Геолошки анали Балканскога полуострва Annales Géologiques de la Péninsule Balkanique	70	83–91	Београд, децембар 2009 Belgrade, December 2009

DOI: 10.2298/GABP0970083H

The influence of the grain-size distribution and soil structure on the unsaturated shear strength of loess sediments in Belgrade, central Serbia

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Abstract. There is a negative pore water pressure or matric suction in the zone above the ground water level in silty loess soil, which can be as deep as 5–10 m in the Belgrade area. This primary characteristic of unsaturated soil, *i.e.*, matric suction, should be included in laboratory testing and geotechnical analyses. Direct shear or triaxial testing of unsaturated soil are very expensive and time-consuming and require specially modified equipment. Instead, the prediction of unsaturated shear strength using the soil water characteristic curve, SWCC, and the effective shear strength parameters c' and φ' is a widely accepted practice. In this study, constitutive soil-water characteristic curves were obtained from the results of experimental testing by draining saturated soil samples under different pressures. This testing was performed for the first time in Serbia in a 15 bar pressure plate extractor according to ASTM standards. The laboratory testing included natural samples of loess sediments with the original macroporous structure and loess sediments with a destroyed soil structure. The influence of the grain-size distribution and natural soil structure on the unsaturated shear strength of Belgrade loess sediments above the ground water level was also evaluated. The obtained results are in accordance with the results from other investigations.

Key words: unsaturated shear strength, matric suction, loess sediments, soil-water characteristic curve, grain-size distribution, structure of soil.

Апстракт. Надизданска зона у прашинастим лесним седиментима у подручју Београда може да буде дебљине 5–10 m. У овој надизданској зони постоји матрична сукција (негативни порни притисак). Основно својство незасићеног тла – матричну сукцију би требало укључити у лабораторијска испитивања незасићеног тла, али и геостатичке анализе. Опити директног смицања или триаксијалне компресије незасићеног тла су дуготрајни, скупи и подразумевају измену конвенционалне лабораторијске опреме. Уместо тога, све чешће се користи поступак одређивања незасићене чврстоће тла помоћу основне конститутивне зависности незасићеног тла влажност/сукција и ефективних параметара чврстоће засићеног тла c' и φ'. У овом раду су, први пут код нас, приказани резултати одређивања конститутивних зависности ефективни степен засићења/матрична сукција, на основу лабораторијских опита дренирања узорака тла под различитим притисцима. Опити су вршени у 15-bar екстрактору са полупропустљивом плочом према стандардима АСТМ. Опити дренирања су спроведени на непоремећеним узорцима са очуваном и измењеном примарном макропорозном структуром. Анализиран је и утицај гранулометријског састава и примарне структуре на конститутивне зависности лесних седимената надизданске зоне у Београду. Добијени резултати упоређени су са резултатима иностраних истраживача и добијена су добра слагања.

Кључне речи: чврстоћа незасићеног тла, матрична сукција, лесни седименти, карактеристична крива влажности, гранулометријски састав, структура тла.

Introduction

Soil in the terrain is often considered saturated, even when it is actually above the ground water level and with a natural water content, *i.e.*, it is, in fact, unsaturated. Unsaturated soil is the soil mostly subject to matric suction or with the presence of a negative pore-water pressure. There are numerous types of soil in engi-

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neering practice the behavior of which is not consistent with the principles and concepts of classical, saturated soil mechanics: collapsible soil, expansive soil, compacted soil and residual soil. Conventional analyses of the lateral earth pressure, bearing capacity or slope stability, which neglects matric suction in soil, give conservative solutions and low factors of safety. It is proved that matric suction in soil decreases the lateral active earth force and increases: the critical height of a slope, the bearing capacity and slope stability. In spite of that, unsaturated soil was not commonly investigated in geological and geotechnical professional and scientific practice. The justification for this could be found in the fact that the results obtained with saturated soil parameters provide more safety and in the absence of a simple and, for the practice, acceptable method for determining the unsaturated shear strength. Triaxial and direct shear tests on unsaturated soils are very expensive and time-consuming and require specially modified equipment. Instead, the widely accepted practice of determining unsaturated shear strength using the soil water characteristic curve (SWCC) and the effective shear strength parameters, c' and φ', was applied in this study for the first time in Serbia. The paper deals with the results of draining samples in a pressure plate extractor, which were obtained to determine the basic constitutive relations for unsaturated loess soil from the Belgrade zone above the ground water level.

Loess sediments of the zone above the ground water table in Belgrade

It is known that the terrain in the Belgrade area consists of two complexes that are considerably different in the engineering-geological sense: silty Quaternary sediments and clay and marls Tertiary sediments. Due to the structural type of the porosity and the location within the terrain, the silty Quaternary sediments and the weathered zone of Tertiary clays and marls perform the function of hydrogeological collector. This is where the ground water level is most often found, and its depth depends on the depth of unweathered tertiary clay and marls sediments.

The terrain of loess covered soil in the Belgrade area can be classified in accordance with its morphological and other characteristics into:

– lowlands between the Sava and the Danube Rivers,
– hilly terrain of the urban area.

The lowlands between the Sava and the Danube Rivers represent the end of the spacious plains of Srem, better known as the Zemun loess plateau. The loess series consists of five loess horizons separated by four horizons of paleoelluvial loess soil. In lithological composition, the paleoelluvial loess soils are represented by clay-sandy alevrolites.

The specific macro-porous structure of the highest loess horizons and their position within the terrain have enabled the formation of a permanent aeration zone of considerable thickness in the vicinity of the Danube (elevation 110–114 m above sea level) where it reaches 20 or more meters. In the area of lower elevations (80 m above sea level), this zone is thinner and is around 8 m thick.

The loess sediments of the zone above the ground water level of the Zemun loess plateau are mainly preserved primary, loose structures. They are characterized by spherical, cm-size aggregates which cause inter-granular and inter-aggregate porosity. The size of the pores is not constant and is between capillary and super-capillary. The pores are continually vertically elongated, approximately round in cross-section and are consistent with tubular porosity. The solid particles are interlinked by crystallized carbonates.

Regarding the grain-size distribution, they are represented with about 70 % content of the fraction 0.06–0.002 mm; the content of fraction >0.06 mm increases with depth, for macroporous and paleoelluvial loess sediments, it is 10–20 % up to a maximum of 90 % for sandy loess soil. The content of the fraction <0.002 mm is also 10–20 % for macroporous and paleoelluvial loess sediments.

In the phase content, air-filled pores, around 30 %, are much more present, whilst the volume of water-filled pores is around 20 %. Content of solid phase gradually increases with depth. The contribution of pores to the total volume of the loess is 45–55 %. Of the total volume 22–32 % is filled with water. The gravimetric water content is about 15–18 % and the degree of saturation in accordance with this varies from 45 % for macroporous loess, about 55 % for sandy loess and up to 80 % for paleoelluvial loess soil.

The dry unit weight is 14.2–17.2 kN/m^3 and the unit weight with a natural water content is 16.4–20.2 kN/m^3. According to the CASAGRANDE classification, the loess sediments of the aeration zone are clays with low plasticity, CL, with a liquid limit w_l = 24–35 %, a plastic limit w_p = 13–20 %, a plasticity index of I_p = 7–15 % and a colloidal activity of $K_p > 1.25$.

The deeper levels of the loess complex are changed in grain size and in structure: they are either sandier, more compressed with many concretions, like sandy loess or they are of greater clay content and dark in color, like paleoelluvial loess soil. In any case, they are found at considerable depth above the ground water table and are unsaturated. According to this, tests and investigations of these different loess sediments were performed on: typical macroporous loess soil, paleoelluvial loess soil and sandy loess soil, all of the Zemun loess plateau, from a part of the Pregrevica area, near the street of Cara Dušana in Zemun.

A typical example of the loess complex covering the hilly terrain of the city's territory is the investigated location near Kralja Aleksandra Boulevard, west of Deskaševa Street to Aradska Street and south of Milana Rakića Street up to Kralja Aleksandra Boulevard. The terrain is mildly sloping towards the southwest with an

Table 1. Results of the identification-classification tests.

Soil	γ	γ_d	w	G_s	e	S_r	w_l	I_p	Fraction %		
	kN/m^3		%	–	–	%			< 0.002	0.002–0.06	>0.06
Sediments of the Zemun's loess plateau zone above the ground water table – Pregrevica location											
Macroporous loess	16.43	14.22	15.49	2.70	0.898	45	32	10	12	70	18
Paleoelluvial loess	20.22	17.17	17.81	2.75	0.602	81	35	10	12	70	10
Sandy loess	17.54	15.03	16.67	2.74	0.823	55	24	10	12	70	90
Sediments of the zone of loess complex above the ground water table – Boulevard Kralja Aleksandra location											
Destroyed structure loess	18.98	16.01	18.52	2.74	0.655	75	39	16	19	73	8
Paleoelluvial loess	19.80	16.80	17.85	2.70	0.607	80	37	15	15	75	10
Clayey loess soil	19.61	16.44	19.30	2.68	0.630	81	36	13	30	62	8

average gradient of up to 5°, and in places up to 15°. The absolute terrain elevation is between 189.5 and 215.5 meters above sea level in Milana Rakića Street and between 187.5 and 190.0 meters above sea level along this part of Kralja Aleksandra Boulevard. The primary morphological characteristics of the terrain are significantly changed due to the activity of contemporary geological processes and, especially, due to human activities and urbanization: excavations, slope cuts and fillings.

The terrain surface is made of a complex of loess deposits up to 15 m in depth. Two loess horizons with partly destroyed structure can be distinguished in the loess complex – layered with paleoelluvial soil and with clayey loess soil. Under them, delluvial clays 2–4 m in thickness are found. Marls and clays are at a depth of 10–15 m. The ground water level is to be found at a depth greater than 5 m.

The loess sediments of this complex genetically fall into the slope type. Only the loess sediments on the hypsometrically highest elevations have maintained their primary macroporous structure and are identical in quality and mechanical behavior to the loess of the Zemun plateau. Due to the concurrent activity of Aeolian and delluvial processes during formation, the deeper layers are richer in clay components – darker, denser and enriched with a carbonate content and have a destroyed primary structure.

In the phase content, the sediments of the lower zone have an increased content of solid components of 60–65 %. The pore content in the total volume is 35–40 %. The remaining volume is filled with water. The absolute water content is 18–20 % and the degree of saturation varies from 75 to 80 %. Dry unit weight is 16.0–17.0 kN/m^3 and the unit weight including the natural water content is γ = 19.0–20.0 kN/m^3.

According to the CASAGRANDE classification, the loess sediments of the aeration zone are medium-plasticity clays, CI, with liquid limit w_l =36–39 %, a plastic limit w_p = 23 %, a plasticity index I_p = 13–16 % and a colloidal activity K_p >1.25.

In accordance with the listed geological and hydrogeological characteristics of the terrain and the physical soil indices (phase content, pore size, absolute water content, degree of saturation) shown in Table 1, it is clear that the sediments of the Zemun loess plateau – location Pregrevica, as well as those from the investigated area at the Boulevard Kralja Aleksandra are above the ground water level and are unsaturated.

Shear strength of unsaturated soil

An unsaturated soil actually consists of four phases. In addition to the solid, air and water phases, there is the air-water interface that can be referred to as the contractile skin (FREDLUND & RAHARDJO 1993). The most distinctive property of the contractile skin is its ability to exert a tensile pull. The soil particles are assumed to be incompressible. Any two of three possible normal stress variables can be used to describe the stress state of an unsaturated soil; hence there are three possible combinations which can be used as stress state variables for an unsaturated soil. However, the combination of the net normal stress ($\sigma - u_a$) and matric suction ($u_a - u_w$) appears to be the most satisfactory for use in engineering practice.

Unsaturated shear strength is a function of the two stress variables: the net normal stress and matric suction (FREDLUND *et al.* 1976). The relationship of the unsaturated soil shear strength function to the matric suction can be established based on the primary constitutive relationships for an unsaturated soil – soil water characteristic curves. In the literature, different equations have been proposed to represent sorption or desorption curves (FREDLUND *et al.* 1996). In this paper, the soil-water characteristic curves are defined as matric suction *vs*. degree of saturation curves according to the BROOKS & COREY (1964) function, one of the most used in practice.

There are three soil parameters that can be identified from the matric suction *vs*. degree of saturation curve. These are: the air entry value of the soil, $(u_a - u_w)_b$, the residual degree of saturation S_{res} and the pore size distribution index, λ. These parameters can readily be visualized if the saturation condition is expressed in terms of an effective degree of saturation, S_e, (Fig. 1):

$$S_e = \frac{S_r - S_{res}}{1 - S_{res}} \tag{1}$$

where: S_e is the effective degree of saturation and S_{res} is the residual degree of saturation.

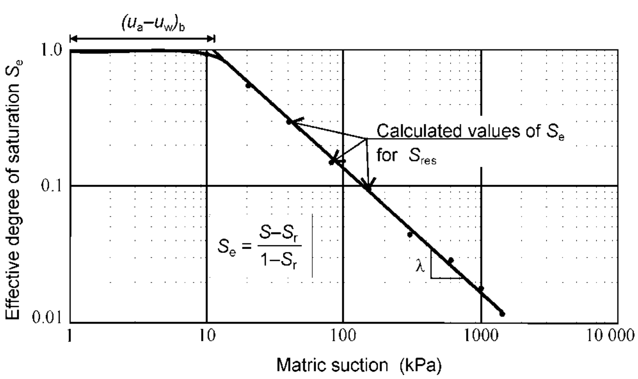

Fig. 1. Effective degree of saturation vs. matric suction (BROOKS & COREY 1964).

The residual degree of saturation is defined as the degree of saturation at which an increase in matric suction does not produce a significant change in the degree of saturation.

The air entry value of a soil, $(u_a - u_w)_b$, is the matric suction value that must be exceeded before air recedes into the soil pores. It is a measure of the maximum pore size in a soil. The sloping line for points having matric suctions greater than the air-entry value can be described by the following equation:

$$S_e = \left[\frac{(u_a - u_w)_b}{(u_a - u_w)}\right]^{\lambda} \quad \text{for} \quad (u_a - u_w) > (u_a - u_w)_b \tag{2}$$

where: $(u_a - u_w)_b$ is the air entry value of the soil and λ is the pore size distribution index, which is defined as the negative slope of the effective degree of saturation, S_e, *vs*. matric suction, $(u_a - u_w)$, curve.

It should be stressed that Eqn. (2) is valid for suction values greater than the air-entry value and for degrees of saturation greater than the residual degree of saturation.

The shear strength of unsaturated soil, τ_f, is then evaluated by the approach proposed by VANAPALLI *et al.* (1996):

$$\tau_f = c' + (\sigma - u_a)\tan\varphi' + (u_a - u_w)\tan\varphi' S_e \tag{3}$$

where: c' is the effective cohesion of saturated soil, φ' is the effective angle of shear resistance of saturated soil, $(\sigma - u_a)$ is the net normal stress and $(u_a - u_w)$ is the matric suction.

The unsaturated shear strength parameter, φ^b, which is the angle of shear resistance with respect to changes in the matric suction, can also be expressed by the effective degree of saturation (VANAPALLI & FREDLUND 1999):

$$\tan\varphi^b fn(u_a - u_w) = S_e \tan\varphi' \tag{4}$$

where: $\varphi^b fn(u_a - u_w)$ is the unsaturated shear resistance for changes in the matric suction $(u_a - u_w)$.

Unsaturated shear strength of loess sediments Belgrade zone above the ground water table

The laboratory investigations were performed on undisturbed samples of several loess soils above the ground water level from two different locations: from the Zemun loess plateau – location Pregrevica and from the hilly area near Kralja Aleksandra Boulevard. The following were determined for the typical unsaturated silty soils:

– the soil-water characteristics curves, *i.e.*, the effective degree of saturation, S_e *vs*. matric suction, $(u_a - u_w)$, curves;

– the unsaturated shear strength, τ_f, *vs*. matric suction, $(u_a - u_w)$, curves;

– the changes of unsaturated shear resistance φ^b with matric suction, $(u_a - u_w)$.

The soil-water characteristic curves were obtained from the results of experimental measurements in which saturated soil samples were drained under different pressures in a pressure plate extractor, according ASTM (1993), standards D2325-68 and D3152-72. The friction angle φ^b was also determined in dependence on the matric suction (HADŽI-NIKOVIĆ 2005).

The pressure plate extractor consists of a high air entry ceramic disc placed in an air pressure chamber. The high air entry disk is saturated and is always in contact with water in the compartment below the disk. The compartment is maintained at zero water pressure. The soil specimens are placed on top of the disk and the airtight chamber is pressurized to the desired matric suction. The disk does not allow the passage of air as long as the applied matric suction does not exceed the air entry value of the disk. The air entry value of the disk is related to the diameter of the fine pores in the ceramic disk. Therefore, the air entry value of the disk and the strength of the chamber control the maximum air pressure, or matric suction, which can be applied to soil specimens.

The application of matric suction to the soil causes the pore-water to drain in the water compartment through the disk. At equilibrium, the soil will have a reduced water content corresponding to the increased matric suction. The water content at each equilibrium condition can be computed from measurement of the change in the water volume. The chamber must be dismantled and the weight of the specimen measured after equilibrium at each applied pressure. This procedure is commonly used with a 15 bar ceramic plate extractor.

Direct shear tests for determining the effective cohesion, c' and the effective angle of shear resistance, φ', of saturated soil are also performed. For undisturbed samples of loess soil with a natural water content, the following results were obtained: $c' = 20$ kPa and $\varphi' = 24°$ for loess; $c' = 37$ kPa and $\varphi' = 23°$ for paleoelluvial loess soil and $c' = 10$ kPa and $\varphi' = 25°$ for sandy loess.

With regards to the sediments above the ground water level from the Zemun loess plateau (macroporous loess, paleoelluvial loess and sandy loess), which have a retained primary structure, and the sediments from the hilly area near Kralja Aleksandra Boulevard (destroyed structure loess soil and clayey loess soil), which have a changed structure without macropores, the obtained results confirmed the effect of primary structure of the loess sediments on their unsaturated shear strength.

Unsaturated shear strength parameters for loess sediments having a macroporous structure

The constitutive relations: the effective degree of saturation, S_e, *vs*. the matric suction, $(u_a–u_w)$, curve, Eqn. (2); the unsaturated shear strength, τ_f, *vs*. the matric suction, $(u_a–u_w)$, curve, Eqn. (3), and the friction angle, φ^b, in dependence on the matric suction, $(u_a–u_w)$, Eqn. (4), are presented in Figs. 2, 3 and 4, respectively, for macroporous loess and in Figs. 5, 6 and 7, respectively, for sandy loess soil.

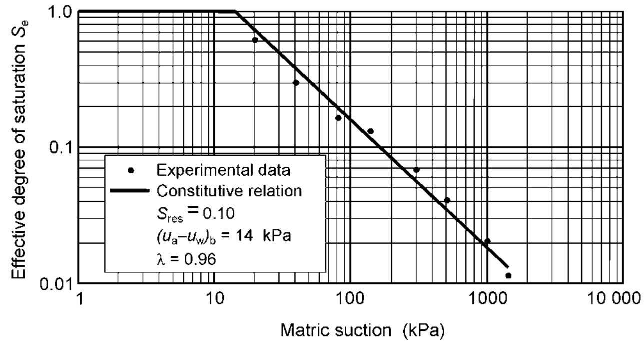

Fig. 2. Effective degree of saturation *vs*. matric suction for macroporous loess soil.

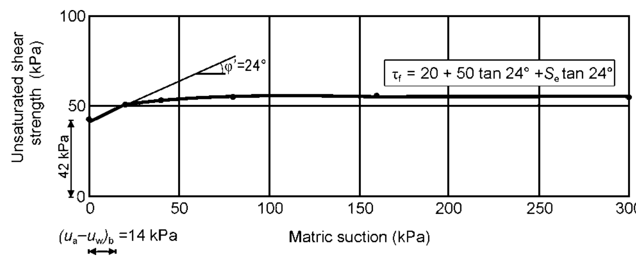

Fig. 3. Unsaturated shear strength *vs*. matric suction for macroporous loess soil.

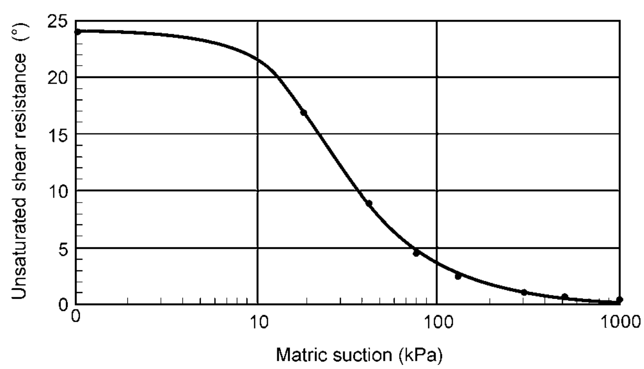

Fig. 4. Unsaturated shear resistance with changes in matric suction for macroporous loess soil.

For eight different values of the matric suction from 20 to 1300 kPa, the obtained values for the degree of saturation were: $S_r = 0.11–0.43$ for macroporous loess; $S_r = 0.39–0.72$ for paleoelluvial loess soil and $S_r = 0.26–0.55$ for sandy loess sediments.

The value of the residual degree of saturation was the lowest for the macroporous loess, $S_{res} = 0.11$, while the values of S_{res} were 0.39 and 0.26 for paleoelluvial loess soil sandy loess sediments, respectively. The desaturation velocity decreased with increasing residual degree of the saturation. This actually means that the unsaturated shear resistance, φ^b, slowly decreased for soil samples with a larger residual degree of saturation.

For values of the matric suction, $(u_a–u_w)$, between 20–50 kPa, the angles of unsaturated shear resistance, φ^b, were 16°–8°, 20°–12° and 11°–7° for macroporous loess soil, paleoelluvial loess soil and sandy loess sediments, respectively. It was observed that the draining occurred very fast for macroporous soils.

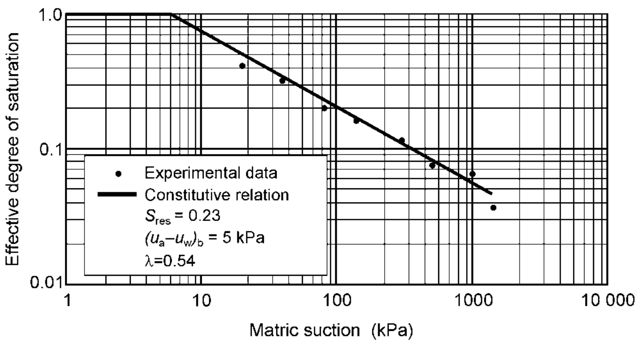

Fig. 5. Effective degree of saturation *vs*. matric suction for sandy loess soil.

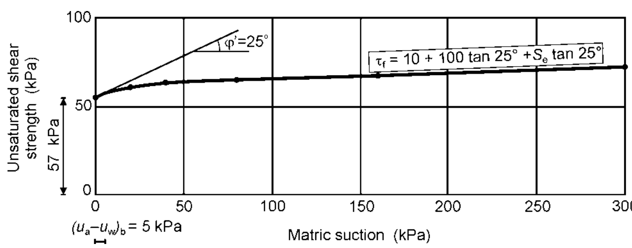

Fig. 6. Unsaturated shear strength *vs*. matric suction for sandy loess soil.

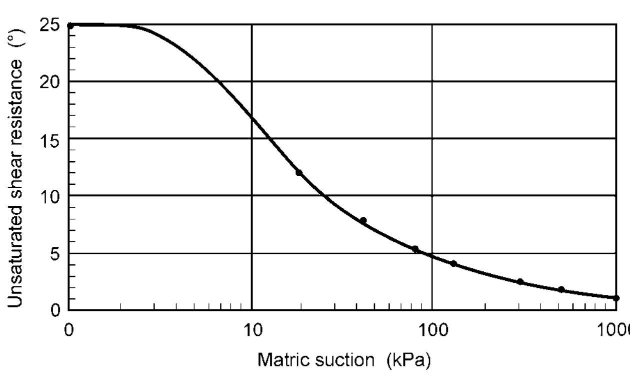

Fig. 7. Unsaturated shear resistance with changes in matric suction for sandy loess soil.

The grain-size distribution was also very significant for both the soil-water characteristic curve and the unsaturated shear strength. With increasing grain size in the soil, the effect of matric suction on the unsaturated shear strength diminished. For macroporous loess soil, however, its primary structure was more significant than grain-size distribution. The macroporous loess samples had the lowest values of the degree of saturation for the same matric suction value, even lower than the value of the degree of saturation for the sandy loess soil having the largest grain size.

The effect of matric suction on the unsaturated shear resistance, φ^b, was more significant at lower matric suction values, with a higher value of the degree of saturation. After a certain matric suction value, the unsaturated shear resistance rapidly decreases.

Unsaturated shear strength parameters for loess sediments with a destroyed structure

The constitutive relations: the effective degree of saturation, S_e, *vs*. the matric suction, (u_a-u_w), curve, Eqn. (2); the unsaturated shear strength, τ_f, *vs*. the matric suction, (u_a-u_w), curve, Eqn. (3), and the friction angle, φ^b, in dependence on the matric suction, (u_a-u_w), Eqn. (4), are presented in Figs. 8, 9 and 10, respectively, for destroyed loess and in Figs. 11, 12 and 13, respectively, for loess clay soil.

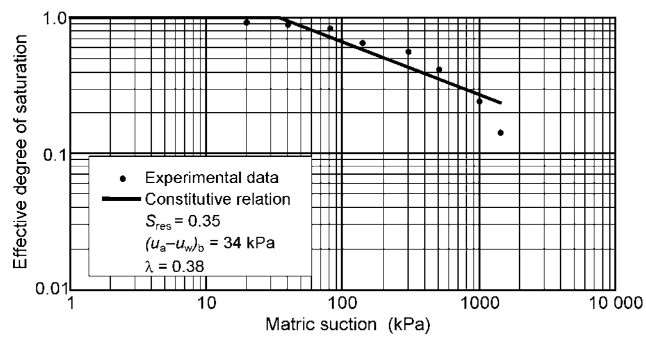

Fig. 8. Effective degree of saturation *vs*. matric suction for destroyed loess soil.

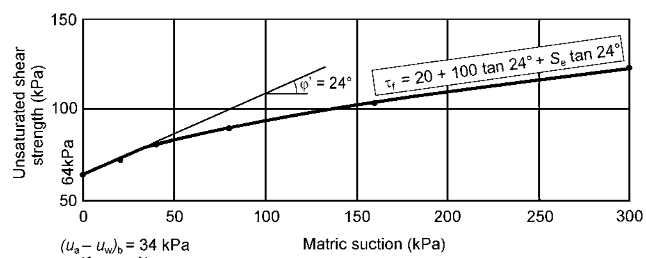

Fig. 9. Unsaturated shear strength *vs*. matric suction for destroyed loess soil.

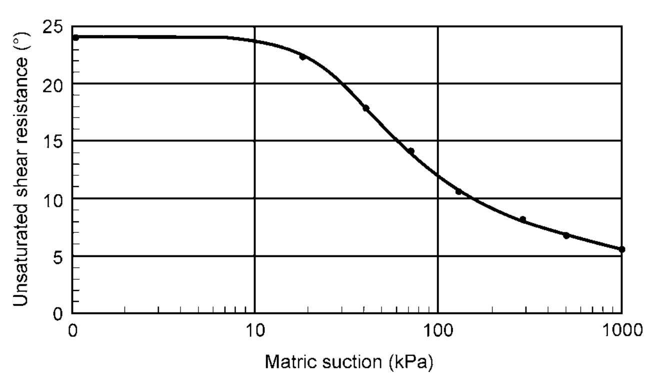

Fig. 10. Unsaturated shear resistance with changes in matric suction for destroyed loess soil.

The soil-water characteristic curves for the destroyed loess soils confirmed that loess sediments in the hilly area of Belgrade had been subjected to processes which led to great changes in their primary structure in comparison with the macroporous loess soils in the Zemun plateau. Namely, the effective degree of saturation *vs.* matric suction curves of the residual loess sediments were above the effective degree of saturation *vs.* matric suction curves for macroporous loess. This means that the soil with a greater silty and sandy fraction had a steeper soil-water characteristic curve in comparison to that of soil with a greater clayey fraction.

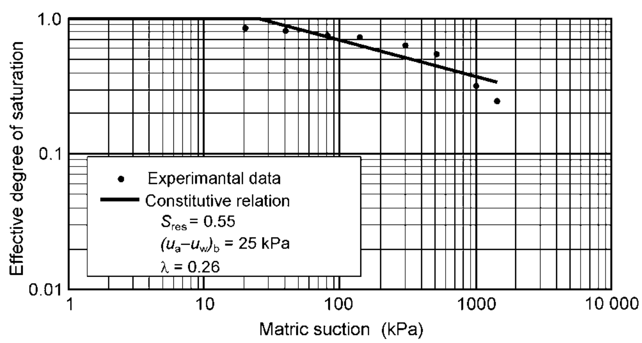

Fig. 11. Effective degree of saturation vs. matric suction for clayey loess soil.

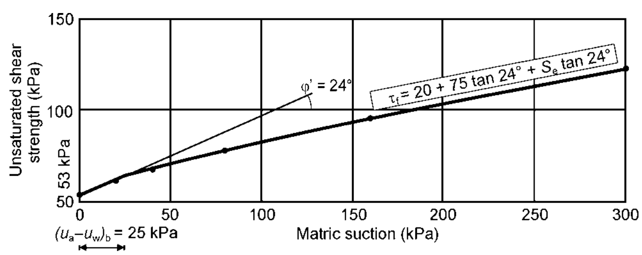

Fig. 12. Unsaturated shear strength vs. matric suction for clayey loess soil.

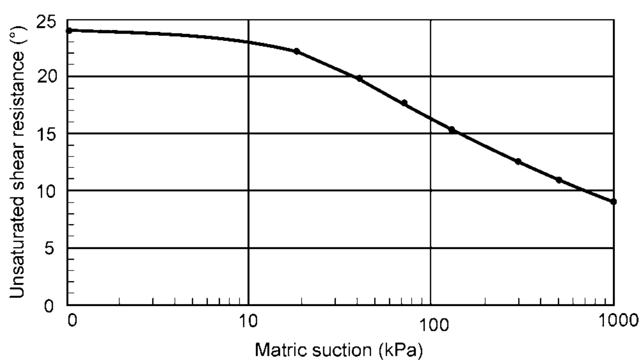

Fig. 13. Unsaturated shear resistance with changes in matric suction for clayey loess soil.

For eight different values of matric suction from 20 to 1300 kPa, the obtained values for the degree of saturation were: S_r = 0.46–0.95 for the destroyed loess soil and S_r = 0.67–0.94 for the clayey loess soil. The residual degrees of saturation for the destroyed loess sediments were higher than those for the macroporous loess sediments, S_{res} = 0.35–0.58.

For values of the matric suction $(u_a–u_w)$ = 20–50 kPa, the angles of unsaturated shear resistance, φ^b were 22°–16° for the residual loess soils. The value of the unsaturated shear resistance decreased more slowly in comparison with those of the macroporous loess soil, because desaturation lasted longer.

Verification of obtained results

Bearing in mind that this type of investigations were conducted in Serbia for the first time, the results obtained in this way were checked by comparison with results from known investigations in which a different method was employed.

The obtained results were correlated by use of the non-dimensional parameter, *K*, determined for different types of soil, and the established dependency of the parameter *K* on the plasticity index I_p. VANAPALLI & FREDLUND (1999) suggested the following equation for determining the unsaturated strength:

$$\tau_f = [c'+(\sigma_n-u_a)\tan\varphi'] + (u_a-u_w)\Theta^{K}(\tan\varphi') \quad (5)$$

where: *K* is a fitting parameter for the predicted and measured unsaturated shear strength and $\Theta = w/w_s$, where *w* is the water content after draining under a certain value of matric suction, $(u_a–u_w)$ and w_s is the saturated water content.

Based on the reverse of this equation, value of correlation parameter *K* was determined for all types of soil for which experimentally determined constitutive relations: the effective degree of saturation *vs.* matric suction and the strength of an unsaturated soil *vs.* the matric suction exist. The obtained values of the parameter *K* are shown in the diagram of the already determined relationship between the fitting parameter, *K*, and the plasticity index, I_p (VANAPALLI & FREDLUND 2000), Fig. 14.

From the diagram, it can be seen that there is a good agreement of the parameter *K* with the established dependency on the plasticity index I_p for silty loess sediments. Furthermore, it can be seen that the parameter *K* is in concurrence with the previously quoted dependency on the plasticity index I_p for silty and silty-sandy loess sediments, primarily for sandy loess and macroporous loess from the Pregrevica location, and also for the destroyed slope loess sediments from Kralja Aleksandra Boulevard. Somewhat less concurrent are the results for the changed loess sediments with a larger clay content at the location in Kralja Aleksandra Boulevard, such as the clayey loess soil and the elluvial loess soil.

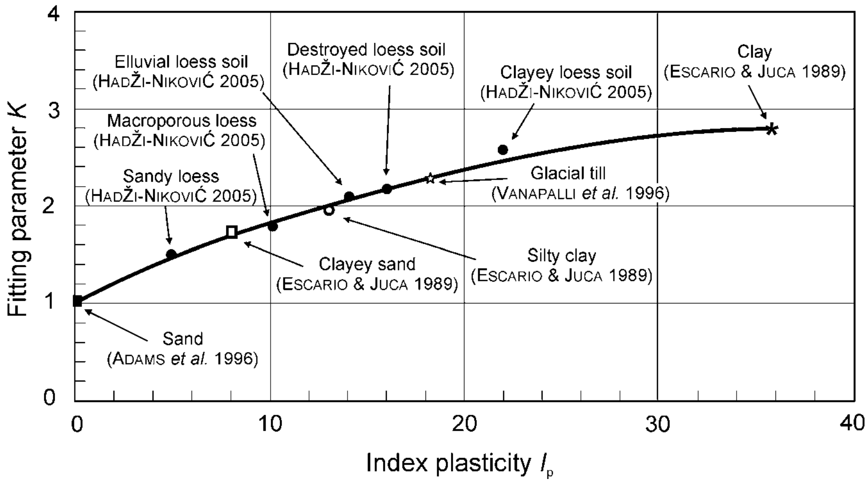

Fig. 14. The relationship between the fitting parameter and the plasticity index (VANAPALLI & FREDLUND 2000).

Concluding remarks

According to the geology and hydrology of terrain in the Belgrade area and the engineering-geological and hydrogeological properties of the soil, it is obvious that the zone above the ground water table can be 5–10 m in depth and the soil is unsaturated in this zone.

Geotechnical analyses of the lateral earth pressure, the bearing capacity and slope stability in respect of the matric suction in the zone above the ground water level confirmed that matric suction can be very important for rational design in geotechnical engineering.

A negative pore-water pressure is present in this zone, which contributes to a larger shear strength of the unsaturated soil. Laboratory investigations were performed on undisturbed samples of several loess soils above the ground water table from two different locations: from the Zemun loess plateau, location Pregrevica, and from the hilly area near Kralja Aleksandra Boulevard. For typically unsaturated silty soils. the following relationships were determined: the soil-water characteristics curves, *i.e.*, effective degree of saturation, S_e, *vs*. matric suction, $(u_a–u_w)$, curves, unsaturated shear strength, τ_f, *vs*. matric suction $(u_a–u_w)$, relations and the changes in the unsaturated shear resistance, φ^b, for changes in the matric suction $(u_a–u_w)$.

Soil-water characteristic curves were obtained from the results of experimental measurements on draining saturated soil samples under different pressures, which were performed in a pressure plate extractor – 15 bar Pressure Plate Extractor 1500 – Soilmoisture Equipment Corporation, Santa Barbara, California, according to ASTM standards D2325-68 and D3152-72.

The unsaturated shear strength was determined by the VANAPALLI Eqn. (1996) using the basic effective degree of saturation *vs*. matric suction curve proposed by BROOKS & COREY (1964), one of the most used in practice.

The contribution of matric suction to the unsaturated shear strength depends on the draining velocity. For the same normal stress and the same matric suction, soil samples with larger degree of saturation have a higher unsaturated shear resistance. Macroporous loess and sandy loess soil with a retained primary structure and large pores exhibited very fast draining with increasing values of the matric suction; hence the rate of the unsaturated shear resistance decreased very fast and abruptly. With decreasing grain size, the velocity of the desaturation decreased. Increasing grain size in a soil, diminished the effect of matric suction on the unsaturated shear strength. However, for macroporous loess soil, its primary structure was more significant than the grain-size distribution.

The obtained results are in accordance with the results of other available investigations.

Acknowledgements

I wish to express my most sincere thanks to the reviewers, KIRIL ANGELOV (University of Mining and Geology „St. Ivan Rilski", Sofia) and ŽELJKO ARBANAS (Faculty of Civil Engineering, Rijeka) for their critical reading of the manuscript and useful suggestions. I am especially thankful to BOŠKO GAJIĆ (Faculty of Agriculture, Belgrade) for his patience and great help in the pressure plate extractor experiments (15 bar Pressure Plate Extractor 1500 – Soilmoisture Equipment Corporation, Santa Barbara, California), which were performed in the Laboratory for Soil Physics in the Faculty of Agriculture in Belgrade. Thanks also go to my dear colleagues, SLOBODAN ĆORIĆ and LASLO ČAKI (Laboratory for Soil Mechanics in the Faculty of Mining and Geology, Belgrade) for their academic support and laboratory facilities. Many thanks to Lidija Beko (Faculty of Mining and Geology, Belgrade) who helped me unselfishly and checked the English language.

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Резиме

Утицај гранулометријског састава и структуре тла на незасићену чврстоћу лесних седимената у Београду, централна Србија

Надизданска зона на одређеним локацијама у подручју Београда има значајну дебљину, 5–10 m. У њој постоје негативни порни притисци или матрична сукција, која повећава чврстоћу незасићеног тла. Приликом решавања одређених геотехничких проблема, који се манифестују изнад нивоа подземне воде, као што су проблеми плитког фундирања, одређивања активног притиска тла, стабилности вертикалних ископа или косина са клизном површином изнад нивоа воде, требало би уважавати принципе механике незасићеног тла, а методе истраживања и лабораторијских испитивања, као и геостатичке анализе, ускладити са реалним теренским условима, дакле уз уважавање постојања негативних порних притисака у тлу.

Лабораторијска испитивања чврстоће незасићеног тла опитима директног смицања или триаксијалне компресије су дуготрајна и скупа и захтевају модификовање конвенционалне лабораторијске опреме. Због тога се чврстоћа смицања незасићеног тла све више одређује посредно, преко кривих зависности влажност/матрична сукција и ефективних параметара чврстоће смицања засићеног тла *c*' и φ'.

У раду су приказани и анализирани резултати дренирања узорака тла, у екстрактору са полупропустљивом плочом под различитим величинама матричне сукције. По први пут код нас, на основу опита дренирања под различитим притисцима, успостављене су криве зависности ефективни степен засићења/матрична сукција и на основу њих и ефективних параметара чврстоће засићеног тла, *c*' и φ', успостављене зависности незасићена чврстоћа тла/матрична сукција. Такође, одређене су зависности величине незасићене отпорности на смицање φ^b од матричне сукције.

Лабораторијска испитивања су вршена на природним непоремећеним узорцима надизданске зоне са очуваном и измењеном примарном структуром. На тај начин је анализиран утицај појединих чинилаца, а пре свега гранулометријског састава и примарне структуре тла, на конститутивне зависности незасићених лесних седимената.

Повећање чврстоће смицања услед постојања матричне сукције зависи од брзине дренирања тла. За исти нормални напон и исту матричну сукцију, узорци који имају већи ефективни степен засићења имају већу чврстоћу.

Макропорозни лес и песковити лес у природном стању имају велике поре, међусобно повезане и показују веома брзо дренирање са повећањем сукције, тако да величина угла φ^b врло брзо и нагло опада, јер се дренирање обавља веома брзо. Са смањењем величине зрна и величине пора у тлу, брзина десатурације опада.

Гранулометријски састав тла значајно утиче на облик криве влажност/ матрична сукција. Повећањем величине зрна у тлу, опада утицај величине матричне сукције на незасићену чврстоћу. За узорке макропорозног леса, међутим, значајнија је његова структура, величина пора и њихова међусобна повезаност од гранулометријског састава. Због своје цевасте структуре, макропорозни лес има најнижи степен засићења за исту величину матричне сукције, у поређењу са осталим, чак и крупнозрнијим тлом, нпр. песковити лесом.

Криве зависности ефективни степен засићења/матрична сукција падинских измењених лесних седимената потврђују промењену структуру у односу на лесне седименте очуване примарне структуре. Криве зависности ових седимената су изнад кривих зависности неизмењених макропорозних лесних седимената, дакле тло са већим учешћем крупнозрније фракције показује стрмију криву зависности влажност/ матрична сукција од тла са већим учешћем глиновите, ситнозрније фракције.

Узорци измењеног падинског леса са локације Булевар Краља Александра имају спорије опадање угла φ^b, јер се дренирање обавља знатно спорије у односу на неизмењене лесне седименте очуване структуре.

Утицај матричне сукције на незасићену чврстоћу, φ^b, већи је за мање величине матричне сукције, при већем степену засићења. Након одређене величине матричне сукције, чврстоћа незасићеног тла почиње нагло да пада.

Добијени резултати упоређени су са резултатима иностраних истраживача и добијена су добра слагања.