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Polyester fabric as reinforcement in soil

Textile polyester comme renforcement de sol

Résumé Du textile a été utilisé en Suède pour accroître la stabilité de remblais routiers construits en argile tendre et en tourbe. Le renforcement en textile augmente le couple de rétention en ce qui concerne un défaut circulaire ou une surface de rupture passant sous le pied du remblai.

Du textile a également été utilisé comme renforcement derrière des murs de soutènement ou des culées. Le textile peut être soit solidarisé des éléments de mur, soit placé librement dans le remblai, afin de réduire la pression latérale des terres agissant sur le mur. Des méthodes sont présentées dans l'article, lesquelles permettent de calculer la pression latérale des terres, la tension du textile, l'espacement des couches et la longueur des zones d'ancrage.

Introduction

Polyester fabric has been used in Sweden as reinforcement to increase the bearing capacity of road embankments on soft clay or peat. The fabric has been placed in horizontal layers at the bottom of the embankments to prevent failure along cylindrical failure surfaces as illustrated in Fig. 1a.

The fabric can also be placed in horizontal layers behind retaining walls constructed of prefabricated concrete elements as shown in Fig. 1b. The fabric can either be tied to the wall elements or be placed loose in the soil. The lateral earth pressure will in both cases be low and the wall elements can be made very light. Fabric when used as reinforcement in soil offers many advantages in comparison with other methods as described in this article.

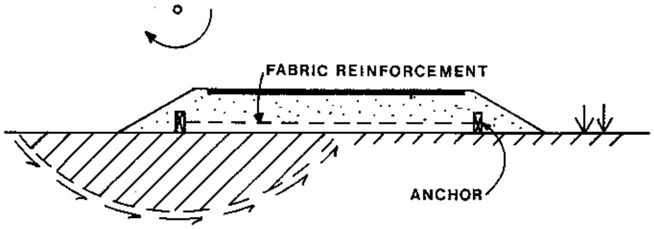


Fig. 1a Use of fabric reinforcement behind retaining wall

Road Embankments

The principle of reinforced earth is not new. Fashines were used extensively in Sweden already in the 17th century to increase the bearing capacity of embankments constructed on soft clay and peat. Also steel rods (ϕ 25 mm) has been used as reinforcement in soil to improve the stability of slopes and the bearing capacity of road embankments e.g. in the Göta River Valley (Wager, 1968).

Polyester fabric was used for the first time in Sweden as reinforcement in soil at Nol located about 40 km north of Gothenburg in the southwestern part of Sweden to increase the stability of an embankment behind a bridge abutment which was supported on point bearing timber piles. The shear strength of the underlying very soft clay was low. The piles had to be vertical because the bedrock sloped steeply towards the bridge. The embankment was reinforced by three layers of fabric (Fodervävnader Teknisk Väv 600) as indicated in Fig. 2 to resist the lateral earth pressure in the embankment and to increase the stability of the slope. The layers were spaced 30 cm (12 in) apart. Inclinometer tubes was installed in the embankment and in the underlying soft clay to measure the lateral displacements of the embankment. Settlements, pore water pressures and earth pressures were also measured. The lateral displacements of the embankment have been relatively small (Massarsch and Holtz, 1976).

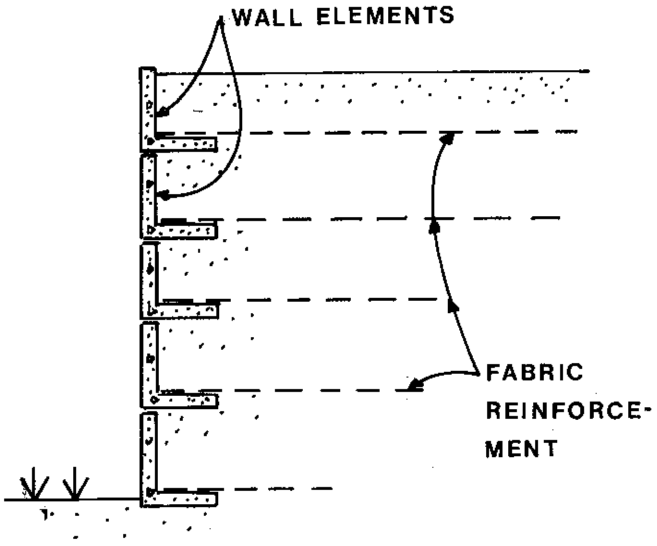


Fig. 1b Use of fabric reinforcement in road embankment

Cloth has also been used as reinforcement in a road embankment (Lismavägen) about 20 km south of Stockholm. The embankment was constructed on a very soft organic clay with an undrained shear strength less than 10 kPa. The stability of the embankment with respect to a circular failure surface was close to 1.0. It was thus expected that the lateral displacement and the settlement of the embankment due to creep in the underlying organic clay would be large if the embankment was not strengthened. Polyester fabric was therefore placed in one layer at the bottom of the embankment at two test sections. Inclinometer tubes were installed at the two sections so that the lateral displacements of the embankment could be measured. The measured lateral displacements have been small (less than 1 à 2 mm).

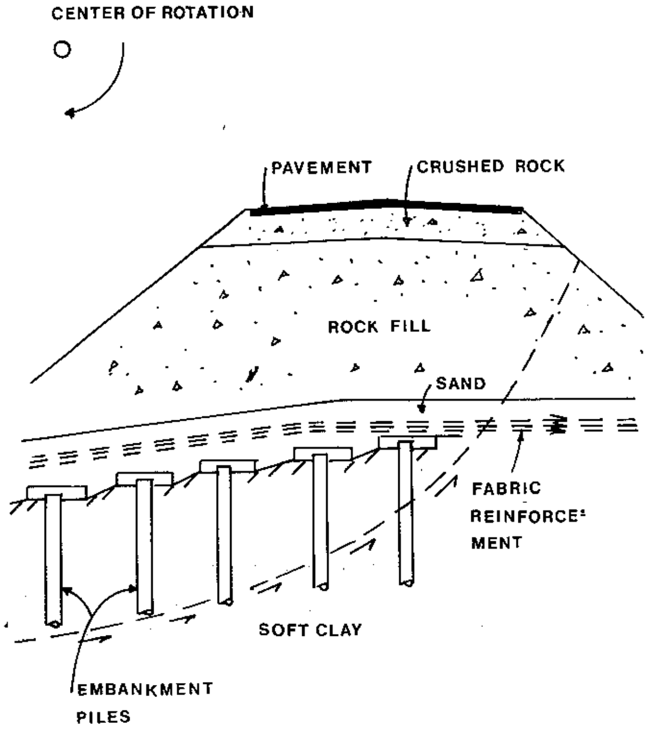


Fig. 2 Polyester fabric as reinforcement in an embankment at Nol.

The load transfer between soil and fabric has been investigated in the field by Lindskog and Eriksson (1974). A 0.3 m thick sand layer was placed on a 1.0 m wide and 8.0 m long strip of fabric (Fodervävnader Teknisk Väv 638). Sand bags were placed on the sand after it has been compacted by a bulldozer. The weight of the sand and the sand bags corresponded to a 0.8 m high embankment with a unit weight of 1.8 t/m^3. The fabric was prestretched 1% before the test.

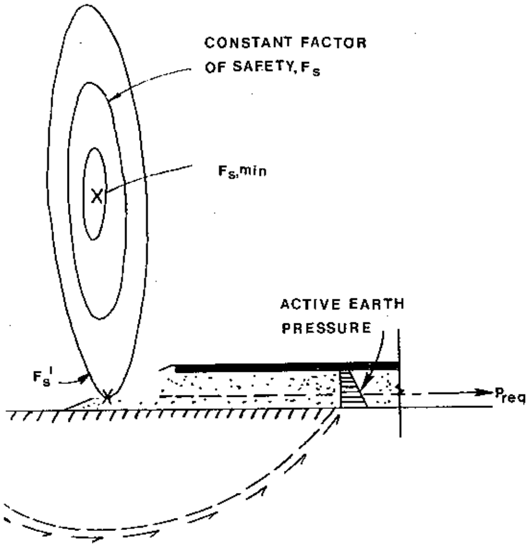


Fig. 3 Calculation of the stability of a road embankment.

The fabric was loaded in tension by pulling the free end of the strip. The resulting axial deformation of the fabric was measured using magnets glued to the surface of the fabric. The spacing of the magnets was 25 cm at the free end. The measured friction coefficient (tg ϕ_a) with respect to the surrounding soil (sand) was 0.57 to 0.60 which corresponds to a friction angle of 29.5 to 31.0 degrees. At the maximum applied load (51 kN/m) the total stretch of the fabric was about 250 mm or 3.1 percent of the total length of the strip (8.0 m). The average force in the fabric was 25.5 kN/m. The ultimate tensile strength of the cloth is about 100 kN/m.

Design Principles The stability of an embankment reinforced with polyester fabric can be evaluated as illustrated in Fig. 3. The stability of the embankment without the reinforcement is first investigated for different assumed failure surfaces and for different assumed centers of rotation. The calculated factor of safety F_s is shown as a function of the location of the center of the assumed failure surface. The point that corresponds to the minimum factor of safety $F_{s,min}$ and thus to the critical failure surface is normally located above the toe of the embankment. It is often assumed in the calculations that the lateral earth pressure in a vertical plane through the embankment corresponds to active Rankine earth pressure as indicated in Fig. 3 and that failure occur along a plane which is inclined the angle ($45^o + 1/2\ \phi'$) with the horizontal to simplify the calculations. Tables and computer programs are available for the calculation of the location of the critical failure surface and the factor of safety.

The fabric increases the restraining moment and lowers the center of rotation of the critical failure surface. The maximum restraining moment of the fabric is limited by the tensile strength of the fabric. The required restraining moment M_{req} and the force P_{req} ($M_{req} = a \cdot P_{req}$) which are required to increase the factor of safety from $F_{s,min}$ to a satisfactory value (1.3 à 1.5) can then be calculated. The critical failure surface of the unreinforced embankment can be used in the analysis. The force in the fabric reinforcement is equal to M_{req}/a where a is the moment arm with respect to the assumed center of rotation as shown in Fig. 3.

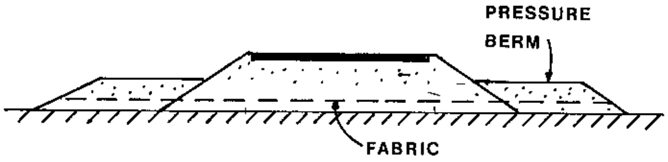
It is necessary that the factor of safety F_s^1 for the embankment without reinforcement is larger than 1.3 to 1.5 with respect to a center of rotation which is located at the level of the reinforcement. It is not possible to reach a factor of safety for the reinforced embankment which is larger than F_s^1 since the maximum possible effect of the reinforcement is to lower the center of rotation to the level of the reinforcement.

The quality of the fabric (tensile or creep strength) and the number of layers which are required to reach the desired factor of safety (1.3 to 1.5) depend on the load that can be allowed in the fabric per unit width. This in turn is dependent of the type of loading (dead or live load), the settlements and lateral deformations that can be allowed and the strength and deformation properties of the fabric. A relatively small axial deformation is required to mobilize the shear resistance of the soil along the fabric in comparison with elongation of the fabric at the ultimate or creep strength of the fabric.

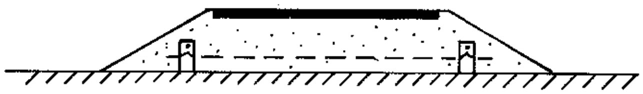
Materials with a high creep rate cannot be used to carry a dead load e.g. the weight of the embankment. The lateral deformations and the settlements of the embankment will in that case be excessive and longitudinal cracks may develop in the direction of the embankment. It is evident that a nonwoven material cannot be used as reinforcement due to the large deformations of the material even at low load levels. It is recommended that the factor of safety for the embankment $F_{s,min}$ without reinforcement should be at least 1.0 with respect to the weight of the embankment excluding live loads (traffic load) and that a woven material which is affected by creep can only be used to carry live loads and to increase the factor of safety with respect to dead loads from 1.0 to a satisfactory value (1.3 à 1.5).

Some uncertainty exists about the function of woven materials as reinforcement when the sensitivity of the underlying clay is high since such clays often are brittle. The failure strain can be as low as 1 to 3 percent. The peak shear strength of the clay may be exceeded before the fabric begins to function. The restraining effect of the fabric reinforcement can then not be added directly to the bearing capacity of the clay.

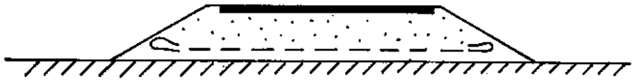
The anchorage of the fabric reinforcement is important so that the tensile or creep strength of the fabric can be utilized. Three methods are shown in Fig.4. In Fig.



(a) PRESSUR BERMS



(b) ANCHOR BLOCKS



(c) FOLDING OF FABRIC

Fig. 4 Anchor systems

4a pressure berms are used which provide the normal pressure required to mobilize tensile or creep strength of the cloth. The length of the anchor zone is measured from the intersection of the critical failure surface and the reinforcement as shown. The pressure berms also function as counter weights and increase further the stability of the embankment. The pressure berms increase also the settlements of the embankment due to the added weight.

Separate anchor blocks are used in Fig. 4b. The available anchor force ought to correspond at least to passive Rankine earth pressure from the bottom of the anchor blocks to the surface of the embankment when this height is less than three to four times the height of the anchor blocks. It might also be possible to develop sufficient anchorage by folding the cloth over a wedge of soil (Fig. 4c). Some uncertainty exist about the function of the anchors shown in Figs 4b and 4c. A relatively large axial deformation, 10 to 20% of the height of the anchor block, will likely be required to mobilize passive Rankine earth pressure. This deformation can be reduced by preloading. Only pressure berms have so far been used in Sweden.

Retaining Walls

A fabric reinforced wall is shown in Fig. 1b. The fabric which has been placed in horizontal layers can either be tied to the L-shaped wall elements which then function as anchors or be placed free in the soil.

Lateral earth pressure The fabric reinforcement reduces the lateral earth pressure behind the wall elements in comparison with a conventional retaining wall. The reduction of the lateral earth pressure can be evaluated for example from triaxial tests where disks of the fabric are placed horizontally as reinforcement in the samples. Test data show that the restraining effect from the fabric reinforcement is equivalent with that of a confining pressure equal to the force per unit width in the reinforcement divided by the spacing of the layers (F/D).

The lateral earth pressure on a wall with fabric reinforcement has been calculated in Appendix A. The analysis shows that the bearing capacity increases rapidly with increasing distance from the wall elements (Fig. A 2). At a distance equal to the spacing of the reinforcement the bearing capacity will be approximately ten times that just behind the wall at $\phi_a = 30^\circ$ and $K_b = 0.5$ (σ_h/σ_v). It can be seen from Fig. A_2 that the ultimate bearing capacity is affected even by small changes of ϕ_a and K_b. An increase of the friction angle ϕ_a by 5 degrees or a change of the earth pressure coefficient K_b from 0.5 to 0.4 will double the bearing capacity at the same distance from the wall. The lateral earth pressure acting on the wall elements will be small since primarily the weight of the soil located above a layer is effective. The weight of the soil located at a distance exceeding the spacing of the fabric reinforcement and any external loads will therefore be carried directly by the fabric reinforcement.

The wall elements can be designed for a uniform lateral earth pressure equal to $\gamma g D K_a$, where D is the spacing of the fabric reinforcement and K_a is the Rankine coefficient for active earth pressure $K_a = \frac{1-\sin\phi'}{1+\sin\phi'}$. The fill behind the bottom element will in that case be able to carry the weight of the overlying soil ($H\gamma g$) at $K_b = 0.5$, $\phi_a = 30$ as can be seen from Fig. A 2 when the height of the wall (H) is less than 10 D and the base of the wall elements (B) is equal to D, the spacing of the fabric reinforcement. When the height of the wall exceeds 10 D or the external loads are high the bottom wall elements had to be designed for a higher lateral earth pressure than $\gamma g D K_a$. The top wall element, however, must be designed to resist active Rankine earth pressure and the lateral earth pressure from any external load.

Spacing of fabric The spacing of the reinforcement should be such that the tensile or creep strength of the fabric is not exceeded. It is proposed to design the wall for a uniform lateral earth pressure equal to that shown in Fig. 5. This lateral earth pressure corresponds to that of an anchored sheet pile wall. The total lateral earth

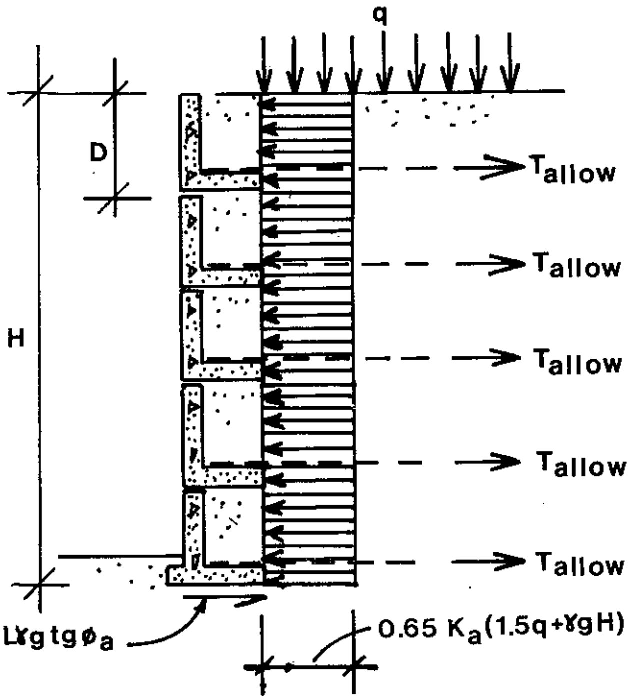


Fig. 5 Spacing of fabric reinforcement.

pressure [$0.65\ H\ K_a\ (1.5\ q + \gamma g\ H)$] which is about 30% larger than the active Rankine earth pressure is resisted by the fabric reinforcement and the friction resistance ($LH\gamma g\ tg\phi_b$) along the base of bottom element. The maximum spacing of the fabric layers can then be calculated from

$$D = \frac{T_{allow}}{0.65\ K_a(1.5\ q + \gamma gH) - L\gamma g\ tg\ \phi_b} \qquad (1)$$

where T_{allow} is the allowable load in the fabric.

The active Rankine earth pressure coefficient $K_a = (\frac{1-\sin\phi'}{1+\sin\phi'})$ varies with the angle of internal friction (K_a is equal to 0.33, 0.27 and 0.22 at $\phi' = 30$, 35 and 40 degrees, respectively). It is proposed to use $K_a = 0.3$ and $\phi' = 30$ degrees in the design when the backfill material consists of sand or gravel. At e.g. $q = 0$, $B = D$, $K_a = 0.3$ and $\phi_a = 30$ degrees.(Eq.(1) is simplified to

$$D^2 = \frac{T_{allow}}{\gamma g\ (0.20\ n - 0.58)} \qquad (2)$$

where n is the number of wall elements ($n = \frac{H}{D}$). At $\gamma = 1.8$ ton/m^3 and $T_{allow} = 25$ kN/m then D = 2.51 m, 1.82 m and 1.50 m at n= 4, 5 and 6, respectively. A 9 m high wall can thus be constructed if the height of the wall elements is 1.50 m (n = 6). The corresponding maximum height is 10 m when the height of the wall elements is 1.0 m (n = 10). The maximum height of the wall is not affected much by the height of the wall elements and by the spacing of the fabric reinforcement.

Length of fabric reinforcement The length of the fabric must be sufficient so that the tension in the fabric can be transferred to the surrounding soil. The force in the fabric reinforcement reaches a maximum at approximately the point where the reinforcement intersects the failure surface indicated in Fig. 6 which is inclined ($45 + \phi'/2$). The direction of the shear stress along the fabric will probably change at this point.

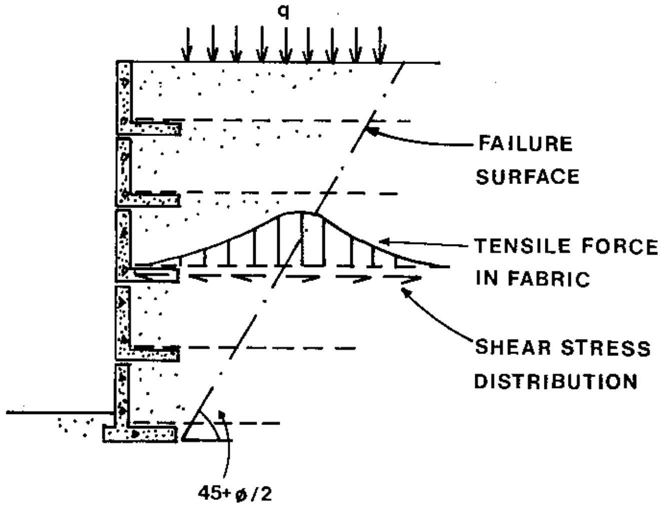


Fig. 6 Shear stress distribution along fabric reinforcement.

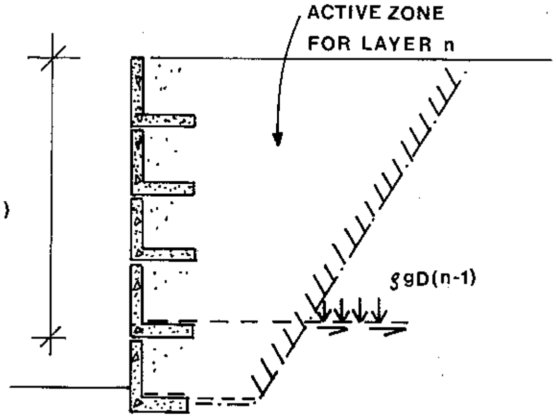


Fig. 7 Active zone for the bottom layer.

In order to develop an axial load in the fabric that corresponds to the allowable (T_{allow}) the length of the anchor zone had to be sufficient. Only part of the back fill located outside the active zone of the following layer should be included in the calculations. In Fig. 7 is shown the active zone for the bottom element. At failure along a rupture surface passing below and behind the fabric reinforcement for the bottom element only the soil located within the active zone will be affected. The fabric reinforcement of wall elements located above the bottom element will not be activated within this zone. The fabric must extend outside this active zone to be effective. The anchor length outside the active zone of the layer below can be calculated from the relationship

$$L_{n-1} = \frac{1.3\ T_{allow}}{\gamma g\ D(n-1)\ tg\ \phi_a} \qquad (3)$$

where ϕ_a is the friction angle between the cloth and the soil and D(n-1) is the depth below the ground surface. It has thus been assumed that a load equal to 1.3 T_{allow} had to be transferred to the surrounding soil. (The factor 1.3 is a safety factor.)

At $\gamma = 1.8$ ton/m^3, $\phi_a = 30^0$, Tallow = 25 kN/m, D = 1.5 m and B = 1.5 m then the required length of the anchor zone will be 2.08 m, 1.04 m, 0.69 m, 0.52 m, 0.42 m and 0.35 m when the depth is 1.5 m, 3.0 m, 4.5 m, 6.0 m, 7.5 m and 9.0 m, respectively. The length thus decreases with increasing depth. In the case the total force in the fabric reinforcement ($n\ T_{allow}$) exceeds the net total lateral earth pressure

$$n\ T_{allow} > 0.65\ K_aH(1.5q + \gamma qH) - B\gamma g\ tg\ \phi_a \qquad (4)$$

it is not necessary that all the layers satisfy the requirement that they extend beyond the active zone of the following layer (Fig. 8).

The total force in the layers which extend beyond the active zone should, however, exceed the net total lateral earth pressure $[0.65\ K_a(1.5\ q + \gamma gH) - B\gamma g\ tg\ \phi_a]$.

The length of the fabric reinforcement had to be checked with respect to other possible surfaces besides those that correspond to active Rankine earth pressure. It is e.g. important to check the stability of the wall with respect to a failure surface passing behind the fabric reinforcement as illustrated in Fig. 9. Failure has been assumed to occur along a plane and a spiral shaped rupture surface. The wall will be stable with respect to the assumed rupture surfaces if the resultant R is located to the left of the center of the logarithmic spiral.

When the fabric reinforcement is not tied to the wall the length of the anchor zone just behind the wall elements should be sufficient to transfer a force equal to $1.3\ T_{allow}$ (kN/m) to the fabric as illustrated in Fig. 9. The length of the anchor zone will be equal to the width (B) of the wall elements. If it is assumed that the friction resistance is proportional to the weight of the overlying soil (DB γg) then

$$2\ DB\ \gamma g\ tg\ \phi_a = 1.3\ T_{allow} \qquad (5)$$

The minimum length of the anchor zone will be less than that calculated from Eq. (5) because the normal pressure will be larger than the weight of the overlying soil.

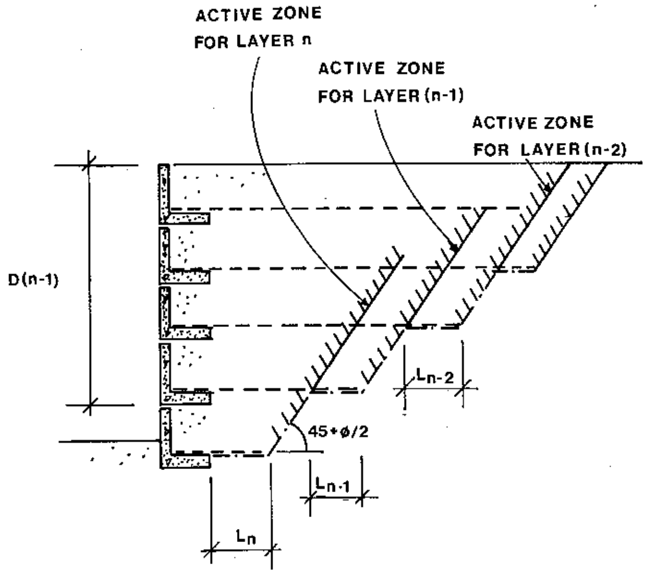


Fig. 8 Required anchor length.

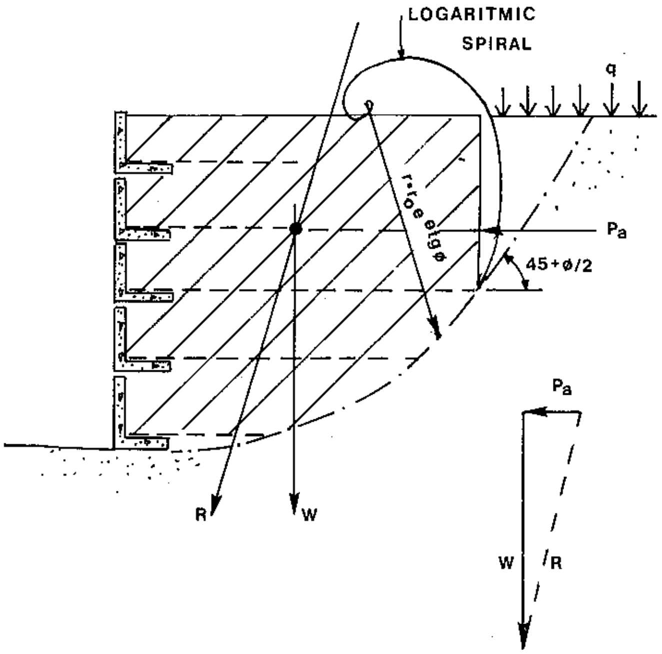


Fig. 9 Stability of the wall with respect to a failure surface extending behind the fabric reinforcement.

Appendix A

Lateral Earth Pressure Behind Retaining Walls Reinforced with Fabric.

The lateral earth pressure acting on a retaining wall where the backfill has been reinforced with fabric is small. Part of the weight of the soil will be carried by the friction along the fabric and the surrounding soil. A section through a fabric reinforced retaining wall where the vertical pressure at the distance x from the wall elements is equal to σ'_v is shown in Fig. A 1. The corresponding friction resistance along the fabric will then be $\sigma'_v\ tg\ \phi_a$ where ϕ_a is the friction angle of the soil with respect to the fabric. Test results indicate that the friction angle ϕ_a for a woven material (Fodervävnader Teknisk Väv 600) and sand is equal to the angle of internal friction and that a very small lateral displacement is sufficient to mobilize the maximum shear resistance $\sigma'_v\ tg\ \phi_a$ of the soil. The bearing capacity is increased to $(\sigma'_v + d\sigma'_v)$ at the distance $(x + dx)$ from the wall because of the mobilized friction resistance along the fabric. It has been assumed in the calculations that the increase of the bearing capacity corresponds to that from an increase of the lateral confining pressure equal to the friction force $(2\ \sigma'_v\ dx\ tg\ \phi_a)$ between x and $(x + dx)$ divided by the distance between two adjacent layers D. It has thus been assumed that maximum friction resistance develop on both sides of a single layer of fabric. The resulting increase of the bearing capacity $d\sigma'_v$ can then be calculated

$$d\sigma'_v = \frac{2\,\sigma'_v\,dx\,\mathrm{tg}\,\phi_a}{D\,K_b} \tag{A 1}$$

where K_b is an earth pressure coefficient. This earth pressure coefficient K_b will be larger than the Rankine coefficient for active earth pressure. The triaxial tests indicate that $K_b = 0.5$ represents a lower limit.

The distribution of the vertical pressure and the bearing capacity can then be calculated as a function of the distance x from the wall

$$\sigma'_v = \sigma'_{vo}\ e^{\frac{2x\ \mathrm{tg}\ \phi_a}{DK_b}} \tag{A 2}$$

where σ'_{vo} is the vertical effective pressure at the wall. At $\phi_a = 30$ degrees Eq. (A 2) can be simplified to

$$\sigma'_v = \sigma'_{vo}\ e^{2.3x/D} \tag{A 3}$$

The vertical pressure is shown in Fig. A 2 as a function of the distance from the wall at $\phi_a = 25^{\circ}$, 30°, 35° and 40° and at $K_b = 0.4$ and 0.5. It can be seen that the vertical bearing capacity of the back fill material increases very rapidly with increasing distance from the wall. In the case the wall elements are designed for a lateral earth pressure equal to 10 kPa then a vertical pressure of 200 kPa can be allowed at $\phi_a = 30^{\circ}$ at a distance equal to the height of the wall elements in the case the tensile or the creep strength of the fabric is sufficient.

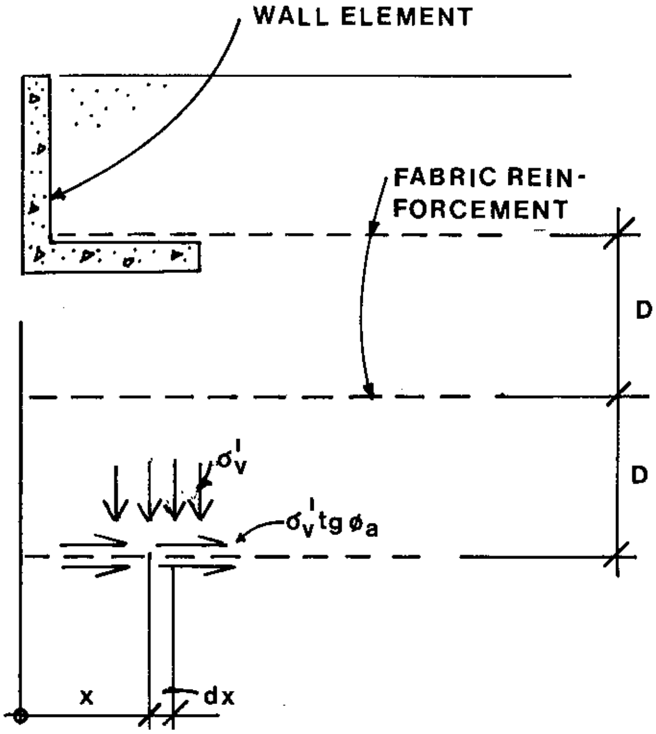


Fig. A 1. Stress distribution behind a retaining wall reinforced with fabric.

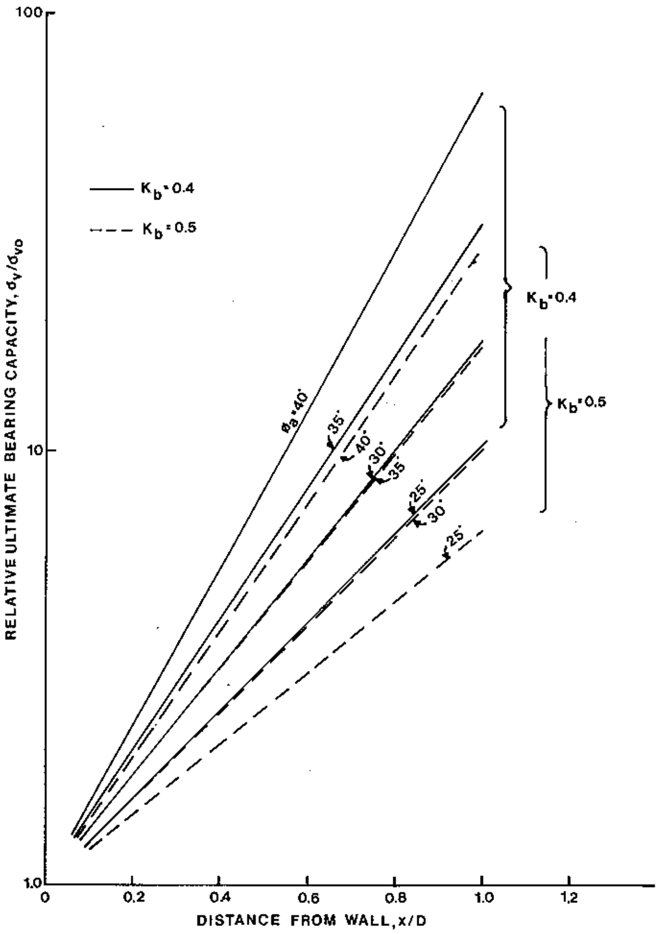


Fig. A 2. Relative ultimate bearing capacity of a retaining wall reinforced with fabric.

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