GEOTECHNICAL REMEDIATION STRATEGIES FOR THE ANCIENT MONASTERY OF DANGKHAR

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Geotechnical Remediation Strategies for the Ancient Monastery of Dangkhar Spiti Valley, Himachal Pradesh, India

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1.0 Introduction

Dangkhar Village, located within the Spiti Valley of Himachal Pradesh in northern India (Fig. 1.1), is the site of the historically significant Buddhist monastery of Dangkhar. Parts of the ancient Dangkhar monastery are estimated at over 1,000 years old, and it is considered as one of the five major monastic centers of the Spiti Valley.

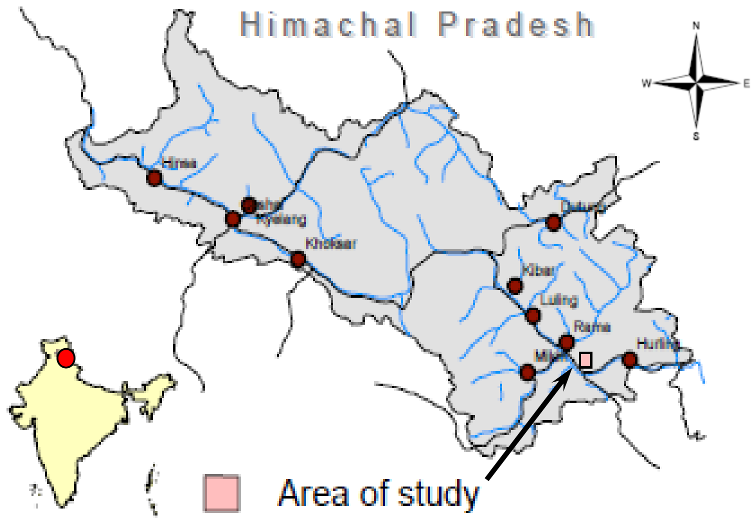

Figure 1.1 Location of the Dangkhar Monastery in Himachal Pradesh, India.

As a result of local architectural and structural deficiencies, usage of the Ancient Monastery has been restricted, and a new monastery has recently been built at a site located about 350 m to the east. Figure 1.2 provides an overview of Dangkhar Village, together with the Castle of the Nono and ancient and new monastery building locations. The building deficiencies are related to original design and construction methods, longevity of aging construction materials, and irregular maintenance and repairs. Geotechnical processes have also resulted in localized cliff encroachment and undermining of foundation elements.

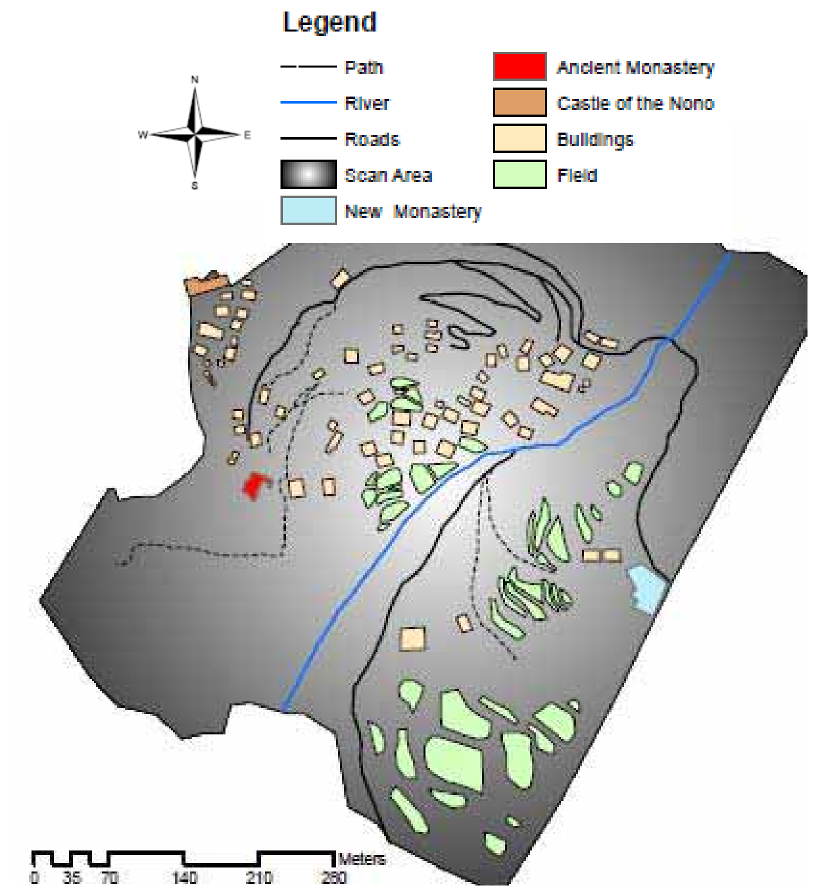

Figure 1.2 Overview of Dangkhar Village, showing locations of the ancient and new monasteries

Cliff erosion is a long-term and ongoing processes, and as depicted in Figure 1.3 through 1.5, has likely contributed to the abandonment and/or destruction of several buildings that formerly occupied the cliffs of Dangkhar. Figure 1.3 shows two historical portrayals of the Ancient Monastery and surrounding buildings (the first is an artist's portrayal from an 1891 publication, and the second, a photograph from Khosla, 1979). As indicated therein, several significant structures surrounding the Ancient Monastery are no longer in existence. The date of the historical photograph (Khosla, 1979) is unknown, but considering that the author collected such photographs during his expeditions to the Western Himalayas, its vintage is judged to lie within the 1960's to 1970's. Figure 1.4 depicts the existing condition of the Ancient Monastery from a similar viewpoint, and indicates the areas of prior significant structures. Figure 1.5 shows the remnants of several building foundations within these areas.

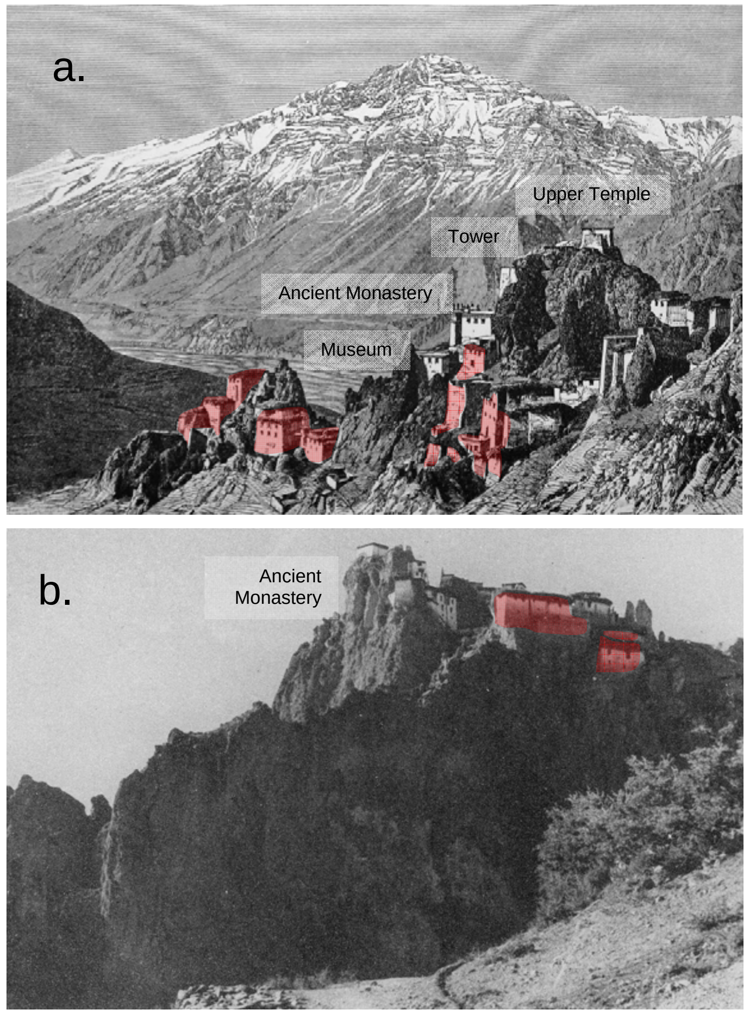

Figure 1.3. Historical portrayals of the Ancient Monastery and surrounding buildings: (a) artist's rendition (Reclus, 1891), and (b) photograph from Khosla, 1979. Red shaded structures no longer exist.

Figure 1.4. Condition of the existing Ancient Monastery, showing approximate areas of prior significant structures as indicated by historical portrayals.

Figure 1.5 Foundation remnants within Areas 1 and 2 of Figure 1.4 (arrows point to the foundation - earth interface).

In an effort to save the culturally significant Ancient Monastery, the *Dangkhar Initiative* was established in 2006. The initiative seeks to combine architectural, structural, and geotechnical conservation, with a sustainable resource-generating program to support the local community, facilities maintenance, and operation. This report represents a contribution to the *Dangkhar Initiative* and focuses on geotechnical remediation strategies for the Ancient Monastery and affiliated buildings.

1.1 Purpose and Scope of Report

The main purpose of this report is to summarize geotechnical processes that are relevant to the long-term stability of the Ancient Monastery and the Castle of the Nono, together with conceptual remediation strategies for mitigating adverse geotechnical conditions and processes. In developing mitigation strategies, preference was given to solutions involving local construction materials and contractor capabilities, rather than sophisticated modern technologies that would have to be imported to the site at great expense.

The information summarized herein is based on the following scope of work:

- Review of available literature pertinent to regional geologic and seismic conditions;
- Geologic mapping, field documentation, and completion of a comprehensive 3D LiDAR (Light Detection And Ranging) site survey, from June 25 to July 3, 2011; and,
- Geotechnical evaluation.

2.0 Geologic and Seismic Setting

The geology of the Himalaya records the process of major continental tectonic collision. As depicted in Figure 2.1, the India land mass has drifted northward for more than 70 million years (My). As the Indian and Eurasian continental masses neared, subduction of oceanic crust occurred, and continued until final closure of the ancient Tethys Ocean. With closure of the ocean, collision of the continental plates commenced, with the Himalayas and Tibetan Plateau being the main manifestation of approximately 55 My of continent-to-continent tectonic collision (Fig. 2.1b).

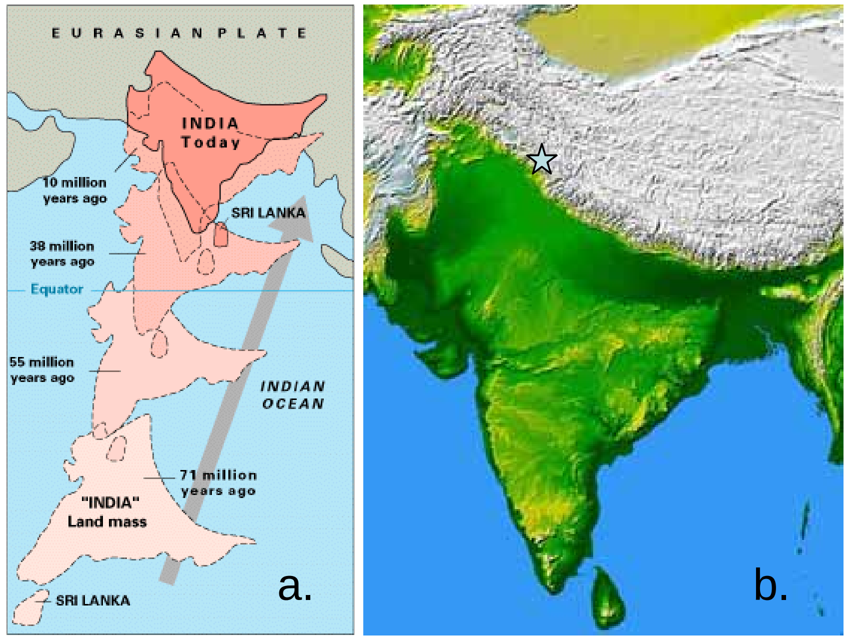

Figure 2.1 (a) Tectonic motion of the Indian land mass over the past 71 million years (http://pubs.usgs.gov/gip/dynamic/himalaya.html), and (b) the Himalaya and Tibetan Plateau: the result of plate collision (site location indicated by star) (NASA Earth Observatory SRTM data).

As shown in Figure 2.2, four major lithologic/tectonic zones comprise the Himalayan orogen, with Dangkhar Monastery being situated within the Tethys Himalaya unit. The Tethys Himalaya represents a composite synclinal structure having a width of approximately 100 km and a length of over 2000 km. The unit includes weakly metamorphosed sedimentary rocks that were originally deposited in the Tethys Ocean basin, then uplifted, faulted, and strongly deformed during the mountain building process. As depicted in Figure 2.3, the Tethyan Himalaya is bordered to the south and north by the Zanskar Shear Zone and Indus Suture Zone, respectively.

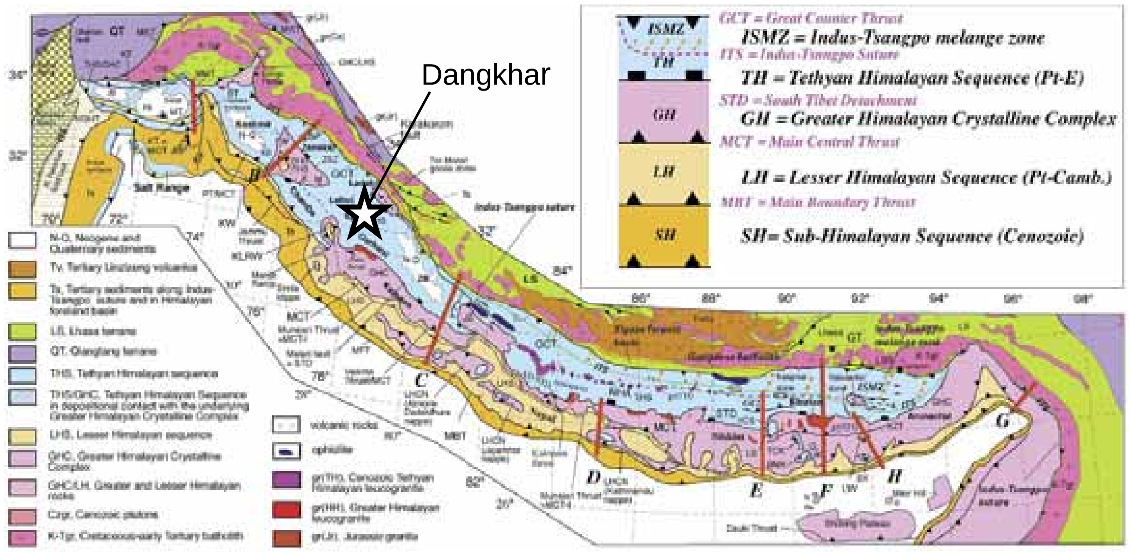

Figure 2.2 Regional geology of the Himalayas, showing major lithologic/tectonic units (Yin, 2005).

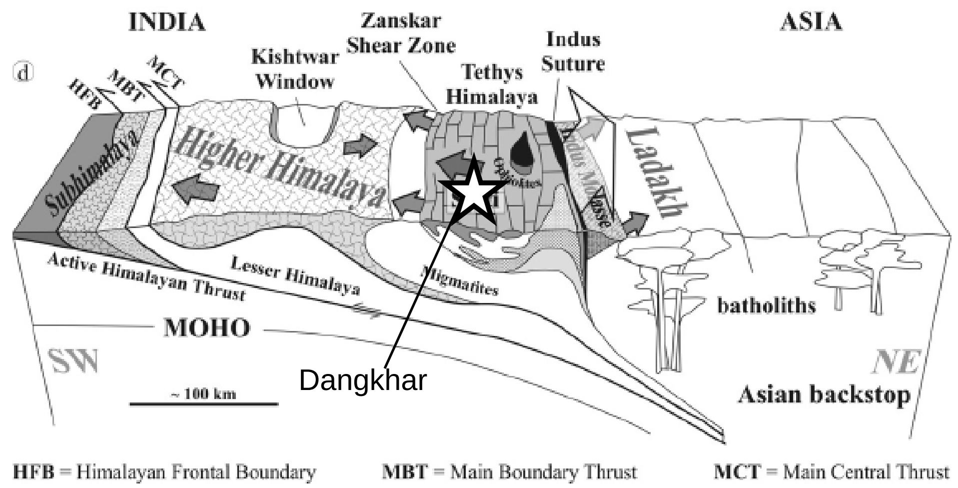

Figure 2.3 Geologic cross section through the Himalayas, showing major lithologic/tectonic units (Yin, 2005).

2.1 Regional Geology

The geology of the Spiti Valley includes Paleozoic successions of shale, sandstone, limestone and metasediments (e.g. quartzites, marble, and slate). Mesozoic formations are also present, and in the site vicinity include the Jurassic age Kioto limestone, the Triassic (?) Spiti shale and the Cretaceous age Giumal sandstone. Structurally, the Spiti Valley is situated in a pull-apart basin lying between the northwest-trending right lateral Karakoram Fault System along the northern margin of the Tethys Himalaya, and high angle faults along the southern boundary (Ni and Barazangi, 1985; Bhargava, 1990).

Based on geomorphic character, the Spiti Valley is divided into the upper and lower Spiti Valley (Fig 2.4). Braided channels and relict fluvio-lacustrine terraces are typical of the upper valley, with the lower valley being characterized by a meandering channel and local bedrock strath terraces. Significant quantities of lacustrian sediments locally flank the Spiti Valley as terraces (Fig 2.4), and suggest the formation of paleolakes caused by landslide-induced damming of the Spiti River (Phartiyal et al., 2009).

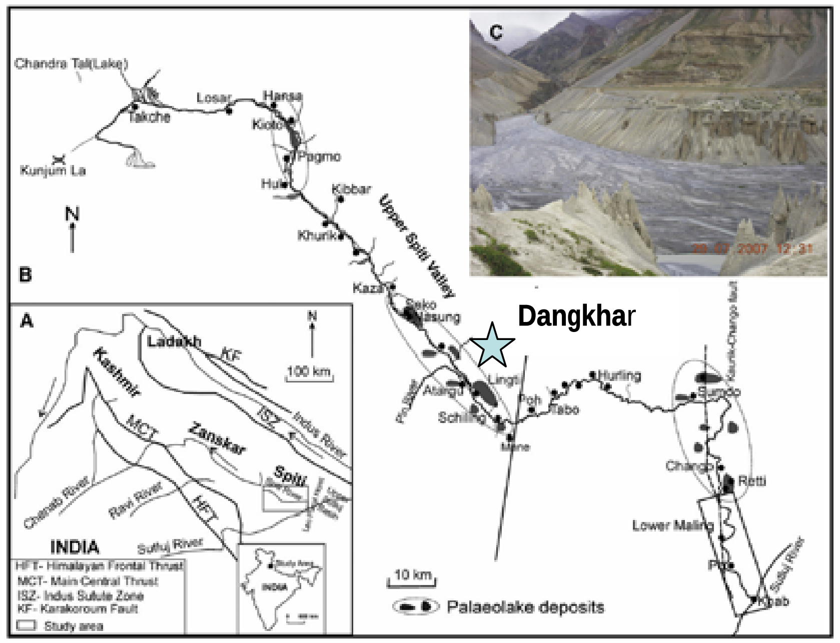

Figure 2.4 Geomorphic classification of the Spiti Valley, showing locations of paleolake deposits (Phartiyal et al., 2009). Site location indicated by star.

2.2 *Regional Seismicity*

Historically, the approximately 2000 km long Himalayan Frontal Arc (from Kashmir to Assam) has been seismically very active due to the ongoing collision between the Indian and Eurasian tectonic plates. More than a dozen earthquakes larger than magnitude 7.5 have occurred in this region since 1897 (Gupta, 1993). Recurrence intervals for earthquakes of magnitude 8 are estimated to be 200 to 270 years, and the amount of time required for the entire Himalayan Frontal Arc to be ruptured in a series of large earthquakes is estimated in the range of 180 to 240 years (Seeber and Ambruster, 1981).

The seismic hazard zonation for India includes four categories, representing a spectrum of exposure ranging from *low damage risk* (Zone II) to *very high damage risk* (Zone V). As shown in Figure 2.5, Dangkhar Monastery is situated within Zone IV, which correlates to *high damage risk*. The conception of high damage is related to the expected Medvedev-Sponheuer-Karnik (MSK) intensity (an empirical scale which considers historically observed effects in earthquake source areas). Seismic Zone IV corresponds to MSK level VIII, as defined below:

MSK VIII (Damaging) - Many people find it difficult to stand, even outdoors. Furniture may be overturned. Waves may be seen on very soft ground. Older structures partially collapse or sustain considerable damage. Large cracks and fissures opening up, rockfalls.

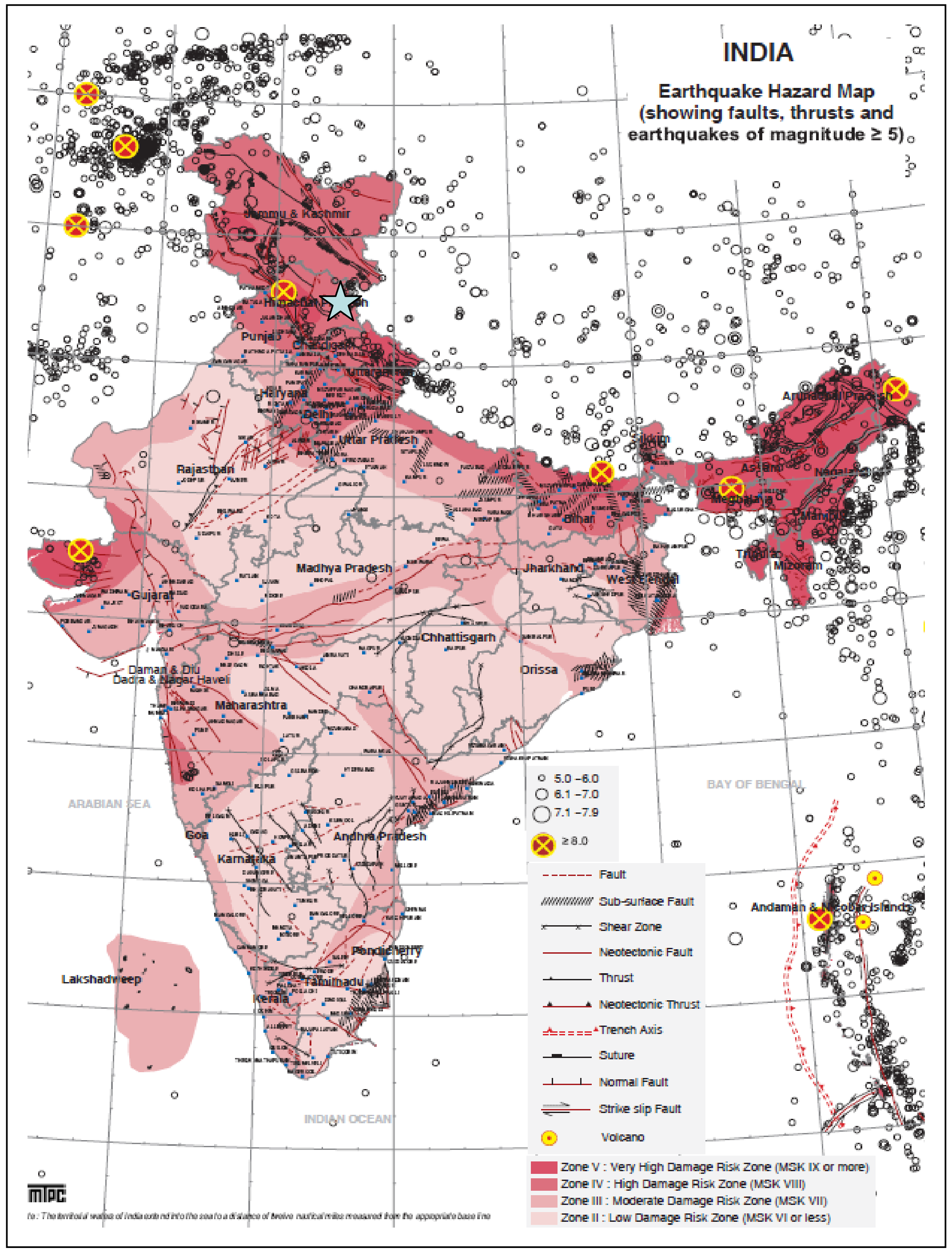

Figure 2.5 Earthquake hazard map of India, showing faults, thrusts, and earthquake magnitudes ≥5 (BMTPC, 2003). Site location indicated by star.

Regional probabilistic seismic hazard assessments covering the study area provide estimates regarding the likelihood of certain thresholds of ground motion (acceleration) being exceeded over a typical structural design life (50 years). According to data published by the Global Seismic Hazard Assessment Program (Fig 2.6), the site is characterized as having a 10% chance of exceeding peak ground acceleration, in the range of 30 to 40 percent of gravity, over the next 50 years.

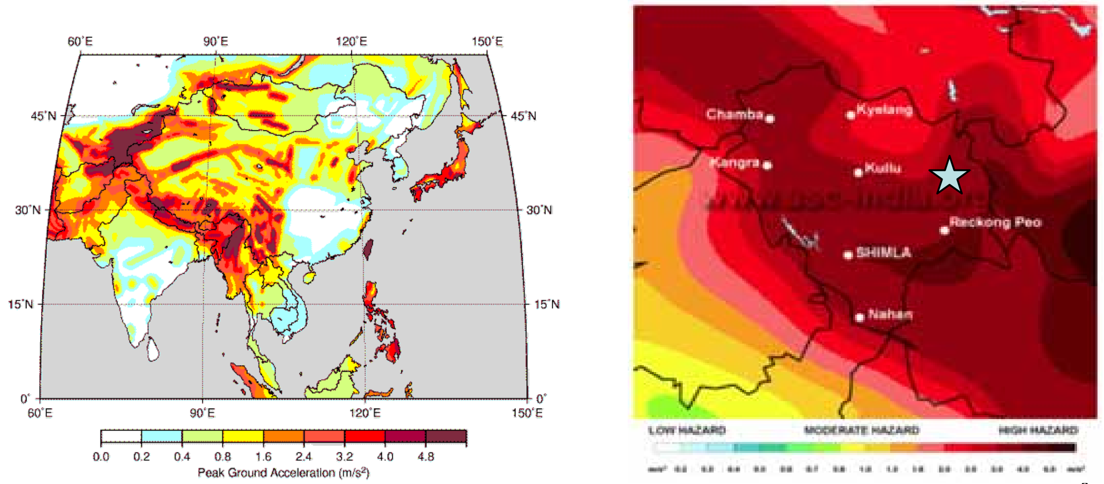

Figure 2.6: (a) Seismic hazard map of Asia depicting peak ground acceleration (PGA), given in units of m/s^2, with a 10% chance of exceedance in 50 years (http://www.seismo.ethz.ch/static/GSHAP/eastasia), and (b) seismic microzonation in the site vicinity, with the location of Dangkhar Monastery indicated by star (http://asc-india.org/maps/hazard/haz-himachal-pradesh.htm).

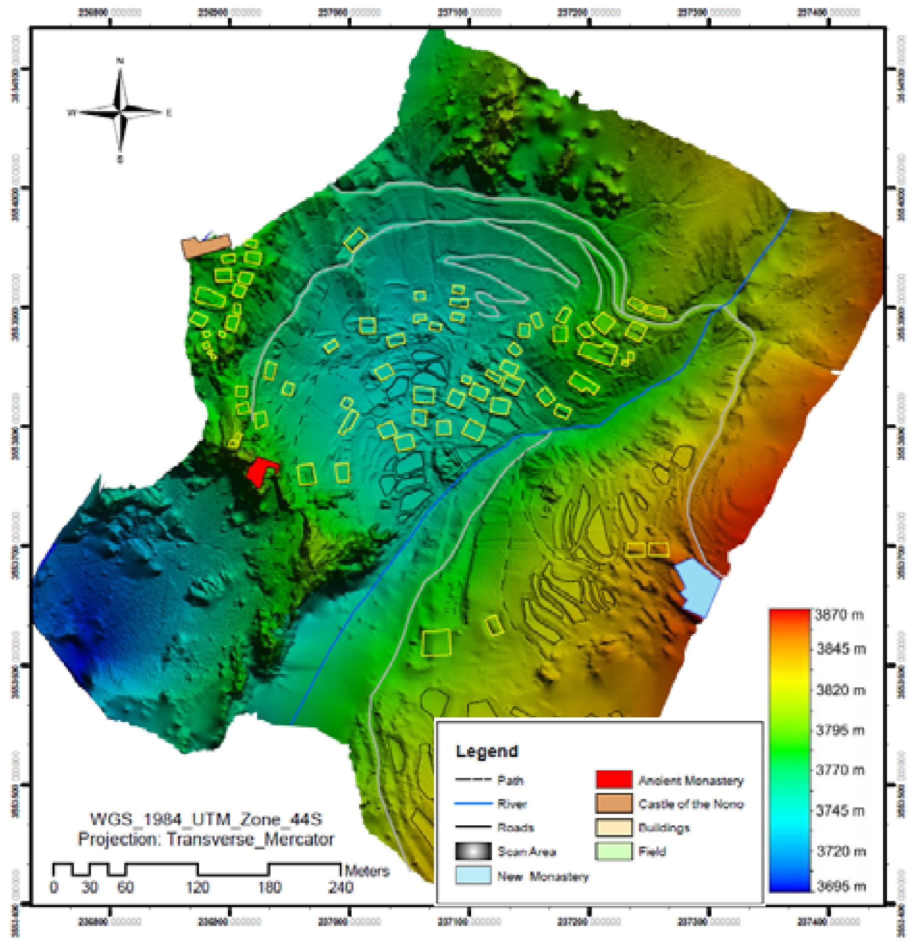

Figure 2.7 Overview of Dangkhar Monastery and Dangkhar Village (LiDAR-generated false-color elevation model)

2.3 Site Conditions

The general layout of Dangkhar Monastery and Dangkhar Village are depicted in the LiDAR-generated false-color elevation base map of Figure 2.7. The Ancient Monastery Complex is situated along the edges of steep rock cliffs overlooking Spiti Valley, with the main structures including the Ancient Monastery building with adjoining Tower, Kitchen, and Museum (Fig 2.8). A separate Upper Temple structure is located above the Tower. Figure 2.9 shows the layout of these structures on a topographic base map (processed from the LiDAR survey performed as part of this study). Also shown in Figure 2.9 are geologic units, as enumerated below.

Figure 2.8 Structures of the Ancient Monastery Complex.

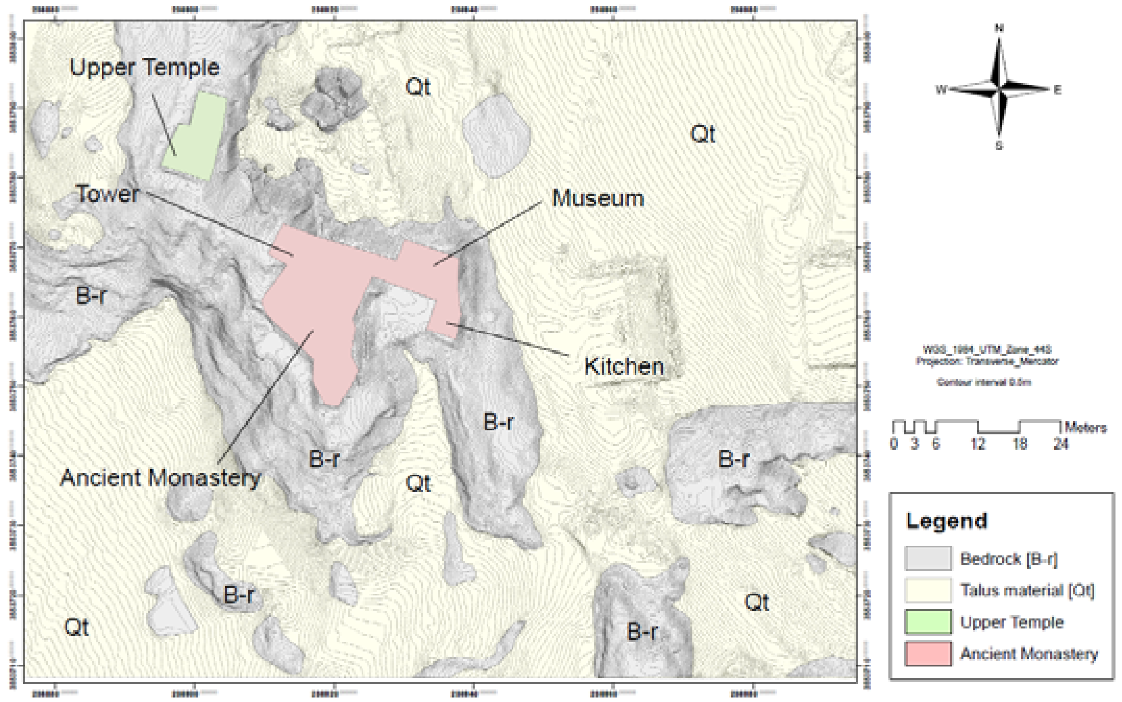

Figure 2.9 Layout of Ancient Monastery Complex Structures: Geologic units: Qt indicates talus deposits; B-r indicates bimrock outcrops (0.5 m contour interval).

Rocks comprising the bold cliffs of Dangkhar are characterized by a heterogeneous and chaotic mixture of angular rock blocks in a fine grained matrix (Fig 2.10). The rock blocks consist primarily of angular to subangular limestone, and range in size from cobbles to over 10 cubic meters in volume. The volumetric proportion of blocks is estimated to typically range from about 30 to more than 50 percent, with blocks tending to be matrix supported. While the origin of these deposits can be debated, it is their engineering behavior that is particularly germane to this study.

Medley (1994) proposed the term *block-in-matrix rocks* (or *bimrocks*) to classify a range of geologic deposits having the overall characteristics of those comprising the cliffs of Dangkhar, and this terminology has been adopted in this study. The engineering properties of bimrocks depend on the volumetric block proportion of the deposit, together with shear strength and stiffness properties of the block and matrix components (Medley, 1994; Lindquist, 1994). While the blocks at Dangkhar exhibit higher strength characteristics than the matrix components, both tend to be strong to very strong (Grades R4 to R5 according to Brown, 1981), with uniaxial compressive strengths for unweathered specimens estimated in the range of 50 to 250 MPa.

Figure 2.10 Typical characteristics of the bimrock materials forming the cliffs of Dangkhar.

The bimrock exposures at Dangkhar are surrounded in their entirety by unconsolidated surficial sediments (Fig 2.11). The sediments range predominately from silt to boulder size, and are interpreted to represent processes of colluviation (diffusive downslope movement of surficial sediments through the action of gravity and water), rockfall accumulation, and in-situ decomposition of parent materials. The overall term *talus* is used to describe these sediments. The distribution of bimrock and talus materials in the vicinity of the Ancient Monastery Complex is shown schematically in Figure 2.9.

Figure 2.11 Bimrock outcrops in Dangkhar Village, surrounded by unconsolidated surficial sediments.

Outcrops of the bimrock at Dangkhar are typically near-vertical, reaching heights of approximately 65 m directly adjacent to foundations of the Ancient Monastery Complex (Fig. 2.12).

Figure 2.12 Bimrock foundation of the Ancient Monastery Complex.

3.0 Observations and Findings

Summarized below are observations and findings pertinent to the erosion and slope stability processes shaping the bimrock cliffs of Dangkhar. Specific observations of adverse geotechnical conditions, for each component of the monastery complex, are also summarized.

3.1 Erosion Processes and Slope Instability

3.1.1 Erosion Processes

Morphologically, the landscape at Dangkhar exhibits a *badlands* character, which is commonly associated with arid environments having little vegetation and variably cemented sedimentary formations, sometimes containing soluble minerals. Figure 3.1 shows the similarity between classical badlands features of Bryce Canyon in the southwestern United States, to features observed at Dangkhar. Badlands landscapes are formed by the action of surface waters and are typified by short steep slopes with narrow interfluves.

Figure 3.1 Badlands features of Bryce Canyon (above) and Dangkhar (below).

A typical feature of badlands landscapes are *hoodoos* (earth pillars), several of which are depicted in Figure 3.2. Hoodoos represent the last vestiges of a landscape progressively eroded by water, and with their eventual destruction, the landscape assumes a lower overall elevation. Hoodoos sometimes are overlain by a resistant *cap rock* (Fig. 3.3), which serves to protect the pillar from the erosive capacity of rainfall, thereby enhancing the pillar's longevity.

Figure 3.2 Hoodoos (earth pillars) located directly north of Ancient Monastery Complex.

Figure 3.3 Resistant cap rock protecting a hoodoo.

Commonly, the hoodoos of Dangkhar exhibit a tapered shape, narrowing toward the base (Fig 3.4). The narrowing is interpreted to result from the erosive action of surface rill and sheet flow, which interacted with the pillar in a former time, when the bordering talus deposits occupied a higher elevation. The surface waters would have been directed down the talus surface to the pillar boundary, where direct exposure to flowing water would result. An example of pillar tapering occurring along the boundary of an existing talus surface is depicted in Figure 3.5. The former talus deposits in the case of Figure 3.4 may have been removed by natural erosion or human activity.

Figure 3.4 Common tapered form of the Dangkhar hoodoos, showing narrowing at the base rock protecting a hoodoo. Left image indicates position of interpreted former talus surface.

Figure 3.5 Active pillar tapering along contact with talus deposits.

Exacerbating the pillar tapering is the activity of livestock. As shown in Figures 3.6, goat herds gain access to the base of the hoodoos, where their action results in minor progressive narrowing of the hoodoo base. Not only does erosion result from hoof action, but also the nibbling of bits of rock (Fig 3.7). The mineralogical content of the pillar material, based on a single X-ray diffraction analysis, is approximately 80% calcite, 10% dolomite; and 10% quartz, suggesting the goats may derive from these materials a calcium-magnesium nutritional benefit.

Figure 3.6 Goats accessing hoodoo base (note dust cloud indicating erosion).

Figure 3.7 Goats nibbling on base of hoodoo.

3.1.2 Slope Instability

The bimrock of Dangkhar generally exhibits favorable stability conditions, as indicated by their capacity to form high vertical cliffs. Nevertheless, geologic processes are operating to eventually consume the bimrock, as it progressively deteriorates into free standing earthen pillars.

As erosion progresses, the more resistant bimrock materials tend to take on bolder forms, increasing their height and steepness. Their exposure is accompanied by stress relief, which manifests itself as tensile cracking of the bimrock. Figures 3.8 and 3.9 show typical examples of the stress relief fractures, which tend to dip very steeply to vertical, and strike subparallel to the free surface.

Figure 3.8 Tensile fracturing of the Dangkhar Bimrock.

Figure 3.9 Tensile fracturing adjacent to monastery structures.

Once formed, the tensile fractures act as potential detachment surfaces for toppling and rockfall-type events. The fracture surfaces are also exposed to water, which tends to slowly erode particles from the exposed surfaces, gradually enlarging the fracture aperture. Eventually, erosion rills develop, which tend to enlarge to eventually form isolated hoodoos (Fig 3.10). Also shown in Figure 3.10 are pits and vugs. Together with the localized occurrence of small caves, these features indicate calcium carbonate dissolution as a component of the erosion process.

Figure 3.10 Development of erosion rills at the site of tension cracks, leading to hoodoo formation.

Isolated hoodoos (Fig 3.11) are subject to continued diffusive particle erosion and dissolution, which may eventually bring the pillar to a critical state of eccentricity, making it prone to toppling (particularly under the action of seismic shaking). In the bimrock erosion process, fine grained components tend to be preferentially eroded through freeze-thaw loosening, wind abrasion, and surface water interaction. Retreat of the finer grained matrix around large block components (Figure 3.12) tends to undermine or loosen the blocks, and precipitate discrete rockfall events.

Figure 3.11 A precarious isolated hoodoo.

Figure 3.12 Differential erosion of block and matrix components, leading to the undermining and loosening of large block components

3.2 *The Ancient Monastery Complex*

Bearing walls and foundation elements of the Ancient Monastery Complex structures are of unreinforced block and mortar construction. Figure 3.12 depicts the layout of these structures, together with the locations of topographic cross sections.

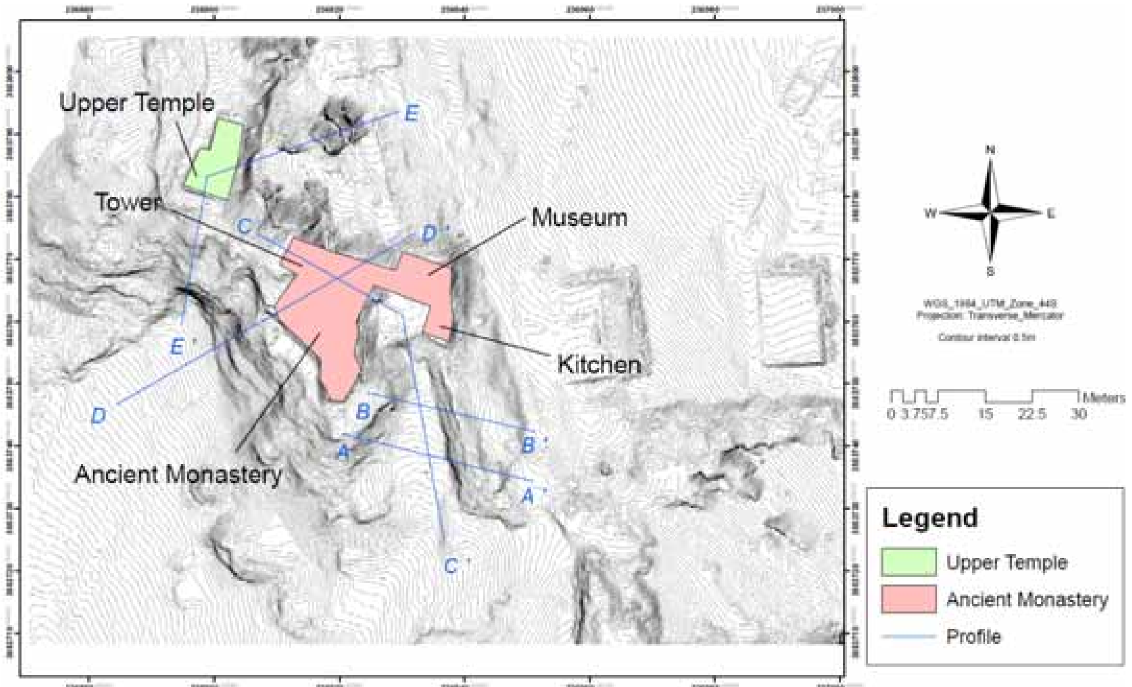

Figure 3.13 Layout of Ancient Monastery Complex structures, together with locations of topographic/geologic cross sections.

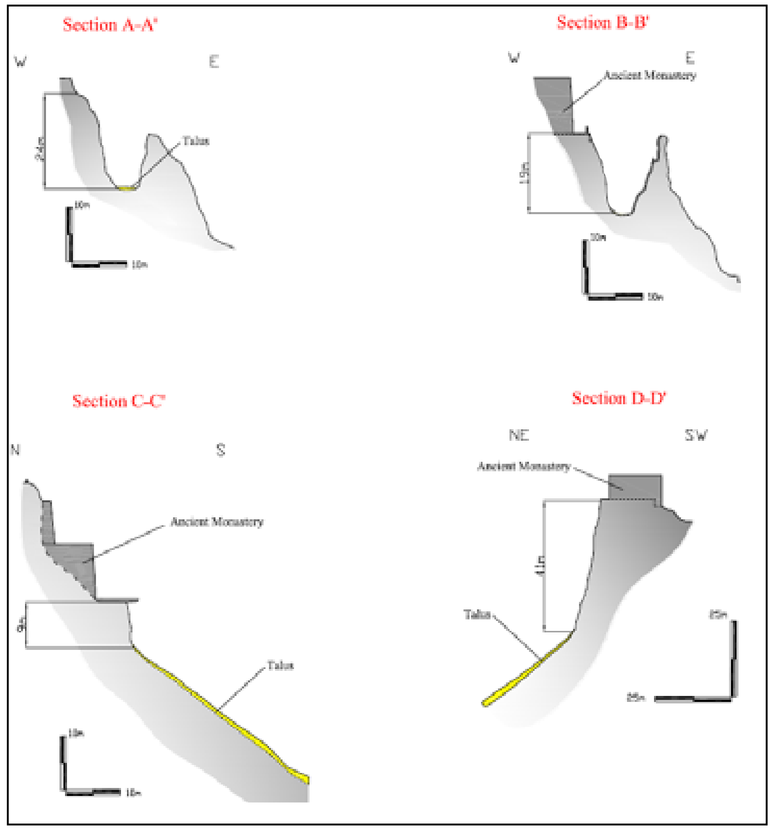

Figure 3.14 Topographic cross sections A-A' through D-D'.

3.2.1 Ancient Monastery

The bimrock cliffs bordering the southern side of the Ancient Monastery are near vertical and range in height from about 10 to 40 m (Fig 3.14). A substantial erosion gully occurs along the eastern side of the Ancient monastery (and along the southern side of the Kitchen). As depicted on the geologic map (Fig. 2.9) and in Figure 3.14, the gully contains loose surficial sediments (talus) in its throat, deposited through the process of cliff erosion and retreat. The cliff retreat has apparently advanced to the stage of requiring mitigating construction, including a cantilevered patio, and block masonry support work in the upper portion of the erosion headwall. Figure 3.14 reveals partial undermining of the block masonry support work, and Figure 3.15 shows four water drainage pipes, discharging over the cliff and directly into the erosion gully.

Figure 3.15 Erosion gully along eastern side of Ancient Monastery and southern side of Kitchen (note partial undermining of block-mortar work in the erosion headwall).

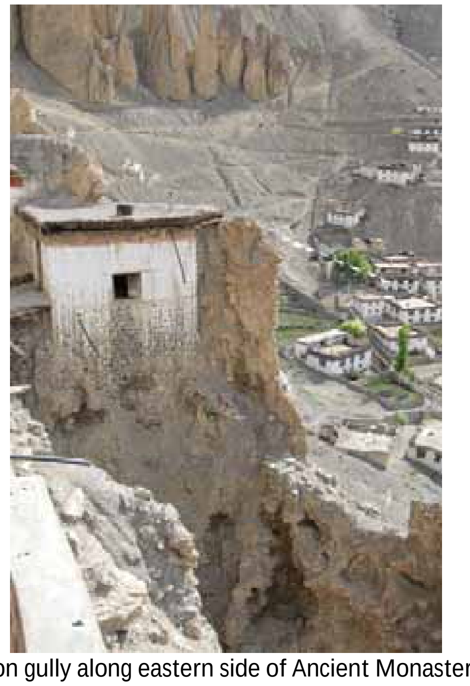

Figure 3.16 Erosion gully along eastern side of Ancient Monastery, view to north (note four drain pipes discharging to gully)

Figure 3.17 shows as a large block that has essentially been isolated by the differential bimrock erosion process (i.e. preferential erosion of fine grained matrix components). The block is situated less than two meters from the eastern monastery wall, and provides support for a small walkway and low protection wall. The large block has been partially undermined, and its lateral extent beneath the walkway is unknown.

Figure 3.17 Partially undermined large block along eastern side of Ancient Monastery.

Prior remedial cliff work for the Ancient Monastery is also indicated by slope repairs consisting of mortar/concrete and block/mortar. Figure 3.18 depicts the two slope repairs, and indicates partial undermining of the building foundation and block/mortar slope repair. Two drainage pipes discharging over the cliff are also shown.

Figure 3.18 Southern side of Ancient Monastery, showing area of prior remedial cliff work (note two drainage pipes, partial undermining at of building foundation at right corner, and partial undermining of block/mortar slope repair).

3.2.2 Museum

Along the northern side of the Museum, an erosion rill has encroached on the structure and partially undermined the foundation (Fig. 3.19). There presently exists only a narrow bimrock fin along the eastern side of the Museum, and continued erosion in this area is judged to have the potential to de-buttress the structure from the eastern side.

Figure 3.19 Erosion rill and partial undermining of foundation along northern side of Museum (note bimrock fin along eastern side).

3.2.3 Kitchen

Along the southern side of the kitchen, two undermining conditions exist, as shown in Figures 3.20 and 3.21. One instance involves undermining of the block/mortar headwall slope repair (discussed in Section 3.2.1), and the second occurs directly beneath the Kitchen foundation.

Figure 3.20 Partial undermining of block/mortar slope repair and foundation along southern side of Kitchen (note drain pipes).

Figure 3.21 Detail of undermined Kitchen foundation.

The narrow bimrock fin along the eastern side of the Museum continues along the Kitchen's eastern wall. As shown in Figure 3.22, tensile fracturing of the bimrock has occurred, which can facilitate detachment of a large block. Such detachment would reduce the buttressing effect along the eastern wall.

Figure 3.22 Tensile fracturing of bimrock fin along eastern side of Kitchen.

3.2.4 Tower

Bordering the southern side of the Tower is a large rock block that appears to have been isolated from the surrounding bimrock by two significant fractures. The fractures intersect along a line plunging toward the southeast, creating a removable block (Fig. 3.23). While the block is presently stable, future adverse climatic events, seismic shaking, or simply the passage of sufficient time, may act to destabilize the block and generate a rockfall. Should a rockfall occur, the trajectory would be through the roof of the Ancient Monastery and toward its southern bearing wall.

Figure 3.23 Potentially unstable rock block bordering southern side of Tower

A potentially unstable rock block also exists along the northern side of the Tower (Fig 3.24). The block appears to be almost completely isolated by the steeply dipping underlying fracture. The stability characteristics are unfavorable, and moderate disturbance may potentially result in block detachment. In the case that a rockfall develops, the trajectory would not be toward the Ancient Monastery Complex, rather toward the new parking garage construction and village below.

Figure 3.24 Potentially unstable rock block adjacent to northern side of Tower.

3.2.5 Upper Temple

The bimrock cliff bordering the southern side of the Upper Temple is near vertical, with a height of about 65 m (Fig 3.25). As depicted in Figure 3.26, the bimrock locally appears fractured and loosened.

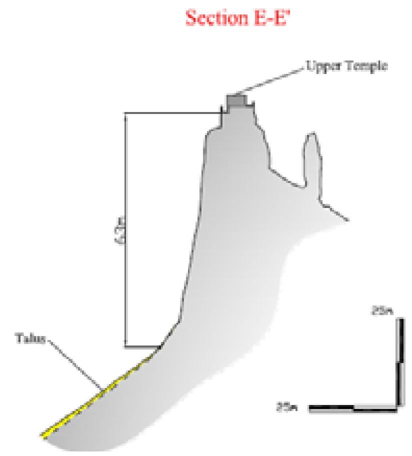

Figure 3.25 Topographic cross section E-E' (for location of cross section, refer to Fig. 3.12).

Figure 3.26 Condition of bimrock cliff along southern side of Upper Temple

Partial undermining of the Upper Temple foundations and access walkways has occurred along the western and eastern sides of the structure. As shown in Figure 3.27, spanning across the undermined areas has been accomplished with timber and steel posts and beams.

Figure 3.27 Foundation undermining along western side of Upper Temple (note wood post and beams).

Foundation undermining along the eastern side is similar in its nature, and has been addressed with remedial block and mortar underpinning and spanning timber beams. Figure 3.28 depicts the undermining along the eastern side of the Upper Temple, together with a drainage pipe discharging directly onto the cliff face in the undermined area.

Figure 3.28 Foundation undermining along eastern side of Upper Temple (note block and mortar underpinning, spanning timber beams, and drainage pipe).

3.3 Castle of the Nono

Along the eastern side of the Castle of the Nono is an overhanging bimrock outcrop having a height of about 3-4 m (Fig 3.29). The overhang is considered a transient feature, with a high susceptibility to long term slope instability. The configuration of the overhang is such that a slope failure, extending from the toe to at a vertical angle (or steeply dipping in the reverse sense of the overhang) could undermine a portion of the foundation (the corner of the white building shown in Figure 3.29.

Figure 3.29 Castle of the Nono, depicting overhanging bimrock outcrop along eastern side of structure.

4.0 Geotechnical Recommendations

The geotechnical recommendations described herein are conceptual in their nature, and are intended to provide guidance in developing final design solutions and preliminary cost estimates. Site conditions are complex in terms of access constraints, and many design details will have to be worked out onsite, based on specific as-built field conditions.

4.1 The Ancient Monastery Complex

4.1.1 Ancient Monastery

The erosion gully developed along the eastern side of the Ancient Monastery (and southern side of the Kitchen) shows signs of active erosion. The gully has a high potential for continuing retreat, and the risk to foundation elements supporting the Ancient Monastery and Kitchen is considered significant.

As enumerated below, diversion and control of surface runoff is imperative to attenuate the erosion process, however, drainage improvements alone are considered insufficient for mitigating the risk of structural undermining. To address this risk, it is recommended that surface protection be provided for the steep side slopes of the gully. Options considered for surface protection include block/mortar walls, chemical membranes (e.g. polyurethane), and a sprayed concrete (shotcrete) membrane. The first option was rendered impractical due to the significant height of the walls, and the lack of firm bearing material in the throat of the gully (which is filled with loose talus). The second option could be implemented, however, the durability of chemical membranes under harsh climatic conditions such as Dangkhar remain unproven. For this reason, the option of a shotcrete membrane was considered most suitable.

The shotcrete membrane serves to seal the ground surface in order to attenuate the long term deleterious effects of rain impact and sheet flow, freeze-thaw action, wind abrasion, and dissolution processes. For preliminary cost estimating purposes, a membrane thickness of 5 cm can be assumed, sprayed over a surface area of approximately 1200 m^2. Polymer additives should be considered to improve the shotcrete bond strength, and weep (drainage) holes should be provided on one meter centers in order to reduce the potential for significant hydraulic pressures developing behind the membrane. To maximize adhesion, it is also recommended that surfaces to be shotcreted first be cleared of dust and loose particles with a high pressure air hose. The specific area identified for shotcrete protection is depicted in Figures 4.1 and 4.2.

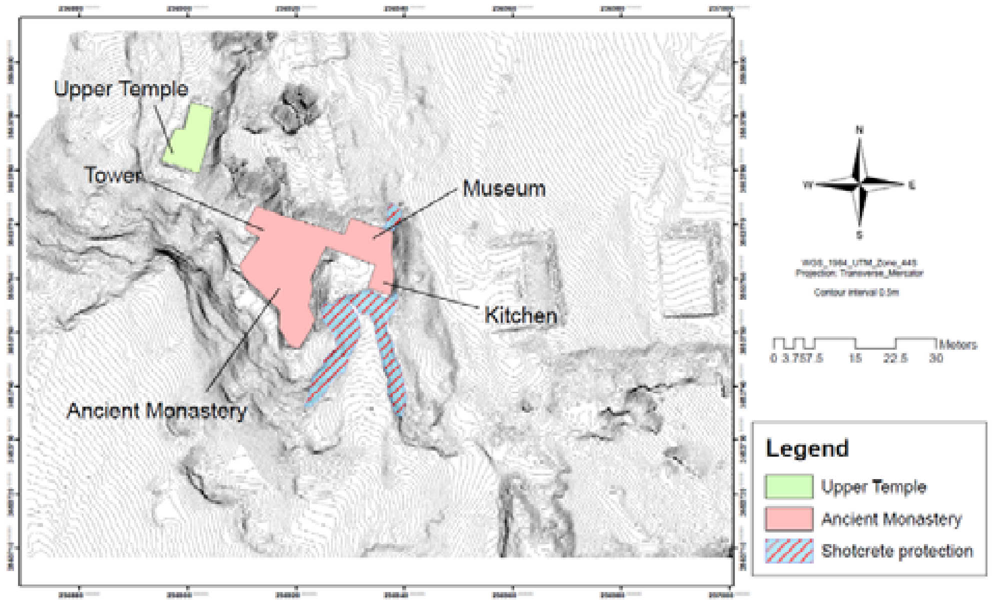

Figure 4.1 Recommended areas for shotcrete protection


Figure 4.2 Shotcrete protection along eastern side of Ancient Monastery and southern side of Kitchen.

The aesthetic properties of traditional shotcrete can be a drawback for cultural heritage restoration work. However, as shown in Figure 4.3, natural pigment additives and a textured finish can result in an attractive, natural looking surface.


Figure 4.3 Example of textured and pigmented shotcrete wall.

Diversion and control of surface runoff, so as to minimize discharge into the large gully, is also recommended. This will require re-grading of surfaces to prevent sheet flow onto the cliff face and re-routing of drainage pipes to low vulnerability areas (such as the more gentle slopes to the north of the Ancient Monastery). Alternatively, runoff can be collected and conveyed in a secured drop pipe (e.g. corrugated HDPE), to a location beyond the toe of the bimrock cliffs. Figure 4.4 depicts four drainage pipes requiring re-routing.


Figure 4.4 Prevent water discharge into gully along eastern side of Ancient Monastery.

As described in Section 3.2.1, a partially undermined block is situated less than two meters from the eastern monastery wall, and provides support for a small walkway and low protection wall. It is recommended that the block be underpinned by constructing a small block/mortar mass below its toe. Due to the steepness of the underlying surface, a horizontal notch will need to be carefully excavated to form an adequate bearing surface for the block/mortar underpin. An alternative method for supporting the block is to fill the undermined area with shotcrete.

Figure 4.5 Underpin large block along eastern side of Ancient Monastery.

Along the southern side of the Ancient Monastery, partial undermining of the foundation and the block/mortar slope repair has occurred (Fig. 4.6). It is recommended that the undermined areas be underpinned with block/mortar construction. Care must be taken to ensure adequate bearing conditions for the underpins, for example by carefully excavating bearing notches.

Figure 4.6 Underpin foundation elements along southern side of Ancient Monastery.

As shown in Figure 4.7, drainage pipes convey water from the monastery and discharge directly onto the cliff face. Re-routing of the discharge to low vulnerability conveying it in a secured drop pipe (e.g. corrugated HDPE), to a location beyond the toe of the bimrock cliffs, is recommended.

Figure 4.7 Prevent water discharge over southern supporting cliff of Ancient Monastery.

4.1.2 Museum

As depicted in Figure 4.1, a second area of shotcrete protection is recommended. The shotcrete protection area is approximately 50 m2 (Fig 4.8), and is intended to mitigate the potential for continued rill erosion and foundation undermining. Specifications for shotcrete placement are consistent with those described in Section 4.1.1. It is further recommended that the undermined foundation area be underpinned with block/mortar construction, or filled with shotcrete.

Figure 4.8 Shotcrete protection and underpinning along northern side of Museum.

4.1.3 Kitchen

Along the southern side of the Kitchen, underpinning of the undermined foundation and block/mortar slope repair is recommended (Fig 4.9). Underpinning can be performed with block/mortar construction, provided that adequate bearing conditions are achieved. Alternatively, as part of the gully surface protection work, underpinning may be performed by filling the undermined areas with shotcrete.

Figure 4.9 also highlights a bimrock mass that has been isolated from the surrounding rock mass by a tensile fracture. As support of this block is not considered feasible/practical, the hazard of a future rockfall should be anticipated.

Figure 4.9 Underpin foundation elements along southern side of Kitchen.

4.1.4 Tower

The large, potentially unstable rock block bordering the southern side of the Tower is considered to pose significant risk, as the failure trajectory would be through the roof of the Ancient Monastery and toward its southern bearing wall (Fig 4.10). For this reason, it is considered prudent to provide supplemental support for the block. Based on restrictive site conditions, a method of support involving anchored straps appears practical. With this approach, two galvanized wire ropes would be strapped across the block, and anchored to the rock mass along the narrow ridgeline between the Tower and Upper Temple. Anchoring can be achieved by providing full strength plate connectors to the ends of the wire rope, then embedding the plates into grouted holes having a nominal depth of about 1.5 m. Anchor placement will be critical for ensuring adequate performance of the supplemental support, and the wire ropes should be lightly pre-tensioned to provide a small amount of active support.

Figure 4.10 Support potentially unstable block along southern side of Tower.

A potentially unstable rock block also exists along the northern side of the Tower (Fig 4.11). In the case that a rockfall develops, the trajectory would be toward the new parking garage construction and village below. It is not considered feasible/practical to support this block. An option for reducing the risk of a future rockfall involves the controlled removal (scaling) of the block. Absent such measures, the hazard of a future rockfall should be anticipated.

Figure 4.11 Potentially unstable block along northern side of Tower.

4.1.5 Upper Temple

It is recommended that undermined foundation elements along the western and eastern sides of the Upper Temple (Fig. 4.12 and 4.13) be underpinned with block/mortar construction. Care must be taken to ensure adequate bearing conditions for the underpins, for example by carefully excavating bearing notches. Additionally, re-routing of the water discharge to low vulnerability areas, or conveying it in a secured drop pipe (e.g. corrugated HDPE), to a location beyond the toe of the bimrock cliffs, is recommended.

Figure 4.12 Underpin foundation elements along western side of Upper Temple.

Figure 4.13 Underpin foundation elements along eastern side of Upper Temple, and prevent water discharge over cliff.

4.2 Castle of the Nono

The overhanging bimrock outcrop along the eastern side of the Castle of the Nono has a high susceptibility to long term slope instability (Fig 4.14). To mitigate to potential for resulting foundation undermining, it is recommended that the slope overhang be supported according to the shoring concept depicted in Figure 4.15. The shoring scheme consists of timber wall plates, rakers, and struts, each envisioned on approximately 1.5 m centers. To achieve adequate bearing, the rakers should be embedded in shallow concrete-filled foundation holes.

Figure 4.14 Overhanging slope at Castle of the Nono.

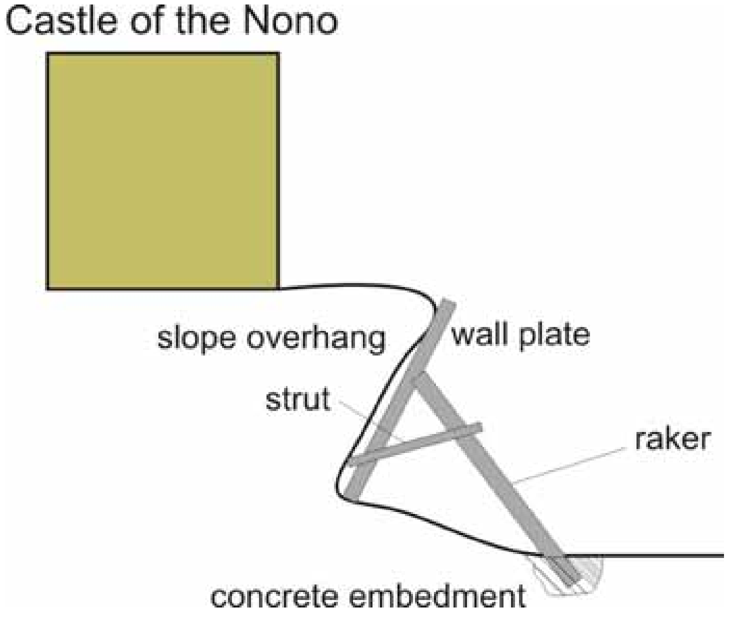

Figure 4.15 Shoring concept for overhanging slope (schematic).

5.0 Discussion

Although the Ancient Monastery of Dangkhar sits in precarious geologic terrain, several measures can be taken to help improve its longevity. The fundamental mitigation strategy developed herein is to:

(i) control surface runoff by directing water flows to low vulnerability areas;

(ii) perform localized underpinning of foundation elements;

(iii) secure critical rock blocks;

(iv) provide surface erosion protection in critical areas, and

(v) perform diligent maintenance and repairs.

The Ancient Monastery Complex and Castle of the Nono are essentially serving the role of hoodoo cap rocks. The benefit of a cap rock relates to its limitation of rainfall and surface runoff along the underlying pillar. In the case of Dangkhar, however, the majority of runoff is presently routed to the steep side slopes of the bimrock foundation. It is considered imperative to control this runoff and convey it to low vulnerability areas.

Recommended underpinning works involve placement of block and mortar in deficient areas. Due to the extreme steepness of the rock cliffs, firm bearing surfaces for the underpinning elements may be difficult to achieve in many cases. To facilitate effective underpinning, it is therefore recommended that bearing notches be carefully excavated in the cliff walls, with supplemental use of short grouted steel shear dowels, as needed.

A critical potentially unstable rock block has been identified along the southern side of the Tower structure. While the block is presently stable, future adverse climatic events, seismic shaking, or simply the passage of sufficient time, may act to destabilize the block and generate a rockfall. Should a rockfall occur, the trajectory would be through the roof of the Ancient Monastery and toward its southern bearing wall. As the resulting structural damage would be very significant, it is considered to prudent to support the block with anchored wire rope straps.

The shotcrete surface protection is considered an integral component of an effective remediation strategy. Geotechnical conditions in the two areas identified for shotcrete treatment are unfavorable, and further progression of erosion has the potential to significantly undermine foundation elements. As shotcrete materials and technology exceed local capabilities, it is anticipated that this work will have to be imported from a major metropolitan area.

Maximizing the longevity of the Ancient Monastery Complex is contingent upon diligent maintenance and repair of the structures. It is recommended that foundation inspections be performed by local personnel on an annual basis, and following unusual events such as extreme monsoonal downpours or seismic activity. Such inspections should reveal areas experiencing progressive deterioration, and form a basis for prioritizing future mitigation activities.

Dangkhar is situated in a region exposed to strong seismic shaking, and considering the (seismically unfavorable) unreinforced block and mortar constructions, significant structural damage can be expected during future large earthquakes, even with the envisioned architectural and geotechnical mitigation measures implemented. Absent such events, however, these measures are expected to extend the useful life of the Ancient Monastery Complex by many years.

The mitigation concepts summarized herein require skilled labour in a hazardous work environment. Execution of the foundation underpinning and shotcrete surface protection are particularly hazardous activities, due to the requirement for working on vertical cliffs. Proper harnesses and scaffolding, together with standard safety gear, are considered necessary components for carrying out these construction activities.

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