Indirect estimation of geotechnical stability of clay rocks in urban territories

ERIY TKACHUK[1]

[1] *South-Russian State Technical University. (e-mail: e_tkachuk@rambler.ru)*

Abstract: A significant characteristic of the geotechnical stability of clay rocks is their degree of lithification. In Lomtadze's classification five groups were determiend. Each group is characterized by values of physico-mechanical properties. However, identification of the groups from the results of standard geotechnical tests is frequently a complicated problem, the solution of which is based on studying the interrelationship of clay rock properties as system objects.

It has been found that various groups of lithification are characterized by various structures of the property interrelationships and are, in particular, best represented as a correlation between the porosity coefficient e and the liquid limit LL in the shape of ellipses. The contours of these ellipses reflect objective quality boundaries for the main groups (stages, zones) of lithification.

Of all the boundaries mentioned the line $e = 1,85LL^{0,8}$, which separates clay rock of a low to that of an average degree of lithification, is the main one and can be used for preliminary estimate of clay foundation reliability. If the correlation diagram e and LL of the clay foundation studied is situated lower than this line, the ground can form a satisfactory foundation for a building; if it is higher then they - are relatively weak or (higher than the line $e = 2,5LL^{0,9}$) are very weak and require a detailed study of mechanical properties.

The use of this diagnostic test has been used to discover the reasons for the deformations in Novocherkassk Voznesenskiy cathedral, to prove the reliability of building foundations and the clay formation beneath the Novocherkassk Polytechnic Institute mining building, and to forecast the change of the condition of loess rocks of Novocherkassk and Anapa territories under the influence of inundation.

Résumé: La caractéristique la plus importante qualitative de la stabilité géotechnique des fondations argileuses des bâtiments et les constructions est le degré de leur la lithification. Dans la classification correspondant de V.D. Lomtadze met en relief 5 groupes. Chaque groupe est caractérisé par les significations les plus probables des paramètres des propriétés physico-mécanique et l'estimation du point de vue de construction. Cependant l'identification des groupes mentionnés selon les résultats des essais géotechniques standard représente assez souvent la tâche complexe. On a trouvé sa solution en étudiant des corrélations des propriétés des roches argileuses comme des objets de système.

On a établi, que les groupes divers de la lithification se caractérisent par la structure diverse des corrélations des propriétés et, en particulier, se manifestent sur les champs de la corrélation du coefficient de la porosité et la frontière de la fluidité WL en forme des ellipses de la corrélation qui sont isolés, parfois flous. Les contours de ces ellipses représentent les frontières objectives qualitatives des groupes principaux (les étapes, des zones) de la lithification et sont observés sur plusieurs unités

Parmi les frontières mentionnées c'est la ligne $e = 1,85LL^{0,8}$, qui est importante. Elle divise les roches argileuses en celles dont le degré de lithification est faible et celles ayant leur degré de lithification moyen. La ligne e peut être utilisée pour l'appréciation préalable de la stabilité des fondations argileuses. Si le champ de la corrélation et WL de la foundations étudiée est disposé beaucoup plus bas que cette ligne, les terrains correspondant peuvent servir de la foundation tout à fait satisfaisante des constructions, s' il se trouve que cette ligne, les terrains sont moins solides ou (si ce champs est au – dessus de la ligne $e = 2,5LL^{0,9}$) assez faibles et exigent l'étude détaillée des propriétés physico-mécaniques.

Le moyen proposé du diagnostic peut être utilisé pour les alluvions subaquales et subaériennes (y compris de loess). Dans le dernier cas on pronostique la qualité des fondations dans le cas de la montée des eaux souterraines de l'apparition de l'humidité (du mauillage).

L'utilisation du moyen proposé du diagnostic a permis de découvrir les causes des déformations de la cathédrale d'Ascension de Novotcherkassk, argumenter le projet de la garantie de la sécurité des structures de construction et la foundation argileuse du bâtiment des Mines de l'Institut polytechnique de Novotcherkassk, réaliser le pronostic du changement de l'état des la fondation de loess du territoire des villes de Novotcherkassk et d' Anapa au cours de la montée des eaux souterraines, etc.

Keywords: engineering geology, sedimentary rocks, geotechnics, stability, urban geosciences

INTRODUCTION

Absence of sufficient geotechnical knowledge of the formations underlying civil engineering structures are the principal causes of deformation or failure of these structures during construction and operation. However, the estimation of the stability and, especially, its forecast under conditions of the powerful influence of the environment of the urbanized territories is a challenge and quite often results in mistakes. Figure 1 shows the distribution of excessive deformation due to inadequate ground investigation and poor geotechnical control during construction (Dudler, 1979)

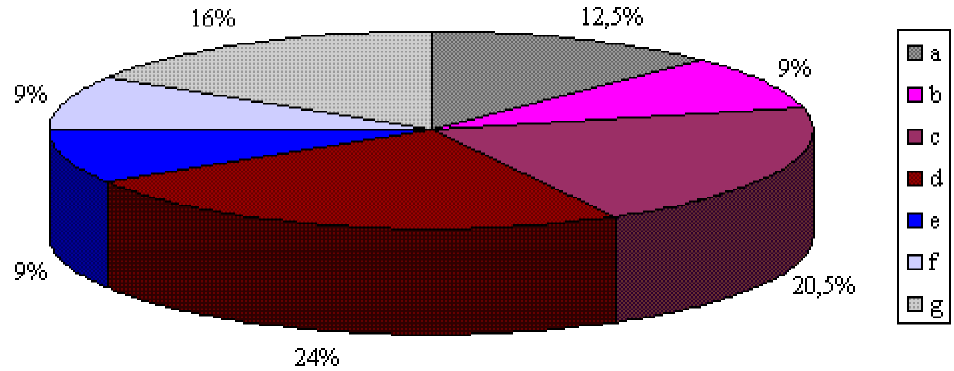

Figure 1. Distribution of engineering-geological mistakes which result in deformation of buildings and infrastructure: (a) insufficient ground investigation (e.g. weak ground is missed); (b) absence of recommendations for drainage; (c) mistakes in or absences of recommendations for strengthening ground; (d) mistakes in the forecast of loss of stability and absence of recommendations to mitigate; (e) mistakes in testing samples; (f) absence of the geotechnical control during construction; and (g) other mistakes.

Figure 1 shows that the majority of mistakes is caused by insufficient estimations of stability of the foundations of civil engineering structures or optimistic forecasts of change of this stability during construction and operation of the structures. The consequence of such mistakes is the absence of necessary protective measures and a possibility of significant remedial engineering.

The overwhelming majority of the cases in Fig 1 concerns clay formations. Such formations are characterized by a range of genesis, the most complex processes of geochemical transformations, syneresis, dehydration, leading to changes of properties during their evolution, and a variability of parameters of composition, condition, structure and properties. Therefore many experts have been engaged in research into clay rocks and their properties over several decades

The greatest attention has been paid to the conditions during deposition and how the subsequent geological processes have upon their physico-mechanical properties. Results of such studies have led to the development of constitutive models of the properties of clay rocks to enable theoretical predictions of their performance to be made.

THEORETICAL FUNDAMENTALS OF ESTIMATING THE GEOTECHNICAL STABILITY OF CLAY ROCKS

Geotechnical stability of the clay formations underlying civil engineering structures is often based on a qualitative description. From this point of view the basic qualitative characteristic of clay rocks is their degree of lithification which is formed in the process of lithogenesis and represents the major influence on their physico-mechanical properties.

The first work in Russia devoted to the basic aspects of the formation of clay rocks, was published by Lomtadze (1955). In this work the basic groups of clay rocks were identified by lithification (muds, clay soft, clay condensed, argillite, argillaceous shale); the basic diagenetic and epigenetic processes of formation of the deposit; the condition and properties of the formation; and the results of the typical values of their water content, density and porosity. This led to the development of a classification chart.

Later Lomtadze expanded his theoretical description of laws of formation of the deposit**,** the structure, condition and properties of clay rocks during their lithification through experimentation. Oxidation-reduction conditions, exchange-adsorption and other processes of change of mineral, chemical and mechanical structure of clay sediments in diagenesis and katagenesis were investigated. The role of other factors that affected physico-mechanical properties of these sediments was characterized.

As a result of this research and other research a new engineering-geological classification of rocks (including clay rocks) has been developed. In this classification clay rocks are divided into five groups (zones) **-** extremely small,

small, average, high and extremely high degree of lithification. Each group is characterized by the major classification attributes, features of structure and the most probable values of parameters of physico-mechanical properties (Lomtadze, 1984).

Lomtadze's ideas have been followed by many researchers, including F.S.Aliev, A.E.Babinets, I.M.Gorkova, , G.L.Koff, I.G. Korobanova, L.I.Kulchitsky, A.M.Monjushko, V.I.Osipov, A.S. Polyakov, E.M. Sergeev, A.B. Shpikov, R.S. Ziangirov, etc. (Tkachuk 2003).

Results of this research have allowed the structure of clay rocks, their durability, deformability and permeability to be explained. This has led to a general theory of formation of properties of dispersive (including clay) sediments during their formation and the subsequent geological development. These works have allowed the specification of major regularities of change of the composition, their condition, structure and properties of clay sediments in process of singenesis, diagenesis, katagenesis and to confirm the presence of several (4-5) zones (stages) of lithification which represent the groups of clay rocks which can be distinguished by their differing stability.

Identification of the group to which a clay deposit belongs (stages, zones) which is based on results of standard laboratory tests, frequently represents a challenge: - distributions of density of probabilities of values of each of the parameters for sediment of various degree of lithification, is large (20-50 % and more). Therefore in order to select appropriate parameters for a given problem an extensive series of tests is required. This includes standard tests for physical-mechanical properties, including mineral, chemical, and mechanical properties, composition of interstitial waters and absorbed cations, absorption capacity, and organic matter. A particular study of the clay sediments of the Baku archipelago has been made from a stage of diagenesis to a stage of katagenesis which needed qualitative and quantitative estimations of microstructures, their morphological and geometrical characteristics, structural connections, orientation of clay particles and microblocks, estimations of magnetic anisotropy, anisotropy of acoustic and mechanical properties (Polyakov, Osipov, Kotlov *et al*. 1979).

It is natural that commercial ground investigation contractors cannot carry out these detailed studies. At the same time the opportunity to identify the degree of lithification of clay rocks during construction is a technique to replicate the laboratory work, and in some cases could form sufficient basis of acceptance of engineering decisions. A means of using diagnostics based on the results of the elementary tests is necessary for this purpose.

The solution of the problem is carried out on the basis of studying clay rocks as system objects.

THE ANALYSIS OF PHYSICO-MECHANICAL PROPERTIES OF CLAY SEDIMENTS AS SYSTEM OBJECTS

The major characteristic of system objects are the interrelations of properties. Using system objects yields results which in scientific and practical terms are much more significant than the simple description of properties (Krats & Eliseev 1979) since they help to understand more deeply the processes of formation of properties and the effect that they have on the subsequent behaviour of the deposit thus solving a number of practical problems (Tkachuk 2004).

Therefore, special attention is given to studying the interrelations of properties. Interrelations of numerous parameters of composition, condition, physical properties, durability, compressibility, swelling, permeability and other characteristics are investigated. Not only interrelations of properties, but also (and it is the main thing) the change of these interrelations during the geological history of the sediments are investigated. It has revealed the quantitative criteria of those qualitative transformations coded by their formation, the subsequent geological development and modern environment. Clay sediments of various origins and age, lying at various depths in various structural - tectonic conditions and forming the foundations to many engineering structures in various engineering-geological regions and areas of Russia and the adjacent countries were investigated.

It is established, that each clay sediment is a complex system containing from one to five subsystems. These subsystems are fixed at three levels and are related to classification indices. As a clay rock develops over geological time each of the subsystems can be in one to six states of equilibrium which are identified by their physical properties and composition. In the modern environment these deposits are dynamic systems that can be in one to four steady state modes which differ by the distribution and interrelations of water content and porosity, and the values of water content.

Subsystems, equilibrium states and steady state modes show elements of clay rocks as complex developing dynamic systems. Sets of these elements (subsystems, equilibrium conditions and steady state modes) and proportions of these sets represent the original "genetic code" of clay sediments, which are individual for the rocks of a specific origin with a particular geological development taking place in a particular natural-geological and technical situation.

During the formation and changes of these components (subsystems, states, modes, elements) various territorial geologic-genetic complexes of clay rocks are formed with a change in the distribution and interrelations of their properties. Thus statistical models of behaviour of mechanical characteristics for systems as a whole, are not suitable for the correct description of their behaviour within the limits of separate components of these systems.

Under conditions of subaqueous lithogenesis for homogeneous saturated clay rocks (having no more than one to two subsystems) within in the limits of each of equilibrium state the constants of the interrelations of their properties are statistically steady, for various states - essentially different, for some group of states changeable, for intermediate states poorly predicted. For loess formations which are taking place in sub aerial conditions, the statistical identity of the constants of interrelations of properties need to include the mode of the modern environment.

From this point of view the most important result of the research are the quantitative borders of the basic equilibrium states of clay rocks.

BASIC EQUILIBRIUM STATES AND THEIR QUANTITATIVE BORDERS AS CRITERIA OF INDIRECT ESTIMATION OF THE DEGREE OF LITHIFICATION AND GEOTECHNICAL STABILITY OF CLAY ROCKS

The equilibrium states reflect the changing quality of clay sediments during their lithification. They correspond to various stages of lithogenesis and are characterized by essentially various structures and interrelations of their properties. Therefore, such states can be expressed as correlations of parameters of composition and physical characteristics. The most informative are the porosity coefficient e and liquid limit LL: clay rocks of a various degree of lithification are bounded by detached ellipses of correlation. Contours of these ellipses are objective (generated in the process of lithogenesis) borders of the basic stages of lithification and represent the quantitative criteria of the estimation of clay sediments quality (geotechnical stability).

For the first time the borders were revealed in 1981-1983 on the basis of a system analysis of materials of a unique complex of clay rocks, the Baku archipelago (Tkachuk 1983). For this purpose results of the tests have been divided into four to five groups of values of parameters of composition, conditions and physico-mechanical properties (Strahov 1965**)**. These groups corresponded to four to five zones of lithogenesis which have been located by researchers investigating more than twenty characteristics. They have been accepted as good practice appearing in many monographs and textbo*oks*. The data on each group are processed by statistical methods (including correlation and multifactorial analysis) with the use of elements of constitutive models. The primary goal of research was the search for such quantitative interrelations of parameters of properties which most sensitively react to change of quality of clay rocks in the process of lithogenesis and can replace numerous complex experiments on identification of stages of this process.

One set of results of the analysis is shown in Figure 2 where equilibrium conditions I... IV are identical to zones of lithogenesis.

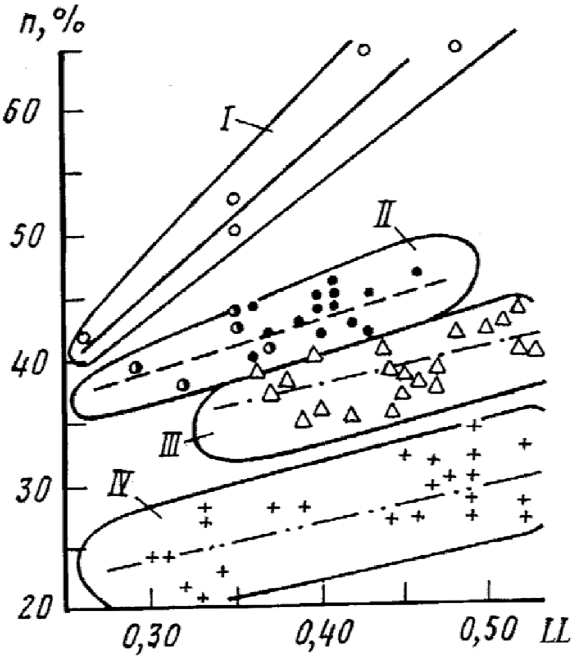

Figure 2. Dependence of porosity n from liquid limit LL of clay deposits of the Alyatinskaya structure of the Bakinsky Archipelago: showing the equilibrium states of rocks (ellipses of correlation I-IV) and the regressive dependency of n on LL and empirical values of parameters of properties

Equilibrium states I shown on Figure 2 correspond to low, II and III - to average, and IV - to a high degree of lithification. Values of *n*, located above ellipse I, characterize clay rocks of extremely small degree of lithification, staying in stage of singenesis (an equilibrium states 0); between ellipses I and II - clay rocks exist in an equilibrium state Ia. The last is characterized by some important features of behaviour of properties and represents states of “instability” at a small degree of lithification.

This simple way of identification of the basic zones of lithification has allowed the stages of subaqueous lithogenesis of clay rocks to be specified and to characterize the major laws of change of physical-mechanical properties during their evolution (Tkachuk 1985).

The subsequent system analysis of parameters of composition, condition and properties of continental deposits has allowed an estimate of the basic equilibrium states of till, lake-glacial, periglacial, alluvial, deluvial and eolian-deluvial (including loessial) clay rocks (Tkachuk 1991).

Table 1 shows the most likely boundaries between the basic types of structural connections; stages, zones, stages of lithogenesis. This allows an identification of a degree of lithification of clay sediments of various compositions, a genesis and the age, lying in various structural-tectonic conditions.

From the borders shown in Table 1, the following relationship is most important:

$$e \approx 1{,}85LL^{0{,}8} \quad (1)$$

where e is a porosity coefficient, LL is liquid limit.

This equation divides clay rocks into those of a small and average degree of lithification and can be used for a tentative estimation of geotechnical stability of the clay formation. If the field of correlation *e* and *LL* of the investigated clay formation is located below line (1) then the ground can be considered a suitable formation for construction; if it is higher then it is either rather weak or is very weak (higher than the line $e = 2{,}5LL^{0{,}9} \approx 0{,}1 + 2{,}5LL$) (Lomtadze 1984) and will require detailed study of the mechanical properties.

Table 1. The most probable quantitative borders of the basic equilibrium states; stages, zones, of lithogenesis and degrees of lithification clay rocks

Equilibrium state	Low border of porosity coefficient *	Degree of lithification by Lomtadze	Type of structural connections by Osipov	Stage of lithogenesis
0	$e \approx 4{,}2LL$	extremely low	distant coagulating	Singenesis
I	$E = 2{,}5LL^{0{,}9}$	low		Diagenesis
I	$e = 1{,}85LL^{0{,}8}$		near coagulating	
II	$e = 1{,}25LL^{0{,}7}$	average		katagenesis
III	$E = 0{,}8LL^{0{,}6}$		intermediate	
IV	$E \approx 0{,}4LL^{0{,}5}$	high		
V	$e \approx 0{,}18$	extremely high	phase	Metagenesis

**LL* - in shares of unit.

EXPERIENCE OF DIAGNOSTICS OF GEOTECHNICAL STABILITY OF CLAY ROCKS

The borders of the basic equilibrium states shown in Table 1 have allowed an estimate of the geotechnical stability of various geologic-genetic complexes of clay rocks, and also the means of separating clay formations.

The greatest range of geotechnical stability (from extremely small up to the high degree of lithification) characterizes the marine clay sediments (see Figure 2). Figure 3 shows the sphere of influence of the separate engineering objects that these sediments form.

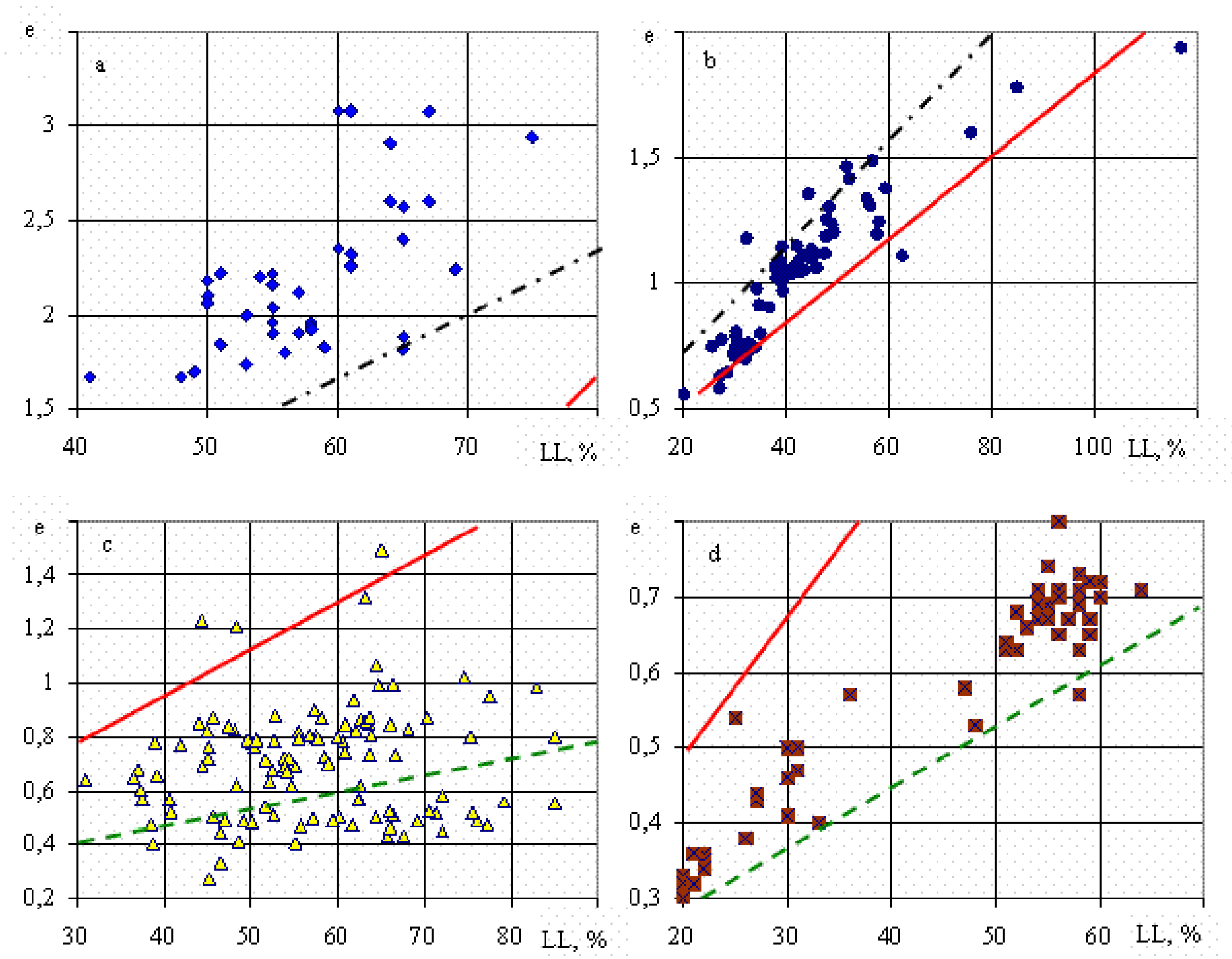

Figure 3. Dependence of the porosity coefficient e from the liquid limit LL of Yoldia clays in the valley of the river Kem (a), Holocene sediments from Kerchenskiy (b), Oligocene clays of the Vostochno-Aiatskoe deposit (c) and Devonian clay sediments of the territory of the city of Novgorod (d) [the continuous red lines show a low degree of lithification, the green dashed line the average degree of lithification and the black dash/dot line the equilibrium condition I close to extremely small degree of lithification]

In Figure 3 (and in the following figures) borders of clay sediments of various degrees of lithification are shown as straight lines. These lines, as a rule, correspond to natural borders (generated in the process of lithogenesis). Such borders are shown as an appreciable (quite often sharp) decrease in the individual values of the porosity coefficient e at a value of liquid limit. Some exceptions to this rule are explained by mistakes in the definition of parameters of properties, errors in the transfer of information and the indirect form of dependence e from LL in a wide range of LL (see Table 1 and Figure 3b).

Figure 3 shows that sea clay sediments using the concept of engineering objects can be states of equilibrium with small (Figure 3b), extremely small (Figure 3a), and average (Figure 3d) degrees of lithification or can cover a wide range of equilibrium conditions from Ia up to the condition of IV (Figure 3c). Thus, almost in all the mentioned ranges there can be identical values of porosity coefficient in spite of the fact that porosity is most sensitive to the process of densification. It confirms the difficulty of the estimation of the geotechnical stability of clay rocks using simple definition of a great number of parameters if they are analyzed without studying their interrelations.

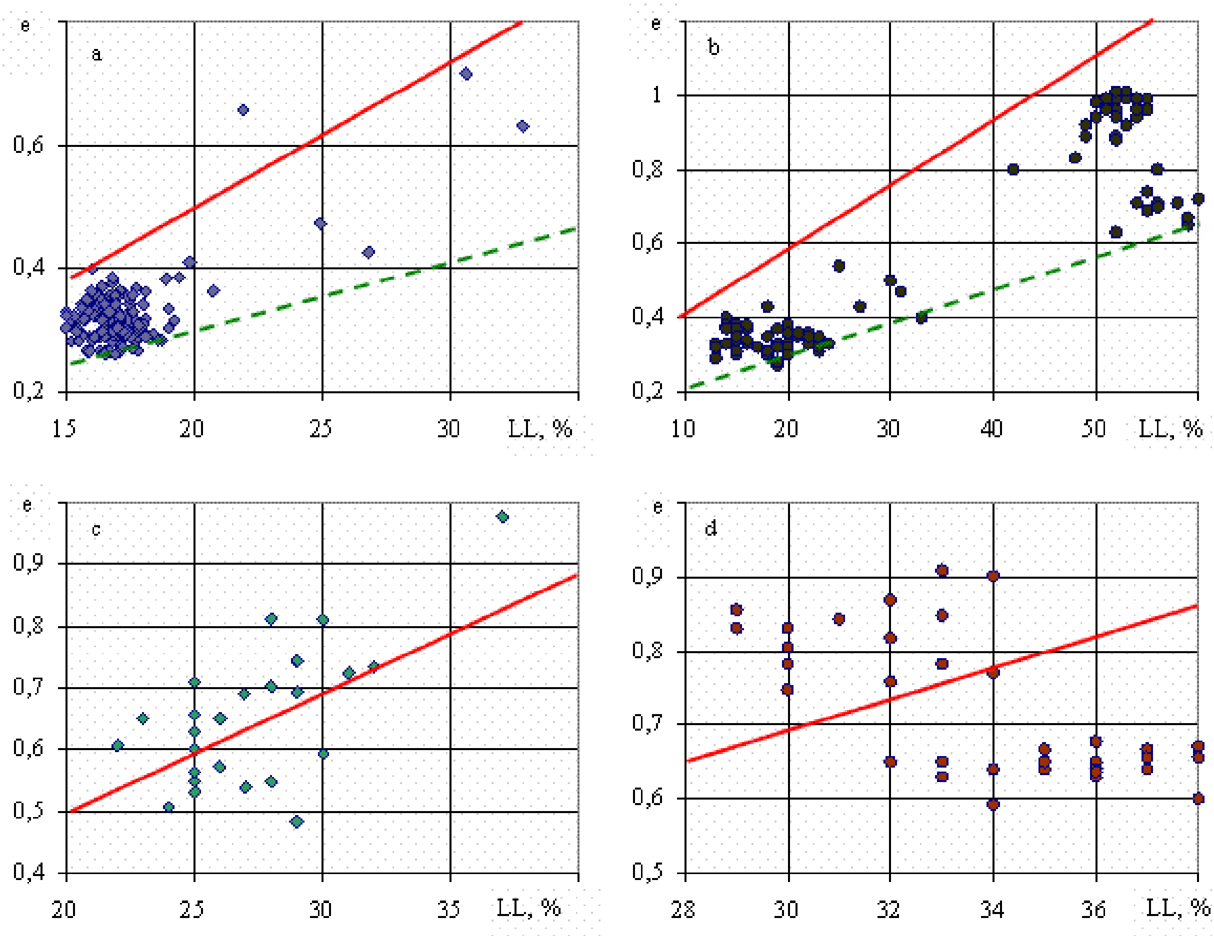

Figure 4. Dependence of porosity coefficient *e* from liquid limit *LL* of the Moscow moraine of territory of city of Minsk (a), glacial clay rocks of the city of Novgorod (b), alluvial sediments of Kingisepp (c) and eolian-deluvial loessial rocks in the basis of a nine storey building of the town of Novocherkassk (d) [the continuous red lines show a low degree of lithification, the green dashed line the average degree of lithification]

Significant variability (heterogeneity) characterizes many genetic types of continental sediments is illustrated in Figure 4. Figure 4 shows that continental clay sediments of an average degree of lithification are characterized by two equilibrium states (Figure 4a, 4b). The geotechnical stability of clay rocks is often fixed not only within the limits of territorial geologic-genetic complexes (Figure 4c), but also in the formations beneath separate buildings (Figure 4d).

Loessial and perpetually frozen grounds are characterized by the greatest variety of geotechnical stability (Figure 5).

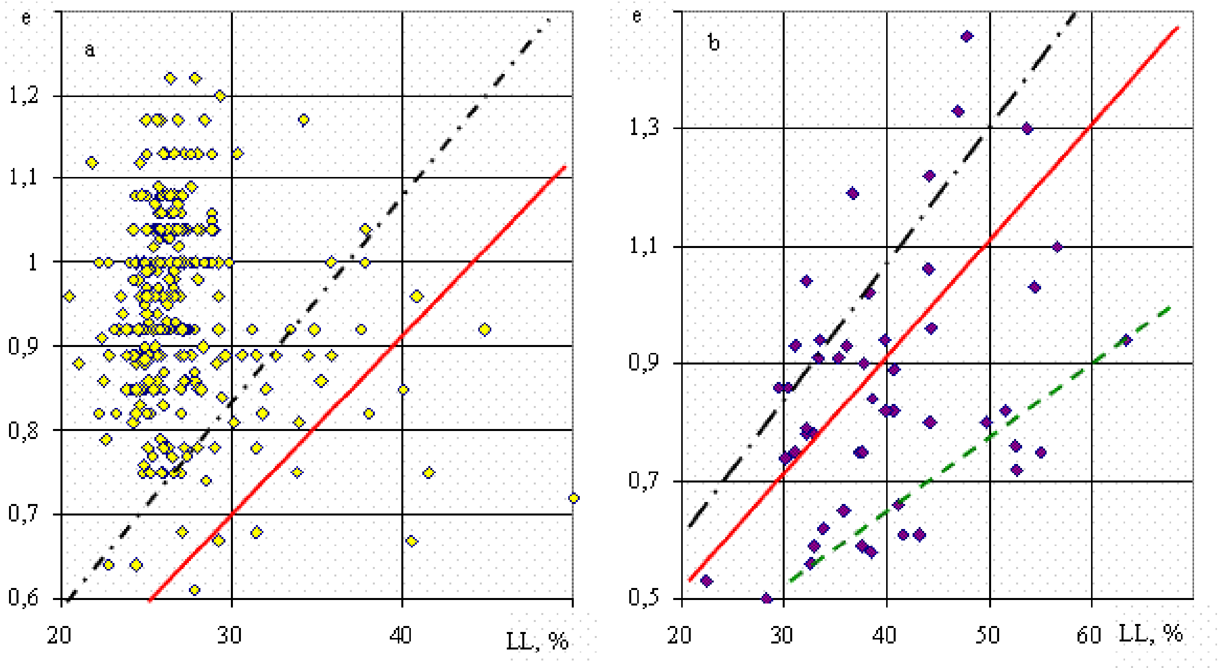

Figure 5. Dependence of porosity coefficient *e* from liquid limit *LL* of the eolian loessial sediments of Northern Caucasus (a) and perpetually frozen clay rocks of peninsula Yamal (b [the continuous red lines show a low degree of lithification, the green dashed line the average degree of lithification and the black dash/dot line the equilibrium condition I close to extremely small degree of lithification]

DISCUSSION

Four to five equilibrium states have been discovered in the various clay formations: from extremely small up to a high degree of lithification. It is important to note that the suggested diagnostic test of the degree of lithification allows a prediction of the geotechnical stability of clay rocks in conditions that are influenced by the environment of the urbanized territories. In particular, Figure 5 shows, that at fixed values of LL (for example, LL = 30 %) the porosity of loessial and perpetually frozen clay rocks reaches 1-1.2. This compares with the lower values for clay sediments of small and extremely small degree of lithification e.g. Kerch strait (see Figure 3b). In other words, inundation of loess sediments or thawing of perpetually frozen ground will lead to a transformation of their geotechnical stability even if there is extremely small or small degree of lithification.

The use of this diagnostic test has enabled the reasons for the deformation of the Novocherkassk Voznesenskiy cathedral (Murzenko & Tkachuk, 2003) to be discovered, to prove the reliability of foundations for buildings (Murzenko, Tkachuk & Skibin 2005), to forecast change of the condition of loessial rocks of the Novocherkassk territory (Rodionova, Bogush et al. 2001) and Anapa (Tkachuk 2004) under the influence of underflooding, and to solve a series of similar geotechnical engineering problems.

It is necessary to note that results of the system analysis of parameters of composition, the condition and properties allows not only an estimate of the degree of lithification of the clay formations of engineering structures, but also to predict the distribution of strength and deformation characteristics (Tkachuk, 2002). However experience of the solution of such problems demands special consideration.

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Corresponding author: Eriy Tkachuk, South-Russian State Technical University, Prosvetsheniya St. 132, Novocherkassk, Rostov Region, 346428, Russian Federation. Tel: +7 86352 2 78 23. Email: e_tkachuk@rambler.ru

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