Some models of soil behaviour for evaluation of consolidation settlement in clays

Certains modèles de comportement des sols pour l'évaluation de la consolidation des argiles

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ABSTRACT

Nowadays geotechnical processes are used in stabilizing ground or to improve the capacity of foundations. The major technical risk for any civil engineering works is in the ground. Therefore it is necessary to investigate the geological and geotechnical conditions on any site in order to produce ground treatment and improvement. A conceptual ground model will identify the nature of the ground beneath the site. Modeling forms a very important part of engineering design but many engineers don't take into account either the fact that they are making assumptions as part of the modeling or the nature and consequences of those assumptions. The paper develops some models of soil behaviour for evaluation of consolidation settlement in clays and is attempting to explain how combining distinct soil models will improve the final accuracy of the results because the final model must be a simplification of the reality. If we can estimate the pore pressures generated by the load and the soil stiffness which controls the vertical strains that develop as the pore pressure dissipate, than we can combine these estimates to evaluate the consolidation settlement. The procedure for evaluation of consolidation settlement in clays combines elements of a number of distinct soil models: an elastic model to calculate the total stress changes which, for a clay layer of uniform stiffness and of either infinite depth or underlain by a rigid layer, are not actually dependent on that stiffness; an empirical model to link total stress changes with changes in pore pressure; and a one-dimensional model for conversion of pore pressure change to settlement. Each of these models introduces its own simplifications which could be: constant pore pressure parameter, isotopic elasticity, constant oedometric stiffness, and variable stiffness layered soil. In terms of a rheological model, the fundamental element consists of a spring, representing the recoverable deformation, in series with a rate process dashpot representing the irrecoverable deformation.

RÉSUMÉ

Aujourd'hui les procédés géotechniques sont utilisés dans la stabilisation de sol ou dans l'amélioration de la capacité des fondations. Le principal risque technique pour tous les travaux de génie civil est dans le sol. Il est donc nécessaire d'enquêter sur les conditions géologiques et géotechniques sur n'importe quel site dans le but de produire un traitement et une amélioration au sol. Un modèle conceptuel du terrain permettra d'identifier la nature du sol sous le site. La modélisation est un élément très important de l'ingénierie de conception, mais de nombreux ingénieurs ne prennent pas en compte ni le fait qu'ils font des hypothèses dans le cadre de la modélisation, ni la nature et les conséquences de ces hypothèses. Le document développe des modèles de comportement des sols pour l'évaluation de la consolidation d'argiles et tente d'expliquer comment la combinaison de modèles des sols distincts permettra d'améliorer la précision des résultats, car le modèle final doit être une simplification de la réalité. Si on peut estimer les pressions générées par la charge et la rigidité du sol, qui contrôle les effets verticales qui se développent quand la pression se dissipe, nous pouvons combiner ces estimations pour évaluer la consolidation. La procédure d'évaluation de la consolidation dans les argiles combine les éléments d'un nombre de modèles de sols: un modèle élastique pour calculer les changements du total stress qui, pour une couche d'argile de rigidité uniforme ou d'une profondeur infinie ou au dessous d'une couche rigide, ne sont pas effectivement dépendantes sur la rigidité; un modèle empirique pour relier les changements dans total stress à des changements dans la pression, et un modèle unidimensionnel pour la conversion du changement de la pression sur la consolidation. Chacun de ces modèles présente ses propres simplifications qui pourraient être: la pression constante dans les pores, élasticité isotropique, rigidité constante, rigidité variable de sol stratifiés. En termes d'un modèle rhéologique, l'élément fondamental consiste d'un ressort représentant la déformation récupérable en série avec un taux représentant la déformation irrécupérable.

Keywords : clay, consolidation settlement, rheological models, recoverable deformation, creep, irrecoverable deformation

1 INTRODUCTION

Much of the geology of Romania is dominated with soft compressible soils, especially clays.

Clays are objects of extensive study in geomechanics due to some functions which they perform and the presence of specific properties inherent in them.

Clay compaction by externally applied stresses and internal capillary tension results in clay structure modifications that are of wide interest because of the influence of such changes on clay mechanical strength.

It is well known the heterogeneous nature of the fabric of clays: different particle sizes, shapes and orientation and a lot of surface characteristics. The special features of clays are their high compressibility and the linear stress-dependency of their oedometer stiffness. These considerations are valid for normal consolidated stress states and do not include secondary compression.

2 THE MODEL OF CLAY CONSOLIDATION

As many real bodies, clays exhibit mixed behaviours of elasticity, viscosity, and plasticity (Carter et al. 1986).

The rheological properties of clays are primarily determined by the water content (Khramchenkov 2003; Vyalov 1986). The

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-425

water molecules held close to clay surfaces are subjected to forces that increased viscosity of the molecules (Israeachvili and Adams 1978; Schoen et al. 1987).

The very slow flow (time-dependent) of adsorbed water molecules results in time-dependent viscoelastic behaviour of clays (Hueckel 1992).

Soil deforms in response to the change of effective stress due to pore water dissipation. (Anderslan and Douglas 1970). This process is called primary consolidation. It has been shown that even after complete dissipation of excess pore water pressure clay soils continue to deform. This phenomenon is called secondary consolidation or creep (Christensen and Wu 1964). During secondary consolidation phase part of highly viscous water between the points of contact is forced out. Any increase in total stress primarily causes excess pore water pressure. By continuous drainage, stress transfers to soil aggregates. Any increase in effective stress causes decrease in void ratio and soil settlement. After the excess pore water pressure has been dissipated the effective stress will be constant.

All soils exhibit some creep. Hence primary compression is always followed by a certain amount of secondary compression. Assuming that the secondary compression is small percentage of the primary compression, the creep plays an important role in problems involving large primary settlements (Peck 1994).

Soil deformation involves time-dependent reorientation and displacement of constituents at microscopic and macroscopic levels, and it is commonly characterized by the relative rate deformation or strain (Day and Holmgren 1952). For geotechnical applications, overall strain and strength properties of the bulk soil are required (Ladd 1977). Fundamental concepts of soil rheology, which describe the flow behaviour of soft soils, are useful for description of the time-dependent stress–strain relationships under various loading conditions (Mitchell 1993; Vyalov 1986).

Many constitutive models for clay have been proposed and studied based on elasto-plastic or elasto-viscoplastic theory. (Borja and Kavaznjian 1985). Since clay behaviour is viscoelastic in the small strain, a viscoelastic-viscoplastic model for clay is necessary to explain the deformation characteristics of clay in both small and large strain levels (Christensen 1971; Yong 2006).

The linear viscoelastic approach is valid for behavior in the small strain range, while viscoplastic modeling of soils is useful in the large strain range, including failure (Tavenas and Leroueil 1987; Tong and Tuan 2007).

Thus, the process of deformation in clays is a combination of recoverable deformation resulting from bending and rotation of individual particles and irrecoverable deformation due to relative movement between adjacent particles at their points of contact. The relative movement between particles is treated as a rate process in which interparticle bonds are continually broken and reformed as the deformation proceeds (Feda 1989). Accordingly, the rate of deformation is governed by the activation energy associated with the rupture of interparticle bonds. The theory of rate processes describes some aspects of macroscopic, time-dependent soil deformation, and creep phenomena (Mitchell 1993). The fundamental of the rate process theory is that movement of the particles relative to each other is constrained by energy barriers separating adjacent equilibrium positions (Hawlader et al. 2003). At any time, only some of the activated flow units may cross the barrier (viscous flow), while others fall back to their initial positions (elastic deformation).

The total volumetric strain is divided into elastic and a viscoplastic creep part, which can be separated into a part during consolidation and a part after consolidation. Following Bjerrum (1967) it is supposed that the pre-consolidation stress depends entirely on the amount of the creep strain being accumulated by time.

3 EXPERIMENTAL, RESULTS, DISCUSSION

In soil mechanics it is very common to determine stress-strain relationships of clays under equilibrium conditions empirically, assuming a rheological model applied to the specific deformation of soil (Aysen 2002). However, the use of empirical stress-strain relationships for study of clay settlements has several weaknesses. The most important is that the method is applicable only for describing bulk volume changes, but it cannot be used to explain pore-scale evolutionary processes. An alternative approach is to develop pore-scale models coupled with intrinsic rheolgical properties (Day and Holmgren 1952).

The complete rheological model for clays consists of a combination of spring and dashpot elements covering the complete spectrum of model properties (Tavenas and Leroueil 1979; Suklje 1969).

Thus, the proposed rheological model for saturated clay consists of two serial-linked distinct elements presented in fig.3 (Botu 1993).

The first model (fig.1) comprise a Hooke spring (H_1), having a modulus of deformation (E_1) and two jagged tags (L_1), which allow the displacement only under the effect of vertical loads acting directly above/below (the inverted movement is blocked). An ideal Hook solid deforms instantaneously when subjected to stress, and the energy invested in deforming is fully stored (Botu 1993). When the stress is removed, the original shape is restored (the deformation vanishes), while the energy is recovered in full.

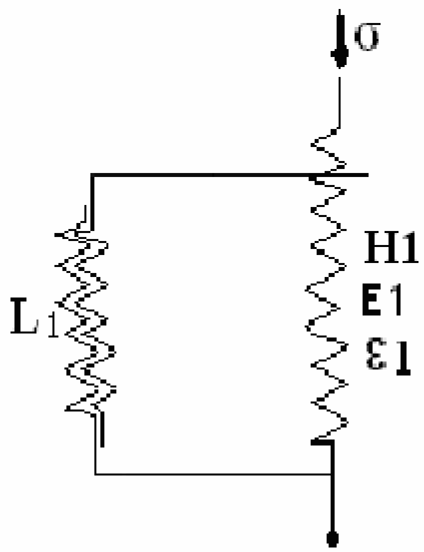

Fig.1. Rheological model representing the recoverable deformation

Thus, under the external effort σ, the Hooke spring (H_1) compress, generating a strain (ε_1) and the descending of the superior jagged tag. The friction between the two jagged tags is neglected. Because the two jagged tags block some coils, only the upper part return to the same position; in the meantime the other one remains compressed.

The second model (fig.2) consists of: (i) a Maxwell spring (H_2) indicating water migration (through the mediation of damping spring N, with η viscosity) and the possibility of water-recurrence after load removal, and (ii) a Hooke spring (H_3) indicating the deformation of the adsorbtion complex. The two springs are parallel connected (N/N). Under the external effort (σ), the springs H_1 and H_2 compress and the damping spring piston (N) and the superior jagged tag of L_2 are moving. Thus, the complete rheological model consists of a combination of springs and damping spring elements covering the complete spectrum of model properties (fig.3).

The response of the rheological model is analyzed for creep and constant strain-rate loading using 3 clay samples submitted to 1.0 daN/cm^2, 2.0 daN/cm^2, 3.0 daN/cm^2 constant loads in oedometer apparatus (Janbu 1963). Dial test indicator readings were realized from 1 second to 30 days. In tables 1-3 are presented the main values t – ε.

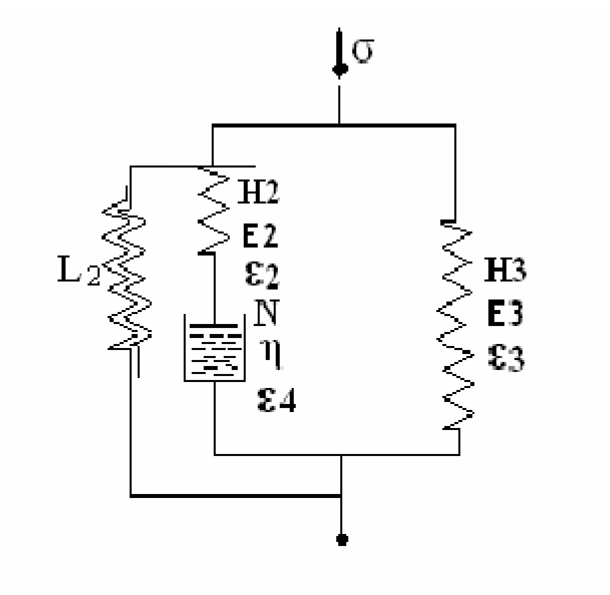

Fig.2. Rheological model representing the irrecoverable deformation

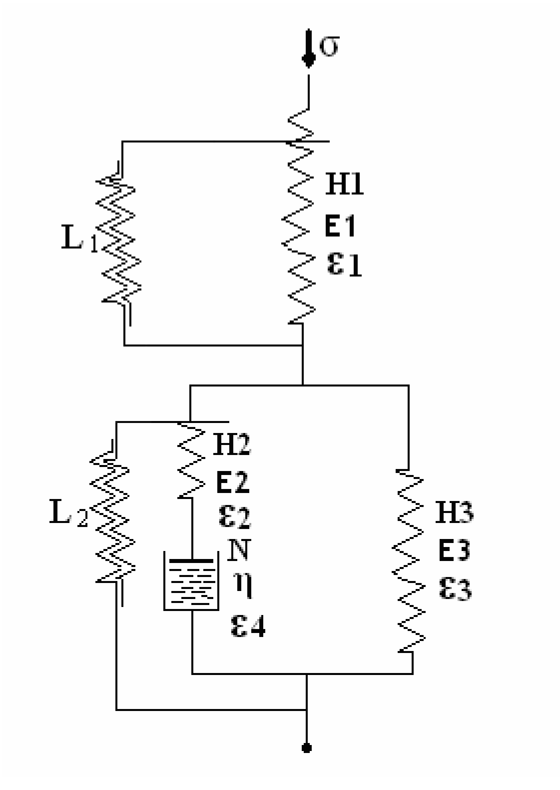

Fig.3. Complete rheological model representing a combination of springs and damping spring elements

Table 1. The response of the rheological model in oedometer apparatus. Sample 1; σ = 1.0 daN/cm^2 ; $ε_0$ = 1.3%

Time	ε	Time	ε	Time	E
	%		%		%
1s	1.56	3 days	2.25	17 days	3.12
10 s	1.60	4 days	2.28	18 days	3.18
30 s	1.62	5 days	2.42	19 days	3.25
1 min	1.65	6 days	2.49	20 days	3.34
3 min	1.66	7 days	2.53	21 days	3.38
5 min	1.68	8 days	2.56	22 days	3.43
10 min	1.72	9 days	2.63	23 days	3.49
30 min	1.73	10 days	2.70	24 days	3.58
1 h	1.85	11 days	2.73	25 days	3.69
2 h	1.87	12 days	2.77	26 days	3.82
4 h	1.93	13 days	2.81	27 days	3.94
8 h	1.99	14 days	2.83	28 days	4.03
1 day	2.03	15 days	2.86	29 days	4.11
2 days	2.20	16 days	3.04	30 days	4.14

Table 2. The response of the rheological model in oedometer apparatus. Sample 2; σ = 2.0 daN/cm^2 ; $ε_0$ = 1.3%

Time	ε	Time	ε	Time	E
	%		%		%
1s	1.97	3 days	5.49	17 days	7.22
10 s	3.11	4 days	5.74	18 days	7.44
30 s	3.21	5 days	5.85	19 days	7.62
1 min	3.25	6 days	5.98	20 days	7.77
3 min	3.32	7 days	6.03	21 days	7.83
5 min	3.46	8 days	6.08	22 days	7.89
10 min	3.57	9 days	6.15	23 days	7.96
30 min	3.73	10 days	6.26	24 days	8.12
1 h	3.85	11 days	6.41	25 days	8.26
2 h	4.01	12 days	6.54	26 days	8.43
4 h	4.18	13 days	6.62	27 days	8.62
8 h	4.49	14 days	6.71	28 days	8.77
1 day	4.97	15 days	6.82	29 days	8.92
2 days	5.28	16 days	7.00	30 days	9.02

Table 3. The response of the rheological model in oedometer apparatus. Sample 3; σ = 3.0 daN/cm^2 ; $ε_0$ = 1.3%

Time	ε	Time	ε	Time	E
	%		%		%
1s	2.63	3 days	9.17	17 days	10.42
10 s	4.35	4 days	9.33	18 days	10.54
30 s	4.85	5 days	9.44	19 days	10.71
1 min	5.07	6 days	9.54	20 days	10.94
3 min	5.56	7 days	9.66	21 days	11.10
5 min	5.83	8 days	9.78	22 days	11.25
10 min	6.01	9 days	9.84	23 days	11.34
30min	6.41	10 days	9.91	24 days	11.42
1 h	6.83	11 days	9.96	25 days	11.51
2 h	7.14	12 days	10.03	26 days	11.58
4 h	7.53	13 days	10.07	27 days	11.63
8 h	8.02	14 days	10.11	28 days	11.67
1 day	8.58	15 days	10.17	29 days	11.74
2 days	9.03	16 days	10.30	30 days	11.83

Table 4. The influence of elastic deformation for different periods of time after 0.5 daN/cm^2 consolidation process

Period of time	Immediate deformation $ε_1$ – % from the measured deformation
	%
1 minute	33.8 – 48.4
1 hour	25.2 – 36.3
1 day	21.3 – 35.8
1 month (30 days)	11.7 – 17.5

In table 4 is presented the influence of elastic deformation for different periods of time, from 1 minute to 1 month, after 0.5 daN/cm^2 consolidation process.

In fig.4 are plotted the creep curves on a halflogarithmic scale after 0.5 daN/cm^2 consolidation process, for σ = 1.0 daN/cm^2, σ = 2.0 daN/cm^2, and σ = 3.0 daN/cm^2.

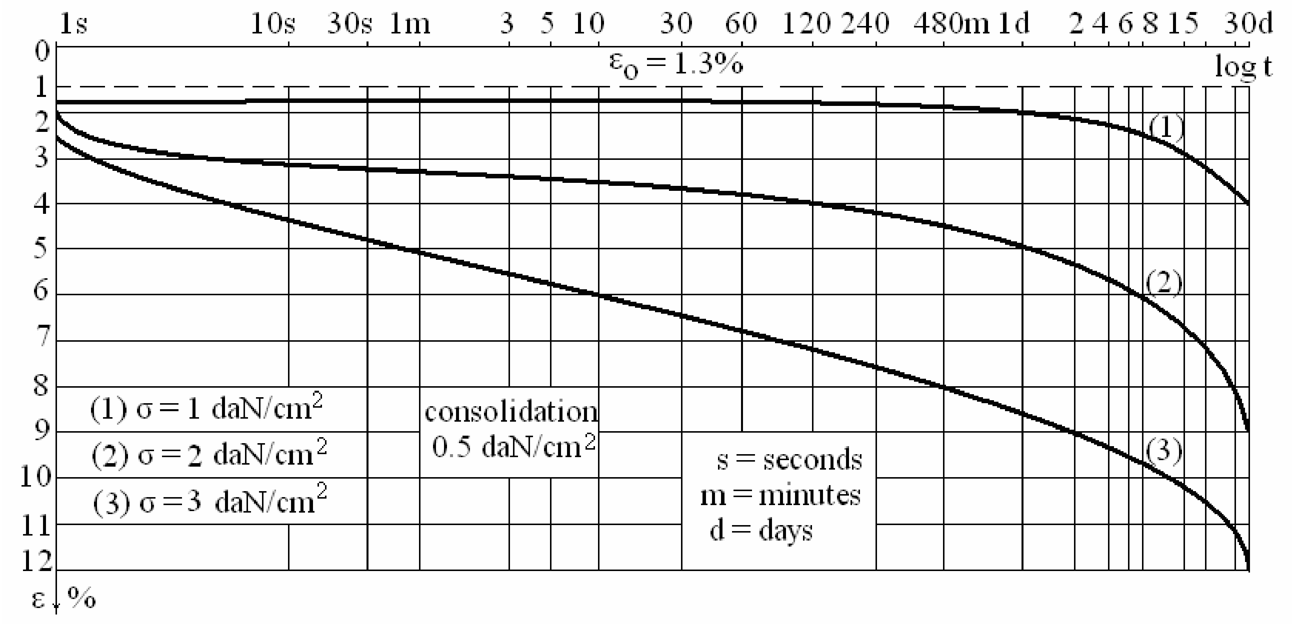

Fig.4. Creep curves on a halflogarithmic scale

4 CONCLUSIONS

The paper presented a rheological constitutive model for the consolidation of clays. It recognizes the importance of structural viscosity in controlling many of the phenomena associated with the consolidation of clays. The proposed rheological model for saturated clay consists of two serial-linked distinct elements: a rheological model representing the irrecoverable deformation and a rheological model representing the irrecoverable deformation. The laboratory tests are used to examine some hypotheses in order to predict secondary consolidation. The dominance of the structural viscosity during the primary consolidation stage has been shown to be the main source of the discrepancy. Creep curves plotted in fig.4 on the halflogarithmic scale are very alike; the differences are due to the recoverable deformation.

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