Engineering geological aspect for urban development in three capital cities in North Eastern India

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Abstract: Physical and anthropogenic activities causing geoenvironmental hazards are of prime importance not only to the sustainable ecosystem development but also to socio-economic conditions of the area. The adverse impacts of landslides, flash floods, earthquake etc., related to physical environmental processes and anthropogenic developmental activity have to be viewed in terms of sustainable progress. The geological aspects of the project on urban development in North-East India, in five capital cities of Agartalla, Aizawl, Gangtok, Kohima and Shillong has been carried out as follows, out of which the former three cities are being discussed here.

- Preparation of landslide incidence maps followed by field checking, in places by ground survey on the base map available at 1:5,000 scales. In the course of preparing this map, individual landslide scars falling en route of the utility services' alignment were studied in detail to enumerate the causative factors and their remedial measures.
- The actual landslide incidences were contoured in terms of the area affected per sq. km grid to produce the landslide over-view map on the base map.
- Preparation of slope percentage, drainage density, land cover and geological map from the base map.
- Compilation of the regional seismotectonic map with teleseismic as well as micro-seismic data.
- Collection of rainfall data to enumerate the subsurface flow of the hydraulic regime.
- By superimposing the landslide over-view map on the thematic maps, the relative involvement of each individual parameter was evaluated and the places of more susceptible zones identified on the Landslide
- Hazard Zonation map of the respective cities.
- The planners can now use these maps for the purpose of aligning their facility services.
- In cases where facility services have to be provided even in adverse conditions, mitigation measures will be suggested for the proposed engineering structures as far as practicable.

Résumé: Les activités physiques et anthropogéniques provoquant geoenvironmental les hasards sont de l'importance primordial pas seulement au développement d'écosystème durable, mais aussi aux conditions socio-économiques de la région. Les impacts hostiles d'éboulements, crues soudaine, le séisme etc., rattaché aux processus physiques de l'environnement et à l'activité anthropogénique du développement doivent être vus du point de vue du progrès durable. Les aspects géologiques du projet sur le développement urbain dans l'Inde Nord-est, dans les cinq villes capitales d'Agartalla, Aizawl, Gangtok, Kohima et Shillong ont été réalisés comme suit, dont anciennes trois villes sont discutées ici.

Préparation de cartes d'incidence d'éboulement suivies par le contrôle de terrain, dans les endroits par la terre étudient sur la carte basée disponible à 1:5,000 la balance. Au cours du fait de préparer de cette carte, les cicatrices d'éboulement individuelles tombant enroute de l'alignement des services utilitaires ont été étudiées en détail pour énumérer les facteurs causatifs et leur.

Keywords: landslides, urban geosciences

INTRODUCTION

The objective of the sustainable urban development in five capital cities of the states of the North eastern region of India, namely, Agartala, Aizawl, Gangtok, Kohima and Shillong, was initiated by the Government of India and is now being assisted by the Asian Development Bank under project TA 4348-IND. The package of consultancy has been dealt with by M/S LEA International Ltd., RVA, LASA, who, in turn, had appointed the author to carry out the engineering geological investigation. The work was carried out under the leadership of Dr. Jeffrey Stubbs, Team Leader/ Urban Development Specialist.

SCOPE OF WORK AND METHODOLOGY

The purpose of the present investigation was the assessment of natural hazard risk to areas, based on geological conditions, with an emphasis on the effects of landslide/subsidence, earthquake and flooding, with a view to suggesting mitigation measures. The basic causes of slope instability are inherent in rock or soil, in its composition or structural inclination of original undisturbed slope, ground water level, transient geodynamic processes and imposed constructional activities. With increased demand from the urban development activities in the hilly terrain, it has become essential to prepare landslide hazard zonation maps delineating areas of potential susceptibility, in order to provide advance, comprehensive information to the planners and decision makers. While approaching the problem, the guideline framed by David Varnes of USGS, Chairman of the IAEG Commission for UNESCO (1977) was broadly followed in order to prepare the susceptibility zonation map in three categories, e.g., Very high, moderately high and low. Such statistical analysis of landslide population provides insight into the fundamental causes of failures (whether induced by changing climatic conditions, stream incision, response to change in slope angle, a change in land use practices, or due to transient geodynamic processes), and allow them to be clustered into groups, in order of priority depending on the population of incidences of a particular landslide type. The objective is to develop an understanding of the processes involved based on geological evidence and present their mitigation measures with reference to the concerned cities.

AGARTALA

Agartala, the capital town of the Tripura state was originally a marshy land at the confluence of the Kata Khal and Haora Rivers, which form a major tributary to the Meghna River in Bangladesh. The backwater flows from the distributary rivers cause frequent inundation of the town in the rainy seasons. As a capital town it faced sudden impact of growth in an unplanned way. The area has a tropical monsoon climate, with temperatures ranging from 4°C in winter to 39°C in the summer, with an annual average rainfall of 2387mm.

Geomorphological considerations

This is a synclinal valley descending westward from a north-south trending ridgeline called Barmuda ridge. The ridgeline and the streams descending along the western slope exhibit immature topography as does the drainage pattern.

Geological considerations

The area belongs to the Himalayan and the Naga Lushai mountain belts / fore deep zone of structural ridges and valleys, the town being located on a synclinal trough with an alluvial fill down to more than 10 m depth. The underlying rock formation of Tertiary age comprises a moderately hard to soft sedimentary sequence of sandstone, shale and clayey material. The valley portion is dominated by thick underlying fine-grained sandstone with intervening thin shale bands and clayey horizons from a depth of 11 m as explored by the Geological Survey of India (GSI) and the Central Ground Water Board (CGWB). Hydro geologically granular layers have been encountered in two main horizons (1) 5-60 m below ground level, (2) 80-300 m below ground level. While the shallow level zone is in an unconfined condition, the deeper level zone is under pressure of piezometric head varying from 0.5m to 14 m below ground level.

Geotechnical considerations

The area being located near the confluence of two westerly flowing streams flowing into the major tributary river to the mighty Meghna River in Bangladesh, it happened to be a marshy land prior to the growth of population. At present it is facing the problem of backwater flow from the distributaries during flood time. Geologically the underlying rocks comprise Dupitila Formation of the Pleistocene age striking NNW-SSE, dipping both westerly and easterly on either limbs of the syncline, plunging to the north and having been bordered by Tipam sandstone of Miocene age to the immediate south, east. The sandstone being porous, it contains absorbed water in the interstices/ pore spaces, which comes out to the surface along the interface with the underlying shale layer and causes inundation in the low-lying areas of the town, which also happens to be the synclinal trough. Thus, the problem of inundation in the core of the Agartala town is mainly due to geological conditions as explained by lithological formations as well as their structural disposition.

Conclusions and suggestive mitigation measures

The problem may be reduced, if not totally overcome by:

- Diversion of the surface streams and the partial diversion of the Haora River to the northern depression, the kata Khal from the eastern part of the town after, of course, enhancing the carrying capacity of the channel by deepening, widening and clearing encroachment.
- Installation of a sub-surface trench drain along the eastern part of the town between Kata Khal and the Haora river in Chandrapur-Reshambagan area, excavated down to 6 m depth and having 3-4 m wide opening on the surface, back-filled with hand-packed sub-rounded pebbles/ cobbles within "Presto" buckets (geosynthetic material). This is lowered into the trench in rows and columns reaching up to less than 1 m from top level, which in turn will be filled up by soil. The trench has to be lined by geotextile of suitable perforation to retain the sub soil to the eastern side of the wall and geomembrane to the western side, as well as at the bottom of the trench in order to prevent escape of the collected water from the bottom. The water within the trench has to be discharged to the northern kata Khal by providing sufficient gradient in the invert of the trench.
- This sub-surface arrangement will itself serve the purpose of solving the water-logging problem in the town of Agartala and there will be no permanent rehabilitation problem, since the temporarily displaced population may be re-housed on top of the trench. This arrangement will be absolutely maintenance free.

AIZAWL

Aizawl, town is highly manifested with the incidences of landslides. The seismotectonic status of the area has contributed to the unstable slope condition. In addition, increased load due to sudden influx of building construction with poor drainage facilities on vulnerable slopes, additional road network, water pipe lines and reservoirs have all contributed to the instability of hill slope to a very large extent. The area under study has a tropical humid climate, with annual average rainfall of 1900 mm. While the summer temperature is fairly consistent at around 26º, the winter temperature varies from 11º to 13º.The humid and heavy rainfall contributes adversely to the inherent strength properties of the rocks.

Geomorphologic considerations

The topography of Mizoram is very rugged and immature. The physiography is depicted by six north-south trending, parallel to sub-parallel, high hill ranges with narrow and deep intermontane gorges. The average height of the hills is 900 m and the highest peak is the Blue Mountain (Phawngpui) with a height of 2156m in the southern part of the state. Geographically the state of Mizoram occupies the southern most part of the North-Eastern region having an international border to the south and west with Bangladesh and to the east with Myanmar (Burma). A national border with Assam is to the north. Narrow valleys, steep slopes and well defined narrow stream channels of more or less straight course, is the characteristic of structural control of the rivers and their immaturity. There are number of youthful rivers and streams (Lui- in local language). In the north, the Tlawang (Dhaleswari), Tuiral (Sonai), Gutur and Tuivvawal starting from central part of the state and flow northward to discharge into the Barak river of the Surma valley. Karnaphuli flows southwest into Bangladesh. The rivers Koladyne and Tyao flow to the south. The city of Aizawl is located on one prominent north-south extending ridgeline amidst subdued hill ranges on either flank, situated between 700 m to nearly 1288 m above sea level and bordered by the river Tlawng to the west and the river Tuirial to the east.

Geological considerations

Geologically, Mizoram forms a part of the Tripura-Arakan geosynclinal basin. The Mizoram hill (the Lushai hill) are considered to form an integral part of the mobile belt constituted of very tight, elongated, asymmetric, N-S trending anticlines alternating or en-echelon with broad saucer shaped synclines showing a slightly arcuate shape with westward convexity. The litho-stratigraphic succession within Aizawl town shows the spatial distribution of various litho-units and indicates that the rocks of the Upper Bhuban formation occur in the anticlinal positions in the western part. The middle Bhuban rocks occupy the limbs of the fold and the lower Bhuban rocks are confined only in the core of high amplitude anticlinal folds, not exposed in the town area. The repetitive sequence of alternating shale and sandstone is well exposed in the rock-quarry sites. The sandstones are grayish brown in color, rich in sericite mica, fine to medium grained, compact and relatively hard due to a calcareous, siliceous and ferruginous matrix. The shales are also gray to brown in color, thinly laminated, micaceous and occasionally clayey. The contact between the two appears to be disturbed due to the crumbled, crushed and pulverized nature of the shale.

The geological structure along and across the elongated hill on which the town is located is represented by N-S trending anticline and NNE-SSW trending syncline, interrupted by faults. Several such fault lines have been observed in the area trending NNW-SSE, NE-SW and E-W. There are at least 15 faults visible within an area of approximately 130 sq km. The E-W faults appear to have displaced the continuity of the N-S trending anticlinal fold, matching well with the westerly facing scarp of the Govt. High School hill, Chanmari-Laipuitlang-Chaltlang Tourist lodge scarp, and Bawngkawn-Durtlang scarp. Other major fault locations are Hunthar Veng-Vaivakwan-lui towards Tlawng River in the NW sector and Vaivakawan saddle-Dinthar saddle and Khathla saddle in the south-eastern sector. The strike of these rock formations is generally NNW-SSE, dipping 40º-45º towards east on the eastern slope and 10º to 15º towards west on the western slope of the range. Both the slopes are of considerable steepness and the rocks dip adversely towards the direction of the hill slope. One favorable phenomenon is the presence of cross or superimposed fold trending in a SSW-NNE direction, which causes rotation of strike of the bedding planes. This in turn provides natural resistance against sliding.

Geotechnical considerations

The top of the hills being capped by sandstone having sufficient porosity, rainwater infiltrates down to the interface with impervious clayey shale layers, and exits to the surface due to gravity. While coming out through the shale/silty layers the water carries with it the slope forming material. As a result the overlying slope gradually sinks due to removal of material from underneath.

There are conspicuous features of highly dragged shale overlain by massive blocky sandstone. The drag folds generally die out towards depth where the rock becomes soft and friable. The cause of such movement appears to be squeezing out phenomenon of the soft plastic layer due to weight of the overlying more rigid layer, which may be referred to as “Piston Slide” after US Highway Research Board Special Report 29, pp 62. There is also indication of part of the upper layer dropping vertically without rotation, into space left by the removal of the plastic layer, very much alike to slump ball or pseudo nodules of penecontemporaneous structures.

Once triggered off, the process, which is a very slow one, results in continuous cycle of gradual upheaval of the weaker strata and the counter adjustment by unloading of the superincumbent load. This has made localized areas of the slope highly unstable and where such phenomenon happens, it is extremely difficult to provide protective measures by construction of any superstructure. Moreover, in such movement in a later phase, the minor partial slide surfaces are likely to join to form a persistent surface along which any abrupt movement due to earthquake shock may lead to a disastrous block glide. Some of the prominent active landslides studied in the Aizawl town are tabulated below.

The physico-mechanical properties of rocks, such as geological structure, fracture patterns, and degree of weathering, were closely observed in the field and data on uniaxial compressive strength and angle of friction of discontinuity planes were collected from most of the landslide-affected areas. Considering (i) the mode of failure to be a simple block sliding along the bedding plane in the form of mud flows in most of the cases, (ii) no resisting force to sliding at the lateral boundary of the failure. (iii) the shear strength of the sliding surface has been defined by cohesion and angle of friction along the failure plane, (iv) the presence of water in the discontinuity plane/ interface between permeable and impermeable rocks causes lowering of the cohesive strength, the determination of safe height of excavation on such hill slopes are considered to be as follows:-

Table 1. Prominent active landslides studied in Aizawl town.

Name of the area of landslide	Length (m)	Maximum (m)	Height from crown to toe in (m)	Approximate area (m^2)	Main causative factor
1. Electric Veng 1983	400	150	200	40,000 200 houses affected	Toe erosion by Thei hai River and subsurface surcharged water
2.Arm Veng 1983,1986,1993,2002	150	300	75	16,000	Toe erosion and subsurface surcharged water
3. Sarwan Veng 1983,1986,1993	400	160	150	45,000	subsurface surcharged water due to improper drainage
4.Vaivakawan 1983	250	250	175	50,000	Toe erosion by Vaivakawan Lui. subsurface water
5.South Hillman 1993	230	250	400	57,000	Under-cut of slope for Rock quarry
6.Zemabawak 1993	150	250	75	15,000	Under-cut of slope for Rock quarry

Table 2. Excavation height vs Factor of Safety

Excavation height (h) in metres	Factor of Safety
0.5	2.48
1.0	1.46
1.5	1.12
2.0	0.95
2.5	0.85
3.0	0.78
3.5	0.73
4.0	0.7
4.5	0.67
5.0	0.65
10.0	0.55

(Source: Dr. Shiv Kumar's post-doctoral thesis, 1997-99, Department of Geology, NEHU, Aizawl)

The landslide prone area in 1991 was 11.48 acres (4.64 hectares), having percentage of 0.04 % of the total area and 0.21 % of the developed area along the major arteries towards Durtlang-Seleshi-Sihphir in the north; Zuangtui-Zemabawk, Mualpui in the east; Tlangnuam-south Hilman-Melriat in the south and Luangmual-Tanhril-Sakawrtuichhun in the west.

In general the eastern side slope is less vulnerable than the western side slope because of higher dip amount of the bedding plane with respect to the topographical slope. There are locations where due to cross-folding movement, the rocks often dip into the hill, making the slope vulnerable to toppling of rock chunks. The steeply dipping fault planes or joint planes towards the hill pose such problems of toppling phenomenon. The following parameters are associated with the toppling phenomenon:

- Dip of discontinuity, 45º on the eastern slope area.
- The topographical slope angle, safe in case of up to 50º and unsafe if it is more than 70º.
- Frictional angle of the interlayer sequence determined by field method as 24º
- Frictional angle in the case of the blocks 1.55 times of the previous.
- Inter-layer thickness ranges from 1-6 m.

For the purpose of preparation of a landslide hazard zonation (LHZ) map, the entire area was divided into 250m grids. Slope percentage and drainage density were calculated by computer, and plotting of actual landslide incidences were done in the field. It was observed that the steep slope areas generally show lesser drainage density and landslide incidences are not however related with any of these parameters. The underlying geology, especially the structural features and the piston effect as discussed earlier, are the causative factors. Active landslide scars have been marked mainly in the central part of the town on its easterly and westerly extension areas and towards southern part of the town where active rock quarrying process is continued unabated. In the northern part of the town the entire western fringe is very highly prone to landslide. In the central part of the town the areas that are very highly prone to landslide are distributed in ENE-WSW direction, following the geological structure (mainly faults) of the area. In the southern part of the town the areas that fall in the category of very highly prone to landslide are restricted along the crest of the anticline, where the major problem is unsystematic rock quarrying and unsupported overhangs. The areas of moderately high proneness to landslide are on either slope of the ridgeline, where the slope condition is less steep but the drainage density is more. The low hazard prone areas are distributed all over the slope area. The LHZ map may be suitably utilized for laying utility services.

The morpho-tectonic disposition reflects neotectonic activity related to NNE-ward push resulted from plate convergence and collision mechanism and as such, the earthquake-induced landslide can never be ruled out. The geotechnical map of India, first edition 1995, published by the Geological Survey of India shows that the town of Aizawl falls in the seismic zone -V with close epicenters to the NE and SE.

Conclusions and suggestive mitigation measures

- The problem of landslide in the area is one of the most critical natural hazards and considering the seismo-tectonic status of the area and the lithological distribution, the probability of earthquake-induced landslide cannot be ruled out.
- The town population recorded a sudden growth rate of 49.17 % in 2001 Census report. This has caused tremendous expansion to the east-west direction in the central region of the town.
- Dwellings have been constructed on precarious slopes adopting methods which are more precarious, resting almost more than two-third of their base on cantilever projection supported in general on bamboo pillars down to 15 m or more on the steeply descending valley slope. Even a thunderbolt may cause triggering effect of house collapse in such cases.
- In such situation any short-term measure can hardly be adopted to solve the problem, unless a total rehabilitation and extensive land-slope reform is made.
- Surface observations are essential in determining the effect of subsurface water on landslide instability.
- Periodic or seasonal influx of surface water to subsurface will not be detected unless subsurface water observations are conducted over an extended time period.
- Landslide movements may open cracks and develop depressions at the head of a landslide that increases the rate of infiltration of surface water into the slide mass.
- Ponding of surface water anywhere on the landslide may cause increased infiltration of water into the landslide and should be immediately drained out.
- Disruption of surface water channels and culverts may also result in increased infiltration of surface water into the landslide.
- Landslide movements may result in blockage of permeable zones that were previously freely draining. Such blockage may cause a local rise in the groundwater table and increased saturation and instability of the landslide material. Subsurface observation should therefore be directed to establishing subsurface water conditions in the undisturbed areas surrounding the landslide.
- Low permeable shale, particularly the crushed and pulverized carbonaceous shale material which are very commonly involved in the landslide of the town have extremely slow response times to changes in subsurface water condition and hydrostatic pressures. Long term subsurface water monitoring is absolutely essential in such type of substratum where piston slides are involved.
- Accurate detection of subsurface water in rock formations is often difficult because shale and clay layers, intermittent fractures, and fracture-infilling or incrustations may occlude subsurface water detection by boring or excavation.
- Boring should never be the only method of subsurface water investigation, nevertheless they are a critical component of the overall investigation.
- For a total uplift of the face of the present problem-stricken Aizawl city, it may be considered that the crest of the ridge lines should be excavated from top to create flat extensive land for dwelling purpose and with well constructed water pipe lines and sewerage pipe lines, the problem may be permanently solved though involving huge cost and hazards in the city life.
- Removal and replacement techniques carry with them their own inherent liabilities. In steep terrain like this available space for stockpile area may be scant, therein requiring the construction of stockpile fences, which may be created by concrete and masonry gravity retaining walls. Such buttress fills happens to be the most commonly employed method of landslide repair in the United States today.
- The entire base of the flat surface excavated should be kept as dry as practicable using modern technology of spraying asphalt-geosynthetics mulch on the uncovered surface, instead of present practice of locally covering by spreading polyester sheet. Soil reinforcing grids serve to increase the unit shear strength of any soil in which they are emplaced, thereby offering much higher long-term factor of safety. In situ soil reinforcement

also allows designer to vary steepness of the slope's finished face, allowing vertical faces when necessary with application of geogrid.

GANGTOK

Gangtok, the capital city of Sikkim is built up at an altitude of 1692m above sea level on a ridge top having at least three saddles along the longitudinal profile. The city had earlier started urban spread down the western flank almost to the Valley of Ranikhola River. Sudden influx of building construction with poor drainage facilities on the vulnerable eastern slope in Chandmari area has aggravated the pre-existing slope stability problem there. The presence of a network of water pipe lines and sewerage lines has all contributed to the instability of hill slope to an alarming extent. The eastern slope area, with a very steep and subsidence-affected topography down to the Rorochu River is physiographically, climatically and geologically unfavourable from the stability point of view. In addition, increased load due to construction of a number of high-rise buildings, and the newly excavated bench for the Indira Bye-pass on the mid-slope region on the western slope have created a new dimension to the problem.

The basic need for planning water resource development from the drainage basin of Rateychu and the slope stability consideration along the water conductor system also comes under the purview of present discussion. In the case of a feasibility evaluation, adequate and reliable hydrological data is a pre-requisite for rational and effective planning. This will determine the need of a storage element vis-à-vis the present system of the run-of-the-river diversion. The required storage capacity depends on the variability of the river flow, its degree of reliability and demand of load. For such examples of run-of-the-river schemes, seasonal and sometimes diurnal fluctuation is of prime importance. The wide variation in altitude results in severe climatic variation. Within a matter of one hour's drive one experiences sub-tropical heat to ice cold weather. The annual average rainfall varies from 340 cm in the southern parts to 64 cm in the northern parts. Rainfall, which happens to be the chief source of water (apart from snow melting), is defined by three variables: volume, duration and frequency. While volume denotes magnitude of rainfall expressed in terms of total volume occurring in the duration of rainfall, frequency denotes return period or recurrence interval of similar rainfall incidence. Vegetative cover and the form of watershed are the factors causing the remaining 5-10% balance.

The flysch type of sediments comprising alternate layers of contrasting permeability of the early Tertiary Group of rocks have exceptional water confining character and therefore may have high run off values in places. Hence in developing run off based on hydro-geologic consideration, it is necessary to compare the rainfall intensity values and the geological formations according to their hydrologic character, with those from the known areas where all the relevant data are available.

Geomorphologic considerations

The territory Sikkim is located in the inner Himalayan belt having north-south extending ridgelines formed as a result of intensive dissection of the east-west extending mountain chain. The city of Gangtok is situated in a more or less central position of the leaf–shaped Rongni Chu (Rani Khola) catchments, surrounded by Rani khola to the west and the Roro Chu to the east, which meet to the south to give rise to Rongni Chu or Rani Khola.

The morphometric analysis indicates that the basin as a whole is slide-prone, though the town of Gangtok is less affected. In general the lower drainage density basins with lower relief ratio are relatively more landslide prone, as the basin tends to achieve maturity. The slope on the eastern side of Gangtok ridge i.e., the catchment of the main river Rongni Chu is more slide/ subsidence prone than its tributary river Rani Khola flowing along the western side slope of the Gangtok ridge. The landslide intensity study, carried out by contouring the percentage of the affected area in the basinal area has revealed a broad pattern, following the structure and tectonic framework of the area. It has been observed that the lithologically incompetent and structurally disturbed rocks in areas of more than 60 % slope (i.e. 30° from horizontal) are generally susceptible to slope failure.

Geological considerations

Stratigraphically, rocks of the area are the oldest group of sediments deposited over the basement complex and presumed to have been brought to the top-most tectonic position by thrust movement. Though the stratigraphic sequence happens to be in the reverse order of superposition, there is no inversion of top-bottom criterion within one tectonic unit, supporting the concept of second order nappe or glide tectonism. The physical continuity of the different nappe units has been obliterated by profuse metamorphism in the root zone, not very far from the area under present consideration. At the sole of the crystalline nappe and away from the main crystalline gneiss, occurs a conspicuous and persistent band of gritty and mylonitic gneiss known in the area as "Lingse gneiss". The northern and north-western part of the city is the location where this gneissic band occurs as a continuous band having blocky and sheared appearance on the surface. This band serves the purpose of the index horizon and easily identifiable in the complicated litho-stratigraphic succession of the inner Himalaya. Structurally the town occurs at the crest of an asymmetrical anticline with both the limbs dipping in an easterly direction, having its axial culmination in a NNE-SSW direction. The dip is of the foliation planes, from the slope stability consideration, is favourable on the western flank due to its hill ward dip while unfavourable on the eastern flank due to its valley-ward dip.

Geotechnical considerations

Land subsidence associated with various types of slope failure such as accelerated soil and rock creep are the major processes operative in the town's eastern side near Chandmari area, locally in the heart of the town near Tadong-

Deorali areas, and in some of the unprotected jhoras above the lately opened Indira Bye pass. The most dangerous problem which threatened the town was the possibility of tilting of the TV Tower towards Chandmari side slope 7-8 years ago. The adjacent slope in Tathangchen is also being threatened by similar problem of accelerated soil and rock creep which is in the process of posing danger to the Secretariat building and the Palace complex in the near future.

The planar geological structures that are involved in these areas are adversely dipping joint planes, foliation planes and the presence of adversely oriented shear zones. These features deeply influence the in situ rock mass properties. The easterly aspect of the topographic slope has an overall inclination of 20°, which coincides with the down-dip schistosity plane. The sheared gneissose rocks and the schistose layers have compounded the adversity.

From the elbow-bend course of the stream Roro Chu which flows downslope of the city at an elevation difference of nearly 500 m at a lateral distance of about 1200 m, it is suspected that the initial cause might have been the toe erosion by the river, which is now covered by the slide debris. The toe erosion by the river proceeds systematically by removal of weaker / less competent rock with the formation of a natural tunnel inside the slope. In high flood period the water level rises up and pushes into the cavity thereby exerting compression. As soon as the water level recedes, there is suction effect, which brings out the material. The continuing process of alternate suction and compression results in the creation of tunnel-like cavities into the slope. This in turn causes gradual subsidence in the overlying slope. The collapsed material covers the mouth of such lateral cavities that cannot be detected from surface unless it is cleared. From the hydrological behavior of the rivers in this terrain, it has been commonly observed that floods are almost invariably associated with landslide and soil slips in such meso-level drainage basins, like the Roro Chu River and its major tributaries. The collapsed material from the adjacent valley walls causes frequent choking and impounding of the river. As the river over-steps such natural barrier, it causes flooding downstream. On the transverse profile, the river shifts its course to the opposite side of the sliding bank initiating toe-erosion there. Thus, ultimately the river valley takes the shape of alternating broad valleys and constricted gorges, the latter causing bottle-necks, susceptible to choking and subsequent pulsation flooding, which are quite frequent in such north to south flowing meso-level drainage basins. It is interesting to note here that on the opposite bank of the river Roro Chu in Bhushuk area, a similar type of subsidence problem already exists and the slope had to be abandoned for dwelling purposes after a detailed geotechnical investigation. The environmental aspect has been further worsened by sprawling settlement and increased activities of building construction without proper drainage planning. Added to the problem, is the selection of the site for the TV tower and its ancillary complex just above the top of such a subsiding zone. The soil from the bottom of the tower gradually started migrating downward and outward posing a serious threat of tilting. This has been temporarily controlled by the construction of a massive reinforced retaining wall at the top of the slope, just below the foundation of the tower. The area at the top has been somewhat stabilized by back-filling the cavities with sand and covering up the undulatory slope with grass plantation etc. Some of the cracks in the platform of the tower foundation and back side of the transmitter building have been repaired and are continuously monitored so that rainwater cannot percolate inside. The proposed vertical chute drain could not be constructed due to local objection. Since the remedial measures implemented remain at a low factor of safety, according to the designer himself, the fate of the structure is purely at the mercy of nature. Accumulation of subsurface surcharge water pressure or earthquake tremor can lead to a catastrophic devastation.

Conclusions and suggestive mitigation measures

- The problem of landslide in the area is one of the most critical natural hazards and considering the seismo-tectonic status of the area the probability of earthquake induced landslide cannot be ruled out.
- The town population recorded a sudden increase leading to tremendous expansion of housing on the eastern slope of the main ridge adjacent to the VIP areas.
- Dwellings have been constructed on precarious slopes adopting methods that are more precarious, resting on cantilever projection supported on poorly designed supports.
- Prior to construction of the dwellings, the steepness of slope should have been reduced and provided with adequate drainage with permanent cement lining.
- Surface observations are essential in determining the effect of subsurface water on landslide instability.
- Periodic or seasonal influx of surface water to subsurface will not be detected unless subsurface water observations are conducted over extended time period.
- Landslide movements may open cracks and develop depressions at the head of a landslide that increases the rate of infiltration of surface water into the sliding mass.
- Ponding of surface water anywhere on the landslide may cause increased infiltration of water into the landslide and should be immediately drained out.
- Disruption of surface water channels and culverts may also result in increased infiltration of surface water into the landslide.
- Landslide movements may result in blockage of permeable zones that were previously freely draining. Such blockage may cause a local rise in the groundwater table and increased saturation and instability of the landslide material. Subsurface observation should therefore be directed to establishing subsurface water conditions in the undisturbed areas surrounding the landslide / subsidence.
- Because of fracture-infilling or incrustations, it may occlude subsurface water detection by boring or excavation.
- Boring should never be the only method of subsurface water investigation, nevertheless they are a critical component of the overall investigation.

- For total uplift of the face of the present problem it is suggested to accurately detect subsurface water in rock formations, which is of course often difficult.
- Provision of berms and benches at regular interval, in order to ease the slope as far as practicable.
- The subsurface water pressure needs to be released by providing trenches with gradient leading towards the side vertical chute drains along existing depressions. The trench is to be made 2-3m wide and 4-6m in depth, lined with geotextile on the hillside and geomembrane on the valley side as well as the base of the trench. "Presto buckets" made of geopolymer to be filled by assorted spherical cobbles and pebbles and lowered into the trench in rows and columns. The purpose of the geotextile will be to allow subsurface water to enter into the trench while retaining the soil material behind. The purpose of the geomembrane will be to retain the accumulated subsurface water within the interstices of the hand-packed cobbles and pebbles and leading it to the side chute drains on either side. The trench should be covered at top 0.5 m by soil and subjected to vegetation turfing. In between the rows of trenches, properly designed cement lined storm water contour/ garland drains also have to be provided leading to the side chute drains, for taking care of the storm rainwater.
- The entire urbanised area should be provided with bitumen top roads with roadside lined drains leading to the chute drains. The domestic sewerage water as well as the water pipe lines should not be allowed to enter the subsurface by leakage.
- The chute drains should be cascaded down with steps to allow water cushioning that will reduce the impact of the flowing water.
- The toe regions of the Chandmari-Tathangchen slides have to be protected by a massive RCC retaining wall.

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