The Interface Friction and Anchor Capacity of Synthetic Georeinforcements

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ABSTRACT: The soil-synthetic reinforcement interface friction and the anchor capacity of a reinforcement in different frictional soils have been studied in large scale pull-out tests [L×B×H=1,80×1,00×0,80 m^3]. The tests were performed with the following reinforcements: a woven textile and grid and two drawn grids. Test soils were sand, crushed rock and light expanded clay aggregate (LECA). The mobilisation of reinforcement anchorage has been presented as a bond coefficient, $f_p=\tan\phi_g/\tan\phi$, where ϕ_g is the soil-reinforcement interface friction angle and ϕ is the soil friction angle. It was observed that the coefficient f_p, was affected by the soil density, grain size, vertical stress and the properties of the reinforcement. The study was performed in connection with a more comprehensive Finnish "Georeinforcements" -project.

1 INTRODUCTION

The pull-out resistance of different synthetic georeinforcements between soil layers was investigated in large scale pull-out tests [L×B×H=1,80×1,00×(0,40+0,40) m^3], Fig. 1. Vertical pressure was applied by a rubber air bag. The reaction structure consisted of a plywood plate with 3-6 steel beams. The length of the sleeve was 0,30 m and the width of a textile specimen was 0,30 m and the width of grids was 0,31-0,33 m according to Farrag et al (1993).

The pull-out load was applied by a hydraulic loading system through steel clamp plates that extended inside the sleeve. The loading system can apply displacement-controlled or load-controlled pull-out tests. Now the tests were conducted using a constant pull-out rate ($d_h/t=2{,}0$ mm/min) except for one test which was conducted by increasing the pull-out load step by step ($\Delta P_h \approx 3$ kN/m). The pull-out force was measured by means of an electric load cell between the jack and clamp.

The displacement of the front of the reinforcement was measured by one LVDT. The displacements along the reinforcement were measured by wires connected to 5 LVDTs in sand and 1 LVDT in crushed rock and in light expanded clay aggregate, Fig 1. The wire (d=0,5 mm) was fixed to textile with a piece of cotton and hot glue. The wire was fixed to grids with a small steel clamp and hot glue.

The dense sand, dense LECA and medium dense crushed rock were placed in four layers of 0,20 m each, levelled and compacted with a vibratory compactor (M=45 kg). The medium dense sand and loose LECA were placed in 0,40 m layers. The density was calculated on the basis of the mass of the soil and the volume of the testing box.

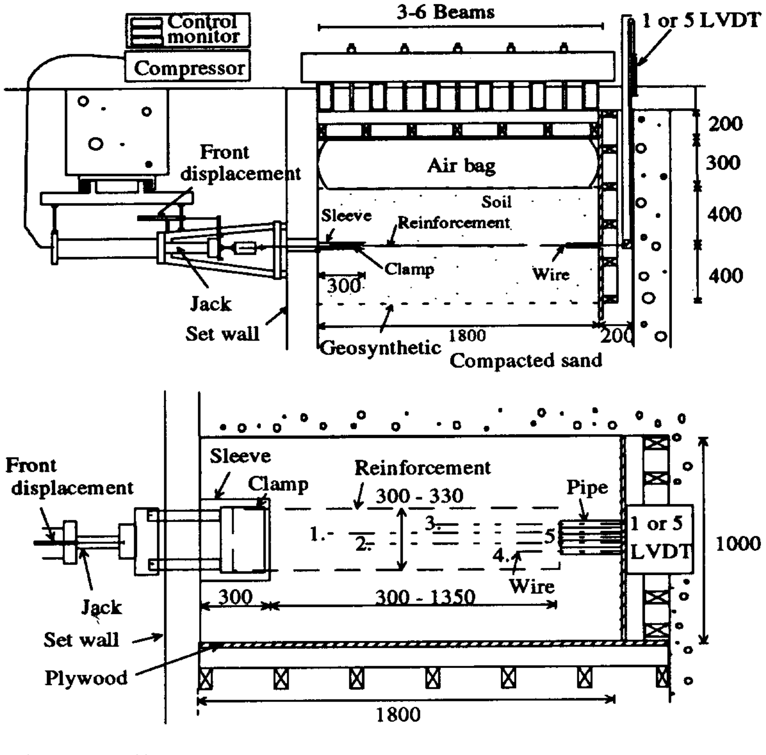

Fig. 1 Pull-out test apparatus

Additional information on the equipment can be found in Forsman (1993).

2 REINFORCEMENTS AND SOILS

The reinforcements used in pull-out tests were: a woven textile A (Stabilenka 200/200), a woven grid E coated with PVC (Fortrac 35/35-35), drawn grids F and G (Tensar SS2 and SR80), Table 1 and 2. Grid F was pulled-out in transverse direction.

The soils in pull-out tests were: Ojakkala sand, crushed rock 0-32mm (CR) and light expanded clay aggregate 4-20mm (LECA), Table 3 and 4.

Table 1 Properties of the reinforcements

Label	Material	Index strength kN/m	$F_{max}{}^d$ =UTS kN/m	$\varepsilon_{max}{}^d$ %	$J_{sec}{}^d$ kN/m ε=4% ; 10%
Text. A Woven	PETP/ PETP	200/ 200 [a]	211,8	9,9	1770 ; 2110
Grid E [e] Woven	PETP/ PETP	35/ 35 [b]	39,9	9,8	300 ; 380
Grid F [f] Biaxially	PP drawn	17,5/ 31,5 [c]	34,5	11,9	490 ; 330
Grid G Uniaxially	PE drawn	80,0/ - [c]	79,5	15,0	900 ; 630

a. DIN 5387, preload 5mN/tex or ASTM 1682/B52576
b. DIN 53857T1 c. Netlon Limited (1984)
d. ISO/DIS 10319.2, Tested at Helsinki Univ. of Technology
e. Coated with PVC f. Pull-out test in transverse direction
PETP = Polyester, PP = Polypropylene, PE = Polyethylene

Table 2 Dimensions of the reinforcements

	Text. A	Grid E	Grid F	Grid G
$S_L \times S_T$, mm^2	-	37×37	40,0×28,0	22,4×160,0
$S_{LA} \times S_{TA}$, mm^2	-	33×31	37,0×24,2	16,0×144,0
μ, g/m^2	450	365	300	700

$S_L \times S_T$ = Grid size $S_{LA} \times S_{TA}$ = Mesh opening size
L = Longitudinal direction T = Transverse direction

Table 3 Index properties of the soils

Unit	Sand 0-4mm	CR 0-32mm	LECA 4-20mm
ρ_s, t/m^3	2,69	-	2,514
ρ_{dmin}- ρ_{dmax}, t/m^3	1,56-1,81	1,59-2,34	0,290-0,311
C_u	3,0	24,0	3,0
d_{50}, mm	1,2	4,0	6,0

Table 4 Strength properties of the soils

Soil	I_D	Direct Shear Test			Triaxial Test		
	-	c_p, kPa	ϕ_p ,°	ϕ_{cv} ,°	c_p, kPa	ϕ_p ,°	ϕ_{cv} ,°
Sand	0,97	5,5	44,9^a	39,8	1,0	44,3^c	37,5
Sand	0,40	10,0	36,9^b	-	-	-	-
CR	0,54		-	-	14,0	44,7^d	41,2
LECA	D		-	-	2,4	46,3^e	-
LECA	L		-	-	4,5	40,8^e	34,8

a 305×305 mm^2, w=0,2 %, d_h/t=0,5mm/min, b 60×60 mm^2
c d×H=100×200 mm^2, w=0,2 %, ε_1/t=12%/H,
d d×H=250×500 mm^2, w=1,8-2,2%, ε_1/t=6%/H
e d×H=250×500 mm^2, w=0,1%, ε_1/t=6%/H, D=dense, L=loose

3 PULL-OUT TEST RESULTS

3.1 Bond coefficient

Generally the bond coefficient between soil and reinforcement has been defined according to equation 1 assuming that the frictional resistance is uniform along the length of the reinforcement.

$$f_p = \frac{\tan\phi_G}{\tan\phi} = \frac{\tau}{\sigma_v \tan\phi} = \frac{P_p}{2L_e B\sigma_v \tan\phi} \qquad (1)$$

f_p = bond coefficient, ϕ_G = angle of soil-reinforcement interface friction, ϕ = angle of internal soil friction, τ = shear stress, σ_v = vertical stress, P_p = pull-out force, L_e = effective length of the specimen, B = width of the specimen

Concerning geogrids equation 1 is not strictly applicable because the anchor capacity of a grid is mainly developed as the bearing earth pressure against the transverse elements of the grid. However, the apparent soil-reinforcement interface friction angles have been calculated on the basis of equation 1 also for geogrids. The decreasing of the effective length of a specimen has been taken into account in the case when the back edge of the reinforcement has moved. In the case when the whole reinforcement did not move before it became broken, the shear stress was calculated on the basis of the effective length of the reinforcement. The shear stress calculated in this way is not the maximum one because the shear stress is still increasing when the whole reinforcement is already moving.

The relationship between the shear stress and the front displacement for different soil-reinforcement combinations and soil densities are presented in Fig. 2. The values of apparent cohesion, angle of friction and bond coefficient are presented in Table 5. The determination of the angle of the soil-reinforcement interface friction is shown in Fig 3. The usually straight line through the plotted data points has been fitted by regression analysis. If the pull-out testing for some soil-reinforcement combinations includes only one vertical stress, the cohesion is assumed to be zero.

In the pull-out tests, for woven grid E and crushed rock as well as for grid E and LECA, the specimen was too short (L=0,33-0,60m). The values of bond coefficient for these combinations (f_p=0-0,17) are misleading, Fig. 2f and table 5. The reason for the low values of bond coefficient was that the longitudinal tension carrying elements glided "through" the junctions to the transverse bearing elements. The pull-out force of the longitudinal elements was not transferred to the bearing elements because there were not enough junctions along the length of the reinforcement. On the basis of the pull-out tests, the average junction strength of grid E was obseved to be 5 % of the tensile strength of a single tension carrying element.

The length of specimens was varied in different tests for the same material combinations as shown in Fig 2a, 2f and 2h. The peak shear resistance for the textile A-dense sand interface decreased 15-27 % when the length of specimen increased from 0,60 m to 1,35 m. This can be observed as decreasing apparent cohesion in Fig 3a. The peak shear resistance is assumed to be uniform along the length of the reinforcement. The peak shear resistance for the grid G-medium dense crushed rock interface decreased 25-31 % when the length of specimen increased from 0,31 m to 0,63 m and 41 % when the length increased from 0,31 m to 0,95 m, Fig 3b. The relationship

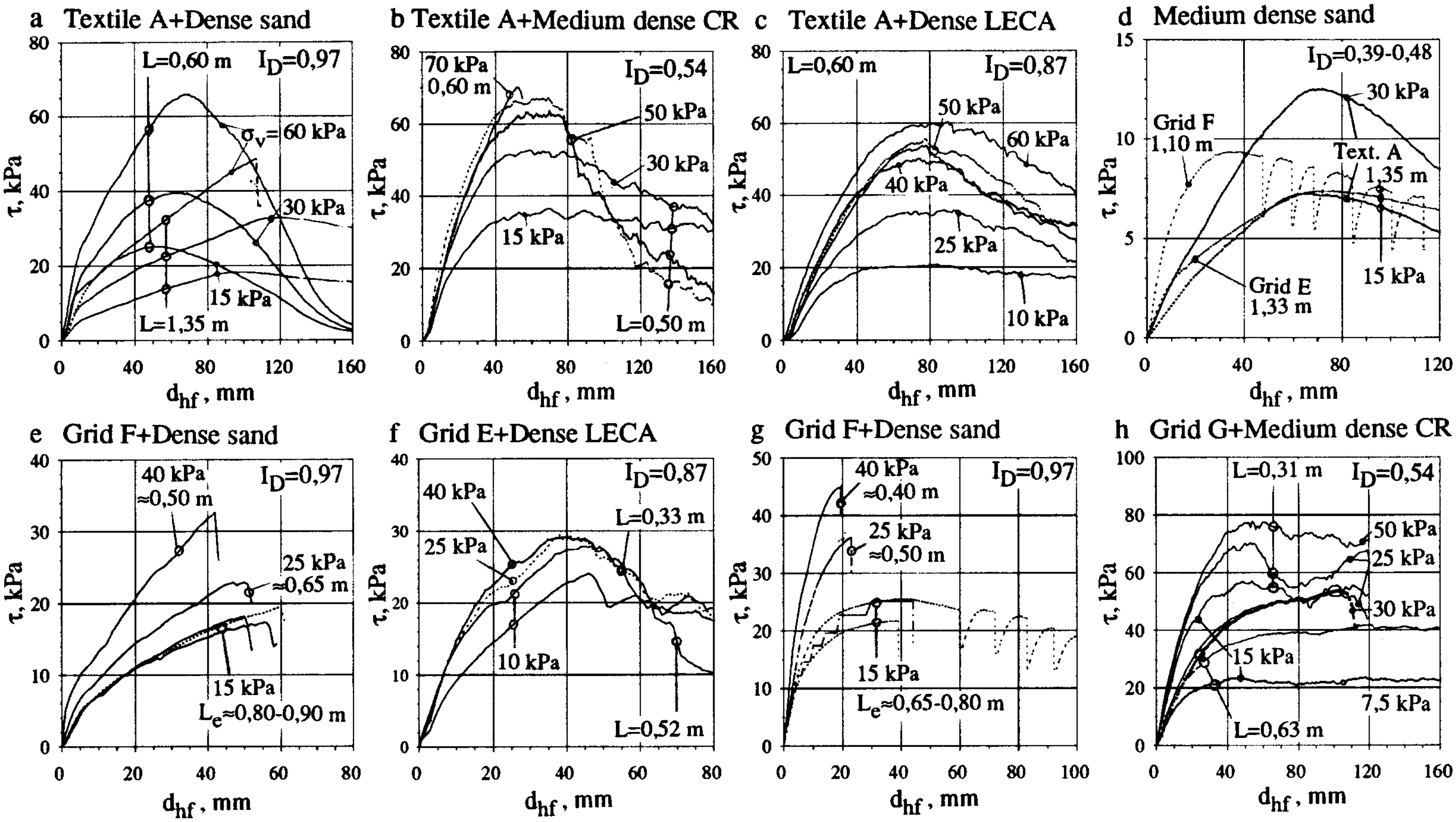

Fig. 2 Pull-out test. Relation between average shear stress (τ) along the specimen and clamp displacement (d_{hf}).

Table 5 Pull-out test. Bond coefficient f_p

Lab.	Soil	I_D,-	L_e, m	c_G,kPa	ϕ_G,°	ϕ,°	f_p	σ_v,kPa
A	Sand	0,97	0,60	12,2	42,0	44,9	0,90	15-70
			1,35[a]	6,0	42,0	44,9	0,90	15-60
A	Sand	0,39	1,35	2,0	19,2	36,9	0,47	15-30
A	CR	0,54	0,50	23,0	44,0	44,7	0,98	15-50
A	LECA	0,87	0,60	10,6	44,7	46,3	0,95	10-60
A	LECA	0,30	0,60	7,6	38,1	40,8	0,91	15-40
E	Sand	0,97	≈0,5-0,9	9,0	31,0	44,9	0,60	15-40
E	Sand	0,48	1,33	0	(26)	36,9	0,65[c]	15
E	CR	0,54	0,33	22,4	(9,5)	44,7	0,17[b]	15-40
			0,60	19,8	(0)	44,7	0[b]	7,5-15
E	LECA	0,87	0,33	27,6	(2,5)	46,3	0,04[b]	10-40
F	Sand	0,97	≈0,4-0,8	11,0	43,0	44,9	0,94	15-40
F	Sand	0,48	1,10	0	(32)	36,9	0,83[c]	15
F	CR	0,54	0,31	30,0	53,0	44,7	1,34	7,5-25
G	CR	0,54	0,31	52,1	28,4	44,7	0,55	15-50
			0,31	37,0	53,0	44,7	1,34	15-25
			0,63	15,8	53,8	44,7	1,38	7,5-30

a L_e ≈ 1,20 m, in case σ_v = 60 kPa   b Too short specimen   c Only one vertical stress between the peak shear resistance and the vertical stress seemed to become unlinear when the vertical stress increased, Fig 3b.

The reason for the decreasing of the average shear resistance along the reinforcement with increasing vertical stress is the fact that the process of progressive failure along the extensible reinforcement length is more obvious when the specimen is longer. Some locking and arching of the grains may also occur in front of the sleeve, especially in coarse grained aggregates. When the length of the specimen increases, the effect of locking and arching decreases.

Theoretically, cannot the value of bond coefficient (f_p) in reinforced soil structures be more than 1,0. The values of the bond coefficient, determined on the basis of the pull-out tests with grid F and G and medium dense crushed rock, were 1,34 - 1,38. One reason for the big values may be that the bond coefficients were calculated according to equation 1 using the angle of internal friction, which is determined from triaxial tests instead of direct shear tests.

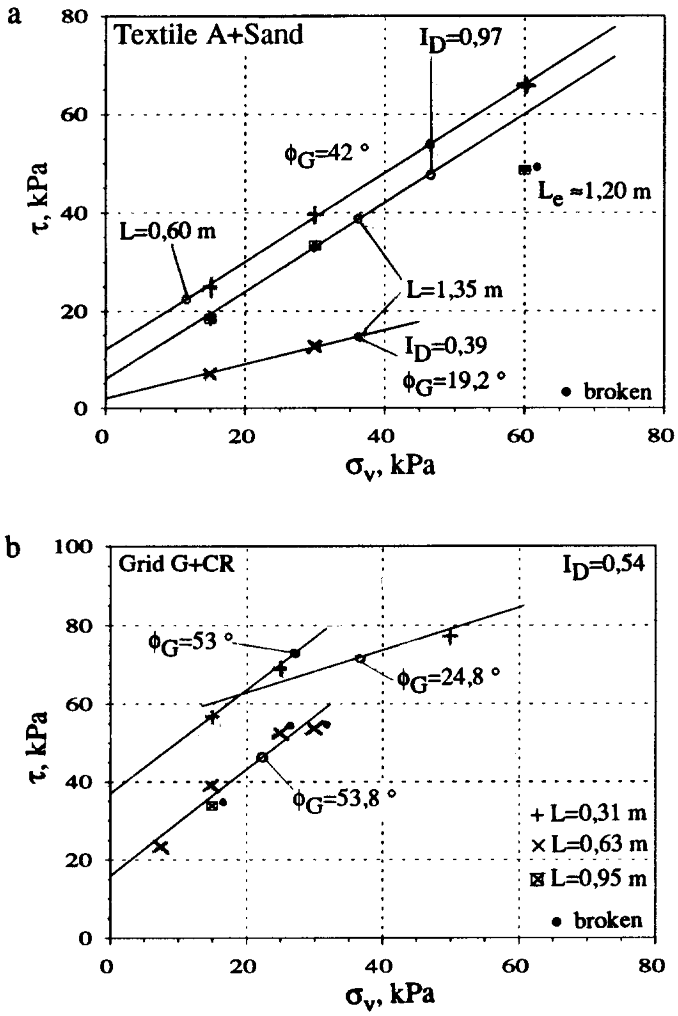

Fig. 3 Determination of the soil-reinforcement interface friction angle from pull-out test results. a Textile A (L=0,60 m and 1,35 m) and dense and medium dense sand. b Grid G (L=0,31 m, 0,63 m and 0,95 m) and medium dense crushed rock.

Another reason can be the restrained dilation. If the dilation is restrained in a pull-out test, the vertical stress along the interface of soil and reinforcement will increase until a critical state is achieved. Locking and arching of the grains in front of the sleeve and the rigid front wall of the box can also have an effect on the value of the bond coefficient.

The determination of the angle of friction for the textile A-medium loose sand interface is also presented in Fig. 3a. It is found that when the density of sand decreases, the value of the bond coefficient also decreases noticeably. The shear resistance of the sand-reinforcement (text. A, grid E and F) interface is 57-64 % lower for medium dense sand (I_D=0,39-0,48) than for dense sand (I_D=0,97-1,0). There is probably no restrained dilation in medium dense sand and therefore the vertical stress along the interface does not increase.

Some modified direct shear tests (L×B=0,30×0,30 m^2) were performed with textile A and Ojakkala sand (I_D=0,60-0,97). The efficiency factor of direct sliding (f_s=0,76-0,79) for sand-textile A interface was not observed to have been influenced by the density of the sand. Makiuchi and Miyamori (1988) have observed the same with sand and a woven polyester textile.

3.2 Displacements of the reinforcement

The displacements along the reinforcement were measured by five LVDTs in pull-out tests from sand. The displacements of a reinforcement (textile A, grid E and F) in three pull-out tests are presented in Fig 4. The aggregate was dense sand and vertical stress was 15 kPa. On the vertical axis are the displacements of the clamp and of the reinforcement and on the horizontal axis are the measuring points at different distances from the clamp. The locations of the measuring points are in Fig. 4d. The observation points are connected by a line to each other and the corresponding pull-out forces are presented at the left end of each line. The measured displacements along the reinforcements demonstrate the non-linearity of displacements and of the shear resistance distribution along the reinforcement during a pull-out test.

Fig. 5b presents the displacements of the textile A, grid E and grid F when the pull-out force at the clamp is 23 kN/m and the vertical stress is 15 kPa. The relationship between the pull-out force and the clamp displacement are presented in Fig. 5a.

Fig. 4 and 5 demonstrate different behaviour of three reinforcements during pull-out tests. The modulus of deformation and the dimensions of grids E and F are almost similar, table 1 and 2. Grid F requires, however, noticeably smaller clamp displacement to mobilize the same pull-out force as grid E, because its transverse bearing ele-

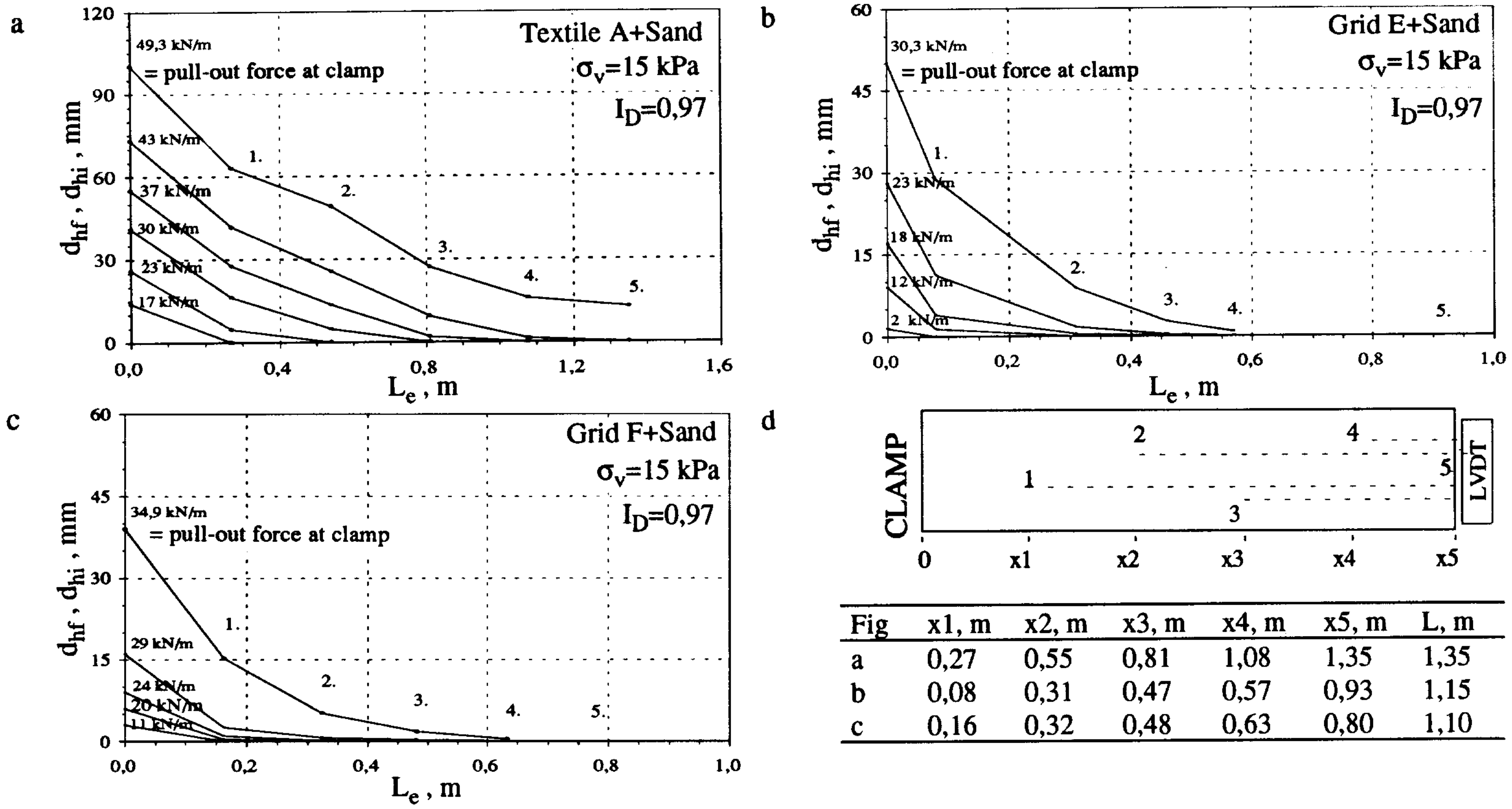

Fig	x1, m	x2, m	x3, m	x4, m	x5, m	L, m
a	0,27	0,55	0,81	1,08	1,35	1,35
b	0,08	0,31	0,47	0,57	0,93	1,15
c	0,16	0,32	0,48	0,63	0,80	1,10

Fig. 4 Pull-out tests from dense sand, I_D=0,97, σ_v=15 kPa. The displacements of the clamp and of the reinforcement (d_{hf}, d_{hi}) are presented on the vertical axis when the pull-out force is 23 kN/m. The distances of the measuring points from the clamp (L_e) are presented on the horizontal axis and in Fig. d. a Textile A, b grid E and c grid F.

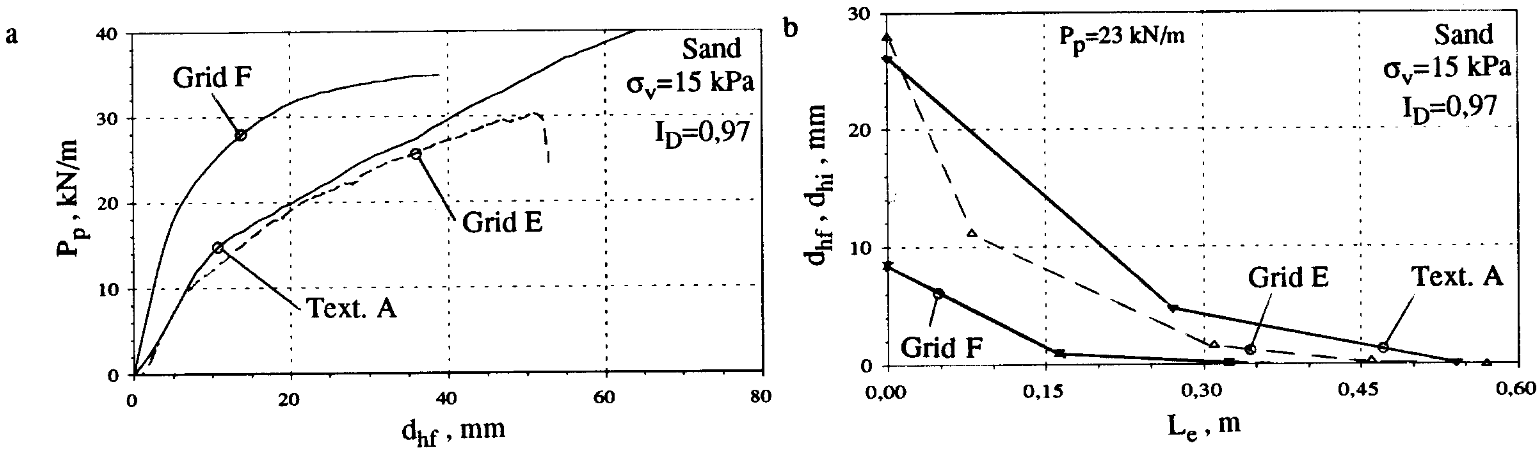

Fig. 5 Pull-out test from dense sand, I_D=0,97, σ_v=15 kPa. a Relationships between the pull-out forces (P_p) and the clamp displacements (d_{hf}). b The displacements of the clamp and of textile A, grid E and grid F (d_{hf}, d_{hi}).

ments are more rigid than the bearing elements of grid E. Additionally no gliding takes place in the junctions between the longitudinal and the transverse elements of grid F.

Textile A and grid E require almost the same clamp displacement although the modulus of textile A is more than five times larger than the modulus of grid E. Based on this it may be concluded that the anchor capacity of grid E is mainly based on the bearing stress developing on the transverse elements, and partly on the frictional resistance of the soil-reinforcement interface, like textile A.

3.3 Failure mechanism of anchorage and the strength of the reinforcement in pull-out test

The failure of anchorage took place in three different ways: the reinforcement slipped between soil layers (slippage), the reinforcement broke when the pull-out force exceeded the strength of the reinforcement (material failure) or the longitudinal tension carrying elements of woven grids slid "through" the transverse bearing elements (junction failure). In the case of the junction failure the pull-out force did not exceed the strength of the reinforcement. The relationship between the ultimate pull-out force of the reinforcement and the standard tensile strength is presented in Table 6. The number of broken reinforcements in the pull-out tests and the number of pull-out tests with the same reinforcement-soil combination are also presented in Table 6.

When studying Table 6, one has to bear in mind that the tensile strength and strain of a synthetic reinforcement are affected by the rate of strain. In the displacement controlled pull-out tests, the rate of strain was changing noticeably in connection with different reinforcements, depending on the modulus of the reinforcement and the failure mechanism of the anchorage. The average strain rate was about 0,15-0,50 %/min. With this strain rate, the maximum tensile force of a reinforcement is about 75-85 % of the maximum tensile strength measured in a standard tensile test in the temperature of +20 °C (BBA 1992; Yeo 1985). About 4,5-8 % of the warps of the textile A specimens became broken when the specimen was fixed to the clamp. This also reduced the maximum tensile force of textile A in the pull-out tests.

The maximum tensile strength of textile A was very low in crushed rock and LECA because the grains of crushed rock are sharply angular and the surface of LECA grains is hard and glasslike. This may cause mechanical damage to the textile. The surface of LECA is also alkaline and the polyester in question is possibly affected by hydrolysis which may also decrease the strength of textile A.

Table 6 The maximum pull-out force as a percentage of the standard tensile strength of a reinforcement and the number of broken reinforcements against all pull-out tests.

	Sand		Crushed rock		LECA	
	I, %	II	I, %	II	I, %	II
A	55	1/7	29-40	3/5	37	1/10
E	75-82	5/6	47-64	2/5	-	0/4
F	95-104	4/6	83-103	3/4	-	-
G	-	-	77-81	3/8	-	-

$I=(P_{pmax}/F_{max})\times 100\%$, $II=n_{broken}/n_{all}$, P_{pmax}=maximum pull-out force, F_{max}=maximum tensile strength, n_{broken}=no. of broken reinforcements in pull-out tests, n_{all}=no. of pull-out tests

4 CONCLUSION

The main conclusions of the present work are the following:

1. The average shear resistance decreases when the length of a specimen increases in a pull-out test. One reason for this is the process of progressive failure along the extensible reinforcement length. The effects of the rigid front wall and the sleeve also decreases when the length of the specimen increases.

2. The sand-reinforcement (text. A, grid E and F) interface shear resistance and the bond coefficient (f_p) decrease noticeably when the density of the sand decreases. The efficiency factor of direct sliding for sand-textile A interface was not observed to have been influenced by the density of the sand in modified direct shear tests.

3. There have to be enough junctions between the longitudinal tension carrying elements and the transverse bearing elements along the anchorage length of a woven grid to transfer the pull-out force to the bearing elements.

4. The properties of reinforcements, like the modulus of deformation, the strength of junctions and the rigidity of the transverse bearing members, affect the relationship between the pull-out force and the clamp displacement.

5. The sharply angular grains of crushed rock and the hard, glasslike surface of LECA will cause mechanical damage and reduce the strength of a reinforcement. The alkaline surface of LECA may also influence the strength of a polyester product.

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