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THE INFLUENCE OF MOISTURE CONTENT ON SHEAR STRENGTH OF COHESIVE SOILS FROM THE LANDSLIDE AREA AROUND GORLICE

1. Introduction

Among basic geotechnical parameters, shear strength is of great practical importance. Knowledge of this parameter is necessary in designing engineering structures or soil embankments as well as in evaluating and predicting slope stability. In the majority of stability analysis, knowledge of effective strength parameters are necessary, but the high labour consumption of this research is the reason why it is often limited or omitted. Due to this, in engineering practice, a method for the determination of shear strength parameters which is more common, is where the values of total stress are known and the direct shear test is used most often. In natural conditions, geotechnical structures and slopes are occasionally fully saturated which furthes complicates calculations necessary for the determination of soil strength. There are however a few methods for characterizing the shear strength of unsaturated soils, among them the most common is the D.G. Fredlund's proposal [2]:

$$\tau_f = c' + (\sigma_n - u_a) \cdot \tan\phi' + (u_a - u_w) \cdot \tan\phi^b \tag{1}$$

where:

c' — effective cohesion,
σ_n — normal stress,
u_a — pore air pressure,
u_w — pore water pressure,
ϕ' — effective angle of internal friction,

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ϕ^b — the angle defining the increase of shear strength due to the increase in matric suction,
$\sigma_n - u_a$ — net normal stress,
$u_a - u_w$ — matric suction.

There are also a number of empirical formulas, which make it possible to determine the strength of an unsaturated medium in an approximate way. They are all presented in Vanapall and Fredlund's paper [7] or in Guan and others' work [4] , however, in most cases they are based on the knowledge of values of effective parameters and suction pressure. The latter parameter (suction pressure) is relatively uncommon in practice, these being parameters which are more often used to indicate the shear strength parameters which are liquidity or consistency indexes, which are a derivative of moisture content. That is why the formula presented in Matsushi and Matsukury's paper [5] is an interesting proposal for the description of the shear strength of unsaturated soils:

$$\tau_f = C \cdot e^{-\mu\theta} + \sigma \cdot \tan\phi' \qquad (2)$$

where:
C — maximum value of cohesion at $\theta = 0$,
e — base of natural logarithm,
μ — reduction coefficient,
ϕ' — effective angle of internal friction,
θ — volumetric water content.

The purpose of this paper was to determine the practicality of the above equation for the purposes of the simulation of the ch anges in shear strength in the aspect of changes in soil moisture content.

In the case of surface slope cover, the process of stability loss often occurs abruptly and the moving speed of sliding soil masses can be very high. Therefore, another purpose of this paper was to determine the influence of shear velocity on the values of the shear strength parameters.

2. Characteristic of testes soils

The tests were carried out on soil samples from the area around Gorlice, where the degree of mass movement activity is particularly high and mostly where structural landslides occur [1, 3, 8, 10, 12], which is mainly connected with the region's tectonics and the occurrence of the area where Magura nappe is thrusting on the Silesian unit.

In May and June 2010, in the area of Gorlice, a number of surface translational slides and mud flows as well as and mud debris flows were activated. In the paper there is an analysis of the shear strength of soils from two landslides, both of which were located between Bystra and Szymbark, in the bottom part of the Bystrzyca's slope and in the Siary village, on the left part of Siary stream valley. In table 1 basic physical parameters of testes soils were presented.

Based on graining, soil from Bystra was classified as a silty-gravely-sandy formation, where content of these three fractions is close. Soil from Siary was classified as clayey-sandy silt, which had a considerable content of silt fraction (54%). Clay fraction contents from both soils were close, from 11.1 to 11.7%, but soil from Bystra had a much higher plasticity.

TABLE 1
Geotechnical parameters of tested soils

Parameters	**Unit**	**Bystra**	**Siary**
Fraction content: — gravel (2–63 mm) — sand (0.063–2 mm) — silt (0.002–0.063 mm) — clay (< 0.002 mm)	[%]	 28.5 25.7 34.7 11.1	 4.4 29.7 54.2 11.7
Soil's type according to [6]		sagrsiS	saclSi
Natural moisture content	[%]	19.6	26.7
Specific density, ρ_s	[g·cm^{-3}]	2.68	2.66
Bulk density, ρ	[g·cm^{-3}]	1.95	1.94
Dry density ρ_d	[g·cm^{-3}]	1.63	1.53
Plasticity limit w_p	[%]	19.2	18.3
Liquid limit w_L	[%]	42.6	27.0
Plasticity index I_p	[%]	23.4	8.7
Swelling	[%]	2.14	1.48
Ignition loss, I_{om}	[%]	1.96	3.95

3. Tests methodology

Shear strength tests were carried out in standard direct shear box apparatus, on 60×60×20 mm samples. Between the upper and lower part of the box, two transitional frames were placed to minimize interlocking, which can occur during the test. Consolidation and shearing of samples were carried out under confining stress 25; 50; 75; 100 and 125 kPa, while for samples with the highest moisture content it was 12,5; 25; 37,5; 50 and 75 kPa. The duration of consolidation depended on the shear velocity. 15 minutes was allowed for samples that were sheared at the velocity of 0,1 mm·min^{-1} and 1 minute for samples that were sheared at the velocity of 1.0 or 10.0 mm·min^{-1}.

The material tested was devoid of grains which were more than 2 mm in diameter. In the tests carried out the shear criterion was maximum value of shear resistance for the relative deformation of samples from 0 to 10%.

Soil samples from Bystra were tested at natural moisture content and at a moisture content which was 5% lower than in natural conditions, as well as 5, 10 and 15% higher than that of natural conditions. Soil samples from Siary were also tested at a natural moisture content and at a moisture content that was 5% higher than in natural conditions, as well as 5, 10 and 15% lower than that of natural conditions. All in all, 110 soil samples were tested.

4. Tests results and their analysis

Tests results are presented in tables 2 and 3. Generally the range of the determined values of the shear strength parameters of both soils was very wide, but with a greater diversity of the angle of internal friction and cohesion found in the soil from Bystra. In each tested soil there was a clear relation between the shear strength parameters and moisture content as well as shear velocity.

TABLE 2
Shear strength parameters of soil from Bystra

Moisture content, |*w* [%]	**Liquidity index, I_L [—]**	**Shear velocity, vs [mm·min^{-1}]**					
		0.1		**1.0**		**10**	
		Angle of internal friction, ϕ [°]	**Cohesion, c [kPa]**	**Angle of internal friction, ϕ [°]**	**Cohesion, c [kPa]**	**Angle of internal friction, ϕ [°]**	**Cohesion, c [kPa]**
14.6	–0.20	44.8	33.2	16.3	17.5	29.3	56.3
19.6	0.02	35.6	20.6	14.5	20.1	12.1	35.1
24.6	0.23	31.2	11.1	—	—	—	—
29.6	0.44	29.2	8.3	—	—	—	—
34.6	0.66	24.0	8.2	6.9	9.4	4.3	5.0

TABLE 3
Shear strength parameters of soil from Siary

Moisture content, |*w* [%]	**Liquidity index, I_L [—]**	**Shear velocity, vs [mm·min^{-1}]**					
		0.1		**1.0**		**10**	
		Angle of internal friction, ϕ [°]	**Cohesion, c [kPa]**	**Angle of internal friction, ϕ [°]**	**Cohesion, c [kPa]**	**Angle of internal friction, ϕ [°]**	**Cohesion, c [kPa]**
12.5	–0.67	39.2	30.8	39.7	38.0	38.3	34.6
17.5	–0.09	37.8	30.0	—	—	—	—
22.5	0.48	37.0	14.4	—	—	—	—
27.5	1.06	36.0	8.2	29.6	8.1	14.2	3.7
32.5	1.63	31.8	9.4	29.4	3.9	17.7	3.5

When comparing the test results for the samples that were sheared with a velocity of 0,1 mm·min^{-1} it can be noticed that in the case of soil from Bystra, the increase in moisture content, which corresponded with change in liquidity index from –0.20 to 0.66, caused a decrease in the angle of internal friction by 20.8° and cohesion by 24.8 kPa, which means that the values of angle of internal friction and cohesion at the lowest moisture content were 46 and 75% respectively higher than the ones obtained at the highest moisture content. When considering soil from Siary with the same increase in moisture content, which at the same time corresponded with a change in the liquidity index from –0.67 to 1.63, caused had a similar impact on the decrease in cohesion (by 21,4 kPa, which corresponded with relative reduction of the value of the parameter equal to 69%), but it had a smaller impact on the value of the angle of internal friction (reduction by 7,4°, corresponding with relative reduction by 21%).

Changes in shear strength parameters were a little different for the tests carried out with higher values of shear velocity. In the test where shear velocity was 1.0 mm·min^{-1} the relative change in values of the angle of internal friction in the analyzed range of moisture content was greater for soil from Bystra (58%) than for soil from Siary (26%), whereas the relative change in values of cohesion for soil from Bystra (46%) was much smaller less than for soil from Siary (90%). The biggest changes in shear strength parameters were for samples sheared with a velocity of 10 mm·min^{-1}. The decrease in the values of the angle of internal friction in the analyzed range of moisture content for soil from Bystra was 24.4° (corresponding to reduction of the angle of internal friction by 85%) and for soil from Siary 20.6° (reduction by 54%), whereas the decrease in the values of cohesion for these soils was adequately 51.3 and 31.1 kPa (corresponding to 91% and 90% relative reduction of cohesion).

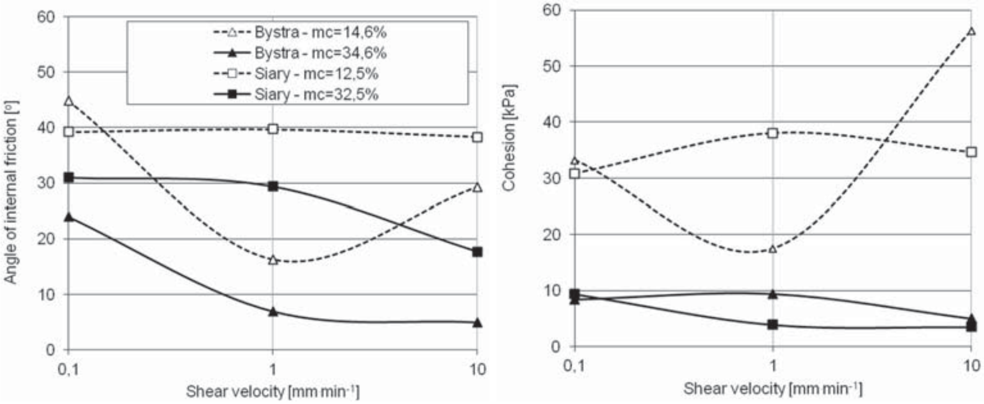

Fig. 1. Relation between values of angle of internal friction as well as cohesion and shear velocity

When comparing the values of the angle of internal friction and cohesion for samples with the lowest moisture content from Bystra, it can be stated that the least favorable values of these parameters were obtained in tests carried out with a shear velocity of 1.0 mm·min^{-1} (fig. 2). While by comparing the shear strength parameters for samples with low moisture content for soil from Siary, it can be noticed that they did not depend greatly on the shear velocity. Whereas tests results for samples with a high moisture content showed (fig. 2) that for both soils, with the increase in shear velocity, there is a decrease in the values of shear strength parameters.

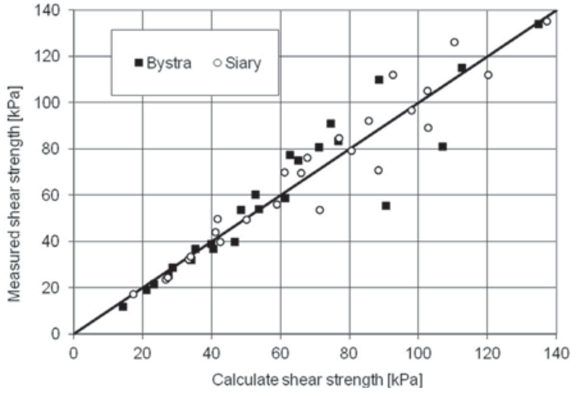

Fig. 2. The results of comparing shear strength calculated using Matsushi–Matsukura's formula and measured shear strength

Comparing the values of shear strength parameters of tested soils obtained at the similar values of the liquidity indexes, it can be stated that at the very stiff consistency (I_L = –0.20 for soil from Bystra and I_L = –0.09 for soil from Siary) the higher values of angle of internal friction and cohesion were obtained for soil from Bystra. In turn, at firm consistency (I_L = 0.44 for soil from Bystra and IL I_L = 0.48 for soil from Siary) more favorable values of the shear strength parameters were obtained for soil from Siary.

The results presented show the shear strength parameters obtained at specific moisture content of tested soils, and in most cases they describe the strength of unsaturated soil. Therefore, results of shear strength at a shear velocity of 0.1 mm·min^{-1} were used for determination of parameters of Matsushi–Matsukura [5] equation. The determined parameters of the equation shown in (2) in the case of tested soils were:

— for soil from Bystra — ϕ' = 24.2°, C = 1111.8 kPa, μ = 11.2,

— for soil from Siary — ϕ' = 33.5°, C = 265.2 kPa, μ = 9.3.

Later in the paper, the shear strength parameters, calculated using the equation shown in (2) and the above parameters for this equation, were compared with the measured results from (fig. 2). The comparison shows that all of the values of soil resistance calculated using Matsushi-Matsukura's equation are basically concurrent with measured results, but low values of soil resistance, for samples with high moisture content, show closer matching.

In order to define the differences between the classic method of describing shear strength, which is based on the simplest form of Coulomb's equation, and the method that is presented by Matsushi-Matsukura for unsaturated mediums in the latter part of this paper, slope stability calculations were carried out for a hypothetical slope with an inclination of 30° and the depth of the potential slip surface of 1,5 m below ground level. Slope stability was estimated in a classic depiction, using Skempton-McLory's [9] equation:

$$FS = \frac{c' + (\gamma_{sr} - \gamma_w) \cdot Z \cdot \cos^2\alpha \cdot \tan\phi'}{\gamma_{sr} \cdot Z \cdot \sin\alpha \cdot \cos\alpha} \tag{3}$$

where:

α — slope angle,
Z — vertical depth of slip surface,
γ_{sr} — unit weight of saturated soil,
γ_w — unit weight of water.

In the calculations it was accepted that the soil medium is unsaturated, therefore, value $\gamma_w = 0$ and the above equation comes down to the formula, which accounts only values of total stress in the ground:

$$FS = \frac{c + \gamma \cdot Z \cdot \cos^2\alpha \cdot \tan\phi}{\gamma \cdot Z \cdot \sin\alpha \cdot \cos\alpha} \tag{4}$$

where: γ — unit weight of soil.

When stability calculations based on Matsushi–Matsukury's equation were carried out using the equation that was proposed by the same team of scientists in their other paper [6]:

$$FS = \frac{\tan\phi'}{\tan\alpha} + \frac{C \cdot e^{-\mu\theta}}{(\gamma_d + \theta \cdot \gamma_w) \cdot Z \cdot \sin\alpha \cdot \cos\alpha} \tag{5}$$

where:

α, Z, γ_w — as in formula (3),
γ_d — unit dry weight of soil,
C, e, ϕ', μ, θ — as in formula (2).

Stability calculation results are illustrated on figure 3 and show, that the factors of stability calculated using formulas (3) and (5) differ significantly. For both soils with a low moisture content, lower values of safety factor were calculated according to the basic Skempton-McLory's formula. For samples with a high volumetric moisture content a more unfavorable safety factor value was calculated using formula (5) which is based on Matsushi–Matsukury's model.

5. Summary

In this paper there are results presented for tests carried out on soils from surface layers of landslide slopes from the area around Gorlice. They showed a significant relation between the determined values of shear strength and moisture content as well as the shear velocity used during tests. The results presented verify the generally known relation, which says that an increase in soil' moisture content causes a decrease in its shear strength values, additionally the range of change is also related to shear velocity. Relations derived from tests carried

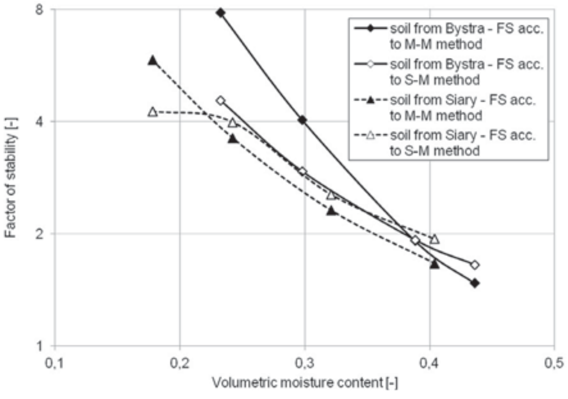

Fig. 3. Comparizon of calculation results of factor of stability using model of homogeneous slope according to Skempten–McLory's and Matsushi–Matsukury's methods

out indicate that the higher the shear velocity, the greater the influence of moisture content on the values of the angle of internal friction and cohesion.

In the case of the analyzed soils, the shear strength values determined using Matsushi and Matsukura's method showed a relatively good conformity with the measured results. However, results of stability calculations based on this method for soils with a high moisture content were worse in relation to Skemtona–McLory's method results. A reverse relation was defined when test soils had a low moisture content. Matsushi–Matsukura's method makes the shear strength of unsaturated soils dependent on their moisture content, which makes this method relatively easy to use in engineering practice for slope stability estimation.

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