GEOLOGIJA. 2009. Vol. 51. No. 1(65). P. 53–58
DOI: 10.2478/v10056-009-0006-0

Influence of water content on compressibility of cohesive dump soils – results of studies on samples of modeled lump size distribution

Henryk Woźniak

Woźniak H. Influence of water content on compressibility of cohesive dump soils – results of studies on samples of modeled lump size distribution. *Geologija*. Vilnius. 2009. Vol. 51. No. 1(65). P. 53–58. ISSN 1392-110X

The studies focused on fragmented clayey soils, which are classified as second-type fragmented substances characterized by a multistorey structure and double porosity. The unstable structure of this substance makes it highly vulnerable to the influence of external factors, particularly changes of water content. The studies enabled the author to evaluate the influence of water content on changes of compressibility parameters and on the character of stress–strain relationships. Differences were emphasized in the behaviour of fragmented clayey soils in comparison to local soils. In author's opinion, the studied samples are a good representation of overburdened soils (dump soils), and the regularities found in this study can be readily applied to them.

Key words: cohesive dump soil, double-porosity, compressibility, Rowe hydraulic consolidation cells, pre-consolidation

Received 20 November 2008, accepted 27 January 2009

Henryk Woźniak. Department of Hydrogeology and Engineering Geology, AGH-University of Science and Technology, al. Mickiewicza 30, 30-059 Krakow, Poland. E-mail: hwozniak.@geol.agh.edu.pl

INTRODUCTION

Dump soils originate from the removal of the overburden during surface (strip or open-pit) mining operations, which is then transported and dumped in an overburden dump. The term "cohesive dump soils" is conventionally applied to soils which once formed cohesive layers as the overburden of a mineral deposit, but now, after removal, constitute a mixture of randomly distributed lumps of very diversified shape and size.

Cohesive dump soil is a particular type of soils. Its specific feature is destruction of the primary, natural structure, an entirely random mixture of various types of soils forming the overburden, and various degrees of changes and transformations undergone by the soil under the action of various external factors. Therefore, cohesive dump soils show a highly unstable structure and varying physical-mechanical properties. The behaviour of such soils is so much different from that of the local soils (particularly under load) that Dmitruk (1965) proposed the definition of cohesive dump soil as "a second-type fragmented soil different from the fragmented soil which is a subject of interest of classic soil mechanics". The structure of such soil was determined by this author as "multistorey", where the "first storey" is the internal structure of local soil lumps, whereas the "second storey" is the arrangement of lumps and connections among them (Dmitruk, 1965).

Another name of this type of soils was proposed by Feda (1998) and Mašin et al. (2005) who determined the cohesive dump soil as "double-porosity soil" and distinguish between the intragranular porosity (n_i, e_i) shown by undisturbed fragments (lumps), and the intergranular porosity (n_e, e_e), i. e. open spaces among the fragments. Both porosities constitute the total porosity (n_t, e_t) which is given by the formulae:

$$n_t = n_i\,(1 - n_e) + n_e, \quad (1)$$

$$e_t = e_i\,(1 + e_e) + e_e. \quad (2)$$

Among the mechanical properties of cohesive dump soils, compressibility is particularly different from that of local soils. The high instability of cohesive dump soils, resulting from their high intergranular porosity, means that even a relatively small load gives rise to significant deformations and changes in the void ratio. Laboratory studies (Rybicki, Woźniak, 1986) have revealed that the void ratio of loose lumps of semisolid clay showing diameters from 5 to 20 mm and subjected to 50 kPa load decreases from 1.98 to 1.40, whereas under 800 kPa it drops down even to 0.69. The transformation of an unstable structure, i. e. also the occurrence of significant deformations and settlement, is a complex, long-lasting, multiphase process. It is initiated as early as during the dumping of the overburden and proceeds with various intensity during the consecutive stages of technological operations (dumping, remediation and land development).

The knowledge of principles controlling the compressibility, particularly the ability to prognosticate and estimate the settlement, plays an important role in solving the geotechnical problems related to the construction and operation of dumps. Of special importance are data suitable for evaluation of slope stability, dimensioning of a dumped fill (particularly a correct estimation of dump volume), evaluation of utilization possibilities of dumped soils as a foundation ground, and decisions on dump recultivation and land reclamation.

The results of author's own studies (Woźniak, 1988; Woźniak i in., 1999) demonstrated that the crucial factor influencing the values of compressibility parameters and their changes as well as the stress-deformation relationships of cohesive dump soils is their water content. This factor is particularly important during an excessive infiltration of meteoric waters into the dump body, during the dumping of soil onto a wet bedrock or directly into water and, most commonly, during the reconstruction of groundwater table in an open-pit backfill.

METHODS

In order to replicate the natural (primary) structure of cohesive dump soils, all the experiments were carried on with samples of fragmented clays with a modeled lump size distribution and diverse natural moisture. This modeling included the hand fragmentation of lumps into the required fractions, preparation of weighted amounts of specific fractions and their thorough mixing in desired proportions. Four fractions were used: 5–10, 10–15, 15–20 and 20–25 mm mixed in various weight proportions. The source materials were montmorillonit (Ca)–illit clays and silty clays collected from the backfill of the Machów native sulphur open-pit mine in southern Poland (Table). The content of smectit in clays is a dozen or so percent.

Samples were loaded in the Rowe hydraulic consolidation cell with the chamber diameter 151.4 mm. The application of this device enabled the author to apply very small load increments, to eliminate very disadvantageous dynamic loads and to get full control and automatic recording of parameters. The incremental loading method was used. Before applying the working load, each sample had been subjected to a 10 kPa preload in order to eliminate deformations caused by inexact adhesion of soil to chamber and filter surfaces and to execute a relatively similar compaction of samples as a reference level for subsequent measurements of axial strain.

RESULTS

As revealed by the settlement-load curves *e*–σ' (Fig. 1), the increase of water content in fragmented clays is reflected in progressing drops of void ratio at the initial loads and the progressing flattening of curves under higher loads. It is the effect of increasing plastic deformations with increasing the water content, which results in the tightening of large intergranular voids and in a significant reduction of porosity. Thus, even under a relatively small load, the soil structure becomes more compact and more rigid.

In cohesive dump soils, an increase of water content at specific intervals causes behaviours different from those observed in local soils, i. e. the modulus of compressibility increases with water content (Fig. 2). This regularity is limited by a specific water content value at which the increase of the modulus caused by increasing compaction is balanced by a decrease of the modulus caused by the increasing liquidity index.

The described shape of settlement-load curves *e*–σ' indicates an unusually high dynamics of the changes of compressibility parameters with increasing the load. A comparison of results obtained by Kaczyński (1981) and Woźniak (1988) demonstrates that the deformability of fragmented dump soil samples with lump size from 5 to 25 mm under a load interval 12.5–400 kPa can be even 10 times higher than that of local soils with an undisturbed structure.

Table. **Characteristics of clays and silty clays from the overburden "Machów" open-pit mine**

Lentelė. **„Machów" karjero molio ir dulkingo molio savybės**

Density, ρ_s [Mg/m^3]	2.72	Plastic limit, w_p [%]	34.9
Bulk density, ρ [Mg/m^3]	2.03	Liquid limit, w_L [%]	73.8
Dry density, ρ_d [Mg/m^3]	1.65	Grain-size distribution:	
Void ratio, *e* [–]	0.65	sand, f_p [%]	4.6
Porosity, *n* [%]	39.3	silt, f_π [%]	58.0
Water content, w_n [%]	23.3	clay, f_i [%]	37.4

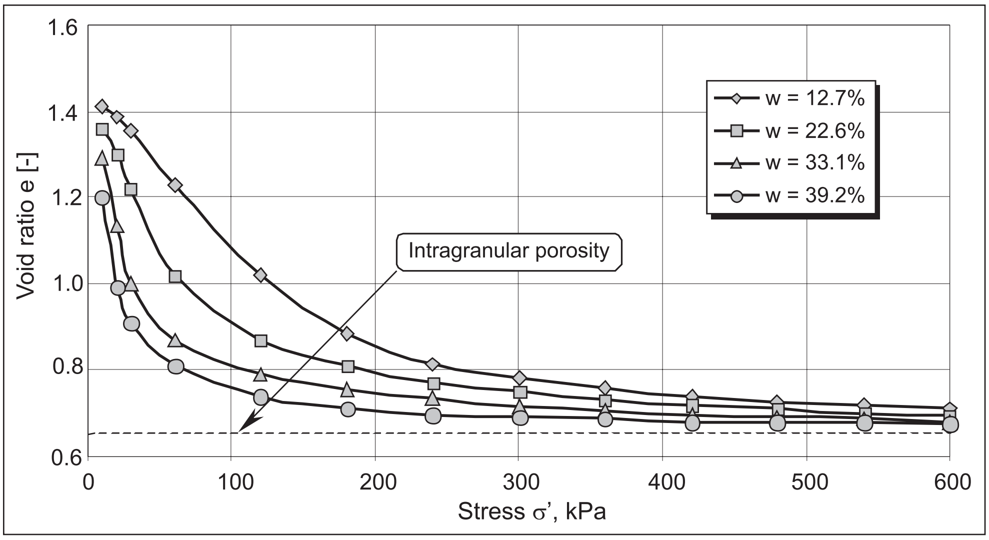

Fig. 1. Influence of water content on the shape of setlement-load curves

1 pav. Drėgnio poveikį atspindinčios kompresinės kreivės

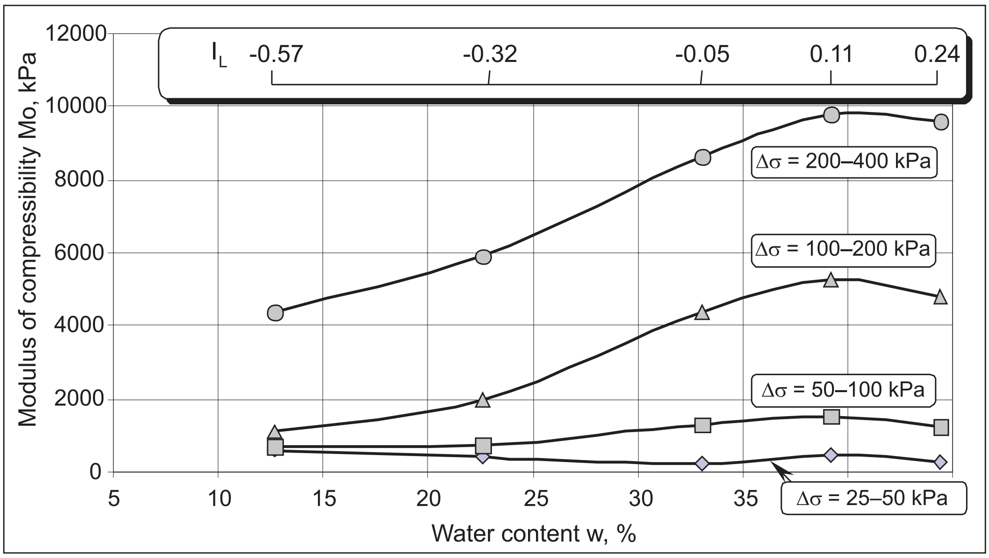

Fig. 2. Variability of compressibility modulus with the increasing water content

2 pav. Nuo drėgnio priklausanti kompresinio modulio kaita

New data on the shape of settlement-load curves for dump soils were provided by Feda (1998) who studied modeled samples composed of very fine clay lumps (1–8 mm in diameter) collected from an overburden of coal seams in western Bohemia (Fig. 3). This author has concluded that a proper approximation of settlement-load curve for soil with a low water content is a two-segment broken line (Line 1), whereas for soils of a higher water content it is a multi-segment broken line (Line 3). However, the authors' own data indicate that a multi-segment broken line is typical of samples composed of lumps showing clearly different water contents. The settlement-load curve for samples in which lumps are mostly crushed during the loading shows several characteristic bends and bears a garland-like shape (Line 2). For samples with a high water content, typical is a smooth curve of an almost vertical initial segment (Line 4) similar to that representative of remoulded samples.

Interesting information on the behaviour of cohesive dump soils can be obtained from the analysis of settlement-load curves drawn at a semi-logarythmic scale. Assuming that dump soils are normally consolidated, it can be expected that the graphic representation of the *e* – lg σ' dependence should be a straight line. However, the obtained results demonstrate that for these soils the *e* – lg σ' plot is a slightly curved line, and its shape depends on water content (Fig. 4). The settlement-load curve for a sample composed of low-water lumps of cohesive soil is distinctly bent upward in its initial load interval, indicating pre-consolidation (Fig. 4a). With increasing the water content, the effect of this apparent pre-consolidation decreases and disappears at a specific water content value (Fig. 4 b, c). Simultaneously, the settlement-load curve becomes progressively concave (Fig. 4 d). Such a plot shape had been noticed by Lancellotta (1985), who ascribed it to sensitive clays, and by Das (1995) who was of the opinion that such shape is typical of remoulded clays.

The apparent pre-consolidation, observed also in compacted soils (Biarez, Hicher, 1994), is presumably a result of a very limited susceptibility to plastic deformations shown

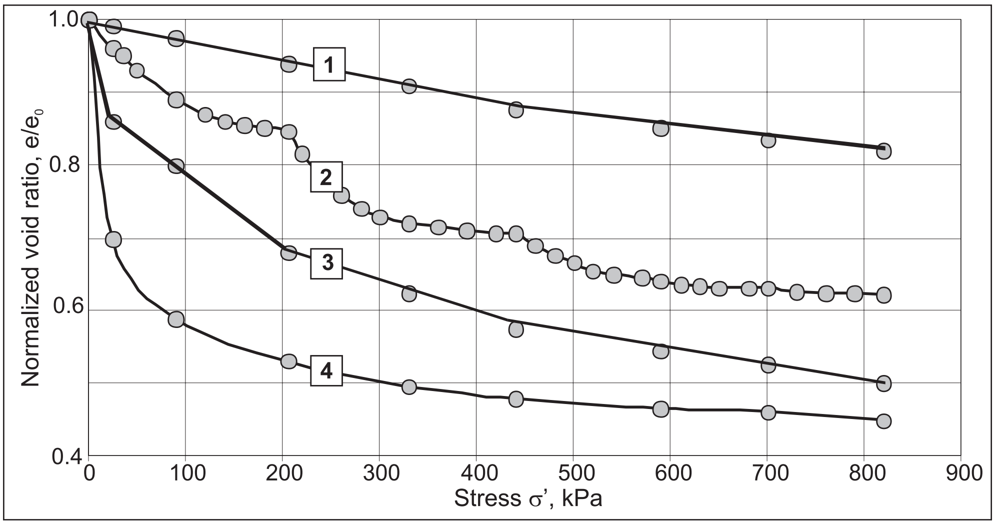

Fig. 3. Examples of settlement-load curves for cohesive dump soils (after Feda, 1998)

3 pav. Rišlių sąvartyno gruntų kompresinių kreivių pavyzdžiai (pagal Feda, 1998)

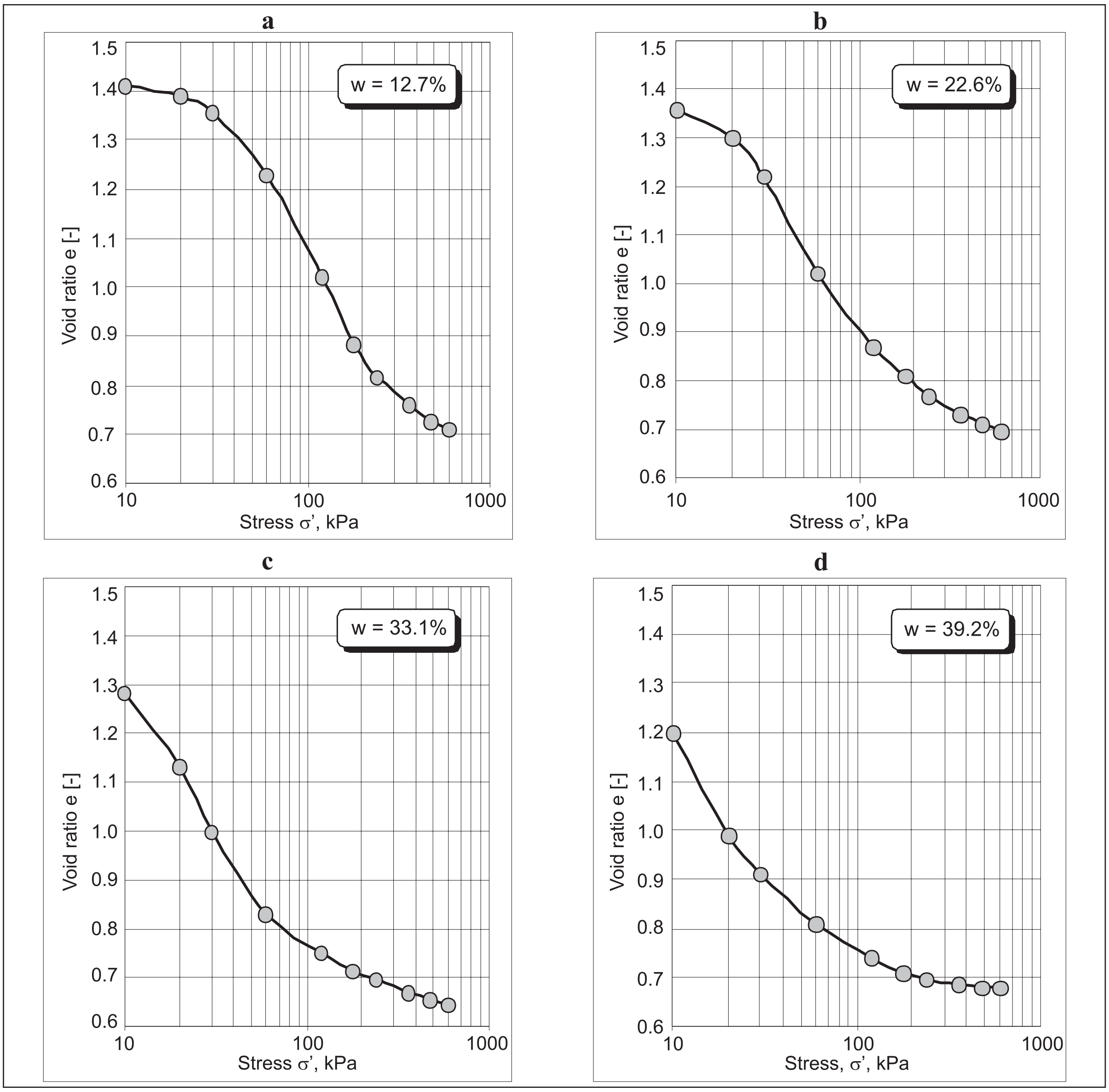

Fig. 4. Influence of water content on the shapes of *e* – lg σ′ settlement-load curves

4 pav. Drėgnio poveikis kompresinių kreivių *e* – lg σ′ pobūdžiui

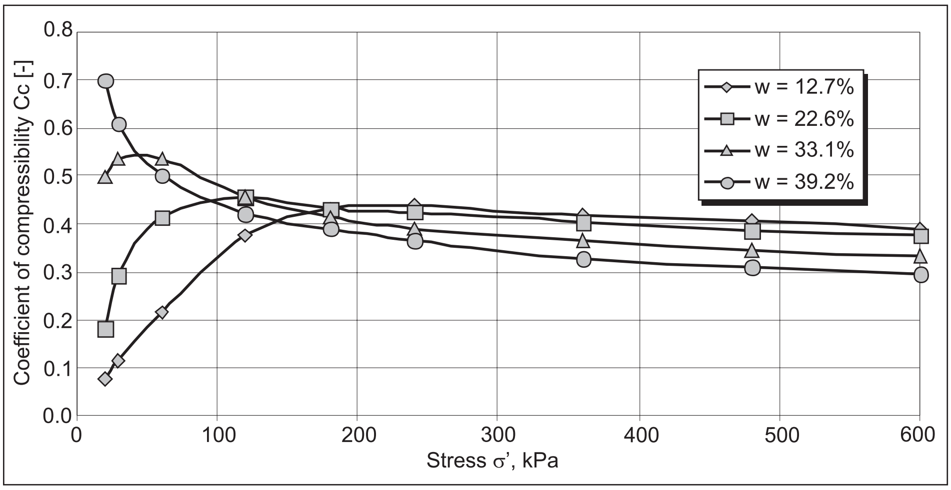

Fig. 5. Variability of compression index for cohesive dump soils

5 pav. Rišlių sąvartyno gruntų kompresijų rodiklio kaita

by an agglomeration of slightly dried, compact lumps which compose a cohesive dump soil of a low water content. A distinct increment of volumetric strains in such a system appears under loads exceeding the cracking and crushing strength of lumps, which is reflected by transition from a curved to a straight line of the settlement-load curve.

The curvature of e – lg σ' plot, observed despite the application of logarythmic scale for load values, indicates that the compaction of dump soils under load is a non-linear process of distinctly diversified dynamics. This non-linear character results in the variability of the compression index C_c whose values initially increase (pre-consolidation effect) and then decrease (Fig. 5). It has also been observed that the stress under which the compression coefficient reaches the maximum value systematically decreases with increasing the water content, i. e. from 200 kPa at the water content 12.7% to about 40 kPa at the water content 33.1%. Moreover, for the sample of the highest water content (39.2%), in which apparent preconsolidation had not occurred, the curve does not show an ascending segment.

The unusual properties of cohesive dump soils led some authors to the conclusion that a realistic prognosis of the behaviour of such soils requires advanced numeric methods and constitutive models. The first attempt was made by Doležalowá and Kořán (2002) who applied a distinct element code to the numeric prognosis of the behaviour of dump soils. Although some interesting results had been obtained, their practical application met several obstacles related to the calibration problems of the applied model. An alternative concept was proposed by Mašin et al. (2005). According to their idea, the behaviour of material of double porosity can be described by a modified cam-clay model supplemented with the effects of internal structure, proposed by Cotecchio and Chandler (2000), and by a function describing the current state of a structure and its degradation. This model is being studied theoretically and subjected to initial laboratory tests.

Data on samples of a modeled lump composition can be applied to prognosticating the true settlement values of dump soils. Examples of such practical usage, together with descriptions of relevant calculations, were published in a separate paper (Woźniak, 2009).

CONCLUSION

1. Cohesive dump soils are substances with a multistorey structure and double porosity. They are characterized by large intergranular voids, an unstable structure and a high susceptibility to external factors, particularly to changes of water content.

2. An increasing water content facilitates plastic deformations of cohesive soil lumps. A as result, under relatively small loads their multistorey structure is subjected to an advanced reconstruction, i. e. intergranular voids are tightened, porosity is highly reduced, and compaction increases. These processes mean that at specific water content intervals the compressibility modulus increases with increasing the water content, contrary to relationships observed in local soils.

3. The character of stress–strain dependence in cohesive dump soils is strongly controlled by water content. In slightly dried soils with a low water content, the e – log σ' curve is similar to that typical of overconsolidated soil. The effect of such an apparent consolidation disappears with increasing the water content.

4. The compaction of dump soils under load is a non-linear process of distinctly diversified dynamics, which results in a variability of the compression index C_c.

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Henryk Woźniak

DRĖGNIO POVEIKIO RIŠLIŲJŲ SĄVARTINIŲ GRUNTŲ GRUMSTINĖS SANDAROS ĖMINIAMS TYRIMŲ REZULTATAI

Santrauka

Rišlieji sąvartiniai gruntai priskiriami antros rūšies dvigubo poringumo susmulkintų gruntų grupei. Tokie gruntai yra nestabilios struktūros – kinta jų fizikinės mechaninės savybės, jiems turi įtakos išoriniai veiksniai, ypač drėgnio kaita. Atlikti tyrimai leido įvertinti drėgnio poveikį spūdumo parametrams bei deformacijos ir įtempio ryšiui. Kad grunto struktūra būtų panaši į natūralią, buvo imami susmulkinto molio su grumstine (luistine) sandara ėminiai. Grumstinės struktūros gruntuose didėjanti drėgio vertė „užgniaužia“ dideles tarpgrumstines poras ir sumažina poringumą, kartu padidindama visos struktūros tankumą.

Pastebėta, jog sąvartiniuose gruntuose padidėjusi drėgnio vertė tam tikrame intervale padidina spūdumo vertę (2 pav.) – priešingai negu natūraliuose gruntuose. Drėgnio poveikis pavaizduotas spūdumo kreivėse (3 pav.). Ėminių su mažu drėgniu kreives aproksimuoja dviejų atkarpų laužtinė linija, ėminių su įvairiaus drėgnumo grumstais – laužtinė linija iš daugelio atkarpų. Ėminių, kuriuose per apkrovą trupinami grumstai, spūdumo kreivėms yra būdingi keli lūžiai (2-a kreivė), labai drėgnų ėminių kreivė yra sklandi.

Priklausomybė $e - lg\ \sigma'$ sąvartiniuose rišliuose gruntuose nėra linijinė (4 pav.). Į viršų išgaubta spūdumo kreivė pradiniame apkrovos etape yra perdžiūvusių grumstų, kurie sudaro mažo drėgnumo sąvartinį gruntą, ribotos plastiškos deformacijos rezultatas. Šis reiškinys – tariamoji prekonsolidacija – nyksta didėjant drėgnio vertei, o esant tam tikrai drėgnio vertei, visai išnyksta. (4 pav., *b*, *c*). Nelinijinės $e - lg\ \sigma'$ priklausomybės ryšys rodo, jog tankėjimas sąvartiniuose gruntuose yra nelinijinis ir kinta įvairiai. Šio nelinijinio proceso pasekmė yra kintanti spūdumo koeficiento Cc vertė: pradžioje ji didėja (prekonsolidacijos efektas), vėliau mažėja (5 pav.).

Генрик Возняк

ВЛИЯНИЕ ВЛАЖНОСТИ НА СЖИМАЕМОСТЬ ГЛИНИСТЫХ ОТВАЛЬНЫХ ПОРОД НА ОСНОВЕ ИССЛЕДОВАНИЙ ОБРАЗЦОВ С МОДУЛИРОВАННЫМ СОСТАВОМ ЧАСТИЦ (КУСКОВ)

Резюме

Глинистые отвальные породы относятся к дисперсным средам второй категории и характеризуются пластовой структурой и двойной пористостью. Данные среды характеризуются нестабильностью структуры и физико-механических свойств, а также высокой податливостью воздействию внешних факторов, особенно изменения уровня влажности. На основании проведенных исследований оценено влияние уровня влажности на изменение параметров сжимаемости (уплотняемости) и на характер соотношения напряжение–деформация. Для отображения натуральной структуры глинистых отвальных пород были проведены исследования на образцах дисперсных суглинков со смодулированным составом частиц.

Повышение уровня влажности в грунтах вызывает в структуре частиц сжатие больших междучастичных (междукусковых) пор и значительное сокращение пористости, а в дальнейшем повышение плотности и твердости структуры. В результате выявлено, что в глинистых отвальных породах повышение уровня влажности в определённых границах вызывает увеличение модуля сжимаемости (рис. 2), иначе, чем это происходит в природных грунтах. Влияние уровня влажности отмечается также и в характере компрессионных кривых (рис. 3). В случае грунтов с невысоким уровнем влажности соответствующую аппроксимацию кривой сжимаемости составляет ломаная линия из двух отрезков (линия 1), а в случае грунтов, состоящих из фракций с разным уровнем влажности, ломаная линия состоит из нескольких отрезков. Кривая сжимаемости образцов, в которых во время нагрузки преобладает раздробление, отображает несколько характерных изгибов (кривая 2), а для водонасыщенных образцов типичной является кривая с плавными переходами (кривая 4).

Зависимость $e - \lg \sigma'$ для глинистых отвальных пород не является линейной (рис. 4). Явный изгиб кривой сжимаемости с выпуклостью кверху, наблюдаемый в начальной стадии нагрузок, предположительно является эффектом весьма ограниченной податливости пластической деформации системы пересушенных частиц, каковой является насыпной грунт с невысоким уровнем влажности. Данное явление, названное видимым предварительным уплотнением грунта (преконсолидацией), при повышении уровня влажности явно понижается, а достигнув определенного уровня исчезает (рис. 4b, c). Криволинейность зависимости $e - \lg \sigma'$ указывает на то, что процесс уплотнения насыпных грунтов является процессом нелинейным, с явно выраженной дифференцированной динамикой. Следствием нелинейности является изменчивость показателя сжимаемости Cc, значения которой сначала увеличиваются (эффект переуплотнения), а затем уменьшаются (рис. 5).