Earth Reinforcement Practice, Ochiai, Hayashi & Otani (eds) © 1992 Balkema, Rotterdam. ISBN 90 5410 093 1

Stabilization of slopes with geo-anchors

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ABSTRACT: A landslide in residual soil and weathered rock in Singapore which has been stabilized successfully with geo-anchors is described. The geo-anchors are constructed by first excavating narrow trenches in the failed slope. The trenches which are lined with high strength woven geofabric are filled with coarse granular material which is compacted in layers. The geofabric lining functions both as reinforcement in the soil and as a filter which increases the stability of the failed slope. The method of analysis and the construction of the geo-anchors are described in the paper.

1 INTRODUCTION

Landslides in residual soils or weathered rocks in Singapore are relatively common. They usually occur during or just after a heavy rainstorm which has been preceeded by several days of contineous rain. (Ramaswamy and Aziz, 1980; Pitts, 1983). The slopes are normally stable when the soil or the weathered rock is partially saturated even when the inclination of the slopes exceeds the angle of internal friction angle, (ϕ' or ϕ_d) as determined by direct shear or by triaxial tests (CU- or CD-tests) since the negative pore water pressure in the slope increases the effective stress in the soil and thus the shear strength. After a period of contineous rainfall when the soil becomes saturated or almost saturated because of infiltration of the rain water into the ground, the initial high negative pore water pressures in the soil are eliminated or greatly reduced, causing a large reduction of the effective stress and of the shear strength. As a result the slopes may become unstable and fail.

2 STABILIZATION OF SLOPES

Several different methods are used at present (1992) in Southeast Asia to increase the stability of steep slopes and to reduce the risk for landslides. The stability can be increased by changing the geometry, by improving the drainage or by the construction of a retaining structure at the toe of the slope. The choice depends primarily on the costs, the probability and the consequences of a failure (Broms and Wong, 1991). In Southeast Asia it is common to increase the stability of a slope by flattening of the slope. However the flattening or the benching of a potentially unstable slope had to be done judiciously to prevent local failures or slumps. Also berms can be used. An other possibility is to replace the unstable material either wholly or partially by a free-draining material often in combination with horizontal drains and drainage blankets.

Because high excess pore water pressure is the major factor causing slope failures in Southeast Asia a properly designed drainage system to intercept the water flow is essential. It is important to divert the surface water with ditches and interceptor drains from areas which can be affected by landslides. Ditches must have adequate size and gradient because of the heavy tropical rainstorms in the region. Open tension cracks should be sealed to prevent infiltration of surface water.

Lining the slopes with concrete or soil cement is sometimes done to prevent erosion and infiltration of water. In Hong Kong, soil cement (CHUNAM) is commonly used to seal the surface. Gunite or shotcrete, reinforced with wire-mesh, is also popular.

Horizontal drains can be used to relieve the high pore water pressures in steep slopes. Drainage blankets with free draining materials which are placed either at the base of the slope or within the unstable soil mass to reduce the excess pore water pressures are also effective.

Concrete gravity walls are often used in both cut and fill slopes. The walls should be provided with drains and weep holes to relieve any excess pore water pressures behind the wall. Also reinforced earth, gabions and crib walls are common in Southeast Asia.

Slopes can also be stabilized with embankments piles (Broms and Wong, 1985) or ground anchors. Contigeuous or closely spaced cantilever piles are sometimes used.

3. USE OF GEOFABRIC TO STABILIZE STEEP SLOPES

Geofabric has been found to be effective to stabilize steep slopes and embankments. The fabric is usually placed in horizontal layers within the slope where the fabric functions as reinforcement. Potentially unstable slopes can also be stabilized with geo-anchors where the geofabric is utilized in the soil both as reinforcement and to improve the drainage as described in the following. This new method can also be applied to stabilize failed slopes, or to improve the stability of embankments as illustrated in Fig. 1.

In a geo-anchor woven the geofabric is wrapped around a pervious core (Fig. 2) consisting of clean granular material (coarse sand, gravel or crushed rock). The geo-anchors which are constructed in shallow trenches as shown will reinforce the slope and reduce the excess pore water pressures since they also function as drains, thereby increasing the shear strength and the stability. The geofabric also serves as a filter around the geo-anchors to prevent clogging of the drains.

One additional advantage with the proposed method is that the temporary reduction of the stability of the slope will be small during the construction of the trenches which are required for the geo-anchors.

3.1 Spacing and Depth of Geo-Anchors

The required spacing of the geo-anchors as

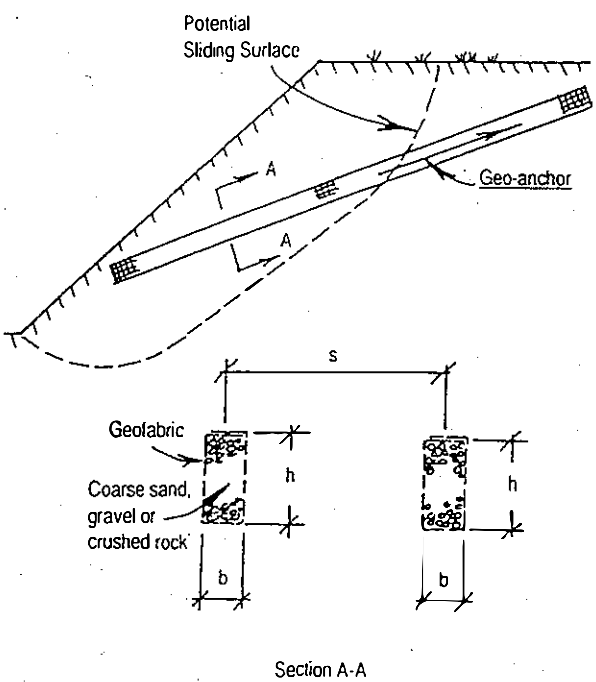

Fig. 1 Slope stabilized with geo-anchors.

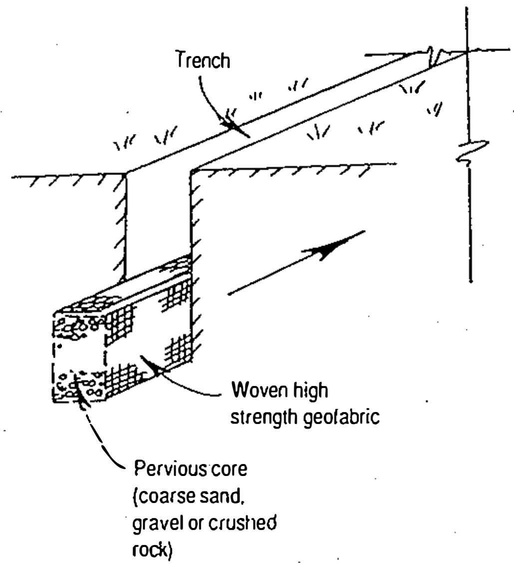

Fig. 2 Geo-anchor

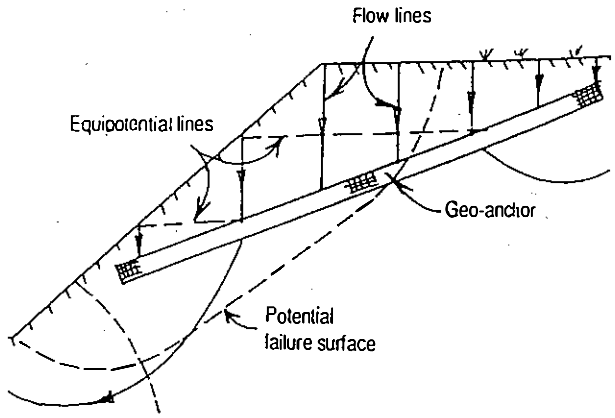

Fig. 3 Flow-net for slope stabilized with geo-anchors.

well as their size depend on the excess pore water pressures that can develop in the potentially unstable slope. For many applications, 0.4 to 0.5 m wide and 0.5 to 0.6 m high drains spaced 3.0 m apart are adequate. The excess pore water pressure can be determined for example by means of a flownet as shown in Fig. 3. It is important that the granular material in the drains is pervious compared with the permeability of the slope material. It can be seen from the flownet that the pore water pressure in the slope will be reduced considerably since the flowlines above the drains are almost vertical as shown in Fig. 3.

The geo-anchors can be used to increase the stability of existing slopes or to stabilize failed slopes. The required depth of the geo-anchors depends on the stability of the trenches to be excavated in the slopes. The maximum depth is about 4 m deep. This depth is usually sufficient for slopes in residual soils or in weathered rocks because most slides are shallow in these materials, less than 3 to 4 m.

3.2 Required Tensile Strength of Geo-anchors

The required tensile strength of the geofabric can be calculated as shown in Fig. 4 by considering all the forces acting on the sliding soil mass above a possible slip or failure surface in the soil. The failure surface is often located at the contact between the completely weathered and the underlying partially weathered material.

For a plain failure surface, the orientation of the geo-anchors should preferably be perpendicular to the resultant to the normal reaction force and the shear resistance of the weathered material along the potential failure surface, as shown in the figure. The optimum orientation is also affected by the maximum depth that can be obtained with the available construction equipment.

The required tensile resistance, T_a of the geofabric per unit width (kN/m) can be determined as follows :

$$T_a = \frac{RS}{2(b+h)} \tag{1}$$

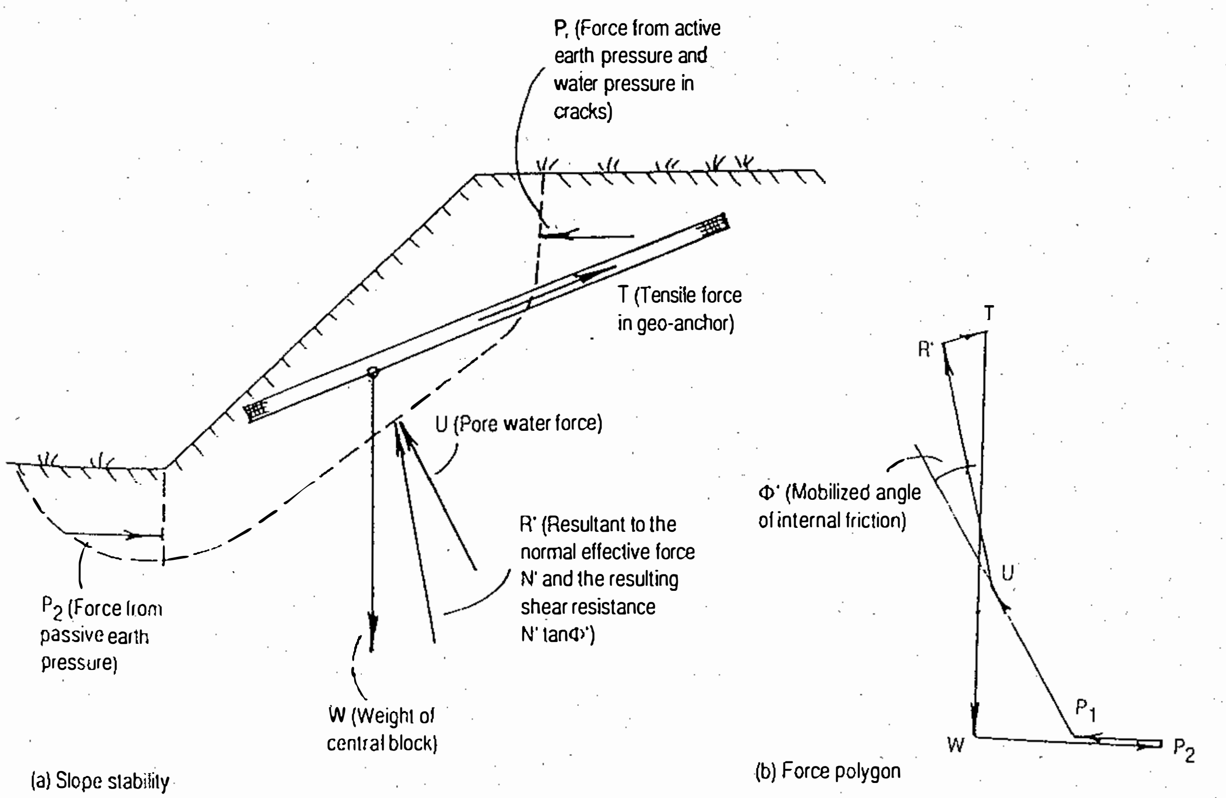

Fig. 4 Stability of slope reinforced with geo-anchors.

where R is the force to be resisted by the geo-anchors per unit width of the slope, S is the spacing , T_a is the allowable tensile resistance of the fabric per m and 2(b+h) is the perimeter of the geo-anchors. The allowable tensile force T_a, which depends on the creep strength of the geofabric and the required factor of safety, is usually 30% to 40% of the short term tensile strength of the fabric.

3.3 Deformations of Geo-Anchors

The geofabric available in the market at present (1992) usually requires an elongation of 14% to 50% before the ultimate tensile strength of the fabric is mobilized. Since the axial strain which is required to develop the required tensile resistance is much less for woven than for non-woven geofabrics only woven fabrics should be considered for the geo-anchors.

The length, L, which is required to transfer the load in fabric reinforcement to the surrounding soil can be calculated as follows :

$$L = \frac{RS}{(2h\ K + 2b\ \sigma'_v)\ \tan \phi'_a} \qquad (2)$$

where σ'_v is the vertical effective stress at the center of the drain, K is the coefficient of lateral earth pressure of the compacted granular material in the geo-anchor, ϕ'_a is the friction angle between the geofabric and the soil, h is the height and b is the width of the geo-anchors. The required transfer length is about 1.25 m for a 0.5 x 1.0 m geo-anchor located at 3 m depth. The transfer length is thus small due to the large surface area. It has been assumed in the calculations that the force in the fabric is 35 kN/m, that the unit weight of the soil is 20 kN/m^3 and that the friction angle ϕ'_a is 25 degrees.

The deformation δ of the geofabric which is required to mobilize the required tensile force can be estimated from the following equation :

$$\delta = L \times \epsilon/100 \qquad (3)$$

where L is the required transfer length and ϵ is the unit elongation needed to mobilize the tensile resistance of the geofabric. In the case ϵ = 3% then the elongation will be 37 mm at a transfer length of 1.25 m. It has been assumed in the calculations that the strain in the fabric increases linearly within the anchor zone.

3.4 Compaction of the Fill

During the construction of the geo-anchors it is important to compact the granular fill in the trenches in thin layers in order to increase the lateral earth pressure in the fill and therefore the friction between the fabric and the trench walls. The compaction should be done in the downhill direction in order to pretension the fabric. In this way, the elongation which is required to mobilize the required tensile resistance of the geo-anchors will be reduced.

4 STABILIZATION OF A SLIDE AT NTI IN SINGAPORE

Geo-anchors have been used to stabilize a landslide on the campus of the Nanyang Technological University (NTU) located in the western part of Singapore Island. The slide occured early 1984, during a period of heavy rainfall between Student Hostel Block E located at the toe of a steep slope and two other dormitories at the crest of the slope. Prior to the failure the average height of the slope was about 7 m and the average inclination 37 degrees. An existing rubble wall with a height varying from 1.70 m to 3.50 m failed during the landslide and a scupper drain at the toe of the rubble wall was damaged. The ground immediately in front of the displaced rubble wall heaved about 200 mm.

The soil mass affected by the slide continued to move at a slow rate during 1984. The total final lateral displacement of the wall was approximately 700 mm. The toe moved about 300 mm.

4.1 Site Investigation

The failed slope was investigated by weight and ram soundings. Also undisturbed block samples were taken of the soil in the failed slope in order to determine in the laboratory the shear strength and other properties of the soil.

The slope material consisted of residual soil and of highly or completely weathered sedimentary rocks, mainly weathered mudstone of the Jurong Formation. A sieve analysis indicated that the slope material consisted of 9% gravel, 7% sand and 84% silt and clay size particles. The liquid

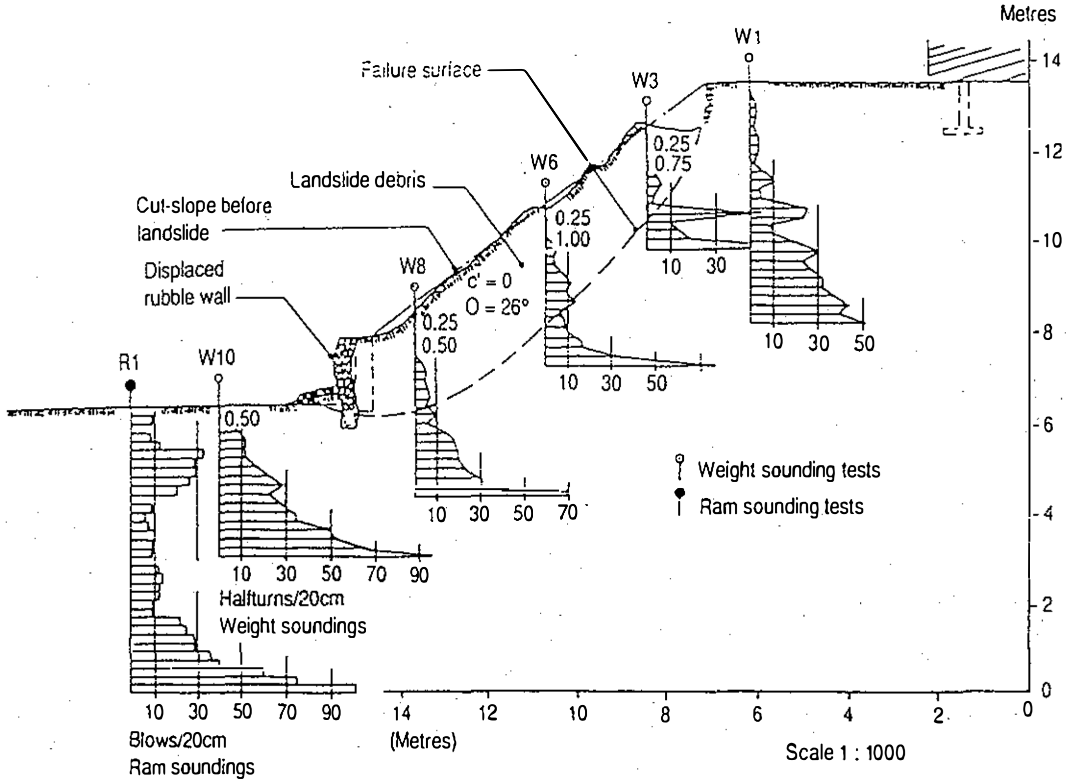

Fig. 5 Weight sounding test results and failure surface - Profile 1, NTU block E Slide.

limit of the material was 56% and plasticity index 29%. The average natural water content of the slide material was 33%, a few percent above the plastic limit. Consolidated-drained direct shear tests (CD-tests) using block samples of the slide material indicated an effective cohesion $c' = 0$ and a peak friction angle (ϕ') of 26^{o}. The residual friction angle, as determined consolidated drained ring shear tests, was low, only 16^{o}. The undrained shear strength determined by triaxial tests (UU-tests) varied between 50 and 100 kPa.

The location of the sliding surface as inferred from the is shown in weight soundings. Fig. 5. The depth and the shape of the failure surface agreed well with the location of the scar after the slip at the crest and the bulge at the toe of the slope.

4.2 Remedial Works

Eight geo-anchors were installed at Block E. They were 0.5 m wide and 1.0 m high and spaced 3.0 m apart. Four layers of FOV Polyester fabric with a ultimate tensile strength of 40 kN at 14% elongation were wrapped around the pervious core. A cross section of the slope with the geo-anchor reinforcement is shown in Fig. 6. The geo-anchor are connected to the crib wall at the toe of the slope. The crib wall is filled with crushed rock in order to improve the drainage.

Horizontal layers of fabric were also placed between the transverse drains to increase the stability of the slope with respect to shallow slides. A layer with geofabric was also placed as a filter between the horizontal strips to prevent the soil from being washed into the drains.

The failed slope was reconstructed in May and June 1985. The up to 4 m deep trenches were easy to excavate from the top of the slope using a backhoe. A temporary bench was cut at the middle of the slope so that the lower part of the trench could be excavated next to the crib wall. The granular material in the trenches was compacted using a plate vibrator.

Horizontal strips of geofabric were placed in the slope to prevent shallow slides during the backfilling. Geofabric was also used behind the cribwall as a filter. The stabilization works was completed in June 1985.

The stabilized slope has withstood several heavy rainstorms. No further movements of the slope or of the crib wall have been observed except at one side beyond the stabilized part of the slope

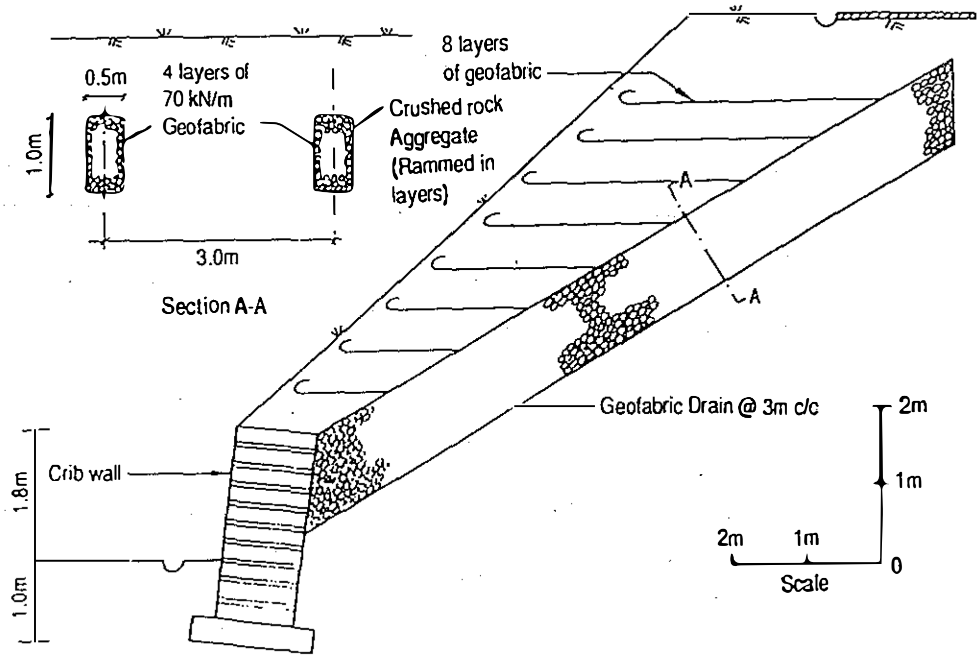

Fig. 6 Stabilization scheme – NTU block E slide

where a minor slip has occured. The cribwall was therefore extended in order to stabilize also this part of the slope.

5 SUMMARY

Geo-anchors have been used successfully to stabilize a steep slope in residual soil and weathered rock on the campus of the Nanyang Technological University (NTU) in Singapore. Woven high strength geofabric was wrapped around the drains which consisted of clean granular materials. The geo-anchors, which were placed in deep trenches excavated in the slope, function both as drains and and as anchors in the soil in order to increase the stability of the unstable steep slope.

The method that was used to evaluate their effectiveness of the geo-anchors as reinforcement in residual soil and weathered rock is described in the paper. No further movements of the failed slope have been observed after the installation of the geo-anchors.

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