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EVALUATION OF UNDRAINED SHEAR STRENGTH OF MIOCENE CLAY FROM THE WEIGHT SOUNDING TEST (WST)

OCENA WYTRZYMAŁOŚCI NA ŚCINANIE W WARUNKACH BEZ ODPŁYWU IŁÓW MIOCEŃSKICH NA PODSTAWIE BADAŃ SONDĄ WKRĘCANĄ WST

Soil strength parameters needed for the calculation of bearing capacity and stability are increasingly determined from field testing. This paper presents a method to determine the undrained shear strength c_{uWST} of the soil, based on the Weight Sounding Test (WST). The innovative solution which allows for a significant reduction of equipment needed for geotechnical field investigation is presented. The proposed method is based on an additional measurement of the torque during testing. It then becomes possible to estimate the undrained shear strength, c_{uWST} of the soil, using the correlation given in this paper. The research results presented in this paper were carried out on selected cohesive soils, Miocene clays from the Carpathian Foredeep.

Keywords: clay material mining, geotechnical engineering, weight sounding test WST, field vane test FVT, undrained shear strength

Do jednych z podstawowych problemów natury geotechnicznej w kopalniach odkrywkowych należy zaliczyć przede wszystkim stateczność skarp i zboczy. Osuwiska zboczy zwałowisk i wyrobisk zaliczane są do głównych zagrożeń naturalnych występujących w górnictwie odkrywkowym (Cała, 2007). W 2013 roku eksploatacja surowców ilastych prowadzona była w 267 zakładach górniczych z czego 244 to odkrywkowe kopalnie iłu na potrzeby ceramiki budowlanej (Bilans, 2014).

W normie PN-EN 1997-1 (2008), w odniesieniu do projektowania posadowienia bezpośredniego, należy rozpatrzyć różne stany graniczne, w tym sprawdzić stan graniczny nośności podłoża. W rozumieniu normy, nośność podłoża jest spełniona, gdy wartość obliczeniowa obciążenia pionowego albo składowa całkowitego oddziaływania, działająca prostopadle do podstawy fundamentu jest mniejsza bądź równa obliczeniowej wartości oporu ścinania. W warunkach bez odpływu, obliczeniowy opór ścinania jest równy iloczynowi wytrzymałości na ścinanie bez odpływu i polu całkowitej powierzchni fundamentu przekazującej nacisk na grunt. Zatem znając wartości wytrzymałości na ścinanie sondowanego gruntu, łatwo ustalić czy dany grunt spełnia warunek nośności oraz na jakiej głębokości minimalnej, ten i inne warunki posadowienia są spełnione.

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Podobna sytuacja ma miejsce w przypadku projektowania nowo wznoszonych budowli ziemnych lub zapewnienia stateczności zboczy naturalnych gdzie wymagana jest ilościowa ocena stateczności. Na stateczność tę wpływa wiele czynników, do których należy zaliczyć: geometrię zbocza, budowę geologiczną, wytrzymałość na ścinanie gruntów tworzących zbocze czy skarpę oraz działające nań obciążenia, ze szczególnym uwzględnieniem wpływu wody gruntowej (Cała, 2007). W analizach stateczności wykorzystywane są różne metody, ale najczęściej metody równowagi granicznej i metody numeryczne, gdzie wynikiem obliczeń jest bezwymiarowy parametr, zwany wskaźnikiem stateczności FS lub wskaźnikiem bezpieczeństwa SF. Określany jest on jako stosunek wytrzymałości gruntu na ścinanie do rzeczywistych naprężeń ścinających działających na powierzchni poślizgu.

Wyznaczenie parametrów wytrzymałościowych gruntów niezbędnych w obliczeniach nośności i stateczności realizowane jest obecnie coraz częściej tylko na podstawie badań polowych. Artykuł przedstawia propozycję metody pozwalającej określić wytrzymałość gruntu na ścinanie w warunkach bez odpływu c_{uWST}, na podstawie badań sondą wkręcaną WST. To nowatorskie rozwiązanie pozwala na znaczne ograniczenie używanego sprzętu w trakcie prowadzenia geotechnicznych badań polowych. Proponowana metoda polega na prowadzeniu dodatkowego pomiaru wartości momentu skręcającego T_{WST} w trakcie wykonywania sondowania WST. Następnie, za pomocą podanych w artykule zależności można, dla badanego gruntu, oszacować wytrzymałość na ścinanie w warunkach bez odpływu c_{uWST}:

$$c_{uWST} = \frac{T_{WST}}{K} \tag{16}$$

gdzie:

c_{uWST} — wytrzymałość na ścinanie w warunkach bez odpływu wyznaczona sondą WST [kPa],
T_{WST} — wartość momentu skręcającego wyznaczona sondą WST [N×m],
K — parametr przyjmujący wartości z zakresu od 0,42 do 0,5.

Pozwala to w praktyce na natychmiastową ocenę czy dany grunt spełnia warunek nośności i od jakiej głębokości ten warunek jest spełniony. Znajomość wytrzymałości gruntu na ścinanie w przypadku skarp i zboczy o prostej budowie geometrycznej i geologicznej (co ma często miejsce w przypadku odkrywkowych kopali surowców ilastych) pozwala już w trakcie geotechnicznych prac polowych oszacować warunki stateczności. Ciągły pomiar wytrzymałości na ścinanie z wykorzystaniem sondy WST daje możliwość lokalizowania stref osłabienia jeszcze przed uaktywnieniem się osuwiska i związanych z nim problemów technicznych i technologicznych dla kopalni.

Prace dotyczące wykorzystania sondy wkręcanej WST do badań gruntów spoistych zostały zapoczątkowane w 2004 w kopalni iłów Zesławice i dotyczyły osuwiska zagrażającego ruchowi kopalni. Przedstawione w artykule badania stanowią kontynuację badań wybranych gruntów spoistych, tj. iłów mioceńskich zapadliska przedkarpackiego. Polowe badania geotechniczne prowadzone były w pięciu rejonach badawczych zlokalizowanych na terenie i w rejonie Krakowa oraz w Połańcu.

Słowa kluczowe: górnictwo surowców ilastych, geotechnika, sonda wkręcana WST, sonda obrotowa FVT, wytrzymałość gruntu na ścinanie w warunkach bez odpływu

1. Introduction

Clayey rocks (soils) are the basic raw mineral used for the production of ceramic building materials. They are also used in the production of cement and lightweight aggregates as well as in ground engineering works. Clayey rock deposits can be found throughout Poland. They represent the Quaternary clays and slack water muds, located mostly in the central and northern parts of Poland. Among the Tertiary minerals, the most important ones are the clays within the Poznan series (the south-west and central Poland) and the clays within the Krakowiec series present in the area of the Carpathian Foredeep. In 2013, clay exploitation was carried out in 267 mining plants, 244 of which were open-pit mines that extracted clayey raw materials for the production of ceramic building materials (Bilans, 2014).

One of the basic geotechnical problems in open-pit mines is slope stability. Slope landslides are among the major natural hazards occurring in open-pit mining (Cała, 2007).

Research work with use of WST testing equipment for cohesive soil testing started in 2004 in the Zesławice clay mine. The Zesławice mine, which mined Miocene clays, is located approximately 10 km north-east from the center of Krakow. In May 1991, a landslide which covered the western slope took place in the Zesławice mine. The displacement process, which generally occurred towards the active workings, covered the area of approximately 6-7 ha. Consequently, it was necessary to establish the safety zone wide enough to ensure regular work in the mine (Mazurek, 2004).

As the mining works continued, regular verification of the western slope stability in the subsequent years of 2004, 2006, and 2009 was necessary. For this reason, a series of geotechnical field and laboratory tests were conducted. Test were primarily aimed at determining the strength characteristics of the clays. Obtaining these characteristics was necessary to carry out subsequent stability analyses (Mazurek, 2004; Olesiak, 2009). Geotechnical tests included drilling and was carried out with use of FVT and WST equipment. At this stage, the WST method was used mainly to locate the weakening zones, i.e. to identify the potential shear surfaces.

The geotechnical standards PN-B-04452 (2002), ISO/TS 22476-10 (2005) and PN-EN 1997-2 (2009) regarding the WST equipment include information on the testing capability of the equipment. The WST equipment can be considered as a very versatile tool suitable for geotechnical field testing of all types of soils, from coarse non-cohesive soils to stiff clays. Moreover, WST can be used to determine the density index, undrained shear strength as well to assess the bearing capacity of shallow and deep foundations. Unfortunately, direct information contained in the aforementioned standards apply to the interpretation of the test results for a very narrow group of non-cohesive soils. The following factors can be determined directly for the test: density index, the effective angle of internal friction and drained Young modulus.

Assessment of the shear strength during WST testing would be very useful for the designing process e.g. shallow foundation for buildings or conducting slopes stability analysis. This would also reduce the amount of equipment used in the field.

In PN-EN 1997-1 (2008) regarding shallow foundation design, attention should be paid to various limit states, including checking the limit state of the ground bearing capacity. In this meaning of the standard, the ground bearing capacity is reached when the calculated value of the vertical load or the component of the total impact (working perpendicular to the foundation base) is lesser than or equal to the value of the design shear resistance. Design shear resistance (for undrained conditions) is equal to the product of the undrained shear strength and the total foundation area which transfers the stresses to the soil. Therefore, knowing the values of soil shear strength enable to determine whether the soil meets the bearing capacity, the minimum depth and other foundation-related conditions.

A similar situation occurs in designing newly-erected earthworks or ensuring stability of natural slopes, where quantitative stability assessment is required. This stability is affected by multiple factors such as: slope geometry, geological structure, shear strength of the soils building the slope and load imposed into the slope, with a special consideration for the impact of underground water (Cała, 2007). In stability analysis, various types of methods are used. The most popular methods are the limit equilibrium methods and numerical methods, where a non-dimensional parameter called factor of stability FS or safety factor SF is calculated. FS is determined as the ratio of soil shear strength to the actual shear stress on the plane of shear failure.

Soil strength parameters needed for the calculation of bearing capacity and stability are also determined from field testing.

2. Geotechnical field testing

Geotechnical field testing was conducted in five test sites (Olesiak, 2010, 2011, 2013, 2014a, 2014b). On the chosen study area, a testing field was established in the shape of a square or rectangle and with the dimensions of 20×20 or 20×16 m and surface areas of 400 m^2 and 320 m^2. During field testing, 12 testing boreholes were made and 20 or 25 WST tests in the grid of 4×4 m were conducted (Fig. 1). The WST tests were performed as deep as 6.5 m and the drilling reached the depth of 6 m.

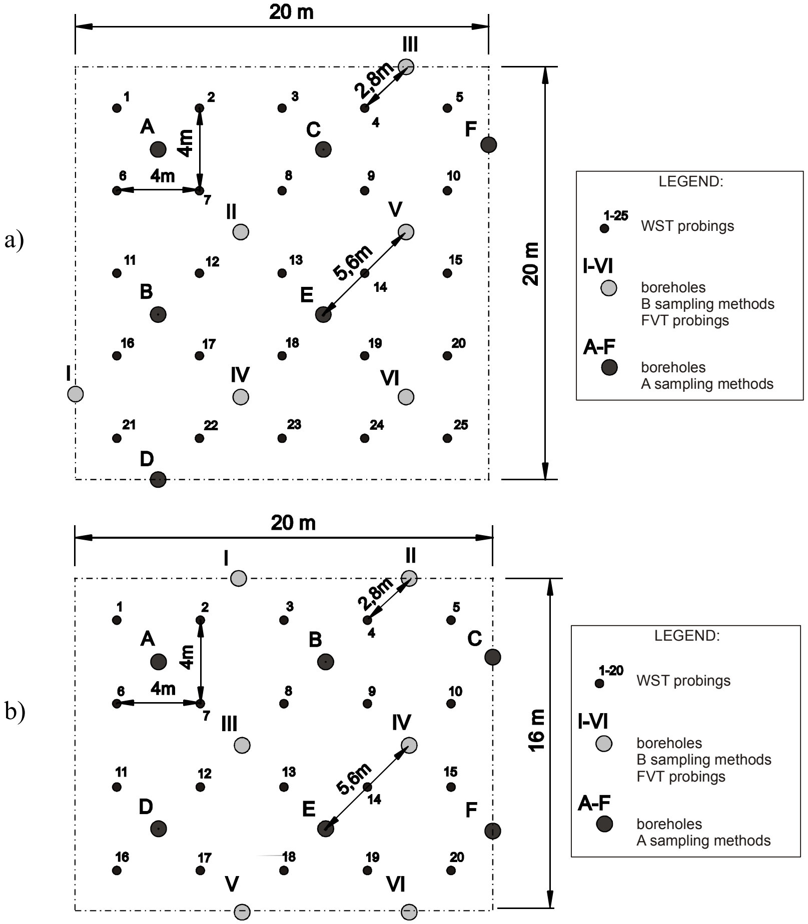


Fig. 1. Layout of test field
a) square (Olesiak, 2010; 2014b), b) rectangular (Olesiak, 2011; 2013; 2014a)

FVT testing was conducted in six boreholes (I-VI) and included measurements of the undrained shear strength c_{fv} and remoulded shear strength c_{rv}, at every 1 m throughout the depth. The FVT testing results and the average strength values from the six boreholes are presented in

Table 1. Additionally, samples for subsequent laboratory testing (sample category B) were collected from the boreholes at every 1 m. In the next six boreholes (A-F), samples for laboratory strength testing were also taken at every 1 m throughout the depth (sample category A). Moreover, macroscopic description mostly aimed at the assessment of clay state was conducted during the field testing (Olesiak, 2010, 2011, 2013, 2014a, 2014b).

TABLE 1

Summary of the FVT field testing results and selected laboratory tests
(Olesiak, 2010; 2011; 2013; 2014a; 2014b)

Test site	Depth below ground surface [m]	Liquid limit w_L, [%]	Field Vane Test probe (FVT)			
			Average undrained shear strength (6 measurements) c_{fv}, [kPa]	**Standard deviation [kPa]**	**Average remoulded shear strength (6 measurements) c_{rv}, [kPa]**	**Standard deviation [kPa]**
Mydlniki	1	80.32	74.2	3.76	29.2	3.76
	2	84.79	121.7	9.83	41.7	2.58
	3	85.74	152.5	6.89	45.8	6.65
	4	85.74	184.2	9.70	57.5	4.18
	5	83.89	206.7	2.58	79.2	5.85
Ruczaj	1	83.00	64.2	8.01	20.8	2.04
	2	82.03	98.3	18.35	33.3	9.31
	3	87.27	122.5	5.24	41.7	6.83
	4	88.12	152.5	10.37	43.3	6.83
	5	87.40	193.3	4.08	55.0	8.37
Tenczynek „1”	1	62.43	67.5	5.24	26.5	5.96
	2	51.39	118.3	8.16	37.5	6.89
	3	49.14	137.5	8.22	55.8	3.76
	4	50.46	152.5	5.24	57.5	7.58
	5	49.67	171.7	6.06	63.3	4.08
Tenczynek „2”	1	63.38	78.3	4.08	27.5	9.35
	2	49.94	118.3	6.06	42.5	6.89
	3	51.81	129.2	4.92	46.7	10.27
	4	52.32	156.7	5.85	64.2	5.34
	5	51.02	170.0	5.48	79.2	7.36
Połaniec	1.5	65.07	71.7	6.83	30.0	4.47
	2.5	65.29	120.0	6.32	40.0	3.16
	3.5	65.38	155.0	4.47	45.0	6.32
	4.5	65.35	178.3	5.16	57.0	6.32
	5.5	66.02	193.3	4.08	72.5	5.24

In order to calculate the undrained shear strength during the WST testing, a measurement of the torque moment was taken. Subsequently, these results were compared with the results of the FVT testing, where the torque moment was tested indirectly too.

The measurement of torque moment values in the mechanical WST tests was conducted automatically and continuously. However, the measurement of torque moment is standard methodology was conducted manually and only for the purposes of data verification. For rods with diameter of 20 mm, which were applied for the manual testing equipment in Europe in the 1960s and 1970s, checking the torque moment was recommended in order to prevent damage of the rod. However, the basic equipment never included the measurement wrench itself.

In this study, the measurement of the torque moment values during WST testing of Miocene clays was taken continuously. The specialized torque wrench manufactured by the Japanese company Tohnichi (Fig. 2) was used in the tests in order to measure the torque moment at each half-turn. In this way, two parameters which allow to characterize the tested ground were obtained:

- load W_{WST} or number of half-turns N_{WST}, for each 10 cm of penetration (Olesiak, 2010; 2011; 2013; 2014a; 2014b),
- weight sounding resistance, in the form of measured torque moment T_{WST}, [N×m].

The other test conditions, i.e. loading, penetration speed, rotational speed for half-turns complied with ISO/TS 22476-10:2005 and PN-EN 1997-2:2009.


a) b)

Fig. 2. View of a WST device equipped with a torque wrench

In order to determine the torque moment values at a specific depth the following calculations were made. Firstly, the arithmetic mean of the measured torque moments within a single test for every 10 cm of penetration was established:

$$T'_{WST} = \frac{\sum_{i=1}^{n'} T'_{WSTi}}{n'} \tag{1}$$

where:

T'_{WST} — arithmetic mean of torque moments at a specific depth within a single test [N×m],

T'_{WSTi} — value of measured torque moment for an i-th measurement at a specific depth, [N×m],

n' — number of torque moment measurements (from 1 to 22).

The number of measurements n' correspond to the number of half-turns (N_{WST}) and was within the range of 1-22, depending on the tested region and the soil consistency (Olesiak, 2010; 2011; 2013; 2014a; 2014b).

Secondly, the arithmetic mean from all the tests (20 or 25) at the specific depth was calculated:

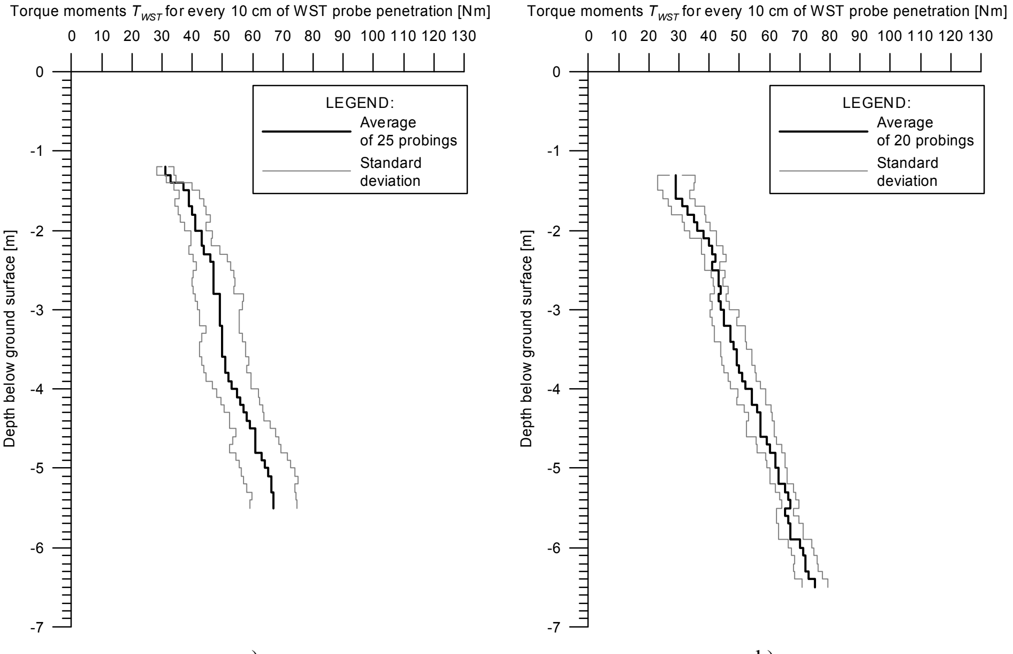
$$T_{WST} = \frac{\sum_{i=1}^{n} T_{WSTi}}{n} \tag{2}$$

where:

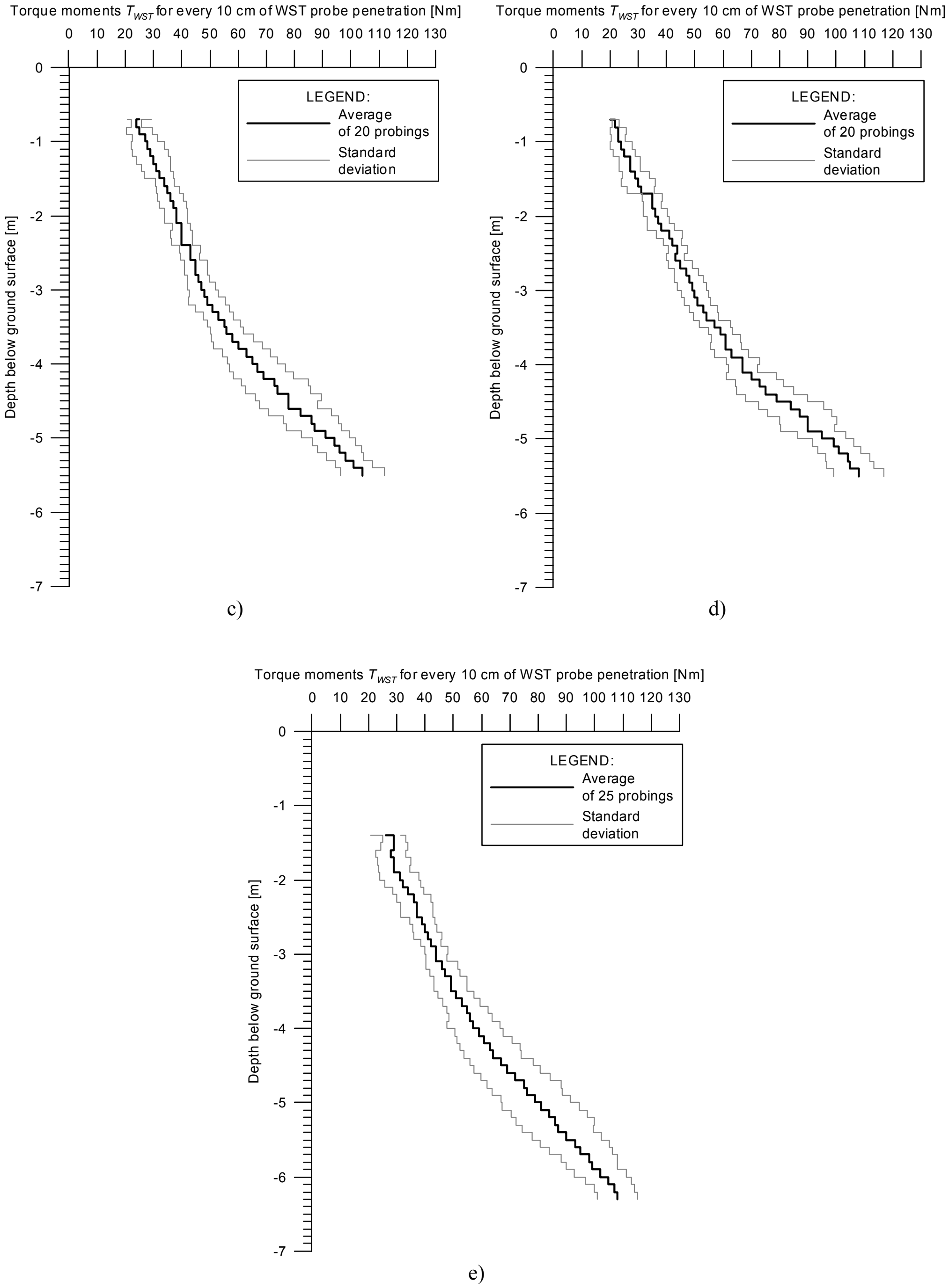
T_{WST} — arithmetic mean of the torque moments at a specific depth in a given test site [N×m],
T_{WSTi} — the torque moment value for an i-th test at a specific depth, [N×m],
n — number of tests (20 or 25).

Test diagrams for each location with the mean torque moment value T_{WST} and the standard deviation value are presented in Figure 3.

The arithmetic mean, N_{WST} (Olesiak, 2010; 2011, 2013, 2014a, 2014b) and T_{WST} (obtained for the segments with the length of 30 and 50 cm) were calculated in order to determine a reliable number of half-turns and the weight sounding resistance (Table 2). Moreover, at these depths, soil parameters were determined during field testing (i.e. the undrained shear strength of soil c_{fv} and c_{rv}) and samples were taken for laboratory testing.-



a) b)



c) d)

e)

Fig. 3. Diagram of the WST tests with the T_{WST} torque moment measurement at sites a) Mydlniki, b) Ruczaj, c) Tenczynek „1”, d) Tenczynek „2”, e) Połaniec

TABLE 2

Summary of results of torque moment measurement T_{WST} during WST testing

Test site	**Depth below ground surface [m]**	**Torque moments (2) T_{WST}, [N×m]**	**Standard deviation [N×m]**	**Torque moments (2) T_{WST}, [N×m]**	**Standard deviation [N×m]**
		30 cm		**50 cm**	
Mydlniki (25 probings)	1	–	–	31	1.2
	2	42	4.0	42	4.0
	3	49	7.3	49	7.0
	4	53	7.0	53	6.9
	5	64	8.6	64	8.7
Ruczaj (20 probings)	1	–	–	–	–
	2	36	4.2	36	4.2
	3	44	3.4	44	3.4
	4	52	4.7	52	4.8
	5	62	3.0	62	3.2
	6	69	3.9	69	3.9
Tenczynek „1” (20 probings)	1	26	4.9	26	4.6
	2	38	4.4	38	4.2
	3	47	4.7	47	5.0
	4	65	9.1	65	9.3
	5	91	8.6	91	8.7
Tenczynek „2” (20 probings)	1	23	3.1	23	2.9
	2	36	3.8	36	3.9
	3	49	5.0	49	4.8
	4	66	5.7	66	6.3
	5	95	8.4	95	8.6
Połaniec (25 probings)	1.5	28	4.7	28	5.5
	2.5	38	5.3	38	5.2
	3.5	50	6.0	50	6.0
	4.5	67	11.0	67	11.2
	5.5	90	12.3	90	12.4

3. Measurement of torque moment values by FVT testing

During the geotechnical field tests, FVT probe vane in the shape presented in Figure 4 was used. Moreover, the FVT device was equipped with a calibrated wrench for direct measurement of shear strength (instead of torque moment). The precision of the tests corresponded to class FV4 (ISO/DIS 22476-9:2010). The probe penetrated the soil dynamically using equipment from dynamic probe. However, the predrilling was necessary due to difficulties encountered during probe penetration. Shear strength were measured at about 1 m below the bottom of the borehole. The effect of soil friction on the friction was reduced thanks to slip coupling.

During testing, the maximal undrained shear strength c_{fv}, and remoulded shear strength c_{rv} were measured. The rotational speed of the probe corresponded to 360° per minute (ISO/

DIS 22476-9:2010). For this reason, introduction of formulas prior to testing enabled the torque moment calculation for this type of vane. It was assumed that the testing applies to an isotropic medium, and that the vane consists of three parts, which cut out two "cones" and one "cylinder" in the soil (Fig. 4).

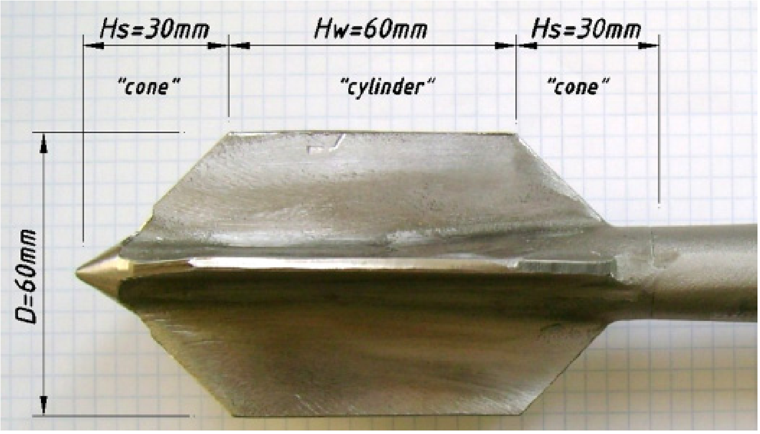


Fig. 4. FVT probe vane and its characteristic dimensions

Thus, the values of torque moments due to forces acting on the side surface of the cylinder and the side surface of the two cones were calculated from:

$$T_{FVT} = T_W + 2 \cdot T_S \tag{3}$$

where:

T_{FVT} — total torque moment value, [N×m],
T_W — torque moment due to forces acting on the side surface of the "cylinder", [N×m],
T_S — torque moment due to forces acting on the side surface of the "cone", [N×m],

Furthermore, the torque moment due to forces acting on the side surface of the "cylinder" is equal to (Walker, 1983):

$$T_W = \frac{\pi \cdot D^2 \cdot H_W}{2} \cdot c_{fv} \tag{4}$$

where:

T_W — torque moment due to forces acting on the side surface of the "cylinder", [N×m],
D — diameter of the "cylinder" and the "cone", [m],
H_W — height of the "cylinder", [m],
c_{fv} — undrained shear strength determined by FVT testing, [Pa].

For the "cone", the torque moment value is expressed as follows (Fig. 5):

$$T_S = \pi \cdot R \cdot l \cdot \frac{2}{3} \cdot R \cdot c_{fv} \tag{5}$$

where:

$$l = \sqrt{R^2 + H_S{}^2} \tag{6}$$

which consequently, after substitution and simplification, gives the following:

$$T_S = \frac{\pi \cdot D^2}{12} \sqrt{D^2 + 4 \cdot H_S{}^2} \cdot c_{fv} \tag{7}$$

where:

T_S — torque moment due to forces acting on the side surface of the "cone", [N×m],
l — length of the side surface of the "cone", [m],
R — radius of the "cylinder" and the "cone", [m],
H_S — height of the "cone", [m],
D — diameter of the "cylinder" and the "cone", [m],
c_{fv} — undrained shear strength determined by FVT testing, [Pa].

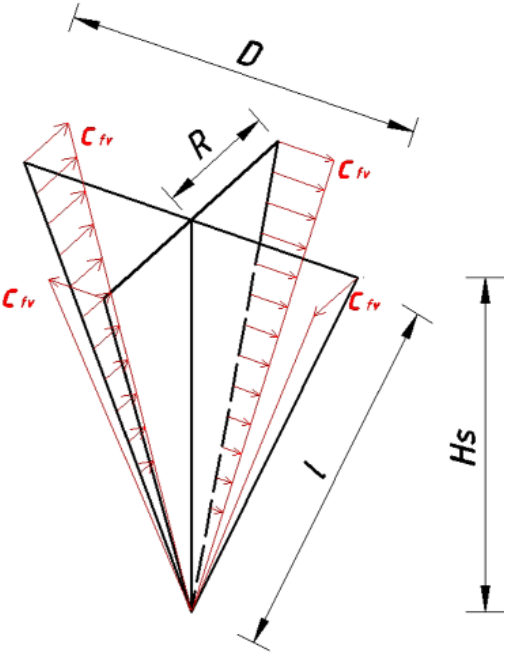


Fig. 5. Sketch used in calculations of the "cone"

For the entire vane (Fig. 4), the torque moment value is expressed as follows:

$$T_{FVT} = \frac{\pi \cdot D^2}{2} \cdot \left(\frac{\sqrt{D^2 + 4 \cdot H_S{}^2}}{3} + H_W \right) \cdot c_{fv} \tag{8}$$

After substitution of the vane dimension data, this simplifies to the following:

$$T_{FVT} = 0{,}4992 \times 10^{-3} \cdot c_{fv} \quad 0{,}5 \times 10^{-3} \cdot c_{fv} \tag{9}$$

where:

T_{FVT} — total torque moment value, [N×m],
D — diameter of the “cylinder” and the “cone”, [m],
H_S — height of the “cone”, [m],
H_W — height of the “cylinder”, [m],
c_{fv} — undrained shear strength determined by FVT testing, [Pa].

Analysis of the results, indicated that the shear strength values determined through *FVT* testing was different from the laboratory values (Cała & Olesiak, 2011; Olesiak, 2015). Therefore, a correction factor (m) was introduced to correct the shear strength, depending on the liquid limit (PN-B-04452:2002; Löfroth, 2008; PN-EN 1997-2:2009; ISO/DIS 22476-9:2010):

$$\mu = \left(\frac{0{,}43}{w_L} \right)^{0{,}45}, \quad 1{,}2 \geq \mu \geq 0{,}5 \tag{10}$$

where:

μ — correction factor,
w_L — liquid limit.

The corrected undrained shear strength is determined on the basis of the following relationship:

$$cu = \mu \cdot c_{fv} \tag{11}$$

where:

c_u — corrected undrained shear strength [Pa],
c_{fv} — undrained shear strength determined by *FVT* testing, [Pa],
μ — correction factor.

The torque moment may be considered similarly, and the formula will take the following form:

$$T_f = \mu \cdot T_{FVT} \tag{12}$$

where:

T_f — corrected torque moment, [N×m],
μ — correction factor,
T_{FVT} — torque moment determined from *FVT* testing, [N×m].

The derivation of the relation for a standard *FVT* tester (cylindrical) vane revealed that the entire upper base of the cylinder does not take part in shearing of the soil. This results from the differences between the theoretical assumptions and the practical design of the vane which requires connection with the rods. Additionally, the soil in this part was already disturbed due to the inserted vane. For the vane used in these tests, described process is even more evident (Fig. 4). The upper “cone” was cut down approximately in its half consequently did not participate in shearing. Because of the vane shape, the disturbance of the soil structure results in additional reduction in the upper “cone” shearing performance. Therefore, it was assumed to disregard the upper “cone” in further calculations. Consequently, the torque moment value is influenced only by the torque moment due to forces acting on the side surface of the cylinder and the lower cone:

$$T_{FVT} = T_W + T_S \tag{13}$$

where:

T_{FVT} — total torque moment value, [N×m],
T_W — torque moment due to forces acting on the side surface of the “cylinder”, [N×m],
T_S — torque moment due to forces acting on the side surface of the “cone”, [N×m].

Therefore, the torque moment value is expressed by the following formula:

$$T_{FVT} = \frac{\pi \cdot D^2}{2} \cdot \left(\frac{\sqrt{D^2 + 4 \cdot H_{S}^2}}{6} + H_W \right) \cdot c_{fv} \tag{14}$$

and after substitution of the vane dimensional data, this simplifies into the following:

$$T_{FVT} = 0{,}4192 \times 10^{-3} \cdot c_{fv} \quad 0{,}42 \times 10^{-3} \cdot c_{fv} \tag{15}$$

where:

T_{FVT} — total torque moment value, [N×m],
D — diameter of the “cylinder” and the “cone”, [m],
H_S — height of the “cone”, [m],
H_W — height of the “cylinder”, [m],
c_{fv} — undrained shear strength determined by *FVT* testing, [Pa].

In this way, two extreme cases were obtained. In the first case, the entire cross-shaped vane takes part in soil shearing and in the other one, the part whose impact on the total torque moment value is insignificant was eliminated. The results of these analyses are summarized in Table 3.

The difference in the values of torque moments (T_{FVT} and T_{WST}) obtained from *FVT* and *WST* (Table 1 and Table 2) vary for the first case (9) from –10 to 39 N×m with an average of 17 N×m, and for the other case (15) from –24 to 24 N×m with an average of 7 N×m. The negative values indicate that the torque moment value specified from *FVT* was lower than the value determined from *WST*. The results visibly improved after application of the correction factor (μ). For the first case (9) the differences vary from –15 to 20 N×m with an average of 7 N×m, and for the other case (15) from –28 to 11 N×m with an average of –2 N×m.

All calculations described above proved that the undrained shearing strength and the torque moment values can be determined during *WST* testing. However, it should be underlined that the difference with respect to results obtained from *FVT* are approximately ±20%. This naturally includes calculations after the correction factor (μ) is applied, but means that *WST* tests somehow “take into account” the kind of clay in light of its liquid limit.

On this basis, the formula for the assessment of undrained shear strength during *WST* testing is as follows:

$$c_{uWST} = \frac{T_{WST}}{K} \tag{16}$$

TABLE 3

Summary of the *FVT* torque moment results

Test site	Depth below ground surface [m]	Torque moments T_{FVT}, [N×m]		Correction factor μ	Corrected torque moment (12) T_f, [N×m]	
		according to (9)	according to (15)		for (9)	for (15)
Mydlniki	1	37.0	31.1	0.77	**29**	**24**
	2	60.8	51.0	0.75	**46**	**38**
	3	76.1	63.9	0.75	**57**	**48**
	4	92.0	77.2	0.75	**69**	**58**
	5	103.2	86.7	0.76	**78**	**65**
Ruczaj	1	32.1	26.9	0.76	**24**	**20**
	2	49.1	41.2	0.76	**37**	**31**
	3	61.2	51.4	0.74	**45**	**38**
	4	76.1	63.9	0.74	**56**	**47**
	5	96.5	81.0	0.74	**72**	**60**
Tenczynek „1”	1	33.7	28.3	0.86	**29**	**24**
	2	59.1	49.6	0.94	**56**	**47**
	3	68.6	57.6	0.96	**66**	**55**
	4	76.1	63.9	0.95	**72**	**61**
	5	85.7	72.0	0.96	**82**	**69**
Tenczynek „2”	1	39.1	32.8	0.86	**34**	28
	2	59.1	49.6	0.95	**56**	**47**
	3	64.5	54.2	0.94	**61**	**51**
	4	78.2	65.7	0.93	**73**	**61**
	5	84.9	71.3	0.95	**80**	**67**
Połaniec	1.5	35.8	30.1	0.85	**30**	**25**
	2.5	59.9	50.3	0.85	**51**	**43**
	3.5	77.4	65.0	0.85	**65**	**55**
	4.5	89.0	74.8	0.84	**75**	**63**
	5.5	96.5	81.0	0.84	**81**	**68**

where:

c_{uWST} — undrained shear strength determined during WST testing [kPa],
T_{WST} — torque moment value, [N×m],
K — parameter with the value within the range from 0.42 to 0.5.

An enormous advantage of this solution is the continuous measurement of the undrained shear strength values during *WST* testing. In the case of manual *FVT* testers, we are required to perform drilling parallel to the testing and the measurement is taken in steps at least every 0.5 m (PN-EN 1997-2:2009).

Table 4 summarizes the results for undrained shear strength values for the *FVT* testing and the values determined using formula (16) for the *WST* testing. Figure 6 shows diagrams of the WST tests including the measurement of undrained shear strength at every location.

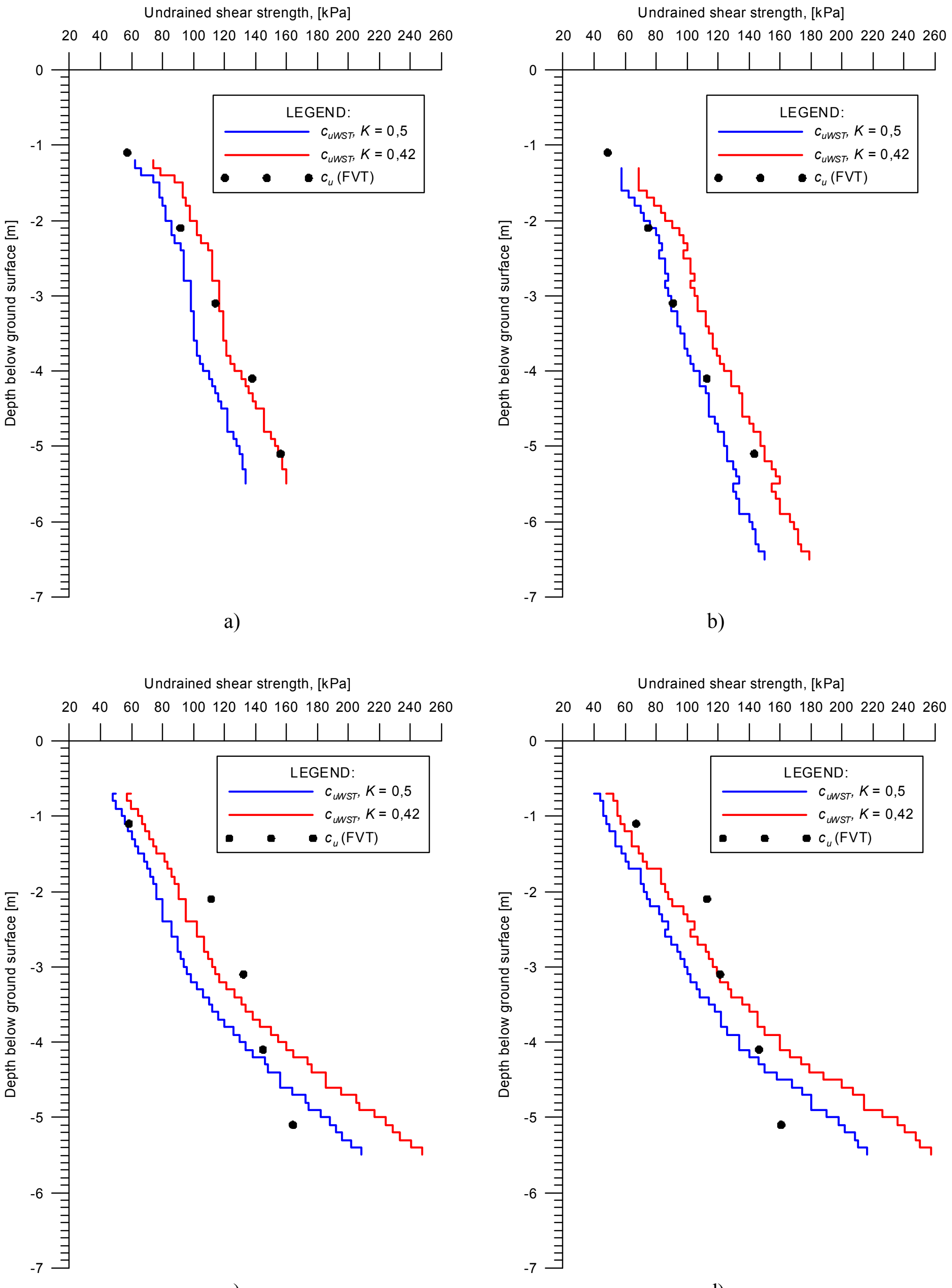
TABLE 4

Summary of the results of undrained shear strength on the basis of the *FVT* and *WST* testing

Test site	**Depth below ground surface [m]**	**Field Vane Test (*FVT*)**			**Weight Sounding Test (*WST*)**	
		Undrained shear strength c_{fv}, [kPa]	**Correction factor μ**	**Corrected undrained shear strength (11) c_u, [kPa]**	**Undrained shear strength (16) c_{uWST}, [kPa]**	
					for $K = 0,5$	**for $K = 0,42$**
Mydlniki	1	74.2	0.77	**57.2**	**62.0**	**73.8**
	2	121.7	0.75	**91.5**	**84.0**	**100.0**
	3	152.5	0.75	**114.1**	**98.0**	**116.7**
	4	184.2	0.75	**137.8**	**106.0**	**126.2**
	5	206.7	0.76	**156.2**	**128.0**	**152.4**
Ruczaj	1	64.2	0.76	**48.7**	–	–
	2	98.3	0.76	**75.0**	**72.0**	**85.7**
	3	122.5	0.74	**90.9**	**88.0**	**104.8**
	4	152.5	0.74	**112.7**	**104.0**	**123.8**
	5	193.3	0.74	**143.4**	**124.0**	**147.6**
Tenczynek „1”	1	67.5	0.86	**58.3**	**52.0**	**61.9**
	2	118.3	0.94	**111.4**	**76.0**	**90.5**
	3	137.5	0.96	**132.2**	**94.0**	**111.9**
	4	152.5	0.95	**144.8**	**130.0**	**154.8**
	5	171.7	0.96	**164.2**	**182.0**	**216.7**
Tenczynek „2”	1	78.3	0.86	**67.1**	**46.0**	**54.8**
	2	118.3	0.95	**112.9**	**72.0**	**85.7**
	3	129.2	0.94	**121.3**	**98.0**	**116.7**
	4	156.7	0.93	**146.4**	**132.0**	**157.1**
	5	170.0	0.95	**160.7**	**190.0**	**226.2**
Połaniec	1.5	71.7	0.85	**60.7**	**56.0**	**66.7**
	2.5	120.0	0.85	**101.5**	**76.0**	**90.5**
	3.5	155.0	0.85	**131.0**	**100.0**	**119.0**
	4.5	178.3	0.84	**150.6**	**134.0**	**159.5**
	5.5	193.3	0.84	**162.7**	**180.0**	**214.3**

The difference of ±20% in shear strength results obtained from the *WST* and *FVT* can be attributed to a few factors. The first factor lies in the difference of rotational speed of the *FVT* and *WST* probes. In the case of the *FVT*, the rotational speed was 360° per minute (6° per second), whereas the rotational speed of the *WST* probe was about 30 half-turns per minute (90° per second). Secondly, the friction on the rods in *WST*, which increases with penetration can significantly influence the results. In the case of *FVT*, the effect of rod friction can be practically eliminated as a result of slip coupling and predrilling.

The results require further verification on subsequent test sites and need to be supplemented with additional data. Consequently, the developed relation should be used with caution and remain a local proposition to approximate the undrained shear strength during *WST*.

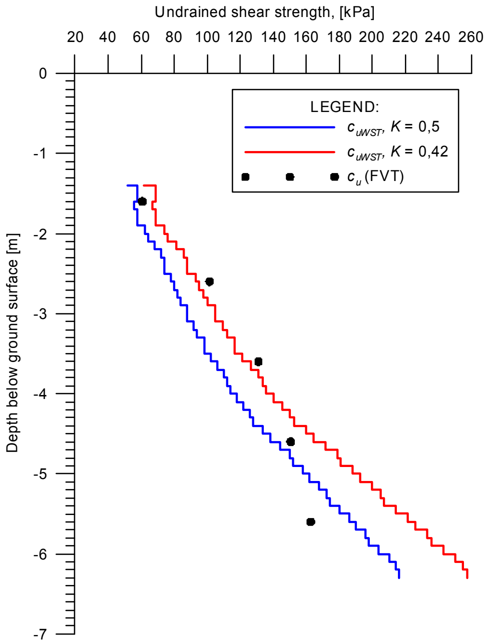

Undrained shear strength, [kPa]
20 40 60 80 100 120 140 160 180 200 220 240 260
Depth below ground surface [m]
0 -1 -2 -3 -4 -5 -6 -7
LEGEND:
c_{uWST}, K = 0,5
c_{uWST}, K = 0,42
c_u (FVT)

a)

b)

c)

d)



e)

Fig. 6. Diagrams of the undrained shear strength based on the WST and FVT testing
a) Mydlniki, b) Ruczaj, c) Tenczynek „1", d) Tenczynek „2", e) Połaniec

4. Summary

Description of the ground properties consists mainly of geotechnical layers identification and determination of their characteristics. The basis for their determination is laboratory tests and increasingly field tests, both of which should complement each other. Recently, the increase in popularity of the field methods is visible, which complies with the guidelines of Eurocode 7. However, field methods application is related to multiple factors. The primary ones include cost, testing time and significant technological advancements in the area of field testing instrumentation and methodology.

The *WST* equipment is a very versatile tool that can be successfully used in field testing of cohesive and non-cohesive soils. It can be used for rocky grounds as well as in waste testing, including municipal waste. *WST* field tests are among the fastest and cheapest in situ soil testing methods. It is a sufficient tool to determine the basic parameters of the ground. *WST* testing can reduce the amount of drilling necessary for soil type indentification. When testing non-cohesive soils, a clear noise can be heard, which disappears during the penetration in cohesive soils. Limited applicability of the *WST* is mainly connected with the deficiency in data interpretation for cohesive soils.

An important modification in the hand-held *WST* testing was described in this study. Modification deals with measuring the torque moment in a continuous manner. Based on this, a method to approximate the undrained shear strength during *WST* testing was presented. However, the results are preliminary and relations developed in this paper should be used with caution. It remains a local proposition for approximation of the undrained shear strength with *WST*. The relations presented in this study require further verification on subsequent test sites and need to be supplemented with additional data.

Knowing the shear strength of soil which build slopes characterized by the simple geometric and geological structure e.g. the case of open-pit mines where clay raw materials are mined enable to assess the stability conditions in the geotechnical field works phase. The continuous measurement of shear strength by means of *WST* testing gives the possibility to locate the weakening zones before activation of a landslide and the related technical and technological problems for the mine.

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