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Enhancing internal stability of reinforced soil slopes with anchors

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ABSTRACT: Reinforced soil structures have found a wide range of applications in slope engineering largely replacing classical retaining walls and other slope repair techniques. Especially, wrap-around geogrid reinforced soil slope systems provide a new approach to slope repair in that it can produce “green” structures, in aesthetic harmony with surrounding natural environment. However, for overall and internal stability, the geogrid reinforcement should have necessary design strength, be located at specific intervals across the vertical section of the reinforced soil, and extend an adequate horizontal distance within the reinforced soil. While the former two conditions are easy to satisfy, the required horizontal lengths may be difficult to reach if heavily over-consolidated soils or rocks are within a short distance from the face of the planned structure. In such “narrow” reinforced fill structures, installing anchors into the stable ground provides an effective solution and widens the application of reinforced soil structures. To support the validity of this proposal, a case history is presented, which is located in Qingdao City, China, where the proposed method was successfully used for weathered rock slope stabilization. Thus, the use of anchors in narrow sections of reinforced soil structures enhances the versatility of soil reinforcement in geotechnical engineering applications.

1 INTRODUCTION

Reinforced soil structures have found a wide range of applications in slope engineering largely replacing classical retaining walls and other slope repair techniques due to their high cost efficiency, ease of construction, and ability to withstand significant total and differential settlements. Especially, wrap-around geogrid reinforced soil slope systems provide a new approach to slope repair in that it can produce “green” structures, in aesthetic harmony with surrounding natural environment. In mainland China, more than 300 major reinforced soil structures have been built over the last few decades. There is no doubt that in the near future, with the fast pace and increasing sophistication of infrastructural development in China, soil reinforcement techniques will play a more important role.

For internal stability, the geogrid reinforcement should have necessary design strength, be located at specific intervals across the vertical section of the reinforced soil, and extend an adequate horizontal distance within the reinforced soil. While the former two conditions are easy to satisfy, the required horizontal lengths may be difficult to reach if heavily over-consolidated soils or rocks are within a short distance from the face of the planned structure (e.g. Lawson, 2004). Where such “narrow” reinforced soil slopes should be constructed due to limited space, installing anchors into the stable ground provides an effective stabilization solution and expands the application of reinforced soil slopes to cases such as repair of steep veneer slopes, rehabilitation of quarries, widening of roads in mountainous terrains, etc.

To support the validity of this proposal, a case history is presented, which is located in Qingdao City, China, where the proposed method was successfully used for weathered rock slope stabilization. A summary of a simplified calculation and design procedure used in this case history is included. The paper starts with a brief discussion of some key aspects of reinforced soil slope design and implications of space constraints.

2 LITERATURE REVIEW

The published works on the presented topic are limited. Small samples of relevant studies are discussed in the following.

Rogers (1992) reported a rock slope repair work at Lake Matthews near Riverside, California. The slope failure was repaired by reinforced fill slope constructed with the crushed rock derived locally from face blasting. At four levels, nearly 6 m long prestressed rock bolts were installed at about 6 m spacing to reinforce the broken rock face and reduce the required wall width from ~7.5 m to ~2.7 m (Figure 1).

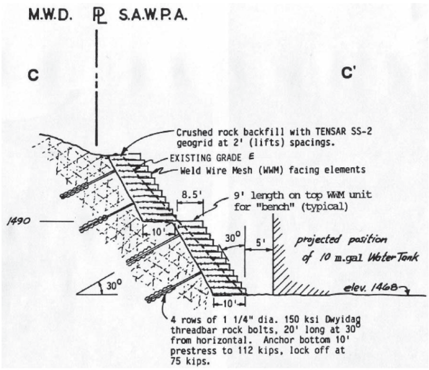

Figure 1. Schematic cross-section of an 18 m high cut slope in granite repaired by combined application of pre-stressed rock anchorage and reinforced rock fill methods (Rogers, 1992).

Zornberg (2004) reviewed the recent advances in design for unconventional loads and geometries in geosynthetic reinforced soil structures. He mentioned a case where geosynthetic reinforcement was used to stabilize a 55 m high steep veneer slope by horizontally placing geogrids in the fill and anchoring them into the bench inside the underlying mass as in cover systems for waste containment facilities (Figure 2). Although he did not refer to the combined use of reinforcement and anchoring techniques, the problem of internal stability of reinforced steep veneer slopes will surely govern the safety of the structure.

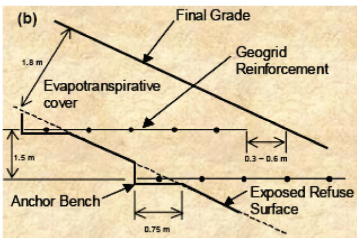

Figure 2. Reinforced cover at the OII Superfund Site: note reinforcement using horizontal geogrids anchored in solid waste (Zornberg, 2004).

Leshchinsky et al (2004) studied behavior of a geosynthetic reinforced segmental retaining wall in limited space through limit equilibrium (LE) and finite-difference (FD) methods and developed a design chart which enables the determination of the reduction in the lateral earth pressure coefficient as a function of space. However, there are many real cases (e.g., problems with complex boundary conditions) to which these design charts are not applicable.

Lawson et al (2004a, 2005b) also discussed the geosynthetic reinforced segmental retaining walls in constrained space and proposed combined use of anchors. Several situations were demonstrated in these papers, with emphasis on the reduction in the lateral earth pressure coefficient. Line of maximum tension was assumed, thus the reinforced area was divided into two parts, i.e. active and passive zones respectively. If a residual tension remains in the passive zone on reaching the rigid zone boundary, then this tension must be dissipated fully (through anchors or nails inserted into the rigid zone or by extending the length of the geogrid reinforcement in the form of a wrap-around at the rear of the reinforced soil zone) for the internal stability requirement to be met. An example of this approach is shown in Figure 3.

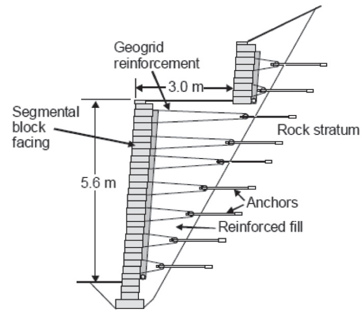

Figure 3. A reinforced soil wall design integrating anchors (Lawson et al, 2004).

In conclusion, current studies and analytical methods mainly focused on reinforced soil retaining walls assume that the potential failure plane could be determined based on traditional Rankine or Coulomb theories. Thus the anchored length of the geogrid reinforcement can be easily computed and consequently a truncated length would be obtained. In reality, it is quite difficult to determine the potential failure plane in reinforced soil slopes. Therefore, it is necessary to look for new design methods for reinforced soil slopes to be built in constrained spaces.

3 CONSIDERATIONS FOR REINFORCED SOIL SLOPES IN CONSTRAINED SPACE

The determination of the gross force T required for equilibrium in reinforced soil slopes is essentially an earth pressure problem and may be conveniently approached by using the limit equilibrium method based on the two-wedge block model shown in Figure 4.

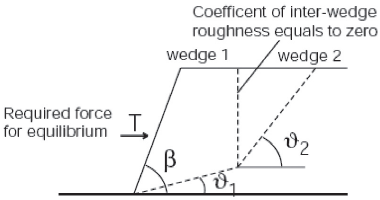

Figure 4. Calculation of the gross maximum required force for a two-wedge block model.

Design charts presented by Jewell (1991) based on the above model allow determination of the earth pressure coefficient K and the length of reinforcement, L, as a function of the slope angle β, the soil friction angle ϕ' and the pore water pressure parameter Ru. This facilitates computation of the total horizontal driving force.

In case of limited space as described above, i.e. anchors installed at the interface of the reinforced soil body, if the reinforcement length is insufficient by a large margin, e.g. only 1/5 to 1/3 of the required length, the driving force has to be balanced totally by the anchors. Otherwise, i.e. if the reinforcement is slightly less than the required length, the driving force is to be balanced partially by the anchors.

Because anchors also provide a stabilizing or reinforcing function for the host medium (rock or soil) at the base of the reinforced soil, design for the anchor should account for the stability of the whole slope.

4 CASE STUDY

A 32 m long repaired slope is a segment of slopes along the newly built Yinchuanxi Road in Qingdao City, China. The original 55° rock slope is underlined by weathered granite, which has a heavily fractured appearance due to unloading, blasting, weathering and jointing (Figure 5). In order to stabilize the slope and vegetate it as well, the wrap-around geogrid reinforced soil slope system has been chosen for the remediation work.

Figure 5. A view of the slope prior to stabilization.

The design and construction of the reinforced soil slope combined with anchors is shown in Figure 6.

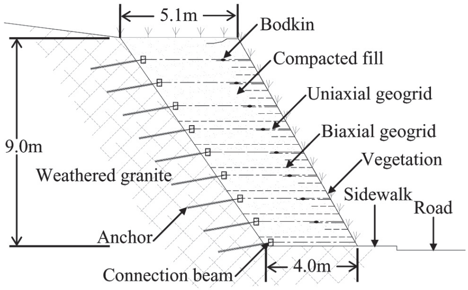

Figure 6. Typical section of the reinforced soil slope combined with anchors as designed and constructed in Qingdao, China.

Values of the design parameters are summarized below:

(1) Slope height and angle: 9.0 m and 60.0°
(2) Slope width at toe and crest: 4.0 m and 5.1 m
(3) Effective internal friction angle f': 28° (clay soil)
Soil density γ: 20.0 KN/m^3
(4) Pore water pressure parameter Ru: 0.1
(5) Type of uniaxial geogrids: EG90 R with long term design strength (LTDS) of 34.0 KN/m
Type of biaxial geogrids: EG2020 with controlled tensile strength of 20.0 KN/m
(6) Bond strength between cement grout and surrounding weathered granite rock: 300 KPa
Diameter of installation holes: 50 mm

The sensitivity analysis of internal stability using the computer program TENAX Slope (based on the above mentioned design charts proposed by Jewell) showed that for a conventional geogrid reinforced soil slope using the parameter values given above (1, 3, 4 and 5), the slope width at toe should be at least 6.64 m and 6.16 at crest. Thus anchors were essential to internal stability of the reinforced soil slope.

Also, from the above calculation, the total horizontal driving force was found to be 187.11 KN/m. For safety consideration, the driving force was decided to be balanced totally by the anchors. At nine different levels, 2.0 m long rock bolts with 2.0 m center spacing were installed. Each anchor was designed to carry an average load of 41.6 KN. The ultimate bearing capacity of these anchors was approximately 94.2 KN.

According to this calculation, reinforcement vertical spacing below 3.0 m from the toe should be 0.5 m and above 1.0 m. In the ultimate design, a uniform interval of 1.0 m was taken for the placement of EG90R uniaxial geogrids. Between every layer of uniaxial geogrid, two layers of 1.0 m (the lower one becoming 4.0 m-4.5 m below 6 m from the toe) long EG2020 biaxial geogrids were installed (Figure 6).

Fastening geogrids and anchors are particularly important in that it should ensure the residual tension in reinforcement to be transferred into anchors effectively. In this case, reinforced concrete connection beams were used, into which both geogrids and anchors were inserted (Figure 7).

Figure 7. Connection beam for joining geogrids and anchors.

The following photograph shows the finished green and stable slope after 20 days from the completion of the project (Figure 8). It worked well in the later two years.

Figure 8. A view of the slope 20 days after completion of stabilization works.

5 CONCLUSIONS

The paper discussed various design methods for reinforced soil slopes where the lateral extent of the space normal to the slope face may be constrained for a number of reasons. In such cases, due to the truncated length of the reinforcement elements, the tensile stress may not be fully dissipated on reaching the rigid zone. To achieve internal stability, these residual reinforcement tensions can be transferred into the rigid zone through anchors.

As it is difficult to predict the potential failure plane within reinforced soil slopes, the authors suggested, on the basis of Jewell's design charts, a simplified method for determination of required anchorage force. The anchors are integrated into the process to balance partially or wholly the total horizontal driving force.

A case study has been presented where a reinforced soil slope was constructed using a combination of geogrid reinforcement and anchors in order to meet the requirement of internal stability in a constrained space. In conclusion, the use of anchors in narrow sections of reinforced soil structures enhances the versatility of soil reinforcement in geotechnical engineering applications.

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