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A computer program for designing reinforced embankments

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ABSTRACT: SINTEF has developed a computer program named REmbank for designing embankments with reinforced soil foundations on poor ground. Both embankments with and without piles are included. The design practice today is varying, and the designer may choose between several theory models for the reinforcing mechanisms. The computer program gives the user the opportunity to select between different calculation methods and safety approaches. The model for reinforcement function in the program is based on classical methods, including a method proposed by SINTEF. The printout gives a full documentation of the input data and the calculated results, including the critical shear circle from stability calculations.

1 INTRODUCTION

To improve the bearing capacity for embankments on soft foundation soil an embankment can be reinforced with a basal reinforcement layer. Settlements can be minimized installing piles in the subsoil beneath the reinforcement, see Figure 1. The computer program calculates the required design strength of the reinforcement and also estimates the strain in and deflections of the reinforcement. The rotational stability is checked and possible contribution to the reinforcement design as regards required strength and bond length is calculated.

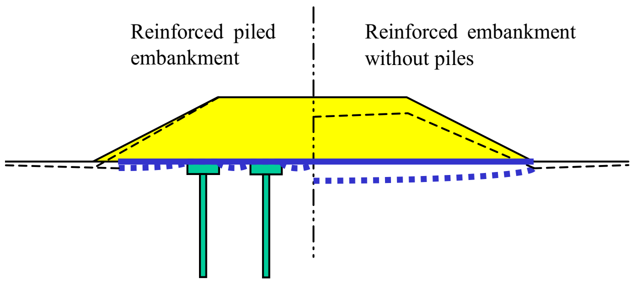

Figure 1. Reinforced embankment with and without piles – deformation pattern

The REmbank program gives the user opportunity to select between different calculation methods and safety approaches, and the user may easily optimize the embankment geometry, pile spacing and pile cap size.

2 REINFORCEMENT MATERIAL PROPERTIES

A reinforcement product database is included in the program. The database comprises reinforcement characteristics on strength and stress-strain behavior given by the manufacturers. The stress—strain relationship is given in a table.

The ultimate strength is given as a characteristic short-term strength and a creep factor. Optionally the characteristic long-term strength may be given. The characteristics are given for both the machine direction, MD, and the cross direction, XD, of the reinforcements.

3 DESIGN SAFETY APPROACH

The designers today may choose between different safety approaches, either a national norm or e.g. the European pre-norm. REmbank uses partial factors for calculations. Two sets of predefined partial factors are given (ENV 1997-1 and BS8006), but user defined factors may also be used.

4 PILED EMBANKMENTS

Piled embankments are often designed to minimize deformations on the surface. The tension in the reinforcement due to the cable effect may then become considerable, and in reality the reinforcement tension will increase the stiffer the reinforcement is. Therefore, a common approach is to calculate the necessary reinforcement strength from a maximum allowed strain. The maximum allowed strain is the reinforcement strain for a tensile load equal to the characteristic long-term strength. REmbank is calculating this strain level, if not given, for all reinforcements in the product database based on data in the stress-strain relationship table and the creep factor.

The tension force in the reinforcement is calculated with reference to “direct sliding” (BS8006), “weight of fill” and stability (slip circle) outside the outer pile cap. The required long-term design strength is either the strength required from “ direct sliding” plus “weight of fill”, or the required strength to get sufficient “stability“, whichever is the largest. The procedure for calculation of the weight of fill carried by the reinforcement is discussed in Section 5.

5 REINFORCEMENT TENSION DUE TO WEIGHT OF FILL FOR PILED EMBANKMENTS

In all the calculation methods it is essentially assumed that a part of the fill weight is carried directly by the pile caps, while the remaining load is taken by the reinforcement. In true life, a part of this load will be transferred directly to the soil below the reinforcement, and the remaining will be transferred to the pile caps through tensile forces in the reinforcement. In design, it is however common to assume that all load taken by the reinforcement is transferred to the pile caps, because long term settlement can reduce the contact stress between reinforcement and subsoil.

The reinforcement has two load carrying directions, and one may therefore assume that the load transferred to the reinforcement, in essence is carried by reinforcement strips between the pile caps, see Figure 2. Two such strips carry the load due to a base area with side length *c*. This means that any load on the white area between the pile caps first is transferred to the shaded area, and then carried further to the pile caps.

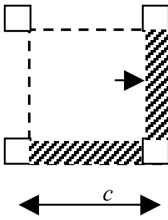

Figure 2: The load is in essence carried by reinforcement strips between the pile caps

The design calculations are based on an even distribution of tension in the reinforcement between the pile caps. This is an idealization, because stress concentrations will occur near the corners of the pile cap plates.

5.1 *Method described by Carlson (1987)*

5.1.1 *Soil weight carried by the reinforcement*

The Carlson (1987) suggests a two-dimensional approach. Between the pile caps, a wedge of soil with an apex angle of 30° is to be carried by the reinforcement. This implies that arching is assumed. The width of the wedge is (*c-a*), and the weight per unit length becomes:

$$W = \frac{(c-a)^2}{4\tan 15^\circ}\gamma \qquad (1)$$

With reference to Figure 3, it is seen that this formula includes only areas of type A between pile caps. The load on area of type B is not considered. This can be non-conservative, i.e. lead to an underestimation of reinforcement loads in case of low *a/c* – ratios. Further, since the method inherently assumes a wedge of height 1.87(*c-a*), it may over predict the reinforcement load at fills lower than this height.

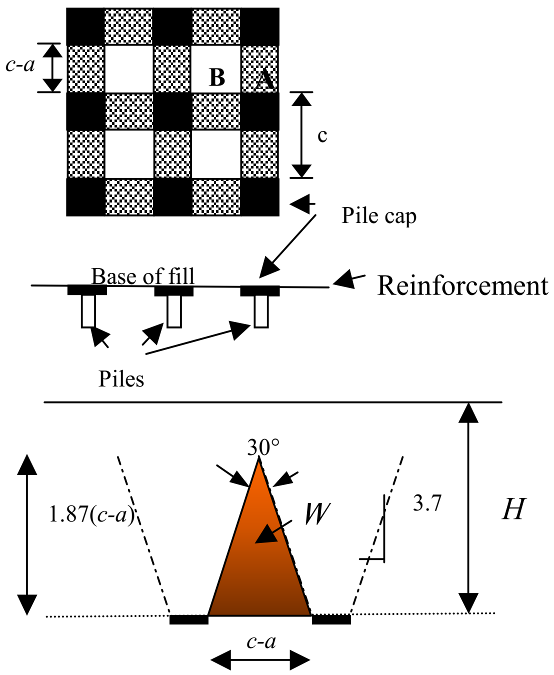

Figure 3: Pile cap configuration and load carrying areas

The reinforcement tension is derived from the deflection. The deflection from the reinforcement strain ε is described according to:

$$d = (c-a)\sqrt{\frac{3}{8}\varepsilon} \qquad (2)$$

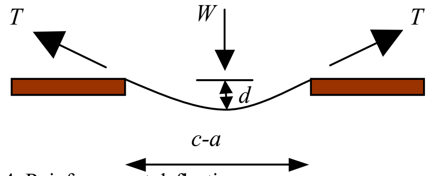

Figure 4: Reinforcement deflection

The reinforcement tension can be calculated from the equation for chains (described by e.g. Hellan (1969)):

$$T = \frac{(c-a)^3}{16\tan 15^\circ}\gamma\frac{1}{2d}\sqrt{1+\frac{16d^2}{(c-a)^2}} = W\frac{c-a}{8d}\sqrt{1+\frac{16d^2}{(c-a)^2}} \qquad (3)$$

Considering the equation for deflection, Eq. (2), this gives the equation for the reinforcement tension:

$$T_S = \frac{W}{2}\sqrt{1+\frac{1}{6\varepsilon}} \qquad (4)$$

5.1.2 *Extension of Carlson's method to 3D*

Rogbeck et. al. (1998) propose a 3D extension of Carlson's method according to:

$$F_{3D} = \frac{1+c/a}{2}F_{2D} \qquad (5)$$

where F_{3D} and F_{2D} refer to corresponding forces for 3D and 2D conditions. This extension will give higher forces than in Carlson (1987).

5.2 *Method described by BS 8006*

5.2.1 *Soil weight carried by reinforcement*

The formulas in BS 8006 imply that full effect of arching occurs at an embankment height of 1.4(*c-a*) or higher. The embankment height should be at least 0.7(*c-a*) to avoid localized differential settlement. The pile caps take the vertical stress p'_C, which in terms of the average vertical stress σ'_V is given by an arching coefficient:

$$\frac{p'_C}{\sigma'_V} = \left[\frac{C_C\,a}{H}\right]^2 \qquad (6)$$

C_C takes the formulas

$C_C = (1.95\,H/a - 0.18)$ for end bearing piles

$C_C = (1.5\ \ H/a - 0.07)$ for friction and other piles

BS 8006 gives formulas for the weight W_T per unit length, and after inserting for p'_C/σ'_V, the formulas read (partial coefficients and surface loads are omitted): (7)

$$W_T = \frac{c^2 - a^2\frac{p_c}{\sigma_v}}{c^2-a^2}\cdot\begin{Bmatrix} 1.4c\,\gamma\,(c-a) & ,H > 1.4(c-a) \\ c\,(\gamma\,H) & ,0.7(c-a) \le H \le 1.4(c-a) \end{Bmatrix}$$

5.2.2 *Reinforcement tension*

W_T is a vertical force per unit length. The reinforcement tension is written as:

$$T = W_T \frac{c-a}{2a}\sqrt{1+\frac{1}{6\varepsilon}} \qquad (8)$$

5.3 *Method proposed by SINTEF*

The SINTEF method is earlier prescribed by Svanø et. al. (2000).

5.3.1 *Soil weight carried by reinforcement*

Like Carlson (1987), we will assume that the reinforcement carries a weight due to a wedge of fill material. But in order to obtain a 3D solution, we will calculate the weight of the hatched area on Figure 3, and assume that this volume is carried directly by the pile cap. The remaining material is carried by the reinforcement. Each pile cap carries a 3D wedge of fill material with slope β:1. The slope β is expected to take values in the range 2.5 to 3.5, and needs to be calibrated (set to 3.5 in the current program version). This means that the wedge has a side a at the base, and a side $a+(2/\beta)*z$ at a height z. The maximum side is equal to the pile distance c, which occurs at $z = (\beta/2)(c-a)$. The fill weight carried by each pile cap then becomes, for $H \leq (\beta/2)(c-a)$:

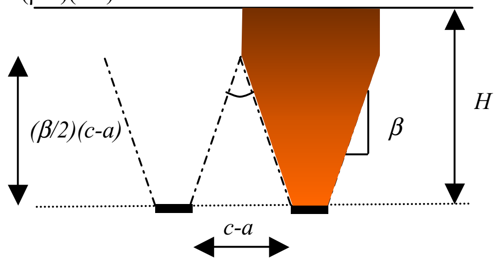

Figure 5: Arching by SINTEF's method

$$Wp = 1/3\gamma\left[\left(a+\frac{2}{\beta}H\right)^3 - a^3\right]\frac{\beta}{2} \qquad (9)$$

The weight carried by the reinforcement will increase until the fill height has reached $H = (\beta/2)(c-a)$. The additional weight of the fill above this height will be entirely carried by the piles. The total soil weight is $W = \gamma c^2 H$. The part carried by reinforcement is $W - W_P$. This part is carried by the reinforcement between two and two pile caps, with a total width $2a$, and the weight per unit pile cap side length becomes $W_S = (W - W_P)/(2a)$. Thus, we get:

$$W_S = \frac{\gamma}{2a}\left(c^2 H - 1/3\left[\left(a+\frac{2}{\beta}H\right)^3 - a^3\right]\frac{\beta}{2}\right) \qquad (10)$$

The 3-D geometric model for the maximum soil weight carried by the reinforcement is shown in Figure 6.

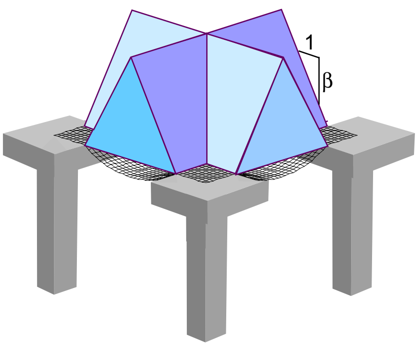

Figure 6: Maximum soil weight carried by the reinforcement

5.3.2 *Reinforcement tension*

The formula for deflection in equation (2) is accurate within 1 % for a deflection up to 10 % of the span length c-a, and is proposed used. However, the formula only includes the reinforcement elongation over the length c-a, the elongation over the pile cap is not included. It is therefore proposed to correct the strain according to

$$\varepsilon' = \varepsilon\left(1+\alpha\frac{a}{c-a}\right) \qquad (11)$$

where ε' is "corrected" strain, ε is actual strain in free span of reinforcement and α is stress ratio, range [0,1], defined below:

$$\alpha = \frac{\overline{T}_C}{T} \qquad (12)$$

Here ,

$\overline{T}_C$ is the average reinforcement tension over the pile cap width a

T is the reinforcement tension over free span length c-a

The reinforcement tension may be calculated similar to the Carlson method. Considering the equation for deflection, Eq. (2), and the elongation over the pile cap, Eq. (11), this gives the equation for the reinforcement tension:

$$T_S = \frac{W_S}{2}\sqrt{1+\frac{1}{6\varepsilon'}} = \frac{W_S}{2}\sqrt{1+\frac{1}{6\left(1+\alpha\frac{a}{c-a}\right)\varepsilon}} \qquad (13)$$

Observe that for α = 0, the span width does not enter the equation, only the weight and the strain.

6 REINFORCED EMBANKMENTS ON SOFT SOIL WITHOUT PILES

The calculation method used is mainly as prescribed in BS8006, involving the elements: direct sliding, foundation extrusion and internal and global stability.

The rotational stability is calculated according to a method prescribed by Kjærnsli et.al. (1956). The required tensile force in the reinforcement to get sufficient safety is calculated for all potential slip circles and the maximum required bond length/ anchoring length is found.

The foundation extrusion as prescribed in BS8006 seems to be very conservative for some problems (i.e. thick foundation layers). An additional method to calculate the bearing capacity is implemented, but is in the current version only checking the average bearing capacity for half the embankment. The next version is also going to include the possibility to define increased shear strength with the depth in the subsoil, which will also improve the method described in BS8006.

7 RUNNING REMBANK

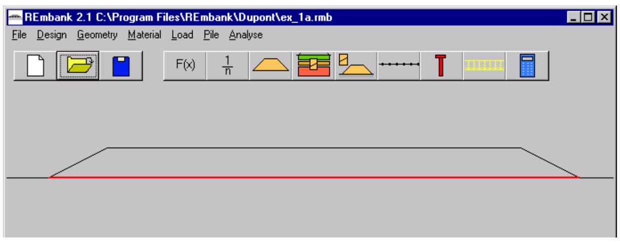

Figure 7: Main window showing selected geometry

The user specifies the geometry of the actual fill, Figure 7, eventually including the pile spacing and pile cap size for a piled embankment. Material parameters for fill and subsoil are also input parameters. The user may define partial factors or choose from default values. A product database includes necessary material data for reinforcements from different manufacturers, Figure 8.

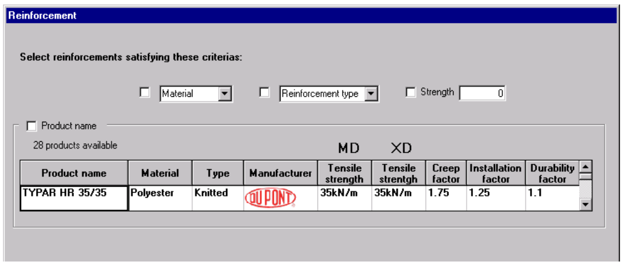

Figure 8: A product database is included

The program has three different methods for designing piled embankments with basal reinforcement, and one method for calculating reinforced embankments without supporting piles.

The stability of the fill is checked according to classical slip circle analyses as prescribed by Kjærnsli et.al. (1956) based on total stresses, Figure 9.

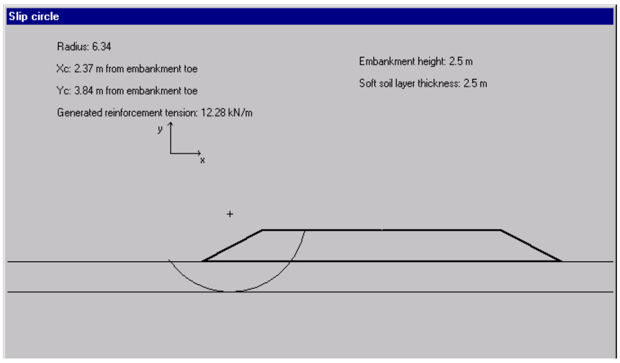

Figure 9: Rotational stability is checked automatically

The program calculates necessary design strength and deformation both along and across the embankment for each of the selected reinforcements in the product list, Figure 10. The calculated deformation, the allowed maximum strains and the characteristic design strength is based on the material data given by the manufacturers.

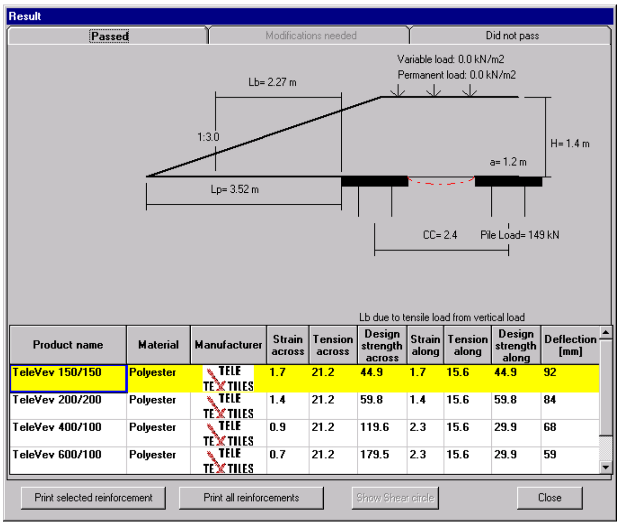

Figure 10: Result window

The program presents the results sorted below three flags in the result window:

– *Passed*: Reinforcement that may be used for the specified geometry.
– *Modification needed*: Reinforcements that did not fail according to strength and therefore may be used if e.g. the slope angle is reduced or a wrap around solution is introduced.
– *Did not pass*: Products that failed according to tensile strength.

The printout includes a full documentation of input values, calculation method used and results for all selected reinforcements.

8 CONCLUSIONS

There are several advantage for using REmbank in design:

1. Using the computer program is easy and, of course, time saving.
2. different geometry and calculation methods may be used.
3. calculates the required reinforcement design strength and find which reinforcements that satisfy this requirement.
4. predicts the strain and deflection of the reinforcement.
5. finds the *minimum* required bond length/anchoring length.
6. calculates the rotational stability, i.e. it is not necessary to use another application to check the stability. REmbank also calculates the required bond length for all possible slip circles that intersect the reinforcement close to the edge.
7. all required reinforcement material data is included in the product database, and the program uses automatically the right strength, stiffness and maximum allowable strain.
8. gives a full documentation printout.
9. The user may easily compare the design according to the different calculation method and load combinations, or optimize the embankment geometry, pile spacing and pile cap size.

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