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Geotechnical properties of compacted clays as buffer and backfill

Saulius Gadeikis, Kastytis Dundulis, Sonata Gadeikytė, Donatas Urbaitis, Domas Gribulis

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Abstract The purpose of the investigation is to assess local clay soils of different composition, physical state and mechanical properties as a base and construction material for establishment of landfills for radioactive waste. The investigations have been carried out for three clay soil types of different age and origin in order to assess the potential of this clay to be used for the establishment of engineering barriers, as well as the base and slopes of landfills. The investigations have been performed by laboratory and field methods for both the natural as well as the disturbed and compacted soils. In order to assess the soil to be used for fill-ins (aggregate), field investigations have been performed at a special test site. Changes in geotechnical features of the soils were observed at the test site in autumn and spring. Seasonal investigations enabled to assess the compacted clay soils according to changes of their features over time.

Keywords *• compacted clay • buffer • backfill • waste • numerical simulation • Stabatiškės • Lithuania*

✉ *Saulius Gadeikis (saulius.gadeikis@gf.vu.lt), Kastytis Dundulis, Sonata Gadeikytė. Donatas Urbaitis, Domas Gribulis, Vilnius University, K. M. Čiurlionio g. 21/27, LT-03101 Vilnius, Lithuania*

INTRODUCTION

The development of nuclear power during the last decades is directly related to the problems of storage of radioactive waste. The technologies applied to bury and store this waste, as well as establishment of specific burial sites present one of the most important engineering tasks. Under favourable geological conditions, one of the best ways to establish the waste storage sites is the use of the underground workings already available or to be newly arranged, such as mines, adits etc. If there are no underground workings, the technologies of establishment of near-surface repositories are used (Read 1999; Tanaka 1999; Push 2008). Here, the system of radioactive waste deposition should provide isolation of the waste and limit the spreading of radionuclides at such a degree that its potential impact on humans and environment were within the acceptable limits and met the general targets of security. The system should embrace the characterisation of wastes, institutional control, engineering and natural barriers related to the concrete area of a landfill. That is, the soil strata used should become a reliable isolation (engineering barrier) that, in case of disaster, would protect the environment from migration of buried radioactive substances. The engineering barriers should also hold the long-term structural integrity of the near-surface repositories and protect waste encasements from disintegration or seeping of waste into groundwater.

In our case, the geotechnical researches are aimed at selection of the sites (Fig. 1) and investigation of three different (in age, origin and composition) clay soils, to find if they could fit to establish isolating strata around the reinforced concrete vaults to be used for storage for radioactive wastes. Additionally, their potential for slope and base formation also had to be explored.

A scheme of one of the near-surface repositories suggested earlier and used in Japan proposed to establish an excavation with drainage system in clay soils and cemented slopes, while it top to be covered by compacted clay. Later this system had been criticised

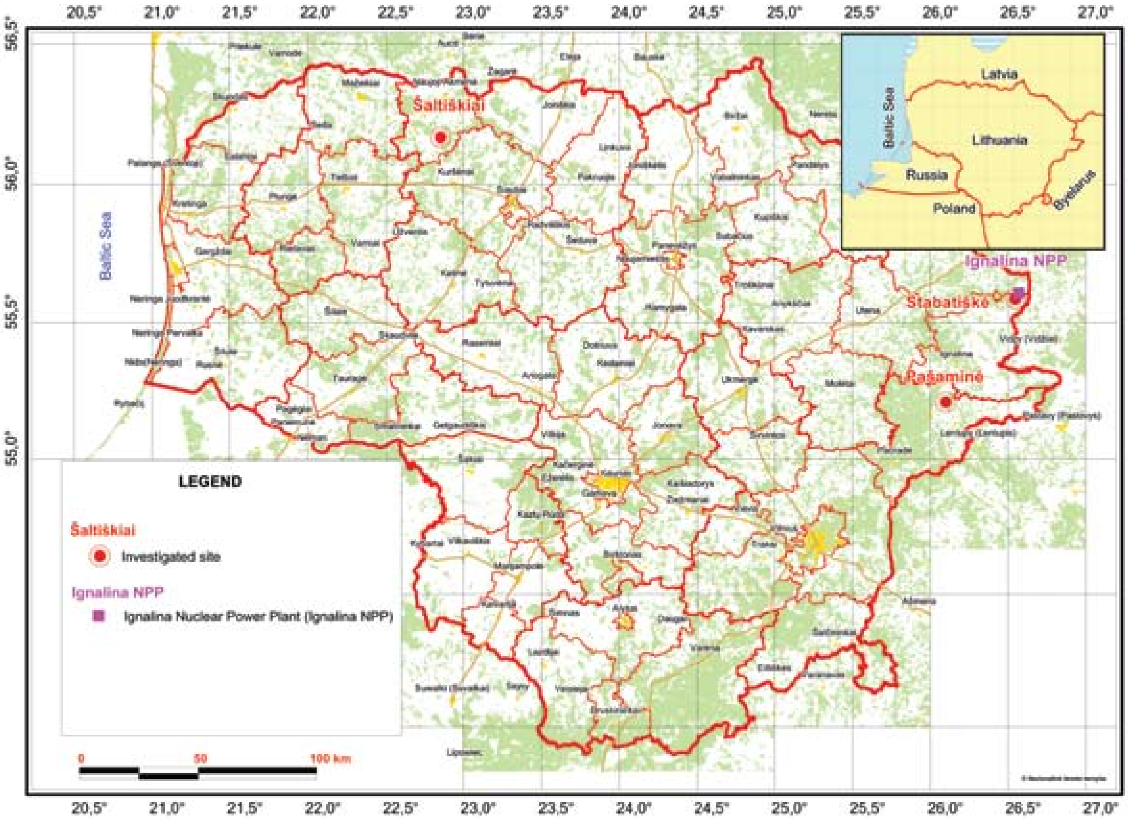

Fig. 1 Location of the test sites.

because of necessity to use a complicated system for groundwater removal (Tanaka 1999).

The clay stratum as a part of engineering barrier is the most important and basic element (Fig. 2). Performing a protection function, at the same time, a construction element must ensure both the protection and the sufficient strength. To lay this stratum, artificially formed material and naturally redepos-

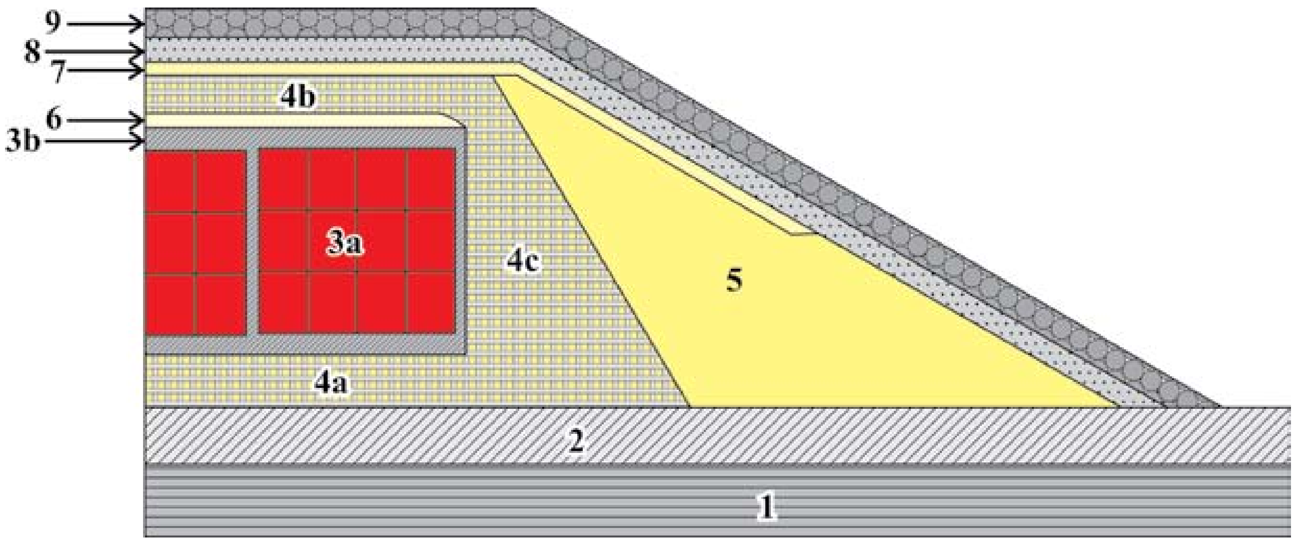

Fig. 2 A conceptual scheme of the mound-type repository for radioactive wastes (SKB-SWECO 2002[1]). Structural elements: 1 – natural base, 2 – levelling layer; the system of vaults: 3a – waste container, 3b – vault walls, floor and covering; the stratum of clay – an aggregate: 4a, 4b – covering aggregate, 4c – lateral aggregate; 5 – the layer of slope development; 6 – gas collector (0.2 m thick); surface barrier: 7 – the layer of silty sand (0.5 m), 8 – the layer of gravel (0.7 m), 9 – the layer of boulder and pebbles (0.8 m).

[1] SKB-SWECO, 2002. Reference design for a near surface repository for low- and intermediate-level short lived radioactive waste in Lithuania. SKB-SWECO International–Westinghouse Atom Joint Venture, LT NSR Final project report (database of the JSC „Sweco hidroprojektas").

ited or compacted soils are used. In the first case, a bentonite or bentonite-sand mixture is most often used (Stewart 1999; Choi 2001; Marcial 2006). In the second case, a natural compacted clay soil containing minerals of smectite is used (Push 2002, 2006, 2008).

Key task of the research was investigation of geotechnical properties of clay soils selected under their natural occurrence conditions as well as assessment of their potential to be used for engineering barriers; the assessment of geotechnical properties of the compacted soils in three polygons of different clay soils established at the special test site by means of soil compaction; studies of changes in compacted clay soils with time.

THE OBJECT AND METHODS OF THE RESEARCH

During the closing of the Ignalina Nuclear Power Plant (NPP) and solving issues of a new NPP project, the burial of wastes of medium and low radioactivity becomes urgent. Dealing with the problems emerging during the selection of a conceptual model for burial storage of these wastes, it is necessary to assess the possibility of use of local natural materials.

Therefore, to select strata for isolation barriers and constructional storage, three investigation objects containing necessary types of soil have been chosen. Because these soils were expected to be potentially used as construction elements, it was necessary to assess their geotechnical properties. Thus, two open pits of clay and, additionally, one local clay deposit have been chosen for the assessment of the potential use of these soils.

Šaltiškiai Clay Pit. The clay bed now being in production contains Lower Triassic clay of the Nemunas Formation (T_1nm). The productive clay seam occurs on the surface of the Permian limestone. This is brown, reddish-brown clay, iron rich and dolomitised, with bluish grey lamina. Its upper cover consists of the Quaternary (Q_3) and Upper Jurassic (J_3) deposits (Fig. 3).

Pašaminė Clay Pit. The clay seam, now in production, is composed of the Upper Pleistocene glacial lake deposits of Grūda Formation (lgIIIgr). This is brown, greyish brown clay, laminated or massive in places. The seam in production is overlain by a thin cover of glacial lake clay, sand and silt deposits (Fig. 4).

Local till soil from the Stabatiškės site. During the construction, by removing the upper cover and excavating the local Upper Pleistocene soils of Baltija and Grūda subformations, the latter can be used as construction layers for the radioactive waste repository (Fig. 5).

First, clay soils occurring naturally in the Šaltiškiai and Pašaminė pits and Stabatiškės construction site have been studied for determination of soil properties. Special test areas have been established in the Stabatiškės construction site for investigations of soil heaps brought in, disturbed and compacted. Three polygons (10 × 5 m, 1.5 m thick) have been formed for each clay soil type. The soil has been spread as 50 cm thick layers. The compaction of soil has been done by a drum vibratory compactor (7.8 HAMM3011) in five–six times.

Determination of geotechnical properties of the compacted soil has been done twice: just after the compaction (in autumn) and after several months (in spring). Analyses of chemical and mineral composition have been done for all three types of soil. The micro–sounding analysis method with scanning electron microscope EVO-50EP and wave dispersion spectrometer has been applied to determine chemical composition of soils. The X-ray diffraction analysis is applied for determination of clay mineral composition. Grain size and physical properties of soil is determined according to the ISO/TS requirements. The geomechanical properties are determined by vane test (10 tests each), plate

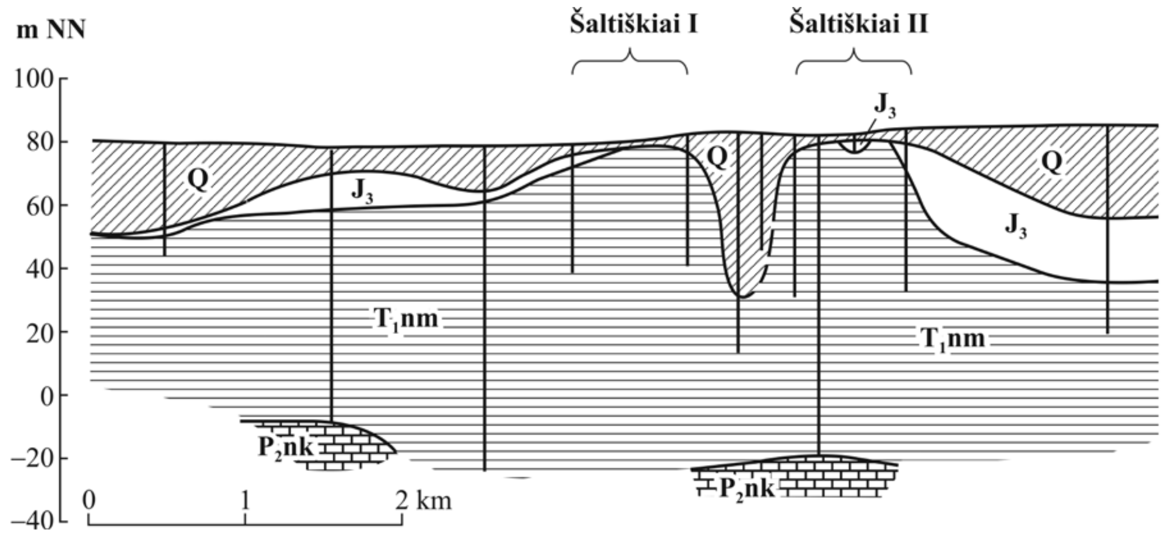

Fig. 3 Geological cross section of Šaltiškiai clay pit (after Gailius *et al.* 1994).

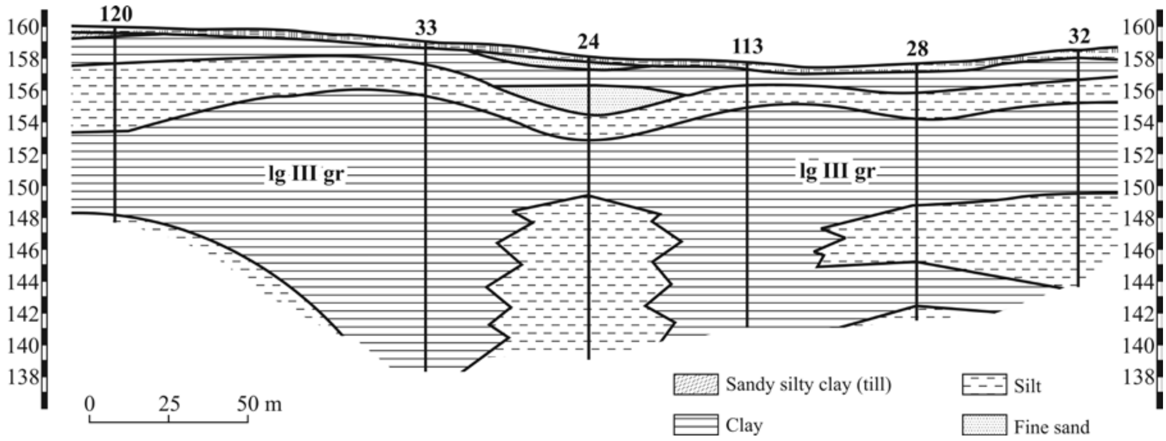

Fig. 4 Geological cross section of Pašaminė clay pit (after Norkus 1990[1]).

[1] Norkus, J., 1990. Švenčioniai district Pašaminės clay deposits exploitation prospecting. Lithuanian Geological work production association, Vilnius. [In Lithuanian] (database of the Lithuanian Geological Survey).

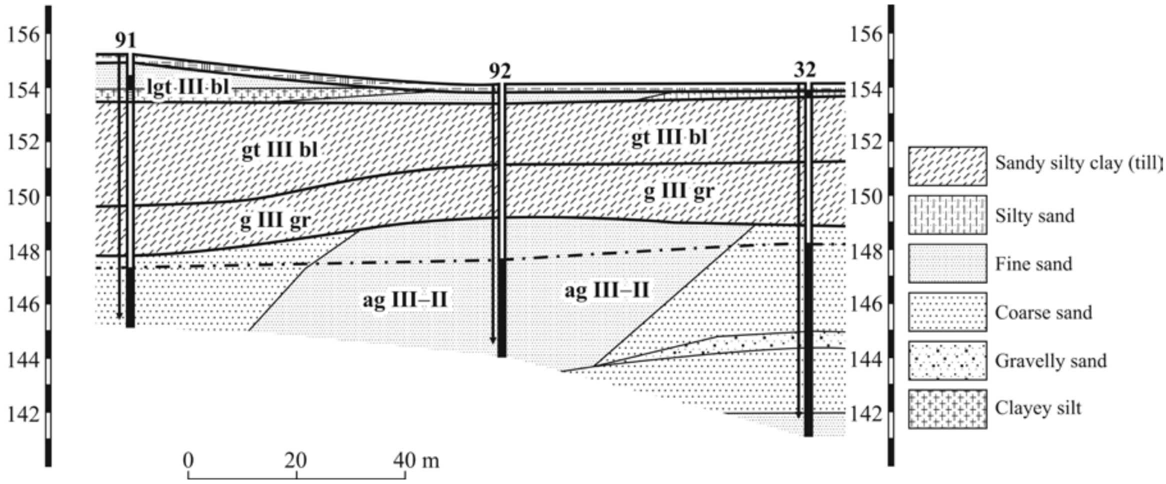

Fig. 5 Geological cross section of local till soil from the Stabatiškės site (after Žaržojus *et al.* 2012[1]).

[1] Žaržojus, G., Gadeikis, S., Trumpis, G., 2012. Near surface repository for low and intermediate level short-lived radioactive waste at Stabatiškės site, Visaginas, project B25-1. Report of detailed geotechnical investigation, Confirmation stage, JSC "Geotestus" (database of the Lithuanian Geological Survey).

loading test (three tests for each polygon) and light dynamic probing (three tests each).

RESULTS

Chemical composition of clay soils indicates that the average content of macro–component oxides is mainly similar (Table 1). A larger difference is observed in the samples taken from the Šaltiškiai Pit, where Na element content is five times lower than that in other clays. This specificity is notable usually for smectite type clays (Steward 1999). Content of such elements as Mg, Al, Ti and Fe are lower in the Stabatiškės till clays, which are notable, however, for higher content of Si as a typical feature of older tills.

Mineral composition shows that the median content of smectite is the highest in Šaltiškiai clay samples and ranging from 32.3 % to 76.4 % in clay fraction (Table 2). Correspondingly, the percentages in total soil make from 8.6 % to 16.0 %. Samples from Pašaminė and Stabatiškės contain high amounts of illite typical for soils formed under glacial conditions. The results obtained clearly show that the Lower Triassic clay of the Nemunas Formation from Šaltiškiai Pit fit the best the requirements for engineering barriers according to the mineral composition.

The results of grain size determinations are given in Table 3. According to the ISO 14688–2:2004 classification of soils, the peculiarities in grain size composition are revealed for the places, where the samples are taken from. The Šaltiškiai clay soil – silty clay (siCl) is most homogeneous with only two fractions detected, i.e. clay (< 0.002 mm) and silt (0.002–0.063 mm). The Pašaminė clay soil is notable for high variations in clay and silt fractions, as is typical of laminated formations in the beds of glacial lake

Table 1 Median percentages of macro-element oxides in clay samples.

Sample	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	Fe_2O_3
Šaltiškiai	0.13	4.33	14.47	47.49	3.22	8.12	0.88	14.99
Stabatiškės	0.65	2.85	10.75	59.94	3.73	8.12	0.5	10.32
Pašaminė	0.66	3.15	14.71	49.76	4.34	7.62	0.87	15.26

Table 2 Median percentages of clay minerals in clay fraction and soil (in parentheses).

Sample	Montmorillonite	Illite	Kaolinite	Chlorite
Šaltiškiai	63.9 (14.2)	31.4 (31.4)	5.8 (1.4)	0 (0)
Stabatiškės	0 (0)	83.3 (15.3)	15.8 (2.8)	0.9 (0.2)
Pašaminė	0 (0)	84.3 (26.1)	14.4 (4.4)	0.7 (0.1)

Table 3 Grain size composition of clay soils.

Fraction	Stabatiškės	Šaltiškiai	Pašaminė
Clay, % (avg.)	11.8÷20.5 (16.4)	27.5÷36.5 (31.8)	19.3÷64.4 (36.8)
Silt, % (avg.)	39.0÷44.8 (42.3)	63.5÷72.5 (68.2)	35.5÷80.3 (62.9)
Sand, % (avg.)	33.3÷43.6 (39.1)	–	0.2÷0.5 (0.4)
Gravel, % (avg.)	0.7÷3.6 (2.3)	–	–

Table 4 Clay soil physical state averages.

Index	Symbol	Measurement unit	Stabatiškės	Šaltiškiai	Pašaminė
Natural moisture	w	[-] (avg.)	0.120	0.198	0.229
Plasticity limit	w_P	[-] (avg.)	0.120	0.322	0.217
Liquid limit	w_L	[-] (avg.)	0.244	0.573	0.450
Plasticity index	I_P	[-] (avg.)	0.124	0.252	0.233
Liquid index	I_L	[-] (avg.)	-0.01	-0.49	0.07
Consistency index	I_c	[-] (avg.)	1.01	1.49	0.93
Skempton's activity	A	[-] (avg.)	0.78	0.80	0.68
Soil density	ρ	Mg/m^3 (avg)	2.29	2.08	2.04

origin. In this case, the classification type ranges from silt (Si) to clay (Cl). The soil from Stabatiškės site distinguishes itself mostly. There is a wide spectrum of soil grains from the finest clay to small amounts of sand, but according to its composition, this clay soil can be attributed to one classification type, i.e. sandy silty clay (sasiCl). According to the grain size, the Stabatiškės till soil stands the closest to the optimal mixtures typical of all till soils in Lithuania.

The assessment of physical state done for clay soils shows a certain regular tendency in relationship of clay fraction content to soil mineral composition (Table 4). The clays of the Šaltiškiai Pit are notable for the highest natural moisture and higher limits of Atterberg values (w_P and w_L). The lowest values of these indicators are characteristic of the Stabatiškės till soil. An intermediate position is occupied by Pašaminė glacial lake clays. According to soil consistency (I_L) values, all clays are attributed to the category of firm (cohesive) and very firm (very cohesive) soils.

After establishing the test site and compacting all three type soils by vibratory drum compactor, the soil density and moisture indices has been determined (Table 5) to differ from those occurring under natural conditions (see Table 4). The density of compacted clay soil from the Šaltiškiai Pit makes up 97% of the natural density, while the moisture content is found to increase by 14%, whereas for the Stabatiškės till soil there is a decrease in density by 2% and moisture by 4% observed. The density of Pašaminė clay soil decreased by 1.5%, and moisture increased by 14%. Significant growth in moisture for Šaltiškiai and Pašaminė soils seems to be related to higher content of clay fraction that created better conditions for soils to swell.

Table 5 Average values of compacted clay soil density and moisture.

Compacted soil	Moisture w, [-]	Density ρ, Mg/m^3
Šaltiškiai clay soil	0.230	2.02
Stabatiškės till clay soil	0.116	2.25
Pašaminė clay soil	0.266	2.03

Investigations of mechanical properties of compacted soils

The compacted soils have been studied in two stages: in October (an autumn stage) and six months later (a

Table 6 Results of static plate loading tests (PLT) during the autumn and spring stages.

Compacted soil	First load deformation modulus E_{v1} MN/m^2		Second load deformation modulus E_{v2} MN/m^2 average values		E_{v2}/ E_{v1} average values	
	autumn stage	spring stage	autumn stage	spring stage	autumn stage	spring stage
Šaltiškiai clay soil	6.82	2.76	18.74	11.05	2.82	3.94
Stabatiškės till clay soil	1.70	2.83	8.92	8.61	5.26	3.08
Pašaminė clay soil	1.67	1.69	5.72	5.78	3.44	3.44

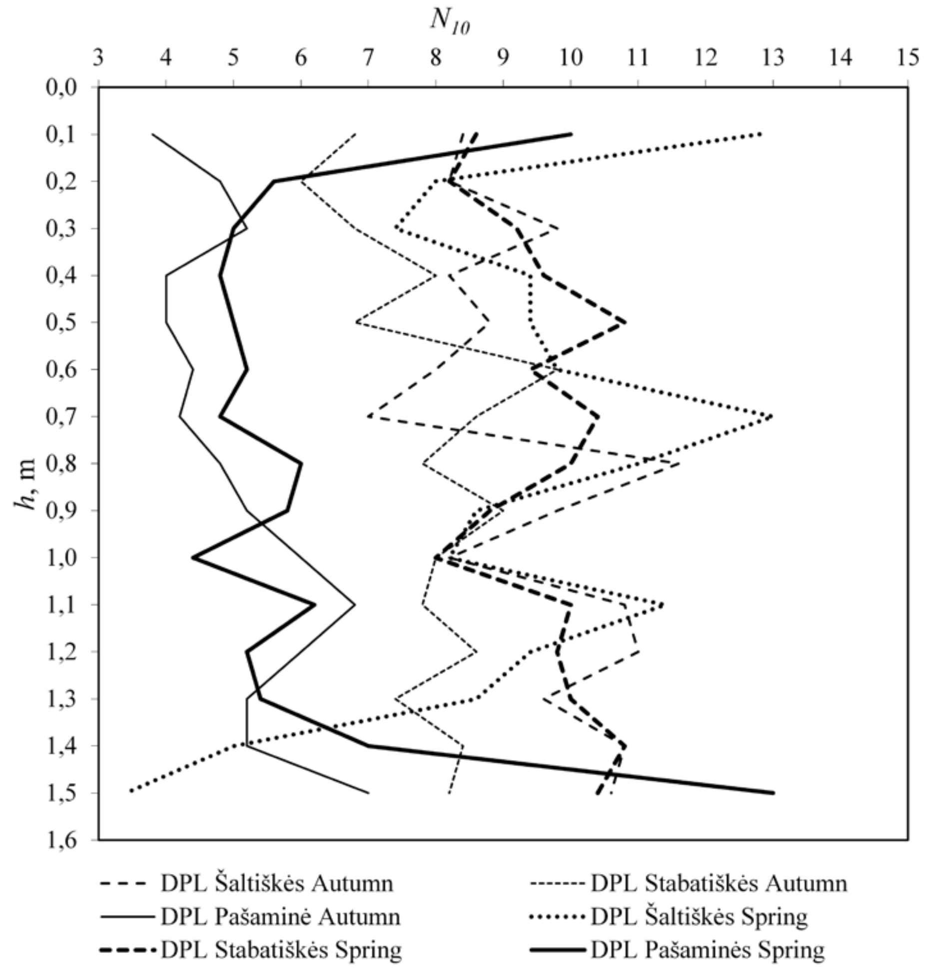

Fig. 6 Diagrams of average values of dynamic probing test.

spring stage). Such an approach has been chosen in order to get possible changes of geomechanical properties of soils in time and expecting to prognosticate mechanical behaviour of soils in the future for several years, also to meet the requirements for secure storage of radioactive waste and protection of environment.

The static plate loading tests (PLT) have been performed. The results have enabled to assess not only differences in deformation properties of different soils types (Table 6), but also their changes in time due to changing climatic conditions (rain, cold, snow etc.). The lowest compressibility has been found for the Šaltiškiai silty clay (siCl), however, with time, there is a tendency of increase in compressibility. An inverted tendency is observed for the Stabatiškės till sandy silty clay (sasiCl), especially during the first loading. The highest compressibility is found for Pašaminė glacial lake clay that, however, witnessed the smallest changes in time.

The undrained shear strength (c_u) investigations by impeller showed generally large strength of all types of soils, mostly above 260 kPa, exceeding the vane impeller measurement capability. Differences that are more distinct are revealed in the upper part of the compacted soil as deep as 0.4 m. Within this depth range, the c_u value for Šaltiškiai soil varies from 220 to 250 kPa, while the c_u vale for Pašaminė soils ranges from 108 to 220 kPa, and for Stabatiškės till within 174–236 kPa. During different study stages, the undrained shear strength values (c_u) vary within 108–240 kPa and do not show a tendency of prominent changes.

Light dynamic probing results show general trend of dynamic resistance from the highest values determined in Šaltiškiai clay soil followed by lower values in Stabatiškės till soil to the lowest dynamic resistance in Pašaminė glacial lake clay. From time point, small tendency of changes is observed in Stabatiškės till resistance that slightly grows with time (Table 7). A decrease in Šaltiškiai clay soil resistance from the depth of 1.3 m is caused by water accumulated at its base in springtime.

Table 7 Results of light dynamic probing during autumn and spring stages.

Compacted soil	Number of blows at 10 cm (N_{10})	
	autumn stage	spring stage
Šaltiškiai clay soil	7–12 (9)	3–13 (9)
Stabatiškėstill clay soil	6–10 (8)	8–11 (10)
Pašaminė clay soil	4–7 (5)	4–13 (6)

Note: the first value is minimal, the second one is maximal, and average number given in parentheses

The investigations of geomechanical properties by vane test[1] (VT) and dynamic probing (DPL) methods have shown that the highest undrained shear strength is observed for Šaltiškiai clay soils (c_u > 260kPa). For Pašaminė clay soils and Stabatiškės till c_u average values are, correspondingly, 226 kPa and 183 kPa. During dynamical probing the average numbers of blows N_{10} for Šaltiškiai clay soils, Pašaminė clays and Stabatiškės till soil are, respectively, 24, 36 and 8 (Fig. 6).

DISCCUSION

The investigations of three clay soil types different in age and genesis allow discussing their geotechnical and isolating properties.

Šaltiškiai silty clays (T_1nm; 240–250 Ma ago) were formed in hot desert conditions repeatedly by rainy and dry stages. Specific climate, periodic pool binding to sea resulted an unexpected particular mineral composition, but also a partial clay dolomitisation. The high content of smectite type mineral in clay fraction (63.9%) is unique compared with Pašaminė and Stabatiškės clay soils. It determines the capabilities of the silty clay layer to be used as radioactive waste disposal in landfill. These compacted clays has good geotechnical properties (I_L = - 0.49), E_{v1} = 6.88 MN/m^2, c_u = 220–250 kPa). On the other hand, a large amount of smectite mineral can cause increased swelling of soil, undermining the soil used as a design element.

Stabatiškės till clays (Upper Pleistocene; gIIInm$_3$) of Baltija and Grūda sub-formations are characteristic glacial sediments close to the optimum grain size composition of mixtures, very stiff consistency, high density, low porosity and high enough geotechnical properties (I_L < 0, c_u = 174-236 kPa). Although this soil does not have smectite mineral and it is not suitable as a barrier, however, can be fully used as material of slopes closed formation, as shown by the construction-accumulated experience.

Pašaminė glacial lake sediments (lgIIIgr) that developed in the ice–marginal lake have a considerably more diverse grain size composition and relatively poorer geotechnical properties (I_L = 0.7, E_{v1} = 1.67 MN/m^2, cu = 108–220 kPa). The latter soil is not suitable for use as an isolating barrier layer, and as experience shows for constructing element.

CONCLUSIONS

According to mineral composition determined for three soil types, the silty clay (siCl) from the Šaltiškiai Pit is the best for establishment of barrier isolation layer (siCl). The compacted clay (siCl) of Šaltiškiai is notable for a rather high density and strength. Due to swelling with time, the increasing resistance of Šaltiškiai clay can be compensated by geostatic pressure of other radioactive waste storage construction layers.

Local Stabatiškės till sandy silty clay (sasiCl) can be used to form other construction layers of storage; this clay is notable for high density, low compressibility and sufficient strength.

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