# DEVELOPMENT OF A NEW DESIGN METHOD FOR REINFORCED SOIL SLOPES

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**ABSTRACT:** Soil slopes reinforced with polymer geogrid reinforcement are generally defined as having a face angle less than 70° to the horizontal, which distinguishes this form of structure from retaining walls, and is also an appropriate distinction in terms of methods used for design. Early in their development reinforced soil steep slopes were commonly designed using chart methods, one of which was developed using a 2-part wedge method of analysis. This was later used as the basis for the HA 68/94 design method. The design procedure firstly establishes the dimensions of the reinforced soil block, and secondly determines the required layout of reinforcement using a spacing curve. This results in an efficient layout of reinforcement being found very quickly but based on a single soil strength and not taking account of foundation strength. The method has been adapted to include earthquake loading and alternative partial factors. It can be used most effectively as a means of finding an initial layout of reinforcement. Stability analysis is then required to verify the final design and take account of more complex conditions that are beyond the scope of the HA 68/94 method.

Keywords: reinforced soil, steep slope, design, 2-part wedge, limit state, earthquake

## INTRODUCTION

The use of soil slopes reinforced with polymer geogrid reinforcement dates back about 40 years, so by now their use has become common practice, although possibly not as frequently used as reinforced soil retaining walls. The normal distinction between these two forms of structure is that retaining walls are steeper than 70° to the horizontal and generally with a hard or concrete facing, whereas steepened slopes are less than 70° and normally with a soft or vegetated facing.

This paper examines briefly the basic approaches to the design of reinforced soil steepened slopes and retaining walls, in order to examine whether or not there is a need for this distinction, defined by the facing angle of 70°. Early methods of design for reinforced soil slopes are described, which then led to the method published by the UK Highways Agency (1994) entitled "Design Methods for the Reinforcement of Highway Slopes by Reinforced Soil and Soil Nailing Techniques", referred to as the "HA 68/94 method" in this paper. The HA 68/94 method was withdrawn from use in 2017, however the method of calculation can still be used, and adapted to other conditions and requirements, as outlined in this paper. It should be noted that the discussion presented here concerns a "design" method, which has the aim of finding an efficient arrangement of reinforcement as readily as possible. This is distinct from "analysis" methods, such as the method of slices or finite element analysis (FEA), which may also be used as part of the design process, but their use to find an efficient layout must be done by trial-and-error, which can be very time-consuming. The conclusion to this paper outlines how a combination of a "design" method and an "analysis" method provides the most effective way to design a reinforced soil steep slope.

## DISTINCTION BETWEEN DESIGN METHODS FOR RETAINING WALLS AND SLOPES

There is a frequent point of discussion as to whether the distinction of a 70° facing angle is necessary with regards to design methods for reinforced soil structures. There are many reinforced soil retaining wall design methods published by national authorities and other bodies such as AASHTO and BSI which all have similar approaches, namely treating the reinforced soil mass as a gravity retaining wall to examine its external stability and thereby establish its dimensions, then using some form of internal stability analysis to establish the required layout and grades of the layers of reinforcement. These methods work well for very steep structures, and are also easily adapted to limit state design approaches based on load factors, such as AASHTO/LRFD, BS8006 and AS4678-2002. With regards to slopes, the use of the gravity retaining wall analogy becomes more doubtful as the angle of the back of the structure reduces, and no longer provides a reliable method of calculation. Clearly, stability analysis adapted to incorporate the resisting forces from layers of reinforcement does provide an alternative method of calculation, which can be applied to any form of reinforced soil structure, but as a design method it is time-consuming to use, requiring a great deal of trial-and-error to find the most economical solution. The conclusion is that, with regards to “design” methods, the 70° facing angle distinction between reinforced soil retaining walls and steep slopes is justified. As regards design methods for reinforced soil steep slopes where the aim is to find an efficient layout of reinforcement directly, early methods were published in the 1980’s based on using charts. One chart method is outlined in the following section.

## CHART BASED METHODS FOR THE DESIGN OF REINFORCED SOIL STEEP SLOPES

Design charts for reinforced soil steep slopes developed by Schmertmann et al. (1987) are shown in Figure 1. The full design method requires two charts: the first (on the left) provides the dimensions of the reinforced soil mass, and the second (on the right) provides a force coefficient used to determine the grade and layout of the reinforcement. These charts are limited to zero cohesion, uniform surcharges and simple geometry, and do not examine foundation stability.

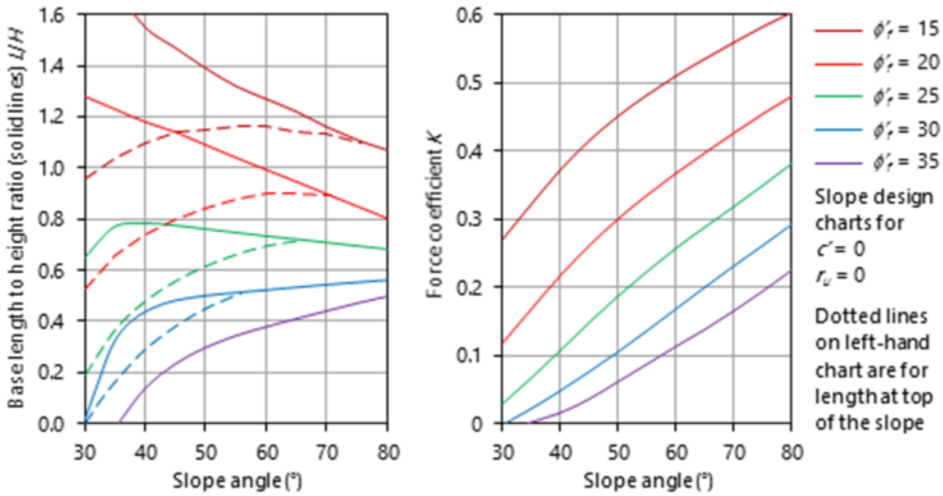


Figure 1. Design charts for reinforced soil steep slopes developed by Schmertmann et al. (1987)

Charts of this type are probably still used for design today and remain very useful to help make an initial sizing of a structure. It should be noted that the soil strength $\phi'_f$ indicated on the charts is the design value after a factor of safety has been applied to the characteristic soil strength. The charts also illustrate some important trends with regards to the design of reinforced soil steep slopes. The right-hand chart shows how the required total reinforcement force rapidly reduces as the facing angle reduces, such that low angle slopes only need relatively light reinforcement compared to retaining walls. The left-hand chart indicates that for lower strength fills, the base reinforcement length tends to increase as facing angle reduces. Reinforcement length at the top of the slope (indicated by the dotted lines) is the same as the base length for very steep structures, but as facing angle reduces, the top length may be less than the base, especially for lower strength fills, resulting in options to use a varying reinforcement length for maximum efficiency.

Jewell et al (1984) published similar charts, which were updated by Jewell (1990). These charts were developed using a 2-part wedge method of calculation with the important distinction that the inter-wedge boundary was a vertical line which was not bound to the back of the reinforced soil mass. The HA 68/94 design method also uses a 2-part wedge approach and is described in detail in the following section.

## DESIGN OF REINFORCED SOIL STEEP SLOPES USING HA 68/94

In the early 1990's the 2-part wedge approach was used to develop the UK Highways Agency Advice Note HA 68/94 providing design methods for the reinforcement of highway slopes by reinforced soil and soil nailing techniques. The HA 68/94 document provides a tabulated solution, similar to the design charts, which may be used to create a design by manual calculation. It also provides an analytical method that may be used to create a computer program that can take into account more complex situations. The only source of a margin against failure in the method is the use of constant volume soil shear strength or a partial factor applied to the characteristic strength of the soil fill material.

The HA 68/94 Advice Note used to be freely available from the UK Highways Agency website, and now may be found by a search on the Internet. It is a useful document with extensive advice on the design of reinforced soil slopes. The 2-part wedge geometry is defined in Figure 2.

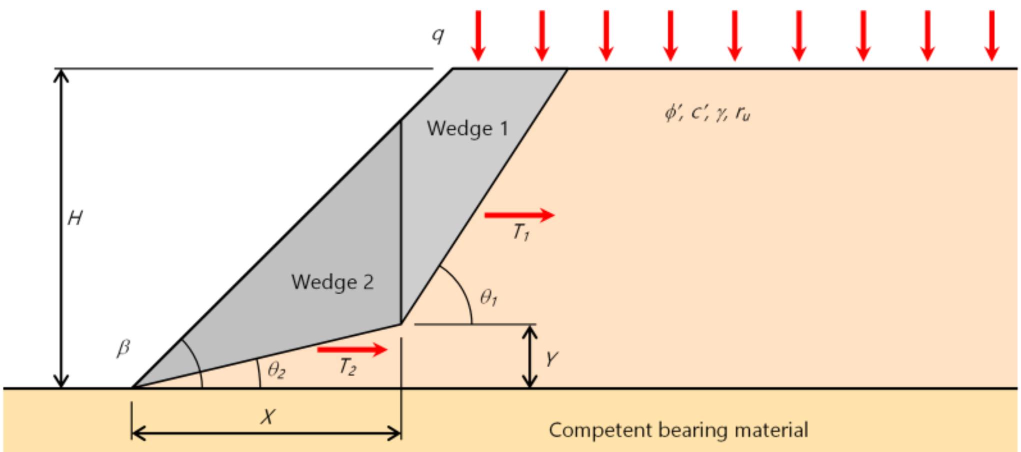


Figure 2. The two-part wedge mechanism used in the HA 68/94 method

The method provides a single unified limit equilibrium design approach for reinforced highway earthworks with slope angles in the range 10° to 70° and soil types with $\phi'$ values in the range 15° to 50°, on competent foundations.

An assumption of the mechanism is that the inter-wedge boundary is vertical and $\theta_2$ is positive. In addition, the method assumes that a competent soil, significantly stronger than the slope fill, exists beneath the retained slope so that the two-part wedge is confined to pass through the toe of the slope. Provided that these criteria are satisfied, the mechanism may take any form and the inter-wedge boundary and outcrop position of the upper wedge may lie behind or in front of the slope crest. A surcharge is modeled by defining an additional thickness of fill ($\Delta H = q/\gamma$) such that the effective slope height is given by $H'$ (= $H + \Delta H$). All calculations are carried out in terms of $H'$. Two mechanisms defined in HA 68/94 are used to determine an initial reinforcement layout:

**The Tmax mechanism**: In any slope it is possible to identify the two-part wedge mechanism which requires the greatest reinforcement force (T1 + T2) in order to attain equilibrium. This mechanism is unique and determines the theoretical total reinforcement force required and is also used to give a minimum length of reinforcement at the top of the structure, based on the theoretical optimum reinforcement layout. The latter is determined such that the uppermost reinforcement layer has just sufficient anchorage length behind Tmax to mobilize its full design strength in pull-out. This ensures sufficient anchorage length for the Tmax mechanism only.

**The Tob mechanism**: This is the critical base-sliding mechanism that requires precisely zero reinforcement force in order to maintain equilibrium. It defines the length required for the reinforced fill block at the base of the structure.

The effect of the magnitude of inter-wedge friction is examined in the HA 68/94 document, which demonstrates that using zero is over-conservative, whereas using the full soil strength $\phi'_f$ is unsafe. Based on this, it is recommended that the maximum value used should be $0.5\phi'_f$.

The first part of the design procedure is to determine the geometry of the reinforced soil block (which is similar to the external stability calculation in reinforced soil retaining wall design). This procedure is given as a series of steps in Table 1, which should be read in conjunction with the definitions in Figures 2 and 3. The final outcome of these calculations is to determine the line defining the back of the reinforced soil block, as indicated in Figure 3.

Table 1. Determining the geometry of the reinforced fill block

| Step | Procedure |
|---|---|
| 1 | Define $L_B$ from the $T_{ob}$ mechanism |
| 2 | Determine geometry of the $T_{max}$ mechanism and magnitude of $T_{max}$ ($T_{max} = 0.5K\gamma H'^2$) |
| 3 | Find the number of reinforcement layers required ($N = T_{max}/T_{all}$) where $T_{all}$ is the design strength of the reinforcement |
| 4 | The depth to each layer of reinforcement is given by. $z'_i = H'\sqrt{(i-1)/N}$ |
| 5 | The depth to the first layer of reinforcement is given by $z'_1 = 0.5z'_2$ |
| 6 | Determine the anchorage length required behind the $T_{max}$ mechanism at the level of the first reinforcement layer, given by $L_{e1} = T_{all}/\lambda_p\sigma'_{v1}\tan\phi'_f$ |
| 7 | The back of the reinforced fill block is then determined by drawing a straight line starting at the point $L_B$ from the toe of the slope, through the end point of the top reinforcement layer to the ground surface |

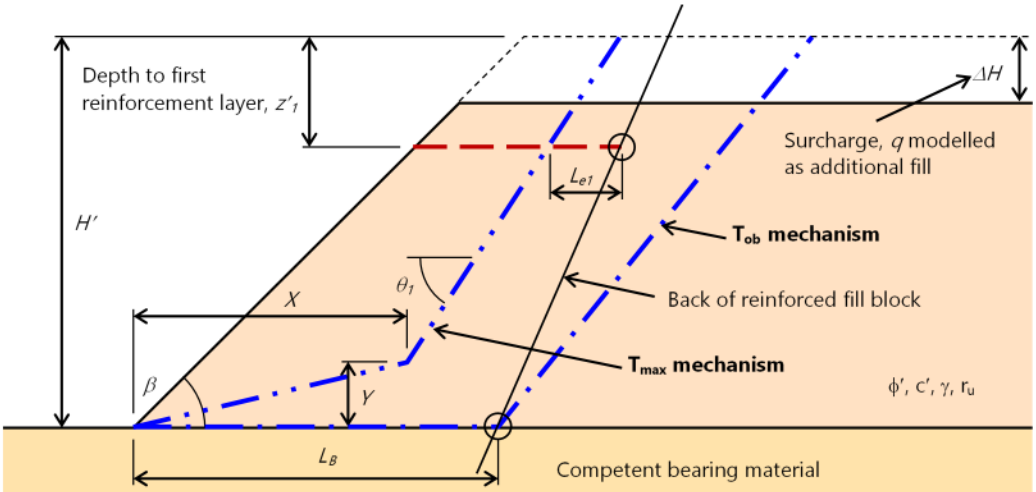


Figure 3. Determining the geometry of the reinforced soil block

The second part of the design procedure is to determine the layout of reinforcement within the reinforced fill block (similar to internal stability analysis in reinforced soil retaining wall design). As outlined in Table 1, the theoretical total number of layers of reinforcement required is $N$ (= $T_{max}$ / $T_{all}$) and the theoretical depth to each layer is given by:

$$z'_i = H'\sqrt{(i-1)/N} \tag{1}$$

The depth to the first layer of reinforcement is given by $z'_1 = 0.5z'_2$, and an additional layer is placed at the base of the slope giving ($N$ + 1) layers in total. The resulting layout is shown in Figure 4. This is an ideal theoretical layout, however, the spacing between reinforcement ($S_{vi}$) changes at each layer, and is unlikely to fit in with typical compacted layer thicknesses. Furthermore it is normal to stipulate a maximum spacing between reinforcement layers, typically 1.0m in slopes.

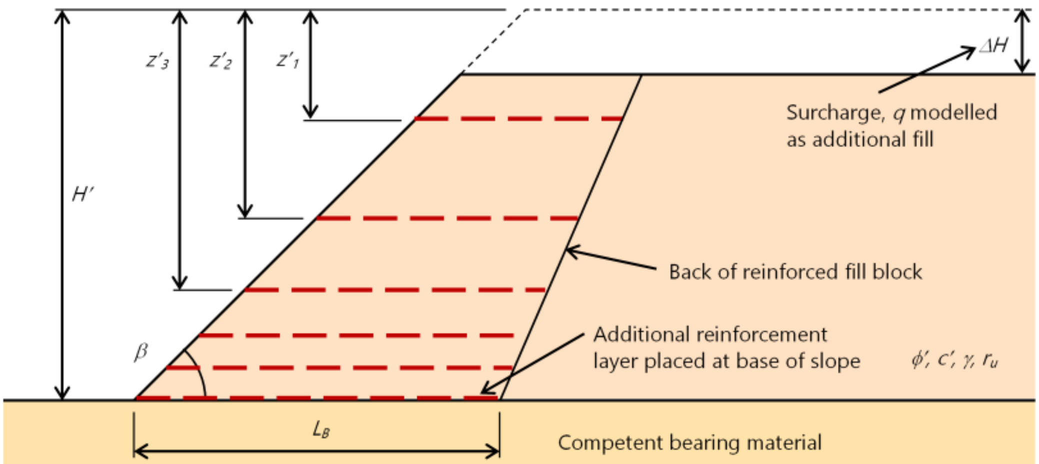


Figure 4. Theoretical reinforcement layout

In order to produce a practical layout of reinforcement, the following relationship between vertical spacing and depth may be used to define a spacing curve:

$$S_{vi} = \frac{T_{all}}{K \gamma z} = \frac{0.5 T_{all} H'^2}{z T_{max}} \qquad (1)$$

In Equation (2), z is the depth to the mid-point of each soil layer. A typical spacing curve is shown as the solid purple line on Figure 5. This gives the relationship between depth below the top of the structure and the maximum permitted spacing between the reinforcement. Each green square plotted point represents the depth to the mid-point between each pair of reinforcement layers versus the vertical spacing between the same reinforcement layers, based on the reinforcement layout chosen. These points should always fall to the left of the spacing curve.

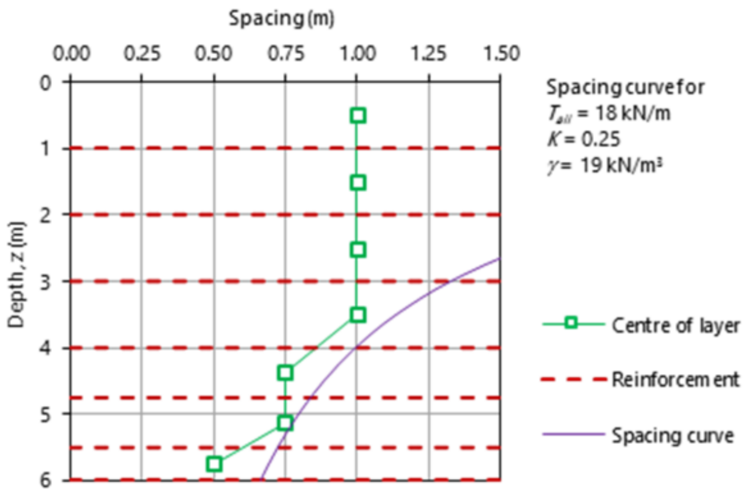


Figure 5. Spacing curve (each grade of reinforcement used will have its own curve)

The spacing curve provides the designer with a quick method of finding a satisfactory layout of reinforcement, based on a practical compacted layer thickness, at the same time meeting the stability requirements. The final reinforcement layout is shown in Figure 6.

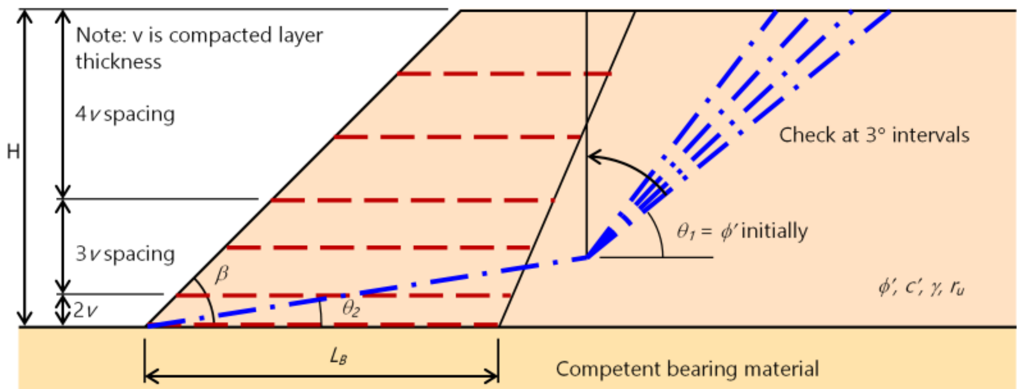


Figure 6. A practical reinforcement layout and the additional wedge checks

The solution tabulated in HA 68/94 has limitations on the conditions which may be modeled. To carry out efficient designs, a computer program is required, which can also check wedges lying behind $T_{max}$ to ensure they intersect sufficient reinforcement, as indicated in blue in Figure 6.

## DEVELOPING A NEW DESIGN METHOD USING THE HA 68/94 CALCULATION TECHNIQUE

HA68/94 was withdrawn in 2017 due to the advent of Eurocode 7 (EC7), however as a calculation procedure, it still provides a good basis for designing reinforced soil slopes. New design methods for reinforced soil slopes have been developed based on the calculation procedure defined in HA68/94 but making some important changes. Firstly, seismic forces have been included making the method suitable for use in earthquake-prone areas, by adding inertia forces (both horizontal and vertical) to the masses of Wedge 1 and Wedge 2, as defined in Figure 2. Secondly the margin against failure is now created by using partial material factors and load factors, for example as given in EBGEO combined with DIN 1054:2012-12, which together form the EC7 National Annex for Germany for reinforced soil design (EC7 itself does not yet include the design of reinforced soil structures). The partial factors are given in Table 2 for three load cases. The characteristic soil strength used should be assessed based on design conditions, and in most cases would be peak strength, selected as a cautious estimate of the value affecting the occurrence of the limit state.

Table 2. Material and load partial factors according to EBGEO (EC7 for Germany)

| Load case | Soil strength | Reinforcement strength & pull-out | Factor on live load |
|---|---|---|---|
| Static | 1.25 | 1.4 | 1.3 |
| Temporary | 1.15 | 1.3 | 1.2 |
| Seismic | 1.1 | 1.2 | 1.0 |

A typical reinforced soil steep slope section, as determined by the adapted HA 68/94 method is shown in Figure 7, including seismic loading and according to the EBGEO partial factors in Table 2. The use of this method in a computer program permits the inclusion of many features which are not possible using the manual solution. In this case, there is a submerged toe and internal water level, a complex geometry for the top of the slope and two isolated surcharges. However, the fill is formed from a single soil type, which commonly may not be the case, and although the foundation indicates the presence of a toe slope, its stability has not been checked by this method. Therefore, an important part of the procedure is to use a method of stability analysis to check these features, such as analysis using the method of slices which is shown in Figure 8.

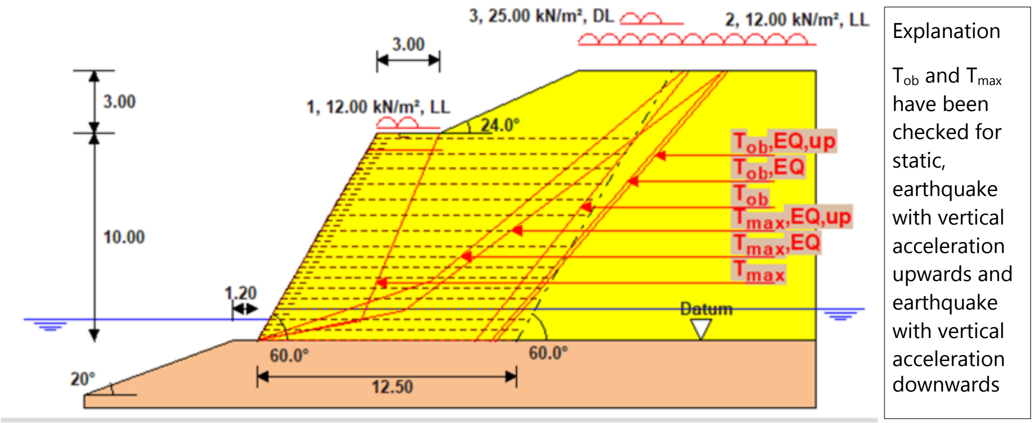


Figure 7. Design of reinforced soil steep slope using the HA 68/94 method (with seismic loading)

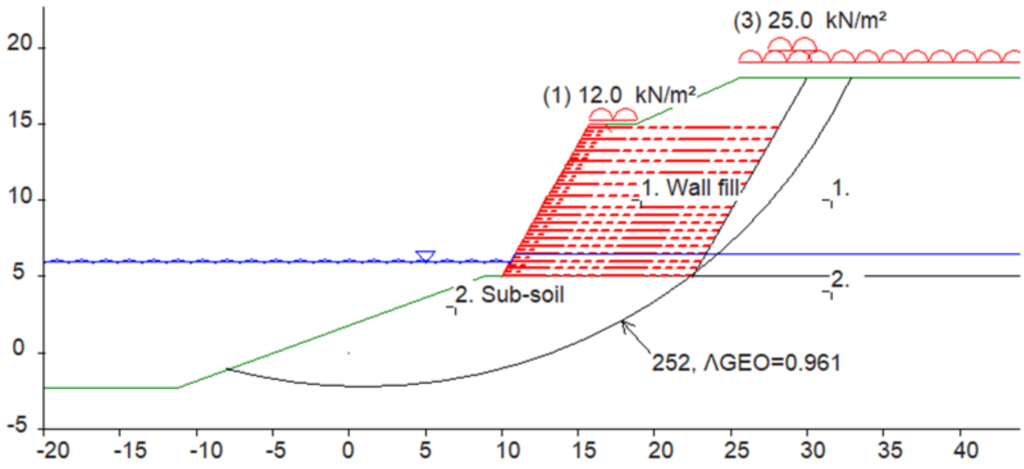


Figure 8. Stability analysis applied to the reinforced soil steep slope to check foundation stability

## CONCLUSIONS

Design of reinforced soil slopes requires a different approach compared to the more common reinforced soil retaining wall design methods, and the commonly used distinction of 70° face angle between the two forms of structure is justified from the point-of-view of design method. Early design methods for reinforced soil slopes were developed based on charts, and some of these methods made use of a 2-part wedge mechanism.

The HA 68/94 design method was developed using a 2-part wedge method of analysis. The method could be used manually for very simple conditions but could also be used to form the basis for computer programs, in which more complex situations could be included in design. HA 68/94 was withdrawn in 2017, but the method of calculation may still be used. In this case, to develop new design methods, taking account of seismic loading and well-defined systems of partial factors. The design method is effective for providing a suitable layout of reinforcement very quickly but should be combined with stability analysis in order to provide a complete design solution.

## REFERENCES


DIN 1054:2010-12. (2010). Subsoil – verification of the safety of earthworks and foundations – supplementary rules to DIN EN 1997-1:2004, Berlin.

EBGEO. (2010). Recommendations for design and analysis of earth structures using geosynthetic reinforcements. Deutsche Gesellschaft fur Geotechnik, Ernst & Sohn, Berlin

Highways Agency (UK). (1994). Design methods for the reinforcement of highway slopes by reinforced soil and soil nailing techniques. Advice Note HA 68/94, Design manual for roads and bridges, London.

Jewell, R. A. (1990). Revised design charts for steep reinforced slopes. Reinforced Embankments: Theory and Practice. Thomas Telford, London.

Jewell, R. A., Paine, N. and Woods, R. I. (1984). Design methods for steep reinforced embankments. Polymer Grid Reinforcement, Thomas Telford, London: 70-81.

Schmertmann, G. R., Chouery-Curtis, V. E., Johnson, R. D. and Bonaparte, R. (1987). Design charts for geogrid-reinforced slopes. Proc Geosynthetics '87, Vol 1, New Orleans: 108-120.