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Fabric reinforced earth retaining walls - Results of model tests

Murs en terre armée par des textiles - Résultats d'essais sur modèles

Le fonctionnement des murs renforcés par des textiles a été étudié par une série d'essais. Le modèle du mur avait une hauteur de 672 mm et une longueur de 1800 mm. On pouvait tourner le mur autour de son bord intérieur. Le mur était ancré en arrière avec le textile placé horizontalement en trois niveaux. Les éssais montrent qu'avec le remblai et la densité utilisés on peut obtenir un mur en équilibre avec une longueur du textile, d'environ 20 cm ce qui correspond à environ 30% de l'hauteur du mur. Pour obtenir un facteur de sécurité au renversement 1,3 - 1,5, une longeur de textile de 26-32 cm est nécessaire, ce qui correspond à la moitié de la hauteur du mur. Un modèle de calcul a été établi et un bon accord a été obtenu entre les résultats de calcul et les résultats de mesures concernant aussi bien les mouvements dans le remblai que les forces d'ancrage.

INTRODUCTION

The Swedish Geotechnical Institue (SGI) has performed a series of model tests with a fabric reinforced earth retaining wall in cooperation with AB Fodervävnader, Borås, Sweden. A fabric reinforced retaining wall is a retaining wall anchored by layers of fabric on different levels in the backfill behind the wall. The aim of the tests was to study the behaviour of this type of reinforced earth retaining walls and to develope a design method for such a construction.

TEST EQUIPMENT

Model wall

The tests were performed in the laboratory. The retaining wall was made of four wooden planks each of the height 168 mm and a thickness of 58 mm. This construction was chosen in order to imitate a wall made of precast concrete elements. The elements were placed upon each other in a frame of U shaped steel beams to a total height of 672 mm. The total length of the model wall was 1800 mm. At the lower edge of the wall a horizontal axis was mounted. The wall could be rotated around this axis by two screw anchors mounted in the upper part of the frame. The three other walls of the model box were fixed. A window was mounted beside the retaining wall in one of the side walls. Through this window the movements in the backfill could be studied and measured.

Fabric

The fabric was a woven polyester No 600 from AB Fodervävnader. The stress-strain relationship for the fabric is as follows: at 1% strain the force in the fabric is 500 N/m, at 1.5% strain 1700 N/m and at 2% strain 4200 N/m. The tensile strength of the fabric is about 65000 N/m. The fabric was placed in three layers between the four elements and rigidly fixed on the front side of the retaining wall. The fabric was placed in the sand when the backfill had reached the upper level of one wall element. The sand was then poured in layers over the fabric as can be seen below.

Backfill

The backfill used was a uniform medium fine dry sand from the island of Bornholm, Denmark (Silver sand No 55) with grain size between 0.2 and 1.0 mm. In order to get a uniform density the sand was poured from a certain height into the model box. The density used was 1.59 t/m^3 corresponding to a relative density of 0.70. The angle of internal friction of the sand at this density was determined by triaxial tests to 40^o. For the actual stress conditions the angle of internal friction should be increased by 4^o according to Bjerrum and Kumeneje (1961). Consequently an angle of internal friction of 44^o has been used in the analysis of the test results. According to previously performed tests (Holtz, 1973) the angle of friction between the fabric and the sand has been assumed to be equal to the angle of internal friction of the sand.

Instrumentation

Two vertical rows of four dial indicators were used to measure the movements of the retaining wall (Fig 1). The indicators were placed in the middle of each wooden element. The necessary forces to hold or push (rotate) the wall was measured by transducers mounted in the two screw anchors (Fig 1). These transducers could measure both compression and tension forces. (The earth pressures against the wall elements were too small to be directly measured by existing equipment.) The total movement and the extension in the fabric were measured by a magnetic sensor inserted in a plastic tube buried in the sand. This sensor indicated the movement of small magnets glued to the fabric. (Fig 1). The total movement of the backfill was measured on steel plates placed in the sand at different levels and at different distances from the retaining wall (Fig 1). These measurements were performed after the termination of each test. The movement of the sand could also be observed through the window in the side wall by placing thin vertical and horizontal coloured sand layers close to the window. The occuring failure surfaces could also be observed through the window.

PERFORMED TESTS

Five model tests have been performed, four with fabric and one reference test without a fabric. At each test the length of the fabric has been the same in the three fabric layers. The lengths of fabrics have been chosen to 275, 330, 420 and 1000 mm.

In all tests the wall was rotated around the horizontal axis through the base of the wall. The rotation was carried out in small steps until a constant force necessary to rotate the wall was reached. At each step forces and deformations were measured and the movement in the sand was followed and registrated at the side wall window.

TEST RESULTS

The fabric was not pre-stressed at the installation but the filling of sand caused minor movements of the wall. The movements were 1-2 mm. These movements correspond to an extension of the fabric of 0.2-0.8% or a force in the fabric of about 200 N/m.

At the first test, No 1, performed as a pilot test, the length of the fabric was 1000 mm. At the end of the test the movement of the top of the wall was 40 mm. From the extension measurements in the fabric it could then be seen that only 500-550 mm of the fabric had been active anchors. In the rest of the fabric no extension was measured. The maximum movement in the middle layer of fabric was 9 mm corresponding to an extension of 1.0% of the active length of fabric and a force of about 300 N/m.

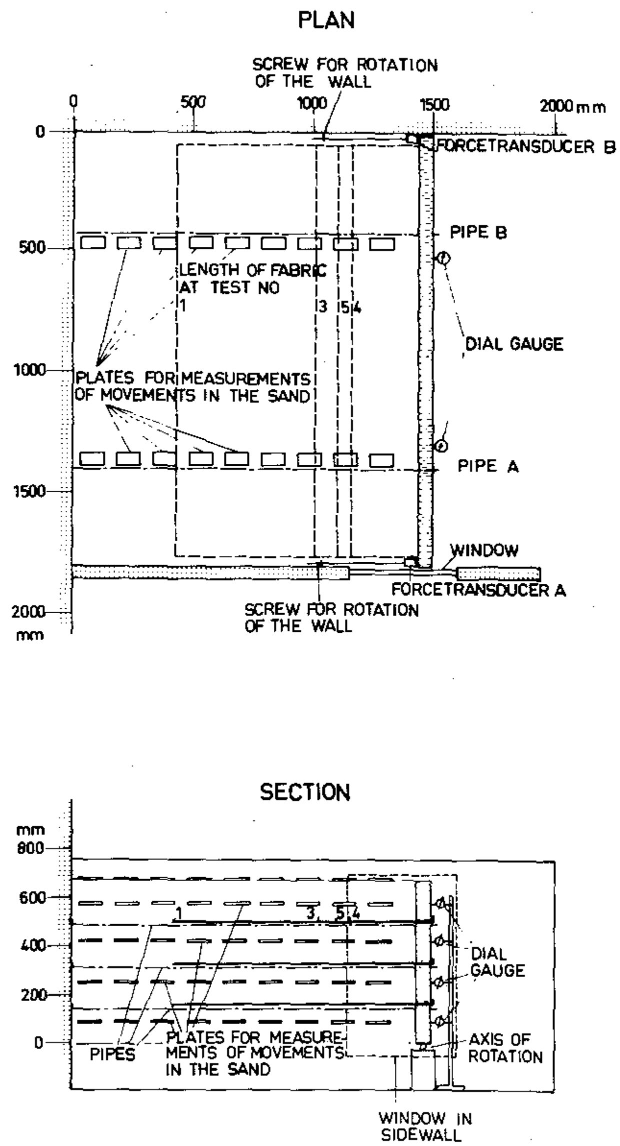
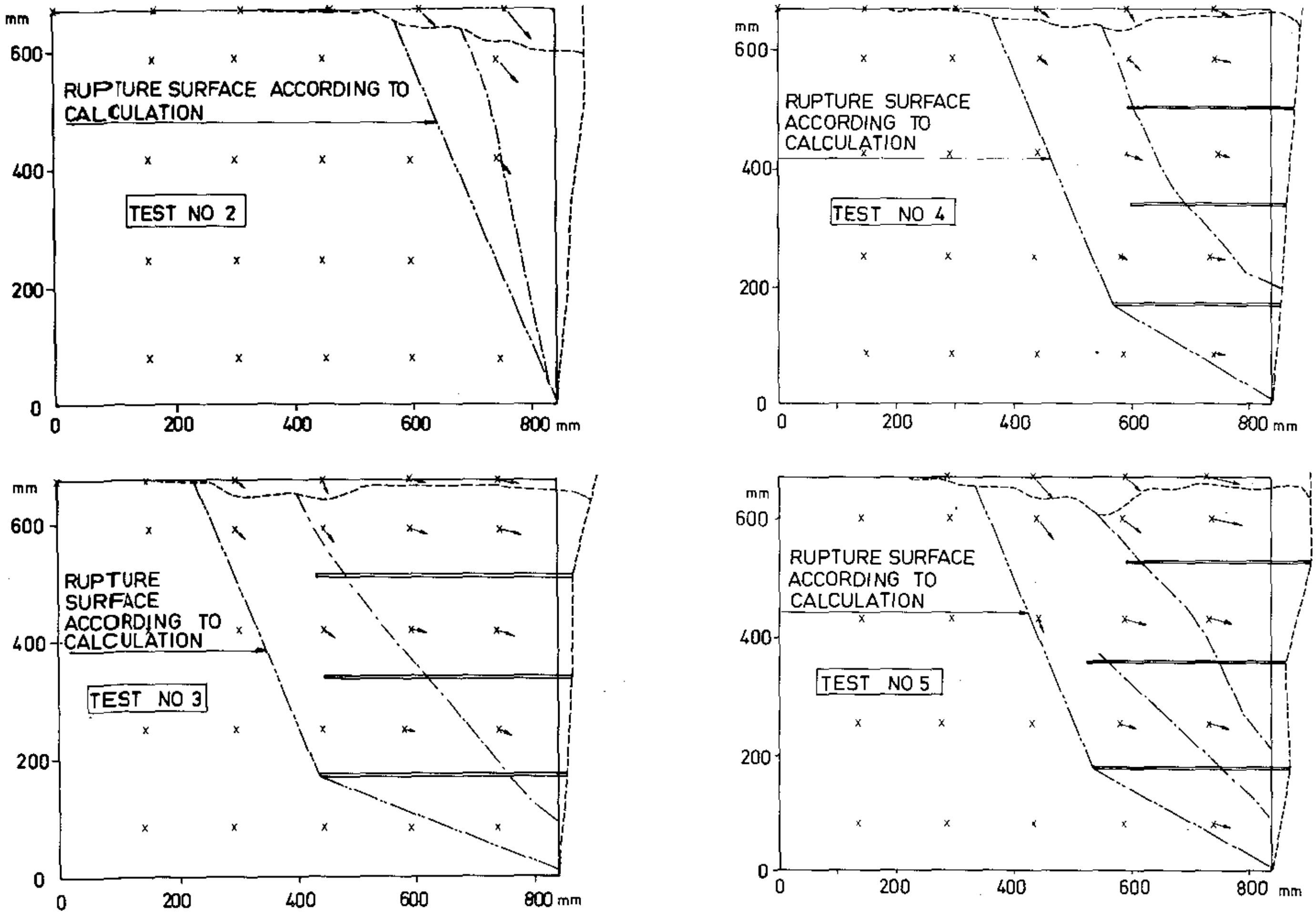


FIG 1. Plan and section of model box.

Test No 2 was performed as a reference test without any fabric. Test number 3, 4 and 5 were performed with 420, 275 and 330 mm length of fabric respectively. The test result is shown in Fig 2. In the figure is shown the position of the wall and the surface of the sand before and after the rotation of the wall. Furthermore the measured movement vectors of the steel plates in the sand and the observed rupture surfaces are shown. Finally the failure surfaces according to calculations are shown.

The result of the test without a fabric shows an inclined plane rupture surface through the axis of rotation. The angle between the failure surface and the horizontal was 45 + $\phi/2$ degrees. At the tests with fabric the



LEGEND

- x STEEL PLATE BEFORE ROTATION OF THE WALL
- ↘ MOVEMENT OF STEEL PLATE IN ACTUAL SCAALE
- ▭ FABRIC AFTER ROTATION OF THE WALL
- —— POSITION BEFORE ROTATION OF THE WALL
- - - - POSITION AFTER ROTATION OF THE WALL
- –·–· RUPTURE SURFACE OBSERVED THROUGH THE SIDEWINDOW

FIG 2. Observed movements and rupture surfaces and calculated failure surfaces at test No 2-5.

measured extension in the fabric pieces variated between 0 and 1.6%. Due to the accuracy of these measurements the calculated extensions are somewhat uncertain.

The measured forces in the anchor screws of the wall are shown as a function of the wall rotation in Fig 3. From this figure it can be seen that at the test without a fabric the measured anchor forces were positive. That means it was necessary to support the wall to prevent it from overturning. At all tests with fabric reinforcements the measured anchor forces were negative, which means that the walls were stable. The difference in measured anchor force in the transducers A and B is mainly due to friction between the sand and the side wall close to the transducer B as the sand there was filled against a rough concrete wall.

ANALYSIS OF RESULTS

Initial stage

The measured anchor force in transducer A (at the window side wall) transformed to force per meter wall after filling but before rotation of the wall was at the test without

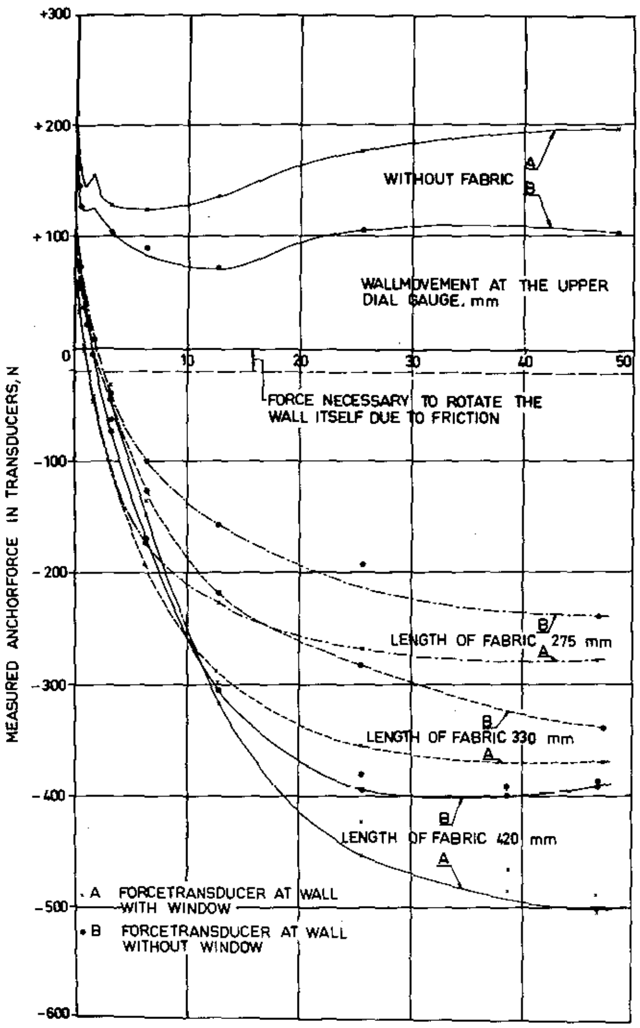


FIG 3. Measured anchor forces as a function of wall rotation.

a fabric 235 N/m. The calculated force according to earth pressure at rest is 325 N/m. The difference can be explained by the above mentioned movement of the wall during filling.

The measured anchor forces at the tests with fabric reinforcements were 215, 180 and 150 N/m respectively (test number 3, 4 and 5). The differences between tests without and with fabric are 20-85 N/m. These forces have been taken by tension in the fabric. The overturning forces have consequently been reduced already during filling.

Failure stage

The measured anchor force at a rotation of the wall giving active earth pressure is 160 N/m at the test without a fabric. This can be compared to the calculated active earth pressure with consideration of an assumed wall friction of 30°. The calculated force corresponding to active earth pressure is 170 N/m. Calculated and measured forces agree quite well.

Total stability

At test Nos 3-5, with fabric reinforcements, the anchor forces are negative, which means that it was necessary to apply a turning force to get the wall to rotate. By comparing the measured anchor force at the wall without a fabric with the anchor forces at the walls with fabric reinforcements the total overturning stability of the wall can be calculated. Such a calculation results in a factor of safety of 3.3 with 420 mm length of fabric, 2.2 with 330 mm and 1.8 with 275 mm. By a rectilinear extrapolation of the relationship between the factor of safety and the fabric length the factor of safety 1.0 is obtained with a length of fabric of about 210 mm. To get a factor of safety of 1.5 the necessary length of fabric is about 260 mm or 40% of the total height of the wall.

Calculated and measured anchor forces

As mentioned above the earth pressure was too small to make direct earth pressure measurements against the wall at different levels. To be able to compare measured and calculated forces a resultant of the earth pressure has been calculated. The calculations are based on the assumption that a plane failure surface is going through the axis of rotation as shown in Fig 4. On the upper part of a certain failure surface an active earth pressure zone is assumed. In cases when the failure surface is crossing a fabric the force in the fabric has been calculated in the following way.

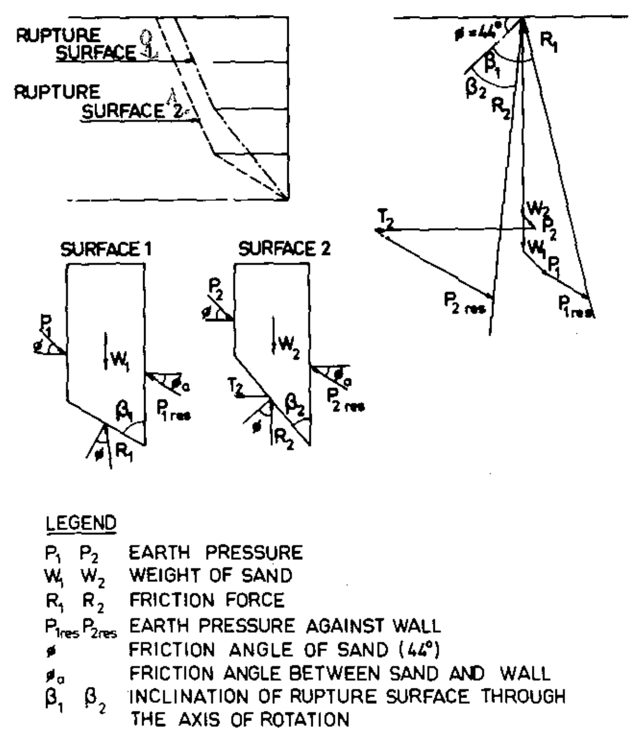


FIG 4. Principle of earth pressure calculations.

Before rotation of the wall the force in the fabric has been based on the measured extension in the fabric during filling. In case of rotation the force in the fabric has been calculated from the vertical stress and friction between fabric and sand. This force was assumed to act on the part of the fabric outside the failure zone. As the elevation of the resultant of the earth pressure not can be obtained by this calculation a certain earth pressure distribution has been assumed. The earth pressure was assumed to increase lineary with depth to the fabric top layer, and below that to be constant.

By these assumptions a force acting in the anchor screws of the wall could be calculated. The results of these calculations are shown in Fig 5. The agreement between calculated and measured forces is relatively good, especially for the longest pieces of fabric.

Length of fabric at a factor of safety of 1.3

At design of earth retaining walls normally a factor of safety of 1.3 is used on the tangent of the angle of internal friction of the soil. Calculated forces in the anchor screws of the wall according to the above described method with plane failure surfaces and with this factor of safety is presented in Fig 5. The necessary length of fabric at a factor of safety of 1.3 is about 32 cm corresponding to about 50% of the height of the wall.

Comparison with Lee's method

The design method proposed by Lee (1973) has also been applied to the test results. According to this method an active failure zone with a plane failure surface through the base of the wall is assumed. Besides a maximum force in the fabric outside the failure surface is used. The earth pressure is assumed to increase lineary down to 2/3 of the height of the wall and below that to be constant. Calculated forces according to this method is also shown in Fig 5. A modified method with forces in the fabrics based on the measured extensions in the fabrics has also been used and the results of this calculation are also shown in Fig 5. The conclusion of this comparison is that there is a substantial difference between calculated and measured forces. This design method, also the modified one, gives unsafe length of fabric.

Calculated failure surfaces and measured movements in the sand

For each test the calculated failure surface has been compared with observed failure surfaces and the measured movements in the sand. As can be seen from Fig 2 both the movement vectors in the sand and the settlements of the sand surface agree very well with the calculated failure surfaces. All failure surfaces could not be observed through the window in the side wall because they were outside the window. The small size of the side window is also the reason why some observed failure surfaces are not complete.

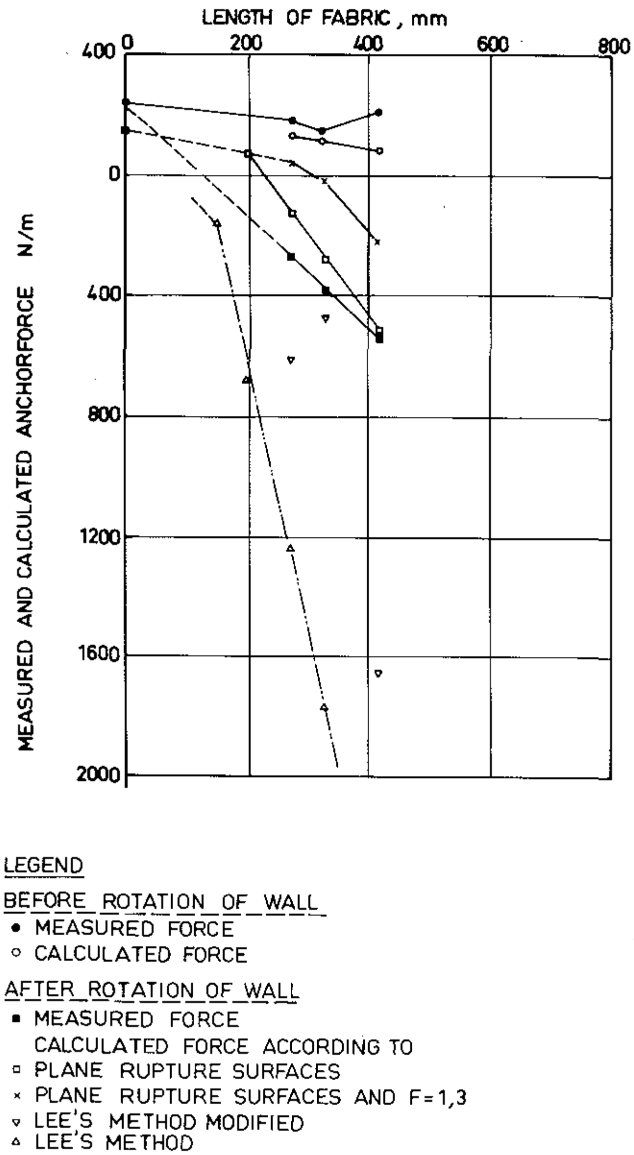


FIG 5. Comparison between calculated and measured anchor forces.

Movements of the wall

The tests performed have also shown that a certain movement of the wall is necessary to get equilibrium of the wall. This movement is about 3 mm (1-2 mm during filling and 1-2 during rotation) corresponding to 0.5% of the height of the wall. The necessary movement to mobilize maximum friction between the fabric and the backfill is about 30 mm or about 5% of the height of the wall. The movement of a specific wall is depending on among other things the compaction of the backfill, the necessary force in the fabric and the chosen factor of safety. The model tests have also shown that a minor creep between the fabric and the backfill has to be considered. The reduction of the anchor force due to creep is in the order of 5-10%.

PROPOSED DESIGN METHOD

According to the agreement between measured and calculated forces and movements the following design method is proposed for fabric reinforced earth retaining walls.

1. The angle of internal friction of the backfill is determined by laboratory tests or is chosen based on experiences.

   The friction between the fabric and the backfill can be chosen as the angle of internal friction of the backfill if this consists of sand. In other cases the friction between fabric and backfill has to be determined separately.

2. A factor of safety of 1.1-1.5 on the tangent of the angle of internal friction is chosen. Normally 1.3 could be applied.

3. The earth pressure resultant is calculated for some length of fabric according to the above mentioned method.

   Necessary length of fabric is obtained by interpolation between calculated earth pressure resultants and applied fabric lengths. The applied factor of safety is reached when the resultant is zero.

4. A control is made that the necessary force does not exceed the acceptable force in the fabric. The acceptable force is among other things depending on the acceptable deformations of the wall.

The proposed design method is valid for fabric reinforced earth retaining walls with the same length of fabric in all layers. The test results indicate that the upper layers of the fabric are not active when calculating the stability of the total wall. This means that the best design probably is one with longer fabric pieces in the upper layers. At design of a wall built of elements the stability of each element has to be checked too.

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