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MINISTRY OF WORKS AND HUMAN SETTLEMENT

"Construction Industry: Solutions through innovation and improved technology"

GEOTECHNICAL STUDY FOR ZHEMGANG EXISTING TOWN AND TINGTIBI

FINAL REPORT

PROJECT CLIENT: DEPARTMENT OF HUMAN SETTLEMENT (DHS), MINISTRY OF WORKS AND HUMAN SETTLEMENT (MOWHS)

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EXECUTIVE SUMMARY

Alpha Geotech and Company (AGC) is pleased to present this Geotechnical Investigation Report for Zhemgang Town and Tingtibi. The geotechnical consulting services were performed under contract between Department of Human Settlement (DHS), MoWHS and Alpha Geotech and Company (AGC) from 21st June 2019 to 4th October 2019.

Before any attempt can be made to design construction with, on, or in the ground, certain geologic/geotechnical information about the subsurface must be gathered, analyzed, and reported in such a fashion that it can be used to adequately design the project. Once data is gathered and analyzed, a geotechnical report is prepared, where all observations, data, test results, and analyses are presented along with recommendations and discussion of potential hazards/difficulties or problems. The main purposes of conducting a geotechnical investigation are (1) to evaluate the suitability of the site for the proposed project; (2) to obtain physical and mechanical properties of the subsurface materials (i.e. soils and rocks), in order to determine their suitability as they may affect the construction and performance of the project; (3) to enable safe and economical design of the project components; and (4) to identify any potential problems or difficulties with the ground conditions that may affect construction or performance of the proposed project.

The geotechnical investigation started with subsurface investigation by trial pits throughout the project site from where soil profiles were studied and sampled to compile their geotechnical properties. The Dynamic Cone Penetration Tests (DCPT) were conducted to compute bearing capacity of the ground at various locations throughout the study area. Soil samples were tested for their geotechnical properties. Next, the various maps such as geologic, engineering geologic, geomorphologic, slope and finally hazard maps were prepared.

At the existing Zhemgang Town about 53% (147 acres) of the mapped area falls in the low hazard zone. Infrastructure development work may be carried out in low hazard areas with some geotechnical measures and normal engineering practice. About 37% (103 acres) of the mapped area falls in the medium hazard zone. Construction for the development of infrastructure can be allowed in this medium hazard zones after

carrying out the proper remedial measures proposed in this report. Engineering practices suitable to hillside construction and floodplain development as recommended in this report are necessary. Only 10% (26 acres) of the mapped area in Zhemgang Town falls in the high hazard zone. Construction or the development of infrastructure should be controlled in the high hazard zone. High hazard zones are recommended to be developed as a green belt. For any construction in "high hazard zones" i.e. red zones, it is recommended that a separate "Site Specific Geotechnical Report" and "Geotechnical Letter of Assurance" be prepared by a competent Geotechnical Engineer. The construction in "High Hazard Zone" may be allowed only upon the approval of such a report by the competent authority, which may be DHS or another agency designated by MoWHS. Similarly for Tingtibi, the low, medium and high hazard areas are 31% (42 acres), 22% (29 acres) and 47% (63 acres), respectively.

The Geotechnical Report was written to give the urban planners and structural engineers the required information to effectively design structures. However, it must be remembered that geotechnical work is still as much art as it is a science. Therefore, well-qualified and experienced geotechnical professionals are needed to interpret this report and to avoid costly mistakes later on. In preparation of this report, we relied on a mixture of skills: 1) observation and measurement, 2) experienced judgment and 3) engineering analysis. If a reliable assessment was to be achieved, each of these three components must be included. Results of all three should be continually cross-checked. The information presented in this report was based on our understanding of the proposed development plan that was made known to us and on the data obtained from our field and laboratory studies. Since this assignment is general geotechnical study carried out as part of feasibility for preparing development plan, our recommendations are based on limited selected field and laboratory sampling and testing. Unexpected subsurface conditions encountered during construction may alter our recommendations. We can be contacted during construction to observe the exposed subsurface soil conditions to provide comments and further verification of our recommendations, albeit at additional cost.

1. PROJECT BACKGROUND

1.1 Introduction

Zhemgang Dzongkhag is situated in the south central region of the country and shares boundaries with Bumthang to the north, Trongsa to the northwest, Sarpang to the southwest, Mongar to the northeast and east, Pemagatshel to the southeast and the Indian State of Assam in the South. Zhemgang is considered as one of the most inaccessible Dzongkhags in the country. It has a population of about 17,763 (Male: 9,195 Female: 8,568) with a total household of 3,803.

The people cultivate mainly maize followed by rice, buckwheat, millet, barley, wheat, foxtail millet, potato, etc. Oranges are the main source of cash income for the southern and central Gewogs. The northern Gewogs depend mainly on livestock products for source of income.

The Dzongkhag is administratively supported by a Dungkhag in Panbang, and eight Gewogs namely- Bjoka, Bardo, Goshing, Nangkor, Nangla, Phangkhar, Shingkhar and Trong. Trong Gewog occupies the northwest corner of the Dzongkhag and falls in the middle Kheng of the agro-ecological zones. The Dzongkhag administration (District Head Office) is located in the northeast corner of this Gewog, close to the boundary with Trongsa Dzongkhag. The study area for geotechnical investigation is shown in **Figure 1.**

Zhemgang Existing Town

The Zhemgang Town is located approximately 22 km from the Trongsa Dzongkhag border in the far northeast of Trong Gewog on a high ridge overlooking the Mangde Chhu valley, predominantly orientated in southwest direction. Dense temperate forest and numerous streams and springs surround Zhemgang Town. The entire Zhemgang Town falls within the Mangde Chhu catchment area. The Town falls in the middle Kheng of the three agro-ecological zones of the Dzongkhag. Trong village is situated in the heart of the town, approximately 230 m up the ridgeline from the Dzong. As the key population group of permanent residents in the Town, the villagers of Trong still play an important and influential role in the development of the municipality. The villagers own most of the land on the slopes below the town area and in Zhemgang Pam below the Dzong on the southeastern side of the study area.

The town is located at about 27°12'52.11"N Latitude and 90°39'24.66"E Longitude. The elevation ranges from 1,754 m to 2,117 m above the sea level. The average temperature is about 3-4°C in winter to 27°C in summer. The monsoon starts from May and lasts till September. The annual precipitation of the town is about 1500mm. The general soil type of the town is Sandy Loam, and geology type consisting of mainly dark grey phyllites.

Tingtibi

Tingtibi is situated 35 km southeast of Zhemgang town on the old highway to Gelephu. This town is located on a raised plateau on the right bank of Mangde Chhu. It is at considerably lower altitude than Zhemgang and as a consequence has a more sub-tropical climate and agriculture. It is located in a basin and surrounded by ridges where several villages are situated. These villages include Bertey, Goling, Zurphey, Tama and Tshanglajung, which form an agricultural hinterland around Tingtibi.

Tingtibi is well situated as a focal point for the important access route connecting lower Kheng Gewogs to eastern regions via Gomphu-Panbang highway. In terms of health and education the township is well provided for by the Regional Referral Hospital at Yebilaptsa, the Tingtibi Lower Secondary School and the Yebilaptsa Middle Secondary School. The township area is located at about 27°8'40.75"N Latitude and 90°41'23.00"E Longitude.

The elevation ranges from 520 meters to 697 meters above the sea level. The average temperature in the lower elevation ranges from 17-32°C. Since it has sub-tropical micro-climate, the annual precipitation of the area ranges from 2000-4000mm. The topography is characterized by river plateau basin surrounded by ridges.

Geotechnical Study

The Zhemgang Dzongkhag Thromde was approved in the 5th session of the second parliament on 10th June 2015. The Dzongkhag Thromde includes existing Zhemgang town and Tingtibi. The Department of Human Settlement (DHS) has a proposal to review and prepare proper development plan for the existing Zhemgang town including Tingtibi in the forthcoming fiscal year. For this purpose, the topographical survey was carried out in the financial year 2017-2018. Now, before the review of development plan is carried out, DHS intends to conduct geotechnical investigations as part of feasibility study to assess the risks of geological hazards in the proposed study area. This is essential for identifying suitable area for development, and proposing alternative countermeasures or engineering solutions to minimize the risks in the unsafe areas. Therefore, geotechnical study is proposed for the following areas:

- Existing Zhemgang Town: Area ≈ 276.30 acres (1.12 sq.km)
- Tingtibi: Area ≈ 134.00 acres (0.54 sq.km)
- Total Area ≈ 410.30 acres (1.66 sq.km)

This Geotechnical Investigation is intended to provide critical information for the client, architects, urban planners, structural engineers, and the contractors. The client wants to know first and foremost if the project site is suitable for the proposed development. The architect or planner may be forced to accommodate different soil/rock conditions in his plan and design. The structural engineer is responsible for the design of economical but strong building foundations. The construction contractor wants to bid a competitive but realistic price for excavation and embankment/retaining wall works. For these reasons, all the players have a stake in the Geotechnical Report. **All these players must be able to understand the implications of the geotechnical study**. The approach and methodology for the proposed project was prepared keeping these myriad requirements in mind.

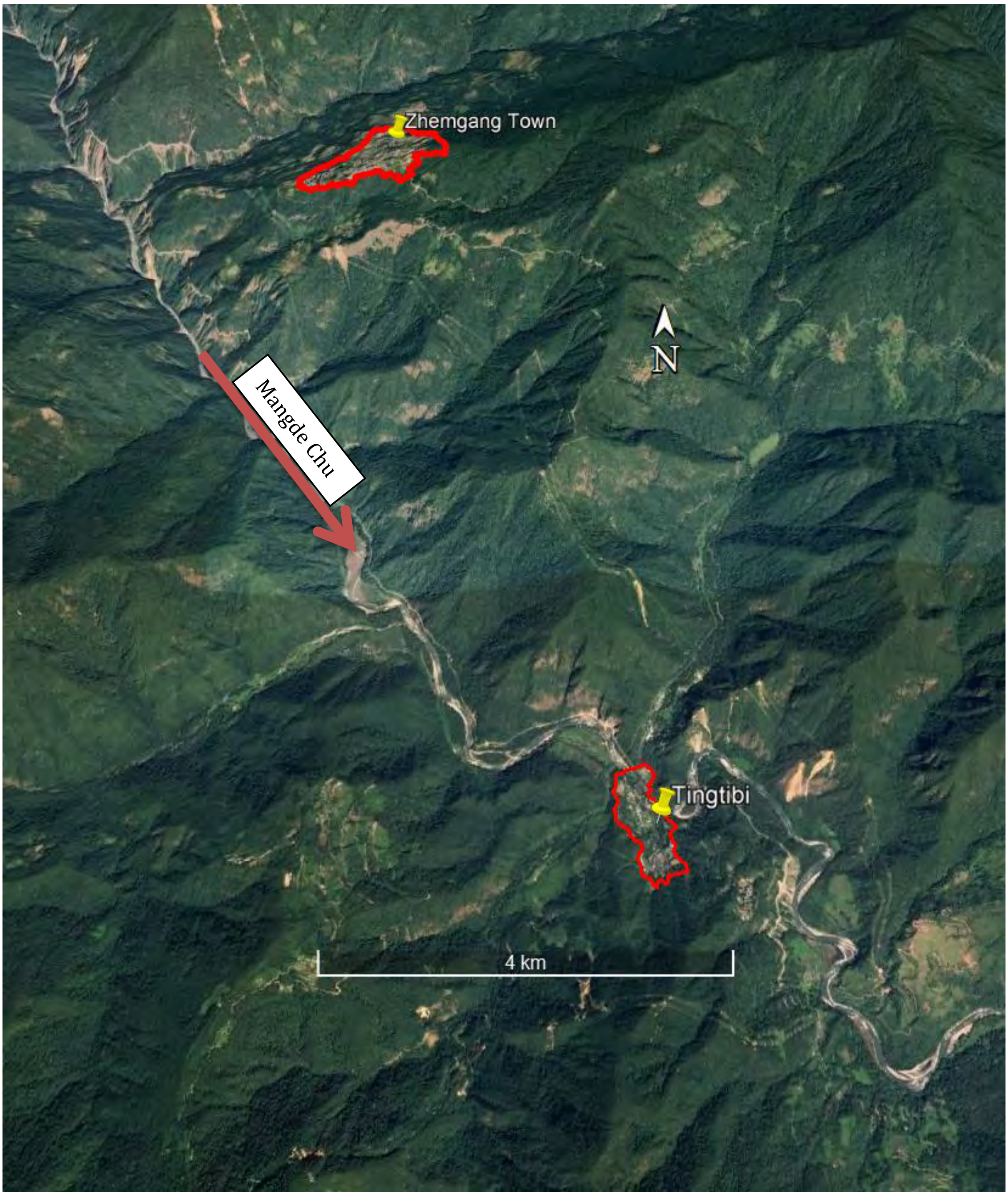

Figure 1: Study area for Geotechnical Investigation (Zhemgang Town and Tingtibi)

1.2 Objectives of the Study

The Geotechnical Investigation for the proposed development plan has the following objectives:

1. Assess the geological stability and geotechnical feasibility of the area identified for the proposed development plan and map different levels of hazards;
2. Evaluate the potential adverse impacts of the development project on the geological stability/geotechnical conditions and
3. Provide appropriate recommendations and mitigation measures to be adopted.

In order to achievement the above objectives, the work involved thorough data collection and field investigation encompassing geology, geomorphology, topography, hydrology, flood, and other geotechnical aspects that impose risk to development activity and environment. Based on the data collected and site investigation, where risks are envisaged, mitigation measures were proposed. It was understood that the DHS plans to use recommendations from the geotechnical Investigation in the preparation of urban development plan. Therefore, the Geotechnical Investigation (GI) report was prepared keeping these objectives in view.

1.3 Scope of Work

The scope of work for the entire study area to be investigated included, but not limited to the following:

a) Undertake field trips to the project area and carry out detailed fieldwork to confirm desktop study interpretation and gather supplementary data.
b) Detect, assess and prepare instability inventory maps (landslides, erosion, debris flow, wedge failure, toppling, etc.) within the study area and indicate the level of hazard posed by the instabilities.
c) Identify and assess slope of the study area indicating the slope classification and levels of hazards posed by the topography.
d) Study and analyze the different types of hazards from different sources.
e) Identify and assess geomorphology of the study area and map instabilities.
f) Recognize, assess, and mark on map all water bodies (springs, creek, streams, both seasonal and perennial, seepages, rivers, etc.) that have impacts on the study area.

g) Assess the strength of geological materials by conducting necessary field and lab tests and analysis. All the required lab tests shall be conducted as per IS codes for the samples collected to determine geotechnical properties.
h) Perform slope stability analysis (both soil and rock slopes) and correlate the instability with geology (rock type, soil and deposits), topography (slopes), landuse, flood, hydrology (rainfall, seepages, and groundwater) and determine the most significant factors that are responsible for causing the instabilities.
i) Inspect high-risk locations to define potential engineering solutions.
j) Determine requirements for engineering structures such as retaining walls, landscaping and complementary bioengineering applications.
k) Prepare hazard map for the project area.

2. BASELINE INFORMATION

2.1 Introduction

First and foremost, the general geologic setting of the area and geologic conditions at and near the project were understood. Then, the characteristics of the foundation soils and rocks and other geologic conditions that could influence design, construction, and long-term operation of the project were identified.

In terms of hazards, the study began with the assessment of slope stability, which included landslides, rockfall, ground subsidence and water-related instability of the hill-slopes for existing Zhemgang Town. For Tingtibi, in addition to the above hazard, the flood effects were studied as the town is located close to Mangde Chhu and other small streams. Based on the location of Zhemgang Town and Tingtibi near the Main Central Thrust (MCT), earthquakes and related hazards were also studied in the current Geotechnical Investigation. In the general the methods of geological and geotechnical investigations are as given below:

- Desktop Study
- Field Investigation
    - Field Reconnaissance and Surface Mapping
    - Soil Penetration Tests (DCPT)
    - Trial Pits

- Geotechnical Lab tests and analysis
- Hazard Assessment
    - Surface exploration / Stability assessment (landslides and other instabilities)
    - Slope stability analysis
    - Flood study
    - Earthquake and related study
    - Hazard mapping and analysis
- Mitigation Measures
- Conclusion and Recommendations

2.2 Desktop Study

A search was made to gather as much data as possible before initiating any exploratory fieldwork. Desktop information was obtained on:

- Topography (Topographical map supplied by the Client)
- Geology (Surficial geology in terms of soil types on a regional and local basis and bedrock geology, including major structural features such as faults)
- Geomorphology
- Hydrology or climatic conditions
- Floods
- Regional seismicity and earthquake history

No data was found on geotechnical study of the current study area. However, the geological map of Bhutan from various sources was used to understand the general geology of the study areas. FEM (DES, MoWHS) had carried out flood study for Zhemgang Dzongkhag in 2019. The results of this study were also discussed in the subsequent chapters.

2.3 Field Reconnaissance and Surface Mapping

Site reconnaissance survey was done to supplement and check the accuracy of the information gathered from desk studies, and to complete the study of the proposed development. Geological mapping was done in traditional geological manner, using base topographic maps and plans. Observations such as spring/stream lines were not only important in delineating probable geological boundaries but also in their own right for hydrogeological modeling. Observation points were marked in the field using GPS. Soils and rock were examined, described and characterized in natural exposures (outcrops) and in trial pits and descriptions were provided. Samples were obtained from the trail pits for transfer to the laboratory, with relatively slight disturbance. The overall view of each of the project site is shown in **Figure 2** and **Figure 3**. Key features observed during field mapping are features of bedrock outcrops within the study area as well as in surrounding areas; for example, bedrock structures, lithology, unit thickness, or other geological data. The geologists could get a great deal of information from examining the landscape, mapping and interpolating information from exposures. This, together with desk study information, allowed preliminary ground models to be developed, which was then used to form the basis for planning ground investigation.

Figure 2: Overall view of existing Zhemgang Town

Figure 3: Overall view of Tingtibi

a. Geologic Map

Attempting to form a ground model of a site based solely on descriptions from limited numbers of trial pits and test results, without recourse to an informed geological interpretation of the data, would be like trying to put together a complex jigsaw without having the picture on the box cover. Geologists are trained to examine rocks and soils at scales of a hand specimen or a quarry and to draw conclusions on the likely origins and history of the sample or exposure. Then, by examining other samples and exposures in and around a site, a picture of how the various different components relate to one another could be developed. The conceptual model for the geology at a site could then be used to extrapolate and interpolate observations to make further predictions on the basis of geological knowledge. Ground investigation can then be designed and used to target remaining unknowns.

The earthquake faults near the project site are shown in **Figure 4.** The faults and contacts are shown as yellow lines. The geologic map of Bhutan is shown in **Figure 5. This map indicates that Zhemgang Town falls under Maneting Formation, which comprises of mainly biotite garnet phyllite interbedded with quartzite**. Maneting Formation is part of the Pele La Group in Bhutan. Globally, this formation is part of TSS (Tibetan Sedimentary Sequence), which has been deposited on the northern Indian passive continental margin and it registers the evolution of the Paleo-Tethys sea, from the pre-rift stage (Cambrian – Ordovician) to the final break-up of Gondwana in early Cretaceous and subsequent sedimentation till Eocene. **Phyllite in general is highly prone to landslides.**

Below Maneting Formation in the center of the Zhemgang klippe lies Chekha Formation. A klippe (German for cliff) is a geological feature of thrust fault terrains. **The contact between the Chekha and Maneting Formations is conformable.** Tingtibi falls under Chekha Formation, which comprises of mainly quartzite and biotite-muscovite garnet schist.

Zhemgang Town and Tingtibi lies about 25 km and 15 km, respectively from Main Central Thrust (MCT), which is one of the most prominent earthquake faults in the Himalayas. Besides, there are several regional faults both to the north and south of these two study sites. These faults generally run east to west and are capable of producing major earthquakes as evident from past earthquake history. An earthquake on any one of these faults could have major consequences for the study sites.

The geologic map of Zhemgang Town is attached at the end of this report. Since the project area was very small (276 acres), there was not much variety in the lithologic units within the study area. The entire 276 acres of study area was divided into two geologic units, namely, phyllites (rocks) and residual soils formed from weathering of the underlying rocks. The rock outcrops are sporadic and not at all extensive. The dark grey phyllites are found as thinly bedded (10 cm to 20 cm thick) to massive (more than 3 m thick layer). The Unconfined Compressive Strength (UCS) of the rocks ranged from 1 MPa to 30 MPa. The rocks strike N45E to N77E and dip 26^{o} to 75^{o} towards the North.

Zhemgang Town is a gentle slope underlain by phyllites. The depth to the bedrock ranges from few meters to about 20 m. The degree of weathering of the rocks decreases with depth meaning more competent rock is found at greater depth. Phyllite in general is a weak rock and is highly susceptible to landslides, especially in steep slopes. Therefore, slope mitigation measures are necessary for site development.

At Tingtibi, the geologic units were classified as Rock (Quartzites), Colluvium, RBM (River Borne Deposit) and Residual Soil. Massive white quartzites are found along the steep slopes of riverbanks and mountain sides. The geologic map of Tingtibi is attached at the end of this report.

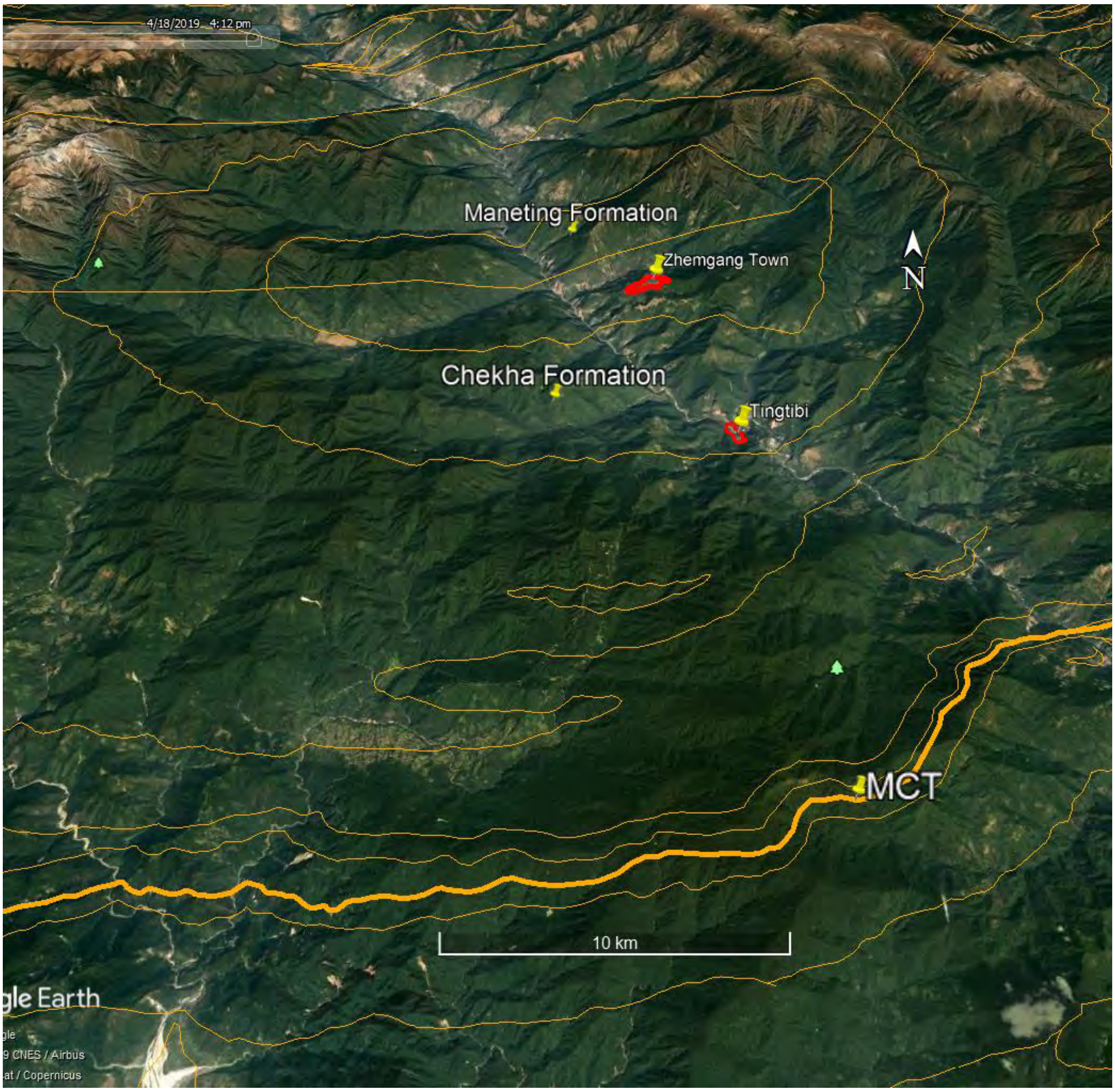

Figure 4: Geology of Bhutan showing the project area (Thick yellow line showing MCT and light yellow showing faults and contacts)

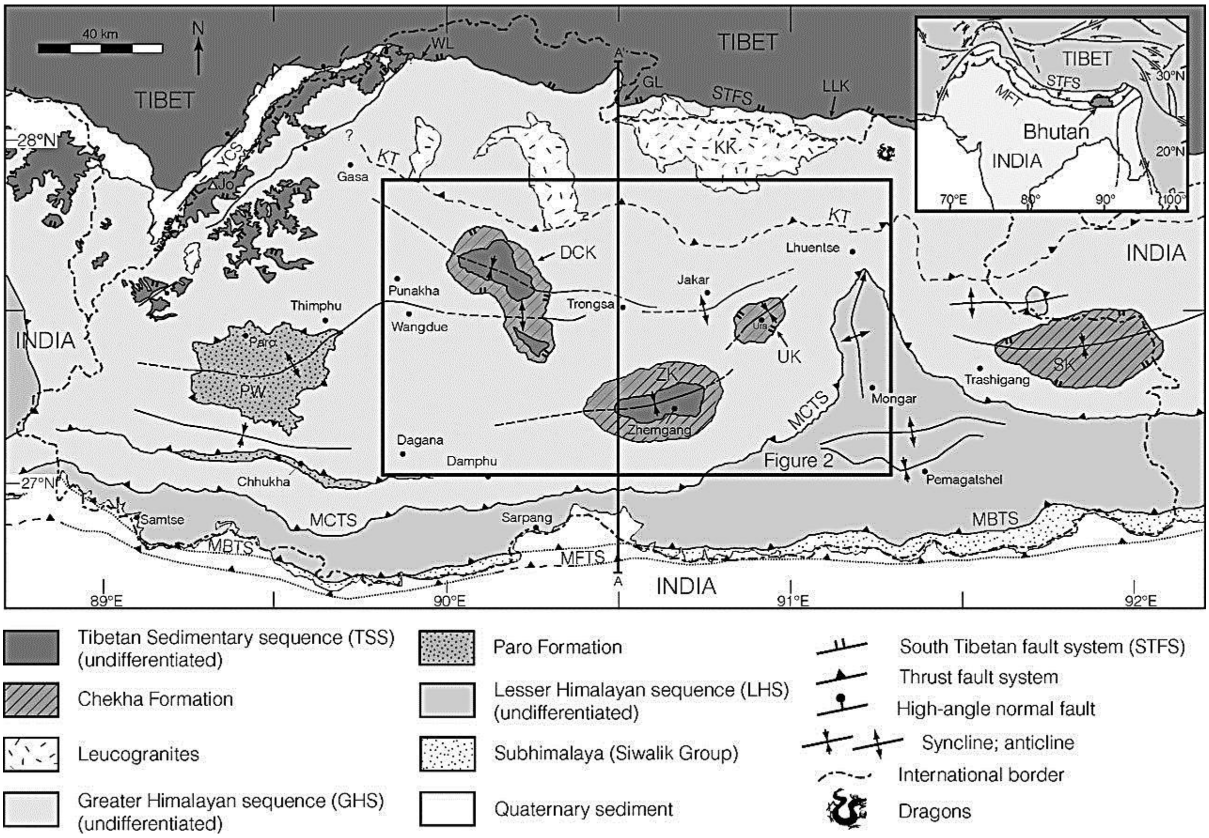

Figure 5: Geologic map of Bhutan

b. Engineering Geology Map

Engineering geology map illustrates the surficial and shallow geologic conditions such as landslides, debris flow, rock-fall and similar failures, subsidence, land degradation, erosion, scouring, and water bodies (springs, creek, streams both seasonal and perennial, seepages, etc.), flood plains, and sources of instabilities (due to liquefaction, landslides, subsidence, etc.). The Engineering Geology Maps of Zhemgang Town and Tingtibi were attached at the end of this report.

At Zhemgang Town, not many features of concern with regard engineering geology were found in the study area. Only few old landslides, marshy area and ground subsidence (refer Engineering Geology Map) were found. In general the units in engineering geology are divided as follows:

- Rock (dark grey phyllites)
- Residual Soil
- Landslides (old)
- Marshy Area

Exposures of rocks (phyllites) were found throughout the study area but each expoures was not extensive. Phyllites (like slates and schist) show a marked tendency to split along the planes and cleavage, creating weak areas prone to weathering. Despite the presence of hard minerals, alteration takes place more easily because of the penetration of water. Phyllite is a foliated metamorphic rock that has been subjected to low levels of heat, pressure and chemical activity. It is a low-grade metamorphic rock that reveals the upper limit of heat and pressure to which the rocks were exposed. It is composed mainly of flake-shaped mica minerals in parallel alignment. The strong parallel alignment of the mica grains allows the rock to be easily split into sheets or slabs. The alignment of the mica grains gives phyllite a reflective sheen that distinguishes it from slate, its metamorphic precursor or Protolith. **Phyllite is usually gray, black, or greenish in color and often becomes tan or brown upon weathering. Its reflective sheen often gives it a silvery, nonmetallic appearance.**

The surface layer is mainly residual soil formed from weathering of underlying phyllites. These soils are loose and unconsolidated and are termed as residual soils. Old landslides were noted south of the Dzong, which sits on the top of a ridge. Signs of ground subsidence and differential settlements were observed under the Dzong and adjacent structures. A marshy area was observed above RDTC Office. No other active sign of landslides of other features related to instability were observed during the field reconnaissance survey at Zhemgang Town.

At Tingtibi, the units of engineering geology were divided as follows:

- Rock (Quartzites)
- Colluvium
- RBM (River Borne Deposit)
- Residual Soil
- Landslides (old)
- Depression

Quartzite is the main rock found at Tingtibi. This rock is hard, non-foliated metamorphic rock, which was originally pure quartz sandstone. Sandstone is converted into quartzite through heating and pressure usually related to tectonic compression within orogenic belts. Quartzites have a massive or layered texture, most often in light, gray, or brownish tones. In most cases, discontinuity surfaces form planes of weakness that govern the geomechanical behavior of rock masses by conditioning the strength of the formation as a whole and the zones and mechanisms of deformation and failure. The control exerted by discontinuities is definitive in quartzites, where the strength of intact rock blocks is much stronger than the strength of planes separating them. In soft rock masses such as phyllites and shales, the difference between the strength of both components may not be very significant; in such cases, the behavior of the overall rock mass may even be determined by the intact rock properties. Quartzite has unit weight of 26 kN/m^3 to 27 kN/m^3 with porosity of 0.1% to 0.5%. Quartzite is moderately strong with Uniaxial Compressive Strength (UCS) of quartzite ranges from 30 to 50 MPa.

The hill slopes at Tingtibi are covered with colluvium (debris), which are unconsolidated material, with significant proportion of coarse material. Colluvium (also colluvial material or colluvial soil) is a general name for loose, unconsolidated sediments that have been deposited at the base of hillslopes by either rainwash, slow continuous downslope creep, or a variable combination of these processes. These soils are generally loose and unconsolidated. The main flat portion of land at Tingtibi on which lies the main town, is underlain by reddish brown residual soil, formed from weathering of underlying rocks. The parcel of land on the left bank of the Mangde Chhu at Tingtibi is made up of RBM or Alluvium, which is loose, unconsolidated soil or sediment that has been deposited during floods. Alluvium is typically made up of a variety of materials, including fine particles.

c. Geomorphological Map

Geomorphology refers to the science of the forms of Earth's surface and the processes creating and reshaping them. This incorporates parts of many different scientific genres (i.e. geophysics, sedimentology, geochemistry, hydrology, climatology, pedology, biology, and engineering) and thus geomorphology deals with the combination of these and their effect on the landscape configuration and development.

Through the study of topographical maps some landforms can be distinguished and some may also be interpreted genetically if the general context is known. Topographical maps however, do not present direct information about the genesis (origin) and distribution of the landforms. These maps also do not inform about smaller and less pronounced forms, the age of landforms, their lithology or their relationship to the geologic settings. Thus, it is impossible to reconstruct the landscape development from topographic maps alone. To better understand the environment and its development through time geomorphological studies and maps are used.

The original intention of geomorphological maps was to be a tool to illustrate or to help explain the distribution of individual landforms in the landscape. As the maps in time have become broader in their descriptions of forms and processes they serve as comprehensive inventories of the mapped areas, often also presenting the interpreted landscape development.

Most engineering projects are constructed close to the land surface and therefore geomorphology is very important. For example, study of river terraces can help determine likely maximum flood levels and can also give some indication of earthquake history in active region. The recognition of past landslides through air photo interpretation is a fundamental part of desk study for many hilly sites. The Geomorphologic Maps of Zhemgang Town and Tingtibi were attached at the end of this report.

In terms of geomorphology, the study area at Zhemgang Town is divided in to the following units:

- Soil-mantled slope
- Remnant Mound
- Rock (Phyllites)
- Ridge
- Drainages

The entire study area at Zhemgang Town is basically a slope, which has been identified as soil-mantle slope. Soil-mantled slope occurs when the rate of soil production is greater than erosion. Here the surface layer is soil cover, which overlies the bedrock underneath. Soil-mantled (rocks mixed with soils) slopes can only get so steep before landslide limits further steepening. Erosion rates are strongly correlated with slope, steeper slopes leading to more rapid erosion. The angle of soil-mantled slopes can only increase to an upper limiting or threshold angle of no more than about 35°, roughly equal to the friction angle of dry granular material, because soils tend to slide off of steeper slopes even when dry. The properties of slope-forming materials exert a profound influence on both hillslope processes and form. Slopes made of loose, unconsolidated sediment, mantled by soil, and slopes that expose bedrock each offer substantially different resistance to erosion and gravity-induced failure. Because of this, the material that makes up a slope strongly influences the processes that determine its evolution and morphology.

Remnant Mound is basically the elevated structures like a mountain top or ridge, which is formed as a result of its relatively more resistance to erosional forces. The portion of land on which the Dzong is founded along with it associated structures is part of this Remnant Mount.

The other feature of the geomorphology at the study area is the exposure of bedrock of phyllites, which are found in small pockets throughout the study area. The bedrock is found at few meters to about 10 m below the sloping ground surface. Bedrock is consolidated rock, meaning it is solid and tightly bound. Overlying material is often unconsolidated rock, which is made up of loose particles. The bedrock is overlain by saprolites, which is rock that has undergone intense weathering. Saprolite has actually undergone the process of chemical weathering. This means Saprolite is not just less-consolidated bedrock, it has a different chemical composition. Flowing water has interacted with minerals in the bedrock to change its chemical make-up. Above the Saprolite lie layers of soil, sand, or sediment.

Similarly, at Tingtibi, the geomorphologic layers have been recognized as follows:

- Rock (Quartzites)
- Soil-mantled slope
- RBM
- Drainages

Compared to Zhemgang Town, the bedrock at Tingtibi is mainly quartzite, which much more hard and consolidated. Here there is a small portion of land on the left bank of Mangde Chhu, which is composed of RBM, which comprises of floodplain deposits.

d. Slope map

For assessment of slope stability, the slope angle is one of the most important parameter. **All other parameters being equal, greater the slope angle, more the chances of slope instability**. Therefore, a slope map was prepared to assist in the slope hazard analysis and multi-hazard mapping. Slope is the measure of steepness or the degree of inclination of a feature relative to the horizontal plane. Gradient, grade, incline and pitch are used inter-changeably with slope. Slope is typically expressed as a percentage, an angle, or a ratio. The Slope Maps of Zhemgang Town and Tingtibi were attached at the end of this report. The results of the slope analyses are as shown in **Table 1** and **Table 2**.

Table 1: Slope Classification for Zhemgang Town

SLOPE ANALYSIS FOR ZHEMGANG EXISTING TOWN						
#	Slope Class	Area				Remarks
		(Sq.km)	(Acre)	(%)	(%)	
1	0 - 10°	0.25	60.95	22.06%	56%	Gentle Slope
2	10 - 20°	0.38	92.89	33.62%		
3	20 - 30°	0.33	81.18	29.38%	29%	Moderately Steep Slope
4	30 - 45°	0.15	37.58	13.60%	15%	Steep Slope
5	> 45°	0.01	3.68	1.33%		
Total		1.12	276.27	100%	100%	

Table 2: Slope Classification for Tingtibi

SLOPE ANALYSIS FOR TINGTIBI						
#	Slope Class	Area				Remarks
		(Sq.km)	(Acre)	(%)	(%)	
1	0 - 10°	0.22	53.21	39.74%	57%	Gentle Slope
2	10 - 20°	0.10	23.62	17.64%		
3	20 - 30°	0.08	19.53	14.58%	15%	Moderately Steep Slope
4	30 - 45°	0.12	30.87	23.05%	28%	Steep Slope
5	> 45°	0.03	6.68	4.99%		
Total		0.54	133.90	100%	100%	

2.4 Subsurface Investigation

In addition to surface mapping, it was important to study the subsurface. At any site, the ground conditions must be assessed to enable safe and cost-effective design, construction and operation of civil engineering projects. In the current project as already identified in the contract, the subsurface was mainly explored through Trials Pits and Penetration Tests (SPT/PPT). In deciding the locations of the field tests, the geologic conditions were considered. For instance, pits were spread over to sample every type of lithology in the study area.

2.5 Exploratory Excavations (Trial Pits)

As per the Terms of Reference, 15 trial pits at Zhemgang Town and 7 trial pits at Tingtibi (up to a minimum of 3.0 m) were dug to cover the project area. All tests and pit excavations were uniformly distributed within the study area to get an average sense of the area. These trial pits were meant to be used for ground profiling (stratigraphy), soil classification (based on appropriate existing standard) and sampling the soil for laboratory tests.

Soil layers within the first 3 m of the ground surface were inspected and described. Furthermore, sampling of soils was done from trial pits. The main purposes of trial pits were to: (1) establish the subsurface geological profile in detail and (2) supply both disturbed and undisturbed materials for laboratory testing. Soils and rock were examined, described and characterized in trials pits and natural exposures.

Zhemgang Town is basically a hill slope. Therefore, the soil/overburden layer, as expected is thin and the trial pits could reveal the entire soil information. At Tingtibi, three types of soil were present, namely residual soil, colluvial deposits and alluvial deposit**.**

A trial pit (or test pit) is an excavation of ground in order to study or sample the composition and structure of the subsurface, dug during a site investigation, a soil survey or a geological survey. They are dug to determine the geology and the water table of that site. The photographs of the Trails Pits for Zhemgang Town and Tingtibi are given in **Annexure A**. The locations of the Trail Pits are shown in **Table 3** & **Table 4** for Zhemgang Town and Tingtibi, respectively. The description of soils/ground conditions at Zhemgang Town are given below.

TP-01

The soil at this site (Trial Pit No. TP-01) comprises of residual soil, which are formed from weathering of underlying bedrock of phyllites. The top layer of about 0.5 m is decomposed organic matter and therefore it is dark in color and very soft. Below this, the soil is dark brown and comprises of predominantly gravels and sand. The gravel content in the soil deposit is more than 30%. The clay portion is insignificant and thus, the soil is only slightly plastic. The soil deposit is loose and weak all the way to 3 m depth and it is somewhat well drained. Groundwater Table (GWT) is not met at the pit bottom.

TP-02

Dark red soil indicating presence of clay was found from the ground surface till about 1.6 m depth in this trial pit. This soil is fine grained and can be classified as silty-sandy soil or sandy loam. The soils are of medium plasticity and moist. Weathered bedrock of phyllite was found at about 2 m depth from the surface.

TP-03

At this Trial Pit, the top layer is dark colored organic soil down to 1.0 m depth. Below this, the soil is fine grained reddish colored and slightly plastic down to 1.5 m depth. The bedrock of dark grey phyllite was found at 1.5 m depth. The rock is moderately weathered with UCS of greater than 1 MPa.

TP-04

The top soil down to 2 m depth comprises of gravelly sand. The gravels made up about 20% of the soil deposit. Majority of the soil matrix is fine grained sandy soil. The bedrock of dark grey phyllite was found at 2 m depth. The soil is moist and somewhat well drained.

TP-05

This site is at a construction site where more than 5 more ground is exposed through excavation. The soil is more than 5 m thick and comprises entirely of totally weathered phyllite. The rock structures are still visible in the soil layer. The soil is slightly plastic and somewhat well drained. GWT or seepages is not seen at the excavation.

TP-06

The soil is dark grey and of medium plasticity throughout the depth of the Trail Pit. The gravel content in the soil deposit is more than 10%. The soil is loose and unconsolidated. GWT was not found at the pit bottom.

TP-07

The top soil contains about 30% gravel in a matrix of sandy soil formed by weathering of underlying dark grey phyllites. The soil is non-plastic and well drained. The bedrock of phyllite was found close to the ground surface at about 1.0 m depth.

TP-08

The top soil up to 0.5 m depth is dry sandy soil, which is dark colored. Below this, we have sandy gravel, which is dark red and has medium plasticity due to presence of some clay. The soil is loose and has significant gravel content.

TP-09

The soil deposit comprises of two types. The top soil is yellowish and silty fine grained non-plastic soil. This soil layer is about 1.5 m thick and loose. The bottom layer is totally weathered phyllites. This soil is wet and also fine grained with hardly any gravel content. This soil is poorly drained. GWT was not met in the Trial Pit.

TP-10

The top soil comprises of moderately weathered phyllites down to about 1.0 m depth. This soil comprises of more than 30% gravel. The soil is non-plastic. Bedrock was found at shallow depth of 1 m from ground surface.

TP-11

The top soil comprises of light brown sandy soil layer till 1.5 m depth. The bedrock of moderately weathered phyllites is found at 1.5 m depth. The soil is loose and non-plastic. It is also somewhat well drained.

TP-12

The whole soil deposit comprise of weathered phyllite. The soil is slippery and loose. The gravel content is more than 30%. The soils are slightly plastic and well grained. GWT was not met in the Trial Pit.

TP-13

Up to 2.0 m, the soil is dark brown fine grained silty soil. Below this, the soil is mainly reddish with medium plasticity. The soil is loose and unconsolidated. The gravel content in the entire 3 m layer of soil is insignificant.

TP-14

The soil comprise of silty brown soil all the way to 3 m depth. The soil is non-plastic and loose. The gravel content is less than 10% and therefore, geotechnical property of the soil will be dominated by soil and not gravel. GWT and bedrock is not met in the Trial Pit.

TP-15

The top 1.2 m thick soil is reddish and non-plastic. The soil is medium dense and moist. From 1.2 m to 3.0 m depth, the soil is dark as it is formed from weathering of dark phyllites. Overall the soil is loose and show low bearing capacity to penetration tests. Bedrock of phyllites was found at about 3.0 m depth.

At Tingtibi, more varieties of soils like residual soil, colluvium and alluvium were present. The descriptions of soils/ground conditions at Tingtibi are given below:

TP-01

This trial pit is located on a flood plain area. As expected, the soil is composed of alluvial deposits of sand and boulders. The boulders are either rounded or sub rounded. The gravels and boulders make more than 40% of the deposit. Therefore, the soil deposit can be classified as sandy gravel. The silt content is insignificant. The soil is unsorted and non-plastic. GWT is not met in the pit.

TP-02

This trial pit is located at the main Tingtibi Town. The soil is red in color and it is silty-sandy soil. This soil can be classified as residual soil. It contains more than 10% gravels. The gravel content increases with depth. The bedrock is not in the pit. The soil is moderately plastic and moist. The soil is also loose and unconsolidated.

TP-03

The soil is dark brown in color and comprise of gravels mixed with fine grained silty-sandy soil. The gravel content is more than 20%. The deposit is non-plastic and well drained. GWT is not met in the pit. The moisture content in the soil layer increases with depth. The soil is loose and weak.

TP-04

This residual soil is dark brown and contains significant amount (more than 20%) of gravels and boulders. The deposits is fine grained and non-plastic. GWT was not met in the Trial Pit. However, there are plenty of boulders of weathered quartzite towards the pit bottom. Overall the deposits are loose and unconsolidated.

TP-05

The soils are yellowish in color and comprise of mainly sand. The amount of gravels and fines is insignificant. The soil is loose and slightly plastic. The soil is moist and somewhat well drained. GWT was not met in the pit.

TP-06

The soil is red in color and belongs to residual soil group. It is moderately plastic and moist. There is almost equal amount of sand and gravels in the soil deposit. The soil is loose and unconsolidated. GWT and bedrock were not met in the pit.

TP-07

The soil comprise of silty sand, which is light brown in color and moist. This is also residual soil formed from the weathering of the underlying rocks. Only about 5% of the soil is gravels. The amount of fines in the deposit is negligible. GWT was not met in the pit even at about 3.0 m depth.

Table 3: Locations of Trial Pits at Zhemgang Town

#	TEST ID	LATITUDE	LONGITUDE	MATERIALS DESCRIPTIONS
1	TP-01	27.21894891	90.66083455	Dark brown fine grained silty soil
2	TP-02	27.21972076	90.66365616	Red fine grained soil of low plasticity
3	TP-03	27.21719444	90.66149136	Dark red fine grained slightly plastic soil
4	TP-04	27.21854832	90.66509345	Red sandy soil with 10% gravels
5	TP-05	27.21520643	90.66288888	Totally weathered phyllites
6	TP-06	27.21516293	90.65795533	Dark soil from totally weathered phyllites
7	TP-07	27.21454296	90.65974522	Dark sandy soil of low plasticity
8	TP-08	27.21519538	90.65551312	Dark red silty soil with 10% gravels
9	TP-09	27.21601234	90.65374088	Yellowish fine gained soil with about 10% gravels
10	TP-10	27.21372204	90.64983102	Weathered phyllites
11	TP-11	27.21710755	90.65691363	Grey sandy soil, non-plastic
12	TP-12	27.21856554	90.65787544	Totally weathered phyllites
13	TP-13	27.2207671	90.65868301	Dark brown fine grained silty soil
14	TP-14	27.21821221	90.65523807	Dark brown fine grained silty soil
15	TP-15	27.21409911	90.6544642	Totally weathered phyllites

Table 4: Locations of Trial Pits at Tingtibi

#	TEST ID	LATITUDE	LONGITUDE	MATERIALS DESCRIPTIONS
1	TP-01	27.14746889	90.69203660	River borne materials
2	TP-02	27.14532965	90.68984036	Red fine grained silty soil
3	TP-03	27.14193731	90.68992273	Dark grey fine grained non-plastic soil
4	TP-04	27.14151394	90.69116221	Dark brown fine grained non-plastic soil
5	TP-05	27.13883163	90.69111538	Brownish fine grained silty soil
6	TP-06	27.13824502	90.69475300	Brownish fine grained slightly plastic soil
7	TP-07	27.14311489	90.69124905	Brownish fine grained slightly plastic soil

Summary of Findings from Trail Pit Study

At both Zhemgang Town and Tingtibi, the soil was predominately residual soil. At Zhemgang, the residual soil was formed from weathering of phyllites while at Tingtibi the residual soil was a product of weathered quartzites. Usually, three layers of subsurface soil were observed. The top surface layer was dark brown or dark fine grained organic soil comprising of roots and grass. Below this, the soil layer was pale brown fine sandy loam. The bottom subsoil was red clay loam and sandy clay loam. The generalized residual soil type at Zhemgang and Tingtibi is shown in **Figure 6**. This soil may be referred to as a loam soil. Loam is soil composed mostly of sand, silt and a smaller amount of clay. Sandy loam soils are dominated by sand particles, but contain enough clay and sediment to provide some structure and fertility. Sandy loam soils have visible particles of sand mixed into the soil. Sandy loam soils have a high concentration of sand that gives them a gritty feel. In gardens and lawns, sandy loam soils are capable of quickly draining excess water but cannot hold significant amounts of water or nutrients for your plants.

Figure 6: Residual Soil found at Study Area (Zhemgang Town and Tingtibi)

2.6 Dynamic Cone Penetration Tests

Dynamic Cone Penetration Tests (DCPTs) were done at every pit location and where the geologic conditions are a suspect. As per the TOR, DCPTs were conducted at 30 locations (i.e. 20 tests at Zhemgang Town and 10 tests at Tingtibi). The DCPT values can be correlated to SPT to classify soils as given in **Table 5**. The DCPT values can be used to calculate bearing capacity of soils as shown in **Annexure B**. At the study sites, adequate bearing capacity of at least 150 kPa is obtained at depths of about 2.5 m from the ground surface.

Table 5: Soil classification based on SPT N value (Source: Clayton, C.R.I. 1995)

Classification	N (Blows/30 cm)
Very loose	0-4
Loose	4-10
Medium	10-30
Dense	30-50
Very dense	>50 (Refusal)

2.7 Geotechnical Lab Tests and Interpretation

When the geological unit at the new development areas has the soil nature, index properties of the ground (grain size distribution or sieve analysis, Atterberg limits, specific gravity, moisture content, unit weight, etc.) and engineering properties (cohesion, internal friction angle, natural unit volume network etc.) should be determined by in situ (investigation excavations by trial pits) and laboratory experiments and calculation methods. The following geotechnical lab tests were done for every sample collected from the trial pits.

- Natural Moisture Content
- Density Test (Bulk & Dry Density)
- Specific Gravity
- Atterberg Limits (Liquid Limit & Plastic Limit)
- Grain Size Analysis
- Permeability Tests
- Direct Shear Test (cohesion & internal angle of friction)
- Proctor Compaction Test

The details of the all the tests are given in **Annexure C** for both Zhemgang Town and Tingtibi. A summary of tests results and descriptions of the tests are given in the following sections.

Table 6: Summary of Lab Tests at Zhemgang Town

Sample No.	w	γ_b	γ_d	Gs	Direct Shear		Atterberg Limits			k
					c	ø	LL	PL	PI	
	%	kN/m^3	kN/m^3		kg/cm^2	deg.	%	%	%	cm/s
TP-01	29.23	16.89	13.07	2.14	0.063	32.62				3.11E-03
TP-02	14.08	17.65	15.47	2.44	0.020	29.25				6.72E-05
TP-03	15.00	16.58	14.42	2.53	0.149	29.68	26.65	19.19	7.46	4.00E-05
TP-04	23.94	17.94	14.47	2.49	0.067	32.09				1.11E-04
TP-05	13.70	19.40	17.06	2.58	0.052	33.70				1.69E-03
TP-06	14.71	17.71	15.44	2.36	0.045	27.97				6.72E-05
TP-07	16.08	18.55	15.98	2.45	0.066	34.88				1.03E-04
TP-08	27.42	16.40	12.87	2.42	0.124	25.78	24.79	14.93	9.86	1.43E-02
TP-09	13.10	16.58	14.66	2.57	0.093	29.96				2.74E-05
TP-10	14.86	18.34	15.97	2.67	0.015	35.83				3.37E-04
TP-11	27.78	15.68	12.27	2.46	0.065	31.57				8.74E-05
TP-12	35.44	16.83	12.43	2.48	0.029	32.61				1.01E-03
TP-13	12.35	16.91	14.51	2.49	0.076	29.18				4.00E-05
TP-14	10.34	17.28	14.63	2.58	0.068	27.83				4.99E-05
TP-15	12.79	17.86	14.56	2.57	0.073	29.04				1.03E-04
Max.	35.44	19.40	17.06	2.67	0.149	35.83	26.65	19.19	9.86	1.43E-02
Min.	10.34	15.68	12.27	2.14	0.015	25.78	24.79	14.93	7.46	2.74E-05
Avg	18.72	17.37	14.52	2.48	0.067	30.80	25.72	17.06	8.66	1.41E-03
INDEX										
w	Moisture Content				ø	Angle of Internal Friction				
γ_b	Bulk Density				LL	Liquid Limit				
γ_d	Dry Density				PL	Plastic Limit				
Gs	Specific Gravity				PI	Plasticity Index				
c	Cohesion				k	Hydraulic Conductivity				

Table 7: Summary of Lab Tests at Tingtibi

Sample No.	w	γ_b	γ_d	Gs	Direct Shear		Atterberg Limits			k
					c	ø	LL	PL	PI	
	%	kN/m^3	kN/m^3		kg/cm^2	deg.	%	%	%	cm/s
TP-01	12.10	18.37	16.39	2.61	0.008	35.11				1.03E-04
TP-02	18.30	17.13	14.48	2.49	0.101	26.57	21.85	12.50	9.35	1.03E-04
TP-03	8.70	16.31	15.00	2.47	0.067	28.90				1.28E-04
TP-04	12.80	16.30	14.45	2.37	0.030	27.26				1.03E-04
TP-05	6.10	17.86	16.83	2.51	0.030	27.70				3.13E-05
TP-06	12.90	16.95	15.01	2.60	0.106	26.42	28.00	14.74	13.26	7.37E-04
TP-07	9.90	15.92	14.49	2.36	0.038	29.54				4.00E-05
Max.	18.30	18.37	16.83	2.61	0.106	35.11	28.00	14.74	13.26	7.37E-04
Min.	6.10	15.92	14.45	2.36	0.008	26.42	21.85	12.50	9.35	3.13E-05
Avg	11.54	16.98	15.24	2.49	0.054	28.78	24.93	13.62	11.31	1.78E-04

2.7.1 Natural Moisture Content

Water is present in most naturally occurring soils. The amount of water expressed as a proportion by mass of dry solid particles is the moisture content, which has a profound effect on soil behavior. Moisture content is regarded as a guide to classification of natural soils and is measured for most samples used for most field and laboratory tests.
The Natural Moisture Content (NMC) for silty sand soil at Zhemgang Town ranges from 10.34% 35.44% while that for Tingtibi ranges from 6.10% to 18.30%. These values are typical of silty-sandy soil on Himalayan slopes.

2.7.2 Dry density

When water is added to dry soil, it helps in bringing the solid particles close by coating them with thin films of water. At low water content, the soil is stiff and it is difficult to pack it together. As the water content is increased, water starts acting as a lubricant, the particles start coming closer due to increased workability and under a given amount of compactive effort, the soil-water-air mixture starts occupying less volume, thus effecting gradual increase in dry density. As more and more water is added, a stage is reached when the air content of the soil attains a minimum volume, thus making the dry density a maximum. The dry density was obtained from wet density and the moisture content. The dry density (γ_d) of the soils ranged from 12.27kN/m^3 to 17.06kN/m^3 at Zhemgang. Similarly, the dry density of soils at Tingtibi ranged from 14.45kN/m^3 to 16.83kN/m^3.

2.7.3 Specific Gravity

Specific gravity (Gs) values for a soil are not normally used strictly for classification purposes, but are used in the calculation and interpretation of other test results. The specific gravity tests are relatively simple and are based upon determination of the dry weight of a sample of the soil, and the weight of the same sample plus water in a container of known volume. The volume of the container is obtained by weighing the container empty, and full of water. Specific gravity depends on the mineralogy of soil and it can reflect the history of weathering. Specific gravity of soils from Zhemgang Town ranged from 2.14 to 2.67. For Tingtibi, Gs ranged from 2.36 to 2.61.

2.7.4 Atterberg Limits (Liquid Limit & Plastic Limit)

Liquid limit (LL) and plastic limit (PL) are used to assess the plasticity of a fine-grained soils and its consistency at various moisture contents. The liquid limit is the empirically established moisture content at which a soil passes from the liquid state to the plastic state. It provides a means of classifying a soil especially when the plastic limit is also known.

The plastic limit is also an empirically established moisture content at which a soil becomes too dry to be plastic. It is used together with the liquid limit to determine the plasticity index (PI) which when plotted against the liquid limit on the plasticity chart provides means of classifying a cohesive soil.

The PL and LL tests could be done only for 2 samples each from Zhemgang Town and Tingtibi since most of the soils are coarse grain with almost no fines. At Zhemgang Town, Plasticity Index (PI) of 7.46% and 9.86% were obtained for Soils Samples TP-02 and TP-08, respectively. Similarly, at Tingtibi, the PI of 9.35% and 13.26% were obtained for TP-02 and TP-06.

2.7.5 Particle size analysis

Particle size analysis expresses quantitatively the proportion by mass of the various sizes of the particles present in the soil. A distribution analysis is a necessary index test for soils especially coarse-grained soils, in that it presents the relative proportions of different sizes of particles. From this, it is possible to tell whether the soil consists of predominantly gravel, sand, silt or clay sizes and to a limited extent which of the sizes range is likely to control the engineering properties.

The results of the sieve analysis are given in percentages of the soil in terms of fines (clay and silt), sand and gravels. The Uniformity Coefficient ($C_u = \frac{D_{60}}{D_{10}}$) and Coefficient of Curvature ($Cc = \frac{D_{30}^2}{D_{10}D_{60}}$) are used to group the soils into different grading. A well graded soil has to meet both the conditions of $Cu \geq 10$ and $1 \leq Cc \leq 3$. The results of the sieve are shown in **Table 8** for Zhemgang Town and **Table 9** for Tingtibi. The results show that soils in general are poorly graded.

Table 8: Grain Size Analysis at Zhemgang Town

Soil Type	TP-01	TP-02	TP-03	TP-04	TP-05	TP-06	TP-07	TP-08
Gravel	43.31	3.49	1.74	19.65	67.25	16.69	30.98	75.99
Sand	56.16	96.05	94.04	78.70	32.12	81.55	68.26	21.64
Fines	0.54	0.47	4.22	1.66	0.62	1.76	0.76	2.37
Total	100	100	100	100	100	100	100	100
Cu	7.43	2.50	4.17	6.00	33.33	4.00	7.50	6.67
Cc	0.70	1.09	1.50	0.67	3.00	1.28	0.53	2.40
GSD type	Poorly graded	Poorly graded	Poorly graded	Poorly graded	Well graded	Poorly graded	Poorly graded	Poorly graded

Soil Type	TP-09	TP-10	TP-11	TP-12	TP-13	TP-14	TP-15
Gravel	1.11	35.83	3.80	36.67	1.17	6.72	44.07
Sand	97.88	63.81	95.22	62.13	97.34	92.31	54.68
Fines	1.01	0.36	0.98	1.20	1.49	0.97	1.25
Total	100	100	100	100	100	100	100
Cu	5.00	11.67	3.67	10.00	3.08	5.00	35.29
Cc	0.80	0.47	1.48	1.06	1.73	1.25	0.16
GSD type	Poorly graded	Poorly graded	Poorly graded	Well graded	Poorly graded	Poorly graded	Poorly graded

Table 9: Grain Size Analysis at Tingtibi

Soil Type	TP-01	TP-02	TP-03	TP-04	TP-05	TP-06	TP-07
Gravel	47.47	17.71	24.51	29.03	2.53	49.46	5.44
Sand	51.29	81.02	74.84	69.64	96.31	49.05	93.47
Fines	1.23	1.27	0.65	1.33	1.15	1.49	1.09
Total	100	100	100	100	100	100	100
Cu	35.29	6.50	7.14	7.50	3.46	1.20	3.85
Cc	0.35	0.62	0.79	0.53	0.75	3.33	1.12
GSD type	Poorly graded	Poorly graded	Poorly graded	Poorly graded	Poorly graded	Poorly graded	Poorly graded

2.7.6 Permeability Tests

The ability to transmit groundwater is termed permeability. The rate at which a soil or rock transmits water depends not only on its total porosity but also on the size of the interconnections between its openings. An example of this is that water passes more readily through the sand than through clay simply because the molecular attraction on the water is much stronger in the tiny openings of the clay than in the sand. It must be noted that no matter how large the interstices of a material are there must be connections between them if water is to pass through. If they are not interconnected, the material is impermeable, for example fresh solid rocks with no joints or clays. Typical values of permeability for different earth materials are given in **Table 10**.

Table 10: Typical Void Sizes for Soil and Associated Permeability

Material	Void Size (cm)	Hydraulic Conductivity (cm/sec)
Clay	$<10^{-4} – 10^{-3}$	$<10^{-6}$
Silt	$10^{-3} – 10^{-2}$	$10^{-6} – 10^{-4}$
Sand	$10^{-2} – 10^{-1}$	$10^{-4} – 10$
Gravel	$>10^{-1}$	$10 – 10^{2}$

The results of the permeability tests in terms of Hydraulic Conductivity are given in **Table 11** and **Table 12** for Zhemgang Town and Tingtibi, respectively. The permeability of soil is an important property that is used for the classification of soils and in the design of structures on/in soils. Permeability property controls the movement of and storage of fluids in soils and rocks, and represents an important characteristic of materials. On the basis of known permeability, possible solutions of engineering constructions can be recommended.

Table 11: Results of Permeability Tests at Zhemgang Town

Sample No.	D20 (mm)		k (cm/s)	Remarks
	mm	cm		
TP-01	1.300	0.130	3.11E-03	Medium permeability corresponding to sand-gravel mixture; fine gravels; coarse, medium & fine sand
TP-02	0.250	0.025	6.72E-05	
TP-03	0.200	0.020	4.00E-05	
TP-04	0.310	0.031	1.11E-04	
TP-05	1.000	0.100	1.69E-03	
TP-06	0.250	0.025	6.72E-05	
TP-07	0.300	0.030	1.03E-04	
TP-08	2.500	0.250	1.43E-02	
TP-09	0.170	0.017	2.74E-05	
TP-10	0.500	0.050	3.37E-04	
TP-11	0.280	0.028	8.74E-05	
TP-12	0.800	0.080	1.01E-03	
TP-13	0.200	0.020	4.00E-05	
TP-14	0.220	0.022	4.99E-05	
TP-15	0.300	0.030	1.03E-04	
Minimum Value			2.74E-05	
Maximum Value			1.43E-02	
Average Value			1.41E-03	

Table 12: Results of Permeability Tests at Tingtibi

Sample No.	D20 (mm)		k (cm/s)	Remarks
	mm	cm		
TP-01	0.300	0.030	1.03E-04	Medium permeability corresponding to sand-gravel mixture; fine gravels; coarse, medium & fine sand
TP-02	0.300	0.030	1.03E-04	
TP-03	0.330	0.033	1.28E-04	
TP-04	0.300	0.030	1.03E-04	
TP-05	0.180	0.018	3.13E-05	
TP-06	0.700	0.070	7.37E-04	
TP-07	0.200	0.020	4.00E-05	
Minimum Value			3.13E-05	
Maximum Value			7.37E-04	
Average Value			1.78E-04	

2.7.7 Direct Shear Test (cohesion & internal angle of friction)

The drained shear strength (effective stress analysis) is of most importance for granular soils to find out the Cohesion and Angle (c) of Internal Friction (ø). The shear strength of granular soils is often measured in the direct shear apparatus, where a soil specimen is subjected to a constant vertical pressure while a horizontal force is applied to the top of the shear box so that the soil specimen is sheared in half along a horizontal shear surface. By plotting the vertical pressure versus shear stress at failure, the effective friction angle as well as effective cohesion can be obtained. These values will be used to calculate the bearing capacities of the ground using Terzaghi's equations and others. The cohesion (C) and Internal Friction Angle (ø) for soil samples from Zhemgang Town and Tingtibi are shown in **Table 13** and **Table 14**.

Table 13: Direct Shear Tests at Zhemgang Town

Strength Parameter	TP-01	TP-02	TP-03	TP-04	TP-05	TP-06	TP-07	TP-08
Cohesion (kg/cm^2)	0.063	0.020	0.149	0.067	0.052	0.045	0.066	0.124
Cohesion (kPa)	6.28	2.00	14.86	6.67	5.23	4.51	6.61	12.39
Internal Friction	32.62	29.25	29.68	32.09	33.70	27.97	34.88	25.78

Strength Parameter	TP-09	TP-10	TP-11	TP-12	TP-13	TP-14	TP-15
Cohesion (kg/cm^2)	0.093	0.015	0.065	0.029	0.076	0.068	0.073
Cohesion (kPa)	9.26	1.46	6.45	2.87	7.59	6.75	7.33
Internal Friction	29.96	35.83	31.57	32.61	29.18	27.83	29.04

Table 14: Direct Shear Tests at Tingtibi

Strength Parameter	TP-01	TP-02	TP-03	TP-04	TP-05	TP-06	TP-07
Cohesion (kg/cm^2)	0.008	0.101	0.067	0.030	0.071	0.106	0.038
Cohesion (kPa)	0.76	10.05	6.68	3.00	7.08	10.63	3.79
Internal Friction	35.11	26.57	28.90	27.26	27.70	26.42	29.54

2.7.8 Proctor Compaction Test

This procedure determines the moisture-density relationship of soils and soil-aggregate mixtures. A quantity of soil and aggregate mixture is prepared at determinable moisture content and compacted in a standard mould using a manual rammer. The wet mass of this compacted sample is divided by the volume of the mould to determine the wet density. Moisture content testing on the material from the compacted mass is used to determine the dry density of this material. This procedure is repeated at varied moisture contents and the results are plotted on a graph. The maximum density and optimum moisture content are determined by selecting a point at the peak of the curve. A summary of the proctor compaction test is given in **Table 15** and **Table 16**.

Moisture content of the soil is vital to proper compaction. Moisture acts as a lubricant within soil, sliding the particles together. Too little moisture means inadequate compaction - the particles cannot move past each other to achieve density. Too much moisture leaves water-filled voids and subsequently weakens the load-bearing ability. The highest density for most soils is at a certain water content for a given compaction effort compaction effort. The drier the soil, the more resistant it is to compaction. In a water-saturated state the voids between particles are partially filled with water, creating an apparent cohesion that binds them together. This cohesion increases as the particle size decreases (as in clay-type soils).

The Optimum Moisture Content (OMC) for soils at Zhemgang Town ranges from 6.00% to 13.50% corresponding to Maximum Dry Density (MDD) of 1.832g/cc and 1.790g/cc, respectively. Similarly, the OMC for soils at Tingtibi ranges from 6.00% to 9.30%. 1.832g/cc and 1.790g/cc, respectively.

Table 15: Summary of Proctor Compaction for Soil Samples from Zhemgang Town

Test No.	OMC (%)	MMD (g/cc)
TP-01	9.50	1.778
TP-02	11.50	1.815
TP-03	8.40	1.800
TP-04	9.30	1.790
TP-05	8.40	1.862
TP-06	8.70	1.778
TP-07	8.50	1.786
TP-08	13.50	1.790
TP-09	8.70	1.770
TP-10	6.00	1.832
TP-11	7.20	1.790
TP-12	6.60	1.852
TP-13	8.20	1.800
TP-14	7.80	1.844
TP-15	7.20	1.780
Maximum	13.50	1.862
Minimum	6.00	1.770
Average	8.53	1.807

Table 16: Summary of Proctor Compaction for Soil Samples from Tingtibi

Test No.	OMC (%)	MMD (g/cc)
TP-01	7.20	1.784
TP-02	8.80	1.840
TP-03	6.60	1.760
TP-04	9.30	1.780
TP-05	6.00	1.800
TP-06	7.60	1.810
TP-07	7.70	1.838
Maximum	9.30	1.840
Minimum	6.00	1.760
Average	7.50	1.798

2.7.9 Consolidation Test

Consolidation test is used to determine the rate and magnitude of soil consolidation when the soil is restrained laterally and loaded axially. The Consolidation test is also referred to as Standard Oedometer test or One-dimensional compression test. This test is carried out on saturated cohesive soils. The consolidation parameters obtained by this test are used to determine the consolidation settlement and time of consolidation for a given loading state (i.e. given height of embankment). These parameters are also used in design of "ground improvement measures", provided for construction of embankment on soft soils. However, at the current project sites in Zhemgang Town and Tingtibi, most of the soils are coarse-grained residuals soils, which do not undergo consolidation settlement due to relatively high hydraulic conductivity. Therefore, consolidations tests are not done.

2.8 Bearing Capacity and Settlement

The bearing capacities were calculated using input of cohesion, internal angle of friction and unit weigh of the soils obtained from geotechnical lab test results. The ultimate bearing capacity (q_u) of the foundation soil was determined using Terzaghi bearing capacity equation:

$$q_u = CN_c S_c + q N_q + 0.5 \gamma B N_\gamma S_\gamma$$

Where

D = Foundation depth

B = Foundation width =

q = Vertical surcharge pressure = γD

Sc and Sγ = Shape factors. For square footing: Sc = 1.3, Sγ = 0.80

Nc, Nq and Nr are Bearing Capacity factors and are functions of c and ø as follows:

$$N_c = \cot\phi\left(\frac{a^2}{2\cos^2(45+\frac{\phi}{2})} - 1\right)$$

$$N_q = \frac{a^2}{2\cos^2(45+\frac{\phi}{2})}$$

$$N_\gamma = \frac{1}{2}\tan\phi\left(\frac{K_{p\gamma}}{\cos^2\phi} - 1\right)$$

Where

$a = e^{\left(\frac{3\pi}{4}-\frac{ø}{2}\right)tanø}$ and $K_{p\gamma}$ = coefficient of passive earth pressure

The allowable bearing capacity may be taken as one-third of the ultimate bearing capacity (q_u). Using input of Cohesion, Internal Angle of Friction, Unit weight and assuming foundation depth of 2.0 m and foundation width of 1.5 m, the bearing capacity of the soils were computed and compared with those values from DCPT as given in

Figure 7 and **Figure 8**. The graphs show that the bearing capacities from field and lab tests are comparable.

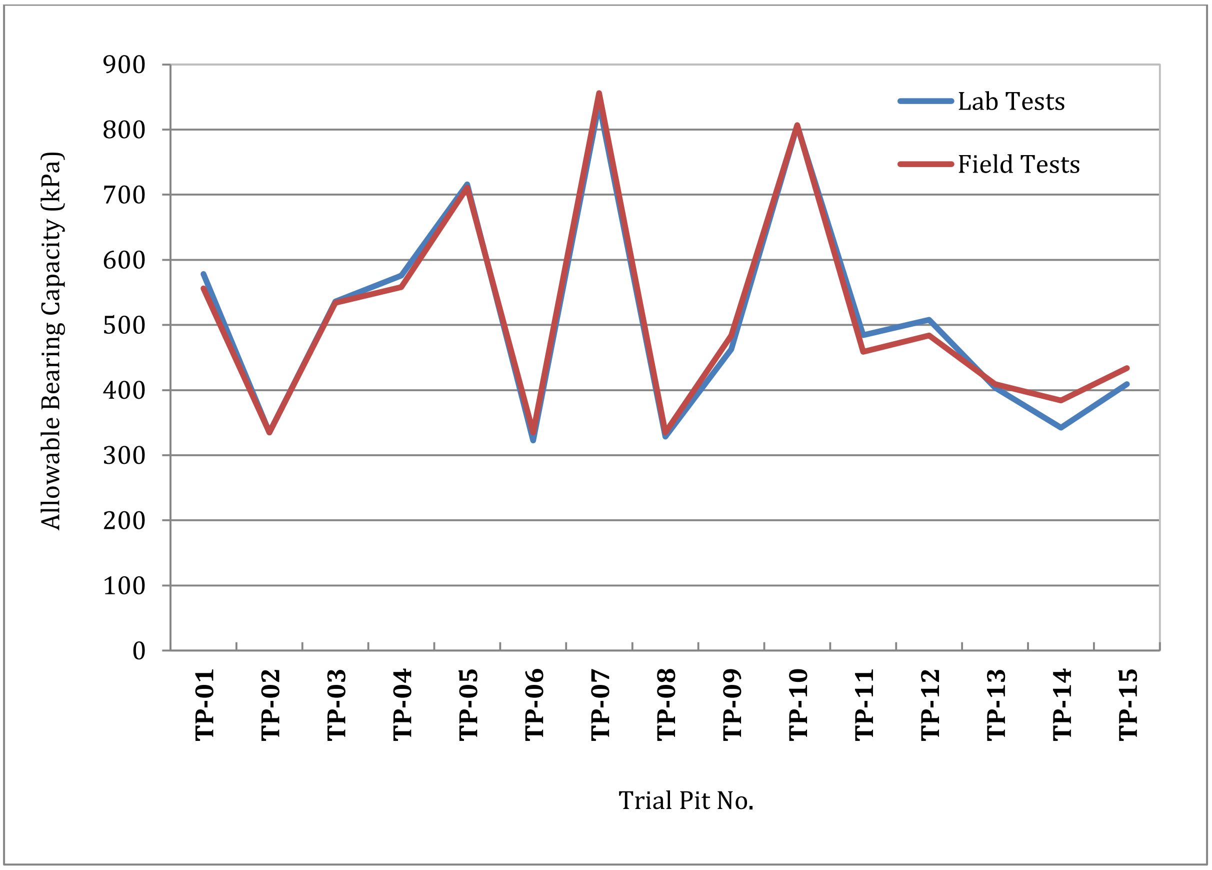

Figure 7: Bearing Capacity from Lab Tests and Field Tests at Zhemgang Town

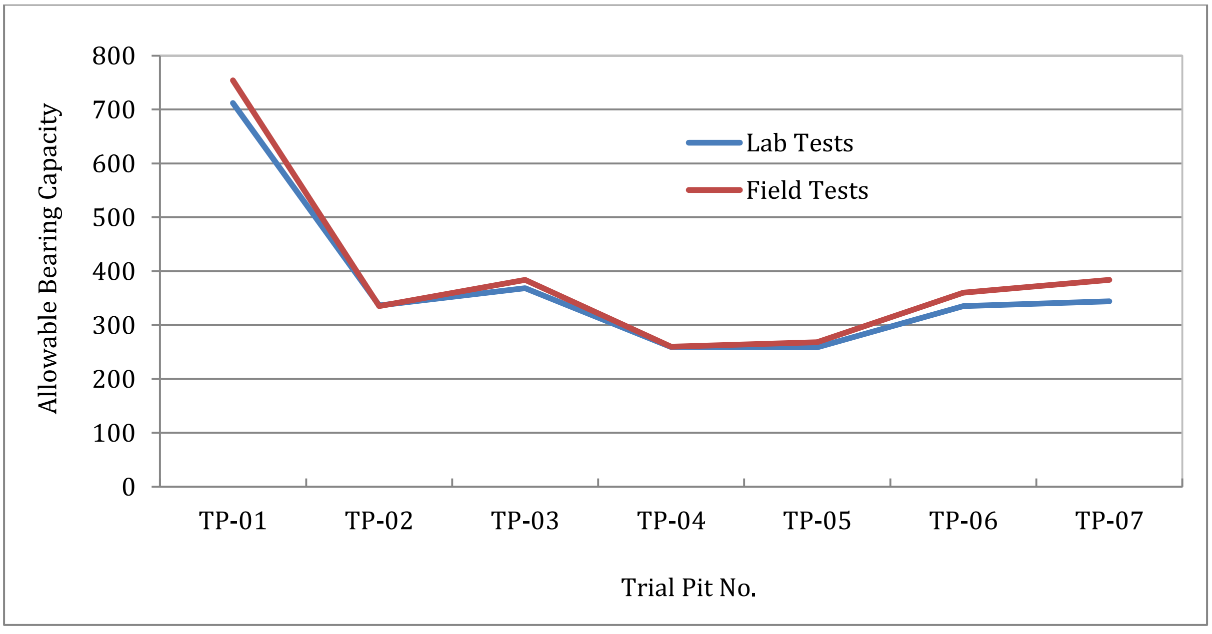

Figure 8: Bearing Capacity from Lab Tests and Field Tests at Tingtibi

2.9 Rock Mass Rating (RMR)

The unplanned excavation of rock slopes for site development and construction and road widening makes the slopes vulnerable. The exposed rock mass, which is already deformed, with steep cut slopes are prone to failure. There are several approaches to ascertain the quality of the rock mass. One of the most widely used methods is the Rock Mass Rating (RMR) technique given by Bieniawski. RMR is widely used as a method of classifying the strength of the rock mass. RMR values are derived from observations of the rock mass characteristics at different rock outcrops and testing of the materials of intact samples using field methods. The following five parameters are used to classify a rock mass using the RMR system (Bieniawski, 1989):

1. Uniaxial Compressive Strength (UCS) of rock material.
2. Rock Quality Designation (RQD).
3. Spacing of discontinuities
4. Conditions of discontinuities
5. Groundwater conditions

The rock mass classification as per RMR is given in **Table 17** for guidance. The RMR is a good indicator of the rock mass strength, which is related to its stability.

Table 17: Rock Mass Classification as per RMR (Bieniawski, 1989)

<table>
<tr><th colspan="2">Parameter</th><th colspan="7">Ranges of Values</th></tr>
<tr><td rowspan="2">UCS</td><td>Values</td><td>> 250 MPa</td><td>100-200 MPa</td><td>50-100 MPa</td><td>25-50 MPa</td><td>5 - 25</td><td>1 - 5</td><td>< 1</td></tr>
<tr><td>Rating</td><td>15</td><td>12</td><td>7</td><td>4</td><td>2</td><td>1</td><td>0</td></tr>
<tr><td rowspan="2">RQD</td><td>Values</td><td>90 - 100%</td><td>75 - 90%</td><td>50 - 75%</td><td>25 - 50%</td><td colspan="3">25%</td></tr>
<tr><td>Rating</td><td>20</td><td>17</td><td>13</td><td>8</td><td colspan="3">3</td></tr>
<tr><td rowspan="2">Joint Spacing</td><td>Values</td><td>> 2 m</td><td>0.6 - 2.0 m</td><td>200 - 600 mm</td><td>60 - 200 mm</td><td colspan="3">< 60 mm</td></tr>
<tr><td>Rating</td><td>20</td><td>15</td><td>10</td><td>8</td><td colspan="3">5</td></tr>
<tr><td rowspan="5">Joint Condition</td><td rowspan="4">Values</td><td>Very rough surfaces</td><td>Slightly rough surfaces</td><td>Slightly rough surfaces</td><td>Slickensided surfaces</td><td colspan="3">Soft gauge > 5 mm</td></tr>
<tr><td>No continuous</td><td>Separation< 1 mm</td><td>Separation< 1mm</td><td>OR gauge < 5mm thick</td><td colspan="3">OR</td></tr>
<tr><td>No separation</td><td rowspan="2">Slightly weathered wall</td><td rowspan="2">Highly weathered wall</td><td rowspan="2">OR separation 1 - 5 mm</td><td colspan="3">Separation > 5 mm</td></tr>
<tr><td>Unweathered wall</td><td colspan="3">Continuous</td></tr>
<tr><td>Rating</td><td>30</td><td>25</td><td>25</td><td>25</td><td colspan="3">0</td></tr>
<tr><td rowspan="2">Ground Water</td><td>Values</td><td>Completely dry</td><td>Damp</td><td>Wet</td><td>Dripping</td><td colspan="3">Flowing</td></tr>
<tr><td>Rating</td><td>15</td><td>10</td><td>7</td><td>4</td><td colspan="3">0</td></tr>
</table>

Each of the six parameters is assigned a value corresponding to the characteristics of the rock. These values are derived from field surveys and laboratory tests. The sum of the six parameters is the "RMR value", which lies between 0 and 100. The rock exposures of phyllites in Zhemgang Town indicate that the rock quality ranges from "very poor" to "poor" (**Table 18**). The bedrocks at Tingtibi are mainly quartzites and rock quality ranges from "fair" to "good" (**Table 19**).

Table 18: Results of Rock Mass Rating for Zhemgang

#	RMR Parameter	RE-01	RE-02	RE-03	RE-04	RE-05	RE-06	RE-07
1	UCS of intact rock (MPa)	30	50	20	1-5	5	10	<1
	Rating	4	7	2	1	2	2	0
2	RQD (%)	30%	25% -	<25%	<25%	<25%	<25%	<25%
	Rating	8	8	3	3	3	3	3
3	Spacing of Discontinuities	<60 mm	>200mm	<60mm	<60mm	<60mm	<60mm	<60mm
	Rating	5	10	5	5	5	5	5
4	Conditions of Discontinuities	soft gouge	soft gouge	soft gouge	soft gouge	soft gouge	soft gouge	soft gouge
	Rating	0	0	0	0	0	0	0
5	Groundwater	Wet	Wet	Wet	Wet	Damp	Damp	Wet
	Rating	7	7	7	7	10	10	7
	Overall RMR	24	32	17	16	20	20	15
	Rock Class	IV	IV	V	V	IV	IV	V
#	**RMR Parameter**	**RE-08**	**RE-09**	**RE-10**	**RE-11**	**RE-12**	**RE-13**	**RE-14**
1	UCS of intact rock (MPa)	30	10	5	30	15	20	15
	Rating	4	2	2	4	2	2	2
2	RQD (%)	40%	50%	<25%	<25%	30%	<25%	<25%
	Rating	8	8	3	3	8	3	3
3	Spacing of Discontinuities	<60 mm	<60 mm	<60mm	<60 mm	>100	<60mm	<60 mm
	Rating	5	5	5	5	8	5	5
4	Conditions of Discontinuities	soft gouge	soft gouge	soft gouge	soft gouge	soft gouge	soft gouge	soft gouge
	Rating	0	0	0	0	0	0	0
5	Groundwater	Wet	Completely Dry	Wet	Damp	Wet	Wet	Wet
	Rating	7	15	7	10	7	7	7
	Overall RMR	24	30	17	22	25	17	17
	Rock Class	IV	IV	V	IV	IV	V	V

Table 19: Results of Rock Mass Rating for Tingtibi

#	RMR Parameter	RE-01	RE-02	RE-03	RE-04	RE-05
1	UCS of intact rock (MPa)	>50	30	70	20	20
	Rating	7	4	7	2	2
2	RQD (%)	>50%	>25%	>25%	<50%	>50%
	Rating	13	8	8	13	13
3	Spacing of Discontinuities	0.6-2.0m	>200mm	>200 mm	>200mm	>200mm
	Rating	15	10	10	10	10
4	Conditions of Discontinuities	Slightly weathered	Highly weathered	Highly weathered	Highly weathered	Highly weathered
	Rating	25	25	25	25	25
5	Groundwater	Wet	Wet	Wet	Wet	Damp
	Rating	7	7	7	7	10
	Overall RMR	67	54	62	57	60
	Rock Class	II	III	II	III	III

3. HAZARDS ASSESSMENT

3.1 Geohazards

All types of possible hazards at the project site from different sources were studied and analyzed. The sources of hazards are either inherent or self-generated sources (such as weak geology, steep topography, presence of marshy area, etc.) or imposed sources (such as earthquake, uncontrolled water seepages, construction-induced, etc.). Based on detailed site investigation, landslides (due to weak geology of weathered phyllites and steep slope), floods from local stream and earthquakes were identified as the main hazards for Zhemgang Thromde (i.e. Zhemgang Town and Tingtibi).

3.2 Seismic Hazard Analysis

While the whole country, Bhutan is susceptible to earthquake hazard, the current project area is even more prone to seismic hazard due to its proximity to Main Central Thrust (MCT). A seismic hazard at a site is defined as a quantitative estimation of the most possible ground shaking at the site. The seismic hazard analysis requires the knowledge about some important factors in the neighborhood of the site. They include geologic evidence of earthquake sources, fault activity, fault rupture length, historical, and instrumental seismicity. Geologic evidence of earthquake sources is characterized by the evidence of ground movement of the two sides of a fault, disruption of ground motion, juxtaposition of dissimilar material, missing or repeated strata, topographic changes, and so on.

Fault activity is characterized by movements of ground at the fault region; it is the active fault that leads to future earthquakes. Past earthquake data regarding the relationship between the fault rupture length and the magnitude of earthquake provide valuable information for predicting the magnitude of future earthquakes and, thus, help in seismic hazard analysis. Historical records of earthquakes and instrumentally recorded ground motions at a site also provide valuable information on potential future earthquake sources in the vicinity of the site.

Deterministic hazard analysis (DSHA) is a simple procedure which provides a straightforward framework for the computation of ground motions to be used for the worst case design. DSHA consists of five steps:

1. Identification of all potential earthquake sources surrounding the site, including the source geometry.
2. Evaluation of source to site distance for each earthquake source. The distance is characterized by the shortest epicentral distance or hypocentral distance if the source is a line source.
3. Identification of the maximum (likely) earthquake expressed in terms of magnitude or any other parameter for ground shaking for each source.
4. Determination of the worst case ground shaking parameter at the site. Selection of the predictive relationship (or attenuation relationship) to find the seismic hazard caused at the site due to an earthquake occurring in any of the sources. Sudhir et al. give seismic wave attenuation relationship for northeast India as follows:

   $$\text{Ln PGA} = -3.443 + 0.706M - 0.828\ln(R);$$

   Where PGA is peak ground acceleration in g, r is the epicentral distance in km and M is the magnitude of earthquake.
5. Determination of the worst case ground shaking parameter at the site.

In terms of potential sources for earthquakes, it has been determined that MCT is the most likely source and capable of producing magnitude M7 earthquakes. The Zhemgang Town and Tingtibi are located at a distance of 25 km and 15 km respectively away from the rupture plane of MCT. Based on this information, the PGA at Zhemgang Town is computed as 0.312g while at Tingtibi, the PGA is slightly higher at 0.476g. Hence, these values should be taken as the horizontal acceleration of Maximum Credible Earthquake (MCE) for design of structures. It should be noted that these values are different from seismic coefficient of 0.360g given for Seismic Zone V of Indian Standard.

3.2 Flood Hazard

In areas adjacent to rivers, the risk of flooding should be taken into account. Zhemgang Town is safe from floods. However, there is flood risk at Tingtibi. Flood Engineering & Management Division, MoWHS had carried out a detailed flood assessment of Mangde Chhu sub-basin in Zhemgang Dzongkhag and produced a report title “Flood hazard Assessment for Zhemgang Dzongkhag” in 2019. The peak discharge profiles of Storm Floods and GLOF in Tingtibi from that report is shown in **Figure 8**. The peak discharge profiles from Cyclone Aila in 2009 and 100-years probable flood and the GLOF estimated in that study are shown. According to the study the peak discharge from the 100-year peak discharge is most significant for Tingtibi at 2,937 m^3/s. Based on the study, MoWHS has produced a flood map for Tingtibi as shown in **Figure 9**. This map shows that the current study area at Tingtibi is not vulnerable to floods from Mangde Chhu. However, a small part of Tingtibi situated at the left bank of Mangde Chhu at Mangde Zam is susceptible to floods from the adjacent stream (i.e. Dakpai Chhu). The soil investigation at this site also revealed river boulders and sand, indicating that this area is a floodplain. As shown in **Figure11**, Dakpai Chhu with its watershed area of 32,000 acres is capable of producing huge floods.

There is also another small stream (dry), which runs right through the main between existing Tingtibi Town and BPC Substation. The watershed for this stream is about 202 acres as shown in **Figure 11**. Currently, the natural channel of this watershed at Tingtibi has been block for construction of retaining walls and temporary structures. However, the streams can be fed by rains and there is risk of flooding from these streams during periods of heavy rain.

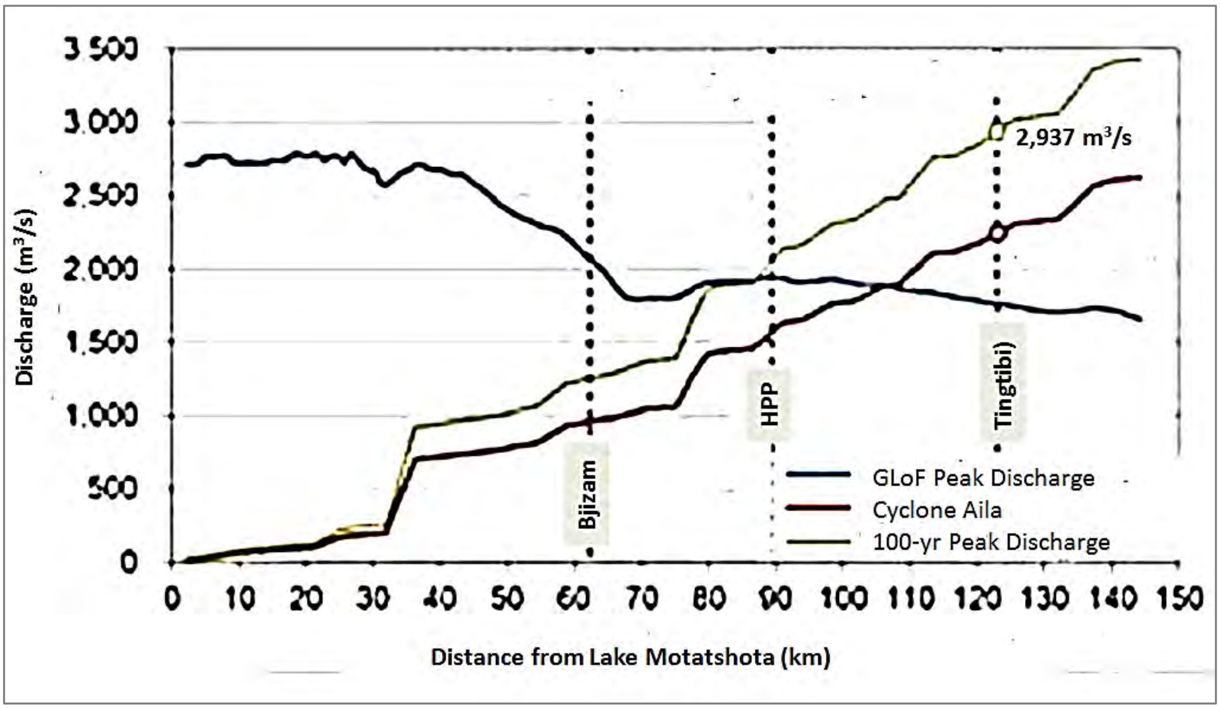

Figure 9: Peak Discharge of storm flood and GLOF at Tingtibi (Source: MoWHS)

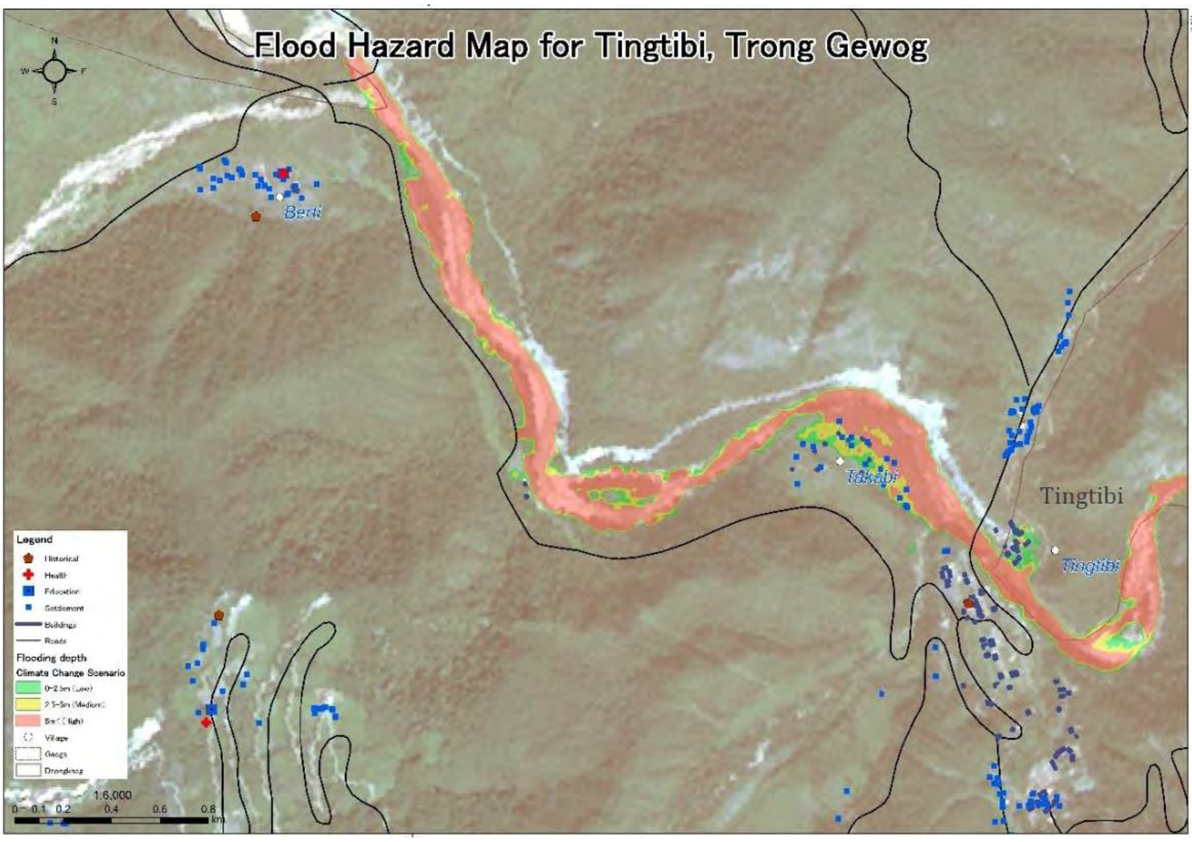

Figure 10: Flood Hazard Map of Tingtibi, Zhemgang (Source: MoWHS)

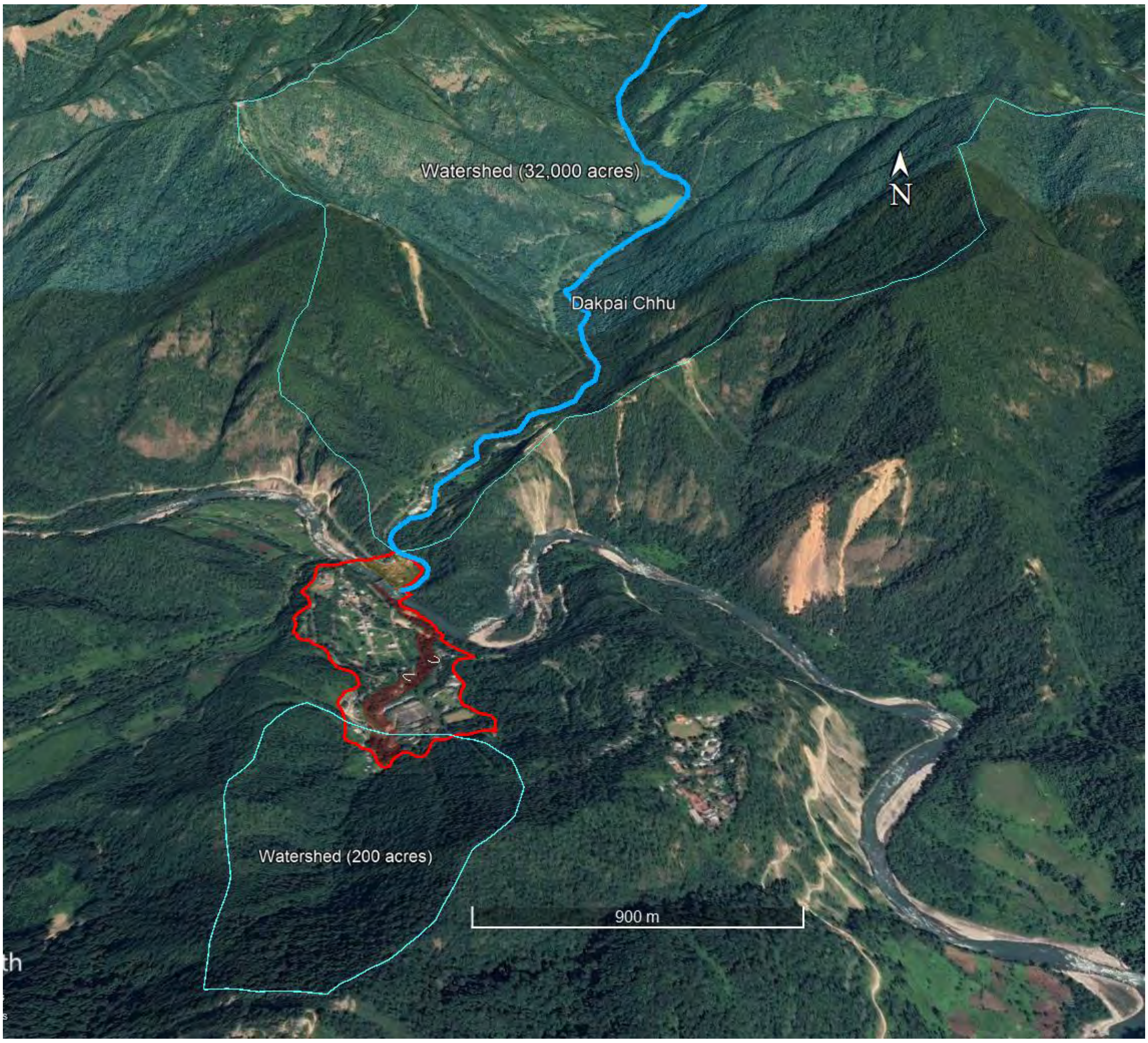

Figure 11: Watershed area for Tingtibi

3.3 Landslides, Ground Subsidence and Other Hazards

The slope profile of Zhemgang Town is shown in **Figure 12** and **Figure 13**. The average slope is only 17% or 10°. **Various studies have found that soil slips, which cause avalanche failures, commonly initiate on slopes greater than 33%;** slower moving earth flows occur most often on slopes 30% to 60%. Nevertheless, serious erosion can occur on much shallower slopes and the potential for erosion is greatest in the period between removal or disturbance of vegetation and re-establishment of new vegetation.

The starting point for landslide study is generally historical records of previous landslides, such as incidents on roads through mountainous regions. From the field survey, it was found that the study area in Zhemgang Town does not have any active landslide area. **However, an old landslide was observed at the south side of the Dzong, which sits on a remnant mound. The main Dzong structure is also located very close to the crown of this landslide. Furthermore, it was observed that the main Dzong and nearby structures have undergone different settlement.** Differential settlement is the term used in geotechnical engineering for a condition in which a building's support foundation settles in an uneven fashion, leading to structural damage. During the field investigation, we learnt that the area nearby the main Dzong is to be developed. **For this site development, it is highly recommended to conduct site specified geotechnical investigation to confirm the bedrock depth either through rotary core drilling or Seismic Refraction Tests.**

At Tingtibi, no ground subsidence or major active landslides were observed. The major hazard in this area is attributable to steep slopes and as mentioned earlier, a small portion of the town on the left bank of Mangde Chhu is susceptible to floods from Dakpai Chhu. The rainfall data for Zhemgang Dzongkhag is shown in **Figure 13**. It shows that annual rainfall in Zhemgang exceeds 580 mm in June and July.

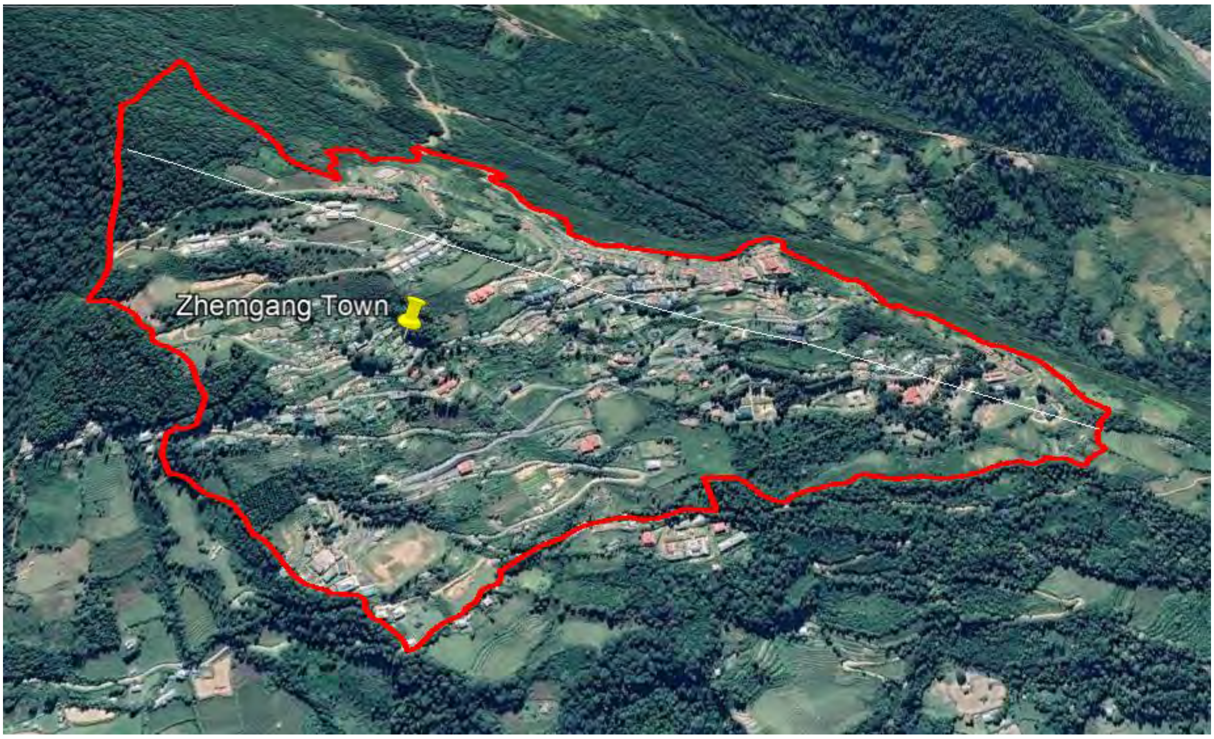

Figure 12: Zhemgang Town Study Area

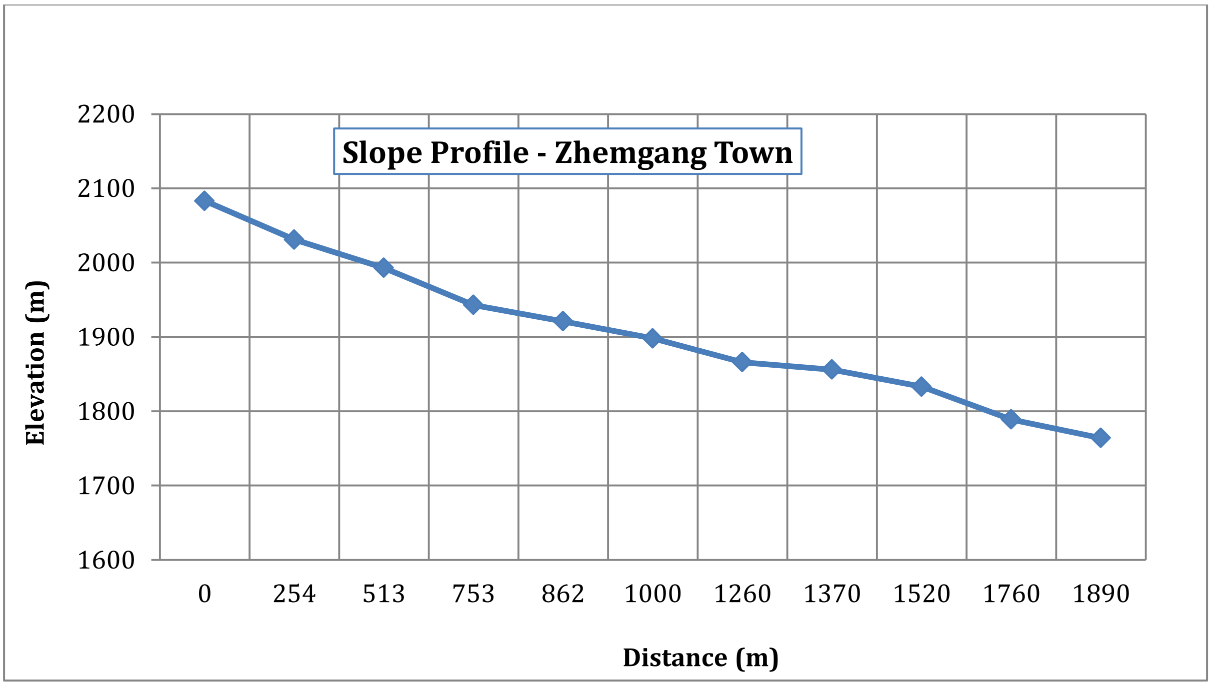

Figure 13: Slope profile of Zhemgang Town (10° slope or 17% slope)

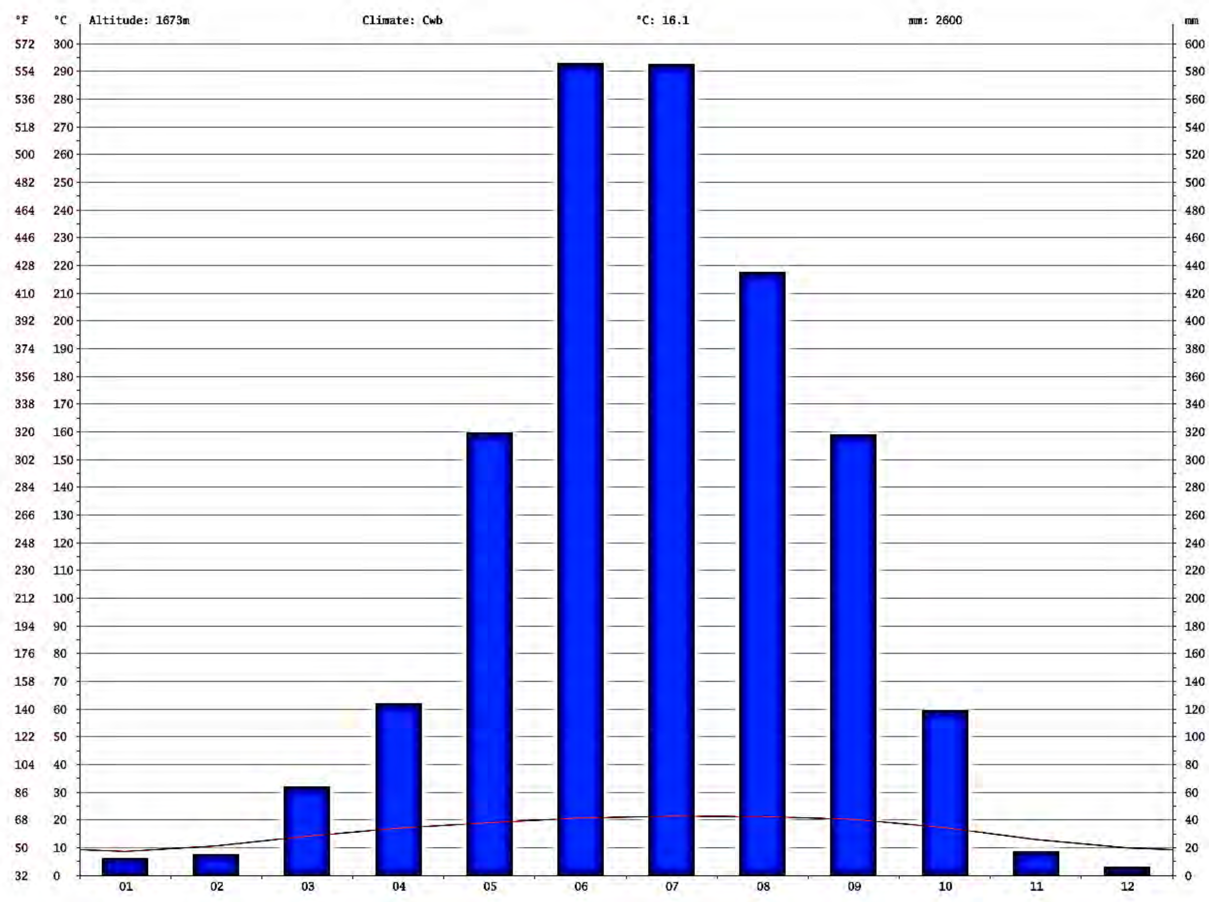

Figure 14: Mean monthly temperature (red line) and precipitation (blue bars) for Zhemgang (source: en.climate-data.org)

3.4 Hazard Mapping

The study areas were divided into 3 (three) hazard zones based on the slope angle of terrain, underlying geologic materials (weak geology due to weathered phyllites, etc.) geomorphology including landslides, gullies, depressions and susceptibility to floods. The hazard classifications at Zhemgang Town and Tingtibi are shown in **Table 20** and **Table 21**, respectively.

At the existing Zhemgang Town about 53% (147 acres) of the mapped area falls in the low hazard zone. About 37% (103 acres) of the mapped area falls in the medium hazard zone. Only 10% (26 acres) of the mapped area falls in the high hazard zone. Similarly, the low, medium and high hazards for Tingtibi are 31% (42 acres), 22% (29 acres) and 47% (63 acres), respectively. The most important natural hazards in terms of loss of life in the current area, however, are earthquakes, flooding (by adjacent screams), landslides and ground subsidence (due to presence of weathered phyllites and steep slopes).

Table 20: Hazard Classification at Zhemgang Town

HAZARD ANALYSIS FOR ZHEMGANG EXISTING TOWN					
#	Hazard Level	Hazard Criteria	Area		
			(km^2)	(Acre)	(%)
1	Low Hazard	Gentle slope with slope angle ranging from 0-20°. Minimal natural or geological hazard.	0.60	147.46	53%
2	Medium Hazard	Slope Angle between 20-30°; Minor ground subsidence, depression and marshy area(s). This type of hazard can be controlled by mitigation measures or other engineering solutions.	0.42	102.59	37%
3	High Hazard	Steep Slope, where slope angles are above 30°; Highly susceptible to landslides in case of continuous heavy precipitation and earthquake. Site specific geotechnical study is recommended for development in these areas.	0.11	26.25	10%
Total			1.12	276.30	100%

Table 21: Hazard Classification at Tingtibi

HAZARD ANALYSIS FOR TINGTIBI			
#	Hazard	Hazard Criteria	Area

	Level		(km^2)	(Acre)	(%)
1	Low Hazard	Gentle slope with slope angle ranging from 0-20°. Minimal natural or geological hazard.	0.17	42.22	31%
2	Medium Hazard	Slope Angle between 20-30°; Minor ground subsidence, depression and other geological hazard. This type of hazard can be controlled by mitigation measures or other engineering solutions.	0.12	28.97	22%
3	High Hazard	Steep Slope, where slope angles are above 30°; Highly susceptible to landslides in case of continuous heavy precipitation and earthquake; Ground Subsidence/Depression; Area(s) within Natural Drainage and Flood Prone Areas.	0.25	62.73	47%
Total			0.54	133.91	100%

4. MITIGATION PLANS AND RECOMMENDATIONS

The basic goals of geologic and geotechnical data analysis and interpretation are to increase knowledge and understanding of site conditions, both surficial and subsurface through evaluation of data collected. These efforts begin with the field observations that are later supported by laboratory evaluations. Geotechnical conditions are part of geologic conditions, which exist close to the ground surface and are more related to construction and human activities. Examples of problematic geotechnical conditions at the study area (Zhemgang Thromde) are existence of problematic geology (highly fractured and weathered bedrock of phyllites), steep natural slopes and floods. Human activities, mainly the construction of buildings, roads and other structures, could also worsen the existing geotechnical conditions. The mitigation plans are proposed based on geotechnical/geological engineering interpretation/ judgment of fieldwork, field tests, laboratory reports and literature references.

4.1 Slope Stabilization Measures

Slope instability was not seen as critical issues at the present Zhemgang Town. This is because the area is sparsely developed with little population. However, if the entire area is developed with buildings and roads, the probability of slope related hazards such as landslides are highly likely. This is because the proposed area is a hillslope underlain by weak rocks (phyllites), which are highly prone to landslides. Elsewhere in Bhutan, where the area was underlain with phyllites, landslides have been a huge challenge. Therefore, down-slope movements of the ground can be triggered by a relatively minor change of circumstances at the study site. In other words, site development could introduce land instability issues due to inherently weak geology of phyllites.

Physical methods of slope stabilization can be divided broadly into measures to reduce runoff (terracing, diversions, waterways, conservation ponds), methods to stabilize slopes and reduce erosion (retaining walls, soil nailing, rock bolting, grouting, etc.), and integrated methods to address specific problems (gully control, trail improvement), although they all tend to have multiple functions. A summary of slope stabilization methods are given in **Table 23**. Some of the important measures are described in the following sections.

Table 22: Slope stabilization methods researched

Stabilization Method	Source of Background Information
Drainage pipes, wells, and channels	Cornforth (2005) Ch. 17
Dewatering	Coduto et al. (2011) Ch. 11
Vegetation	Abramson et al. (2002) Ch. 7
Buttressing / rip-rip	Abramson et al. (2002) Ch. 7
Geosynthetics	Gee (2015)
Remove and replace	Duncan & Wright (2005) Ch. 16
Re-grading and benching	Cornforth (2005) Ch. 15
Lightweight fill	Abramson et al. (2002) Ch. 7
Retaining walls	Cornforth (2005) Ch. 19
Soil nails / rock bolts / tieback anchors	Abramson et al. (2002) Ch. 7
Mechanically stabilized earth embankments	Abramson et al. (2002) Ch. 7

(a) Drainages

A common cause of slope failure is the presence of groundwater in the soil. An increase in porewater pressure (due to groundwater) leads to a decrease in effective stress (σ'), which in turn leads to decrease in soil shear strength. Therefore, one of the easiest and cheapest ways to stabilize the slope is to control groundwater and surface water entering the soil/ground.

Drainage decreases the amount of water in the slope material. Surface drains, trenches, horizontal drains, and drainage wells are methods to control water. Surface drains limit the amount of infiltration into the soil. Trenches, drains, and wells divert water away from slopes. Placement of drainage features in the lower part of a slope can increase slope stability. Surface drainages should be provided at top of cut and fill slopes. **Figure 15** shows a simple example of drainage feature use. Horizontal pipe drains at the bottom of trenches can channel water away.

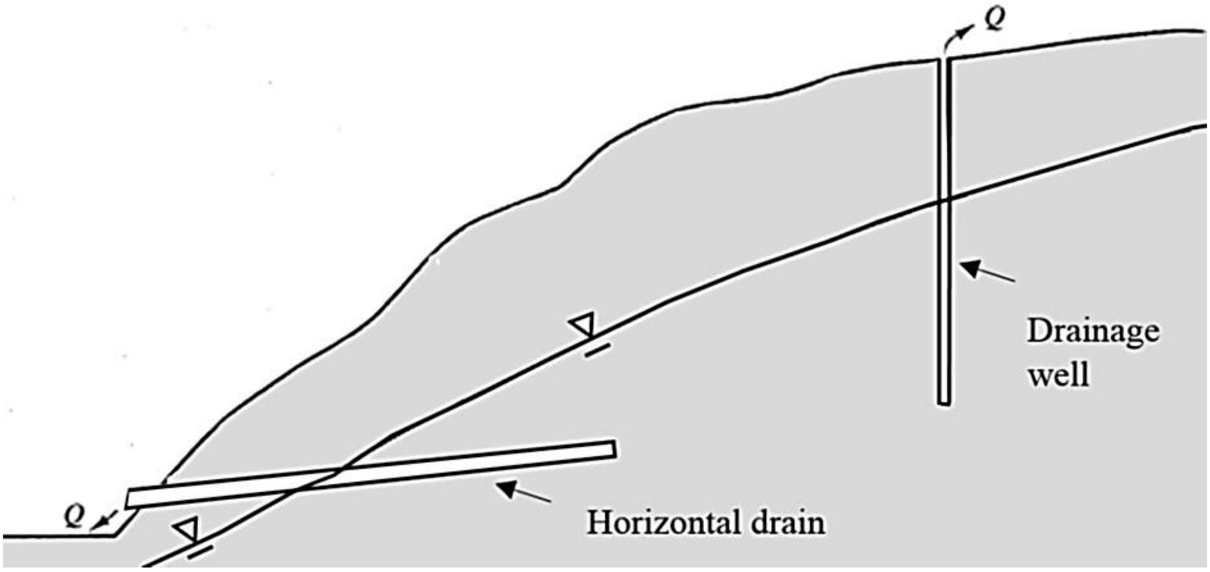

Figure 15: Example of common drainage features (from Coduto et al., 2011)

(b) Geometrical Method (Benching or Terracing)

This is the most common method that has been used in residential areas. This method is usually simple and less costly. The changing of the slope angle from steep slope to a gentler slope increases the stabilization of slope (**Figure 16**). This method has been used in all the mining projects in Bhutan. Terracing is the technique of converting a slope into a series of horizontal step-like structures with the aim of controlling the flow of surface runoff (by guiding the runoff across the slope and conveying it to a suitable outlet at a non-erosive velocity); reducing soil erosion by trapping the soil on the terrace; and creating flat land suitable for development. Terraces can be made in a variety of ways. The best approach depends on many factors including the steepness of the slope, the intended use, and the soil. The terraces are easily constructed. The spacing between the terraces depends on the slope of land; the distance between terraces goes down as the slope increases. Benching, also called terracing, allows the use of sections steeper than the overall slope.

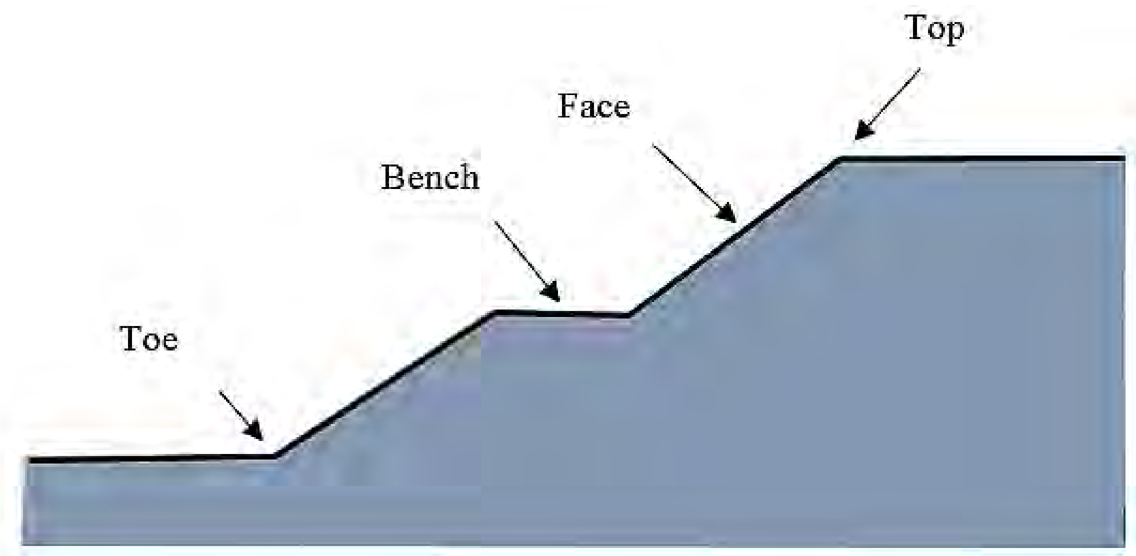

Figure 16: Benching/terracing on slope

(c) Buttressing

Buttressing is another method to stabilize a slope. It is basically placing a soil or rock mass against a slope face to add stabilizing force and decrease the overall slope height as shown in **Figure 17.** Buttressing can be as simple as pushing material against the slope. Temporary buttresses can provide cover and stabilizing support for construction projects. For temporary slopes left steeper than ideal, buttressing is a way to add stability.

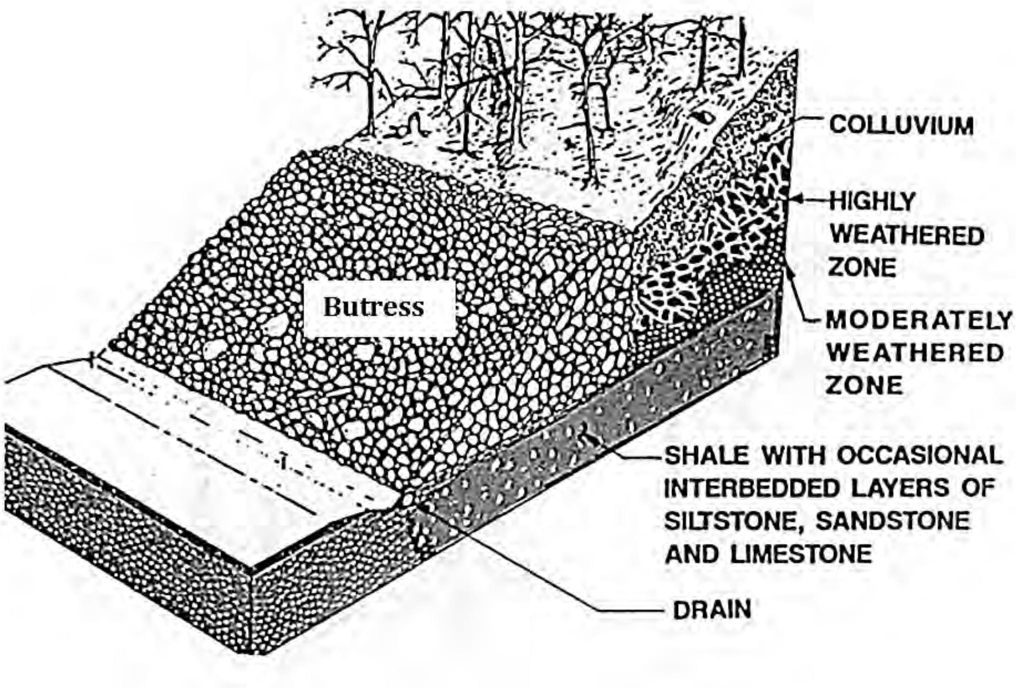

Figure 17: Rock Butress used to control unstable slope

(d) Reinforced Structures

Installing reinforcing structures can increase resisting forces and improve Factor of Safety (FOS). There are standardized design approaches for many stabilizing structures. Retaining wall is an option for projects in which space is an issue. A well-designed and constructed retaining wall enables design teams to work around severe grade changes (**Figure 18**).

Engineered retaining walls with both surface and subsurface drainage should be constructed prior to the building. Retaining walls should be provided with a drainage system extended at least two-thirds the height of the wall. At the base of the drain system, a subdrain covered with a minimum of 12 inches of gravel should be installed, and a compacted fill blanket or other seal placed at the surface. The clean bottom and subdrain pipe, behind a retaining wall, should be observed by the competent Geotechnical Engineer, prior to placement of gravel or compacting backfill. The concept of active and passive earth pressures may be taken in to due consideration for the design of the retaining walls to support slopes in the soil. All retaining walls are recommended to be designed by a competent Geotechnical Engineer.

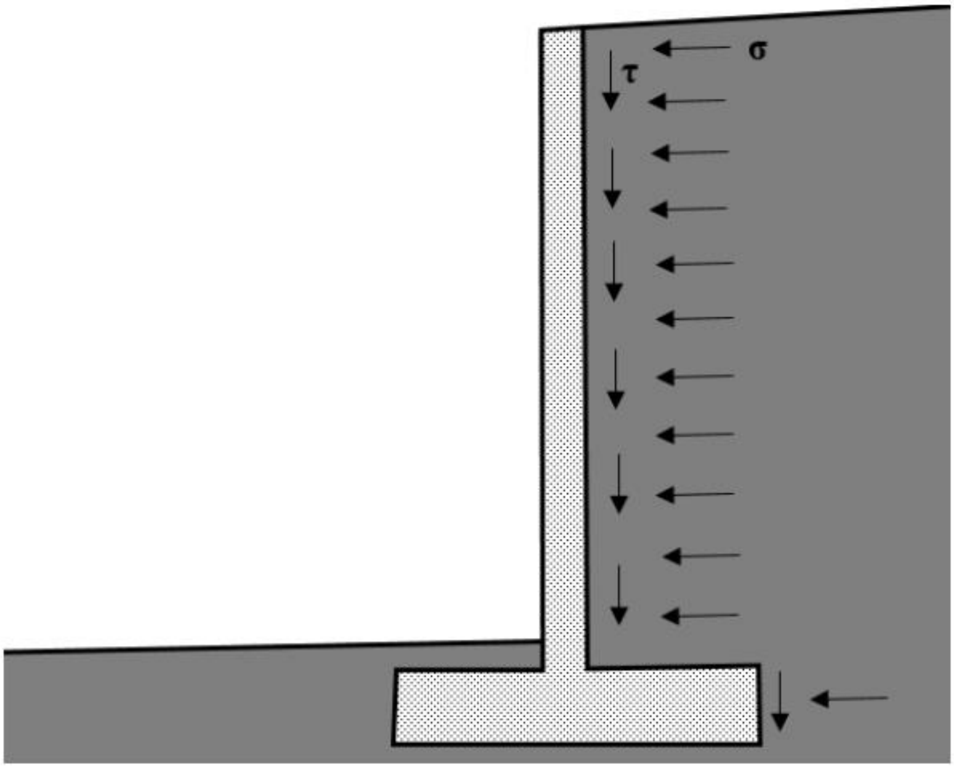

Figure 18: Retaining wall with lateral earth pressure shown (Coduto et al., 2011)

4.2 Mitigation Measures for Earthquakes

Effective means of protecting structures from earthquake forces are by way of using various methods of structural control. They are not only effective for mitigating earthquake forces, but also are equally useful in controlling undesirable vibrations of structures produced due to wind and other dynamic excitations.

A basic element in earthquake design is the calculation of the active or passive seismic pressures against the retaining structure during seismic excitation. For all the critical structures, appropriate seismic coefficients and pressures (both active and passive) based on the ground characteristics and closeness of the site to the fault is necessary. The PGA at Zhemgang Town is computed as 0.312g while at Tingtibi, the PGA is slightly higher at 0.476g. Hence, these values should be taken as the horizontal acceleration of Maximum Credible Earthquake (MCE) for design of structures.

4.3 Planning of Site Layout

Hill-site development plan should be done in a way to suit the natural contour and minimize cut and fill of earthworks. It is also important to orient the building layout to minimize potential differential settlement, especially if parts of the buildings fall on fill material. This can be achieved by arranging the longitudinal axis of the building along the contour lines of the original topography.

The structures should be design to maintain the hillside character of the site by minimizing the disturbance to the terrain, avoiding cuts or fills unless they are absolutely necessary.

4.4 Soil and Excavation Characteristics

The in-situ soils can be generally excavated with moderate effort using conventional excavation equipment. Caving should be anticipated in unshored excavations, especially if the depth of the excavation is more than 2.0 m. All onsite excavations must be conducted in such a manner that potential surcharges from existing structures, construction equipment, and vehicle loads are resisted. The soils encountered near the proposed foundation level are considered to have a “very low” expansive potential based on the granular nature of the soil and are classified as “non-expansive”. The recommendations presented herein assume that the building foundations and slabs will derive support in these granular soils or bedrocks.

4.5 Excavation of Cut Slopes

Permanent excavation cut slopes may be included in the site development. Cut slopes should not exceed 3 m in height and should not be steeper than about 1V:2H (i.e. 1 vertical to 2 horizontal) for most soils. Permanent cut slopes of greater than 3 m or steeper than 1V:2H must be analyzed on a site specific basis by a competent geotechnical engineer. With excavations of any kind, care must be taken to avoid weakening the stability of existing buildings.

Cutting and filling should be minimized during development of the site for construction. Fill material should be reused on site wherever possible. The natural drainage lines should not be blocked during excavations.

4.6 Backfilling and Compaction

Place backfill adjacent to any and all types of structure and compact to at least 90% of laboratory Maximum Dry Density (MDD). Prepare ground surface on which backfill is to be placed as a smooth surface. Do not fill over existing vegetation and topsoil. Do not include stumps, trees, vegetation, topsoil, boulders, building rubble, etc in the fill.

4.7 Site Grading

Grading is anticipated to include excavation of site soils for foundations as well as placement of backfill for walls. The existing residual and colluvial soils encountered during exploration can be re-used as an engineered fill, provided any encountered oversize material (greater than 15 cm) and any encountered debris are removed. Deleterious debris such as wood and root structures should be exported from the site and should not be mixed with the fill soils.

If construction is performed during the rainy season and the excavation bottom becomes saturated, stabilization measures may have to be implemented to prevent excessive disturbance of the excavation bottom. All foundation excavation bottoms must be observed and approved in writing by the Geotechnical Engineer, prior to placing bedding sands, fill, gravel or concrete.

The ground surface adjacent to the structure should be sloped to promote water flow away from the foundation system and flatwork. Water flow from the roof of the structure should be captured and directed away from the structure. Care should be taken to not direct water onto adjacent property or to areas that would negatively influence existing structures or improvements.

4.8 Foundation Design

The proposed building structures may be supported on conventional continuous and/or isolated spread footings bearing on natural, undisturbed soil or weathered bedrock. Foundations should be deepened as necessary to penetrate through unsuitable soils and derive support in the competent undisturbed residual soils or bedrock. Where allowable bearing less than 150 kPa is encountered, pier foundation on rock or mat foundations are recommended.

All the building foundations must be designed by a competent geotechnical engineer, to withstand the geologic forces anticipated to be exerted by the specific soil condition. In order to be sure that the structure is being placed in a location which has an acceptable level of geologic hazard risk, and the best soil conditions, it is recommended that a site specific soils test be performed prior to the final design of the structure.

4.9 Buildings in Floodplain

A small parcel of land, situated on the left bank of Mangde Chhu at Tingtibi, is vulnerable to floods from Dakpai Chhu. This is a low lying area marked as alluvial deposit or RBM in the Engineering Geology Map. Floodplain is a zone of alluvial deposition along valley floor, subject to periodic flooding. The alluvium builds up over time, much of it formed as overbank flood deposits, which are mostly fine grained and horizontally bedded.

Flooding is natural and inevitable on floodplains. The average rainfall is no longer a good guide to the likely effects because instances of localized but more intense rainfall are becoming more common – an effect of climate change. Furthermore, it is highly possible that the narrow stream channel could be blocked by trees and debris during floods. The breakage of such a dam could lead to damaging consequences. Further, the watershed area of Dakpai Chhu is huge at 32,000 acres. Therefore, it is strongly recommended that this flood plain be left as open space and not use for settlement or construction of buildings.

4.10 Construction Monitoring

Construction monitoring including geotechnical engineering observations and materials testing during construction is one of the most critical aspect of the geotechnical engineering contribution to any project. Unexpected subsurface conditions are often encountered during construction. The site foundation excavation should be observed by the geotechnical engineer during the early stages of the site construction to verify that the actual subsurface soil and water conditions were properly characterized as part of field exploration, laboratory testing and engineering analysis. If the subsurface conditions encountered during construction are different than those that were the basis of the geotechnical engineering report then modifications to the design may be implemented prior to placement of fill materials or foundation concrete.

Compaction testing of fill material should be performed throughout the project construction so that the engineer and contractor may monitor the quality of the fill placement techniques being used at the site. Generally we recommend that compaction testing be performed for any fill material that is placed as part of the site development. Compaction tests should be performed on each lift of material placed in areas proposed for support of structural components. In addition to compaction testing we recommend that the grain size distribution, clay content and swell potential be evaluated for any imported materials that are planned for use on the site.

4.11 General Recommendations

a) For slopes greater than 20° post and beam construction should be used which steps with the site. This may include a lower part level with a concrete slab as shown in **Figure 19**. Single slab on ground construction should not be used. Building on stilts is another way of addressing steeply sloped sites. This avoids the need for expensive foundations. The other benefit is that it leaves the ground untouched. The lowest floor of the house should be designed above the seasonal high water table. If a basement is built below the water table, input should be sought from a geotechnical engineer for dewatering techniques.

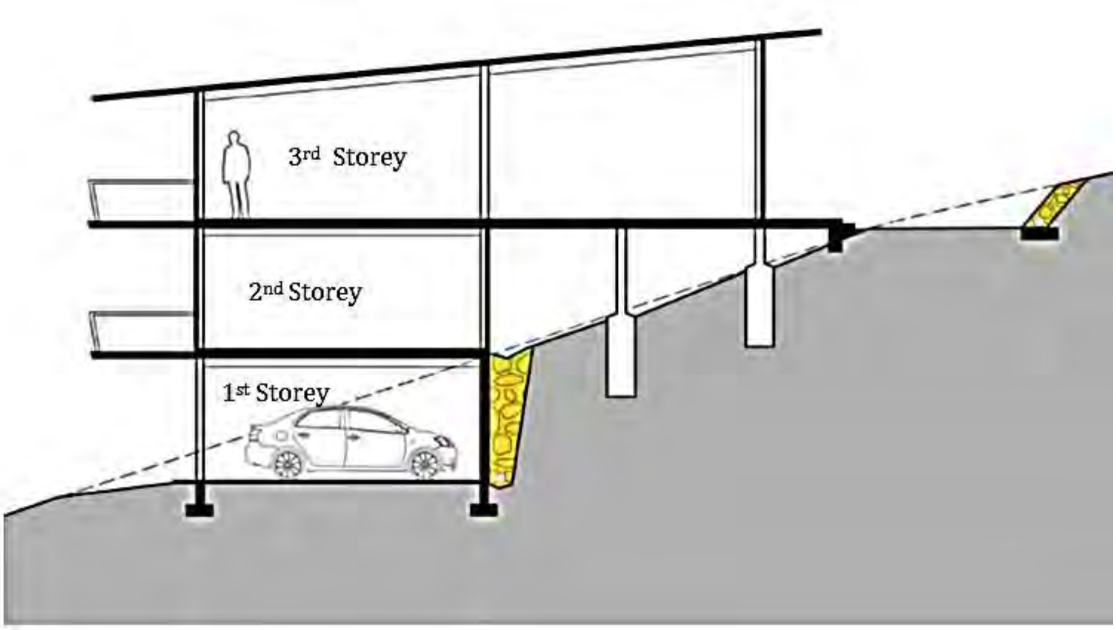

Figure 19: Building foundation at different levels on a slope

b) On slopes greater than 20°, it is recommended to limit the height of the building to 3 (three) storeys. Furthermore, recommended ground coverage should not be more than 20% on such slopes.

c) Building techniques are available to enable development of many higher risk sites. Inappropriate development on the site and neighboring properties can cause slope failure and serious damage. Inappropriate development includes:
   - unsupported excavation or placement of fill.
   - excessive clearing of vegetation.
   - introduction of water to the slope.
   - surface footings founded on the mantle of soil and rock fragments.

d) Sheet Pile Wall should be used to retain a soil or water for a specific period of time, whenever we excavate near existing building or other structures. For example; if we want to build a structure with a basement floor (underground) and this structure is surrounded by other structures, when the excavation process starts, if the soil under the surrounding structures is not retained by sheet pile, this soil will fail and move to the excavation site, and the structure above this soil may collapse suddenly, so before establishment of excavation process, sheet pile must be constructed to retain this soil and prevent it from failing.

e) Finally, it must be remembered that the owner's decision to develop the site on a hill generally involves an acceptance of a level of risk following development as assessed by the consultant. Even with suitable hillside construction techniques some minor cracking may occur.

5. CONCLUSIONS AND DISCUSSIONS

At the existing Zhemgang Town about 53% (147 acres) of the mapped area falls in the low hazard zone. Infrastructure development work may be carried out in low hazard areas with some geotechnical measures and normal engineering practice. About 37% (103 acres) of the mapped area falls in the medium hazard zone. Construction for the development of infrastructure can be allowed in this medium hazard zones after carrying out the proper remedial measures. Engineering practices suitable to hillside construction and floodplain development as recommended in this report are necessary.
Only 10% (26 acres) of the mapped area falls in the high hazard zone. Construction or the development of infrastructure should be controlled in the high hazard zone. High

hazard zones are recommended to be developed as a green belt. For any construction in “high hazard zones” i.e. red zones, it is recommended that a separate “Site Specific Geotechnical Report” and “Geotechnical Letter of Assurance” be prepared by a competent Geotechnical Engineer. The construction in “High Hazard Zone” may be allowed only upon the approval of such a report by the competent authority, which may be DHS or another agency designated by MoWHS. Similarly, the low, medium and high hazards for Tingtibi are 31% (42 acres), 22% (29 acres) and 47% (63 acres), respectively.

The information presented in this report is based on our understanding of the proposed development plan that was made know to us and on the data obtained from our field and laboratory studies. Our recommendations are based on limited field and laboratory sampling and testing. Unexpected subsurface conditions encountered during construction may alter our recommendations. We can be contacted during construction to observe the exposed subsurface soil conditions to provide comments and futher verification of our recommendations. We are available to review and tailor our recommendations as the project progresses.

6. LIMITATIONS AND UNIFORMITY OF CONDITIONS

The mitigation measures and recommendations in this report pertain only to the site investigated. They are based upon the assumption that the soil conditions do not deviate from those revealed in the investigation through trial pits, DCPTs and site survey. If any variations or undesirable conditions are encountered during construction, or if the proposed construction differs from that anticipated herein, Alpha Geotech and Company should be notified so that supplemental recommendations can be given albeit at additional cost.

This report is issued with the understanding that it is the responsibility of the project owner, or of his representative, to ensure that the information and recommendations contained herein are brought to the attention of the urban planners, architects and engineers for the project and incorporated into the plans, and the necessary steps are taken to see that the plot owners and contractors carry out such recommendations in the field.

The findings of this report are valid as of the date of this report. However, changes in the conditions of a proposed project land can occur with the passage of time, whether they are due to natural processes or the works of man. In addition, changes in applicable or appropriate standards may occur, whether they result from legislation or the broadening of knowledge. Accordingly, the findings of this report may be invalidated wholly or partially by changes outside our control. Therefore, this report is subject to review and should not be relied upon after a period of certain period, usually three years.

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