BHUTANESE ROAD AND BRIDGE RESILIENCE TO FLOODS AND LANDSLIDES – FIRST SUGGESTIONS FOR ASSESSMENT AND RESPONSE

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ABSTRACT

Bhutan is a country with one of the lowest per capita incomes and very limited financial and industrial resources. Situated in the Himalayan foothills and mountains, its road transport network must negotiate very challenging terrain in terms of topography, rainfall and earthquake propensity with a widespread risk of flooding and landslides. For the majority of communities, there is only a single road or bridge by which markets and services may be accessed. If such roads or bridges are cut by flood or landslide, communities upstream of the cut will, effectively, become isolated. The paper describes the initial conclusions drawn from an investigatory visit to assess the current vulnerability of such lifeline roads and to propose simple means of evaluating problems before roads become impassable and improving remedial responses. It is concluded that small-scale activities could be undertaken to improve preparedness and to speed repairs but that locating resources would need careful planning given the uncertainties of the time and location of future events.

BACKGROUND

Bhutan is a small country in the Himalayan Mountains, squeezed between India to the south and Chinese Tibet to the north. With a population of less than 800,000 citizens, it has a relatively low Human Development Index (0.61 in 2015), high infant mortality (34/1000), high maternal mortality (180/100,000 live births) and is identified as a "Least Developed Country" on the DAC List of ODA Recipients (OECD, 2018) due to the low per capita income.

Until the year 1962, Bhutan had no roadway network and all transportation was done by foot or using pack animals. Political changes in neighbouring countries have led to a change in policy and greater, albeit somewhat limited, openness to the exterior. A limited road network was built in the late 1960's (Ito, 2011) connecting the border town of Phuentsholing to the capital Thimphu and the town of Paro. Since then, the network has grown slowly, and now has a total of about 12000 km of roads of which around 2600 km are national, paved roads (some of which are single carriageway) with around 7000 km of feeder roads of various service levels, mostly single carriageway, with many being unsealed.

OBJECTIVES

The main objectives of this paper concern the impact of two types of natural hazards – slope instability and floods at river/stream crossings – on the transportation network. The first objective is to highlight the vulnerability of the road network to these hazards. The second objective is to evaluate how the risks posed by these two natural hazards can be prevented or limited. The third objective is to define how remediation can be effected. The achievement of these targets must be in a manner compatible with the economic, geographic and climatic conditions and means available in Bhutan, while being also sustainable and environmentally-friendly, compatible with the long term objectives of the country.

VULNERABILITY OF THE ROAD NETWORK

The Bhutanese road network is extremely non-redundant and any event, such as a landslip or flood, that prevents use of a segment of the main roads, will isolate significant portions of the population from the rest of the country and the exterior. Conversations with local engineers reveal that it is not uncommon for transport to be halted by such events for 3 or more days during the heavy monsoon season (late June through to late September). There are no significant alternatives to the road network, as there is no railway, and because rivers are not navigable. The country has four commercial airports: Paro International airport, which has limited capacity and requires specially trained pilots due to the surrounding mountains, and Bathpalathang, Yongphulla and Gelephu internal airports, which can only be used by small aircraft.

The topography is characterized by very steep slopes, with high mountains separated by deeply incised river valleys (Norbu et al., 2003). As an indication, the national road from Samdrupjongkhar to Trashigang (a 182 km long national road connecting the east of the country to one of the 4 border crossings with India) crosses slopes that are steeper than 36% for 60% of the road's length (Thapa et al, 2015). Therefore, for large proportions of their length, these roads must be built, with many switchbacks, as ledges across the slopes using both cut and fill methods.

Bhutan lies at the interface between the converging Indian and Eurasian continental plates. The result of this convergence is the Himalayan region, the most recent geological mountain formation of the planet. As a result, most of the strata encountered in road construction in Bhutan are metamorphic rocks (often amphibolites, schists and phyllites in the study area) and greatly distressed (Long et al, 2011). Furthermore, many have been subjected to subtropical or alpine weathering which has exploited the many tension features in the rock caused by tectonic movements. This has resulted in weak and highly fractured rock that is prone to landslides, frequently closing roads for significant periods of time.

Due to differences in altitude, the climate in Bhutan varies very significantly. Southern Bhutan has a sub-tropical climate, while the central part is significantly cooler. The Indian monsoon causes heavy rain, particularly in the southern regions. This is the critical period for landslides and bridge and culvert washout failures. These occur because, the monsoon, combined with the orography of the region, means that most rivers flood annually in what are, frequently, very dramatic events. This poses a very large risk in terms of scour, erosion and flooding.

With a very low annual income, per capita, of around US$2030 (2015 data), Bhutan only has limited resources to overcome these problems. Moreover, Bhutan has to grapple with the tensions that result from its desire to improve life quality and economy while, at the same time, preserving its natural patrimony, limiting external influences on its cultural and economy, and maintaining those conditions that make it a unique touristic destination.

RISK ASSESSMENT & MITIGATION APPROACHES

The road network of Bhutan was built using very limited machinery and materials and intensive labour. Thus cut and fill were kept to the bare minimum, roads are frequently narrow, while engineered structures (bridges, culverts) are only built when indispensable.
The section of the national road in analysis herein links Phuentsholing to the capital Thimphu and Paro airport. This is the most important road in the country, as it provides a link between the capital with a population of c100,000, to India, the main source of raw materials, fuel, medication, and manufactured products. Although Phuentsholing and the Bhutanese capital, Thimphu, are only separated by 76 km of land, the road joining them extends 176 km, snaking across an extremely mountainous area, with an altitude gain of 2000 m and a high point of 2900 m at Chapcha.

Lower-volume, feeder, roads to this link have also been studied along with video records of roads in other parts of Bhutan in helping to refine observations and conclusions.

Most emphasis on mitigating the effects of landslide and culvert washout events on the transportation network in mountainous countries (Thapa et al, 2011; Li et al,2009; Chen et al, 2017; Honjo et al, 2011; Cordero Carballo, 2011; Fookes et al, 1985; Hearn & Griffiths, 2001; Hearn and Shakya, 2017) has focused on quantifying the vulnerability of the network and trying to minimize this vulnerability. In particular, Hearn & Griffiths (2001) and Thapa et al (2015) developed methods to assess the risk of landslides in Nepal and Bhutan, respectively. Both used a discrete scale, in terms of a set of parameters described in Table 1. Both authors indicate that extensive parts of the network are exposed to high or very high risk of landslides, which can be easily confirmed by considering the repair history or by a site visit.

Table 1 Some factors used in risk assessments

Hearn & Griffiths (2001)	Rock type, Slope aspect, Valley type, Land use, Slope angle, Channel proximity
Thapa et al (2015)	Geology, Fault type at locality (if any), Land use, Slope angle, Drainage density, Annual mean rainfall

Methods used to mitigate the risk of landslides, and other ground movements, damaging or destroying roads in developed countries usually involve protection structures (e.g. rock chutes, rock shelters, tunnels, and viaducts). This type of response is fundamentally impossible in Bhutan as a result of the limited economic resources of the country, the very limited construction capacity resulting from this, and the widespread need. In Bhutan, traditionally, risk is mitigated by using retaining walls either above or below the road, built using stone masonry or gabions. The walls above the road are usually small (often being considerably less than 4 m in height), while walls below the road can be up to 20 m high.

Although risk mitigation is critical in segments where existing slope movements are identified or where there appears to be a very strong probability of such movements occurring in the future, there will never be capacity to reinforce all potential sites. For this reason, the approach now proposed is based on a 3-tier methodology:

- Before incident: reinforce very high probability sites,
- Immediately after incident: apply mitigation measures that allow a fast, even if potentially partial, recovery of service level,

- After the end of the monsoon season: undertake more extensive repairs, to guarantee future stability of damaged sites, avoiding an increase of failure risk as a result of repair works.

Figure 1 Incipient failure of fill slope made apparent by deformation arcs in asphalt road surfacing

CLASSIFYING GROUND MOVEMENTS RELATIVE TO THE ROAD

Many classification systems have been proposed in the literature for soil and rock mass movement on slopes (Nemčok et al, 1972; Varnes, 1978; Hutchinson, 1988). For the most part, these are based on geotechnical, geological and geomorphological understandings. Whilst these have great value from a scientific and technical viewpoint, they would have limited use for local authorities and road managers in Bhutan. Their need is to determine the appropriate intervention methods for incipient (Figure 1) or recent failure (Figure 2) events, on the basis of limited information, and often in a very tight timeframe. Following a visit to several sites along the area of interest, the authors believe that a simplified classification of landslides is required to better address risk assessment, repair and maintenance decisions. This partly incorporates a classification suggested by Hearn et al (2011). The proposed classification system is purely geometrical, and can be performed visually by road managers familiar with the typical failures observed in this infrastructure – see Table 2.

For each slope failure type, according to this new classification, current typical practice and its drawbacks are given together with suggested responses, firstly so that the road may be quickly re-opened and secondly, longer term remediation – perhaps delayed until the next dry season. Based on observations made during a 10-day visit to the country by the first three authors, discussions with technical staff at the Department

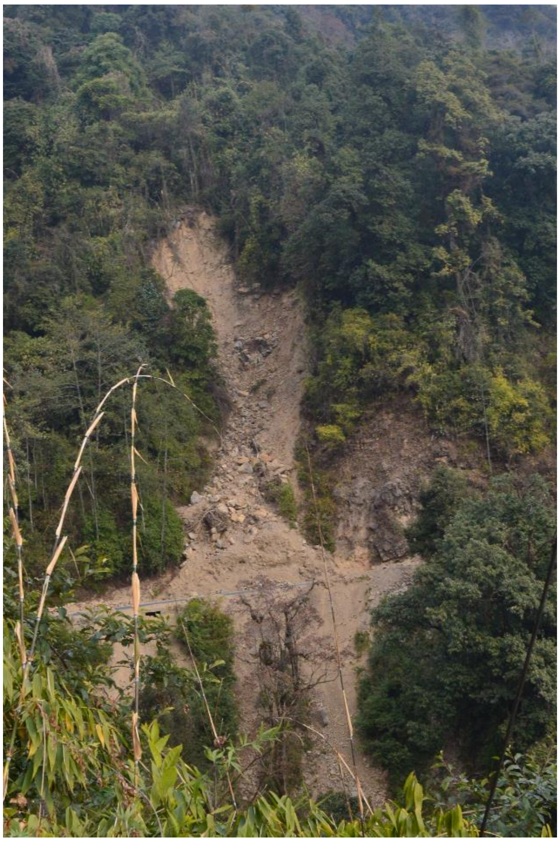

Figure 2 Gulley slide onto road with talus scree below road showing disposal path of cleared materials

Table 2: Ground movements – types and responses (movement types partially adapted from Hearn et al (2011))

Movement relative to road	Type of movement	Typical current rapid response	Problems with typical response	Proposed immediate response	Proposed longer-term response
Above road	Rock fall from cliff	Clear road by hand or light equipment	i) Fill is typically disposed over low side of road ii) Possibility of follow-on falls/ slides/ flows are largely ignored	i) Clear road longitudinally to 'windrow' on pavement edge, or dispose over edge if slope too steep to hold any loose debris ii) Monitor frequently to avoid impact from retrogressive rock falls	i) Exploit 'windrow' as aggregate source for adjacent road projects ii) Loosen and detach remaining at-risk blocks
	Rock slide			i) Clear road longitudinally to 'windrow' on pavement edge ii) Install wire mesh over remaining on-slope loose stone to reduce danger of stone-vehicle impacts	i) Exploit 'windrow' as aggregate source for adjacent road projects ii) Provide retaining wall (masonry or gabions) from larger stones in 'windrow' iii) Fix lasting wire mesh or other arrestors
	Gulley wash out (debris flow)			i) Clear road longitudinally to 'windrow' on pavement edge ii) Install wire mesh over remaining on-slope loose stone to reduce danger of stone-vehicle impacts	i) Exploit 'windrow' as aggregate source for adjacent road projects ii) Provide retaining wall (masonry or gabions) from larger stones in 'windrow', leaving space for water drainage and access for periodic stone removal from behind wall
Under road	Landslip of fill	Cut into upslope to provide enough carriageway around lost road	Tends to destabilise upslope	For short affected sections make Bailey bridge available to span gap. For longer affected lost road, rapidly provide gabions or reinforced soil with foundation below slip surface into original slope profile or lower of sufficient height to provide sufficient carriageway width.	Provide retaining wall with foundation below slip surface into original slope profile or lower. Wall may be masonry, gabions or reinforced soil. If immediate response included gabions or reinforced soil, check quality and either replace or complete reconstruction, as appropriate.
	Foundation failure of fill retaining wall				
	Retaining wall bulging	Infill sinking road surface	Ignores problem	Infill sinking road surface	Replace retaining wall with foundation below slip surface into original slope profile or lower. Wall may be masonry, gabions or reinforced soil.
Entire slope	Slide carrying road	Various large scale approaches	Rapid solutions may have short life as they seldom fix slip.	For short affected sections make Bailey bridge available to span gap. For longer affected sections road realignment may be needed. Temporary retaining wall with foundation below slip surface into slipped mass may be satisfactory.	Full solutions are often challenging as deeper seated failures may be seasonally reactivated. Tall retaining structures founded on ground below failure surface may be required, but they must then support both the road and the slip mass above the road.

of Roads and at the Ministry of Agriculture and Forests, and engagement with staff at the College of Science and Technology of the Royal University of Bhutan, good and bad practices were identified that have been codified into the suggested responses given in Table 2.

One particularly common, but unhelpful, response at present is to push slide debris off the road alignment, downslope (Figure 2). Unless the road is formed as a ledge on a cliff this is liable to result in a talus slope at the material's angle of repose immediately on the downslope side of the road (Figure 3). Being only marginally stable, such slopes commonly slide themselves, pulling parts of the downslope edge of the road with them (Hearn & Hunt, 2011). By stockpiling this material on the road, it has potential to become a resource with which to effect repairs while avoiding the slope instability issue (although this may limit carriageway width).

Figure 3 Scars of two large and one small slip onto a road and multiple talus slope scars below road

CLASSIFYING DAMAGE OF BRIDGES AND CULVERTS

Due to the nature of road construction in Bhutan, the existing network includes a limited number of bridges. However, a significant number of culverts are required to cross the many tributary streams and gullies. Most bridges in Bhutan are either reinforced or pre-stressed bridges or steel bridges. Steel bridges, often Bailey bridges, are used for shorter spans due to the difficulties in transporting large steel elements in Bhutan. Culverts are built using either reinforced concrete or masonry.

Concrete and steel bridges are sensitive to corrosion. However, the distance to the sea and the low pollution levels in Bhutan reduce corrosion rates significantly. However, the climate in Bhutan is associated, as described above, with a short period of very intensive rain. During this period, streams' flow can be very intense carrying boulders of large dimensions (boulders with diameter above 1 m are common, even in small streams). As a result, some common deterioration modes, including scour, are more intense in Bhutan while modes unusual elsewhere, like concrete erosion (Hong-kai, 2004), are present in many structures.

The failure of a bridge or a culvert will result in very severe consequences to the network. However, unlike landslides, failure of bridges are, to some extent, easier to predict. Erosion of concrete is easily observable visually, and once reinforcement is exposed, repair is clearly necessary (Figure 4a). A record of thickness of critical members would provide a good indication of the need to perform maintenance in the short term. Blockage, too, is easy to see once monsoon river/stream levels have abated. Scour is, in most cases, very difficult to observe. However, in this respect, the Himalayan region is unique. Since the rivers flood yearly, most piers stand outside the river bed for most of the year, making visual inspection, mitigation and repair activities significantly simpler than in other regions (Figure 4b).

(a) (b)

Figure 4 Examples of damage to bridge causes by high energy flows: (a) impact of boulder on culvert (see arrow); (b) the results of scour, seen in the dry season

As a result of the risks identified during the visit to Bhutan, Table 3 proposes a classification of risks, identification and quantification of damages and remedial measures.

Table 3 Risk assessment & mitigation measures for bridges & culverts

Failure mode	**Inspection**	**Mitigation**	**Repair**
Attrition of concrete	Measurement of element thickness	Monitor	New concrete cover
Corrosion	Visual inspection of key elements	Monitor	Replacement of corroded re-bars or new reinforced concrete layer
Scour	Observation of foundations	Protect pier areas with stabilized rock material (e.g. using gabions)	Replace removed foundation material
Impacts	Identification of boulders or tree trucks that can obstruct water	Clean underbridge, remove material that can cause obstructions	Local repair of concrete
Blockage	Identification of boulders or tree trucks that can obstruct water	Clean underbridge, remove material than can cause obstructions	Clean underbridge. Remove obstruction

Unlike slope failures, where short-term responses can often be applied when a road is cut due to a landslide, it is necessary to take steps, as far as practicable, to prevent total loss because replacement of a stream or river crossing will usually require significant construction work. For breaks in the road of only a few metres, replacement by ad hoc timber and planking may be possible as a temporary solution, but for breaks of greater length, preparatory and bridge/culvert construction works, even if using 'kit' parts (such as a Bailey bridge), cannot be implemented very rapidly. Bailey bridges are already used widely, being relatively easy to deploy and repair (Gopalakrishnan, 1999). Therefore, provided access to the missing bridge or culvert is possible, these bridges often offer the quickest, if not very immediate, solutions and can last several years until a permanent solution can be afforded and installed. To expedite installation of a Bailey bridge, it will be prudent to widely distribute kits of parts so that even cut-off communities can access them when they seek to re-establish a severed route.

CONCLUSIONS

Bhutan's roads provide lifelines to much of the country's population, but are at risk from slope instabilities and bridge/culvert decay; risks that are significantly enhanced by the results of the annual Indian monsoon which reduces soil and rock strengths and generates flood flows in rivers and streams.

This paper has:

a) highlighted the vulnerability of the Bhutanese road network as a consequence of climate and topographical issues,
b) shown that there is limited practical ability to prevent disruption of the network due to the risks posed by slope instability and floods,
c) proposed simple assessment approaches, appropriate to the economic and technical capabilities available, and
d) outlined remediation strategies that can be effected.

For slopes, the prediction of failure is not simple. Although mitigation measures can be applied at the most obvious at-risk locations, many landslips will still occur, so rapid remediation measures are needed so that the affected road may be re-opened quickly. Hence, resources must be deployed in a distributed manner if remediation equipment and materials can be accessed when instability does occur. Longer term solutions may be applied after the monsoon season. To assist with anticipating instabilities, and understanding failures, this paper has presented an initial, geometrical, classification of the different landslides each of which is matched to simple solutions for immediate and longer term.

Bridge and culvert operation must also be assured if the road is to remain open all year. This is best managed by annual inspections and necessary remediation as functional replacement can seldom be achieved rapidly. Therefore an initial proposal for inspection, mitigation and repair methods has been presented, dependent on the types of challenge that the structure faces.

It is recognised that such simple approaches will necessarily be limited in their reliability so that disruptions to the road network cannot be wholly avoided. Also, there are, undoubtedly, many issues in empowering and motivating road stakeholders to take preventative action, yet it is hoped that this paper will provide some stimulation to the process of enabling Himalayan communities to maintain functional roads year-round.

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