Stabilization of Slope at Cabo Hill, Goa, India – A Case Study

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ABSTRACT

Forensic Engineering is an important discipline relating to the application of Engineering principles in investigation of failures and suggesting remedial measures. In this regard, a case study of the slope stability studies carried out by the Geological Survey of India on the Cabo Hill in Goa, is presented. Raj Bhavan, the official residence of the Governor of Goa, is located on Cabo Hill at a height of 40m above the sea level. Cabo Hill consists of laterites that occur as capping over the parent rock and the duricrusts developed over the lateritic profile occupy the top surface. The four centuries old Raj Bhavan constructed by the Portugese is a two-storied monumental structure constructed with 0.7m thick walls comprising of laterite blocks in mud mortar. The hill slope was reported to have been undergoing a gradual distress due to natural processes over several decades with cracks appearing at the pavement as well as the rocky floor. The initial studies made by the Central Building Research Institute attributed distress to ground subsidence and concluded the structure as unsafe. Some protective measures by constructing Buttress walls, Retaining walls, Sea-walls etc., by the State Public Works Department in the 1960s, did not yield desired stability and the slope continued to exhibit distress in the form of deepening of cracks and related tilting of parts of the structure, indicating downward slope movement. In view of above, the Geological Survey of India (GSI) took up a detailed investigation on the slope distress and identified the causative factor as sliding along a shear plane. GSI recommended installation of pre-stressed cable anchors at crucial centers, besides RCC grid blocks, micro-piles etc. The work was executed by ITD Cementation India ltd.

INTRODUCTION

The Cabo Hill is essentially a lateritic hill housing Raj Bhavan-the official residence of His Excellency, the Governor of Goa. The hill has an elevation of 40m. The Raj Bhavan shown in Fig 1 is reported to have been constructed 400 years ago. It is said that the western and northwestern slopes close to Raj Bhavan, facing the Arabian Sea was experiencing slope distress over a past few decades. The effect of slope distress was manifested as development of cracks in the pavements, and on the floor of the verandah and the rear part of Raj Bhavan building. The Cabo Hill housing the Raj Bhavan, forms a cape facing the Arabian sea in the State headquarters – Panaji. Cabo Hill forms part of the Survey of India Topo-sheet 48E/15.

Figure 1 Raj Bhavan on Cabo Hill top

STUDY AREA

Fig 2 shows the study area. The hill trends NW-SE bounded by Mandovi River in the North, Zuari River in the South and Arabian Sea in the West. The crest housing Raj Bhavan is convex in its profile.

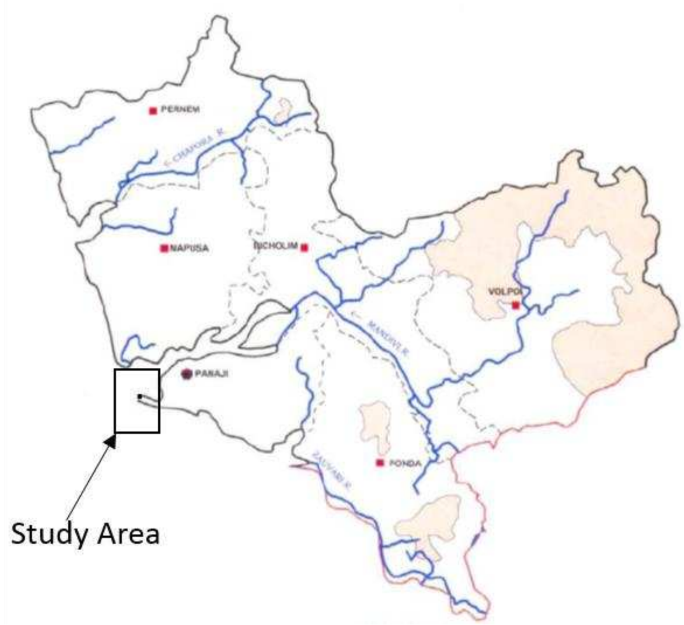


Figure 2 Study area

Geology

Goa situated at the west coast of India, forms a part of Precambrian shield of India, in which the Precambrian Greenschist Supra-crustal rocks overlie a basement consisting of Gneissic rock (Peninsular Gneiss) intruded by Mafic to Ultramafic Dykes and Granites. The geological map of Goa is shown in Fig 3. Late Cretaceous Basaltic rocks (Deccan Traps) occur at the northeastern periphery of Goa (Fig. 4a). Laterite occur as a capping over most of the rocks along the coastal stretches in the state as shown in Fig 4a. A 10m wide Dolerite dyke trending NW-SE characterized by vertical joints is reported close to the Cabo Hill part facing the sea. The dyke at the Cabo Hill is also reported to have a laterite cover. The lateritic profile is rather thick around 60m and the geological studies around the area have indicated the presence of rocks such as Schists, Quartzite, meta-Basalt, Greywacke, Phyllite, Siltstone/Shale intruded by Dolerite and vein-Quartz. Drilling at selected spots have revealed the presence of unaltered rocks at a depth of -42m, trending NNW-SSE with a northerly dip varying between 35° and 70°(Panduranga et al, 2008).

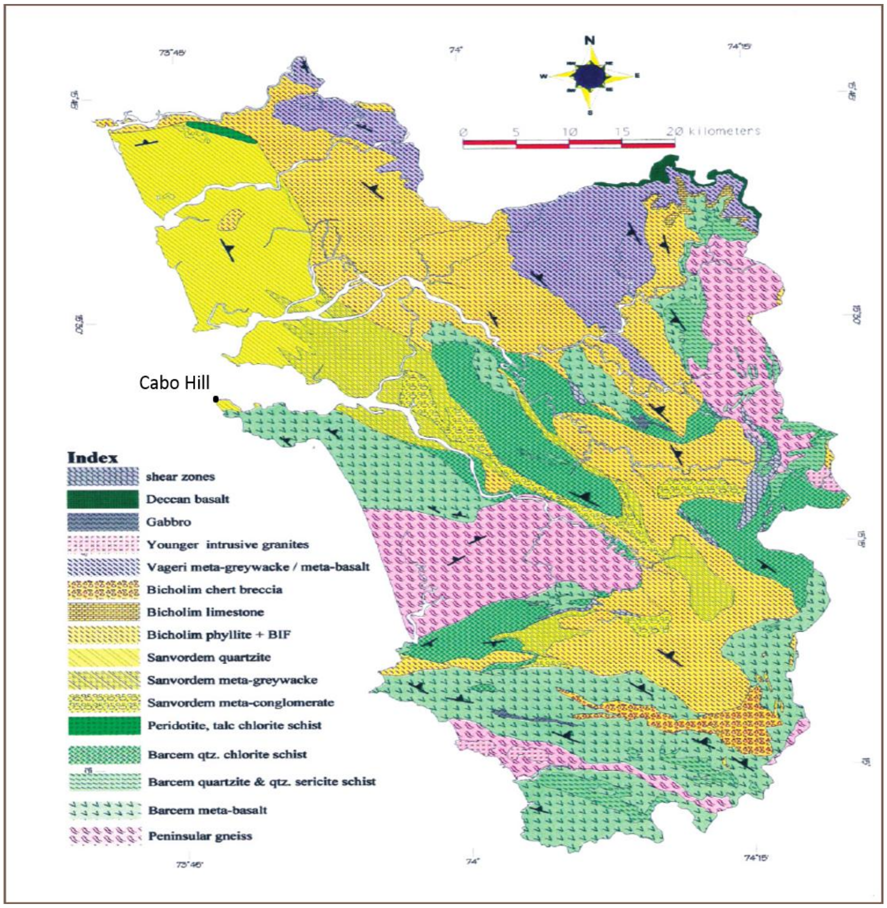
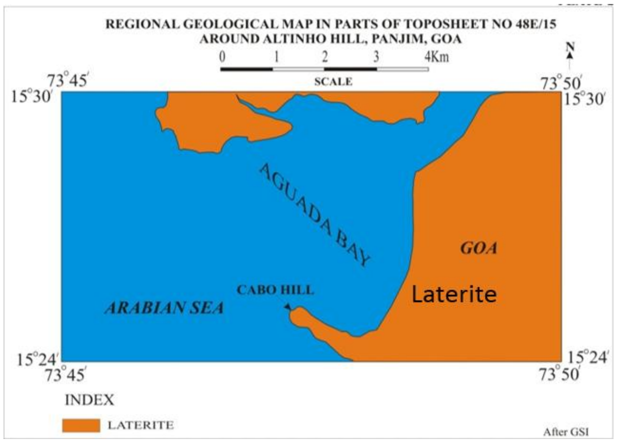


Figure 3 Geological map of Goa (Maruti et al, 2010)

The Cabo Hill comprises of lateritic material (Fig. 4b). Laterite represents a type of rock rich in iron and aluminum and is commonly considered to have formed in hot and wet tropical areas. The laterites have a typical profile and are in general rusty-red in colour on account of high iron oxide content. This rock develops by intensive and prolonged weathering of the underlying parent rock under specific climatic conditions.



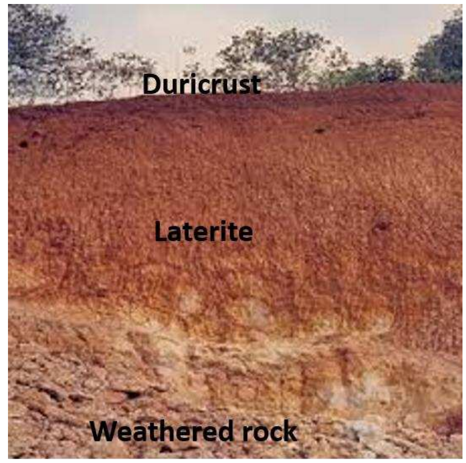


Figure 4(a) Laterite occurrence along the Coastal stretch (b) General laterite profile

The laterite at the site contains a very hard and ferruginous duricrust at the top. The duricrust is a hard crust that forms at the surface of a lateritic profile, which hinders water infiltration and the emergence of seedlings. In the vicinity of Raj Bhavan are also seen fairly steep escarpments that are essentially controlled by joints. At the middle part of the Cabo Hill slope, dislodged blocks are present as debris or a scree.

SLOPE DISTRESS CHARACTERISTICS

The western and northwestern slopes of Cabo Hills are reported to have been undergoing distress over a long period. The south and south eastern slopes that were once stabilized also continued to show distress. Cracks were seen developed on asphalted pavement behind the Raj Bhavan. Small concentric cracks at the Crown were noticed on the asphalted pavements in front of Chapel. The parapet wall constructed around the edge of the steep slope adjacent to Raj Bhavan had developed cracks at many places indicative of horizontal and lateral movement. Five sets of parallel cracks trending in NNW direction were also present at the staircase leading to Grotto – a small Chapel. In addition to it five sets of joints exposed in the laterite was open, showing clear displacement along horizontal and vertical directions.

Steeper slope angles at the higher reaches of the slope, poor shear strength of the subsoil, excessive loading over the steep slope coupled with heavy infiltration of rainwater and sewerage water in an already unstable mass at the crown part were reported to have been responsible in making the subsurface susceptible for continuous distress along the rupture zone. In addition, the scree present at the mid slope part reflects its derivation due to instability effect of the top part of the hill. The material is assorted comprising lateritic, silty clay, saprolite and weathered materials. These materials are found to overlie the fresh and unaltered rocks at depth.

BACKGROUND INFORMATION

Prior to GSI taking up investigation in 2002, M/s Descon Engineering consultants, Bombay had carried out geotechnical investigation between 1969 and 1971, over the slope instability issue, then had suggested grouting and a curtain of rotary drilled anchor piles along the margins of the pavement. Later M/s Central Water Power and Research Station (CWPRS), Pune while investigating the cause of slope failure during 1988-89, found out a zone of tension at the bottom of the lateritic formation leading to development of cracks at its capping. M/s Central Building Research Institute (CBRI), Roorkee in their structural engineering and geological investigations in 1996 recommended some of measures like RCC piling, construction of new toe wall, stitching of cracks on the surface of laterite cap and cantilever support for the first floor verandah to address the problem.

Even though the above recommendations were followed, instability continued to occur affecting the slopes especially the western and northwestern slopes. Subsequently the Geological Survey of India (GSI) took up the investigation following the request of Govt. of Goa and suggested remedial measures (Panduranga et al, 2008).

CAUSES OF SLOPE DISTRESS

The Geological Survey of India (GSI) commenced geotechnical investigation at the portion of the distressed slope in 2002 (Panduranga et al, 2008). A geotechnical map prepared on scale 1:500 showed the weak zones and distribution of scree and debris, duricrust, paleo-scars, cracks as well as appropriate borehole locations. Based on the investigations coupled with borehole analysis, the remedial measures suggested include pre-stressed anchor cables at selected weak zones, vertical and horizontal piles, retaining walls, weep holes etc. The geotechnical map of the Cabo Hill (after GSI) is shown in Fig 5.

When the GSI took up the investigation, cracks had already developed even on the pavement which was asphalted later, parapet wall, corner of verandah and the staircase of Grotto (a chapel at the Cabo Hill), buttress, cladding wall and seawall. This led to a conclusion that the protective measures carried out earlier were not effective. Even the south and south-eastern part, near Grotto, happened to be the continuation of the part of the slope that were once stabilized, found to experience distress. Besides the cracks in the building, five sets of joint planes within the laterite were open indicating clear dislocation.

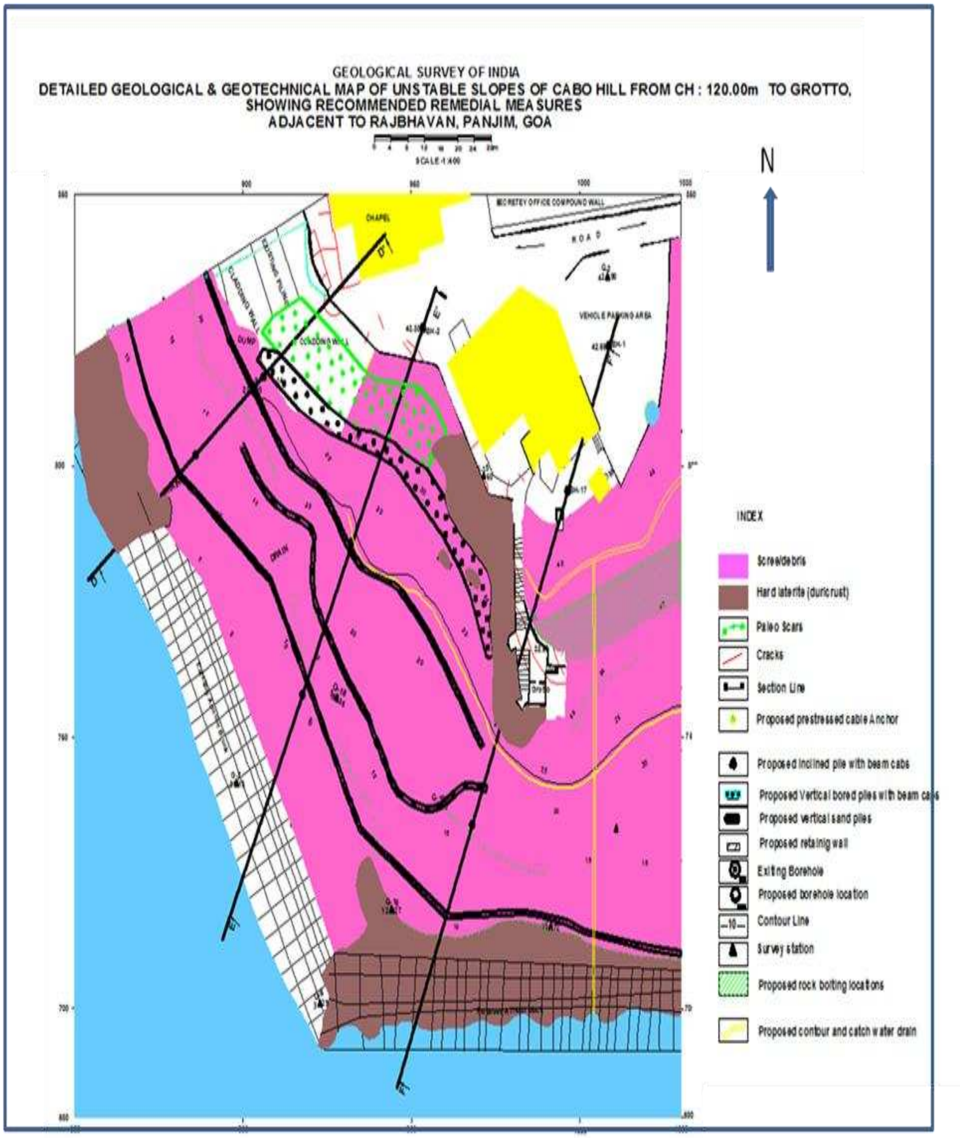


Figure 5 Geotechnical Map of Cabo Hill (After GSI)

Later, GSI took up a detailed geotechnical investigation to find out the cause and suggested remedial measures at the request of Govt. of Goa. GSI carried out drilling up to a maximum of 40m in selected locations and collected undisturbed samples from various horizons and the samples were subjected to geotechnical analysis enabling construction of a critical slip circle. In-situ tests were also carried out by Standard Penetration Tests (SPT) (Maruti et al, 2010). The geotechnical parameters determined on undisturbed samples included particle size distribution, specific gravity, bulk density, natural moisture content, porosity, compressive strength, cohesion and angle of internal friction values. The critical slip circle of the distressed slopes was constructed duly integrating the various geotechnical parameters and the engineering properties of the sub-soil. Later in the year 2009, the geotechnical data obtained by studying the borehole samples were utilized in carrying out stability analysis at the request of Govt. of Goa and revised the measures for stabilization.

The study has revealed that many geological and man-made factors responsible for the distress. These factors can be summarized as:

- The rock has well defined joints that are fairly wide and vulnerable for failures
- The presence of incompetent material between the lateritic duricrust and fresh rock
- Angle of slope is relatively steep in relation to cohesion and angle of internal friction values of sub soil
- Toe cutting or erosion by wave action
- Disproportionate increase in constructional load
- Improper drainage
- Unscientific waste disposal affecting the fractures and joint planes in the laterites enabling water infiltration

SUGGESTED MEASURES

On the basis of geotechnical studies taking into account the slip circle, slope morphometry, geotechnical properties of material forming the slope, the following measures were recommended by GSI for various segments of the slope.

Upper part of the slope

The upper part of the slope is stabilized by using pre-stressed cable to tie up the fractured, hard lateritic media into a monolith and fixing to the intact part of the duricrust. Cable anchors were planned at different levels between 3 and 40 m R.L over a length of 20 m at an inclination of 20° at a spacing of 2 m at each row. Apart from arresting the mobility of the distressed blocks, anchors are expected to arrest further development of any tensional cracks resulting in subsequent distressing. This measure improves the mechanical behaviour of the fractured hard duricrust of the laterite. Also grouting was done for the cladding wall and for the sealing of ground cracks as shown in Fig. 6. In addition to this, vertical piles are laid and rock bolting (Fig 7) was also done to prevent the widening of the rock joints in laterite.

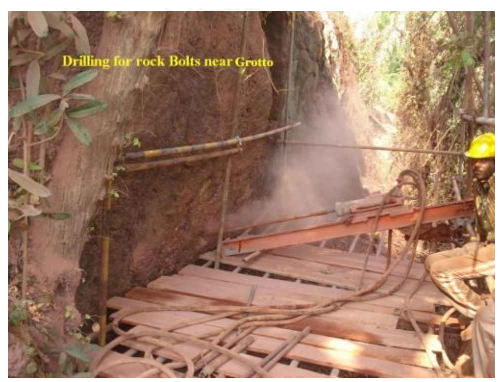


Figure 6 Grouting over the cladding wall

Figure 7 Drilling for Rock bolting

The provision of intermediate shear interceptors at the foot of the steep slope also helps to stabilize the slope. These shear interceptors are inclined bored piles with beam caps.

Middle part of the slope

The middle part of the slope is stabilized by installing shear interceptors of 15m length as vertical micro piles for achieving desired shear resistance to the creeping mass. Also a row of vertical sand piles on the mid slope was provided to release the possible pore water/ ground water pressure from the slope-forming media. The progressive creep of the slope material can be countered by making the slope gentle and by providing surface drainage. Accordingly GSI had recommended grading of mid-slope into terraces utilizing boulder sausages. The boulder sausages were to be provided with weep holes to drain subsurface water and also to overcome pore pressure. Turfing or terrace gardening was done over the treated soil to create a geo-green blanket for aesthetics as well as stability.

Toe part of the slope

The toe part of the slope is stabilized by the construction of retaining walls with effective weep holes and graded filtering. As an effective shore protection work, armour block claddings were recommended all along the shoreline of the unstable slope to protect the toe of the distressed slope from scouring.

Once the remedial measures are adopted, GSI suggested certain measures to monitor the distressed unstable slopes of Cabo Hill. They include the slope movement monitoring, settlement observations, measurement of pore water pressure and monitoring of ground cracks.

Execution of Civil Works

M/s ITD Cementation India carried out the work for the Govt. of Goa in two phases, duly implementing the recommendations of GSI. The first phase of work commenced in 2006 and the later phase was in 2011 at the cost of Rs. 4.45 crore and Rs. 10.73 crore respectively. The second phase could commence only after ensuring that desired stability was achieved from the operations in the first phase. The sponsoring governmental agency was the Water Resources Department (WRD). The main task for the Company was to arrest the sliding which is known to have been occurring along a definite shear plane in the weak rock and the toe of the slip surface extended till the bottom of the slope.

As per the recommendation of GSI, rock anchors were used on a specific grid pattern arrangement. Micro piles were installed to act as shear interceptors. Grouting was done to fill voids and crevices. An important task of stitching the moving rock mass with a rigid and stable rock mass of the Cabo Hill was achieved by using 15 m pre-stressed rock anchors at 4-m staggered spacing (Fig. 8). It was ensured that the rock anchors extended beyond the pre-identified failure surfaces. Also a network of RCC grid beams was utilized as a bearing surface to facilitate pre-stressing and to distribute the pre-stress over a larger area (Fig. 9). Shotcreting (Fig. 10) and rock bolting was also carried out as per the recommendations.

Figure 8 Rock bolting **Figure 9 RCC Grid** **Figure 10 Before shotcreting**

Vertical and raker micro-piles were utilized to act as shear interceptors (Fig.11). Weep holes were also positioned at selected places in the retaining walls to effectively counter the effect of water saturation. Later, the treated slopes were given an aesthetic look by turfing and terrace gardening (Fig. 12).

Figure 11 Vertical piling in progress **Figure 12 Turfing**

As per ITD cementation, the entire work was very challenging as it was carried out on the slope that was showing signs of instability. The slope's surface was strewn with boulders of various sizes, along with vegetal growth and matured jungle, much of which could not be removed due to environmental concerns, which inhibited movement, installation of equipment, supply of material, erection of scaffoldings and platform for drilling. Boulders had to be disintegrated to facilitate slope profiling. Drilling and anchoring were problematic as numerous cavities and crevices that were encountered had to be punctuated with consolidation grouting to fill them up before drilling operations. Besides, an existing buttressed retaining wall along the slope showed signs of disequilibrium and was dangerously poised while the work was in progress. Hence the wall had to be removed right from its foundation and the hollow portion was grouted.

Field monitoring through instrumentation

GSI had recommended field monitoring through instrumentation to monitor stability conditions at the hill slope. Accordingly, M/s ITD Cementation India (www.itdcem.co.in) installed inclinometers at selected spots as shown in Fig. 13.

Fig. 14 shows the settlement gauges fixed to accurately measure deformation in soil and rock. Piezometers were also placed at selected spots to measure pore water pressure.

Figure 13 Inclinometer

Figure 14 Settlement gauge

CONCLUSIONS

Forensic Engineering is a field where scientific methodology is applied to investigate the failure of materials, components, products and structures and obviously poses a great challenge for the Engineers and Scientists. The stability of Cabo Hill slope in Goa presents one of the classic case history in the field of Forensic Engineering in India. The Cabo Hill is a lateritic hillock facing the Arabian sea and is situated in Panaji. Raj Bhavan, the official residence of His Excellency, the Governor of Goa, is housed atop the hillock at an elevation of 40 above MSL. The 400 year old building had been experiencing continued distress since a few decades. The remedial measures following investigations earlier failed to stabilize the slopes and safeguard the structure. Subsequently investigation to arrest slope failure was taken up by GSI. Based on drilling and in situ testing by SPT methods as well as a detailed geotechnical analyses on the undisturbed borehole samples collected at various levels, certain remedial measures to stabilize the distressed slope were suggested. Currently, the slopes are being monitored for the stability with the help of various instruments installed at the site since 2011.

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