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Transmission of linear tensile forces by means of fabrics

La prise de forces de traction linéaires par des tissus de construction enterrés

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SYNOPSIS For super-lightweight construction in the form of composite fabric structures a flexible soil-buried anchorage made of fabrics has been developed. The underlying experimental tests as well as the analysis pattern and the practical utilization are being described. Experiences from the erection of experimental buildings are being given. The angular anchor developed is especially suitable to carry forces from air-supported structures into non-cohesive soil. If the limits of utilization of the present labour code are followed the pull-out tests required by now are no longer necessary.

INTRODUCTION

Geofabrics used as soil reinforcement have the task to give "tensile strength" to non-cohesive soils. The effect of soil reinforcement is based on the fact that primarily occurring soil deformations cause strains and thereby tensile forces, too, in the reinforcement by means of friction bond between fabric and soil. Thus the reinforcement guarantees the stability of the composite system. Reversing this principle of reinforcing it is possible to anchor a primarily tensioned fabric in the soil by utilizing the friction bond mentioned above.

TASK

Structures in which technical textiles in the form of structural fabrics (i.e. materials with well-defined requirements of high-quality and reliability) are used as the basic building element have been increasingly applied worldwide for about 30 years. Thus air-supported structures (in the following designated as ASS) have a central place in the field of composite fabric construction. Their space-enclosing membrane consists of structural fabrics. Their stability is acquired by a pressure difference between the enclosed air and the atmosphere outside the structure. The thus developing stabilizing pressure as well as the active lateral wind load result in tensile stresses inside the structure. Along the edge of the membrane they occur as linear tensile edge forces. For ASS of medium span (< 40 m) representing the majority of such structures in the German Democratic Republic these tensile forces are smaller than 15 kN/m. Depending on the geometry of the membrane and the distribution of the imposed load the direction of these forces in relation to the horizontal line varies.

The tensile edge forces must be carried by the anchoring structure. Internationally plenty of possibilities are known (Herzog, 1976), (Kerreit, 1984). Most frequently concrete counterweights in the form of precast concrete elements which are joined together or monolithic concrete strips are used (as shown in Fig. 1), and, to a smaller extent, also screwing-in piles, arrowhead type piles and spreading steel piles are used. Using a concrete counterweight the disadvantages are as follows:

- In the design principle a contradiction arises between the extremely light membranes and the necessary mass volume for the anchorage elements: In an ASS over a rectangular plan with the dimensions of length = 45 m, width = 20 m, height = 8 m there is a mass volume of the membrane of about 1.5 t versus about 190 t of the required self-weight concrete anchorage. The expense of transport capacity resulting is disproportionately high.
- The linear tensile force of the membrane is concentrated into single forces with the help

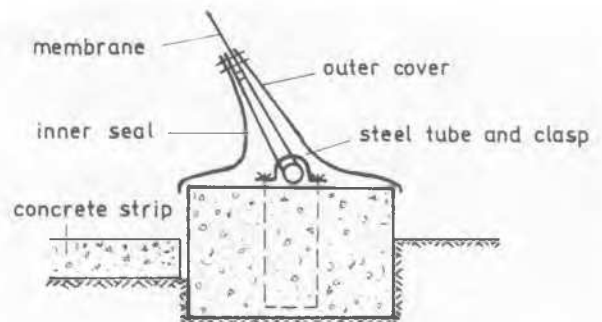


Fig. 1 Section through the concrete counterweight

of special structural elements (e.g. steel tubes and clasps, as shown in Fig. 1). In the example given above some 0.8 t of steel are required.

To guarantee a strict observance of the structural lightweight principle in the erection of ASS the research team TEXTILVERBUNDBAU at the TH Leipzig/Sektion Ingenieurbau has been developing a flexible soil-buried anchorage. In this research project special emphasis has been laid on the following targets:

- Optimum design of the anchor form with a view to the load-bearing behaviour and the placing technique.
- A special dimensioning process adapted to the anchorage of variable tensile forces shall be developed. Its validity is to be examined and confirmed by full scale tests in order to eliminate the pull-out tests so far necessary for anchorage structures.

EXPERIMENTAL TESTS

Previously carried out small-scale model experiments proved an angular anchor as shown in Fig. 7 to be the most suitable variant with a view to placing technique and load bearing capacity as well as to material expenditure.

Field Tests

As a fabric-type anchorage material the PVC-coated polyamid fabric SP& 360 canvas was used which has for a long time also been used in the erection of ASS. Its tearing strength is 3,500 N/5 cm. The angular anchor cut out from this material had the following dimensions: width 'b' = 3,000 mm; horizontal length ' l_H ' = 1,200 mm and 1,500 mm; burying depth 't' = 1,200 mm. The so-dimensioned anchor was subjected to pull-out tests in the experimental process shown in Fig. 2. The pulling angle was ' ϕ ' = 55° and 90° in relation to the horizontal line. In this test the anchor was buried in a conventionally graded moist sand. Its most significant soil physical parameters were:

- medium grain size $d_{50} = 0.77 \text{ mm}$
- coefficient of uniformity $U = 3.2$

- bulk density $\gamma = 18 \text{ kN/m}^3$
- capillary cohesion $c' = 3 \text{ kPa}$
- efficient friction angle $\phi' = 36^\circ$

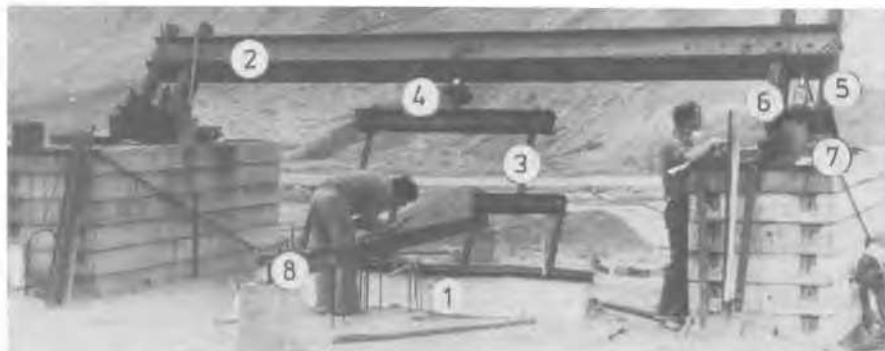
In each of the 15 full-scale tests which have been carried out the load-relevant displacements of the anchor head, the elongations and deformations of the canvas as well as soil raisings were measured for the single load increments. Prior to the determination of the possible ultimate tensile force ' Z_{Gr} ' of the fabric anchor the service load ($\leq 15 \text{ kN/m}$) was repeatedly entered for three times. The most significant test results are:

- Failure of the anchor results from passing beyond the frictional limit between fabric and soil. The anchor will be pulled out.
- In the anchor dimensions studied the ultimate tensile forces ' Z_{Gr} ' which were achieved varied between 20 kN/m and 30 kN/m.
- Under inclined tension and on increase of the horizontal anchor length ' l_H ' the ultimate tensile forces rise markedly.
- Anchor head displacements of ultimately 135 mm horizontally and 90 mm vertically occurring in the service load range are negligible for the operation of ASS.
- Horizontally upward anchor raisings in the service load range are mainly caused by strains in the anchor fabric. These raisings decrease in relation to the number of load cycles.

Friction tests

Since the load bearing behaviour of the soil anchor is based on the friction between fabric and soil a quantitative study of the specific frictional resistance between the coated canvas material and the non-cohesive soil was necessary. These tests which were carried out by means of specially developed pull-out devices in three non-cohesive soils are generally described in (Fritzsche et al., 1984) and in a more detailed way in (Kerreit, 1984). From an evaluation of 152 individual tests the following conclusions may be drawn:

- In the soil area studied for building works the density of the soil and water saturation do not affect the frictional coefficient μ^a .



- 1 fabric anchor, 3 m wide
- 2 main traverse
- 3 traverse system
- 4 dynamometer
- 5 traverse guiding
- 6 portable jack
- 7 support to enable the incline
- 8 support for dial gauges (soil raisings)

Fig. 2 Installation for field test

- For a fractional range of $0.2 \leq d_{50} \leq 2.6$ mm $\mu^* = 1.0$ may be assumed as the lower limit value of the confidence interval (95 per cent statistically determined safety) and may be given as a value for analysis.

DIMENSIONAL DESIGN OF FABRIC ANCHOR

The displacement analysis of the loaded anchor determined from the field tests serves as the basis for the model of analysis.

To analyze the load bearing capacity of the anchor the latter is separated into five ranges as of influence due to the displacement characteristics as shown in Fig. 3.

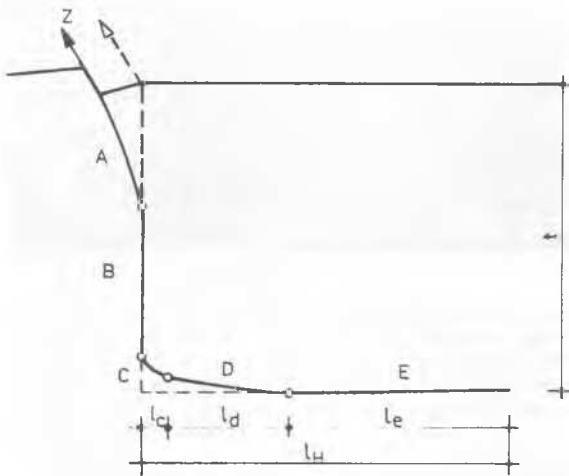


Fig. 3 Displacement of the loaded angular anchor

A - range of inclined tension; B - undisturbed vertical range; C - range of clearly defined change of force direction; D - raised horizontal range with friction on the upper side; E - horizontal range with friction on both sides

For reasons of simplification it is assumed in the model of analysis that in ranges A to C the anchor force 'Z' is only changed in its direction and is not reduced due to non-existing friction. Thus when entering range D force 'Z' becomes effective in full scale. In ranges D and E which are fully loaded by the soil, the tensile force of the anchor is diminished by friction. Fig. 4 demonstrates the balance in these ranges. To calculate the load-depending dimensions in range D the horizontal line component of the resulting friction force 'R_d' is entered at the rear of the range. This is done analogous to the simplifying representation of Fig. 5.

As a supporting line in range D results:

$$z(x) = 2 \tan(\alpha - \frac{x^2}{2l_d}) \quad (1)$$

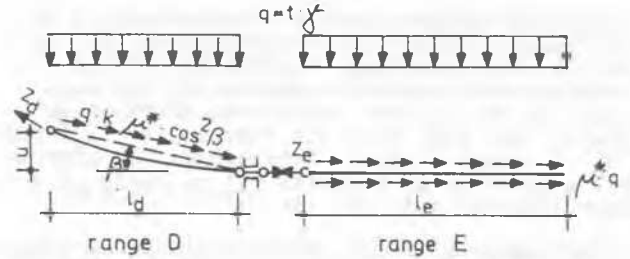


Fig. 4 Balance of forces in the D and E ranges

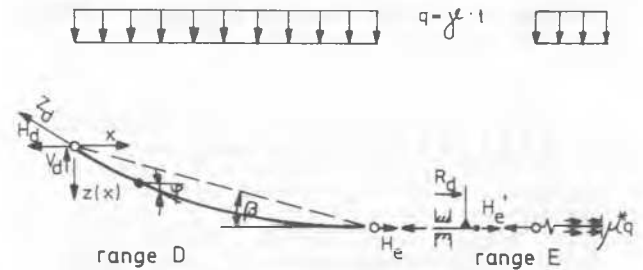


Fig. 5 Simplified model of range D

from which follows as a first derivation:

$$\frac{dz(x)}{dx} = 2 \tan \beta (1 - \frac{x}{l_d}) \quad (2)$$

The edge forces 'H_d' and 'V_d' are:

$$H_d = H_e = \frac{q \cdot l_d}{2 \tan \beta}; \quad V_d = q \cdot l_d \quad (3)$$

Friction force 'R_d' originating in range D but acting only at the rear of the range due to Fig. 4 is:

$$R_d = q \cdot l_d \cdot k \cdot \mu^* \cdot \cos^2 \beta \quad (4)$$

For forming the canvas of length 'L' in range D the initial length 'l_d' must be elongated:

$$\int_0^L dL = l_d + \int_0^L \frac{z(x)}{E} dL + \Delta l_e \quad (5)$$

With $F(x) = H_d / \cos \varphi$; $dL = dx / \cos \varphi$; $H'_e = H_e - R_d$ and

$$\Delta l_e = \frac{H_e^2}{2E \cdot \mu^* \cdot q} = \frac{q \cdot l_d^2}{2E \cdot \mu^*} \left[\frac{1}{2 \tan \beta} - \frac{k \cdot \mu^*}{1 + \tan^2 \beta} \right]^2 \quad (6)$$

as well as with equations (2) and (3), equation (5) can be integrated, resulting in

$$\frac{1}{2} \left[2 \tan \beta \sqrt{1 + 4 \tan^2 \beta} - \ln(\sqrt{1 + 4 \tan^2 \beta} - 2 \tan \beta) \right] = 2 \tan \beta + \frac{q \cdot l_d}{E} \left[1 + \frac{4}{3} \tan^2 \beta \right] + \frac{q \cdot l_d \cdot \tan \beta}{E \cdot \mu^*} \cdot \left[\frac{1}{2 \tan \beta} - \frac{k \cdot \mu^*}{1 + \tan^2 \beta} \right]^2 \quad (7)$$

With both, a given module of elasticity E of the anchor fabric and a soil loading ' q ', as well as the frictional coefficient μ^* , by iterative solution of equation (7) for each quantity of ' l_d ' the associated inclination angle β and with this the edge forces ' Z_d ' and ' H ' of range D can be determined. The numerical evaluation of equation (7) by means of a desk computer resulted in:

- The quantity of the utilized module of elasticity of the anchor fabric notably affects ' l_d ' and ' β ', but does hardly affect the horizontal length ' l_d ' and ' l_e ' required for carrying a certain tensile force as shown in Fig. 6.

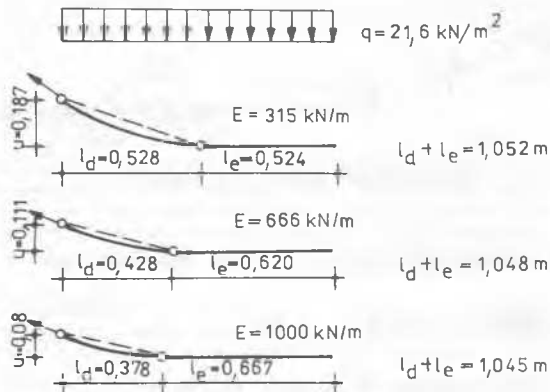


Fig. 6 Module of elasticity and horizontal anchor length ' l_d ' and ' l_e '

- The raisings in the anchor range D are higher in the calculation than in the test which may result from the fact that the experimentally determined and applied module of elasticity of the fabric only insufficiently represents the mechanical behaviour of the soil anchor's fabric material. At present the strain behaviour of fabrics can only be studied according to the specifications of the textile industry, i.e. as a simple uni-axial tensile strip test without taking into account the soil contact.
- The correspondence of the limit tensile forces in field tests and in the calculation with a maximum variation of four per cent can be regarded as very good.

As a result of the calculations carried out a dimensioning diagram has been worked out which unsophisticatedly provides a quick determination of the required anchor dimensions depending on the anchor force.

PRACTICAL APPLICATION OF SOIL FABRIC ANCHORS

The result of the studies undergone is a specification on the application of soil fabric anchors in building practise. According to this specification the anchorage is only possible in

sites in which the existing soil meets the following criteria:

- Index of organic admixtures < 0.05
- The soil must be composed of a proportion of less than 15 per cent of particles with a grain size smaller than 0.06 mm and a proportion of less than 25 per cent with a grain size larger than 30 mm.

To examine and confirm the theoretical results in practise in 1980 and in 1983 two air-supported structures with fabric anchors have been erected as experimental buildings (see Fig. 7).

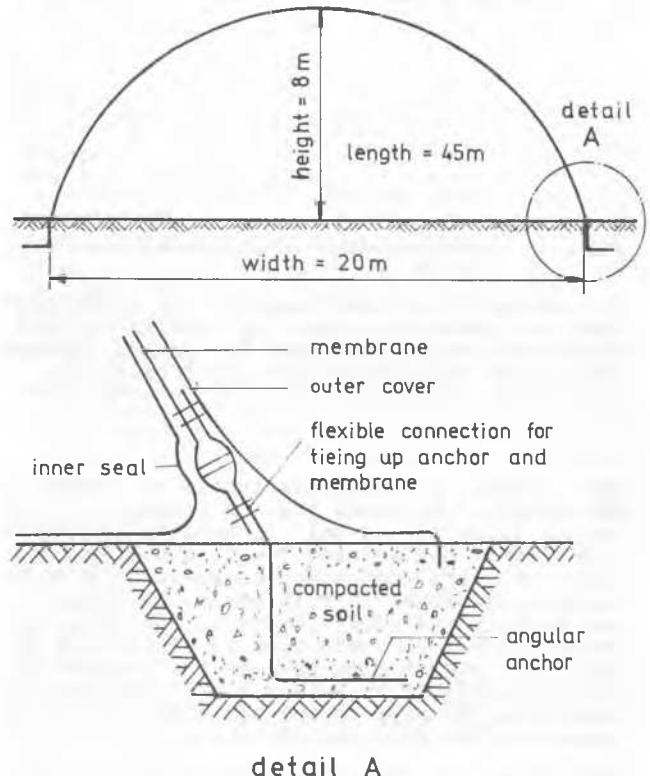


Fig. 7 Experimental structure, 1980

Experience gathered by now may be summarized as follows:

- To avoid any problems in the later connection of the membrane to the fabric anchor structure it is a decisive presupposition for the latter to fit accurately into the previously defined ground-plan. This is achieved by a simple auxiliary assembling device which ensures the anchor head against displacement when backfilling and compacting the soil in the circumferential anchor ditch.
- Unavoidable inaccuracies are most suitably to be compensated for at the corners. These are backfilled only after the stabilization of the membrane.
- The type of anchorage described has proved successful in long-time operation for four years. During this period the exchange of the membrane has been tested likewise. For the canvas material used a maximum service life of 15 years is assumed when applied for soil anchorage.

CONCLUSIONS

- (1) For strict application of the principle of lightweight construction the linear tensile forces of air-supported structures may be safely carried into the soil using a flexible angular fabric anchor buried in the soil.
- (2) Full-scale tests in non-cohesive soil have shown that failure of the anchorage results from a situation when the frictional resistance between fabric and soil passes beyond its limit value. The anchor is pulled out.
- (3) The stresses arising in the angular range may result in the formation of sliding planes in the soil. This phenomenon is secondary as compared to the failure of the anchor due to friction.
- (4) Dimensioning the soil fabric anchor is possible with a design method which assumes a frictional failure of the anchorage. The correspondence of the ultimate tensile forces in field tests and in the calculation with a maximum variation of four per cent can be regarded as very good. The practical use of the design method developed can be rendered favourable to the user by dimensioning diagrams. Such a diagram has been worked out and is ready to use for the anchors in sand which were examined.
- (5) When applying the soil fabric anchors in building practise emphasis is to be laid on strictly observing the previously given anchor form by means of an auxiliary assembling device. Ensuring the anchor head against displacement when backfilling and compacting the soil in the circumferential ditch is an essential prerequisite to connect the anchor to the membrane of the ASS without any difficulty.
- (6) If the regulations and limits of application in the "Specification on the Use of Flexible

Soil Anchors for Air-Supported Structures in Non-Cohesive Soil" are strictly followed the pull-out tests hitherto required for anchorage structures are no longer necessary.

ACKNOWLEDGEMENTS

The authors thank the VEB Textil- und Veredlungsbetrieb Neugersdorf comprised in the VEB Kombinat Technische Textilien Karl-Marx-Stadt, GDR, for having financially supported these studies. The field tests were made possible by active support of KB Industriebau Bautzen within VEB BHK Kohle und Energie, GDR.

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