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Stress-strain-strength characteristics of macroporous loess in Belgrade

Caractéristiques de contrainte-déformation-résistance des loess macroporeux à Belgrade

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SYNOPSIS Extensive investigations of the slope loess of Belgrade have been performed in the Laboratory for Soil Mechanics, Department of Geotechnics, at the Belgrade Faculty of Mining and Geology. The results obtained show that the mechanical behaviour of macroporous loess depends to a large extent on the value of the consolidation pressure. Such behaviour is described with two hyperbolic models: one is over a range of "low" and the other of "high" stresses. The limiting stress, obtained from laboratory triaxial tests, is 85 kPa. The comparison of numerical and experimental results has shown that the proposed finite element procedure, based on the incremental Hooke's law and the developed constitutive model, can accurately represent the behaviour of loess soil under complex stress - strain conditions. The finite element analyses were performed on the DEC 20 computer at the Computer Centre of the Faculty of Civil Engineering, Belgrade.

Loess soil of different thickness spreads over the entire territory of Belgrade. It is more than 12 - 15, sometimes even 30 m thick, in places where erosion, landsliding and/or human activities have not destroyed it.

Because of its extension and distinct characteristics, the loess soil is the subject matter constantly dealt with by a number of research workers.

Systematic and comprehensive investigations have been carried out in the Soil Mechanics Laboratory at the Belgrade Faculty of Mining and Geology in the last four year (1980 - 1984) period.

In this paper the stress - strain characteristics of the slope loess will be presented. Being over the maximal ground water level during the geological past, the loess investigated has altered in some degree only. Its average physical properties are therefore as follows:

Dry unit weight	$\gamma_d = 13,5 - 16 \text{ kN/m}^3$
Porosity	$n = 42 - 50 \%$
Water content	$w = 18 - 22 \%$
Degree of saturation	$S_r = 54 - 87 \%$
Clay fraction (< 0,002 mm)	$c = 8 - 10 \%$
Liquid limit	$w_L = 36 - 44 \%$
Plasticity index	$I_p = 15 - 24 \%$
AC Clasification	CL/CI
Dominant clay minerals	illite and montmorillonite
Consistency index	$I_c = 0,9 - 1,10$

As for the mechanical properties, the results of the triaxial compression have shown a high degree of dependence on consolidation pressure.

So, in case of $\sigma'_3 \leq 75 \text{ kPa}$ slope loess at Mirijevo behaves like a stiff material, while for $\sigma'_3 \geq 100 \text{ kPa}$ its behaviour is plastic (Fig. 1).

According to our experience, such behaviour is the consequence of failure in the internal loess structure exposed to a corresponding critical stress state.

Due to a partial - local, or complete break of internal links, the detached particles move away from each other - sliding, rolling, rotating and better arranging themselves, densifying thus the entire mass. The original macroporous, coherent medium, after having been subjected to the critical stress state, changes into a well arranged granular mass. Under these conditions the inherent, primary cohesion is highly weakened, practically exhausted - at least that part of rigid links conditioned by hardened carbonate salts. A similar effect has the remaining part of links, namely the hydrocolloidal ones, if the water content in loess has not changed.

However, only a small increase of moisture quickens the destruction of the loess structure as the hydrated clay particles expand. It seems their most powerful effect happens when the moisture content approaches the swelling limit, closely above the plastic one ($w_s \approx w_p$). This amount could vary depending on one side, on the quantity of clay particles and, on the other, on their predominant mineralogical composition (illitic or montmorillonitic).

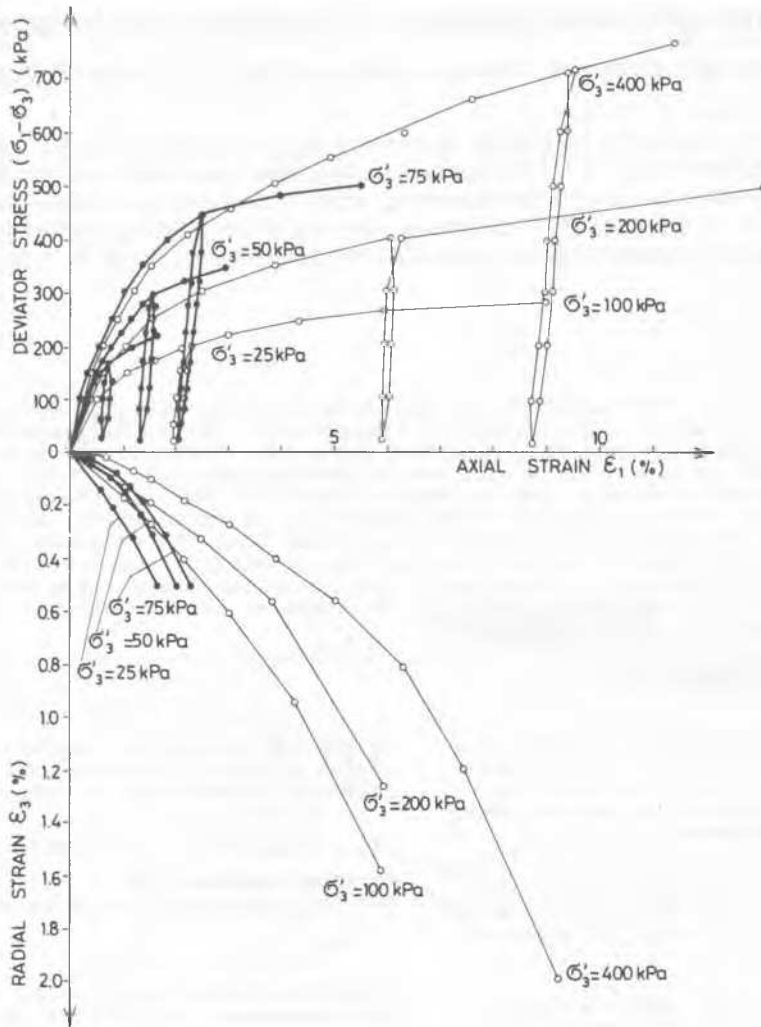


Fig. 1 Stress - Strain Curves for Loess Obtained by Drained Triaxial Tests

Considering the specific structure of loess investigated, it is estimated that the critical moisture increase, contributing to its failure, amounts from 2 or 3, up to 5 % i.e. $w = 22$ % total.

By a further increase of moisture content, as well as of the stress state (over the critical one), the hydrocolloidal links are restored again. But their effect is completely different now. Altered in this way the loess represents a qualitatively new coherent medium. Its behaviour is markedly plastic now and the strength grows up with the depth, i.e. with the loading intensity.

As mentioned above, for the soil investigated (with the water content $w = 18 - 22$ %) the critical state of stress separating the two "loesses" - stiff and plastic - is 85 kPa. This value was determined by interpolating stress - strain triaxial curves.

The stress - strain behaviour of loess soil is therefore defined with two hyperbolic models: one is over a range of "low" ($\sigma'_3 \leq 85$ kPa) stresses, while the other is over a range of "high" ($\sigma'_3 > 85$ kPa) ones.

These models can accurately represent the mechanical behaviour of macroporous loess soil exposed to complex loading conditions.

According to the hyperbolic stress - strain model developed by Duncan and his associates (1970 - 1980) and applied in this study, the tangent Young modulus (E) and the tangent Poisson ratio (ν) may be expressed as:

$$E = \left[1 - \frac{R_f (1 - \sin \varphi') \cdot (\sigma_1 - \sigma_3)}{2 \cdot c' \cdot \cos \varphi' + 2 \cdot \sigma'_3 \cdot \sin \varphi'} \right]^2 \cdot K \cdot R_f \cdot \left(\frac{\sigma'_3}{P_a} \right)^n \quad (1)$$

$$\nu = \frac{G - F \cdot \log \left(\frac{\sigma'_3}{p_a} \right)}{d \cdot (\sigma'_1 - \sigma'_3)} \quad (2)$$

$$1 - \left[\frac{R_f \cdot (1 - \sin \varphi') \cdot (\sigma'_1 - \sigma'_3)}{2 \cdot c' \cdot \cos \varphi' + 2 \cdot \sigma'_3 \cdot \sin \varphi'} \right] \cdot K \cdot p_a \left(\frac{\sigma'_3}{p_a} \right)^n$$

where:

- σ'_1, σ'_3 = the major and minor principal stress
- c', φ' = the Mohr - Coulomb strength parameters
- K, n, R_f, G, F, d = stress - strain parameters (Table I)

derived from the results of triaxial (CD) tests with radial strain measurements

p_a = atmospheric pressure (in the same unit as σ'_1, σ'_3).

The stress - strain behaviour of loess soil is formulated by using the Young modulus and the Poisson ratio before the failure, and the zero shear modulus with a constant bulk modulus after it.

The applied hyperbolic model is based on the Mohr - Coulomb failure criterion. It should be mentioned that the angle of shearing resistance $\varphi' = 47^\circ$ used not to be frequent practice, at least on average, small samples in the laboratory conditions ! However, this is a mere consequence of the sample stiff behaviour (over the range of low stresses), having low water content ($w = 18\%$, $I_c = 1,08$) and fine, vertical or subvertical, continuous pores !

For the analysis of the settlement of a model (rigid strip) footing on loess soil, a finite element nonlinear programme was developed.

The programme is based on the proposed hyperbolic models and the incremental form of Hooke's law.

The finite element analysis was performed on the DEC 20 computer at the Computer Centre of the Faculty of Civil Engineering, Belgrade.

The plane strain finite element mesh used in this analysis contains 163 rectangular elements and 191 nodal points. The nodal points along the center line beneath the footing and those on

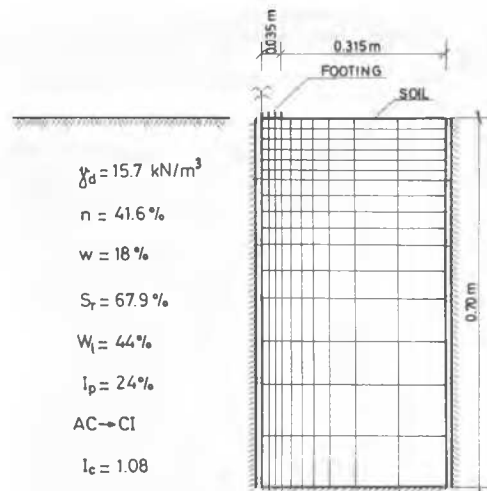


Fig. 2 Finite Element Representation of Model Footing on Loess

the right vertical boundary were constrained to vertical movements, while those along the bottom boundary were fixed. The boundaries were established in order to simulate a semi-infinite soil mass (Fig. 2).

A uniform loading was applied to the footing in seven increments. The first and the second were of 50 kPa and the others of 100 kPa. In the beginning of each increment Young modulus (Eq. 1) and Poisson ratio (Eq. 2) were determined, according to the stress state in the middle of each element.

The analysis was performed using the parameters shown in Table I.

The lowest limiting stress - strain curve, in the numerical procedure, corresponds to $\sigma'_3 = 5$ kPa.

The calculated settlement of the footing was compared with the experimental values obtained on the site. These measurements were performed on slope loess at Mirijevo, one of the suburbs east of city centre (Fig. 2). The field test included vertical displacements of model footing measured by deflectometers.

T A B L E I

Summary of Stress - Strain Hyperbolic Parameter for Loess at Mirijevo

Loess	c' (kPa)	φ' (°)	R_f	K	n	K_{ur}	G	F	d
$\sigma'_3 \leq 85$ kPa	13,5	47	0,729	617	0,234	1234	0,0964	0,189	18,4
$\sigma'_3 > 85$ kPa	39,5	26	0,811	248	0,133	1364	0,180	0,149	5,47

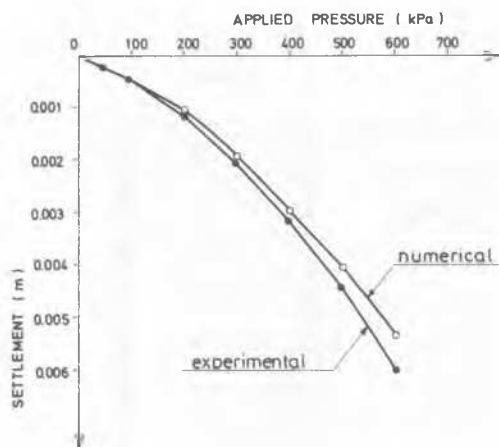


Fig. 3 Load - Settlement Curves of Model Footing on Loess

Both the observed and the calculated load - settlement curves are shown in Fig. 3.

They are in excellent agreement. For example:

- (i) At the maximum loading $q = 600$ kPa the difference in settlement is 11,8 % and
- (ii) At a smaller loading $q = 200 - 250$ kPa, used for loess soil in the engineering practice in Belgrade, the difference is below 5 %.

As far as we know, the mechanical behaviour of loess soil has been presented here for the first time by the hyperbolic stress - strain model.

The results obtained have confirmed the general character of the model and thereby expanded the range of its application.

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