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DETERMINATION OF REDUCED PHYSICOMECHANICAL PROPERTIES OF TWO-PHASE SOILS PECULIAR TO LANDSLIDES OF NORTHERN TIAN SHAN

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ABSTRACT: This article is devoted to integral analysis of physicomechanical properties of surface soils peculiar to Akkain, Kok Tobe and Shymbulak landslides of Trans-Ili Alatau located in close vicinity to city borders and in Almaty. While analyzing previous landslides of this region, the authors determined three main reasons of landslide occurrence on these mountain slopes: water saturation of surface subsoils during spring rainfalls, technogenic and gravitational reasons. It has been concluded that in many cases landslides occur due to water saturation of subsoils. It is proposed to consider landslide subsoils as two-phase medium. Algorithm of prediction of reduced physicomechanical properties of two-phase subsoil is summarized. Actual predictions are carried out using the proposed procedure and algorithms. The obtained results for certain types of loose subsoils, such as sandy clay, various loams and clays, are summarized in tables which are required for deep study of landslide occurrence in water saturated subsoils of these slopes on the basis of strain–stress states.

Keywords: Filtration, Landslide, Mountain slope, Subsoil, Two-phase medium, Water saturation.

1. INTRODUCTION

Landslide processes occur on slopes of Northern Tian Shan as in other mountain areas of the world. As is known, landslides can vary depending on type, scale, sliding velocity, amount of sliding bulk, mechanism, etc. In the case of Berezka landslide located between Almaty and its satellite, Talgar, in spring 2004, about 1 million t of slide bulk moved from mountain slope. This bulk nearly instantly covered the distance of about 500 m and buried 28 citizens in two-storey residential building. Upon Kolsai landslide in spring 2018, slide bulk of about 50 million t with width of 900 m and the length of 177 m was flowing for five days.

The state of Kok Tobe mountain slope was always insecure, nowadays it also troubles the citizens of eastern regions of Almaty because of landslide hazard. In addition to modern high-rise buildings and structures in the vicinity of mountain root in Dostyk avenue, the western slope is also densely populated and built up.

Landslide state of this mountain has not been studied using modern methods of mathematical simulation, numerical mathematics, computer graphics, geomechanics, and deep drilling techniques. The height of Kok Tobe is 250 m, and the height of TV tower erected on its western slope on loose subsoils is 372 m. In early spring 2005, after abundant rainfall there occurred emergency situation on Kok Tobe: the surface was cracked, subsoil started to slide and buildings were destroyed. The landslide could in fact proceed to flow over neighboring residential regions.

The subsoils have not been studied by modern methods of geomechanics and specialized drilling in terms of their stability and strength with account for structure anisotropy, degree of water saturation. Moreover, prior to landslide occurrence their physicomechanical properties transferred into two-phase state and this fact has not been analyzed.

The latter issue is the starting point of the research.

2. SURVEY OF NORTHERN TIAN SHAN LANDSLIDES

The difficulty upon erection of the TV tower was loose soil of Kok Tobe slope: loam.

Initially the concept of TV tower erection on Kok Tobe was proposed by Kunaev, Chairman of the Council of Ministers of the Kazakh SSR. The TV tower project was implemented by two institutes: Melnikov Institute and Fundamentproekt, as well as Kazakhstan affiliate of TsNIIproektstal'konstruktsiya. The project was headed by Kartashova, a well-known architect, Prof. of New York Academy of Urban Planning. This project was implemented; however, the TV tower was erected on loose soils of western slope of Kok Tobe illustrated in Fig. 1.

Fig.1 East and north-west slopes of Kok Tobe mountain (left, center) and high-rise buildings in Almaty near the root of the mountain (right)

Krylov, Head of emergency prevention department of Almaty, mentioned that the subsoils of Kok Tobe were unstable [1]. Later cracks were generated in Sakhariev street near eastern bypass road (Fig. 2). General analysis of landslide occurrences in mountain slopes of Northern Tian Shan makes it possible to conclude that in addition to water saturation, the influence is also exerted by technogenic actions, that is, slope trimming during road construction. The third reason is comprised of slow gravitational processes related with tectonic compressions of sedimentary rocks of the Earth's crust. This is evidenced by noticeable and measurable tectonic forces. As a consequence, the Trans-Ili mountains rise at the rate of 1.5 cm per year. If the tectonic compression leads to rising of mountain ridges, then the gravitational compression leads to flattening of slope subsoils and various elevations. That is, slow shear and separated movements of subsoil bulk are directed from weakly fixed locations to lower stepwise points, close to horizontal positions. Occurrence of Kolsai landslide can be attributed to these reasons, the landslide occurred on calm days without significant rainfall and flowed for five days. This is a good example of gravitational reason of landslide occurrence. An important issue of analysis of reasons and mechanisms of landslide initiation is study of structure and physicomechanical properties of surface subsoils. Studying anisotropy is of high importance. These issues were systematized by Bugrov and Golubev [2]. Later these issues were studied by such Kazakhstan researchers as Kurmanbekkyzy [3], Rysbayeva, Seinassinova, R.B. Baimakhan, A.R. Baimakhan, and others [4,5].

The Akkain (Berezka) landslide is attributed directly to abundant rainfalls during several days. The Kok Tobe landslides proceeded both under dry weather and rainy seasons. In this case the influence was exerted by slope trimming during construction of eastern bypass road across north-west slope of Kok Tobe (at the left, Fig. 2). In this case landslides occur despite retaining walls as a consequence of violation of natural stress condition.

Due to abundant rainfalls, the subsoils started to slide already in 2005. Municipal services examined the east slope and detected the crack with the height of 2.5 m, the width of 5 m, and the depth of 1.5 m illustrated in Fig. 2 (to the right). The landslide threatened a building № 93a and two more buildings № 87 and 87a were also in the risk area.

Fig.2 Initial cracks on the slopes and slide bulks on the roads at the root of Kok Tobe

Shevchenko reported that "All submountain regions of Almaty are absolutely dangerous. The local subsoils are characterized by weak structures. Therefore, the exclusive residential areas of Almaty: Kok Tobe, Kamenskoe plateau, Butakovka, Remizovka, are unsuitable for construction" [6].

Prof. Khomyakov reported that "Water drying is by far slower deep in the Earth. According to research, the moisture content on surface is 15–16%. Theoretically, this value should be lower but it is as high as 22–25%" [6]. This is also supported by Shevchenko: "In fact, due to penetration of thawing, atmospheric and technogenic water, the subsoils contacting with vegetation layer are more water saturated. Prior to initiate construction on and beneath the slope, it is required to analyze whether it would be strengthened or not. Thus, it is required to examine its stability and wettability. With time, the slopes become heavier due to moisture content" [6]. These opinions confirm two-phase state of surface subsoils, especially in spring during abundant rainfalls. This also refers to the state of landslide subsoils in other countries. The consequences of subsoil saturation with water are also mentioned by Alvioli et al. [7]. Various properties of precipitations upon simulation of minor landslides are highlighted by Ran et al. [8]. Landslide occurrence due to rainfalls is mentioned by Ali et al. [9]. Ronco landslide, a deep-seated gravitational slope deformation in Italy, was simulated by Longoni et al. [10].

Slope trimmings during road construction are the places of landslide occurrence. Slope stability on the roads is estimated by Harabinova [11]. Quite often surface subsoils of slopes are formed by loess. The loess landslide in South Jingyang tableland was studied by Leng et al. [12].

Only in early spring 2017, in the east area of Almaty, there occurred 64 spontaneous landslides. In May, due to sharp warming, snow thawing and abundant rainfalls, 35 landslides were detected.

Review and analysis of Kok Tobe data make it possible to assume that in the subsoils of its slopes, there occurs dangerous accumulation of water in deep layers. When it reaches the surface of bottom rocks, then spontaneous sliding of subsoil bulk is highly possible. Analysis of state of these hazardous landslides should be initiated by predictions of reduced physicomechanical properties for two-phase state of subsoils.

3. METHODS

Elastic properties of wet subsoils were studied by Cherepanov [13], Alyushin, Ter–Martirosyan [14], and those of water saturated two-phase subsoil – by Eisler [15,16]. Elasticity modulus $\boldsymbol{E^V}$ can be predicted by regular expressions of theory of elasticity using experimental shear modulus $\boldsymbol{G_0}$ or volumetric deformation $\boldsymbol{K_0}$. Ter–Martirosyan presents some equations for water saturated subsoil [14] illustrated in Figs. 3a and 3b. It can be seen that with the increase in moisture $\boldsymbol{W}$ at various dry density, the shear modulus $\boldsymbol{G_0}$, volumetric deformation and strength properties $\boldsymbol{C}$ and $\boldsymbol{\varphi}$ decrease.

In order to perform theoretical simulations, except for the work by Eisler, there are no explicit analytical expressions for determination of Young modulus E^V, Poisson coefficient V, as well as bulk density γ, $1 \cdot 10^2 MN/m^3$ for water saturated subsoil [16,17].

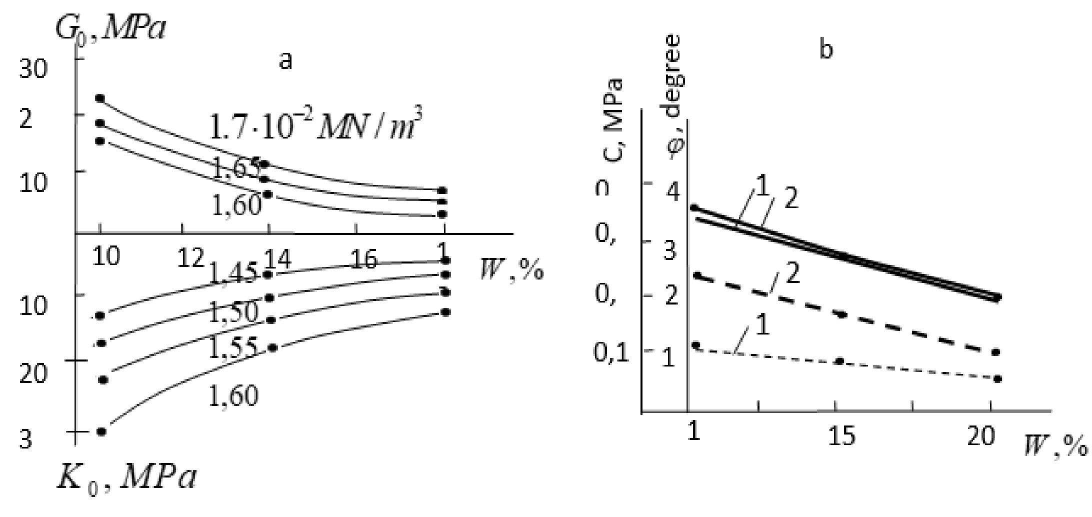

Fig.3 Shear modulus 0 and bulk deformation 0 at various specific gravity (a); and cohesion , internal friction angle (b) as a function of moisture of aerated subsoil zone

For each increase in moisture content, using G_0 or K_0 detected by these plots, it is possible to predict the Young modulus E^V for water saturate subsoils as follows:

$$\boldsymbol{E^V = 2G_0(1+\nu), E^V = 3K_0(1-2\nu)} \quad (1)$$

Since the Poisson coefficient $\boldsymbol{\nu}$ varies insignificantly and nearly does not effect the results, it is possible to assume that it is constant.

Upon experimental determination of elastic multicomponent material, the errors are added due to averaging in the form of quasi-uniform material. Such errors are inevitable also upon theoretical consideration, they effect regularities of distribution and concentration of stresses in the object. Some considerations concerning approximate analysis of this issue for water saturated subsoil are given below.

According to [16-18] the modulus of volumetric compression of subsoil is determined as follows:

$$\boldsymbol{K_V = \frac{E_s}{3(1-2\nu_s)}}, \quad (4)$$

where $\boldsymbol{E_S}$, $\boldsymbol{\nu_S}$ are the modulus of elasticity and the Poisson coefficient for dry subsoil, respectively. The reduced volumetric modulus for water saturated subsoil is determined by combinations of moduli for solid particles $\boldsymbol{K_{sp}}$ and water $\boldsymbol{K_w}$:

$$\boldsymbol{K_{sp} = \frac{E_{sp}}{3(1-2\nu_{sp})}},$$

$$\boldsymbol{K_w = \frac{E_w}{3(1-2\nu_w)}}, \quad (5)$$

$$\boldsymbol{K^+ = \frac{K_{sp}K_w}{K_{sp}-K_w}}$$

Despite the fact that in pure form water is uncompressible, there exist experimentally established values. It is known that in artillery, the property of insignificant volumetric compression (elasticity) of liquid is used for thrust roller. Therefore, it is established that the volumetric compression of water is: $\boldsymbol{K_w = 2,000}$ MPa [17]. Using the aforementioned expression and according to Eisler [15], it is possible to write the elastic properties for averaged material which simulates water saturated subsoil. Now, for quasi-single-component medium, with consideration for their combined motion, it is possible to write for volumetric compression:

$$\boldsymbol{K_V^{ws} = \beta K^*} \quad (6)$$

where $\boldsymbol{\beta = 1 + \frac{nK_V}{K^+}}$, $\boldsymbol{K^* = \frac{K_{sp}K_w}{nK_{sp}+mK_w}}$ – is the modulus of bulk compression of subsoil, $\boldsymbol{n}$ and $\boldsymbol{m}$ are the bulk portions of solids and liquids (gas saturated).

Similarly, the reduced elasticity modulus for water saturated subsoil, $\boldsymbol{E^{ws}}$, the Poisson coefficient $\boldsymbol{\nu^{ws}}$ and the shear modules $\boldsymbol{G^{ws}}$ are as follows:

$$E^{ws} = \frac{9\beta K^* G}{3\beta K^* + G}$$

$$\nu^{ws} = \frac{\beta K^* - 2G}{2(3\beta K^* + G)}, \quad (7)$$

$$G^{ws} = G.$$

Specifying the degree of subsoil porosity according to Tsytovich [18]:

$$\eta = \frac{n}{m} \text{ or } \eta = \frac{n}{1-n} \quad (8)$$

As can be seen, $n + m = 1$. They are directly included in the equation for K^*. According to Eq. (8), it is possible to define the subsoil types. Thus, η equaling to 0.2 ÷ 1.5 corresponds to regular subsoil, 2 ÷ 12 – to organic mineral subsoil, otherwise, η <1 is referred to compressed subsoil, and η >1 – to loose subsoil.

4. RESULTS

According to Eqs. (1)–(8), we predicted elastic properties for water saturated subsoils of landslide slopes with various combinations of solid to liquid ratios of the subsoils. The results are summarized in Table 1.

During flowing of landslide bulk, upon contact with an obstacle (irregularity, roughness, and so on), there would occur uplifting. Generally, the uplifting is also possible upon natural drying of water saturated subsoil and upon global tectonic compression. In all these cases, the uplifting takes place due to reverse compression or expansion. Thus, it would be reasonable to determine $\sigma_{\exp}$ theoretically by Mohr circles. With known critical parameters of strength, C : the cohesion force, and φ : the internal friction angle, it is possible to apply them on $\tau 0 \sigma$ coordinates and to determine the respective $\sigma_{\max}$ and $\sigma_{\min}$. According to Trollope, the latter value with opposite sign will correspond to expansion stress, that is $_{\exp} = -\sigma_{\min}$ [20]

Table 1 Types of water saturated subsoils of landslide slopes

Subsoil	E_S, MPa	ν_S , MPa	*n*, %	*m*, %	E^{EM}, MPa	ν^{ME} , MPa
Clay, banded laminar plastic	8	0,42	90	10	7.99	0.419
			80	20	7.97	0.418
			70	30	7.92	0.406
			60	40	7.81	0.390
Sandy clay	9	0.32	90	10	8.99	0.318
			80	20	8.93	0.310
			70	30	8.81	0.292
			60	40	8.54	0.253
Loam	12	0,40	90	10	11.99	0.399
			80	20	11.95	0.394
			70	30	11.85	0.383
			60	40	11.65	0.360
Fluid sandy loam	18	0,31	90	10	17.97	0.308
			80	20	17.86	0.300
			70	30	17.59	0.280
			60	40	17.04	0.257
Clay, thin-laminated solid	300	0,35	90	10	299.63	0.348
			80	20	298.40	0.342
			70	30	294.59	0.326
			60	40	287.23	0.293

Note: E_S is the elasticity modulus at natural moisture content of subsoil, ν_S is the Poisson coefficient at natural moisture content of subsoil, *n* is the portion of solids in subsoil, *m* is the portion of liquids in subsoil, E^{EM} is the reduced elasticity modulus for water saturated subsoil, ν^{EM} is the reduced Poisson coefficient for water saturated subsoil.

Complete physicomechanical properties are presented for the subsoils summarized in Table 2. The table shows the values according to Bulychev [19] and Kurmanbekkyzy [3], and Table 3 shows the data according to Maslov [20]; $\sigma_{\exp}$: shear expansion resistance, σ_{comp} : shear compression resistance, and τ_{sh} : ultimate shear resistance are determined theoretically using the Mohr circles:

1) $\gamma_c = \frac{\gamma_S}{1+W}$ is the subsoil dry density;

2) $\gamma_{sp} = \frac{\gamma_S}{1-W(\gamma_S - 1)}$ is the subsoil specific density;

3) $n = \frac{\gamma_{sp} - \gamma_c}{\gamma_c}$ is the subsoil porosity;

4) $\varepsilon = \frac{n}{1-n}$ is the porosity coefficient;

5) moisture capacity (subsoil moisture content at this porosity in the case of total saturation with water): $W_e = \frac{\varepsilon \gamma_S}{\gamma_{sp}} *$,

6) subsoil specific density at respective total moisture capacity: $\gamma_e = \gamma_c (1 + \frac{W_e}{100})$.

Table 2 Physicomechanical properties of certain water saturated subsoils

#	Subsoil	*W*, %	$\gamma_S *\ ^2$, MN/m^3	C*$\mathbf{10^2}$, MPa	φ^0	ν_S , MPa	E$_S$, MPa
1	Clay, banded laminar plastic	36	1.89	0.8	16	0.42	8
2	Sandy clay	22	1.98	1.2	20	0.32	9
3	Loam	20	2.04	2.0	22	0.40	12

Table 2 Continued

4	Fluid sandy loam	15	2.28	2.0	26	0.31	18
5	Clay, thin-laminated solid	12	2.15	20.0	25.0	0.35	300.0

Note: *W* is the natural moisture content of subsoil, γ_S is the subsoil bulk density, C is the cohesion coefficient, φ is the internal friction angle, ν_S is the Poisson coefficient, E_S is the elasticity modulus.

Table 3 Critical stresses for various moisture contents

#	n, %	ε	W_W, %	γ_C *10^2, MN/m^3	γ_{sp} *10^2, MN/m^3	γ_W *10^2, MN/m^3	$\sigma_{\exp}$ *10^2, MPa	σ_{comp} *10^2, MPa	τ_{shear} *10^2, MPa
1	50.7	1.030	70	1.37	2.78	2.32	1.15	2.4	1.4
2	35.8	0.558	44	1.62	2.52	2.33	1.78	3.09	2.25
3	34.1	0.517	41	1.70	2.58	2.59	2.8	5.3	3.6
4	29.2	0.425	34	1.98	2.82	2.65	2.7	6.2	3.8
5	22.9	0.297	25	1.92	2.49	2.40	22.4	64.8	33.6

Note: *n* is the subsoil porosity, ε is the porosity coefficient, W_W is the total moisture content, γ_C is the bulk dry density, γ_{sp} is the specific weight, γ_W is the subsoil bulk density at total moisture content, $\sigma_{\exp}$ is the shear expansion resistance, σ_{comp} is the shear compression resistance.

Table 4 summarizes predicted water amounts required for preset moisture content at unit volume; the moisture content was preset in the range from natural moisture content to total moisture capacity, predictions were performed according to the Maslov equations [20], using the procedure by Kurmanbekkyzy [4]:

1) bulk density of subsoil of respective moisture content (W_{pr}): $\gamma_{pr.w.} = \gamma_c(1+\frac{W_{pr}}{100})$,

2) water bulk density: $q_w = \gamma_c(W_{pr} - W)$.

Table 4 Classification of subsoil types by its groups and its coefficients

Subsoil	W_M, %	$\gamma_{p.m.}$*10^2, MN/m^3	q_W, t
Clay, banded laminar plastic	40	1.91	0.055
	45	1.99	0.123
	50	2.06	0.191
Sandy clay	30	2.11	0.129
	35	2.19	0.210
	40	2.27	0.291
Loam	25	2.13	0.085
	30	2.21	0.170
	35	2.29	0.255
Fluid sandy loam	20	2.38	0.099
	25	2.48	0.198
	30	2.57	0.297

Table 4 Continued

Clay, thin-laminated solid	15	2.21	0.057
	20	2.30	0.153
	25	2.40	0.249

5. CONCLUSION

Surface subsoils, such as loams, sandy clays, clays, loess, can be saturated with water as a consequence of atmospheric precipitations (infiltration), rising of underground water (filtration) as well as of technogenic impacts. Investigations related with determination of stability of hazardous landslides are often based on physicomechanical properties of mainly dry subsoils due to unavailability of data on elastic properties of water saturated subsoil. The tables presented in this article can eliminate this drawback and allow to study in details stress and strain state with actual accounting for two-phase state of slope subsoil.

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