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CONSISTENCY DEPENDENT NATURE OF SLIDING DEFORMATION IN SWELLING SOILS

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The work is devoted to the changes in the nature of sliding deformation in swelling soils, depending on the change in soil consistency. Slip resistance tests were performed with both single-plane shear test rigs and torsion test rigs. At a soft plastic consistency, there is no peak sliding resistance in the constant speed sliding displacement test. Torsion tests show that in the case of soft plastic soils, sliding deformation occurs along the entire height of the test specimen without localization of the deformation and the formation of a displacement surface. In the case of overconsolidated clay soil, in the case of a constant velocity uniplane shear test, the dependence of the shear stress-shear strain is extreme, the shear resistance reaches a peak value. Then, during further displacement, the sliding resistance decreases to reach the minimum residual sliding resistance value. During the sliding test, when the deformations reach a certain critical size, deformation localization occurs, a localization zone is formed, after which the upper part of the sample moves relative to the lower stationary layer. Moreover, both the upper and lower parts are not subject to sliding deformations.

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***Keywords*:** argillaceous clays, swelling soils, swelling-shrinking, swelling deformations, sliding resistance, torsion method.

Research Methods. In swelling soils the mechanism of the land slide process development essentially depends on the conditions of the occurrence, as well as on the further post-genetic processes. Due to the swelling and decondensation of swelling soils, their rheological features essentially change (slide resistance, creep properties).

In the Armenian Republic territory ultra-dense argillaceous, reddish clay formations of montmorillonite composition, widespread in Erebuni and Nubarashen areas, are the tipical representatives of the swelling soils. Those clay formations, which during the history of their geological development and as a results of sediment accumulation were subjected to higher natural pressures than they are at present, are

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considered to be ultra-dense. In the conditions of natural humidity, they have high structural cemented bonds, resulting in high sliding resistance. In the areas of those soils, distribution of creep processes development is mostly absent. When the noted soils are moisturized, they are subjected to swelling, as a result of which the slide resistance gets sharply smaller, resulting in landslide phenomena.

In over-dense argillaceous clays, as a result of weathering processes, periodically swelling-shrinking, an elimination of rigid structural bonds takes place and this causes their decondensation over the time, as well as embrittlement in a certain soil area. As a result of the further hydration, in the certain area of the upper horizons, the embrittled soil is in soft-plastic, fluid-plastic state, causing plastic landslides and landslide-flows develop in the gummy-plastic soil mass.

Let us refer to the characteristics of sliding deformation in swelling clays, connected with their consistency changes due to hydration. The slide resistance values of the soil are the main ones, with which we make the estimation of the natural slopes stability. Due to hydration, with the consistency change, for the purpose of revealing the mechanism of soil mass slide deformation, in Erebuni–Nubarashen area for three different consistency states GT 1.2.11 of the reddish over-dense swelling clays with a single-deck automated cutting tester. The experiments of the slide resistance determination were realized with the sample diameter of $d = 71.4$ *mm* and height $h = 35$ *mm*. The clays of hard consistency, GT1.2.11 with a single-deck automated cutting tester were tested for 0.5 *mm*/*min* with the slide speed movement, and the water saturated samples with soft-plastic consistency were tested in the conditions of unconsolidated fast mode with 1.0 *mm*/*min* speed movement [1–4].

The samples were tested: in natural humidity; after the swelling deformation stabilization, caused by the additional humidity; in the embrittled state of the soil, due to swelling-shrinking in multiple intervals after the additional humidity. The values of the soil hydrophysical properties are brought in Tab. 1.

Table 1

The soil hydrophysical properties

Borehole / Depth	Density, g/cm^3			Porosity ratio, e	Humidity, W	Plasticity			Consistency, I_L
N / Depth, m	soil, ρ	mineral, ρ_s	skeleton, ρ_d			W_L	W_P	I_P	
1/8.0–9.0	2.05	2.66	1.67	0.593	0.227	0.482	0.257	0.241	<0
1/8.0–9.0	1.77	2.68	1.23	1.170	0.435	–	–	–	0.739
1/1.5–2.0	1.28	2.68	1.16	1.310	0.101	–	–	–	<0
1/1.5–2.0	1.67	2.68	1.15	1.330	0.456	–	–	–	0.826

As it is seen from Tab. 1, the soil, taken from the depth of 8.0–9.0 *m*, where swelling shrinking opportunities are absent, under natural installation conditions it is in a super dense state. In the noted soils in water saturated state the consistency index is small from [2, 5],

$$I_L = (W – W_P)/(W_L – W_P) < 0,$$

in other words, in water saturated state it is in a state of rigid consistency.

The relative free swelling deformations of super dense clays were determined. Free swelling relative deformations results are brought in Tab. 2.

Table 2

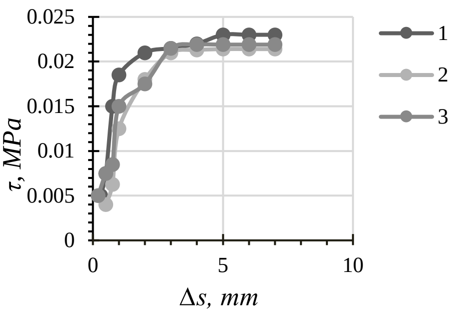
Free swelling relative deformations

Borehole *N* / Depth, *m*	1/8.0–9.0	1/8.0–9.0	1/8.0–9.0
Swelling relative deformation, *δsw*	0.175	0.185	0.175

Results and Discussion.

1. Let us represent the test results of the sliding resistance test of the soils that have been repeatedly softened as a result of swelling shrinking from the upper parts of the soil thickness, and which appeared in a soft plastic state after the further water saturation with kinematic mode and twisting method.

GT1.2.11 a single-deck automated cutting tester with kinematic mode, $\sigma = 0.05$ *MPa*; $\sigma = 0.1$ *MPa*; $\sigma = 0.15$ *MPa* under the influence of compressive loads, the sliding stress τ-sliding displacement Δs dependences are obtained (Fig. 1, a–c).



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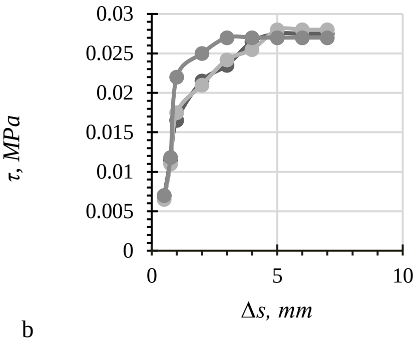

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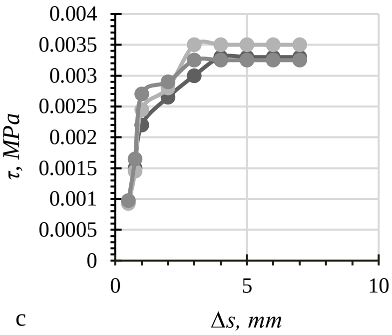

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Fig. 1. The test results of the determination of the sliding stress sliding displacement dependence in the kinematic mode of the soil in a fluid plastic state after water saturation of the reddish swelling clay soil, subjected to repeated swelling shrinking and embrittlement, in case of the following values of the normal stresses:
a) $\sigma = 0.05$ *MPa*;
b) $\sigma = 0.1$ *MPa*;
c) $\sigma = 0.15$ *MPa*.

Table 3

The results of the slide resistance test of clay soil

Normal stress, *σ, MPa*	Slide resistance, τ_f, *MPa*	Interior friction coefficient, tg*φ*	Connectivity, *C, MPa*
0.05	0.022	0.114	0.0163
0.1	0.0275		
0.15	0.0335		

In Tab. 3 the average results of the slide resistance test are brought, in Fig. 2 we have the diagram of the slide resistance.

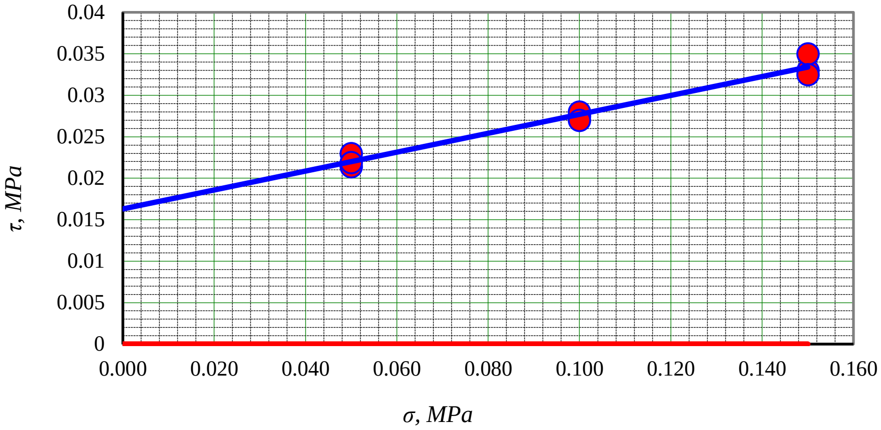


Fig. 2. The diagram of sliding resistance tested in kinematic mode after water saturation of reddish swelling clay soil in an embrittled state, as a result of regular swelling shrinking.

The equation of the sliding resistance will be expressed in the following way:

$$\tau_f = 0.114\ \mathrm{tg}\varphi + 0.0163\ (MPa).$$

The results of the sliding resistance test by torsion method and standard way are given in Tab. 4, and the diagram of sliding resistance is brought in Fig. 3.

Table 4

The results of the sliding resistance test of clay soil by torsion method standard mode

Normal stress, σ, *MPa*	Slide resistance, $\tau_{st.}$, *MPa*	Interior friction coefficient, tgφ	Connectivity *C, MPa*
0.05	0.0263	0.125	0.02
0.1	0.0325		
0.15	0.03875		

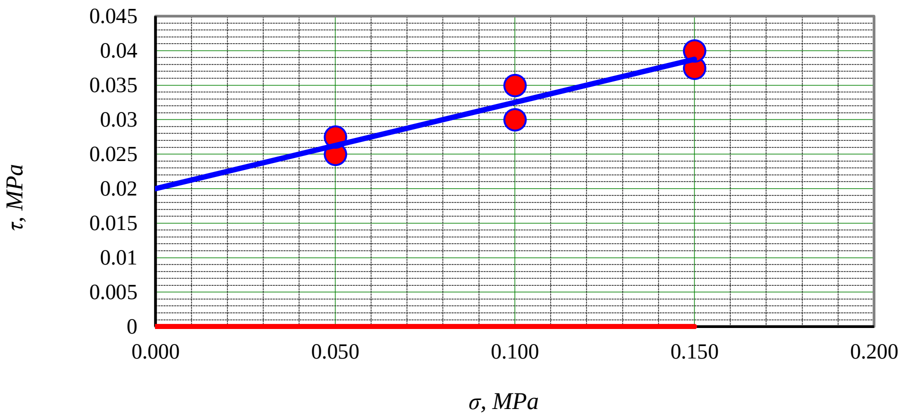


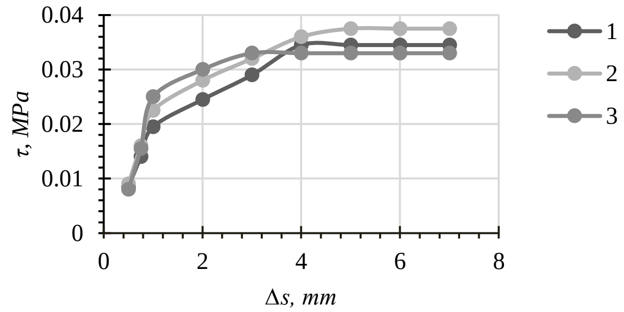
Fig. 3. The diagram of sliding resistance determined by torsion method standard mode.

The equation of the sliding resistance determined by torsion method will be expressed in the following way:

$$\tau_{st.} = 0.125\ \mathrm{tg}\varphi + 0.02\ (MPa).$$

2. Let us represent the test results of the sliding resistance by kinematic mode and torsion method after stabilization of swelling deformation from water saturation of reddish swelling clays.

After water saturation, stabilization of free swelling deformation with GT1.2.11 single-deck automated cutting test machine with kinematic mode, σ = 0.05 *MPa*; σ = 0.1 *MPa*; σ = 0.2 *MPa*, in case of the influence of the compaction loads sliding stress τ-sliding displacement Δs dependences are brought in Fig. 4, a–c, the sliding resistance diagram is brought in Fig. 5, the test results are brought in Tab. 3.



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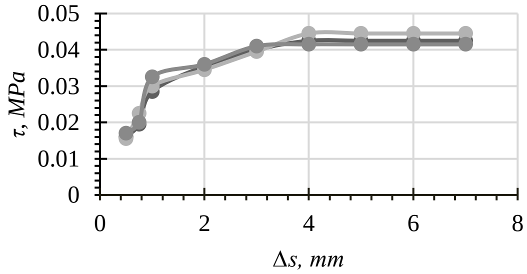

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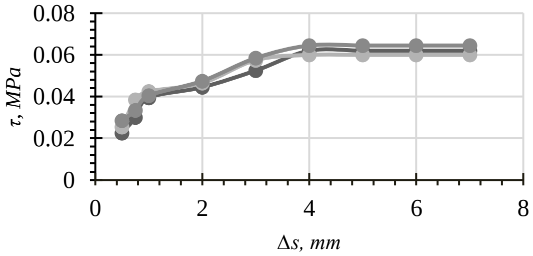

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Fig. 4. The results of sliding stress-sliding displacement test in kinematic mode after stabilization of swelling deformation free from water saturation:
a) σ = 0.05 *MPa*; b) σ = 0.1 *MPa*; c) σ = 0.2 *MPa*.

In Tab. 5 the results of sliding resistance test are brought, in Fig. 5 the diagram of sliding resistance is brought.

Table 5

The results of sliding stress-sliding displacement test in kinematic mode after stabilization of swelling deformation free from water saturation

Normal stress, σ, *MPa*	Slide resistance, $\tau_{st.}$, *MPa*	Interior friction coefficient, tgφ	Connectivity *C*, *MPa*
0.05	0.035	0.183	0.0253
0.1	0.0428		
0.15	0.0622		

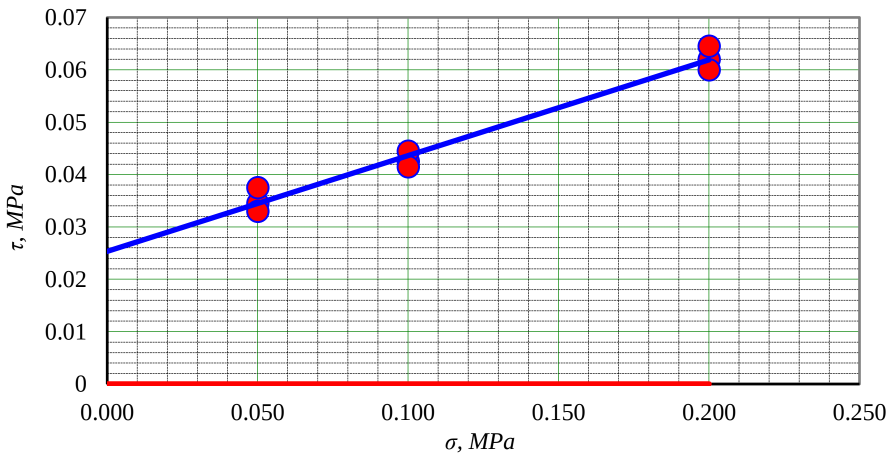


Fig. 5. The diagram of sliding resistance by kinematic mode after water saturation free swelling deformation stabilization.

The equation of sliding resistance will be expressed in the form of

$$\tau_f = 0.183\ \mathrm{tg}\varphi + 0.0253\ (MPa).$$

Tests of determination sliding resistance in swelling state were realized by M-5 type torsion test machine [1, 4, 6]. The results of the sliding resistance determination by torsion method are brought in Tab. 6, and the diagram of the sliding resistance is brought in Fig. 6.

Table 6

The results of the sliding resistance determination by torsion test machine in swelling state

Normal stress, σ, *MPa*	Slide resistance, $\tau_{st.}$, *MPa*	Interior friction coefficient, tgφ	Connectivity *C*, *MPa*
0.05	0.0215	0.146	0.0151
0.1	0.03125		
0.15	0.04375		

The normal stress dependence equation of the sliding resistance, determined in standard mode by torsional method, will be expressed in the form of

$$\tau_{st.} = 0.146\ \mathrm{tg}\varphi_{st.} + 0.0151\ MPa.$$

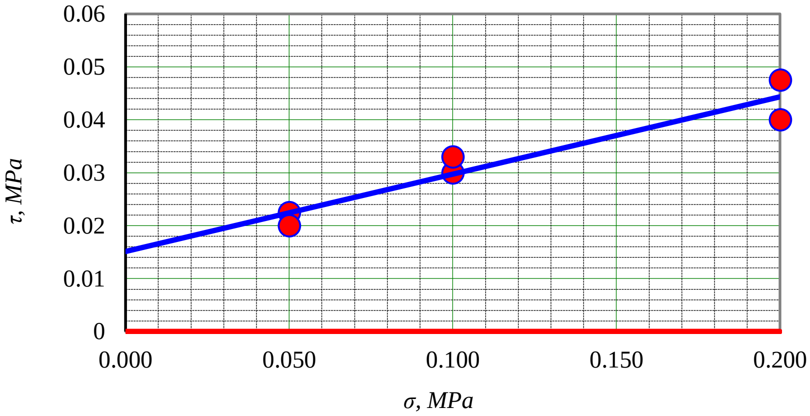


Fig. 6. The diagram of the sliding standard resistance, determined by torsional method after stabilization of the awelling deformation free from water saturation.

As it can be seen from the results of the sliding test, in the kinematic mode of soil in soft plastic state after water saturation of soft plastic fluid plastic and ultra-dense reddish swelling clays after stabilization of swelling deformation after water saturation of swelling clay soil, which has been thickened as a result of swelling shrinking for several times in the upper part of the soil thickness, sliding stress τ-sliding displacement Δs dependence (Figs. 1, 4) do not have an extreme character. Up to a certain sliding displacement, an increase is observed in sliding displacement, after which the sliding resistance remains constant, in other words, the soil has no sliding peak resistance.

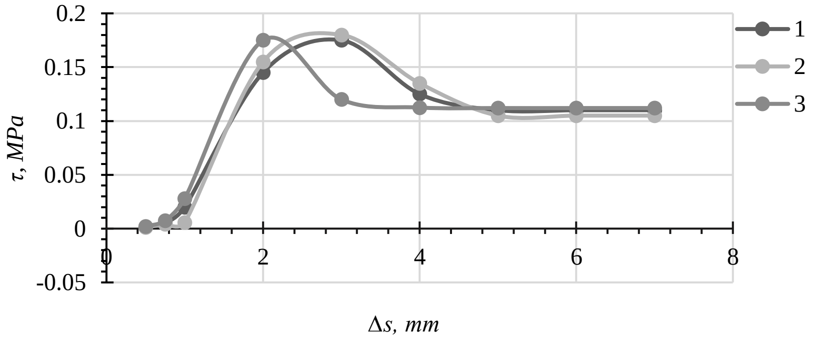
In the whole process of torsion, all the observations of the deformation process show that plastic deformations occur along the entire height of the specimen, the localization of the sliding deformation is missing.

Comparing the sliding resistance values determined by the kinematic mode test with the sliding resistance values, determined by standard method with torsion mode, we come to conclusion that the values of the sliding resistance soil, tested by torsion method with standard mode are smaller from the values of the sliding resistance determined by kinematic mode test.

3. Let us represent the test results of the sliding by kinematic mode and torsion method of the swelling reddish clays taken from 8.0–9.0 *m* depths in ultra-dense (ultra-consolidated) state.

Below we represent the results of the sliding stress-sliding displacement test in kinematic mode of ultra-dense (ultra-consolidated) reddish swelling clay soil without water saturation in case of compressive stresses $\sigma = 0.1\ MPa$; $\sigma = 0.2\ MPa$; $\sigma = 0.3\ MPa$ (Fig. 7, a–c).

As it is seen from Fig. 7, the stress-sliding displacement has got an extreme nature. When the displacement deformation accumulates getting to a critical value, the sliding resistance reaches the peak value, after that during the further displacement the sliding resistance drops reaching the residual value of the sliding resistance. It is important to note that peak sliding resistance depends on the sliding test speed, with the increasing speed the sliding peak resistance increases, the residual sliding resistance does not depend on the test speed.



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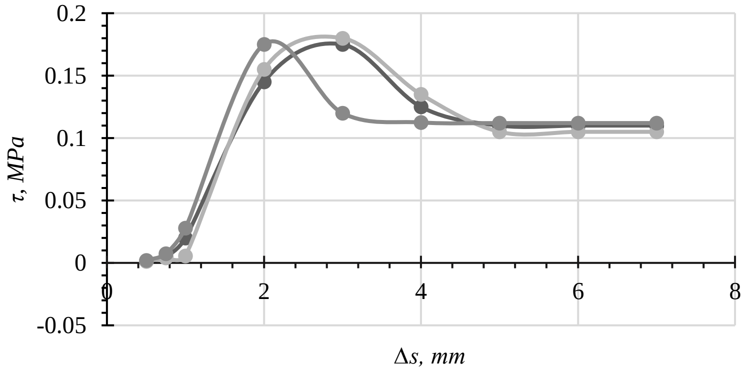

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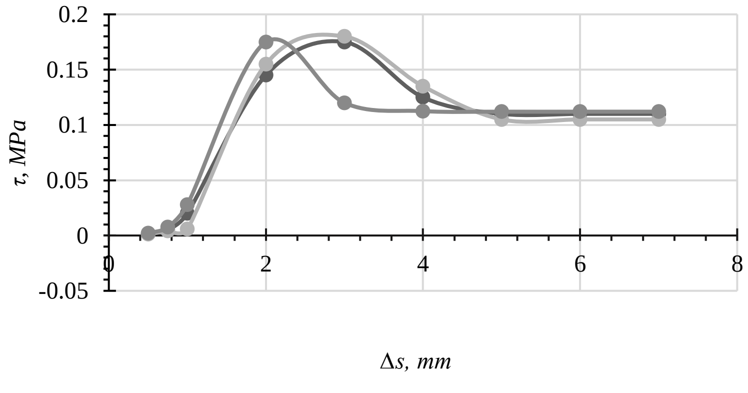

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Fig. 7. Curves of sliding stress-sliding displacement dependence of naturally formed argillaceous reddish swelling clay soil, tested with water saturation free in kinematic mode in case of: a) σ = 0.1 *MPa*; b) σ = 0.2 *MPa*; c) σ = 0.3 *MPa*.

In Tab. 7 the results of the sliding peak and residual resistance are brought. In Fig. 8 the diagrams of sliding peak and residual resistance diagrams are brought.

Table 7

The sliding peak and residual resistance of clay soil

Normal stress, σ, *MPa*	Peak sliding resistance, τ_{max}, *MPa*	Residual sliding resistance, τ_{min}, *MPa*	Peak interior friction coefficient, $\text{tg}\varphi_{max}$	Residual interior friction coefficient, $\text{tg}\varphi_{min}$	Peak connectivity C_{max}, *MPa*	Residual connectivity C_{min}, *MPa*
0.1	0.122	0.0292	0.260	0.242	0.0963	0.0042
0.2	0.149	0.0525				
0.3	0.174	0.0775				

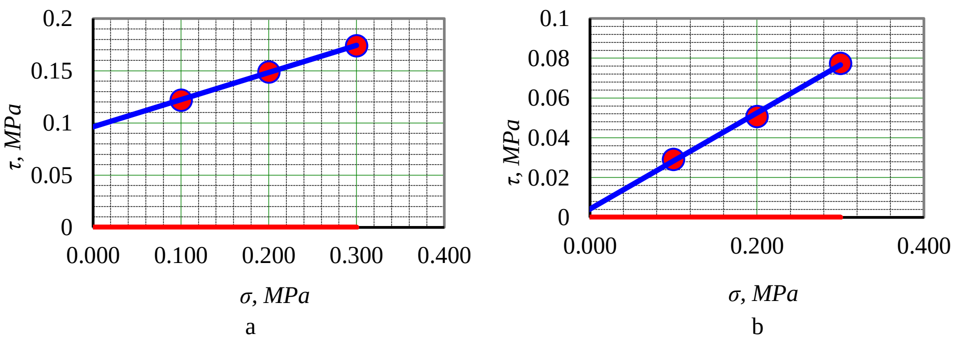

Fig. 8. The diagrams of sliding resistance: a) peak sliding resistance; b) residual sliding resistance.

Tests to determine the sliding resistance were carried out in a standard way with M-5 type torsion tester [1]. The results of the determination of the sliding resistance, determined by the torsion method, are brought in Tab. 8, and the diagram of the sliding resistance is brought in Fig. 8.

Table 8

The results of the determination of the sliding resistance in a standard way with M-5 type torsion tester

Normal stress σ, *MPa*	Sliding resistance, $\tau_{st.}$, *MPa*	Interior friction coefficient, $\text{tg}\varphi_{st.}$	Connectivity, $C_{st.}$, *MPa*
0.1	0.0575	0.300	0.0292
0.2	0.0925		
0.3	0.1175		

The views of the torsion tests, the whole process of the deformation show that the accumulations of torsional deformation along the entire height of the sample, reaching a certain critical value, the localization of sliding deformation takes place, after which along the localized slip plane a displacement of the upper layer with respect to the lower part is observed. Moreover, the upper part and the lower part of the displacement zone are not subjected to sliding deformations. Comparing the values of sliding resistance determined by the kinematic mode test with the values of sliding resistance determined by the standard torsional method, come to conclusion, that the values of the sliding resistance determined by the standard torsional method are small from the values of the sliding resistance determined by the kinematic mode test.

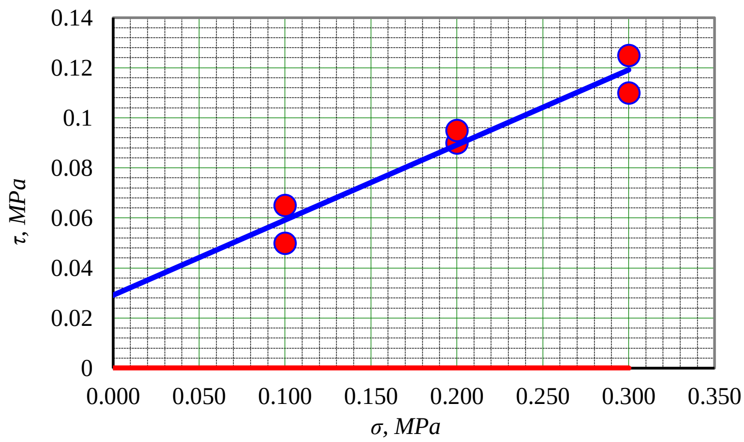

Fig. 9. The diagram of the sliding resistance determined by M-5 type torsion tester with standard way.

As it is seen from Tab. 1, the soils taken from depths of 8.0–9.0 *m* in natural installation conditions are in ultra-dense (ultra-consolidated) state.

In Tab. 9 the parameters of the swelling soils sliding resistance in three different states, interior friction coefficient (tgφ) and connectivity (C) are shown, in Tab. 10 the values of the sliding resistance relativities are shown.

Table 9

The parameters of the swelling soils sliding

The values of the reddish clay sliding resistence being in ultra-dense state, sliding peak and residual resistance				Reddish clays sliding resistance values, as a result of periodic swelling deformation swelling-shrinking, embrittled, water saturated		Reddish clays sliding resistance values, after the water saturation swelling deformation	
tgφ_{max}	C_{max}	tgφ_{min}	C_{min}	tg$\varphi_{sat.}$	$C_{sat.}$	tg$\varphi_{sat.sw.}$	$C_{sat.sw.}$
0.260	0.0963	0.242	0.0042	0.114	0.0163	0.183	0.0253

As it is seen from Tab. 10, because of swelling, comparing with natural form of ultra-dense clay, the interior friction coefficient decreases for 1.42 times, connectivity decreases for 3.8 times, as a result of swelling-shrinking embrittled, water saturated state tested soil interior friction coefficient decreases for 2.12 times, the connectivity decreases for 5.9 times. Test researches have shown that after the periodically swelling – shrinking determined interior friction coefficient, comparing after water saturated swelling stability clay interior friction coefficient, it gets smaller for 1.60 times, connectivity gets smaller for 1.55 times.

Table 10

Shear resistance ratio of soils

Correlations of the reddish clay sliding resistance values in ultra-dense state (sliding peak and residual resistance values – $tg\varphi_{max}$, C_{max}, $tg\varphi_{min}$, C_{min}) and the sliding resistance values because of periodically swelling-shrinking embrittled, water saturation				The correlations of the sliding resistance values of reddish clay in the super-dense state (peak sliding resistance values) and swelling-sliding resistance values in water saturated state		The correlation between the sliding resistance values after the reddish clay water saturated state and the values of the sliding resistance in swelling-shrinking water saturated state	
$tg\varphi_{max}/tg\varphi_{sat.}$	$C_{max}/C_{sat.}$	$tg\varphi_{min}/tg\varphi_{sat.}$	$C_{min}/C_{sat.}$	$tg\varphi_{max}/tg\varphi_{sat.sw.}$	$C_{max}/C_{sat.sw.}$	$tg\varphi_{sat.sw.}/tg\varphi_{sat.}$	$C_{sat,sw.}/C_{sat.}$
2.28	5.9	2.12	0.258	1.42	3.8	1.60	1.55

From here it follows that the ultra-dense clays of Erebuni, in the presence of water as a result of swelling, swelling-shrinking, from a hard consistency passes to a soft-plastic consistency, the sliding resistance values decrease sharply. Due to this, landslide phenomena with a viscous-plastic mechanism are spread widely, where sliding surfaces are absent.

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REFERENCES

1. Meschyan S.R. *Experimental Rheology of Clayey Soil.* Yerevan, Gitutyun NAN RA (2008), 495.
2. Trofimov V.T., Korolev V.A., et al. *Soil Science*. Moscow, MGU (2005), 1024.
3. Boldyrev G.G. *Methods for Determining the Mechanical Properties of Soils with Comments to GOST 12248-2010*. 2nd edition. Moscow, PRONDO (2014), 812.
4. Meschyan S.R. *Rheological Processes in Clay Soils*. Yerevan, Hayastan (1992), 395.
5. Hairoyan S.G. *Impact Shrinkable Fractuning of Shear Strength in Clay*. Madrid (2005), 6-14G-005.
6. Maslov N.N. *Physical and Technical Theory of Creep of Clay Soils in Construction Practice*. Moscow, Stroyizdat Publishing House (1984), 176 (in Russian).

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ՈՒՌՉՈՂ ԿԱՎԵՐՈՒՄ ՍԱՀՔԻ ՊՐՈՑԵՍՆԵՐԻ ՄԵԽԱՆԻԶՄԻ ԱՌԱՆՁՆԱՀԱՏԿՈՒԹՅՈՒՆՆԵՐԸ ՈՒՌՉՄԱՆ ՀԵՏԵՎԱՆՔՈՎ ԿՈՆՍԻՍՏԵՆՑԻԱՅԻ ՓՈՓՈԽՈՒԹՅԱՄԲ ՊԱՅՄԱՆԱՎՈՐՎԱԾ

Ամփոփում

Աշխատանքը նվիրված է ուռած հողերում սահող դեֆորմացիաների բնույթի փոփոխությանը՝ կախված հողի հետևողականության փոփոխությունից: Սայթաքման դիմադրության փորձարկումներն իրականացվել են

ինչպես մեկ հարթության կտրվածքի փորձարկման սարքերի, այնպես էլ ոլորման փորձարկման սարքերի վրա: Փափուկ պլաստիկի հետևողականության դեպքում մշտական արագությամբ սահելու փորձարկման ժամանակ չկա սահելու գագաթնակետային դիմադրություն: Տորսիոն փորձարկումները ցույց են տալիս, որ փափուկ պլաստիկ հողերի դեպքում սահող դեֆորմացիան տեղի է ունենում փորձանմուշի ողջ բարձրության վրա՝ առանց դեֆորմացիայի տեղայնացման և տեղաշարժման մակերեսի ձևավորման: Չափազանց խտացված կավե հողի դեպքում, երբ փորձարկվում է հաստատուն արագությամբ միակողմանի կտրվածքի համար, կտրվածքային լարման կախվածությունը կտրվածքային լարվածությունից ծայրահեղ է, և ճեղքման դիմադրությունը հասնում է իր առավելագույն արժեքին: Այնուհետև, հետագա շարժումով, սահող դիմադրությունը նվազում է մինչև մնացորդային սահող դիմադրության նվազագույն արժեքի հասնելը: Սահող փորձարկման ժամանակ, երբ դեֆորմացիաները հասնում են որոշակի կրիտիկական արժեքի, տեղի է ունենում դեֆորմացիայի տեղայնացում. ձևավորվում է տեղայնացման գոտի, որից հետո նմուշի վերին մասը շարժվում է ստորին ամրացված շերտի համեմատ: Ընդ որում, և՛ վերին, և՛ ստորին հատվածները չեն ենթարկվում սահող դեֆորմացիաների:

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ХАРАКТЕР ДЕФОРМАЦИИ СКОЛЬЖЕНИЯ В НАБУХАЮЩИХ ГРУНТАХ, ЗАВИСЯЩИЙ ОТ ИХ КОНСИСТЕНЦИИ

Резюме

Работа посвящена изменению характера скользящих деформаций в набухающих грунтах в зависимости от изменения консистенции грунта. Испытания на сопротивление скольжению проводились как на одноплоскостных испытательных стендах на сдвиг, так и на испытательных стендах на кручение. При мягкой пластичной консистенции пиковое сопротивление скольжению при испытании на скольжение при постоянной скорости отсутствует. Испытания на кручение показывают, что в случае мягких пластичных грунтов деформация скольжения происходит по всей высоте испытуемого образца без локализации деформации и образования поверхности смещения.

В случае переуплотненного глинистого грунта при испытании на одноплоскостной сдвиг с постоянной скоростью зависимость напряжения сдвига от деформации сдвига является экстремальной, сопротивление сдвигу достигает максимального значения. Затем при дальнейшем перемещении сопротивление скольжению уменьшается до достижения минимального значения остаточного сопротивления скольжению. При испытании на скольжение, когда деформации достигают определенной критической величины, происходит локализация деформации – образуется зона локализации, после чего верхняя часть образца перемещается относительно нижнего неподвижного слоя. При этом как верхняя, так и нижняя части не подвержены скользящим деформациям.