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Interface friction coefficient of extensible reinforcement and its influence on designing of retaining structures

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ABSTRACT: The interface friction coefficient is the basic factor influencing the frictional resistance of reinforcement and as a result the internal stability of an earth structure. Field and laboratory investigations on interface friction coefficient between materials of extensible reinforcement (geotextiles, flexible straps) and fills (industrial wastes) were carried out. Two methods were used to determine interface friction coefficient i.e. shear box test and pull-out test. The test results obtained from both methods demonstrated that values of interface friction strongly depend on vertical stress (with its increase are diminishing) and derived from shear box test were greater than those obtained from pull-out test. Detailed calculation procedures for designing two experimental retaining structures using geotextiles and flexible straps are given and results of calculations are presented. Strong dependence of reinforcement length on values of friction coefficient was evidently revealed.

1 INTRODUCTION

In the Upper Silesian Region of Poland great concentration of underground coal mining industry causes a lot damage to the earth surface infrastructure due to mining subsidences. Another problem is connected with the great amounts of colliery spoils and fuel ashes as the area for depositing them is strongly limited and they also affect the human environment.

One of the basic ways of utilization of great amount of these wastes is applying them for civil engineering structures as man made building soil. As the reinforced soil techniques have become quite popular nowadays all over the world in numerous application areas, the use of colliery spoils and fuel ashes as a fill in retaining structures using reinforced soil technique can give considerable technical and economic benefits.

Since there is no experience in erecting retaining structures from industrial wastes in Poland, the research project comprising two experimental reinforced soil structures 3 m high has been initiated and performed on fuel ash lagoon and colliery spoils dumping ground in Przezchlebie next to Gliwice: First of them was constructed from exhausted railway timber ties as facing units, straps from cut exhausted conveyor belts as reinforcement and colliery spoils as a fill. The second one was constructed in a different way with the use of geogrids and geotextiles as reinforcement, forming a facing wall by wrapping around the particular fill layers. Colliery spoils and fuel ashes were used as a fill. Both walls consisted of a number of sections 3-m high, independent from static point of view.

These structures were designed according to two design procedures, based on the coherent gravity hypothesis and tie-back hypothesis (Jones, 1988). The retaining wall constructed with the use of reinforcing strips from exhausted conveyor belts was designed basing on coherent gravity hypothesis, following the rules given by the relevant Polish Standard. The embankment reinforced with geotextiles and geogrids was designed according to the tieback hypothesis basing on the principles given by LOTRAK designer's handbook (DON & LOW LTD. 1996). In both cases only the internal stability of structures was considered.

The interface friction coefficient is the basic factor influencing the frictional resistance of reinforcement and as a result the internal stability of a reinforced earth structure. Length and spacing of reinforcing elements strongly depend on this factor, so determining of the interface friction coefficient is of essential importance. Taking that into consideration two methods for determining the friction characteristics of reinforcing materials were applied, i.e. laboratory shear box test and field pull-out test in full scale.

2 DESCRIPTION OF METHODS USED

The shear box test was performed using a large (300× 300mm) shear box apparatus, adapted specially for the test by fitting a timber block into the bottom of

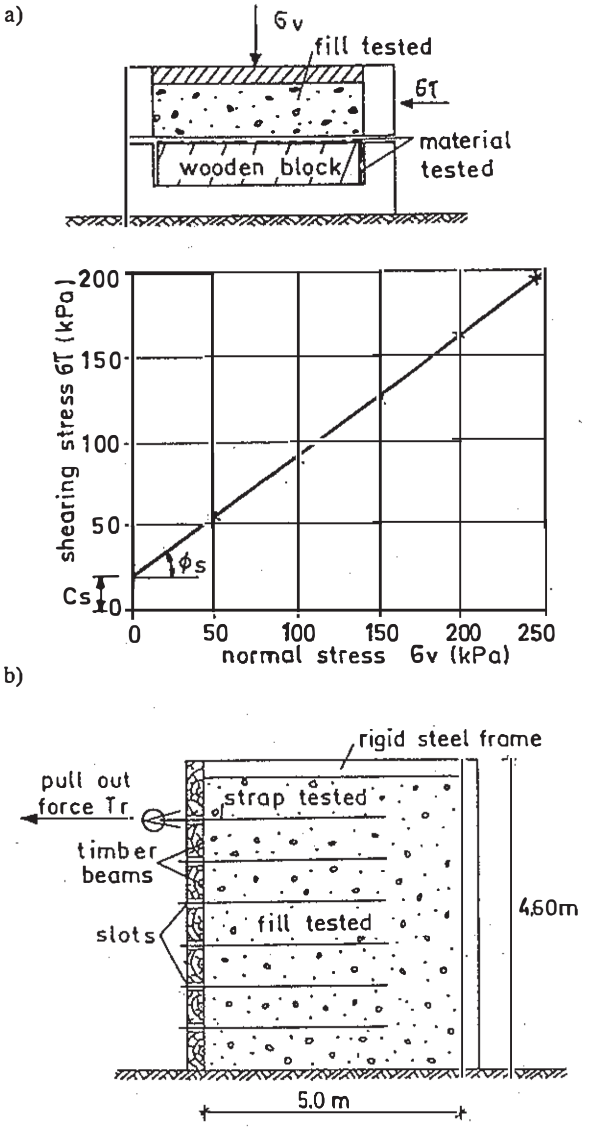

Figure 1. Determining the interface friction coefficient: a) shear box test b) pull-out test.

the lower half of the box. The reinforcing material was attached to the block on its one edge so it could move on the block towards the acting shearing force to include the material flexibility during the test.

The upper half of the box was then filled with compacted fill material (degrees of compaction of the particular fill materials are given in Table 1) and a normal load was applied. The shear force required to cause sliding was then measured using a constant rate of strain of 1.0 mm/min at normal stresses of 50, 100, 150, 200, 250 kPa (Fig. 1a).

The friction coefficient μ obtained from the shear box test was calculated by the formula:

$$\mu = \frac{C_s}{\sigma_v} + \tan\phi_s \tag{1}$$

where C_s = adhesion [kPa]; σ_v = vertical stress applied, or overburden pressure [kPa]; ϕ_s = angle of interface friction [°].

Table 1. Results of shear box determining of interface fiction characteristics.

Fill	Material of reinforcement	Angle of friction ϕ_s [°]	Adhesion C_s [kPa]
Colliery			
spoils	exhausted conveyor belts	36.8	35.4
R.C. = 0.99	new conveyor belts	34.5	31.8
$\phi = 41°$	"Paraweb" straps	32.6	24.2
$C = 41$ kPa			
Colliery			
spoils	Geotextiles F 650M	37.8	19.2
R.C. = 0.98	Geotextiles Ha Te 600	34.1	29.7
$\phi = 38°$	AW (geocomposit)		
$C = 51$ kPa			
Pulverised			
fuel ash	Geotextiles F 650M	33.1	20.5
R.C. = 0.88	Geotextiles Ha Te 600	32.5	19.1
$\phi = 28°$	AW (geokompozyt)		
$C = 29$ kPa			

Note: R.C. = Relative Compaction = Degree of Compaction obtained from Standard Proctor Test

The full scale pull-out test was carried out at Barony colliery (Scotland) using a large open-topped box with one open end, constructed from rigid steel frame and timber railway sleepers. The test the box was 5 m long by 4.60 m high being 3.1 m wide. During test the box was filled with compacted test material and at specific levels reinforcing straps were laid passing through the front wall of the box. A specially designed pull-out jack delivered by British Coal Minestone Services was used to pullout individual straps with continuous record of load and displacement up to achieving the maximum pull-out force just before sliding of the strap (Fig. 1 b).

The apparent friction coefficient μ was obtained from this test using the formula:

$$\mu = \frac{T_r}{2 \cdot B \cdot L \cdot \gamma \cdot H} \tag{2}$$

where T_r = maximum pull-out force [kN]; B = width of strap [m]; L = length of strap [m]; γ = unit weight of fill [kN/m^3]; H = height of fill above reinforcement [m].

3 TEST RESULTS

Results obtained from the shear box tests carried out on reinforcing straps made from exhausted conveyor belts and new Paraweb straps (British make) in colliery spoils and pulverized fuel ash are presented in the Table 1.

Having these data and the data obtained from pull-out tests (Michalski 1989) the relationships between values of interface friction coefficient μ, developed

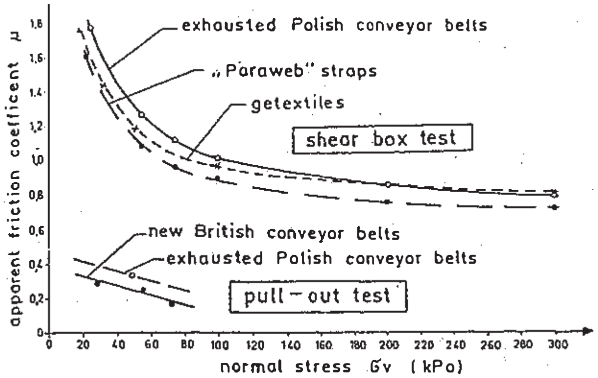

Figure 2. Values of interface friction coefficient μ obtained for colliery spoils versus vertical stress σ_v.

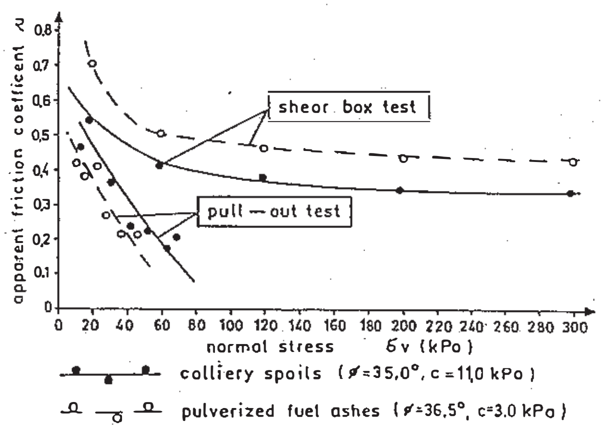

Figure 3. Values of interface friction coefficient obtained for the British straps in colliery spoils and fuel ash.

using formulas 1 and 2, and vertical stress σ_v were made. They are demonstrated in a graphical form in Figure 2.

For comparison the analogous graphs were prepared basing on British test results, performed in the same way given in (Bouazza et al. 1990). They are presented in Figure 3.

The test results obtained from both methods demonstrated that values of interface friction μ strongly depend on vertical stress and with its increase are diminishing however are discrepant. Values μ coefficient derived from shear box test were much greater than those obtained from pull-out test, especially at low vertical stresses. These results confirm the results obtained by other authors (Finlay et al. 1988) from the tests carried out in similar fills. In the authors' opinion μ values obtained from shear box tests are overestimated, particularly for small values of vertical stress σ_v but values μ obtained from pull-out test are underestimated. It can be explained by the fact that the probable distribution of the frictional force along the pulled-out strap is uniform only towards the front end and is dropping off to a low value at the free end. It reduces the value of friction coefficient (Finlay et al. 1988). So, the basic question arises

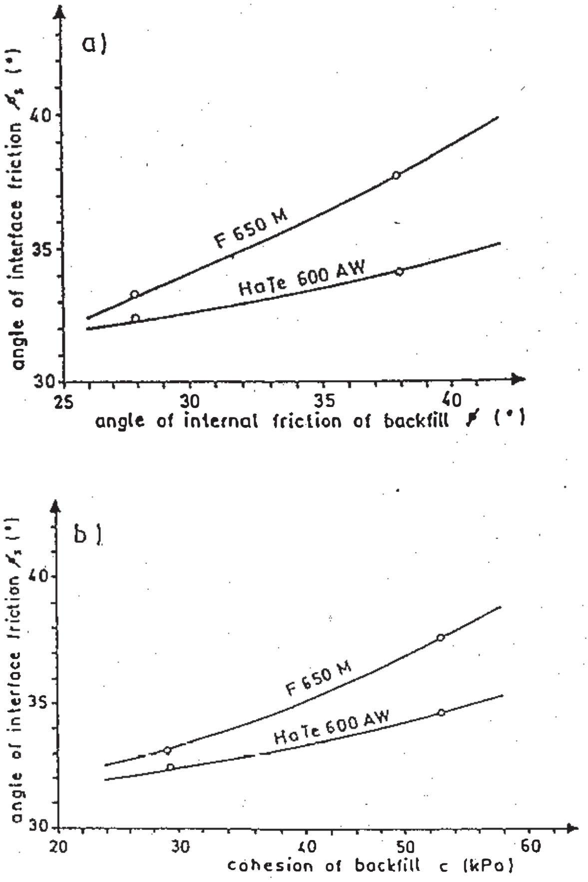

Figure 4. Influence of backfill parameters: ϕ (a) and c (b) on the angle of interface friction ϕ_s. Results obtained from shear box tests for geotextiles.

which values should be used for design calculations. Test results also demonstrated the influence of the fill shearing strength parameters on the interface friction characteristics. These relationships between values of angle of internal friction and cohesion and the angle of interface friction obtained from shear box tests are presented in Figure 4.

It is evidently visible from the graphs that the grater shearing strength of a fill material gives the higher values of interface friction between the reinforcement and the fill.

4 INFLUENCE OF INTERFACE FRICTION PARAMETERS ON THE PREDICTED LENGTH OF REINFORCEMENT

To facilitate the analysis in what way the values of interface friction coefficient influence predicted lengths of reinforcement some calculations were made according to two hypotheses, i.e. coherent gravity hypothesis and tie-back hypothesis (Jones 1988) (Fig. 5).

Calculation procedure basing on the coherent gravity hypothesis and rules given in PN-83/B-03010 were

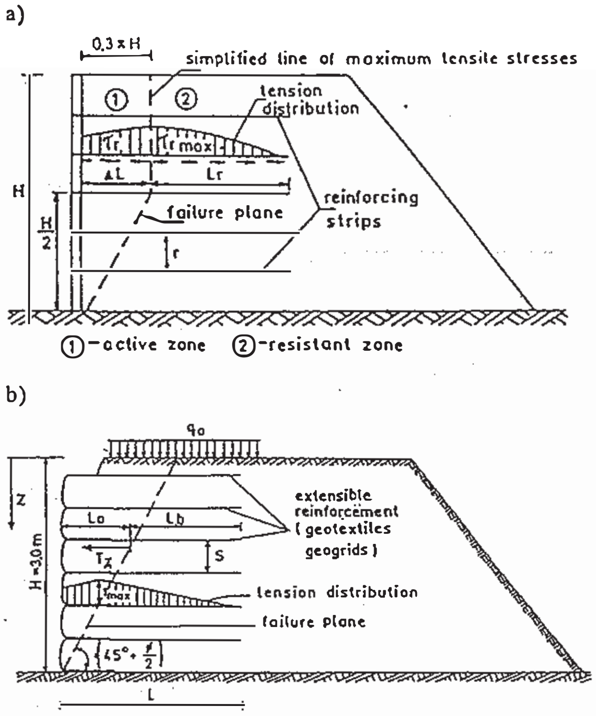

Figure 5. a) coherent gravity hypothesis, b) tie-back hypothesis.

applied for the retaining structure reinforced with Paraweb straps and the straps made of exhausted conveyor belts. The procedure was as it follows (see Fig. 5a).

Tensile stress in fill acting on reinforcement:

$$\sigma_3 = K \cdot \sigma_1 \text{ (kPa)} \tag{3}$$

where K = soil pressure coefficient:

$$K = (1 - \sin\phi_u) \cdot \left(1 - \frac{z}{6}\right) + \frac{z}{6}\tan^2\left(45^\circ - \frac{\phi_u}{2}\right) \tag{4}$$

for $z \leq 6$ m, where ϕ_u = angle of internal friction of the fill, z = depth below soil surface [m];

σ_1 = vertical stress on reinforcement strip:

$$\sigma_1 = \sigma_\gamma + q \text{ [kPa]} \tag{5}$$

where σ_γ = overburden pressure:

$$\sigma_\gamma = \gamma \cdot h \tag{6}$$

where γ = unit weight of soil [kN/m^3], h – fill height above reinforcement [m]; q = extra load on the soil surface [kPa].

Maximum tensile force in reinforcement was obtained from:

$$\tau_{r\,\max} = \frac{r}{n} \cdot \sigma_3 \text{ [kPa]} \tag{7}$$

where σ_3 = as above; r = vertical spacing of reinforcement [m]; n = number of strips per running meter of the wall [1/m].

Tensile force at the facing panel:

$$\tau_r = 0.75 \cdot \tau_{r\,\max} \text{ [kN]} \tag{8}$$

Working length of the reinforcement strip:

$$L_r = \frac{\tau_{r\,\max}}{m_1 \cdot 2 \cdot B \cdot \mu \cdot \sigma_1} \text{ [m]} \tag{9}$$

where τ_r max, σ_1 = as above; B - width of reinforcement [m]; μ = apparent coefficient of adherence between soil and reinforcement [-]; m_1 = safety factor = 0.75.

Total length of the strip:

$$L = L_r + \Delta L \text{ [m]} \tag{10}$$

where ΔL = extent of active zone [m].

The embankment with a vertical facing slope reinforced with geotextiles and geogrids was designed according to the tie-back hypothesis and specifications given in LOTRAK designer's handbook (DON a LOW LTD. 1996). The applied calculation procedure was as below (see Fig. 5b).

Tensile force pulling out the reinforcement at given level was obtained from:

$$T_s = \sigma_n \cdot s \text{ [kN/m]} \tag{11}$$

where s = vertical spacing of reinforcement (in all cases $s = 0.5$ m);

$$\sigma_n = K \cdot \gamma \cdot z + K \cdot q_0 \text{ [kPa]} \tag{12}$$

$$K = (1 - \sin\Phi) \cdot \left(1 - \frac{z}{6}\right) + \frac{z}{6} \cdot \tan^2\left(45^\circ - \frac{\Phi}{2}\right) \tag{13}$$

where K = soil pressure coefficient; Φ = angle of internal friction of the fill [°]; z = depth below embankment crest [m]; q_0 = extra load on the embankment crest [kPa].

Having calculated the maximum tensile force T_z the working length of the reinforcement embedded in the passive zone was obtained from the formula:

$$L_b = \frac{F_b \cdot T_Z}{2 \cdot \gamma \cdot z \cdot \tan\delta} \text{ [m]} \tag{14}$$

where T_z = as above; F_b = safety coefficient = 1.2; γ = unit weight of fill [kN/m^3]; z = as above; δ = angle of friction between fill and reinforcement material, obtained from shear box test [°].

L_0 value at given level was calculated from the formula:

$$L_0 = (H - z) \cdot \tan\left(45^\circ - \frac{\Phi}{2}\right) \text{ [m]} \tag{15}$$

where H = total height of the embankment [m] (H = 3.0 m); z, Φ = as above.

Having calculated L_b and L_0 values, the L value was obtained as:

$$L = L_0 + L_b \text{ [m]} \tag{16}$$

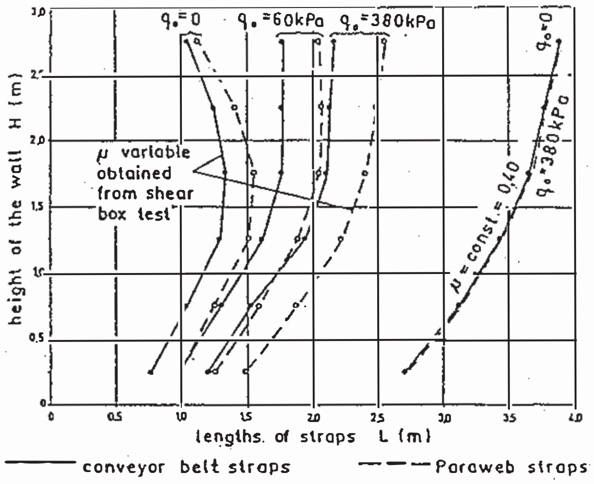

Figure 6. Influence of μ values on predicted strap length.

Results of strap length calculations are presented in Table 2.

Standard design procedure assumes the constant value of interface friction coefficient irrespective of reinforcement level. The value of 0.4 was developed from shear box tests as the equal half of stabilised value μ (= 0.8) and it approximately equals the value μ obtained from pull-out tests (Fig. 2). It results from Table 2 that predicted lengths of reinforcing straps are diminishing with the depth when the constant g values are assumed, but they are changing in a different way when the variable μ values are used, relevant to the actual vertical stress σ_v. Generally, lengths of straps calculated at $\mu = 0.4$ are 3–4 times greater then those determined for variable μ values whereas the variable p values determined for particular reinforcement levels are 3–18 times greater then value of 0.4.

The most interesting is the analysis including an extra load imposed on the embankment surface. Results of the calculations in graphical form are illustrated in Figure 6.

These graphs demonstrate the dependence of predicted strap lengths on extra vertical load acting on the surface of the structure. It results from these graphs that when the constant μ value is assumed, the predicted length of reinforcing straps does not depend on an extra load q_0. This apparent paradox results from the fact that the greater horizontal forces caused by the greater load qo are compensated in full by the greater frictional resistance produced by the greater vertical stress acting on the reinforcing straps.

Table 2. Total length of reinforcing straps in colliery spoil predicted for various and constant values of μ.

H	Overburden pressure σ_v	μ determined from shear box tests (variable) $\mu = \frac{C_S}{\sigma_v} + \mathrm{tg}\phi_S$ Conveyor belts		Paraweb straps		μ = constant = 0.40
						Conveyor belts and Paraweb
[m]	[kPa]	μ	L[m]	μ	L[m]	straps L[m]
2.75	5	7.050	1.04	5.50	1.11	3.87
2.25	15	2.810	1.23	2.26	1.39	3.77
1.75	25	1.960	1.36	1.61	1.56	3.66
1.25	35	1.600	1.29	1.33	1.51	3.43
0.75	45	1.395	1.04	1.17	1.27	3.11
0.25	55	1.260	0.77	1.08	1.01	2.68

Table 3. Predicted lengths of geotextile reinforcement calculated for the constant value of the angle of the interface friction δ obtained from shear box tests.

H	Colliery spoils $\delta = 35°$ L_0	L_b	$L = L_0 + L_b$	Pulverised fuel ash $\delta = 32°$ L_0	L_b	$L = L_0 + L_b$
[m]	[m]	[m]	[m]	[m]	[m]	[m]
2.80	1.37	0.16	1.53	1.68	0.25	1.93
2.5	1.22	0.16	1.38	1.50	0.24	1.74
2.0	0.98	0.15	1.13	1.20	0.24	1.44
1.5	0.73	0.15	0.88	0.90	0.23	1.13
1.0	0.49	0.14	0.63	0.60	0.22	0.82
0.5	0.24	0.14	0.38	0.30	0.22	0.52

In the case when variable μ values relevant to the actual vertical stress are assumed the calculated length of straps are increasing with the increase of vertical stresses, because greater horizontal forces are not compensated in full by frictional resistance due to diminishing μ values, therefore the lengths of straps have to be greater.

Generally the predicted lengths are diminishing with the depth below structure surface because the extent of acting zone is getting smaller (Fig. 5). The similar analysis was made for geotextiles where the length of reinforcement was calculated according to the tie-back hypothesis (Fig. 5) and (DON & LOW LTD. 1996), assuming the constant values of the angle of the interface friction obtained from the shear box tests. Results of these calculations are presented in the Table 3.

As previously, where the constant value of the friction coefficient was assumed the predicted lengths of reinforcement are diminishing with the depth below the embankment surface. The calculations were also made including an extra load qo and the results obtained revealed that there is no influence of an extra load on the predicted length of the reinforcement due to the same reason as in the previous case because the 8 value was assumed as con stant. The limitation of an extra load is only due to the tensile strength of reinforcement itself (ultimate limit state) or its extensibility (serviceability limit state).

5 EXPERIMENTAL RETAINING STRUCTURES

Taking into consideration the calculation results presented above two experimental structures in full scale (3 m high) were erected but due to technical reasons in practical design the constant lengths of reinforcement on all levels have been applied. The retaining wall was erected with the use of 4 m long straps and in the reinforced embankment the reinforcement 3.50 m long from geotextiles and geogrids was applied both in colliery spoils and in pulverized fuel ashes. The horizontal displacement of these two structures in their lifetime and caused by dynamic load (produced by numerous passes of heavy building plants) have been systematically recorded and the results (Michalski 2000) show that the behaviour of the structures is fully satisfactory and the internal stability has not been affected.

6 CONCLUSIONS

1. The interface friction coefficient strongly depends on the method of its determination and values obtained from shear box tests are greater than those derived from pull-out tests.

2. The value of normal stress σ_v acting on the reinforcement influences the value of friction coefficient – when σ_v is increasing, the values of friction coefficient are diminishing irrespectively of the determination methods.

3. The predicted length of reinforcement strongly depends on the friction coefficient and at its lower values the designed length of reinforcement should be greater.

4. If the constant value of interface friction coefficient is assumed in both design procedures described in the paper the calculated length of reinforcement does not depend on an extra vertical load.

5. The design procedures described in the paper can be recommended to use for temporary structures however designing should be yet conservative up to establishing the optimum method for determining the interface friction coefficient because this problem remains still open.

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