УДК 622.2 DOI: 10.33839/2708-731X-24-1-114-121

V.G. Shapoval, Dr. Sc, **O.A. Pashchenko**, Ph.D., **S.R. Zhilinska**, Ph.D.,
V.L. Khomenko Ph.D., **H.P. Ivanova**, Ph.D.

National Technical University Dnipro Polytechnic, 19 Dmytra Yavornytskoho av., 49005, Dnipro,
e-mail: inteldriller@gmail.com

APPLICATION OF SHASHENKO CRITERION TO PREDICTING THE STRENGTH OF SANDY LOAM SOILS DURING HORIZONTAL DIRECTIONAL DRILLING

We pursued the goal of assessing how acceptable the strength criterion of A. Shashenko is for taking into account the physical nonlinearity of sandy loam soils.

Theoretical studies of geomechanical processes using analytical and numerical mathematical methods. Analysis and generalization of the results of theoretical research.

It is shown that, in the area of experimental data variation, A. Shashenko strength criterion allows one to describe the strength properties of the soil more accurately than the Coulomb–Mohr criterion.

It was found that when extrapolating the curves to the region of low pressures, the Coulomb–Mohr strength criterion is the most preferable.

For the first time, using specific experimental data, the question of using the strength criterion of A. Shashenko to take into account the physical nonlinearity of the strength properties of sandy loam soil has been investigated.

The results obtained by us allow us to reasonably apply A. Shashenko strength criterion to take into account the nonlinear properties of sandy loam soil.

Key words*: shear tests, Mohr–Coulomb strength criterion, A. Shashenko strength criterion, single-plane shear device, shear strength, consolidated shear.*

Introduction

Today, in the best foreign practice, 95% of the volume of work on the laying and reconstruction of underground utilities is carried out by trenchless methods, which makes it possible to reduce the costs of repairing pipelines by 10-40% (depending on their diameter) [1].

In many large foreign cities, the laying of engineering communications in an open way is already prohibited. It should be noted that in Europe the number of objects is constantly growing, where methods of trenchless technology of repair, reconstruction and laying of communications are used. This growth is more rapid than in the United States, since the largest European cities were mainly founded several centuries ago.

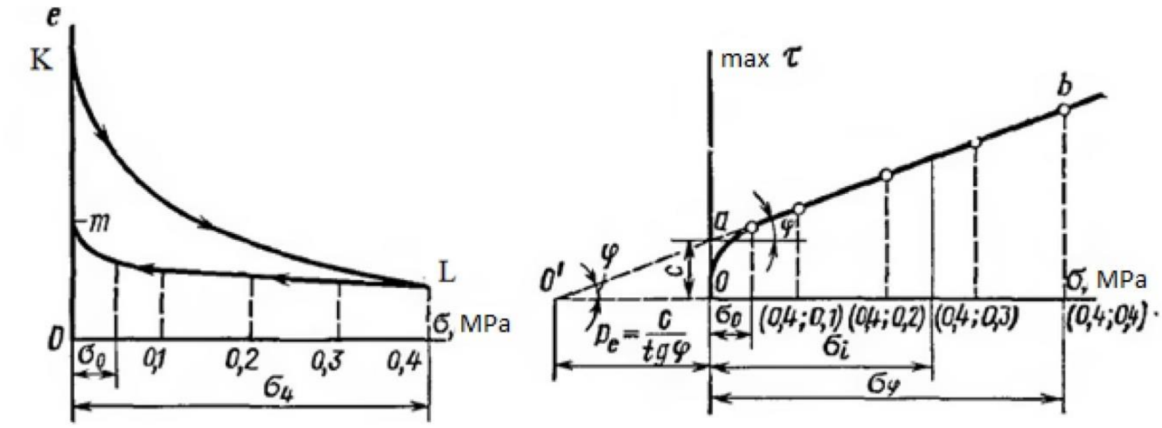
In order for horizontal directional drilling (HDD) to become the main method of carrying out such work, several circumstances at once were required. First, technologies were to emerge that would make horizontal directional drilling possible at all. Secondly, the use of HDD on an industrial scale should have become profitable (otherwise everything would have remained at the stage of experimental work).

One of the most important tasks in HDD is to ensure the stability of the walls of the expanded borehole from collapse during inevitable technological interruptions in the pipeline pulling.

Literature review

It is known that the experimental dependences «breaking shear stress – vertical load» has the form of a curved line, which is sometimes called the Coulomb–Mohr envelope [2, 3].

According to the data of researchers with zero vertical load on the sample, the breaking shear stress in clay soils is also zero. In this case, the Coulomb–Mohr strength criterion gives the value of the breaking shear stress equal to the specific cohesion (ie, nonzero; Fig. 1). This, in turn, leads to an overestimation of the holding forces when calculating the stability and strength of soil foundations and structures.



a *b*

Fig. 1. Curves of ultimate shear strengths of cohesive clayey soils in an open system (consolidated-drained; data by N.A.Tsytovich): a – dependences of soil porosity on load (KL curve) and unloading (mL curve); b – shear curve

As a result of the analysis, it was concluded that the problem of taking into account the physical nonlinearity of the strength properties of clayey soils is relevant, and one of the ways to solve it is the use of A. Shashenko strength criterion, widely known in rock mechanics [4, 5].

The research task was formulated as follows:

1. Known experimental results of consolidated-drained tests of sandy loam soil in a single-plane shear device.

2. It is necessary to:

2.1. Approximate experimental data using a linear relationship (Coulomb–Mohr strength criterion).

2.2. Approximate experimental data using nonlinear dependence (A. Shashenko strength criterion).

2.3. Using the relative root-mean-square error, evaluate the accuracy of the approximation.

2.4. Extrapolate the results of the approximation to the region of low pressures.

Methodology

Theoretical studies of geomechanical processes using analytical and numerical mathematical methods. Analysis and generalization of the results of theoretical research.

Results

To determine the properties of the soil and its classification, we used the recommendations [4, 5]. The physical properties of the sandy loam tested by us are presented in table 1.

Table 1. **Physical properties of sandy loam soil**

IGE No. 3 - PALE-YELLOW AND YELLOW SUPES									
NAME OF CHARACTERISTICS	PRIVATE VALUES CHARACTERISTICS								
1	2								
Laboratory room	1	2	3	4	8	10	11	12	14
Development and its number	w.20	w.20	w.20	w.20	w.20	w.20	w.20	w.20	w.20
Sampling depth, m	8,20	8,60	9,0	9,4	17,0	19,0	20,0	21,0	30,0

End of table 1

1	2								
Moisture at the fluidity limit, unit fraction	0,19	0,19	0,23	0,21	0,19	0,21	0,20	0,18	0,20
Humidity at the border of rolling, unit fraction	0,16	0,16	0,17	0,17	0,15	0,17	0,16	0,15	0,15
Plasticity number, unit fraction	0,03	0,03	0,06	0,04	0,04	0,04	0,04	0,03	0,05
Natural humidity, unit fraction	0,04	0,04	0,06	0,04	0,06	0,09	0,14	0,09	0,12
Water saturation moisture, unit fraction	0,23	0,25	0,27	0,27	0,24	0,20	0,20	0,16	0,17
Indicator of fluidity, unit fraction	-4	-4	-1,83	-3,25	-2,25	-2,00	-0,50	-2,00	-0,60
Density of soil particles, g/cm^3	2,67	2,67	2,61	2,67	2,67	2,67	2,67	2,67	2,67
Soil density, g/cm^3	1,68	1,63	1,68	1,58	1,70	1,85	1,94	2,00	2,03
Density of dry soil, g/cm^3	1,62	1,57	1,52	1,52	1,60	1,70	1,70	1,83	1,81
Porosity, unit fraction	0,39	0,41	0,43	0,43	0,40	0,36	0,36	0,31	0,32
Porosity coefficient in natural constitution, unit fraction	0,65	0,70	0,76	0,76	0,66	0,57	0,57	0,46	0,47
Moisture degree, unit fraction	0,16	0,15	0,21	0,14	0,24	0,42	0,66	0,53	0,68
Lack of water saturation, unit fraction	0,19	0,21	0,21	0,23	0,18	0,11	0,06	0,07	0,05

The strength of the soil was determined in accordance with the recommendations [6].

The results of determining the strength of the soil at its natural moisture content are presented in table 2.

Table 2. **Test results for sandy loam soil of natural moisture in a single-plane shear device**

IGE No. 3. PALETO-YELLOW AND YELLOW SUPES									
RESISTANCE TO SHEARING SAMPLE IN NATURAL STATE (SHIFT CONSOLIDATED)									
Vertical load σ, MPa	Breaking load τ, MPa								
0,200	–	0,132	0,163	–	0,148	0,128	0,123	0,148	0,145
Vertical load σ, MPa	Breaking load τ, MPa								
0,400	–	0,252	0,275	–	0,265	0,225	0,234	0,265	0,269
0,600	–	0,350	0,271	–	0,361	0,313	0,323	0,359	0,352
Partial values of strength characteristics (standard method; Coulomb–Mohr strength criterion)									
Internal friction angle φ, degrees	–	29	27	–	28	25	27	28	27
Specific adhesion c, MPa	–	0,027	0,062	–	0,045	0,037	0,027	0,026	0,048

The analysis of the data presented in Table 1 allowed us to conclude that the properties of the sandy loam soil we tested are typical for the Dnieper region.

To determine the material constants of the Coulomb–Mohr strength criterion, which has the form we used the generally accepted technique [6]:

$$\tau = \sigma \cdot tg(\varphi) + c,$$

where τ – destructive shear stress; σ – vertical load on the soil sample, φ and c – material constants to be determined (respectively, the angle of internal friction and specific cohesion) of the Coulomb–Mohr strength criterion.

In this case, we used the technique described in [6] to determine the material constants of the A. Shashenko strength criterion, which has the form:

$$\tau = \sqrt{\sigma \cdot c \cdot tg(\varphi) + c^2}\,.$$

It turned out that the dependence of the soil strength on the vertical pressure on the sample within the framework of the Coulomb–Mohr strength criterion has the form:

$$\tau = \sigma \cdot 0,4793 + 0,0512\,.$$

where $tg(\varphi) = 0,4793$ from where $\varphi = 25,61$ degrees and c = 0.0512 MPa.

It turned out that the dependence of the strength of the soil on the vertical pressure on the sample in the framework of the A. Shashenko strength criterion has the form:

$$\tau = \sqrt{\sigma \cdot 0,2289 - 0,0259}\,,$$

where c^2 = –0,0259, whence $c = \pm 0,161 \cdot i$ MPa; $tg(\varphi) = \mp 1,422 \cdot i$, whence $\varphi = \mp(90 + 50,04 \cdot i)$. Here $i = \sqrt{-1}$ is the imaginary unit.

The obtained values of the material constants included in the strength criterion of A. Shashenko are either imaginary (specific adhesion) or complex (angle of internal friction) numbers.

The results of approximation of the dependences «breaking load – vertical load on the sample» are shown in Fig. 2.

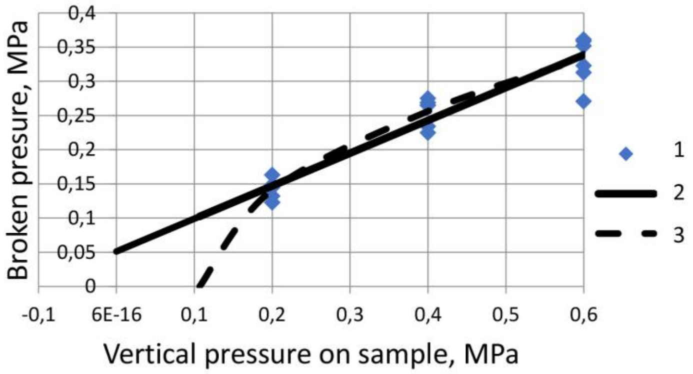


Fig. 2. The results of determining the curves «breaking load – vertical pressure on the sample». Row 1 – experiment; row 2 – criterion of strength of Coulomb–Mohr; 3 – A. Shashenko strength criterion

To assess the compliance of strength criteria with experimental data, we use the formulas

$$\varepsilon = \sqrt{\frac{1}{n}\left(\frac{\tau_э - \tau_p}{\tau_э}\right)^2}\,.$$

where ε is the relative root mean square error between the experimental ($\tau_{э,i}$) and calculated ($\tau_{p,i}$) the values of the breaking shear stresses; i – test number; n – the total number of tests.

It turned out that in the case of the Coulomb–Mohr strength criterion ε = 0,101, and in the case of A. Shashenko criterion ε = 0,0,094. On this basis, it was concluded that in the field of changes in experimental data $\left(\sigma \in \{2,0...6,0\}\ МПа\right)$ A. Shashenko strength criterion is more accurate.

Further, we extrapolated the strength criteria to the region of low pressures (Fig. 2). It turned out that with a vertical load less than 0.1 MPa, A. Shashenko strength criterion gives us negative values of the breaking load, which contradicts modern ideas about the nature of destruction of soils and rocks.

In this regard, in the pressure range $\left(\sigma \in \{0,0...6,0\} \ \ M\Pi a\right)$ A. Shashenko strength criterion should be presented as:

$$\tau = \begin{cases} 0 \text{ at } \sigma \leq 0{,}113; \\ \sqrt{\sigma \cdot 0{,}2289 - 0{,}0259} \quad \text{at } \sigma > 0{,}113. \end{cases}$$

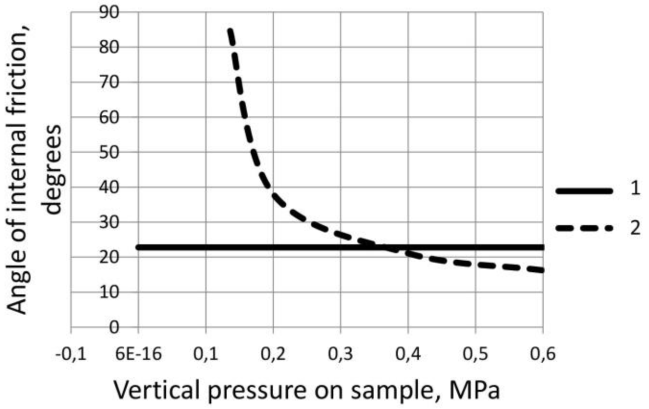


Fig. 3. Results of determining the curves «angle of internal friction – vertical pressure on the sample». Row 1 – Coulomb–Mohr strength criterion; 2 – A. Shashenko strength criterion

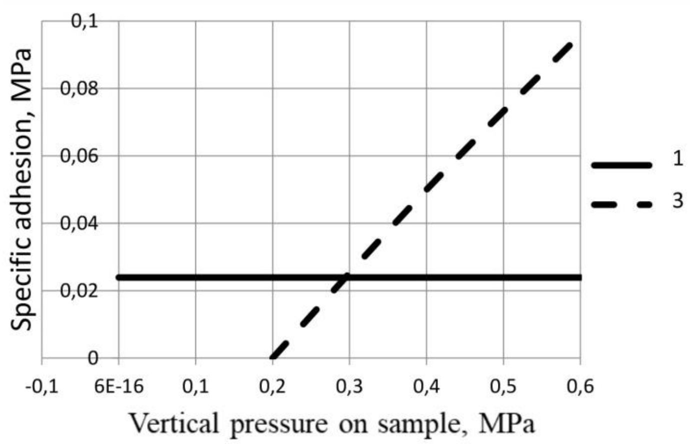


Fig. 4. Results of determining the curves «specific cohesion – vertical pressure on the sample». Row 1 – Coulomb–Mohr strength criterion; 2 – A. Shashenko strength criterion

In the course of further analysis, we compared the dependences of the angle of internal friction (Fig. 3) and specific cohesion (Fig. 4) on the pressure on the ground.

To determine the «tangent» angle of internal friction and specific adhesion at a point with the current coordinate «σ» we used the formulas:

$$\left.\begin{aligned} \varphi &= arctg\left\{\frac{\partial \tau}{\partial \sigma}\right\}; \\ c &= \tau - \sigma \cdot \frac{\partial \tau}{\partial \sigma}. \end{aligned}\right\}.$$

It follows from Fig. 3 that the angle of internal friction established within the framework of the Coulomb–Mohr strength criterion does not depend on the pressure on the ground.

In this case, the «tangential» angle of internal friction calculated within the framework of the strength criterion depends on the normal pressure on the ground. In this case, there is a clear tendency for the angle of internal friction to decrease with increasing load on the soil.

It follows from Fig. 4 that the specific adhesion established within the framework of the Coulomb–Mohr strength criterion does not depend on the pressure on the ground.

In this case, the «tangential» specific cohesion calculated within the framework of the strength criterion depends on the normal pressure on the ground. In this case, there is a clear tendency for the specific cohesion to increase with increasing soil load.

It should also be noted that in the case under consideration, the results obtained using A. Shashenko strength criterion are in good agreement with modern concepts of soil failure during shear in the range of experimental data (i.e., at $\sigma \in (2{,}0...6{,}0) \ \ M\Pi a$).

Conclusions

The research materials presented in this work made it possible to draw the following conclusions:

1. It has been established that the soil strength criterion proposed by A. Shashenko may well be used to predict the strength of sandy loam soils.

2. It is shown that in the area of experimental data variation the dependence "breaking load – vertical pressure on the ground", established within the framework of the strength criterion of A. Shashenko, has a better agreement with the experiment than the analogous dependence established within the framework of the Coulomb–Mohr strength criterion.

3. It has been established that the extrapolation of experimental data to the region of low pressures using the A. Shashenko strength criterion gives worse results than using the Coulomb–Mohr strength criterion for similar purposes.

In general, it was concluded that the strength criterion of A. Shashenko may well be used to predict the strength of sandy loam soils.

В.Г. Шаповал, О.А. Пащенко, С.Р. Жилінська, В.Л. Хоменко, Г.П. Іванова

Національний технічний університет «Дніпровська політехніка»

ЗАСТОСУВАННЯ КРИТЕРІЮ ШАШЕНКО ДЛЯ ПРОГНОЗУ МІЦНОСТІ СУПІЩАНИХ ҐРУНТІВ ПРИ ГОРИЗОНТАЛЬНО-НАПРАВЛЕНОМУ БУРІННІ

Нами переслідувалася мета оцінити, наскільки прийнятним для врахування фізичної нелінійності супіщаних ґрунтів є критерій міцності О. Шашенко.

Теоретичні дослідження геомеханічних процесів із використанням аналітичних і чисельних математичних методів. Аналіз і узагальнення результатів теоретичних досліджень.

Показано, що в області зміни експериментальних даних критерій міцності О. Шашенко дозволяє більш точно, ніж критерій Кулона – Мора, описати властивості міцності ґрунту.

При цьому встановлено, що при екстраполяції кривих в область малих тисків найкращим є критерій міцності Кулона – Мора.

Вперше з використанням конкретних експериментальних даних досліджено питання про використання критерію міцності О. Шашенко для обліку фізичної нелінійності характеристик міцності властивостей супіщаного ґрунту.

Отримані нами результати дозволяють обґрунтовано застосовувати для обліку нелінійних властивостей супіщаного ґрунту критерій міцності О. Шашенко.

***Ключові слова**: випробування на зріз, критерій міцності Мора – Кулона, критерій міцності О. Шашенко, прилад одноплощинного зсуву, міцність на зріз, консолідоване зрушення.*

В.Г. Шаповал, А.А. Пащенко, С.Р. Жилинская, В.Л. Хоменко, А.П. Иванова

Национальный технический университет «Днепровская политехника»

ПРИМЕНЕНИЕ КРИТЕРИЯ ШАШЕНКО ДЛЯ ПРОГНОЗА ПРОЧНОСТИ СУПЕСЧАНЫХ ГРУНТОВ ПРИ ГОРИЗОНТАЛЬНО-НАПРАВЛЕНОМ БУРЕНИИ

Нами преследовалась цель оценить, насколько приемлем для учета физической нелинейности супесчаных грунтов критерий прочности А. Шашенко.

Теоретические исследования геомеханических процессов с использованием аналитических и численных математических методов. Анализ и обобщение результатов теоретических исследований.

Показано, что в области изменения экспериментальных данных критерий прочности А. Шашенко позволяет более точно, чем критерий Кулона – Мора, описать прочностные свойства грунта.

При этом установлено, что при экстраполяции кривых в область малых давлений наиболее предпочтительным является критерий прочности Кулона – Мора.

Впервые с использованием конкретных экспериментальных данных исследован вопрос об использовании критерия прочности А. Шашенко для учета физической нелинейности прочностных свойств супесчаного грунта.

Полученные нами результаты позволяют обоснованно применять для учета нелинейных свойств супесчаного грунта критерий прочности А. Шашенко.

***Ключевые слова**: испытания на срез, критерий прочности Мора – Кулона, критерий прочности А. Шашенко, прибор одноплоскостного сдвига, прочность на срез, консолидированный сдвиг.*

Література

1. Горизонтально-направленное бурение: учебное пособие. / Пащенко А.А., Ратов Б.Т., Хоменко В.Л. и др. – С.: КОУ, 2020. – 367 с.
2. Механика грунтов, основания и фундаменты: учебник / Л. Н. Шутенко, А. Г. Рудь, О. В. Кичаева и др.; под ред. Л. Н. Шутенко; Харьков. нац. ун-т гор. хоз-ва им. А. Н. Бекетова. – Харьков: ХНУГХ им. А. Н. Бекетова, 2015. – 501 с.
3. Шашенко А. Н., Пустовойтенко В. П., Сдвижкова Е. А. Геомеханика. – К.: Новый друк, 2016. – 560 с.
4. Shapoval, V., Shashenko, O., Hapieiev, S. et al. (2020). Stability assessment of the slopes and side-hills with account of the excess pressure in the pore liquid // Mining of Mineral Deposits. – 2020. – 14, N 1. – С. 91–99; doi: 10.33271/mining14.01.091.
5. ДСТУ Б В.2.1-2-96. Ґрунти. Класифікація. К.: Державний комітет України у справах містобудування і архітектури. Київ, 1997. – 47 с.
6. ДСТУ Б В.2.1-17-2009. Ґрунти. Методи лабораторного визначення фізичних властивостей. К.: Мінрегіонбуд України, 2010. – 32 с.

Received 07.06.21

References

1. Pashchenko, A.A., Ratov, B.T., Khomenko, V.L. et al. (2020). *Gorizontalno-napravlennoe burenie [Horizontal directional drilling]*. S.: KOU [in Russian].
2. Shutenko, L. N., Rud, A.G., Kichaeva, O.V. et al. (2015). under.. *Mekhanika gruntov, osnovaniia i fundamenty [Soil mechanics, foundations and foundations]*. L.N. Shutenko (Ed.). Kharkiv: A.N. Beketov KhNUGH [in Russian].
3. Shashenko, A.N., Pustovoitenko, V. P., Sdvizhkova, E. A. (2016). *Geomekhanika [Geomechanics]*. – Kyiv: Novyj druk [in Russian].
4. Shapoval, V., Shashenko, O., Hapieiev, S. et al. (2020). Stability assessment of the slopes and side-hills with account of the excess pressure in the pore liquid. *Mining of Mineral Deposits, 14, 1*, 91–99.
5. Grunty. Klasyfikatsiia [Soils. Classification]. (1997). *DSTU B V.2.1-2-96*. Kyiv: Derzhavnyi komitet Ukrainy u spravakh mistobuduvannia i arkhitektury [in Ukrainian].
6. Grunty. Metody laboratornoho vyznachennia fizychnykh vlastyvostei [Soils. Methods for laboratory measurement of physical powers]. (2010). *DSTU B V.* 2.1-17-2009. Kyiv: Minrehionbud Ukrainy [in Ukrainian].