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Shear strength investigation of soils in landslide areas

Tymoteusz Zydroń,

Eugeniusz Zawisza

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The paper presents results of testing the peak and residual shear strength of soils of flysch origin, taken from the areas of shallow landslides situated in Beskid Mały and Beskid Niski regions of southern Poland. The tests were carried out in a standard direct shear apparatus with the box dimensions 120 × 120 × 97 mm, its intermediate frames forming a shearing zone 10 mm high. It was stated that for calculating the stability of landslide slopes, it seems to be the safest to take the residual strength parameters determined at the maximum moisture content of the soil subjected to shearing in the range of relative deformations of a sample in the order of 10%. The obtained residual values of the angle of internal friction of the test soils significantly depend on the values of the liquid limits and plasticity index, i. e., with increasing these parameters, the values of the angle of internal friction decrease. However, the nonzero residual values of cohesion, obtained from tests, should be omitted in stability calculations.

Key words: shallow landslides, peak and residual shear strength, Carpathian flysch

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Tymoteusz Zydroń, Eugeniusz Zawisza. Department of Hydraulic Engineering and Geotechnics, University of Agriculture, al. Mickiewicza 24/28, 30-059 Kraków, Poland. E-mail: kiwig@ur.krakow.pl

INTRODUCTION

Landslides can be rated among the natural phenomena that influence the relief to a significant extent. There are estimates showing that costs due to mass movement damages are greater than those due to earthquakes (Graniczny, Mizerski 2007). For example, in the years 2000 to 2001, the costs of damages caused by landsides in Malopolska Voivodship exceeded 173 mln PLN (Poprawa, Rączkowski 2003). That is why any actions aiming at determining the mechanism of the origin of the phenomenon, including a geological and geotechnical survey as well as analyses of slope stability conditions, are of high importance.

Shear strength, characterized by the angle of internal friction and cohesion is one of the basic geotechnical parameters describing the mechanical characteristics of soil in the aspect of its stability. In the case of standard tests (PN-88/B-04481), the strength parameters are determined on the basis of the value of a maximum resistance to the tangential stresses. Whereas, from the point of view of active slope stability, the residual strength, which characterizes soil strength after overcoming the maximum shear resistance, seems to be important. That is why the determination of the peak and the residual shear strength of soils of flysch origin from Beskid Mały and Beskid Niski regions of Southern Poland was the subject of the tests presented in the paper. The study related to landslides in these regions has taken a few years (Michalski et al., 2006; Zydroń, Niebylski, 2008; Zydroń et al., 2010).

CHARACTERISTICS OF THE TEST SOILS

The soils for tests were taken from the areas of shallow landslides (Fig. 1) situated in:

– Targanice near Andrychów (Beskid Mały), where in August 2005, after a heavy rainfall, loss of the stability of several slopes occurred (on Złota Górka and, among other places, in the vicinity of Wrzosowa and Brzezińska streets). Soil samples from Złota Górka were taken from an intact part of the slope, up the slide that had damaged an unsurfaced forest road. Samples from the neighborhood of Wrzosowa Street were taken from the slide colluvium, and soil samples from Brzezińska Street were taken from an intact part of a slope of one of the three landslides that had arisen in that place;

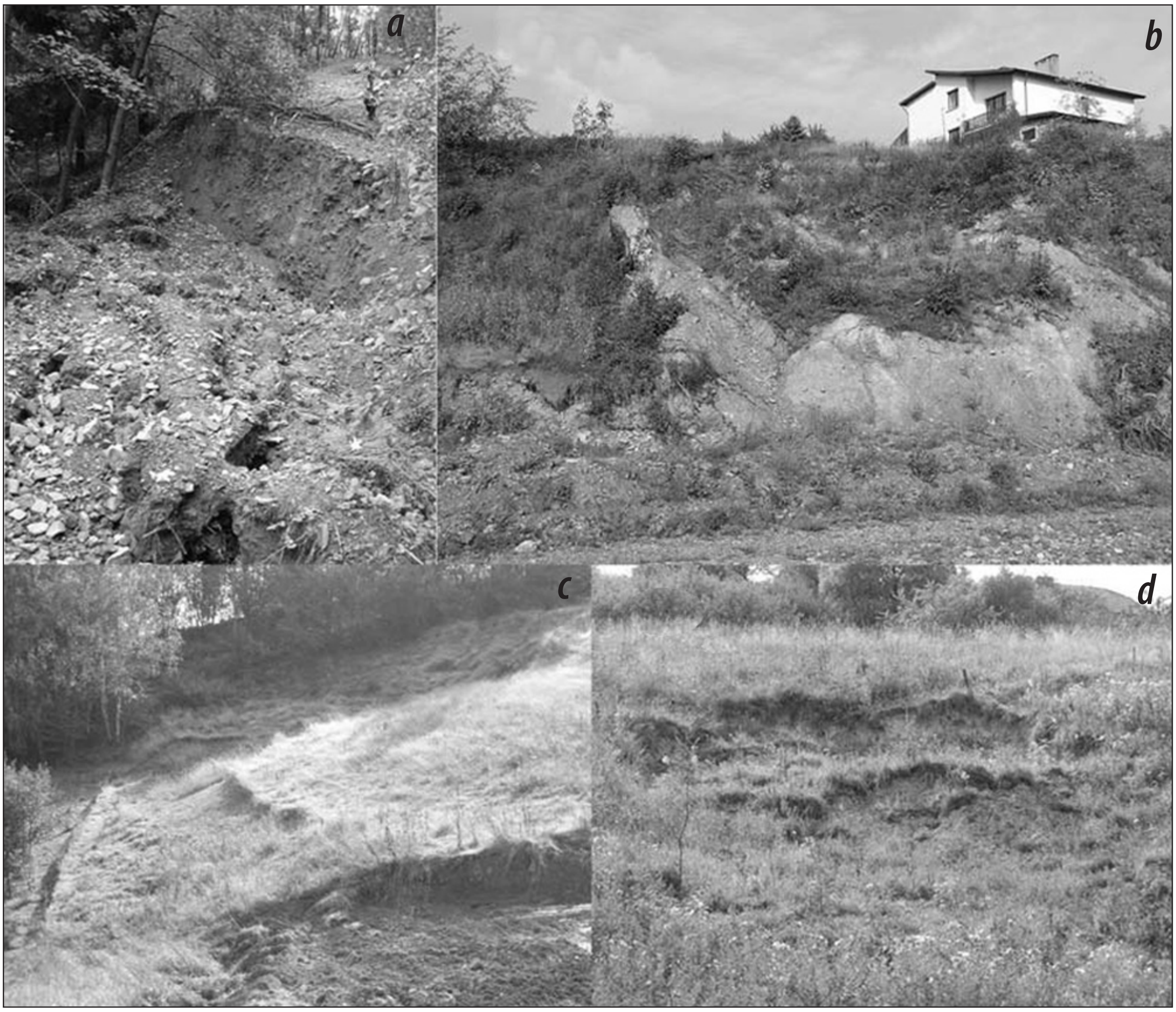

Fig. 1. Sampling sites: *a* – landslide at the road on Złota Górka, *b* – landslide in the vicinity of Wrzosowa Street in Targanice, *c* – landslide in the vicinity of Brzezińska Street in Targanice, d) slide niche in Szymbark
1 pav. Bandinių paėmimo vietos: *a* – nuošliauža Złota Górka kelyje, *b* – nuošliauža Wrzosowa gatvės (Targanice) apylinkėse, *c* – nuošliauža Brzezińska gatvės (Targanice) apylinkėse, *d* – nuošliauža Szymbark vietovėje

– Szymbark (Beskid Niski), where in June 2006, in the lower part of Wiatrówka slope, a shallow landslide occurred. Soil samples were taken from the material of the landslide colluvium (No. 1) as well as from a lower intact part of the slope (No. 2). It should be stressed that on this slope, periodically, an active deep structural slide occurs, which, among other things, damages the houses situated within its limits.

The basic physical properties of the test soils were set together in Table 1. Soils from the Beskid Mały region were coarse-grained gruss formations of Godula sandstone and shales from the borderland of the Silesian and Subsilesian Units (Western Outer Carpathians, Poland); their granulation corresponded to that of silty gravels. Moisture content in the described soils was comparatively low, they were of hard and moderately hard consistency (I_L = –0.35 to –0.15). Soils from Beskid Niski (Szymbark) were cohesive formations of the edge part of the Magura Nappe and contained a small amount of coarser chips of rock corresponding to gravel fraction, and their granulation corresponded to clayey silts. Soil from the colluvium was of slightly plastic, close to moderately hard consistency, whereas the soil occurring beneath was of hard consistency (I_L = –0.19 to 0.08).

METHODS

The tests were carried out in a standard direct shear apparatus, box dimensions 120 × 120 × 97 mm, with intermediate frames forming a shearing zone 10 mm high – in order to limit the influence of the so-called apparent cohesion resulting from grains interlocking and blocking against one

Table 1. **Physical properties of test soils**
1 lentelė. **Tirtų gruntų fizikiniai parametrai**

Parameter	Sampling site					
	Złota Górka	Targanice Wrzosowa Str.	Targanice Brzezińska Str.		Szymbark	
			Soil No. 1	Soil No. 2	Soil No. 1	Soil No. 2
Fraction content, %:						
– cobbles >63 mm	–	12.0	–	–	–	–
– gravel 63–2 mm	41.8	53.1	50.2	57.7	8.2	9.9
– sand 2–0.063 mm	18.8	19.2	15.7	17.6	14.3	8.5
– silt 0.063–0.002 mm	33.0	11.1	25.0	20.6	62.7	58.6
– clay < 0.002 mm	6.4	4.6	9.1	4.1	14.8	22.9
Name acc. to PN-EN ISO 14688 (5)	siGr	siGr	siGr	siGr	siCl	siCl
Density of solid particles, $g \cdot cm^{-3}$	2.75	2.83	–	2.70	2.78	2.69
Natural moisture content, %	13.0	10.9	13.9	14.6	20.5	17.8
Total moisture content, %	16.7	19.1	18.3	17.0	32.4	18.6
Bulk density, $g \cdot cm^{-3}$	2.13	2.04	2.06	2.12	1.76	2.11
Dry density, $g \cdot cm^{-3}$	1.88	1.84	1.81	1.85	1.46	1.79
Porosity, –	0.46	0.54	0.49	0.46	0.90	0.50
Consistency limits[a], %						
– plastic	15.2	13.5	17.3	16.5	19.0	22.4
– liquid	21.5	30.8	27.1	26.4	38.6	46.5
Plasticity index, %	6.3	17.3	9.8	9.9	19.6	24.1
Liquidity index, –	–0.35	–0.15	–0.35	–0.19	0.08	–0.19

[a] For the fraction finer than 2 mm.

another. Materials for the tests contained no grains coarser than 10 mm. The samples were formed directly in the box of the apparatus at the natural or close to total moisture content, and in the latter case the formed samples stayed in water for several days before the tests. Before shearing, consecutive samples had been loaded for one minute with a vertical load of 12.5; 25; 37.5, 50 and 62.5 kPa and then sheared at the rate of 1.0 mm/min. Each sample was sheared four times (the upper base of the apparatus was reversed to the initial position after each shearing) to determine the shear resistance, i. e. to get the residual shear strength.

The peak shear strength was determined during the first shearing as a value of the maximum resistance (brittle shear) or resistance corresponding to a relative deformation of samples (10 and 15%). The former value results from the requirements of a standard procedure of tests in a direct shear apparatus in the case when there is no brittle shear (PN-88-/B-04481). The latter value corresponds to the maximum relative deformation possible to obtain in the used apparatus; it aimed at determining the value of the soil shear resistance for a wide range of deformations. The residual shear strength was determined as an established value of resistance in the last shearing of a sample. Calculations of the shear strength were carried out using the formula

$$\tau = \frac{F}{A}, \quad (1)$$

where F = force causing the box displacement, A = the area of a sample.

So, it was assumed that the area of shearing is constant, independent of the value of the box displacement, which is in agreement with recommendations of the British standard (BS 1377: Part 7: 1990). For the quantitative assessment of a decrease of shear strength of the test soils, the Haefeli (1965) index was calculated using the formula

$$\lambda_B = \frac{\tau_r}{\tau_p}, \quad (2)$$

where τ_r = residual shear strength, τ_p = peak shear strength.

The values of the shear strength parameters, i. e. the angle of the internal friction and the cohesion, were calculated using the least squares method.

RESULTS AND DISCUSSION

The values of the parameters describing the shear strength of the test soils are within a fairly broad range (Table 2). The relatively high values of these parameters result probably from the presence of sharply-edged pieces of rock in the test soils as well as from their relatively low moisture content corresponding basically to the soils of moderately hard and hard consistency (I_L = –0.35 to 0.08).

On the basis of the obtained results, it was stated that the values of the shear strength and the parameters describing it to a large extent depended on the moisture content of the soils. Although the increase of moisture content in the soils from the natural level to the one corresponding to the total moisture content was insignificant (3 to 8%), changes in

Table 2. **Values of shear strength parameters of test soils**
2 lentelė. **Tirto grunto kerpamasis stipris**

Origin of the soil sample	Name of the soil	Moisture content	Liquidity index	Range of relative deformation	Maximum parameters		Residual parameters	
					Angle of internal friction	Cohesion	Angle of internal friction	Cohesion
		[%]	[–]	[%]	[°]	[kPa]	[°]	[kPa]
Złota Górka	siGr	13	–0.35	10	41.5	21.0	37.4	9.1
		16	0.13	10	21.4	11.8	24.1	5.9
Targanice Wrzosowa Str.	siGr	13	–0.15	10	37.3	18.5	36.2	3.9
				15	37.3	18.5	38.2	6.4
		19	0.32	10	10.6	5.5	11.6	2.8
				15	14.1	5.4	14.5	4.1
Targanice Brzezińska str. – soil No. 1	siGr	14	–0.35	10	41.8	41.1	39.2	10.4
				15	41.8	41.1	39.4	12.5
		18	0.07	10	28.6	3.0	26.3	0.2
				15	31.3	3.5	29.6	2.6
Targanice Brzezińska Str. – soil no. 2	siGr	14.5	–0.19	10	42.2	34.8	42.7	4.6
				15	42.2	34.8	46.7	4.2
		17	0.05	10	26.8	18.8	26.9	5.2
				15	30.3	17.2	31.9	7.1
Szymbark – soil No. 1	clSi	23	0.08	10	30.5	16.7	31.3	12.5
		31	0.61	10	6.6	3.2	6.6	1.5
Szymbark – soil No. 2	clSi	17.5	–0.19	10	37.4	46.7	23.3	6.0
				15	37.4	46.7	28.6	5.1
		22	–0.02	10	24.1	29.1	8.6	8.7
				15	24.1	29.1	9.8	9.1

the peak shear strength of the soils were very distinct (Figs. 2 and 3), and in extreme cases a multiple decrease was noted. Changes in the shear strength of soils were also reflected in the changed values of the angle of internal friction and cohesion. For example, for soil No. 2 from Brzezińska Str. in Targanice, the increase of the moisture content only by 2.5% caused a decrease in the value of the angle of internal friction by 12–15° and in cohesion by 16–18 kPa. Then, the biggest changes of the strength parameters were noted for soil No. 1 from Szymbark, in which the increase of moisture content by 8% caused almost a fivefold decrease of the angle of internal friction (from 30.5° to 6.6°) as well as of cohesion (from 16.7 to 3.2 kPa).

A multiple shearing of a sample of soil was found to create a weak surface and to decrease the initial shear strength (Figs. 2 and 3). The obtained values of the Haefeli index varied from 0.23 to 0.97, indicating that the values of residual strength were 23 to 97% of the value of the peak shear strength. The differences between the values of the peak and residual shear strength significantly correlated with the moisture content of soils. At the moisture content close to natural, the obtained values of the Haefeli index varied within 0.23–0.82 and were significantly lower than in the case of tests conducted at the moisture content close to total (0.29–0.97). The obtained differences in the Haefeli indexes resulted from different characteristics of the relationship of shearing resistance to deformation at the consecutive shearings of the soil samples. In the tests conducted on samples with the moisture content close to natural, in most cases the first shearing was brittle with a distinct maximum, whereas the next shearings were of a plastic character, and the least value of the shear strength was reached usually during the last shearing (Fig. 4a). In such cases, the difference between the values of the peak and residual shear strengths was great, whereas in testing soil samples with the moisture content close to the total one, the nature of the relationship between shearing and deformation corresponded to the plastic shearing both at the first and at the consecutive shearings of the same samples (Fig. 4b). Hence, the difference between the peak shear strength during the first shearing of a sample and the established shear strength during its last shearing was small.

The reduction of shear strength was principally connected with a distinct decrease of cohesion and small changes in the angle of internal friction. For part of the samples, the obtained values of the residual angle of internal friction were bigger than its maximum values. Similar relationships are presented also in other papers (Borecka et al., 2006, Zabuski et al., 1999) and result from the fact that the relative reduction of the shear strength along the broken surfaces decreases along with an increase of the normal stresses.

In the literature (Atkinson, 1993) one can read that the residual strength is obtained at a broad range of relative deformations of samples. In the case of the test soils, the obtained values of shear strength parameters were slightly dependent on the relative deformation of samples. The

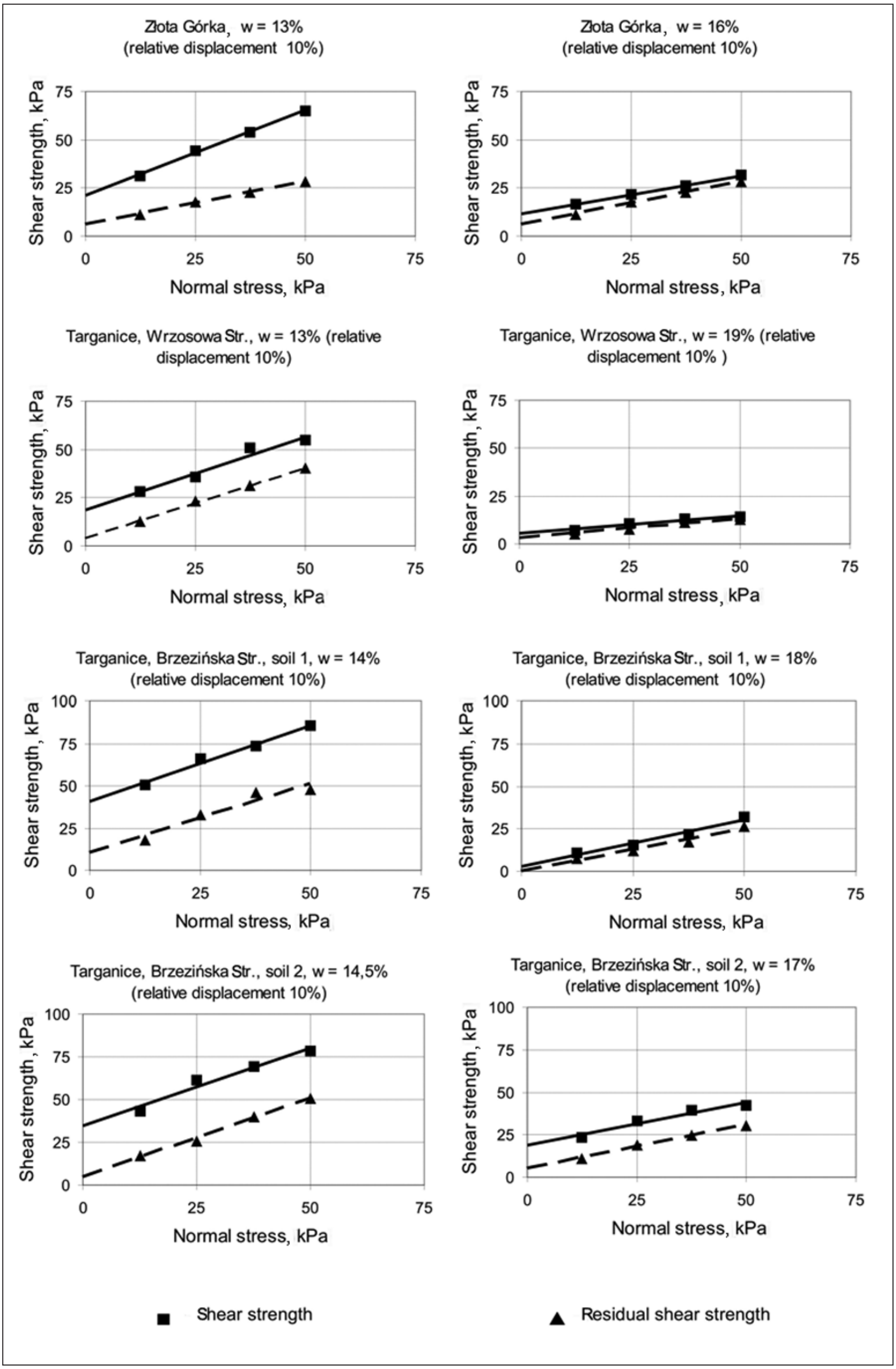

Fig. 2. Shear strength of soils from Beskid Mały

2 pav. Beskid Mały grunto kerpamojo stiprio testai

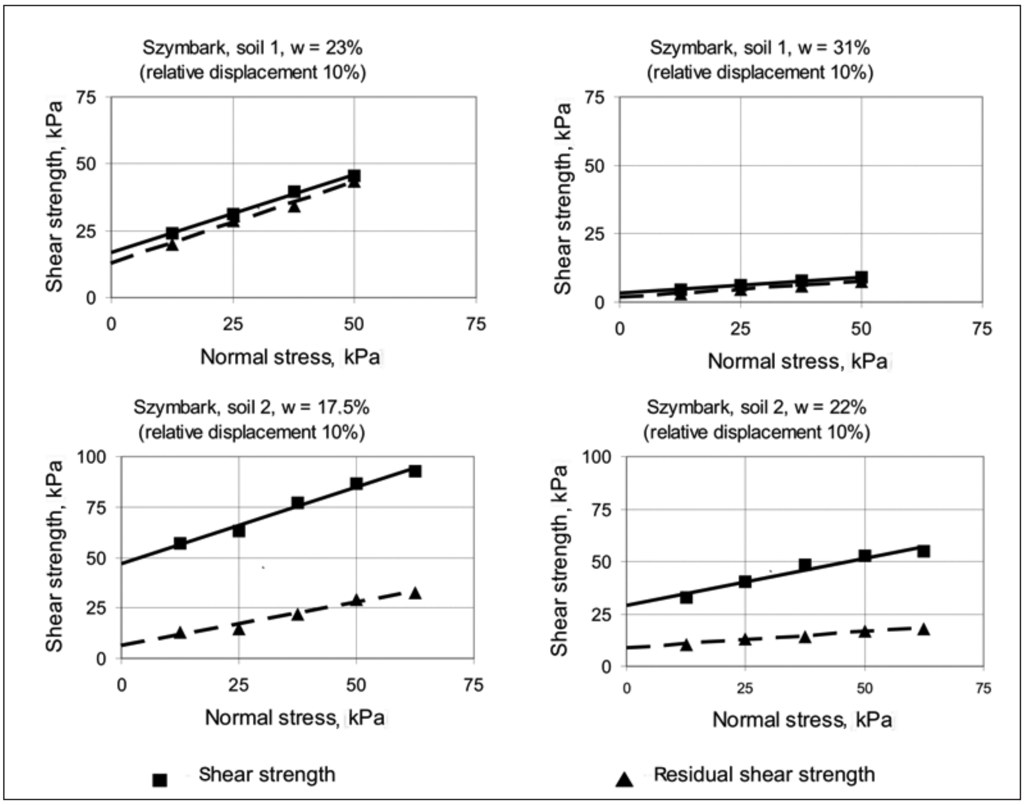

Fig. 3. Shear strength of soils from Beskid Niski
3 pav. Beskid Niski grunto kerpamojo stiprio testai

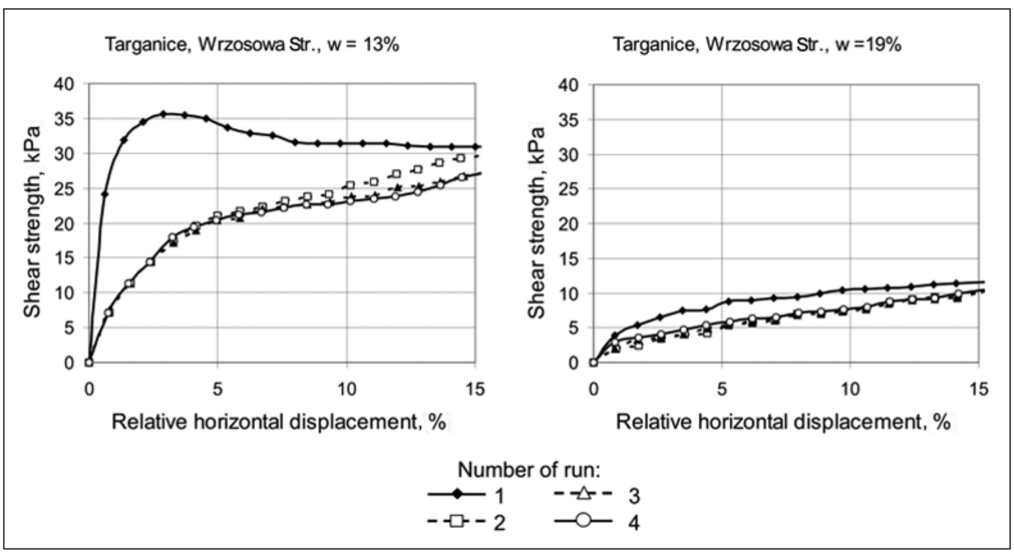

Fig. 4. Examples of relationships between shear strength and relative deformation of soil (normal stress 25 kPa)
4 pav. Sąryšio tarp kerpamojo stiprio ir santykinės grunto deformacijos pavyzdžiai (normalus įtempis – 25 kPa)

values of the angle of internal friction and cohesion, corresponding to the peak shear strength of the samples with the natural moisture content, basically show no dependence on the magnitude of deformation, since the relationship between the resistance of soil and deformation was of the character corresponding to a brittle shearing, and the maximum value of the shear strength was noted at the initial phase of shearing. However, the relationship was different when the shearing was of a plastic character: part of samples during the first shearing (mainly soils with the moisture content close to total) as well as all the samples during the consecutive shearings. During these tests, a constant increase of shear resistance occurred, and the obtained values of shear resistance at a 15% deformation of samples were higher than the values obtained at a 10% deformation, which influenced mainly the values of the internal friction angles, i. e. samples subject to bigger deformations gained bigger values of the maximum (by 0.0 to 3.5°) and residual angles of internal friction (by 0.2 to 5.3°, on average 2.1°)

Attention should be paid to the fact that in the case of the test soils, non-zero values of residual cohesion were obtained. In the literature on the subject (Smoltczyk, 2002), residual strength is described only by the value of the residual angle of the internal friction. On the other hand, results of tests from landslides (Carubba, Fabbrio, 2008, Gullà et al., 2004, Wen et al., 2007) show that soils of the slide zones can have a non-zero cohesion. In the case of the test soils, lower and lower cohesion values were noted at the consecutive shearings, and the final values of this parameter (after the last shearing) usually did not exceed 10 kPa. The obtained residual cohesion to a large extent results from a linear description of the shear resistance envelope. As stressed, among others, by Stark and Eid (1990), a curvilinear strength envelope should be used for assessing the residual shear strength, which permits making the residual shear strength to depend only on the value of the angle of internal friction. Moreover, an additional factor responsible for the residual cohesion is the effect of capillary forces in soil.

Some authors (Collotta et al., 1989, Stark, Eid, 1990) say that the residual shear resistance of cohesive soils depends on their mineral composition, clay fraction content and liquid limit, which is the indicator of the above-mentioned soil characteristics. Nevertheless, an investigation of Wen et al. (2007), conducted *in situ* on soils in sliding zones, showed a very weak relationship between the residual strength and the contents of clay fraction and consistency limits (Atterberg limits). However, this strength was to a large extent correlated with both the contents of gravel fraction and of the finest fractions (silt and clay fractions together). In the case of the test soils, the smallest value of shear strength, and thus the most unfavourable values of the angle of internal friction and cohesion, were obtained for samples with the moisture content close to the total one subjected to shearing in the range of 10% of relative deformation. A comparison of the obtained results shows that the values of the residual angle of internal friction of the test soils were to quite a good degree correlated with the values of liquid limits and plasticity indexes (Fig. 5). The highest values of the residual angle of internal friction were obtained for the soils from Złota Górka and Brzezińska Str. in Targanice. They showed low values of liquid limit (21.5 to 27.1%) and a low plasticity (plasticity index 6.3 to 9.9%). Medium values of the residual angle of internal friction were obtained for the soil from Wrzosowa Str. in Targanice of medium plasticity (liquid limit 30.8% and plasticity index 17.3%), and the smallest values were found in soils from Szymbark, which showed the biggest values of liquid content (38.6 to 46.5%) and plasticity index (19.6 to 24.1%).

Results of the shear test revealed that multiple shearing caused a decrease of the initial shear strength of the test soils. In practice, it may be important to determine how the residual parameters change the slope stability conditions. In the further part of the paper, there are presented results of stability calculations for an example of a slope at the assumed cylindrical slip surface. The values of the safety factors were calculated using the ordinary method of Slices (Fig. 6). The calculations were made assuming that the values of the angle of internal friction and cohesion, obtained at the maximum moisture content, corresponded to the undrained shear test, and the influence of the groundwater surface on the stability can be represented by seepage forces (see Table 2). Calculations of slope stability

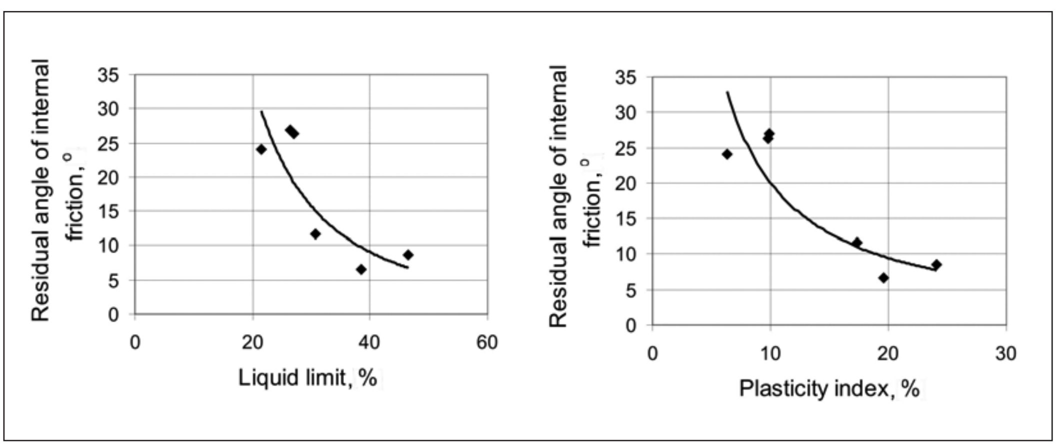

Fig. 5. Relationships of obtained residual values of the angle of internal friction versus liquid limit and plasticity index of test soils
5 pav. Sąryšis tarp grunto vidinės trinties kampo liekaninių reikšmių, takumo ribos ir plastiškumo indekso

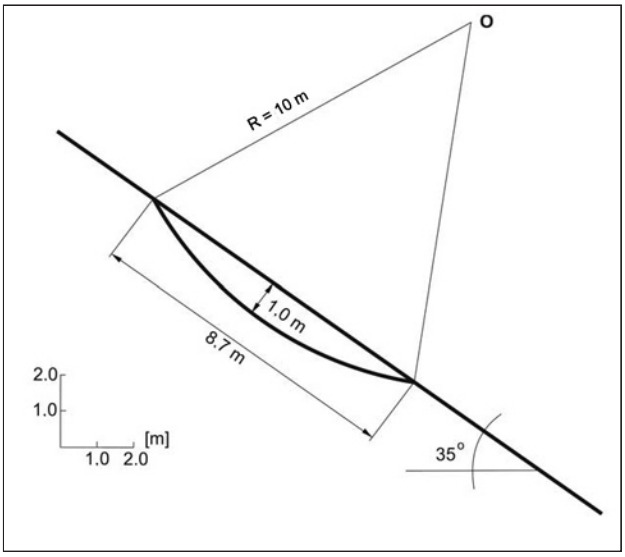

Fig. 6. Scheme of stability calculation
6 pav. Stabilumo apskaičiavimo schema

(Table 3) revealed that calculations performed using residual parameters gave significantly lower values of the safety factors, safer from the point of view of estimating the slope stability conditions.

Table 3. **Results of slope stability calculations**
3 lentelė. **Šlaito stabilumo apskaičiavimo rezultatai**

Origin of slope sample	Values of safety factors determined for:	
	peak shear strength	residual shear strength
Złota Górka	1.56	0.95
Targanice Wrzosowa Str.	0.73	0.45
Targanice Brzezińska Str. – soil No. 1	0.70	0.36
Targanice Brzezińska Str. – soil No. 2	2.40	0.91
Szymbark – soil No. 1	0.43	0.24
Szymbark – soil No. 2	3.48	1.05

CONCLUSIONS

On the basis of the obtained results, we could state that the values of the shear strength and the parameters describing it, obtained for the soils from the areas of shallow landslides, are very diverse and strongly depend on variations in moisture content. At the natural moisture content (I_L = –0.35 to 0.08), the obtained values of the angle of internal friction and cohesion of the test soils were big and guaranteed stability even at a big inclination of slopes. A small increase of moisture content (in the order of a few per cent; I_L = –0.02 to 0.61) caused a significant, even multiple, decrease of the values of strength parameters.

The multiple shearing of the soils caused a braking of their structure integrity and, as a consequence, a decrease of the initial shear strength, in the extreme cases even by 80%. The value of the reduction of the peak shear strength of soils depended on the moisture content: changes in the strength of soils with a higher moisture content after breaking the integrity of their structure were small. These changes were mainly caused by the decreased cohesion and, to a smaller extent, by the changed angle of internal friction.

The results of the tests showed also a limited influence of the relative deformation of the sheared samples on their strength parameters. In the case of very moist soils, smaller and consequently safer values of the angle of internal friction, both maximum and residual, were obtained in the range of the relative deformations of a sample in the order of 10%.

To calculate the stability of landslide slopes, it seems to be the safest to take the residual strength parameters determined at the maximum moisture content of the soil subjected to shearing in the range of relative deformations of a sample in the order of 10%. The obtained residual values of the angle of internal friction of the test soils are significantly dependent on the values of the liquid limits and the plasticity index, i. e., with increasing these parameters, the values of the angle of internal friction decrease. However, the non-zero residual values of cohesion, obtained in the tests, should be omitted in stability calculations.

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Tymoteusz Zydroń, Eugeniusz Zawisza

GRUNTO KERPAMOJO STIPRIO TYRIMAI NUOŠLIAUŽŲ SRITYSE

Santrauka

Remiantis tyrimų rezultatais nustatyta, kad kerpamasis stipris ir kiti mechaninių savybių parametrai yra labai kaitūs ir tą lemia daugiausia ryškūs drėgnio pokyčiai nuošliaužų srityse. Natūralaus drėgnio sąlygomis (I_L = –0,35 iki 0,08) nustatytos gana didelės tirtų gruntų vidinio trinties kampo ir sankibos reikšmės užtikrina šlaitų stabilumą net didelio šlaito polinkio kampo atveju. Tačiau ir nedideli uolienos drėgnio pokyčiai (I_L = –0,02 iki 0,61) labai pakeičia grunto stiprio parametrus. Daugkartinis grunto uolienų kirpimas pažeidė jų struktūrinį vientisumą, todėl uolienų stipris kai kurias atvejais sumažėjo iki 80 %. Šiuos stiprio pokyčius daugiausia lemia drėgnis, kuris labai paveikia sankibos parametrą ir mažiau – vidinės trinties kampą.

Raktažodžiai: seklios nuošliaužos, didžiausias ir išliekamasis kerpamasis stipris, Karpatų flišas