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RESTORATION OF A DAMAGED SLOPE DUE TO LANDSLIDE FOR THE SAFETY OF A MICROWAVE TOWER

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ABSTRACT: Severe damages in the slopes at the site of a fully operational microwave transmission tower in Bangladesh have been observed recently. The soil of the slopes consists predominantly of clay along with the presence of significant amount of silt and sand. In order to identify the possible causes of the failure of these slopes at the tower site, slope stability analyses and the susceptibility to downslope migration of the slope materials have been performed. These analyses reveal that the slopes of the tower site are adequately safe against slope failure under normal operating condition and the downslide of the slopes is caused mainly by soil migration accelerated via heavy rain cut during monsoon. Possible remedial measures were envisaged and finally an anchored earth slope protection system has been suggested to restore the damaged slopes in order to ensure safety of the tower and adjacent structures. The anchored earth slope protection system includes compacted sand backfill, anchor blocks connected to the end of the coated plain rebars, synthetic sand bags as facings and clay blanket on top of the facing bags to protect the bags from ultra violet radiation. In order to prevent clogging of the newly compacted sand backfill via mixing with the soil of the existing slope, a geotextile layer is provided at the interface of the existing slope soil and the compacted backfill. In order to facilitate the discharge through the compacted backfill, a gravel-packed geotextile wraparound toe drain is also provided.

KEYWORDS: Slope stability, heavy rainfall, erosion, remedial measure, anchored earth system

INTRODUCTION

In Bangladesh, many hill slopes have been cut in the past years in order to maximise land utilization. This, coupled with frequent rainstorms in tropical climate, has resulted in occurrences of landslides. Although landslides in Bangladesh are not comparable in scale to those of other Southeast Asian countries, they nevertheless are of appreciable significance and have posed considerable problems to Geotechnical engineers in Bangladesh. Being in the hot and humid tropical climate, soils in Bangladesh are constantly subjected to active erosion and weathering process. The incidence of landslides in Bangladesh during periods of intense rainfall indicates the crucial influence of rainfall and subsequent movement of groundwater in slope stability. Generally, the effect of rainfall in inducing landslides is deemed to be due to the loss of soil suction as the wetting front advances into the soil (Lumb, 1975; Brand, 1984). Increase in unit

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weight of the soil as its degree of saturation increases, and the continuous rainfall of sufficient intensity to saturate the soil are pertinent factors. The incidence of landslides is also considered to be a function of rainfall intensity and duration and the depth to which the wetting front penetrates. Pitts (1983) reported that recent major occurrences of landslides in the western parts of Singapore are due to severe rainstorms. Ramaswamy and Aziz (1980) also reported similar results. The causes of landslides in clayey region have been reported by Hirata et. al (1987).

A microwave transmission tower is situated on top of a 15m high hill in Sylhet, a district in the Northeast part of Bangladesh. Since 1973, the tower has been of extreme importance in terms of providing continuous telecommunication support to the Sylhet zone in particular and to the whole country in a greater extent. However, only over the last three years, the mild slopes (mostly 2H:1V) of the geological formation started showing signs of instability. It was observed during the field visit that the slopes on the Southeast, South and Southwest parts of the tower have suffered some damages due to erosion of the topsoil of the slopes. In order to restrict further landslide due to erosion of these slopes, measures were taken in the form of laying boulders on the slopes and driving of timber piles. These preventive measures, although, apparently reduced the risk of potential landslides, some active cracks were observed in the structural members of the equipment room abutting these slopes. The slopes on the Northwest part have also undergone tremendous loss of topsoil due to erosion caused by heavy rainfall during monsoons. The one-storied storeroom, adjacent to the crest of the Northwest slope (Fig. 1), was found abandoned due to the danger of inevitable structural collapse. In the West part of the formation, near the water tank for the premise, the angle of failed slopes was found to be near vertical (Fig. 2).

This paper presents the results of comprehensive field and laboratory investigations on soils at the microwave tower site. Possible causes of landslides and proposed methodology for restoration of the damaged slopes are also presented in the paper.

GEOLOGY OF THE PROJECT AREA

Bangladesh has been subdivided into 24 physiographic sub-regions of which the following are most important:

- Himalayan Piedmont Plain
- Flood plains of the Teesta, Old Brahmaputra, Jamuna, Ganges and Meghna rivers
- Barind Tract
- Madhupur Tract
- Foothills of the Shillong Massif
- Haor Basin
- Tippera Surface

- Delta
- Chittagong Hill Tracts

Nearly 85 percent of Bangladesh is underlain by quaternary sediments consisting of deltaic and alluvial deposits of the Ganges, Brahmaputra and Meghna rivers and their numerous tributaries.

The deltaic deposits are sediments that are deposited on the active delta, which is defined as the area south of the Ganges River and mostly west of the Meghna estuary. Most of the delta is less than 15 metres above mean sea level. The delta is crossed by parallel south-southeast flowing distributary channels. Alluvial deposits range from flood sand to overbank silt and ponded clay. The Brahmaputra River valley is inset between active and Pleistocene fan deposits and contains a very wide, braided channel. The Ganges River flows between the active delta and deposits of the Barind Tract. The Meghna River flows between the Fold Belt and the Madhupur Tract through the subsiding Sylhet depression. Both the Ganges and Meghna Rivers have wide meandering channels. All three rivers flood annually in response to the monsoon; they merge to form the Meghna estuary, through which passes the world's largest annual discharge and sediment load.

The project area lies in the Sylhet depression, which is a large gentle depressional feature of Bengal basin located in the north-eastern Bangladesh. The Sylhet depression is bounded by the Old Brahmaputra flood plain in the West, the Meghalaya Plateau's foothills in the North and the Sylhet high plain in the Southeast and Meghna flood plain in the Southwest.

The Old Brahmaputra Floodplain stretching from the south-western corner of Garo Hills along the eastern rim of Madhupur Tract down to the Meghna river exhibits a gentle morphology composed of broad ridges and depressions. The later are usually flooded to a depth of more than 1 m, whereas the ridges are subject to shallow flooding only in the monsoon season. The Meghna flood plain is an earlier build up of the lower course of the Old Brahmaputra. The flood plain lies between 1.5 m and 3 m above mean sea level. Due to gentle inclination of the plain, the river and its tributaries meander and braid, thus creating only physiographic positive features such as levees, channel bars and meander bars.

Numerous lakes (*beels*) and swamps (*haors*) cover this saucer shaped Sylhet depression area of about 7250 km^2. The area is regularly flooded during the monsoons. According to the study of Morgan and McIntire (1959), this area is still undergoing persistent subsidence.

In addition to the hills located along the southern spur of the Shillong Massif, a number of hillocks, locally known as *tila*, form minor but morphologically distinct ranges around Sylhet. These elevations, as for instance, Kailas Tila, Dupi Tila and the tilas at Beani Bazar east of Sylhet, are generally built up of Plio-Pleistocene clastic sediments and reach maximum elevation of about 60 m above mean sea level. South of the Kusiwara, one source of the Meghna river, six hill ranges project into the Sylhet district from the Tripura hills in the south. These hill ranges are the northern portions of northwards plunging anticlinal trends of Miocene and Pliocene clastics. The Harargaj peak (336 m height) is the highest elevation in this portion of the Sylhet district.

The project area is surrounded by a number of seismically active structures of which the Shillong Plateau, the Mikhir Hills, the main boundary faults of the Himalayas, the Sub-Dauki fault and the Bogura fault and Tripura fault are most important. A number of major earthquakes that occurred in the past in these structures influenced the project area. Of these the following earthquakes are worth mentioning (Ansary and Sharfuddin, 2000).

- Cachar Earthquake of 1869
- Bengal Earthquake of 1885
- Great Earthquake of 1897
- Srimangal Earthquake of 1918
- Gauhati Earthquake of 1923
- Dhubri Earthquake of 1930
- Sylhet Earthquake of 1997

The project area mainly consists of the following types of soils (Alam et al., 1990):

Alluvial Deposits of Silt and Clay

It consists of medium to dark-grey silt to clay. Colour is darker as amount of organic material increases. It includes flood-basin silt, backswamp silty clay and organic-rich clay in sag ponds and large depressions. Some depressions contain peat. Large areas underlain by this unit are dry only few months of the year. The deeper parts of the depressions are and *beels* contain water throughout the year.

Paludal deposits of Marsh Clay and Peat

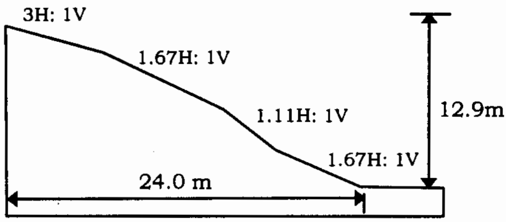
Paludal deposits of marsh clay and peat are also underlain to some extent in this area. Paludal deposits are mainly grey or bluish grey clay, black herbaceous peat and yellowish grey silt. Alternating beds of peat and peaty clay are common in *beels* and large structurally controlled depressions. Peat layer is thickest in the deeper parts. Thin beds of peat and clay are interbedded with alluvial silt in the north-central Sylhet depression. Chains of linear lake north of the Ganges river and south of the Shillong Plateau in the Sylhet depression suggest that these areas are subsiding.

Fig. 1. Damaged store room on North-west slope

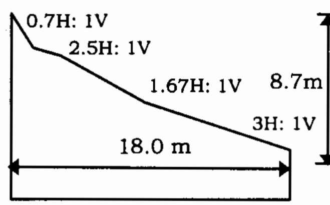
Fig. 2. Near vertical West side slope abutting the water tank

CONTOUR SURVEYING

A comprehensive contour surveying of the tower site was carried out in order to assess the extent of damage and soil loss from the slopes. Bottom surface of the water supply tank (shown in Fig. 2) for the premise, near the West side slope, was considered as datum. The reduced level of this datum was assumed to be 100 m. Compared with this datum level, reduced levels at different locations along the periphery of the slopes were determined. Using the reduced level data of the slope surfaces, altogether nine critical sections were identified, typical of which are presented in Fig. 3.



(a) South-west



(b) West slope

Fig. 3. Typical sections of damaged slopes

GEOTECHNICAL INVESTIGATIONS AT THE TOWER SITE

Field Investigations

The field investigation at the microwave tower site consisted of drilling six boreholes, recording density/stiffness characteristics of soil layers by carrying out Standard Penetration Tests (SPT) and collecting sufficient numbers of disturbed and undisturbed tube samples. The borelogs of North-West and South-West slopes are shown in Fig. 4. Split-spoon sampler was used to obtain the disturbed samples. Undisturbed samples were retrieved from cohesive layers of the boreholes by pushing conventional 76 mm external diameter thin-walled Shelby tubes following the procedure outlined in ASTM D1587 (ASTM, 1989). All the samples were later transported to the laboratory of Bangladesh University of Engineering and Technology (BUET) for detailed investigation.

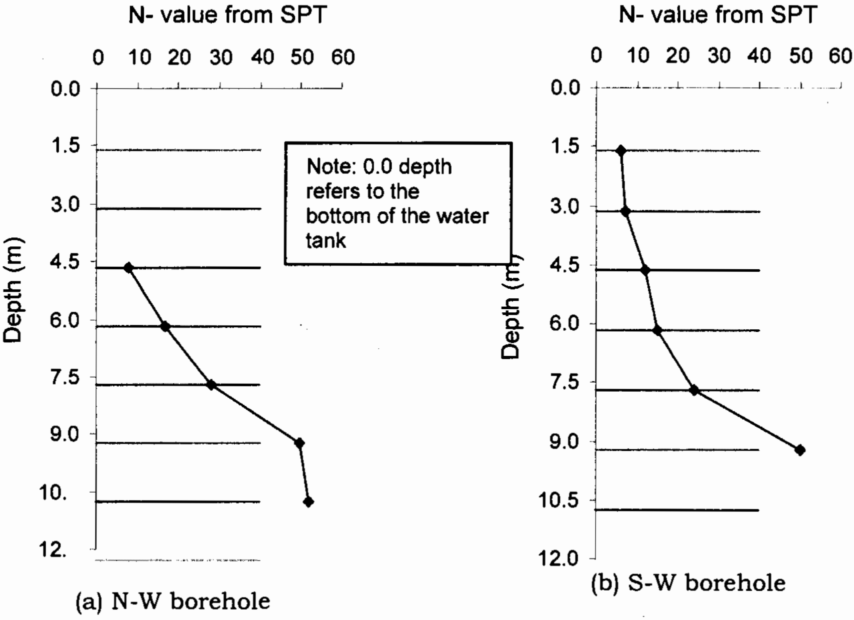


Fig. 4. Typical borelogs at the microwave tower site

Laboratory Investigations

A comprehensive laboratory investigation was carried out on the disturbed and undisturbed samples. The physical and index properties were determined using the disturbed samples. The shear strength parameters were obtained by carrying out consolidated undrained direct shear tests on the undisturbed tube samples.

Physical and Index Properties of Soil Samples

A series of physical and index tests was carried out on the disturbed samples obtained from different boreholes and depths. The per cent clay (< 0.002 mm), per cent silt (0.002 mm to 0.06 mm) and per cent sand (0.06 mm to 2 mm) were determined using MIT Textural Classification System. The results of grain size analyses, presented in Table 1, show that the per cent sand, per cent silt and per cent clay for the cohesive soil samples vary from 7 to 57, 28 to 56 and 15 to 41, respectively. The per cent sand present in the cohesionless soil samples ranged from 66 to greater than 92. The values of physical and index properties, presented in Table 2, show that the specific gravity, liquid limit, plastic limit and plasticity index of the cohesive samples range from 2.65 to 2.68, 40 to 49, 18 to 24 and 14 to 27, respectively. Using these index properties, soil samples have been classified according to Unified Soil Classification System (USCS) as clays of low to high plasticity (USCS Symbol is CL).

Table 1. Grain Size Distribution of Soil Samples from the Microwave Tower Site

BH No./ Sample No.	Depth (m)	% Finer No. 200 Sieve	Sand (%)	Silt (%)	Clay (%)	D_{60} (mm)	D_{10} (mm)
BH-1/D-1	1.5	69.8	34	39	27	0.038	< 0.0008
BH-1/D-2 & D-3	3.0 & 4.5	34.5	> 66 %	-	-	0.13	< 0.075
BH-1/D-4 D-5 & D-6	6.0, 8.0 & 9.5	97.3	7	56	37	0.008	< 0.0008
BH-2/D-1 & D-2	1.5 & 3.0	88.4	19	40	41	0.0095	< 0.0008
BH-3/UD-1	2.5 to 3.0	91.8	10	51	39	0.0095	< 0.0008
BH-4/D-1	1.5	19.6	> 80 %	-	-	0.21	< 0.075
BH-4/D-2 & D-3	3.0 & 4.5	50.9	57	28	15	0.14	< 0.0008
BH-5/D-2 D-3 & D-4	3.0, 4.5 & 6.0	7.5	> 92.5 %	-	-	0.27	0.09
BH-6/D-1 & D-2	1.5 & 3.0	78.5	27	41	32	0.016	< 0.0008

Table 2. Index Properties of Soil Samples from the Microwave Tower Site

BH No./ Sample No.	Depth (m)	G_s	LL	PL	PI	LS (%)	USCS Symbol
BH-1/D-1	1.5	2.65	40	20	20	10	CL
BH-1/D-4 D-5 & D-6	6.0, 8.0 & 9.5	2.66	49	22	27	-	CL
BH-2/D-1 & D-2	1.5 & 3.0	2.66	45	20	25	-	CL
BH-3/UD-1	2.5 to 3.0	2.65	43	21	22	-	CL
BH-4/D-2 & D-3	3.0 & 4.5	2.68	38	24	14	11	CL
BH-6/D-1 & D-2	1.5 & 3.0	2.68	41	18	23	-	CL

Direct Shear Test Results

Five consolidated undrained direct shear tests were carried out on reconstituted samples obtained from the six boreholes. In each test, laboratory compacted cylindrical samples of 63.5 mm diameter by 25 mm high were initially consolidated using three different normal loads and subsequently sheared under undrained condition. From the failure envelopes of the samples, the values of undrained cohesion (c_u) and undrained angle of internal friction (ϕ_u) of the samples have been determined. The values of c_u and ϕ_u, presented in Table 3, vary from 5 kN/m^2 to 60 kN/m^2 and 30° to 35°, respectively.

Table 3. Summary of Consolidated Undrained Direct Shear Test Results

BH No./ Sample No.	Depth (m)	Average Water Content (%)	Average γ_d (kN/m^3)	c_u (kN/m^2)	ϕ_u
BH-1/UD-1	2.5 to 3.0	19.0	16.39	21	30°
BH-3/UD-1	2.5 to 3.0	20.7	17.23	25	33°
BH-4/D-1	1.5	10.6	17.43	10	32°
BH-5/D-2, D-3 & D-4	3.0, 4.5 & 6.0	11.8	16.06	5	35°
BH-6/D-1 & D-2	1.5 & 3.0	11.4	16.39	60	32°

OVERALL STABILITY OF CRITICAL SLOPE SECTIONS

Stability analyses were carried out to evaluate the factor of safety against overall stability of the nine critical sections of the slopes. This has been carried out to identify whether or not the critical slope sections are stable under their normal operating conditions. The program used for stability analysis was XSTABL, which is a fully integrated slope stability analysis program. XSTABL performs a two dimensional limit equilibrium analysis to evaluate the factor of safety for a layered slope using the Simplified Bishop Method. The program can be used to search for the critical failure surface and the factor of safety can be determined for specific surfaces.

Circular failure surfaces were assumed for all cases of analyses as mentioned above. The minimum values of undrained cohesion (c_u) and undrained angle of internal friction (ϕ_u), obtained from CU direct shear tests, were used in the slope stability analyses. The values of c_u and ϕ_u used in all the analyses were 5 kN/m^2 and 30°, respectively. A two layer soil model has been used. The location of the water table in all the slope sections has been assumed to be at a height of 3m above the toe of the slopes. A constant pore pressure ratio (r_u) of 0.1 has been assumed in the saturated surfaces of the slopes. The moist and saturated unit weights of the slope and foundation soils were taken as 18 kN/m^3 and 16 kN/m^3, respectively. For each slope section 100 potential failure surfaces, including deep and shallow surfaces, were generated. Of these 100 critical surfaces, 10 most critical surfaces were separated. An example of analysed slope is shown in Fig. 5. The minimum Bishop factor of safety of the slope sections, so determined, varied from 1.15 to 1.65. Therefore, it appears that all the nine critical slope sections has adequate overall stability under their normal operating conditions.

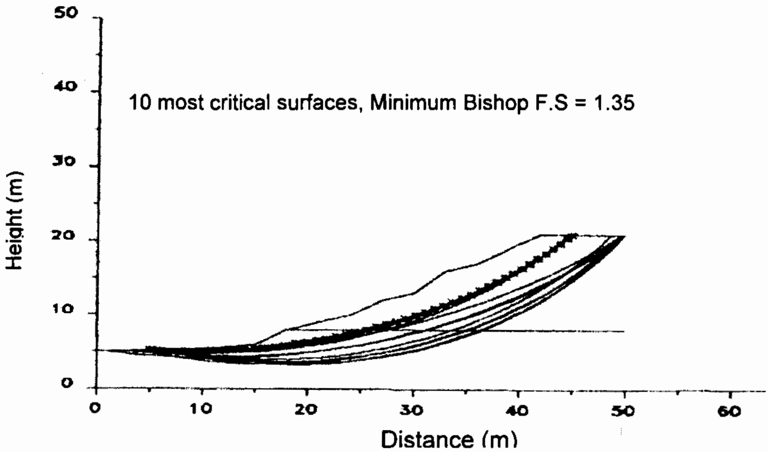


Fig. 5. Typical example of slope stability analysis

IDENTIFICATION OF SOIL SUSCEPTIBILITY TO DOWNSLOPE MIGRATION

The problem of downslope migration is most apparent in silts, sandy silts and fine sands. The minor cohesive properties of these types of soils tend to encourage high mobility of small single grains at relatively low hydraulic gradients. The distinction between soils susceptible to downslope migration and those not susceptible is related to grain size, permeability and degree of cohesion.

An investigation in to the susceptibility of the slope materials to downslope migration was carried out. Permanent International Association of Navigation Congress (PIANC) recommends a general method of identifying soils susceptible to downslope migration. Soils susceptible to downslope migration will satisfy the following conditions, PIANC (1987):

a) A proportion of particles must be smaller than 0.06 mm.
b) Additionally, the soil will satisfy at least one of the following:

(i) The uniformity coefficient, $c_u = \frac{d_{60}}{d_{10}} < 15$

(ii) 50% or more of the particles will lie in the range 0.02 mm < d < 0.1 mm.

(iii) The plasticity index (PI) will be less than 15.

The plasticity index is the difference between the moisture content at liquid limit and the moisture content at plastic limit. If I_p is unknown at the preliminary design stage then the following criterion may be substituted:

$$\frac{\text{proportion of clay } (d < 0.002 \text{ mm})}{\text{proportion of silt } (0.002 < d < 0.06 \text{ mm})} < 0.5$$

The numerical values of different parameters used to identify susceptibility to downslope migration of the soils from the slopes of the microwave tower site are presented in Table 4. These parameters were compared with the recommended identification criteria as shown above to examine whether downslope migration of soil particles will occur. It has been found that the three non-plastic samples are susceptible to downslope migration. It, therefore, appears that measure should be taken to prevent downslope migration of soil particles along the slopes. This could be achieved by adopting appropriate techniques of stabilising the slopes.

Table 4. Values of Various Parameters Used to Assess Susceptibility to Downslope Migration of Soils from Microwave Tower Site at Sylhet

Sample Identification	% of particles ≤ 0.06 mm	$C_u = D_{60}/D_{10}$	% of particles in the range of 0.02 mm to 0.1 mm	Ratio of clay fraction to silt fraction	PI	Remarks*
BH-1/D-1	66	> 48	8	0.69	20	NS
BH-1/D-2 & D-3	<34.5	>2	48	-	Non-plastic	S
BH-1/D-4 D-5 & D-6	94	> 10	22	0.66	27	NS
BH-2/D-1 & D-2	80	> 12	25	1.03	25	NS
BH-3/UD-1	90	> 12	21	0.76	22	NS
BH-4/D-1	20	>3	23	-	Non-plastic	S
BH-4/D-2 & D-3	43	> 17.5	25	0.54	14	NS
BH-5/D-2 D-3 & D-4	<7.5	>3	11	-	Non-plastic	S
BH-6/D-1 & D-2	73	> 20	24	0.78	23	NS

*NS = Not susceptible to downslope migration,
S = Susceptible to downslope migration

CAUSE OF LANDSLIDE AT THE TOWER SITE

From the overall stability analyses of the slope sections it was found that the slopes are adequately stable under normal operating conditions. Identification of susceptibility of the soils to downward migration, on the basis of PIANC guideline, indicates that the soils at the microwave tower site are susceptible to downward migration. It may be noted that annual rainfall in Sylhet ranges from 2500 mm to 3000 mm. The intensity of this rainfall coupled with the susceptibility of the soils downward migration at the tower site might have caused the erosion and eventual damage to the slopes. This failure mechanism conforms to the observation of the local people.

PROPOSED REMEDIAL MEASURE

Various methods may be used to prevent soil erosion such as regrading of slopes and the use of reinforced concrete retaining walls, surface and subsurface drainage, ground anchors, soil nails, tied-back walls, contiguous bored-pile walls and other types of restraining structures. As a remedial measure of the slope protection in the vicinity of the microwave tower at Sylhet, anchored earth system is suggested. This system has been chosen considering its ease and speed of construction, availability of the component materials, economy and above all its suitability to deal with the current problem of landslide.

Features of the Proposed Anchored Earth System

Detail of the proposed anchored earth system for slope protection, for a typical slope section, is presented in Fig. 6. The external and internal stabilities of the proposed anchored earth slope system have been checked by the method outlined by Lee and Oh (1997), Jones (1996) and BS 8006 (1995).

The principal components of the system and the functions of each of these components are presented below:

(i) Synthetic sand bag facings located at the face of the slopes are used to prevent local loss of soil. The sand material in the bags is used to facilitate uninterrupted flow of water towards the toe drain.

(ii) Horizontal steel reinforcements running through the sand bags to the required length are intended to withstand the horizontal thrust due to self weight of the backfill, pore water pressure and surcharge at the top surface.

(iii) The vertical dowel bars inserted through the bundle of every three bags are provided to secure the bags in place during the construction activities and to eliminate chances of possible dislodging during the service life of the structure.

(iv) The clay blanket on top of the synthetic bags filled with sand is provided to protect the synthetic bags from degradation due to ultra violet radiation. Vegetation is also required to be grown on the clay blanket to secure the clay blanket against the likely migration/loss due to rainfall and human activities.

(v) Granular material, intended to facilitate the flow of rain water, is used as backfill compacted in layers up to the full height of the slope.

(vi) Geotextile wraparound gravel filled drain located at the toe of the slopes are designed to collect and discharge the water flowing through the compacted granular backfill.

(vii) Geotextile filter layer placed at the interface of the stepped cutting of the original slope and the new compacted backfill is provided to serve two purposes:

- it will keep the soil of the existing slope at bay from mixing with the new granular compacted backfill and hence will not hamper the drainage capacity of the granular backfill.

- it will retain the soil of the existing slope and ensure uninterrupted water flow due to rainfall.

(viii) Concrete anchor blocks connected to the rear end of the reinforcements with nut and bolt are intended to mobilise passive resistance at each level of reinforcement to internally stabilise the horizontal thrust so that no force is transferred to the bag facings.

OVERALL STABILITY OF SLOPE SECTIONS AFTER EXCAVATION

As mentioned previously that for the proposed reinforced anchored earth system for the protection of slopes significant amount of earth cutting will be required at the interface of the existing slope and the fill to be placed. Excavations at the interface could lead to unstable slope and create constructional problems for the proposed anchored earth system. Therefore, stability analyses of the critical slope sections after excavations were also investigated. The values of the minimum Bishop factor of safety of the cut slope sections, so determined, varied from 1.18 to 1.53. It, therefore, appears that all the slope sections are likely to have adequate overall stability even after excavations required for the execution of construction the proposed anchored earth system.

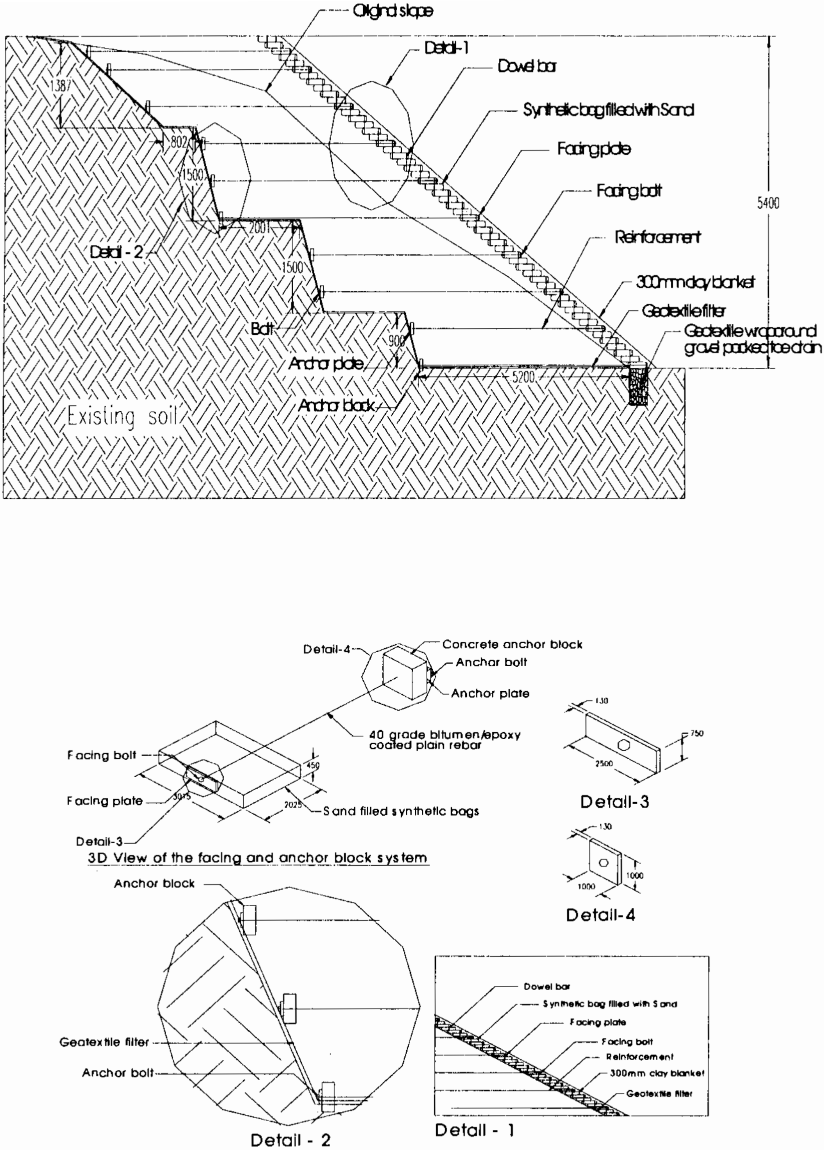


Fig. 6. Details of suggested anchored earth protection system

CONCLUSIONS

On the basis of the observed damages in the slopes of the tower site, a comprehensive field and laboratory soil investigation has been performed. It was identified that the soil of the slopes consists of 15 to 41 per cent clay, 28 to 56 per cent silt and 7 to greater than 90 per cent sand. The values of consolidated undrained cohesion of the soils range from 5 kN/m^2 to 60 kN/m^2 and the values of angle of friction range from 30° to 35°. In order to identify the possible causes of the failure of these slopes of the tower site, slope stability analyses and the susceptibility of downslope migration of the slope materials were carried out at nine critical sections. These analyses reveal that the minimum Bishop's factor of safety of the slope sections varied from 1.15 to 1.65. This indicates adequate safety of the slopes against slope failure under normal operating condition. The analyses for susceptibility to downslope migration, according to PIANC (1987), show that the slopes of the tower site consist of soils that are susceptible to downslope migration. This suggests that the damages in the slopes at the tower site have been caused mainly by the soil migration accelerated via heavy rain cut during monsoon. Possible remedial measures were envisaged and finally an anchored earth slope protection system has been suggested to restore the damaged slopes in order to ensure safety of the tower. The anchored earth slope protection system includes, compacted sand backfill, anchor blocks connected to coated plain rebars, synthetic sand bags as facings and clay blanket on top of the facing bags to protect the bags from ultra violet radiation. In order to prevent clogging of the newly compacted sand backfill via mixing of the existing slope soil with the newly compacted backfill, a geotextile layer is provided at the interface of the existing slope soil and the compacted backfill. A geotextile wraparound toe drain is also provided for collecting the discharge through the compacted backfill. The anchored earth slope protection system has been suggested considering the economy and ease of construction that utilises the available know-how of the local contractors.

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NOTATION

LL	liquid limit
LS	Linear shrinkage
PL	plastic limit
PI	plasticity index
USCS	Unified Soil Classification System
G_s	Specific gravity of solids
C_u	Uniformity coefficient
γ_d	Dry density
ϕ_u	Undrained angle of internal friction

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NOTATION

LL	liquid limit
LS	Linear shrinkage
PL	plastic limit
PI	plasticity index
USCS	Unified Soil Classification System
G_s	Specific gravity of solids
C_u	Uniformity coefficient
γ_d	Dry density
ϕ_u	Undrained angle of internal friction