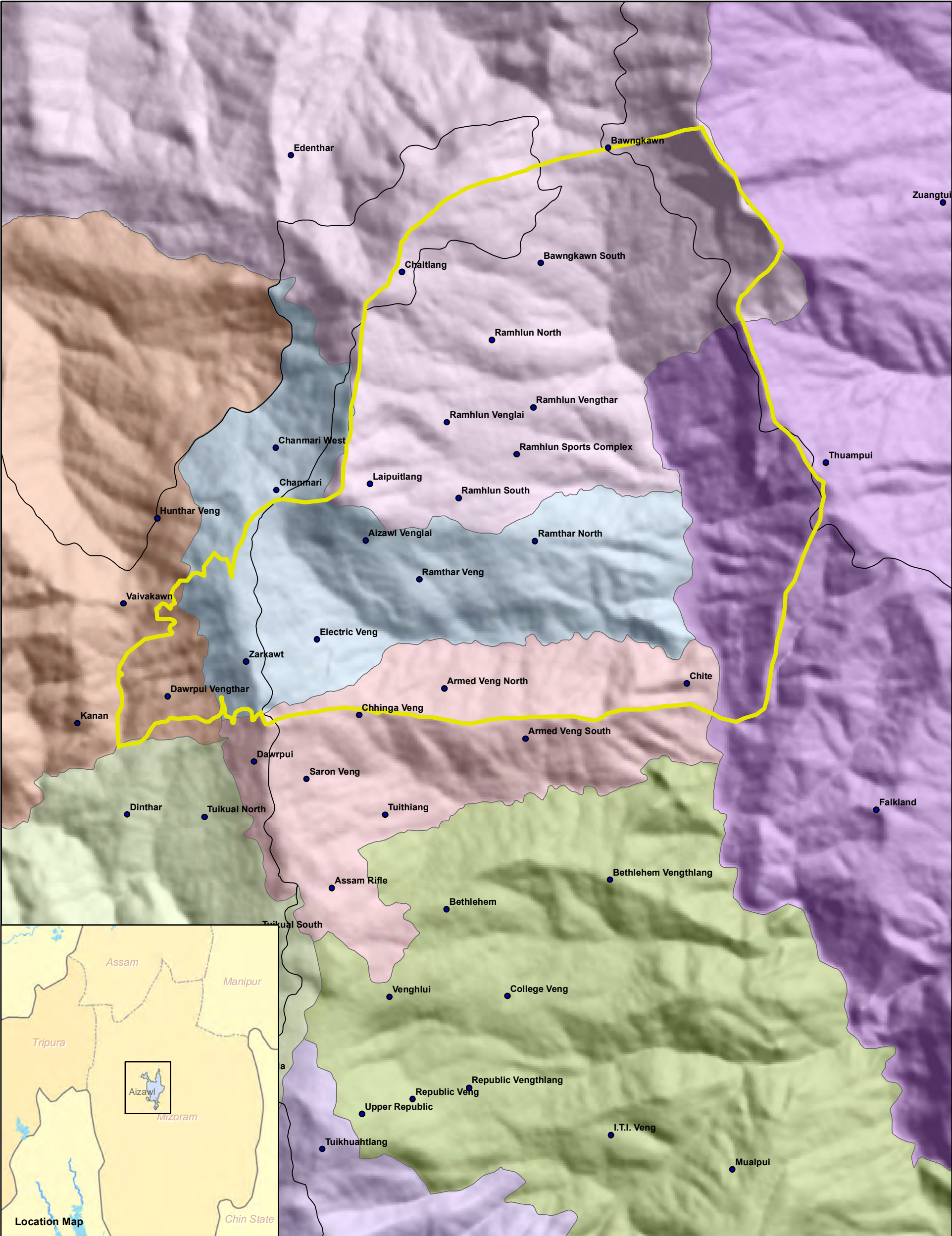
9.0 Conclusions

Aizawl's geologic conditions create very severe levels of landslide hazard, as evidenced by the 88% of the study area located in the "high" or "very high" landslide hazard zones. The landslide data for the region, which include landslide inventory data, laboratory testing, slope stability calculations, and discontinuity data, are limited but support these high hazard classifications. Additional data collection including better scale topographic mapping, landslide mapping, and subsurface investigations in the Aizawl area are needed to further refine these landslide hazard zones. Despite the benefits additional information will provide, it is abundantly clear from the available information that a strong earthquake such as the M7 scenario earthquake we describe will cause numerous, perhaps hundreds, of devastating landslides in Aizawl.

10.0 References

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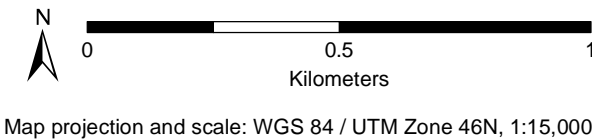
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EXPLANATION

- Village Name
 - Major Roads
 - ▭ Tlawng River
 - ▭ Pilot Study Boundary
 - ▭ AUA Boundary
- Stratum Boundary

▭ Aizawl East I	▭ Aizawl South II
▭ Aizawl East II	▭ Aizawl West I
▭ Aizawl North I	▭ Aizawl West II
▭ Aizawl North II	▭ Sairang
▭ Aizawl South I	▭ South Extension



Administrative Units of Aizawl Urban Area

Aizawl Slope Stability


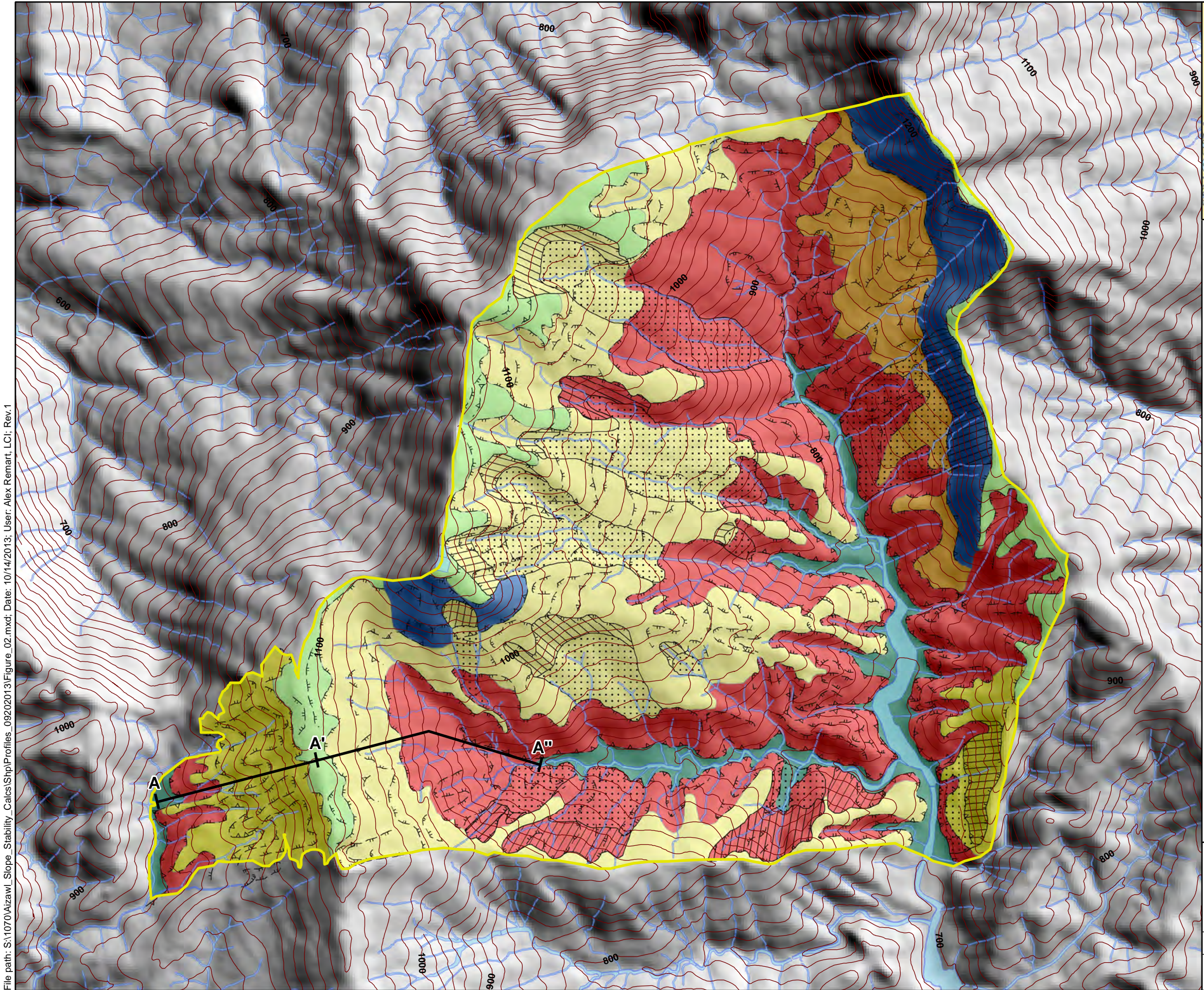
 Lettis Consultants International, Inc.

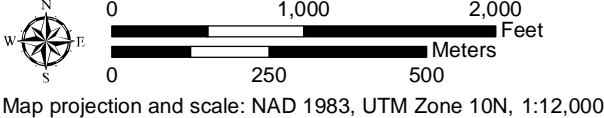
Figure 1

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EXPLANATION

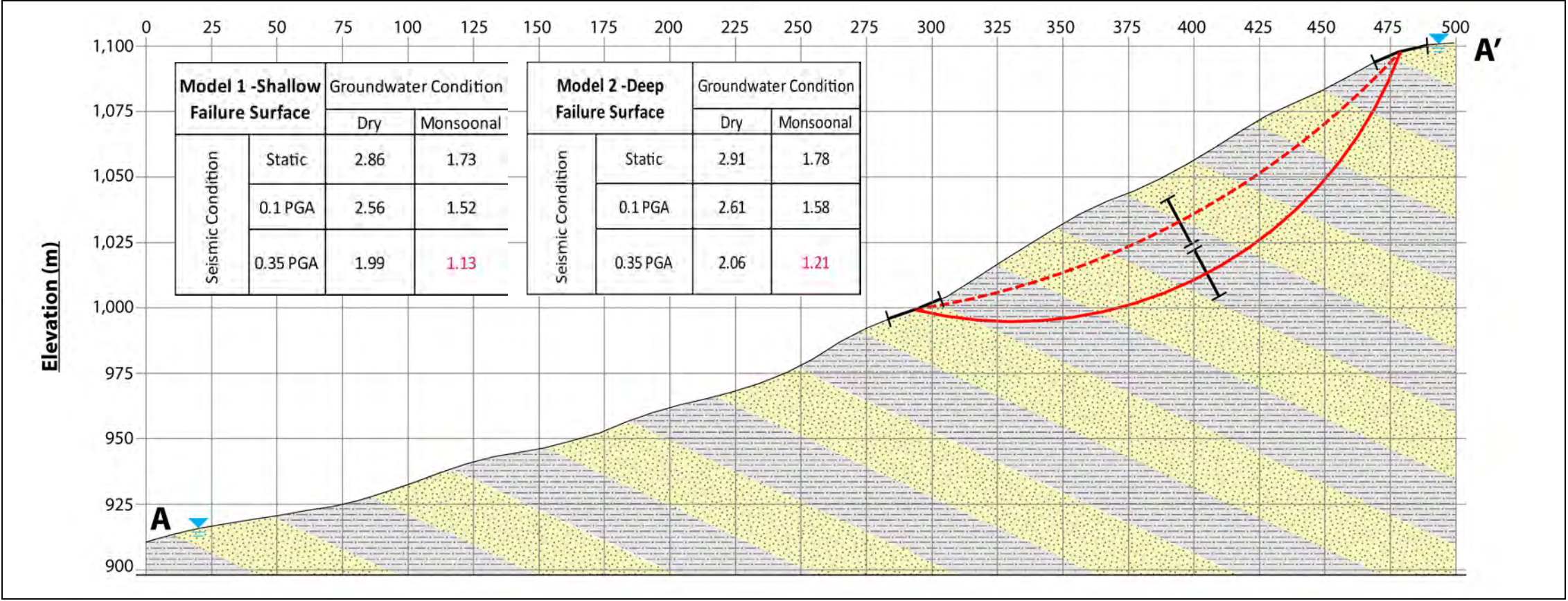
- A A'** Cross Section Location
- Yellow Outline** Pilot Study Area
- Morphology**
 - Rounded concave break in slope
 - Rounded convex break in slope
- Landslide Complexes**
 - Deposit
 - Scarp
- Terrain Units**
 - Cliff
 - Incising
 - Mid-slope fan
 - Mid-slope bedding perpendicular
 - Mid-slope bedding parallel
 - Upper
 - Valley



Engineering Geomorphological Terrain Map

Aizawl Slope Stability

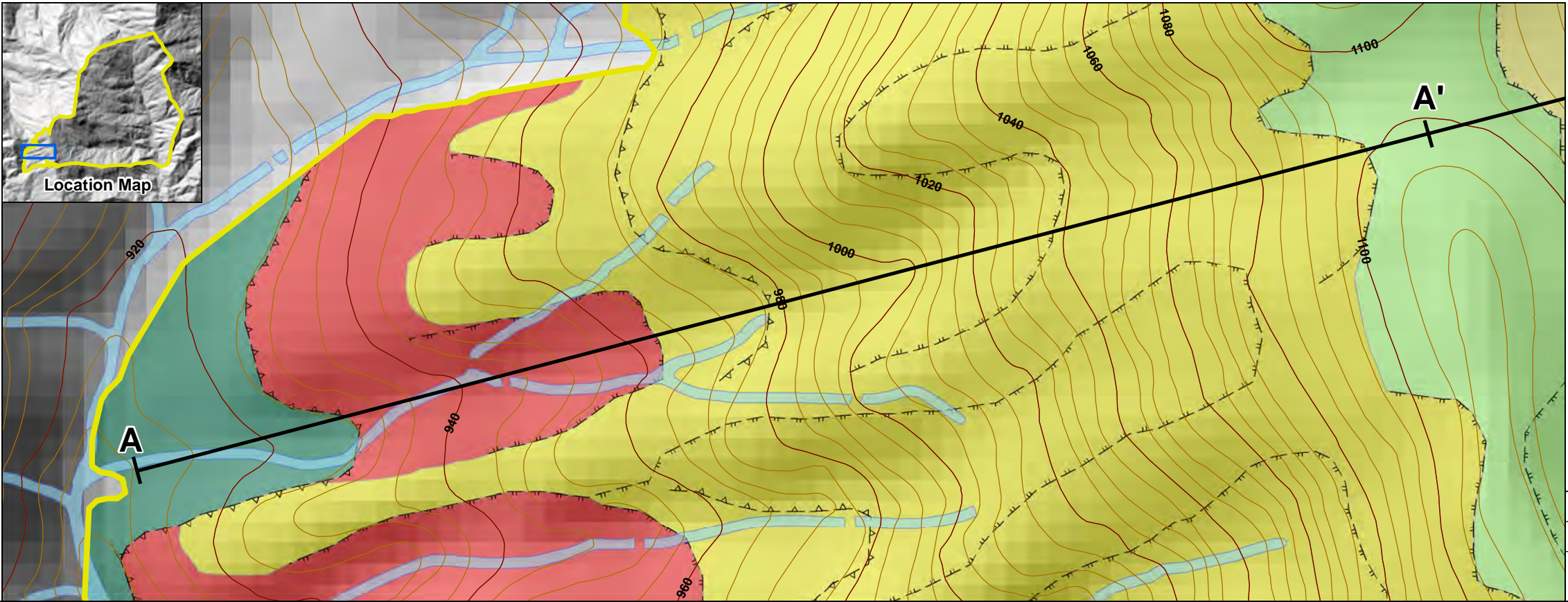
a.



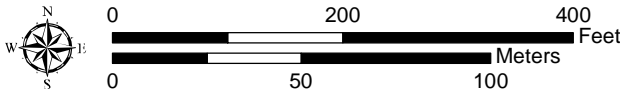
Explanation

- a.
- Model 1 Failure Surface
 - Model 2 Failure Surface
 - Multiple Analysis Restraint
 - Monsoonal Ground Water Conditions (1 m b.g.s.)
- MODELED STRATIGRAPHY
- Sandstone
 - Shale
- b.
- A A' Cross Section Location
- Pilot Study Area
- MORPHOLOGY
- Rounded concave break in slope
 - Rounded convex break in slope

b.



- TERRAIN UNITS
- Cliff
 - Incising
 - Mid-slope fan
 - Mid-slope bedding perpendicular
 - Mid-slope bedding parallel
 - Upper
 - Valley

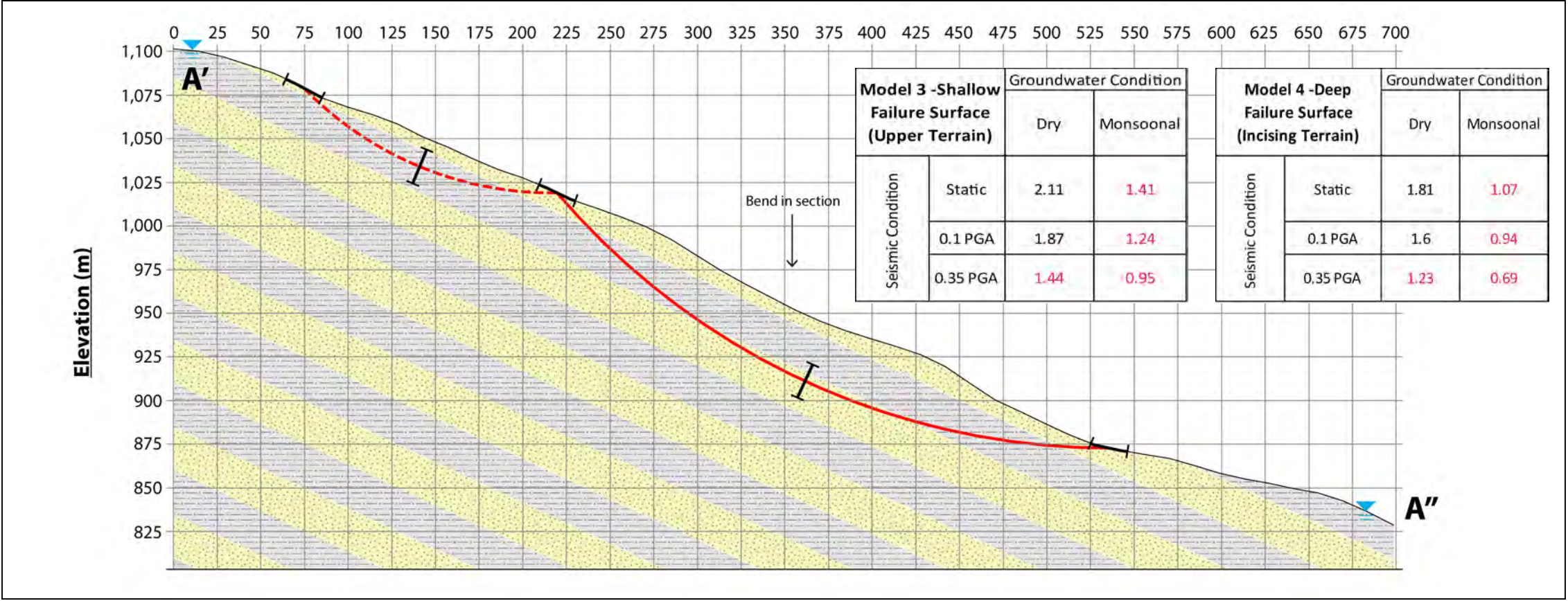


Map projection and scale: WGS 1984 UTM Zone 46N, 1:2,000

Profile A - A'

Aizawl Slope Stability

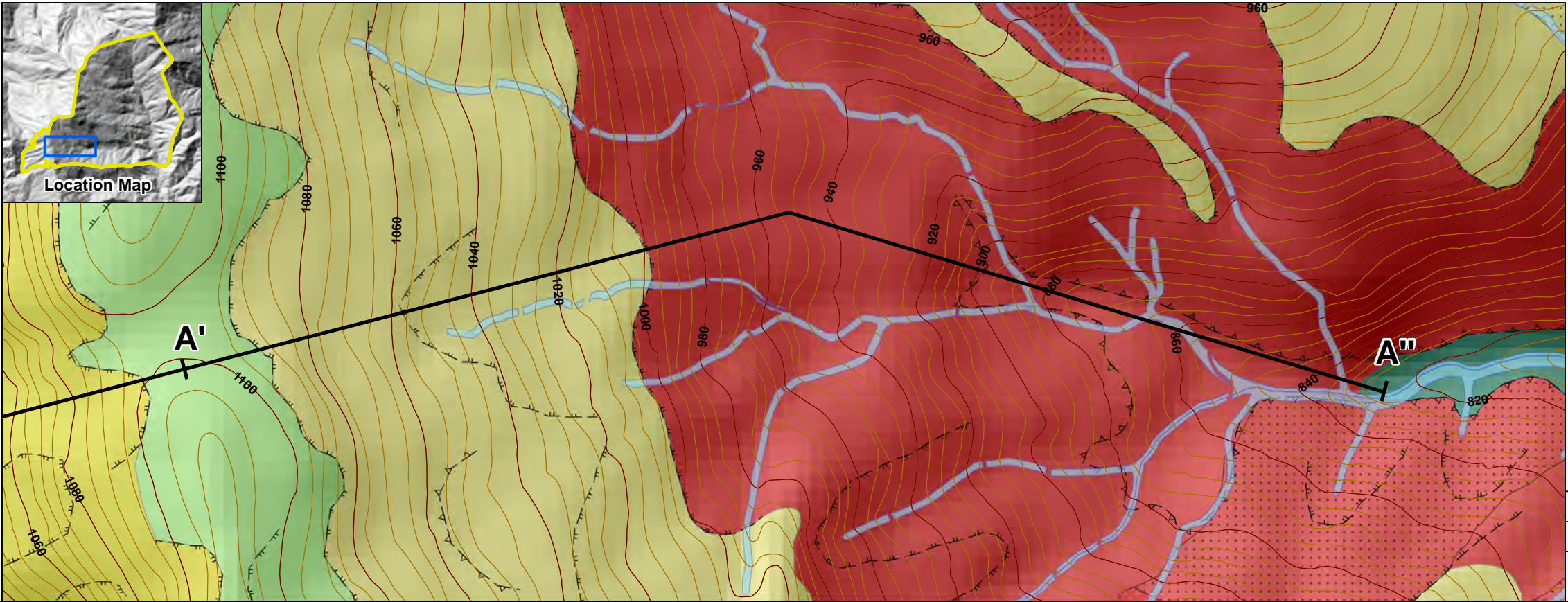
a.



Explanation

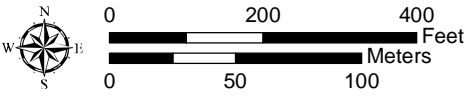
- a.**
- Model 1 Failure Surface
 - Model 2 Failure Surface
 - Multiple Analysis Restraint
 - Monsoonal Ground Water Conditions (1 m b.g.s.)
- MODELED STRATIGRAPHY**
- Sandstone
 - Shale
- b.**
- Cross Section Location
 - Pilot Study Area
- MORPHOLOGY**
- Rounded concave break in slope
 - Rounded convex break in slope

b.



TERRAIN UNITS

- Cliff
- Incising
- Mid-slope fan
- Mid-slope bedding perpendicular
- Mid-slope bedding parallel
- Upper
- Valley

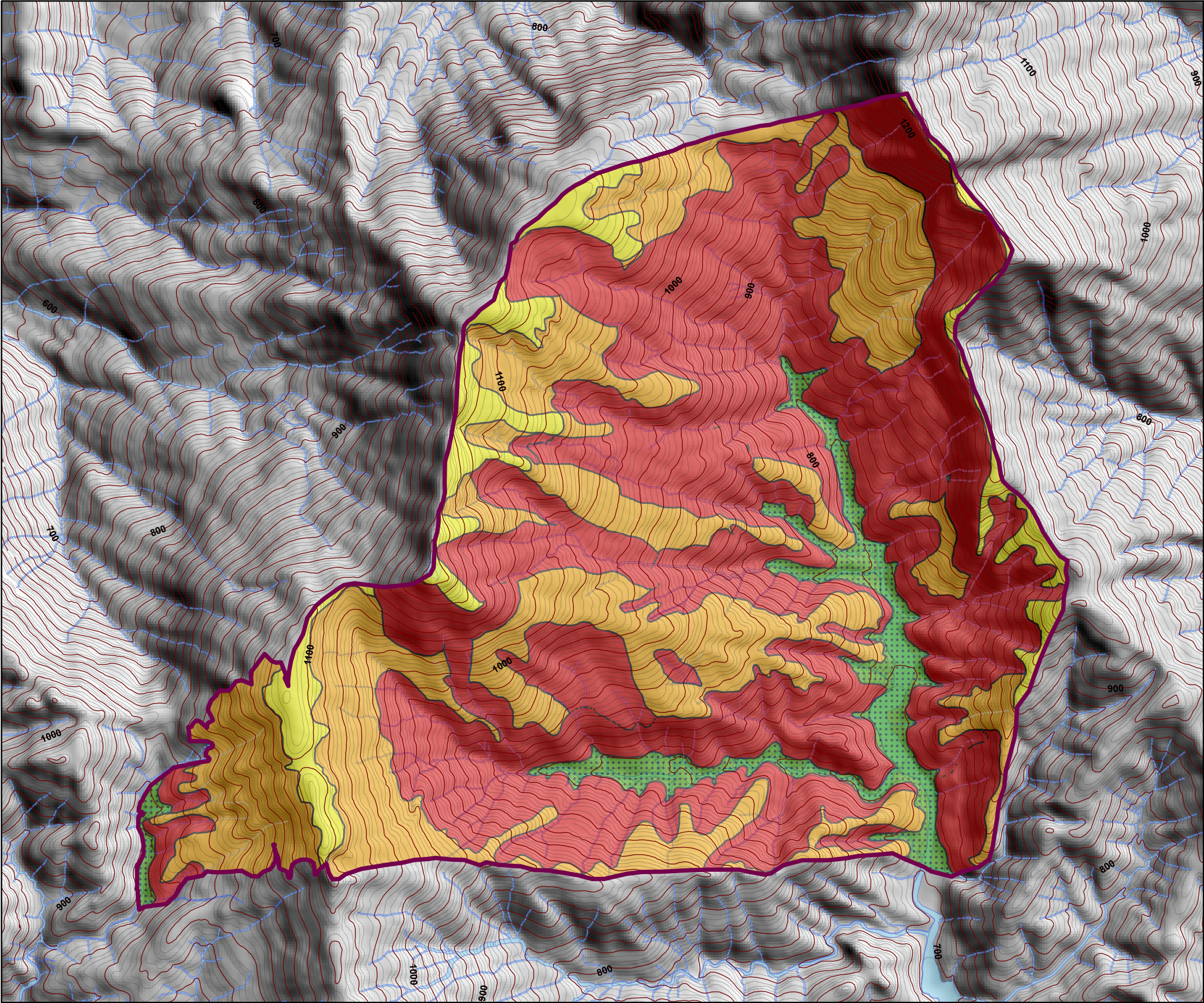


Map projection and scale: WGS 1984 UTM Zone 46N, 1:3,000

Profile A' - A''

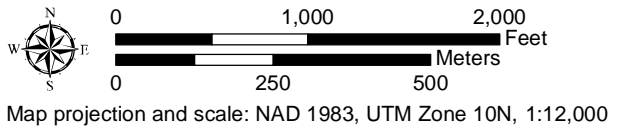
Aizawl Slope Stability

File path: S:\1070\Aizawl_Slope_Stability_Calcs\Shp\Profiles_09202013\Figure_05_Hatching.mxd; Date: 03/03/2014; User: Alex Remart, LCI; Rev.1



EXPLANATION

- Pilot Study Area
- Landslide Hazard Zones**
 - Very High
 - High
 - Moderate
 - Low








Landslide Hazard Map

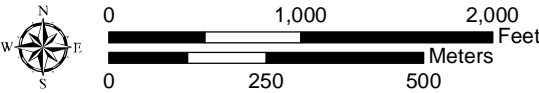
Aizawl Slope Stability

File path: S:\1070\Aizawl_Slope_Stability_Calcs\Shp\Profiles_09202013\Figure_05_BW.mxd; Date: 03/04/2014; User: Alex Remart, LCI; Rev.1



EXPLANATION

-  Pilot Study Area
- Landslide Hazard Zones**
-  Very High
-  High
-  Moderate
-  Low



Map projection and scale: NAD 1983, UTM Zone 10N, 1:12,000

Landslide Hazard Map

Aizawl Slope Stability

File path: S:\1070\Aizawl_Slope_Stability_Calcs\Shp\Profiles_09202013\Figure_06.mxd; Date: 03/05/2014; User: Alex Remar, LCI; Rev:1



EXPLANATION

Landslide Hazard Zones

- Very High
- High
- Moderate
- Low



Aizawl Landslide Hazard 3D View

Aizawl Slope Stability



Appendix C

Buildings

Collapsing buildings cause the majority of deaths when an earthquake strikes. Collapsed buildings also block roads and damage infrastructure, which impedes emergency response and slows the community's recovery. Workers must clear away and dispose of the rubble before streets can re-open and new buildings can be built to replace those that failed. For these reasons, estimating the number of building collapses during the scenario earthquake is critical to determining the impacts on people, transportation, response efforts and recovery.

The procedures for estimating building collapses and the deaths they may cause in future earthquakes have been well established by professionals who specialize in estimating earthquake losses. Starting with information on the types of buildings in the city and the prevalence of each type of building, structural engineers then determine the expected percentage of collapses for each building type, using statistical relationships based on past earthquake damage, computer simulations, or professional judgment. The next step is to estimate the number of people present in each type of collapsed building, by estimating how many people usually live or work in each type of building and how many are likely to be inside at the time of the earthquake. Finally, engineers arrive at the estimated number of deaths by applying a rate of expected fatalities to the number of occupants affected in the collapse of each building type. Heavy buildings, such as reinforced concrete or masonry, kill a higher proportion of occupants during collapse than light buildings do. In Aizawl, landslides triggered by an earthquake will increase fatalities. The city will experience larger and more devastating landslides during monsoon season, which means that fatalities will be higher during monsoon season than during the dry season.

The following sections describe how we estimated the building collapses and fatalities caused by the scenario event. We do not estimate how many buildings will suffer less severe levels of structural damage, because these levels of damage primarily cause economic and functional losses, rather than deaths and injuries. We do expect many buildings that do not collapse to be badly damaged and require major repairs or replacement.

Aizawl Building Types and Typical Vulnerabilities

Though every building is slightly different, engineers group buildings into a manageable number of basic types for a given scenario. For this scenario, we use three basic types. Engineers define building types such that it will be reasonable to assume that all buildings within each type will experience similar levels of earthquake damage for a given strength of shaking. Buildings within a type often have the same construction materials, structural system, and approximate building height. Other characteristics that affect a building's vulnerability to collapse, such as whether or not the building has earthquake-resistant features, are also shared within a building type. Concepts from statistics account for the variability of building responses within each building type to the same strength of ground motion.

Aizawl has three main types of buildings:

- traditional timber buildings often referred to as *Assam-type* and classified as Ordinary buildings by the Aizawl Municipal Council (AMC);
- lightweight wall buildings with reinforced concrete beams and columns often referred to as *semi-pucca* and classified as Semi-permanent buildings by AMC; and
- reinforced concrete frame buildings with brick infill walls often referred to as *RCC* and classified as Permanent buildings by AMC.

We further divided the semi-pucca and reinforced concrete building types into subtypes, to account for the different behavior expected 1) when a building's concrete frame has steel reinforcement that has been properly placed (called *ductile detailing*) so that the frame experiences benign, gradual damage during an earthquake, or 2) when the building's frame does not have such ductile detailing so the frame experiences sudden brittle failure. Beginning in 2007, the Aizawl Development Authority and AMC mandated compliance with the National Building Code (2005), so buildings built from 2008 onward are much more likely to have earthquake-resistant ductile detailing than buildings constructed before that time. We also divided the Assam-type buildings into older and newer subtypes to account for the greater vulnerability of older Assam-type buildings.

Because of Aizawl's hilly terrain, the majority of buildings are on a slope, in contrast to most cities elsewhere in India. For concrete buildings, the team differentiated between buildings constructed on a level pad (with a retaining wall behind on sloped sites) and those with foundations that step down the hill. Semi-pucca and Assam-type buildings are assumed to step down the hill or be supported on tall "stilt" frames. Aizawl has a small number of other building types, such as load-bearing masonry buildings belonging to the Assam Rifles, but there are not enough of these buildings relative to the total to justify a separate type.

Aizawl's buildings have several important characteristics that reduce their ability to resist collapse during earthquake shaking. A lack of earthquake-resistant design and problematic construction practices create one set of significant vulnerabilities. The methods used to accommodate the steeply sloping terrain, such as tall stilt supports and stepped foundations, as well as the larger earthquake demands that hillside buildings experience, create other important vulnerabilities. Landslides are not the only problem on Aizawl's steep slopes. Buildings built on moderate to steep slopes are much more vulnerable to earthquake damage than buildings on flat ground. The short, stiff supports on the uphill side must resist most of the lateral force as the earthquake pushes the building out from the hill. The long supports on the downhill side must move a long way as the building twists around the stiff uphill side supports. Both uphill and downhill supports must resist higher demands than the designer or builder likely intended, which can lead to failure, especially in cases where the supports are already vulnerable due to weak members or poor connections.

Traditional Timber (Assam-type) Buildings

For Assam-type buildings, rot-resistant timber or reinforced concrete foundation posts embedded in the ground form the foundation system. Figure 1 shows a typical Assam-type house on timber posts. The foundation posts support slender timber posts that extend up to the floor of the lowest living level. A modest number of equally slender cross braces provide lateral stability to the post support system; sheathing fastened to vertical and horizontal studs provides lateral resistance for the living spaces above the post support system. Because the walls in the living space are typically stiffer than the post support system, the post supports experience most of the earthquake-induced deformation. The post supports can be either natural round timbers or sawn lumber, with natural timber being more vulnerable because it is more difficult to make good connections.



Figure 1. A traditional timber Assam-type building on an active landslide in Ramthar Veng (left) showing an inadequately braced natural timber post support system that accommodates the slope; a tenuous splice connection in a vertical support post in the same structure (right)

Due to the slope, vertical posts under the living space can be quite long on the downslope side of the hill (generally a full storey height or more), requiring one or more splice connections (see Figure 1). From field observations, we expect that these splices will not be able to accommodate much shaking before they fail. Connections in Assam-type buildings, including the critical connections in the post support system, often contain the minimum number of fasteners needed to support the building under gravity loads; earthquake forces do not appear to have been considered. These buildings also have few interior walls, and the roof is not stiff enough or strong enough to help hold the building together during strong shaking. Assam-type buildings appear most likely to collapse due to a failure in the post support system, either through sidesway or loss of gravity load carrying capacity due to a connection failure.

Semi-Permanent (Semi-pucca) Buildings

For semi-pucca buildings, the detailing and strength of the reinforced concrete beams and columns, and the geometry of the frame as the building steps down the hill, govern the response to earthquake shaking. Semi-pucca buildings are typically built by masons without engineering design, but we observed that a number of masons build semi-pucca buildings with ductile detailing. Semi-pucca buildings without ductile detailing are considerably more vulnerable to collapse than those with ductile detailing. Semi-pucca buildings tend to have columns that are much more slender, and thus weaker, than similarly sized reinforced concrete buildings. One reason is that AMC building regulations do not require structural drawings for semi-pucca buildings, so these buildings are unlikely to have code-mandated strength levels. Semi-pucca buildings are also generally lighter than reinforced concrete buildings because they do not have concrete floor slabs and brick walls, which helps reduce the amount of strength needed to resist loads from gravity and earthquakes. However, owners tend to add brick walls to semi-pucca buildings over time, and some owners build concrete floor slabs despite regulations, as Figure 2 shows. Both additions increase the weight and therefore the forces the frame must resist. Brick walls can also fall out of the frame and harm occupants or those outside. For semi-pucca

buildings without ductile detailing, a brittle failure at the beam-column connections or in the columns is most likely to cause collapse. For buildings with ductile detailing, excessive sidesway of one or more storeys after significant flexural yielding in the frame is most likely to cause collapse.



Figure 2. Semi-pucca buildings in southeast Aizawl; note concrete slab at top level of building under construction and lightweight walls that have been replaced by brick in building on right.

Reinforced Concrete (RCC) Buildings

Aizawl's reinforced concrete buildings exhibit significant variety in age, height, configuration, level of seismic design, condition, and construction quality. Despite this variety, several characteristics tend to dominate the seismic vulnerability, and these characteristics differentiate between buildings that are likely to collapse during the scenario event and those that are not. The first differentiating characteristic is whether the frame has ductile detailing that will prevent the columns from failing in a sudden, brittle manner. The second is whether the building steps down the hill, with fewer and fewer columns to resist the earthquake forces from the storeys above, as Figure 3 shows. The third is whether the building has an open storey with fewer walls, which makes the building more vulnerable to collapse because damage tends to concentrate in the open storey, as numerous past earthquakes in India and elsewhere have shown. Many buildings in Aizawl have open storeys, often at the road level to accommodate shops. Due to the steep slopes, many buildings have several storeys or basements extending downhill below the road level.

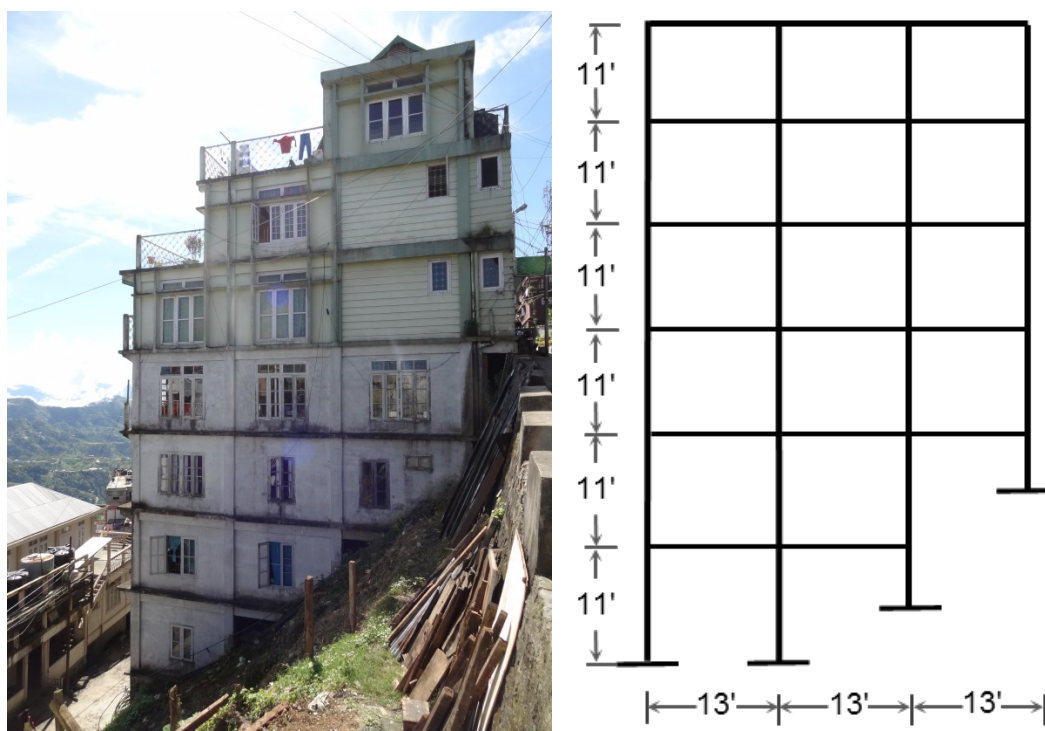


Figure 3. Reinforced concrete building with steps down hill (left) and simplified version used for analysis (right)

Aizawl's concrete buildings have a number of other vulnerabilities, such as upper floors that cantilever out further than the floors below, irregular arrangements of beams and columns, added storeys that increase loads beyond what the design engineer originally intended, and inadequate gaps between buildings that cause buildings to hammer together during shaking. Many buildings, even new ones, have columns with the same dimensions and reinforcing over the entire building height, causing damage to concentrate in the ground storey where forces are highest relative to the capacity of columns to resist them—rather than spreading out the damage over multiple storeys, as the building code intends. If present, these vulnerabilities (and the general vulnerabilities mentioned previously) will affect how individual buildings respond to earthquake shaking.

Building Inventory

After defining the building types, the next step is to determine the number of buildings of each type. This can be accomplished either by taking a detailed inventory of all the buildings in the city or by estimating the prevalence of each building type from census data, extrapolation from inventories for representative areas, or satellite or aerial imagery.

For this scenario, the project team obtained data on the overall number and type of buildings in Aizawl city from the Houselisting and Housing Census 2011 of the Government of India; current AMC building permission records; and an AMC houselist survey completed in 2009 for the 76 localities that were part of AMC at that time (as of 2013, AMC had expanded to 92 localities). The team also identified four case study neighborhoods and obtained more detailed information for each from Google Earth satellite imagery and walking surveys. The case study neighborhoods of Electric Veng, Zarkawt and Dawrpui Vengthar represent an east-to-west “slice” of Aizawl's main ridge that captures the range of predominant slope conditions in the

city. The fourth neighborhood is Dawrpui, the city's major commercial district located atop the main ridge. We present results for the Electric Veng case study in the main document.

The Houselisting and Housing Census 2011 contains information on the total number of dwellings or other units (called Census Houses in the census), the number of units by use type (residential, commercial, school, hospital, etc.), and the number of units with various wall, roof and floor materials. A single building can have multiple units. One household was assumed to occupy one residential unit. The Aizawl Urban Area was taken as equivalent to the urban portion of Tlangnuam Sub-district of Aizawl District. The number of units of each of the three basic types was inferred from the wall, roof and floor material, though there is some uncertainty because the roof, floor and wall materials for Assam-type (traditional timber) and semi-pucca can be the same.

Building permission records from AMC, available from 2008-present, when combined with estimated completion percentages, provide the number of reinforced concrete and semi-pucca buildings constructed under AMC or Aizawl Development Authority building regulations—and therefore are more likely to have ductile detailing. The AMC building permission records were also used to provide an estimated update of the total numbers of each building type to March 2013 levels; housing census data includes buildings completed through approximately April 2010. The total number of buildings was estimated from the total number of units using the ratio of buildings to units (0.65) obtained from the 2009 AMC houselist survey, which covers approximately 75% of Aizawl's building stock. Using this conversion, Aizawl has approximately 49,000 buildings.

Table 1 shows characteristics of Aizawl's building stock. Extrapolating field survey data from the case study neighborhoods to the rest of the city, we estimate that 90% of pre-2008 reinforced concrete buildings have stepped foundations, while the remaining 10% are built on flat sites. We estimate that the percentage is slightly lower for newer buildings, with approximately 80% on stepped sites. Aizawl's building stock has evolved over time, with recent trends favoring reinforced concrete construction.

Table 1. Aizawl building stock information

Building Type	Total Units		Residential + Residential-cum-Other Units			Non-residential Units		
	Number	% of Total	Number	% of Total Residences	% of Total	Number	% of Total Non-residences	% of Total
Assam-type (total)	31,885	42%	29,977	46.5%	39.6%	1,908	16.9%	2.5%
Older	14,692	19%	13,765	21.4%	18.2%	927	8%	1.2%
Newer	17,194	23%	16,212	25.2%	21.4%	982	9%	1.3%
Semi-pucca and other (total)	9,380	12%	7,586	11.8%	10.0%	1,794	15.9%	2.4%
Pre-2008	9,080	12%	7,299	11.3%	9.6%	1,781	16%	2.4%
2008 onward	300	0%	287	0.4%	0.4%	13	0%	0.0%
Reinforced concrete (total)	34,465	46%	26,863	41.7%	35.5%	7,602	67.3%	10.0%
Pre-2008 Flat base	3,037	4%	2,301	3.6%	3.0%	736	6.5%	1.0%
2008 onward Flat base	409	1%	386	0.6%	0.5%	24	0.2%	0.0%
Pre-2008 Stepped base	29,381	39%	22,634	35.1%	29.9%	6,747	59.7%	8.9%
2008 onward Stepped base	1,638	2%	1,542	2.4%	2.0%	95	0.8%	0.1%
Total	75,730	100%	64,426	100%	85.1%	11,304	100.00%	14.9%

Estimating Building Collapses Caused by Shaking

The expected percentage of collapses for each building type were determined using statistical relationships, called *fragility curves* or *fragility functions*, which relate the probability of collapse to the strength of ground shaking. Fragility curves can be based on data from past earthquake damage to similar buildings, on computer simulations of damage, or on professional judgment of experienced structural engineers. Though engineers have developed many fragility curves for building types around the world, Aizawl's buildings are unique enough that existing curves do not apply to the majority of buildings. In particular, almost all existing fragility curves were created for buildings on flat ground.

Due to the previously-described vulnerabilities of Aizawl's Assam-type buildings, we could use collapse fragility curves for timber buildings in other parts of the world only with significant modifications. Because they are located on vulnerable post support systems on steep hillsides, Aizawl's timber buildings are more vulnerable to collapse than typical timber buildings used to develop existing fragility curves, necessitating a reduction in the median collapse capacity and an increase in the uncertainty. We obtained the collapse fragility curve for Aizawl's Assam-type buildings by reviewing existing timber building fragility curves in a database created by the Global Earthquake Model¹ and creating a modified curve based on engineering judgment.

We created fragility curves for ductile and non-ductile semi-pucca buildings by assuming that semi-pucca buildings follow the same general fragility relations as reinforced concrete buildings. We assumed that lighter weight walls and floors offset the increased vulnerability due to smaller, weaker columns.

For reinforced concrete buildings stepping down the hill, Dr. Siamak Sattar of University of Colorado developed fragility curves using the FEMA P-695 methodology². FEMA P-695 prescribes a type of computational simulation called *incremental dynamic analysis* in which a computer model of a building (that is able to represent expected types of earthquake damage) is shaken by stronger and stronger ground motions until it collapses. Using a large set of ground motions (for example, this study used 44) generates the data needed to develop the statistical relationships for a fragility curve. Dr. Sattar analyzed the simplified archetype building in Figure 3, with member sizes and detailing based on structural drawings provided by Aizawl Municipal Council. He analyzed two cases: (a) the building has ductile reinforcement detailing and will experience ductile failure due to flexure; and (b) the building does not have ductile detailing and will experience brittle failure due to shear failure of columns.

Table 2 shows the expected probability of collapse for the scenario peak ground acceleration (PGA) of 0.35 g, which we obtained from the collapse fragility curves we developed. In simple terms, if a building type has a 25% probability of collapse at 0.35g, then we expect 25 out of 100 buildings of that type to collapse during ground shaking of 0.35g. These values represent the median probability of collapse for the expected level of shaking; as with any probabilistic assessment of this type, significant uncertainties exist and the actual number of collapses

¹ Data obtained from draft versions of *Existing Empirical Fragility and Vulnerability Relationships: Compendium and Guide for Selection* and *Existing Analytical Fragility and Vulnerability Relationships: Compendium and Guide for Selection*, provided by the Global Earthquake Model Foundation.

² US Federal Emergency Management Agency (2009). *Quantification of building seismic performance factors, FEMA P-695*, available online at www.fema.gov.

during a real earthquake producing the same level of shaking could be substantially higher or lower.

Table 2. Percentage of buildings of each type expected to collapse under 0.35 g shaking

Building Type	Probability of collapse at 0.35g
Older Assam type	25%
Newer Assam type	19%
Non-ductile semi-pucca	25%
Ductile semi-pucca	5%
Flat non-ductile reinforced concrete	12%
Flat ductile reinforced concrete	1%
Stepped non-ductile reinforced concrete	25%
Stepped ductile reinforced concrete	5%

We expect approximately 19-25% of Assam-type buildings to collapse during the scenario event. For semi-pucca and reinforced concrete buildings, the collapse rate depends on the foundation type and presence of ductile detailing. Approximately 25% of the most vulnerable sub-type would collapse, compared to only 1% of buildings constructed to code on flat bases.

In especially dense neighborhoods with steep slopes, it is possible that collapsing buildings at the top of the slope could slide down into the buildings down slope, creating multi-building cascading collapses. Fragility relations do not exist for these types of multi-building collapses, but a very rough estimate can be made using engineering judgment. We can assume that on average, one third of concrete or semi-pucca building collapses result in collapse of a building down the slope, so we have increased the total number of reinforced concrete and semi-pucca building collapses caused by shaking by one-third to account for these multi-building collapses. Assam-type buildings are very light and are unlikely to cause other buildings below to collapse, so we have not increased the number of Assam-type collapses. Applying this one-third increase to the percentages in Table 2 provides adjusted percentages we then apply to the total numbers of units of each type from Table 1, after removing collapses due to landslides, to obtain the total number of collapsed units due to shaking. Finally, we converted the number of collapsed units to collapsed buildings using the ratio of buildings to units (0.65) from the 2009 AMC houselist survey.

A detailed building inventory, which is not available for Aizawl, would be required to provide a detailed distribution of collapsed buildings throughout the city. Rather, we used the case study neighborhoods to examine what may happen in the city. The number of collapses in a particular neighborhood naturally depends on the type and age of buildings, as well as the steepness of the slope. Neighborhoods with steeper slopes tend to have a greater number of vulnerable buildings that step down the hill.

Estimating Building Collapses Caused by Landslides

We assumed that all buildings within the area of landsliding estimated in [Appendix B: Landslides](#) will collapse. The area of landsliding includes only the source zones of the landslides, rather than the runout zones. To account for the landslide debris traveling further down slope

and collapsing buildings (as happened in the May 2013 Laipuitlang landslide and in many others around the world), we have increased the estimated area of landsliding in the high hazard zone by 50%. No multipliers are used for the other landslide hazard zones because development can be sparse there. We assumed that estimated areas of landsliding affected all building types equally. Applying these estimated areas of landsliding to the building stock produces 2.5% collapses due to landslides during the dry season and 13.2% collapses during the monsoon.

Buildings in areas that do not slide are exposed to the collapse fragilities for shaking only. Because the area of landsliding is larger during the monsoon season, more buildings collapse due to landslides, leaving fewer buildings exposed to the collapse fragilities for shaking. This means fewer buildings will collapse due to shaking only during the monsoon season, though the total number of collapses increases.

Exposure

The number of people present in buildings at the time of the earthquake determines how many people are exposed to the risk of collapse. For example, nearly the entire population in a city like Aizawl will be indoors at home late at night or very early in the morning. During the day, people will be outdoors and in shops, offices and schools, in addition to homes. The 2011 Census of India provides population data for Aizawl. Taking the urban portion of Tlangnuam sub-district of Aizawl district as equivalent to Aizawl Urban Area, the total 2011 population is 299,366.

For a daytime event, we assume that 20% of the population is outside buildings, 20% is inside residential buildings, and the remaining 60% is inside non-residential buildings. We assumed that in a daytime event a larger proportion of the population would be inside concrete buildings, due to the number of people working in offices or visiting shops. Of those in non-residential buildings during the daytime scenario event, we assumed 84% would be in reinforced concrete buildings, 8% in semi-pucca buildings and 8% in Assam-type buildings. For a night-time event, the entire population would be proportionally distributed to the different types of residential units (i.e., if 47% of residential units are Assam-type, 47% of the population would be in Assam-type buildings). Combining these assumptions with population data gives the assumed location of Aizawl's population at the time of the scenario earthquake, shown in Figure 4. For the scenario, slightly more than half of Aizawl's people are assumed to be in the most prevalent and most lethal building type, older reinforced concrete buildings with stepped bases.

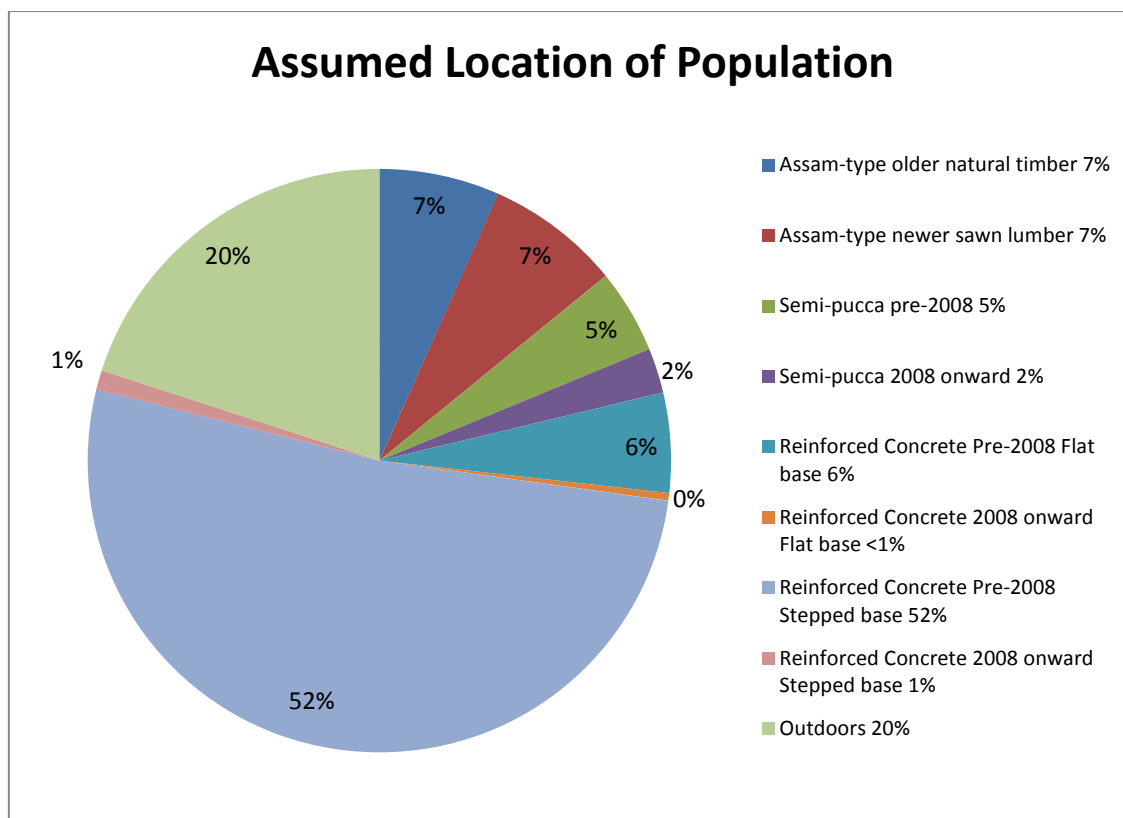


Figure 4. Assumed location of population for the scenario event, assuming a daytime earthquake

Population data are not available at the locality level, so the population in the case study locality was estimated by assuming a median household size of five persons (based on AMC guidance and Census of India data). The AMC household 2009 survey data provided the number of households per locality.

Estimating Casualties

Lethality rates estimate the percentage of occupants in buildings of a particular type who are likely to be killed if the building collapses while they are inside. Data on deaths from past earthquakes, along with professional judgment, are used to create lethality rates. We used published lethality rates, with judgment-based modifications for Aizawl's hillside conditions, to determine the likely number of deaths caused by building collapses due to the scenario event.

For Assam-type buildings, we increased the lethality rate of 5% for wood buildings in HAZUS (loss estimation software for the United States, which also has a large population living in wood buildings) to 10% to account for hillside conditions. Aizawl's steep terrain means both that the building will fall farther initially and that the debris from a building collapse is more likely to slide downslope, increasing the chances that people inside will be killed. We estimate that a lack of medical care for major injuries due to hospital damage and blocked roads will cause an additional 4% of the occupants of collapsed Assam-type buildings to die.

For reinforced concrete buildings, published fatality rates³ range between 10% and 20% of occupants killed directly by a collapse, though researchers note⁴ that recent earthquake data indicate that fatality rates can be significantly higher for particularly lethal types of collapse. We assumed a higher reinforced concrete building lethality rate of 25% in Aizawl, due to hillside conditions. An additional 10% of the occupants in collapsed reinforced concrete buildings would die due to lack of medical care or because they were not rescued due to a lack of heavy search and rescue equipment needed to free trapped survivors in heavy concrete buildings.

We assumed semi-pucca buildings have a lower lethality rate of 17% because they do not have concrete floor slabs. We assumed that an additional 5% of the occupants of collapsed semi-pucca buildings would die of their injuries. Building subtypes are assumed to have the same fatality rate as the main building type. We assumed the same lethality rate for collapses caused by earthquake shaking and for collapses caused by landslides, because lethality rates for landslide-induced building collapse were not available.

Table 3 shows estimated fatalities for the scenario earthquake under dry and monsoon conditions.

Table 3. Estimated fatalities caused by the scenario event

Cause of Death	Lethality Rate	Total Fatalities, Dry Conditions	Total Fatalities, Monsoon Conditions
Building collapse due to shaking, immediate			
Assam-type	10%	900	800
Semi-pucca	17%	900	800
Reinforced Concrete	25%	13,200	11,800
Building collapse due to shaking, lack of medical care			
Assam-type	4%	400	300
Semi-pucca	5%	200	200
Reinforced Concrete	10%	5300	4700
Building collapse due to landslide, immediate	Same as for shaking collapse	1300	6800
Building collapse due to landslide, lack of medical care	Same as for shaking collapse	500	2700
Falling brick from infill walls	5%	3000	2800
Buried by landslide	50% in areas that slide only	100	400
Total		25,800	31,300

This number of collapses results in an 8.6% overall lethality rate for the population for dry conditions, and a 10.5% lethality rate for monsoon conditions.

³ Spence, R. and So, E. (2009). Estimating shaking-induced casualties and building damage for global earthquake events, *Final Technical Report*, NEHRP Grant number 08HQGR0102, Cambridge Architectural Research Ltd.

⁴ Liel, A.B. and Deierlein, G.G. (2012). Using collapse risk assessments to inform seismic safety policy for older concrete buildings, *Earthquake Spectra*, Volume 28, No. 4, p. 1495–1521.



Appendix D

Infrastructure

Infrastructure provides Aizawl with life-sustaining services. The purpose of this appendix is to provide interested readers with descriptions of the major infrastructure systems and with information on how we obtained estimates of damage to the water supply and electrical power systems.

Water System

System Description

Aizawl's potable water comes from diverse sources. About 15 percent of the water, serving about 15 to 20 percent of residents, comes from springs, wells and harvested rainwater. The municipal water system supplies the remaining 85 percent. The municipal system consists of two raw water intakes and treatment plants at Reiek Kai on the Tlawng River, where the raw water is aerated, clarified, filtered and disinfected. Treated water is pumped 8 kilometers to the main reservoir at Tuikhuahtlang, about 1,116 meters above the treatment plant. Water is then distributed to 29 zonal tanks at 22 locations within the community. Booster pumps feed another large reservoir at Laipuitlang. Due to a supply shortage, municipal water is typically distributed on a rotating basis once a week to neighborhood distribution points and to homes and businesses. In addition, private lorry tankers sell water purchased from private suppliers to the community. Homes and businesses maintain on-site storage tanks. These tanks are supplied by periodic municipal deliveries, collected rainwater and private lorry tanker deliveries. Typically, a home has one or more tanks with a total storage capacity ranging from 1,000 to 3,000 liters.

There are two municipal water supply systems, Greater Aizawl Water Supply Scheme (GAWSS) Phase I and Phase II, which transport water through separate pipelines. Phase I was completed in 1988 and has capacity of 10.8 million liters per day (MLD). Phase II was added in 2007 and provides 24 MLD in additional capacity. Concrete weirs at Reiek Kai raise the river level to feed jackwells, from which electric intake pumps draw raw water to the treatment facilities. The raw water pumping system does not have backup power. Phase I has one set of four pumps at the treatment plant (two electric pumps and two diesel backup pumps), and an identical set of four pumps at the second stage pumping station along the pipeline, to move treated water to the reservoir at Tuikhuahtlang. Only the second set of Phase I pumps has emergency backup, using pumps with diesel motors. Phase II has four primary pumps (two electric and two diesel) but no booster pumps. The Phase II diesel pumps can supply only 5 MLD, a little more than one quarter of the total Phase II pumping capacity.

Water Supply and Distribution Damage Repair Estimates

Earthquake shaking can sever water lines because it causes the ground surface to move as seismic waves pass through, or it causes failure due to landslides and other processes. Movement of the ground due to shaking is called *ground deformation*, which can be either transient or permanent. Transient deformations occur when soil compresses and expands as waves transmit shaking energy. Permanent deformation is what remains after soil recovers from wave-associated movements. Pipeline vulnerability depends primarily on the strength of shaking, pipeline material, length of pipeline exposed to various shaking intensities, and the frequency of ground failures including the number of landslides. The repair rate, the number of repairs required per kilometer, is most closely correlated with the peak ground velocity (PGV) and pipeline material, rather than with the peak ground acceleration (PGA). For this scenario, ground shaking intensity is described by a peak ground velocity (PGV) of 40 cm/sec for all of

Aizawl, estimated by the US Geological Survey using its ShakeMap software in a similar manner to the peak ground acceleration discussed in the main scenario document.

Pipeline materials comprising main elements of the Aizawl water treatment and distribution system are spiral welded steel, ductile iron and galvanized steel. For this scenario the repair rate relationship from Jeon and O'Rourke¹ for welded steel joint pipelines is used. Repair rates for welded steel joint pipelines following the Northridge Earthquake were higher than other material, probably because this material is used in steep areas with a high potential for landslides.

Figure 9 of Jeon and O'Rourke gives the best-fit equation for welded steel joint distribution pipelines as $\log(Y) = 0.75 \cdot \log(X) - 4.80$ where Y is Repair Rate (RR) or the Number of Repairs/km, and X is the Peak Ground Velocity (PGV). Repair rate is used to estimate the number of line breaks in the following table.

Table 1. Estimated number of line breaks in water system

Pipeline	Diameter (mm)	Length (meters)	Material	Repair Rate (RR)	Estimated Number of Breaks	
GAWSS Phase I	350	7,200	Spiral welded steel	0.13	.94	1
GAWSS Phase II stage I raw water	711	unknown	Spiral welded steel			
GAWSS Phase II, Stage II treated water	457	8,000 (two parallel, 4,000m pipelines)	Spiral welded steel	0.13	1.04	1
GAWSS Phase II, Stage II treated water	711	3,000	Spiral welded steel	0.13	.39	0
Feeding Mains	65 to 150	64,000	Ductile Iron	0.13	8.32	8
		95,000	Galvanized Iron	0.13	12.35	12
Distribution Lines	40 to 150	182,000	Galvanized Iron	0.13	23.66	24
Total						46

An estimate of the number of pipeline breaks due to landslides and permanent land movements can be made by projecting the landslide density obtained for the landslide study area described in [Appendix B: Landslides](#). The number of slides in Aizawl triggered by the scenario shaking was estimated using empirical relationships for the density of earthquake triggered landslides per kilometer in each hazard zone. Using this estimation method, there will be approximately 1,100 slides throughout Aizawl for the scenario shaking. Only a portion of these slides will affect water mains and distribution lines. We assume about 10 percent will affect streets, and only half of those slides would sever pipelines. By this reasoning, waterlines would be severed by landslides at 50 locations.

Estimates of needed repairs due to transient and permanent movements have a great degree of uncertainty, but indicate that there will be multiple breaks requiring access for repairs. Making these repairs requires access over congested roads to leak locations, delivery of excavation equipment, replacement pipeline materials, and welding supplies. Water pipeline repairs will

¹ Jeon, S.-S., O'Rourke, T.D. (2005). Northridge Earthquake Effects on Pipelines and Residential Buildings, *Bulletin of the Seismological Society of America*, Vol. 95, No. 1, pp. 1-25.

compete for access and resources with repair activities for other infrastructure and emergency response activities. For this scenario we assume repairs will be needed at 50 locations due to transient movements, plus 50 locations due to landslides. The majority of repairs will be on the feeding mains and distribution lines. However, repairs could also be required in the pipelines that link the treatment plants to the reservoirs at Tuikhuahtlang. We assume a landslide will sever one of these pipelines.

Wastewater Systems

Most homes rely on toilet soak pits or septic systems for disposing human waste. Sullage (grey water) from washing collects in drains and pipelines and flows by gravity downhill into the rivers. Human waste and sullage mix in some locations. Street drains, swales, and channels collect runoff from rain and direct the flow to the natural drainage system. The *Master Plan for Aizawl: Vision 2030*² states that 80 percent of the 160 liters per day per capita—about 128 liters per person per day—becomes wastewater. Because much of this water flows over open slopes or is disposed through pits and septic tanks, it seeps into underlying soils and rocks, contributing to the landslide hazard by increasing the weight of the mass, building pore pressure, and facilitating the chemical process that weakens rocks.

Electrical System

System Description

The electrical system is operated by the Mizoram State Power and Electricity Department. The headquarters office is in Electric Veng. Most of the power for Aizawl comes from the North East Grid by way of three 132 kV transmission lines operated by Power Grid Corporation India, Ltd. (PGCIL). One line comes from Jiribam, Manipur, one from Badarpur, Assam and the third from Kumarghat, Tripura. One line delivers power to the PGCIL 132 kV substation at Luangmual; another line delivers power to Zuangtui. About 30.5 MW is generated in Mizoram state from mini and small power plants, including a 1 MW hydroelectric plant at Serlui, 10 km from Aizawl, and a 22.9 MW standby heavy fuel oil generator at Bairabi.

The PGCIL Luangmual substation is where operators switch power to a substation at Zuangtui and to the nearby Department of Power and Electricity substation also at Luangmual. Transformers at Luangmual and Zuangtui reduce the voltage from 132 kV (high voltage) to 33 kV (lower voltage) for distribution to seven 33 kV substations, where the power is transformed to 11 kV distribution line voltage. Substation equipment consists of transformers, circuit breakers, and switches that allow the use of a variety of lines and control incoming and outgoing sources. Low tension, 440 V distribution lines are generally carried on poles throughout the community. Smaller transformers reduce voltage for homes and most businesses.

The electrical system in Aizawl consists of the following components:

- 755 km of 132 kV lines
- 7 132/33 stepdown substations with a transformation capacity of 128.1 kVA
- 828 km of 33 kV line with 39 substations
- 4,292 km of 11 kV line
- 2,252 km of low tension 440 V line

² Aizawl Development Authority (2013). *Master Plan for Aizawl: Vision 2030*.

- 70 power transformers
- 1,245 distribution transformers
- Headquarters located in Electric Veng
- The staff consists of
 - Superintending Engineer, Aizawl Power Circle
 - 3 Executive Field Engineers
 - 14 Sub Divisional Officers (located in various offices)
 - 300 technical workers of various categories

Loss Estimates

The methodology used to estimate damage to the electrical system in substations uses fragility curves published in the technical manual for loss estimation software HAZUS³.

Substations

Substations are classified as high voltage (350 kV and above), medium voltage (150 kV to 350 kV) and low voltage (34.5 kV to 150 kV). All are considered to be typical (unanchored) with standard components. The 132 kV Grid switching station, the two step-down stations, and the seven 33 kV substations are considered “low voltage.” The Table 2 indicates that for 0.35g Peak Ground Acceleration, damage would be “extensive.”

Table 2. Estimated Damage States for Substations with Unanchored / Standard Components, Table D-1 from HAZUS MH MR5 Technical Manual (FEMA).

		Peak Ground Acceleration	
Classification	Damage State	Median (g)	Std. Deviation
Low voltage (ESS2)	Slight/minor	0.13	0.65
	Moderate	0.26	0.50
	Extensive	0.34	0.40
	Complete	0.74	0.40

Extensive damage in substations is defined as the failure of 70 percent of disconnect switches (e.g., misalignment), 70 percent of circuit breakers, 70 percent of current transformers (e.g., oil leaking from transformers, porcelain cracked), or by failure of 70 percent of transformers (e.g., leakage of transformer radiators), or the building being in extensive damage state.

Distribution Circuits

The distribution system is divided into a number of circuits. A distribution circuit includes poles, wires, in-line equipment and utility-owned equipment at customer sites. A distribution circuit also includes above ground and underground conductors. Distribution circuits either consist of anchored or unanchored components. Circuits in Aizawl are considered standard or unanchored components (p. 8-66 of HAZUS MH MR5 Technical Manual).

³ FEMA. *HAZUS MH MR5 Technical Manual*, Department of Homeland Security, Federal Emergency Management Agency, Washington, D.C. p.8-64 to 8-75. Available at www.fema.gov/plan/prevent/hazus.

Table 3. Estimated Damage States for Distribution Circuits Table D-2 from HAZUS MH MR5 Technical Manual (FEMA).

		Peak Ground Acceleration	
Classification	Damage State	Median (g)	Std. Deviation
Standard Components	Slight/minor	0.24	0.25
	Moderate	0.33	0.20
	Extensive	0.58	0.15
	Complete	0.89	0.15

This table indicates that the damage to distribution circuits would be “moderate” to “extensive” and that as a result 12 to 50 percent of the circuits would fail. Because distribution circuits in Aizawl would be damaged extensively by building damage and landslides, we assume that 50 percent of the circuits would be damaged.

Communications Systems

This section provides more detailed descriptions of Aizawl’s major communications systems.

Landline Telephone Systems

Bharat Sanchar Nigam Limited (BSNL) operates the landline telephone system in Aizawl. The system consists of feeder lines and wires strung between buildings and poles, and switching equipment and electricity that are provided in a mid-1990s reinforced concrete four-story control building at the foot of Tuikhuahtlang. Two transformers receive electrical power to operate the telephone system. Backup batteries and two diesel generators are located on the bottom floor of the control building. The batteries could provide up to two hours of service and the generators have about five hours of fuel. The system is equipped with switches that can give priority to emergency lines.

Cellular Telephone Systems

Airtel, Vodafone, Aircel, Reliance, Idea and BSNL operate cellular telephone systems in Aizawl. Cellular systems rely on transmitters and receivers to communicate signals between phones. Only BSNL and Airtel have a main switching center in Aizawl. Airtel’s switching center is in a seven-story reinforced concrete building. Airtel has a dedicated transformer and backup uninterruptable power supply (UPS) batteries that provide six hours of power. There is a backup generator, but reserve fuel is not stored on site. All battery racks are anchored to the floor, and the switches are all anchored. A cooling system cools switches in an air-conditioned room. Transmitters generally are located on towers and tall buildings, and they require electricity to function. Backup batteries at these sites have limited life, so mobile emergency generators are used when the length of power loss exceeds battery life. Because cellular systems are built to handle only a small fraction of their customers concurrently, they quickly become overloaded following earthquakes, when many customers try to contact friends and family simultaneously. Individual phones depend on batteries that are charged from the electrical system, or in some instances from solar chargers.

Police and Military Satellite Communications Systems

The Directorate of Coordination Police Wireless (DCPW) in the Ministry of Home Affairs (MHA) operates a satellite-based national police telecommunication system called POLNET. In Aizawl, the Assam Rifles are connected to POLNET. The Mizoram Police Department has access to the

system but typically do not have the budget to maintain connectivity. POLNET depends on computers and electricity, and has an uninterruptible power supply (UPS) for backup. UPS systems have limited backup capabilities. The Assam Rifles have a separate military communications system, both in Aizawl and at their several other outposts in other locations in Mizoram. In Aizawl, the Assam Rifles' system has several layers of backup, including generators and enough stored fuel to last several weeks. Outposts also have stored fuel and generators.

Broadcast Radio and Television

Aizawl has one radio station, All India Radio Aizawl, and one television station that broadcast signals to the community from antennas placed on towers. Aizawl has two cable television stations, ZONET and Laldailova Pachuau & Sons (LPS). A small number of people have TATA Sky, a satellite television service. About 90 percent of families have television sets, and almost all have radios. Backup batteries and emergency generators are available at broadcast facilities when power is lost. A number of residents rely on satellite dishes to receive television signals. Most residents have backup power inverters for televisions, but these provide limited power and for a limited time.

The radio station, All India Radio Aizawl, broadcasts an FM signal from a free standing steel tower and has backup generators. Residents' radios may have batteries with relatively long life and operate for days. Some mobile phones can receive broadcast radio signals.

Newspapers

Aizawl has eight daily newspapers, two published in English and six in Mizo. The local government printing office has presses as well. Printed materials such as newspaper are excellent tools for providing detailed information and instructions, if presses remain functional. Print media consists of a system of writing, layout and printing. The system relies on computers for many of these functions. Electricity powers these systems, and local area networks provide connections within buildings. Some newspapers have emergency generators.

Internet

Aizawl has internet connections that allow users to seek and transmit information and data. Connectivity depends on the continued functioning of the internet service providers' servers and equipment, as well as the connection links to India's internet infrastructure. BSNL provides internet by fiber optic cable. Airtel, Reliance, Vodafone and Aircel also provide internet by using BSNL's lease line and through wireless service from towers. Local connections rely on telephone lines or cables to connect internet service providers with users. Electricity is needed.

The state government uses the Statewide Area Network (SWAN), which provides an internet connection using BSNL's lease line and fiber optic cables linking district headquarters. The internet connection is provided by National Informatics Centre (NIC) from Delhi, then Delhi to Noida to West Bengal via satellite, West Bengal to Guwahati via fiber optic cable, and Guwahati to Silchar to Aizawl via BSNL's lease line. In Aizawl, the connection to the internet is set up in the District Commissioner's office, which is connected to the other district headquarters. The main center for SWAN operations in Aizawl is in the Secretariat Building Annex 2.

Transportation Systems

Aizawl city is directly served only by road and by helicopter. The airport serving Aizawl is located at Lengpui, 32 km from Aizawl. The nearest railhead is at Bairabi, 120 km north.

Road Systems

All food, fuel and supplies arrive on lorries navigating roads that link Aizawl with the other main cities in the northeast. The most important roads are national highways NH44A from Agartala, State of Tripura and the airport at Lengpui to the west; NH154 from Shillong, State of Meghalaya from the north; NH54 from Silchar, State of Assam on the north; and NH150 from Imphal, State of Manipur on the northeast. The national highways linking Aizawl to other cities traverse steep slopes. Landslides frequently occur, blocking the way. These roads have several major bridges.

The system of urban streets within the built up areas of Aizawl are critical to circulation and delivery of needed supplies and for pedestrian movement. The main spine road follows the ridge from Bawngkawn to Kulikawn. There are few east-west arterials and few parallel roads providing alternatives for north-south travel. The system of urban streets has narrow carriage ways that accommodate automobiles, motor bikes, pedestrians, surface drainage channels and parking. The urban streets are congested during weekdays. Connecting streets frequently join the spine road at an acute angle. Roadways are often steep. Highly congested intersections that connect roads at steeply sloping acute angles are the choke points in the roadway network. Pedestrian walkways and stairs connect the roads and lead to homes and businesses between the roads.

Both the regional roads and city streets are subject to multiple slides and rockfalls that undermine the road or block passage. There are active slides along the highway to Lengpui airport and within the urban area. These conditions exist under normal circumstances and are exacerbated during the monsoon season. Following earthquakes, the number of slides and rockfalls and the amount of movement would increase in these areas. The number of active slides already existing in the area indicates the potential for landslides to sever access roads at multiple locations. Earthquakes reactivate dormant slides and trigger additional sliding in already-susceptible areas. The damage potential depends on the strength and duration of ground shaking, and the amount of water in the slide mass, among other factors. More slides would occur during monsoon season when the ground is saturated. Bridges are vulnerable to landslides that undermine abutments, and to deck failures when supporting beams slide off of abutments or piers. Bridge approaches can settle, making it impossible to reach otherwise functional bridges until ramps are built.

Airports

Aizawl is served by Lengpui Airport. The airport consists of a 2,500-meter runway, terminal building, fuel supplies and communications equipment. It has an instrument landing system to aid landing during poor weather conditions. The airport serves as a key transportation link. It is about 32 km from Aizawl. The reinforced concrete terminal building at Lengpui airport, constructed during the mid-1990s, has long spans and open areas and may suffer structural damage during shaking.

Other airports are located at Silchar, 180 km from Aizawl; Imphal, 240 km from Aizawl; and Agartala, 550 km from Aizawl. The Tuirial Airfield located 22 km east of Aizawl is no longer used as an airport. However, the runway is still in place. Small planes could land and take off under emergency conditions. Aizawl also has a helipad at Thuampui, from which helicopters can take off and land.

