GEO Technical Guidance Note No. 11 (TGN 11)
Enhancing the Reliability and Robustness of Engineered Soil Cut Slopes

1. SCOPE

1.1 This Technical Guidance Note (TGN) presents some technical guidance on means to enhance the reliability and robustness of engineered soil cut slopes, based primarily on lessons learnt from landslide investigations. The findings of a detailed review of key lessons learnt from GEO's systematic landslide investigation programme, together with observations on areas for attention or improvement in respect of slope engineering practice in Hong Kong, are documented in GEO Technical Note No. TN 5/2002 entitled "Enhancing the Reliability and Robustness of Engineered Slopes" (Ho et al, 2002). Reference should be made to the above Technical Note for a more detailed discussion of the related topics and the relevant background.

1.2 Any feedback on this TGN should be directed to Chief Geotechnical Engineer/Landslip Preventive Measures 1 of the GEO.

2. TECHNICAL POLICY

2.1 The technical recommendations promulgated in this TGN were agreed by GEO Geotechnical Control Conference (GCC) in February 2003.

3. RELATED DOCUMENTS

3.1 Ho, K.K.S., Sun, H.W. & Hui, T.H.H. (2002). *Enhancing the Reliability and Robustness of Engineered Slopes*. Technical Note No. TN 5/2002, Geotechnical Engineering Office, Hong Kong, 64 p.

3.2 Wong, H.N., Pang, L.S., Wong, A.C.W., Pun, W.K. & Yu, Y.F. (1999). *Application of Prescriptive Measures to Slopes and Retaining Walls*. GEO Report No. 56. Second Edition, Geotechnical Engineering Office, Hong Kong, 73 p.

4. BACKGROUND

4.1 Of the 1725 landslide incidents that were reported to the GEO between the years 1997 and 2001, a total of 96 cases involved the failure of engineered slopes. Of the 96 cases, 51 affected engineered soil cut slopes. Of these 51 landslides, 15 were major failures (i.e. failure volume $\geq$50 m^3) and 36 were minor failures (i.e. failure volume <50 m^3). All these 51 failures involved unsupported soil cuts, with no structural support such as soil nails or earth retaining structures.

4.2 Minor failures on the engineered soil cut slopes noted above were mainly associated with the following problems:

(a) uncontrolled surface water flow,

(b) inadequate slope maintenance, and

(c) presence of local adverse geological features and adverse groundwater conditions.

4.3 While insufficient control of surface water and presence of local weaknesses can sometimes be contributory factors in major landslides, the use of an over-simplified geological and/or hydrogeological model which does not adequately cater for safety-critical features in the ground is the most important cause of major failures on engineered soil cut slopes. The main problems in the cases noted above were associated with the following:

(a) adverse geological features, and

(b) adverse groundwater conditions (e.g. significant build-up of perched water pressure and/or rise in base groundwater table).

4.4 For the purpose of this TGN, reliability refers to the chance of satisfactory performance (i.e. one minus the chance of failure) in a given time period. Robustness reflects the vulnerability of a slope design to undetected (or unforeseen) conditions adverse to slope stability (e.g. high transient groundwater condition or presence of adversely orientated and weak clay seams). A more robust design solution means that the slope will be less vulnerable to undetected adverse conditions not accounted for in the slope stability analysis.

5. TECHNICAL RECOMMENDATIONS

5.1 MEASURES TO REDUCE THE CHANCE OF MINOR FAILURES

5.1.1 The following measures are recommended to mitigate minor failures in engineered soil cut slopes:

(a) A detailed appraisal of the likely flowpaths of surface runoff and the potential for concentration of surface water flow affecting the slope should be undertaken to facilitate design of the surface drainage system. Sufficient redundancy should be allowed for in the design based on engineering judgement, with due regard given to the site environmental setting and consequence in the event of blockage of the drainage channels.

(b) Improved slope surface protection and drainage detailing (Wong et al, 1999; Ho et al, 2002) should be adopted to reduce the chance of local failure. The detailing should guard against ponding above the cut slope crest and overflow of surface water onto the cut face. Erosion control measures provided for vegetated slopes should be adequate and properly anchored.

(c) As minor failures due to local adverse groundwater regimes or weak geological features can be difficult to guard against fully in the design, a pragmatic approach incorporating suitable mitigation measures as an integral part of the slope design, where appropriate, to cater for possible local detachments is recommended. Such measures could include wire mesh netting, or debris traps, toe barriers or buffer zones where space permits.

5.2 MEASURES TO REDUCE THE CHANCE OF MAJOR FAILURES

5.2.1 General

5.2.1.1 In addition to the recommendations given in Section 5.1, the following measures are recommended to mitigate major failures in engineered soil cut slopes:

(a) early recognition of potentially problematic sites,

(b) improved ground investigation (GI) practice and enhanced engineering geological input,

(c) adoption of robust design solutions, and

(d) provision of prescriptive drainage measures.

5.2.2 Early Recognition of Potentially Problematic Sites

5.2.2.1 Potentially problematic sites should be identified at a sufficiently early stage so that adequate geotechnical input, including in particular engineering geological input, commensurate with the complexity of the slope and the site setting is provided. Due attention should be paid to the following indicators of potentially problematic sites:

(a) sites with relict failures that could have significant influence on the stability of the cut slope,

(b) evidence of high groundwater level or high level seepage associated with a drainage valley, subsurface drainage concentration (e.g. depression in the rockhead profile), dykes or persistent subvertical discontinuities infilled with relatively impermeable material,

(c) planar geological features (such as joints, faults, seams, bedding, foliation and planar soil-rock interfaces), especially where they are dipping out of the slope (e.g. as indicated by eutaxitic foliation in some fine ash tuff), laterally persistent, showing evidence of previous movement, associated with zones of weak materials such as kaolin, or affecting groundwater flow,

(d) evidence of progressive slope deterioration and slope movement,

(e) slopes with a history of minor or major failures,

(f) complex groundwater conditions with a significant storm response or delayed response,

(g) large cuttings in deep weathering profiles, and

(h) slopes with abundant erosion pipes (e.g. in bouldery colluvium) that are liable to result in rapid build-up of high transient water pressure should the pipes become blocked.

5.2.3 Improved Ground Investigation Practice and Enhanced Engineering Geological Input

5.2.3.1 Improved GI practice entails detailed planning and sufficient project-specific input by experienced geotechnical professionals to identify the key questions to be addressed by the investigation following detailed desk study and aerial photographic interpretation. As far as possible, site visits should be made during or shortly after heavy rainfall to observe transient seepage and surface water flow. More frequent use of shallow piezometers sited at potential perching horizons is strongly encouraged. Sufficient piezometers should be placed at locations of subsurface drainage concentration. Piezometer buckets should be installed in all piezometers to monitor the peak transient groundwater response. Water pressure sensors capable of providing continuous readings may also be considered, particularly for sites with high and complex groundwater conditions.

5.2.3.2 There should be adequate engineering geological input to the GI, formulation of representative ground models for stability assessment and design verification during construction. Mapping of the exposed slope face to review the adequacy of design assumptions should be done by a qualified and suitably experienced geotechnical professional during construction. The geotechnical professional responsible for the design review should consider the need to seek further specialist advice, or second opinion, from an experienced engineering geologist where deemed appropriate (e.g. for slopes with very complex ground and hydrogeological conditions).

5.2.3.3 Special care should be exercised in the evaluation of the design groundwater condition for a cut slope where the hard surface cover is to be replaced by a vegetated cover. In this case, the recorded groundwater conditions during the GI stage may not be representative of the likely future groundwater and response given the changes in the environmental setting of the slope. Due allowance should be made for possible enhanced infiltration which could give rise to a higher base groundwater level or localized perched water table.

5.2.4 **Adoption of Robust Design Solutions**

5.2.4.1 Given that improved GI practice and enhanced engineering geological input could still miss the more subtle adverse geological features, robust design solutions (e.g. soil nails, reinforced concrete retaining wall or reinforced concrete facing, toe weighting, etc.) that are less sensitive to local adverse geological and groundwater conditions (in comparison with solutions based on no positive slope reinforcement or support) are recommended.

5.2.4.2 Large unsupported cuts, particularly those with significant consequence-to-life or major economic consequence in the event of slope failure, should be avoided as far as possible because these are especially vulnerable to undetected adverse ground and groundwater conditions due to lack of redundancy. Positive slope support/reinforcement systems such as toe weighting or soil nailing, supplemented with subsurface drainage measures where necessary, are generally preferred to cutting back alone even though the calculated factors of safety of the different schemes based on conventional limit equilibrium analyses may be the same.

5.2.4.3 Soil nails can bridge over local weaknesses in the ground through stress redistribution, and hence a nailed slope behaves as a reinforced ground mass and is less sensitive to undetected adverse features (i.e. it is more robust than an unsupported cut). An added advantage of soil nailing is that the failure mode is likely to be more ductile with some prior warning of an impending failure (e.g. through progressive development of slope distress) and that the debris mobility is reduced. Sufficient confinement at the slope surface (e.g. with adequately sized nail heads and sufficiently closely spaced nails) must be provided to prevent movement and disintegration of the ground mass at shallow depths so that the full capacity of the soil nails in the passive zone can be utilised. Connecting the soil nail heads together by means of structural beams, grillages, wire mesh netting or a reinforced shotcrete cover (where necessary), will further enhance the confinement effect and promote integral action of the reinforced ground mass.

5.2.4.4 Use of soil nails as the only stabilisation measure in localised steep slope profiles or back scarps, in overhangs or in areas of high erosion potential should be avoided. Consideration should be given to suitable local trimming, as necessary, prior to soil nail construction. Trimming to a locally smoother and less steep slope profile can also facilitate more effective installation of erosion control mats and provide safer and easier access for maintenance and will reduce the chance of minor failures.

5.2.4.5 It is important that the scope of GI and the level of engineering geological input should not be unduly compromised simply through the adoption of a robust solution (such as soil nails), especially for potentially problematic sites, unless the conditions satisfy the qualifying criteria for prescriptive measures as defined in GEO Report No. 56. Soil nailing, for example, cannot replace the need to have a good understanding of the ground and its possible behaviour, especially where the slope is sizeable and would pose a significant consequence in the event of a failure.

5.2.4.6 Special care should be taken with the consideration of soil nails for sites with past massive landslides because the ground mass may have been significantly disturbed (e.g. opening up of subvertical relict joints). A more suitable robust scheme in this case may involve toe weighting together with suitable subsurface drainage provisions.

5.2.4.7 It is important to ensure that soil nails are not installed entirely within disturbed ground mass (i.e. the nails must be bonded in competent ground) and that there are no major adversely orientated weak discontinuities beyond the nailed zone. Where very long soil nails are adopted, caution is needed in the analysis because conventional simplified analytical methods may not adequately model the load transfer mechanism of nail-ground interaction and they may over-estimate the efficiency of long nails in mobilising the full capacity. Caution is also needed with nails installed at a steep angle relative to the critical slip surface because such steeply inclined nails will not be effective in developing tension forces because of the mechanics of nail-ground interaction.

5.2.4.8 Caution is needed in the use of soil nails in slopes with a high groundwater level in that the drilled hole may require a temporary casing or other measures (e.g. temporary drainage measures or pre-grouting) to prevent hole collapse during drilling and grouting. Uncontrolled hole collapse due to high groundwater level could disturb the surrounding ground mass (which may lead to ground movement as well as adversely affect the design nail capacity) and is liable to compromise the integrity of the grout column of the soil nail. The necessary construction control measures to ensure proper construction of soil nails in such adverse conditions and minimise ground movement to any sensitive nearby facilities or services will require careful consideration. Designers should consider the need for field trials to confirm the practicability and effectiveness of any proposed special construction control measures in ground with a high groundwater level prior to commencement of the prototype soil nails.

5.2.5 Provision of Prescriptive Drainage Measures

5.2.5.1 Prescriptive subsurface drainage measures, such as raking drains or counterfort drains (which are particularly suitable for shallow perching situations), as contingency provisions are prudent in view of the innate variability of groundwater conditions. This is especially relevant in colluvial and saprolitic ground profiles and where a hard slope surface cover is to be replaced with a vegetated cover. Designers should exercise due judgement in prescribing the necessary subsurface drainage measures. As a guide, situations where prescriptive subsurface drainage measures may be warranted include:

(a) locations with evidence of seepage from the slope face,

(b) at interface of materials with significant permeability contrasts giving rise to the potential for perching,

(c) where there is a sizeable catchment draining to the slope,

(d) presence of buried stream course or subsurface drainage concentration within the slope or in its vicinity with the possibility of lateral drainage towards the slope,

(e) slope whose stability is especially sensitive to changes in design groundwater level,

(f) as contingency provisions against possible leakage from nearby water-carrying services, and

(g) where there is concern about possible damming effects of closely-spaced soil nails on groundwater flow.

5.3 SITE SUPERVISION AND AUDITS

5.3.1 Slope failures may occur due to poor workmanship or non-compliance with the specification during construction. In this regard, it is important to ensure adequate and vigilant site supervision by suitably experienced and properly trained and briefed supervisory staff who should provide full-time supervision of all the critical construction activities (e.g. insertion of steel bars into the drilled holes and grouting of soil nails). In addition to the above, regular audits of the adequacy of site supervision by an independent team are also important to prevent substandard work during construction.

6. ANNEXES

6.1 Nil.

(R K S Chan)
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