GEOLOGIJA. 2012. Vol. 54. No. 3(79). P. 89–99

Geological conditions, environmental situation and development possibilities of the Paldiski Northern Harbour, north-western Estonia

Arvo Käärd,

Anto Raukas

Käärd A., Raukas A. Geological conditions, environmental situation and development possibilities of the Paldiski Northern Harbour, north-western Estonia. *Geologija.* Vilnius. 2013. Vol. 54. No. 3(79). P. 89–99. ISSN 1392-110X.

The paper presents information about the history of the Paldiski Northern Harbour, geotechnical characteristics of the bottom sediments, geology of the bedrock and environmental situation. Harbours of Paldiski are virtually ice-free, deep and well protected from the winds blowing from the open sea. Some 300–400 m west of the Paldiski Northern Harbour, the depth of the sea already reaches 20 m. The harbour was founded by Peter I, Czar of Russia, in 1718. During the Soviet occupation it was a closed naval port. After the retreat of Russian troops from Estonia in 1995, the sea floor and land area of the harbour were strongly polluted. For the time being the residual pollution has been liquidated. The extension of the harbour and large-scale construction works in the area are planned. Due to the variable thickness and changeable composition of the bottom deposits the engineering-geological conditions in the harbour area are complicated.

Key words: bottom deposits, bedrock, engineering-geological properties, buried valley, past pollution

Received 11 November 2012, accepted 27 November 2012

Arvo Käärd. Estonian Maritime Academy, Kopli 101, 11712 Tallinn, Estonia. E-mail: akaard@hot.ee

Anto Raukas. Institute of Ecology at Tallinn University, Uus-Sadama 5, 10120 Tallinn, Estonia. E-mail: anto.raukas@mail.ee

INTRODUCTION

Estonia is a maritime country. From the west and north-west it is washed by the open sea, from the north by the Gulf of Finland and from the south-west by the Gulf of Riga. Estonia has 1 240 km of coastline on the mainland and 2 540 km on the islands. Estonia's gross domestic product (GDP) is greatly determined by the sea transport which, in its turn, depends on the availability and number of good harbours. According to the type of ownership, there are state-owned, municipal and privately-owned harbours in Estonia. The Port of Tallinn consists of four constituent harbours, located at a certain distance from each other: Old City, Muuga, Paljassaare and Paldiski South Harbour. Kunda, Loksa, Sillamäe, Bekker and the Russian-Baltic Port in Tallinn are large privately-owned harbours, while Pärnu, Paldiski Northern Harbour and Miiduranna are in municipal ownership.

The former Soviet naval ports – the Southern and Northern Harbours of Paldiski – which are deep, virtually ice-free all year round and well protected from the open sea winds by the Pakri Islands (Fig. 1), have a good logistic location and therefore a great development potential. Ämari Airport is situated in the vicinity. A disadvantage is the low capacity of the railway leading to Paldiski. To overcome the problem, construction of

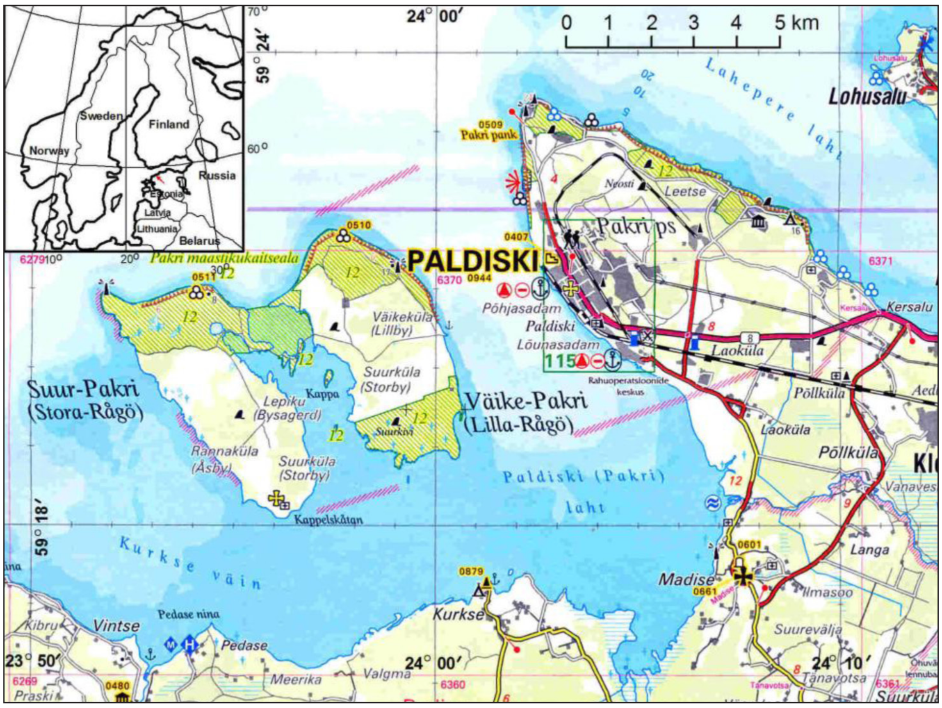

Fig. 1. Location of the Paldiski harbours (in rectangle). Põhjasadam – Northern Harbour, Lõunasadam – Southern Harbour (Map from the REGIO Estonian Road Atlaas)

1 pav. Paldiski uosto geografinė padėtis (pažymėtas plotas). Põhjasadam – šiaurinis uostas, Lõunasadam – pietinis uostas (žemėlapio išbraiža iš REGIO Estonian Road Atlaas)

a new railway line, which will bypass Tallinn and join the Tallinn–Pärnu railway, is planned. The Paldiski Northern Harbour has a regular ferry connection to Kapellskär in Sweden. The Paldiski Northern Harbour is deeper than the Southern Harbour and creates much more favourable conditions for receiving big ships. Some 300–400 m west of the harbour, the sea is already deeper than 20 m. At the Southern Harbour the sea is shallower; some 600 m off the harbour the sea is only 15 m deep.

The Paldiski Northern Harbour (Fig. 2) is located on the south-western part of the Pakri Peninsula in the north-eastern part of the Gulf of Paldiski (Pakri). Its geographical co-ordinates are 59°21’ N/24°03’ E. The land territory of the harbour is 157 886 m^2 and the water area is 792 062 m^2. In the harbour there are 5 quays with the total length of 385 m, the water depth near the quays is up to 5 m. With dredging the draught of the landing ships can be increased.

The main goal of the present work is to study geological preconditions for more rapid development of the Paldiski Northern Harbour with the building of new quays and deepening of the shipping line. Detailed engineering geological and environmental geological studies serve as a basis.

HISTORICAL BACKGROUND

The first traces of human settlement on the Pakri Peninsula date from the Iron Age. In the 13th century it was inhabited by the “Coastal Swedes” with the centre of their settlement being located at Laiduscae (current Laoküla) near the ancient harbour (Odres, 1996). At the site of the present Paldiski Southern Harbour, there was a landing place which was called Kocle (Koka). The later Swedish harbour was located to the north from it. In the war with Sweden, it was important for Russia to have a military stronghold on the northern coast of the Baltic Sea. Peter I, Czar of Russia, ordered to search the whole coastline from St. Petersburg up to Stettin for finding a suitable harbour site. Best proved the site between the Small-Pakri (in Estonian Väike-Pakri, in Swedish

Fig. 2. View to the Paldiski Northern Harbour. Photo by A. Käärd
2 pav. Paldiski šiaurinio uosto vaizdas (A. Käärd nuotrauka)

Lilla Rågö) Island and the Pakri Peninsula in Rogerwick Bay (now Pakri Bay), which was checked personally by Peter I in 1715. In 1718, at the presence of Czarina, higher clergy and fleet officers he laid the cornerstone for the Rogerwick Naval Port. He also made its first sketches. The project drawn by the Engineer Colonel L. J. P. Luberace foresaw the construction of a dam between the Island of Small-Pakri and the Pakri Peninsula with star strongholds at its both ends. A naval and trading port was supposed to be built behind the dam. Convicts were used as the main labour force. The report of 1724 wrote that an average of 2 284 people and 380 horses were engaged in the construction work annually (Tarassov, 1914). After the death of Peter I in 1725 the work practically stopped and was restarted only in 1746 under the reign of Czarina Jelizaveta. The Rogerwick Naval Port was renamed as Baltiiski Port (Baltiski). In the 1930s it was changed into Paldiski. The Pakri Islands were inhabited by Swedes in 1345, the inhabitants were mainly engaged in agriculture and fishing.

In 1870 Paldiski became the terminus of the St. Petersburg railway. The goods meant to be transported to Petersburg were unloaded in the ice-free Paldiski Harbour and transported to Petersburg by railway. Large storehouses, extending from the railway station to the harbour, were built. In 1922 the harbour was reconstructed and a railway branch was constructed on the quay along the dam. Paldiski got the rights of a free harbour.

With a secret appendix to the Molotov-Ribbentrop Pact and after the so-called bases agreement forced onto Estonia by Russia, Paldiski became a military base of the Soviet Union in 1939. During the course of two weeks the entire population of Paldiski was evacuated. Their land and buildings were taken over by the Soviet Army. The last Russian soldiers left the town only in 1995.

GEOLOGICAL SETTING

The study area is situated on the East-European Craton recognized as a tectonically stable region. Prior to the Osmussaar earthquake, which took place north of Paldiski near the Island of Osmussaar on 25 October 1976, the whole of Estonia was considered a seismically inactive region. As a result of numerous studies, the former concepts about the seismicity of Estonia have been entirely changed. According to Sildvee and Vaher (1995), twenty four macroseismic and numerous small ($M < 3.5$) events occurred in Estonia from 1602 till 1991, their intensity being 3–7 and magnitude 1.5–4. The Osmussaar earthquake (magnitude 4.7, intensity 6–7) was felt over an area of 191 000 sq km (Kondorskaya et al., 1988). This means that we should not eliminate the possibility that rather strong earthquakes can occur in the area of the Paldiski Northern Harbour.

In the region under consideration, the Earth's crust is about 50 km thick and consists mainly of Palaeoproterozoic igneous and metamorphic rocks. The rather flat surface of the crystalline basement lies at a depth of 182–205 m (in Põllkü-la borehole F-317 186 m) and its uppermost part (mainly gneisses) is strongly weathered (Einasto, Mens, 1996). Thickness of the sedimentary cover is mainly ranging from 100–150 m. It is represented with Vendian (Ediacara), Cambrian and Ordovician rocks, belonging to different regional stages (Raukas, Teedumäe, 1997). Basement is overlain by Upper Vendian clastic rocks, mainly sandstones with thin interlayers of clays and siltstones about 35–50 m in thickness (Kotlin Stage).

The covering Lower Cambrian rocks (Lontova and Dominopol stages) are represented by clays, sandstones and siltstones with a total thickness of about 100 m. The topmost part of the Cambrian (Tiskre Formation) consists of light fine-grained silt- and sandstones, some 4 m thick, with green claystone interlayers, which crop out only in the cliff of Pakri north of the harbour (Fig. 3).

The Cambrian terrigenous rocks are overlain by Ordovician medium- and fine-grained sandstones of the Pakerort Stage, about 4 m thick, and dark-brown kerogen-bearing graptolite argillite (Türisalu Formation), about 4.5 m thick. The overlying Varangu, Hunneberg and Billingen stages are represented by clays (0.15–0.45 m) and glauconitic silt- and sandstones (3.5–4.0 m). The topmost part of the section is composed of carbonate rocks of Volkhov, Kunda, Aseri, Lasnamäe and Uhaku stages (Fig. 3).

The bedrocks show monoclinal bedding regionally dipping about 7'. Present shape and features of bedrock topography result from the erosion caused by the continental ice, which retreated from the Pakri Peninsula some 11 500 ^{14}C years ago (Raukas, 2009). Later the territory was flooded with the waters of Baltic Ice Lake, the Yoldia Sea, Ancylus Lake, the Litorina Sea and the Limnea Sea. The peninsula emerged from the sea during the regression of Ancylus Lake when in the central part of the peninsula a rocky island formed (Miidel, 1996). Since then the Pakri Peninsula has been subjected to wave action. The eroded deposits are transported by longshore currents southward and the process is still in progress. The land uplift at the present is some 2.5 mm / year and the sea is still retreating.

Geomorphologically, the Paldiski Northern Harbour is situated in the area of the Harju Plateau and Fore-Klint Lowland bordered by an escarpment – North-Estonian Klint, which starts in the vicinity of the harbour and reaches a height of 25 metres a. s. l. at the tip of the peninsula. The escarpment forms a terraced coast composed of relatively uniform hard carbonate rocks.

The Uuga Cliff immediately north of the harbour exposes under relatively thin Quaternary cover limestones of the Uhaku, Lasnamägi and Aseri stages, ca 1-m-thick kukersite-bearing limy sandstones of the Pakri Formation (Kunda Stage), glauconite limestones (0.9–1.6 m) of the Volkhov and Billingen stages and 3–4-m-thick glauconite sandstones of the Hunneberg Stage. The total thickness of carbonate rocks is about 8–9 m. They are dissected by joints, primarily of west, north-east and north-west orientation.

Geological setting of the Pakri Bay is complicated since it is located above a deep ancient buried valley (Tavast, Raukas, 1982). In contrary, the Quaternary cover in the Pakri Peninsula is thin, rarely reaches 5 metres, but usually it is even less than 1 m. In large areas the Quaternary cover is entirely lacking and the Ordovician limestones are overlaid only by 10–20-cm-thick humus rich soils. The Quaternary deposits are prevailed by sands, gravel and shingles of the Litorina and Limnea seas. The till of the last glaciation occurs only in places. Its thickness does not exceed 2–3 m.

PAST POLLUTION

In 1939–1941 and 1944–1995 the Pakri Peninsula and Pakri Islands (Small Pakri and Big Pakri) belonged to the administrative field of the former Soviet Union and Russian Army. In 1941–1944 the area was occupied by German troops and was likewise closed to local people. In 1941 the retreating Soviet troops destroyed the harbour and most of the Paldiski Town. In 1944 the foundation was laid to extensive construction work. The harbours were adopted for reception of submarines. A training centre for Soviet nuclear submarine crews was constructed on the peninsula.

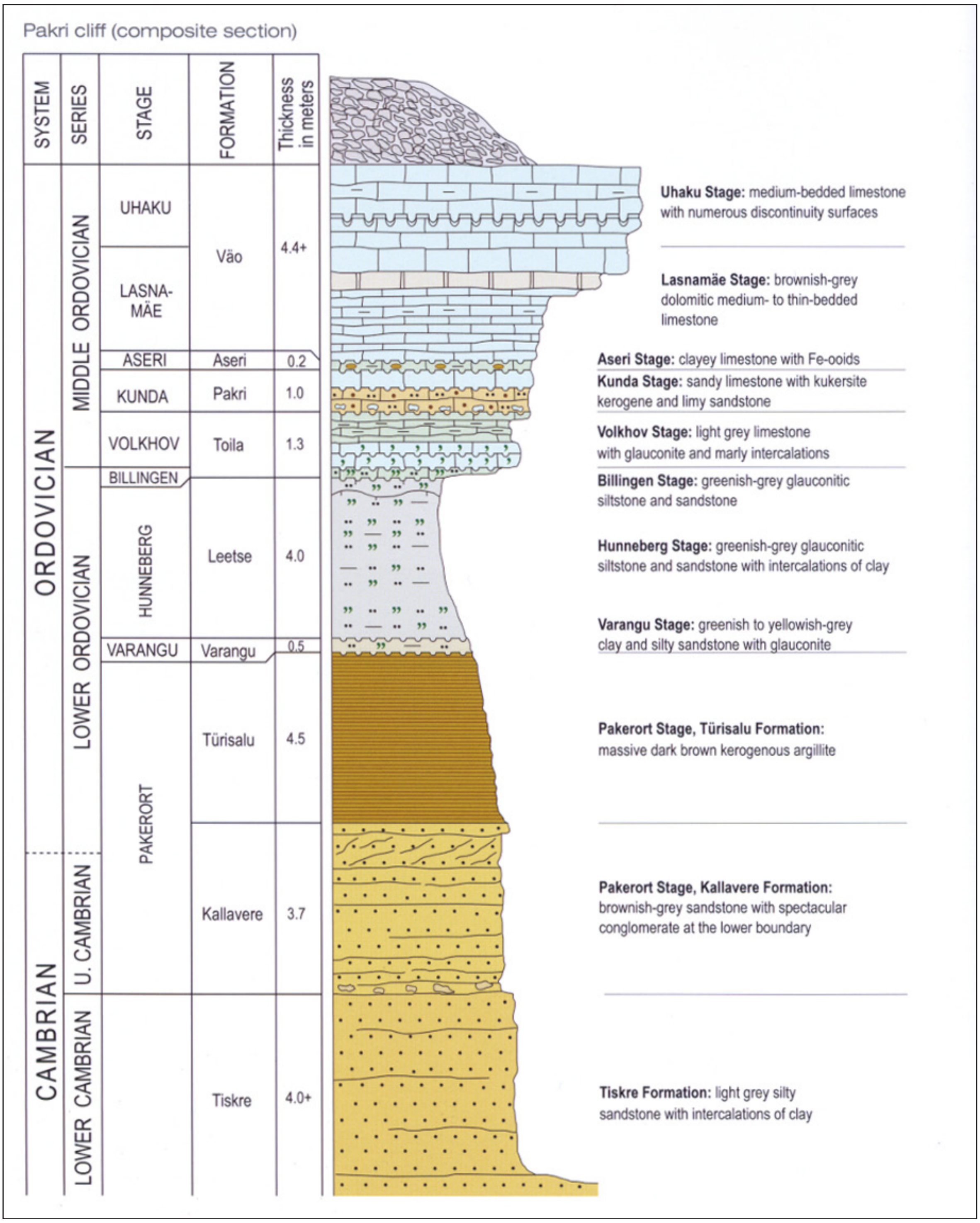

Fig. 3. Geological section of the Pakri Cape (Einasto, Mens, 1996; Tuuling et al., 2011)
3 pav. Pakri iškyšulio geologinis pjūvis (Einasto, Mens, 1996; Tuuling et al., 2011)

It included two exact on-shore models of nuclear submarines completed with nuclear reactors (70 and 90 MW).

Beside the submariners training facility the peninsula located several mine and torpedo warehouses, naval unit No. 10717, rocket unit No. 031115 with missile bases Leetse I and Leetse II, signal batallion and frontier-guard unit No. 2198, which all left behind high residual pollution. The Islands of Pakri were used as a practice bombing range not only of the Soviet Union, but also other Commonwealth Countries. Not only land turned upside-down, but also mines, shells and unexploded bombs were left in great quantities on the islands. By 1996, 2 949 bombs had been blown up (Raukas, 1999).

After the retreat of the Russian troops on 26 September 1995, the sea floor in the harbours was contaminated with metal constructions, iron bars, barrels, and abundant rubbish. Even to date, the water quality in the harbours is endangered by the oil originating from the former central boiler house (Fig. 4) and fuel storage of the Northern Harbour which has leaked into the limestone cracks. Calculations by Maves Ltd. have shown that every day an average of 160 kg, on rainy days even 400 kg of fuel oil reached the sea because of inefficiently operating oil traps and reckless treatment of black oil.

Large environmental hazardous objects were two missile bases. Leetse I missile base (area 18.1 ha) was located on an alvar ca 200 m from Lahepera Bay and used dangerous liquid fuel. Leetse II missile base (area 35.1 ha) used both solid and liquid fuel. Concentrated acid resulting from the use of liquid fuel was kept in two storehouses in an area of 2 ha, where waste water was dumped into the ground during 20 years.

The untreated wastewater originating from the coast guards unit at the tip of the Pakri Peninsula, coast guards centre on the northern boundary of the town of Paldiski was released directly into the sea. From more hazardous objects, e. g. the galvanic department, the wastewater was guided through a deep-water outlet farther into the sea, but untreated sewage from the missile bases and concrete plant was dumped straight into the soil. In the same way the waste problem was solved in the living and summer houses belonging to the military units.

Waste water treatment facilities of Paldiski were constructed at the end of the 1950s and during the course of 20 years they were hopelessly worn out. In the middle of 1980s, the Soviet army undertook construction of new facilities; however, less than a half of the construction was completed. As a result, not only oil pollution, but also elevated concentrations of heavy metals, including lead and mercury, have been recorded in bottom deposits of the Gulf of Pakri (Kink, 1999).

Fig. 4. Heavy pollution in the Paldiski central boiler house in 1995. Photo by Hugo Tang
4 pav. Paldiski centrinio boilerio gedimo sukeltas teršimas, 1995 (Hugo Tang nuotrauka)

GEOTECHNICAL CONDITIONS

For the reconstructing of the Northern Harbour and building of the Peetri Quay with the participation of the first author 27 boreholes were drilled and physical-mechanical properties of soils for the foundation of hydrotechnical constructions were investigated (Table). The influence of waves on bottom deposits can be assessed by the energy of wave-induced near-bottom fluxes, which is proportional to the near-bottom velocity squared. Thus, when designing the harbour constructions it must be considered that it may cause changes in wave parameters and this, in its turn, will affect the transport of bottom sediments at the entrance of the harbour. The ice-push has great danger in the harbour area. In Estonian coasts almost every spring, ridges of pressure ice up to 10 m high are generated by persistent unidirectional winds and are pushed forward against the shore and harbour constructions with an enormous force. It is very complicated to predict the ice-push processes.

A dense set of boreholes (Fig. 5) allowed compilation of detailed cross sections (Figs. 6 and 7). The grain-size composition, compressibility, consolidation, groundwater aggression and corrosion of samples were analysed.

Engineering geological conditions are complicated due to the changeable composition and different thickness of the Quaternary deposits. The total thickness of the latter ranges in the studied sections from 10 to 25 m (Figs. 6 and 7). The

Table. **Geotechnical parameters of the investigated bottom deposits**

Lentelė. **Tirtų dugno nuosėdų geotechniniai rodikliai**

Sediment type	Parameters							
	Natural moisture content,%	Liquid limit, %	Plastic limit, %	The number of plasticity	Liquidity index	Specific density, g/cm³	Coefficient of porosity	Saturation coefficient
	W	W_L	W_P	I_P	I_L	ρ_S	e	S_r
Loose silty fine sand	31.1…42.9 35.7 (12)	–	–	–	–	2.56…2.65 2.59 (6)	0.88…1.14 0.996 (6)	0.87…1.00 0.96 (6)
Floating sandy loam	34.0…39.0 (1)	31.8 (1)	26.5 (1)	5.3 (1)	1.89 (1)	–	–	–
Floating heavy loam and light clay	28.8…62.6 44.43 (6)	21.7…46.7 38.0 (3)	14.5…28.4 23.3 (3)	7.2…18.5 14.7 (3)	0.8…2.02 1.56 (3)	2.71…2.72 2.715 (2)	1.19…1.58 1.39 (2)	0.98…1.05 1.02 (2)
Fine-grained loose sand	19.5…27.6 22.65 (4)	–	–	–	–	2.52 (1)	0.74 (1)	0.87 (1)
Sandy loamy till rich in clasts	7.0…9.2 8.1 (2)	14.7 (1)	10.7 (1)	4.0 (1)	–0.65 (1)	2.68 2.68 (2)	0.16 0.16 (2)	1.0…1.07 1.03 (2)
Sandy loamy till with less clasts	7.9…26.0 13.8 (23)	12.8…14.8 14.7 (10)	10.7…12.8 11.6 (11)	0.5…4.1 3.1 (10)	–1.55…3.7 0.53 (10)	2.67…2.68 2.67 (11)	0.21….0.29 0.27 (9)	0..68…1.27 1.05 (9)
Glauconite sandstone	10.5…19.6 15.6 (46)	17.8…23.9 20.8 (14)	13.5…22.0 17.3 (13)	1.1…6.3 3.5 (13)	–5.23…0.79 –1.02 (13)	2.69…2.76 2.70 (24)	0.35…0.61 0.47 (26)	0.69…1.02 0.84 (23)
Soft graptolite argillite (dictyonema “shale”)	20.1…20.8 20.5 (2)	31.5…32.7 32.0 (3)	22.6…23.8 23.3 (3)	7.7…9.2 8.7 (3)	–1.05…-0.33 –0.7 (3)	2.39…2.64 2.42 (32)	0.28…0.54 0.38 (32)	0.48….1.09 0.74 (32)
Soft silty sandstone	12.9…21.9 18.02 (16)	22.1…27.6 24.2 (4)	17.9…24.0 20.0 (4)	3.4…6.0 4.3 (4)	–2.5….0.53 –0.7 (4)	2.61…2.68 2.64 (44)	0.25…0.61 0.45 (44)	0.62…1.25 0.96 (44)

In the numerator – the experimental values, in the denominator – the regulative data, in brackets – the number of analyses.

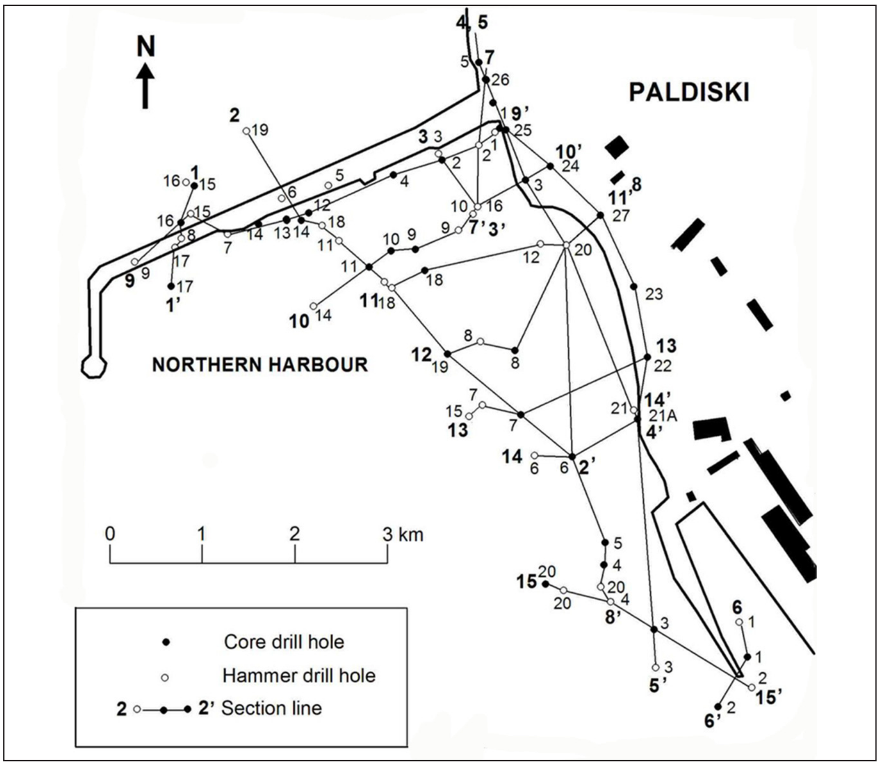

Fig. 5. Location of boreholes and geological profiles
5 pav. Gręžinių ir geologinių profilių geografinė padėtis

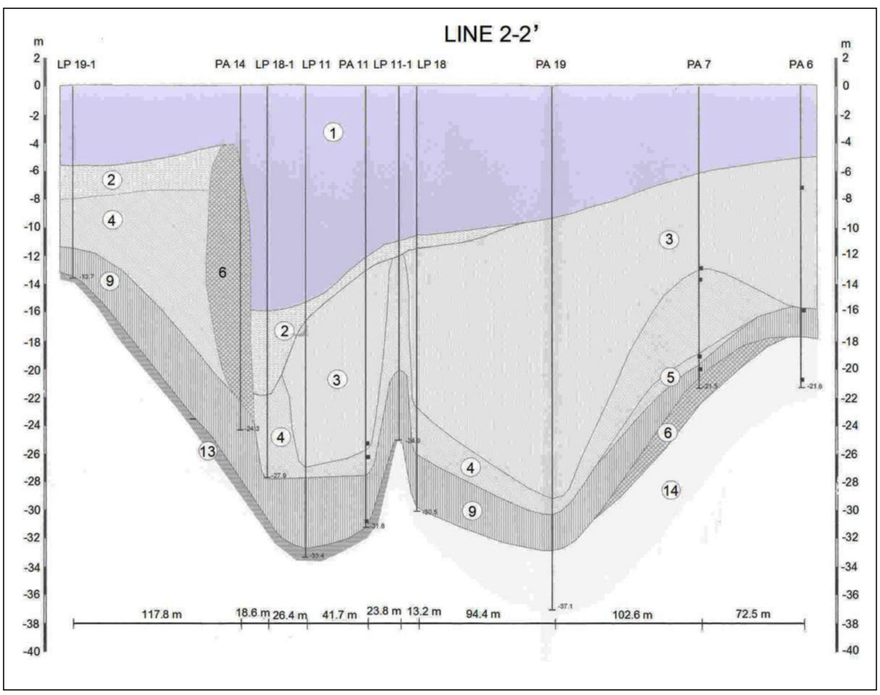

Fig. 6. Geological section line 2-2' from NW to SE. PA – Core drill hole, LP – Hammer drill hole
6 pav. Geologinis profilis 2-2', orientuotas ŠV–PR. PA – gręžinys su kerno pakėlimu, LP – kalamasis gręžinys

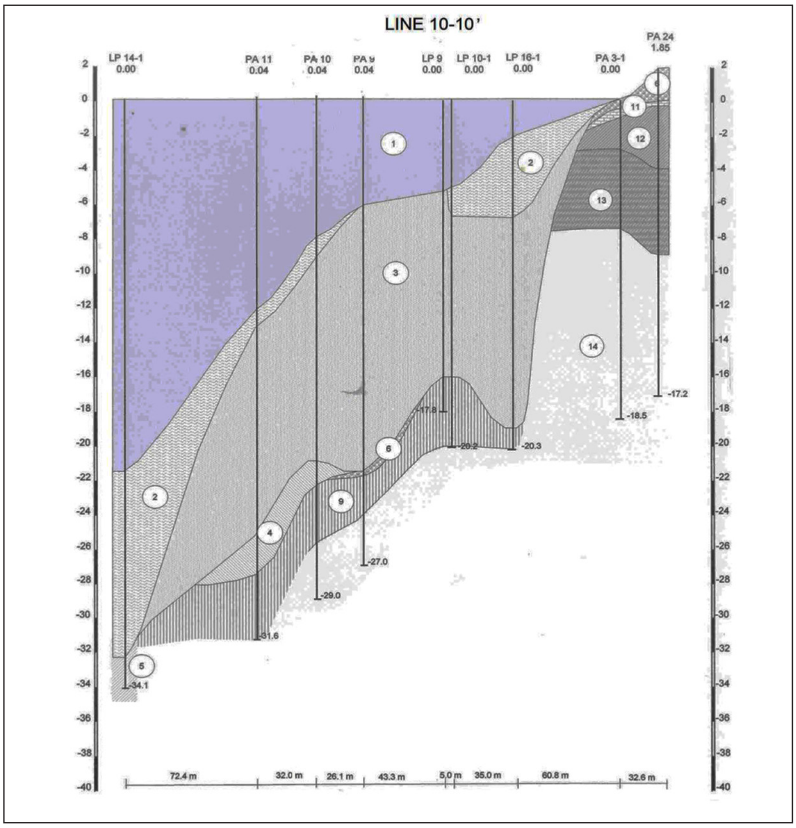

Fig. 7. Geological section line 10-10' from W to E. Legend for Figs. 6 and 7 (for location of sections and boreholes see Fig. 5): *1* – water; *2* – clayey mud; *3* – loose silty fine sand; *4* – floating sandy loam; *5* – floating heavy loam and light clay; *6* – blocks and lumps (technogenic material); *7* – loose fine sand; *8* – sandy loamy till rich in clasts; *9* – sandy loamy till with less clasts; *10* – limestone; *11* – glauconite sandstone; *12* – graptolite argillite (dictyonema shale); *13* – soft sandstone; *14* – hard sandstone

7 pav. Geologinis pjūvis 10-10', orientuotas V–R. Legenda 6 pav. ir 7 pav. (profilių geografinę padėtį žr. 5 pav.): *1* – vanduo, *2* – molingas dumblas, *3* – nekonsoliduotas aleuritinis smulkiagrūdis smėlis, *4* – nekonsoliduotas smėlingas priemolis, *5* – nekonsoliduotas sunkus priemolis ir lengvas molis, *6* – blokai ir nuolaužos (technogeninė medžiaga), *7* – nekonsoliduotas smulkus smėlis, *8* – smėlingas moreninis priemolis su daugybe nuotrupų, *9* – smėlingas moreninis priemolis su retomis nuotrupomis, *10* – klintis, *11* – glaukonitinis smiltainis, *12* – graptolitinis argilitas (diktioneminis skalūnas), *13* – minkštas smiltainis, *14* – kietas smiltainis

natural geological situation is complicated by an abundance of technogenic material (building waste), the distribution of which does not reveal any regularity. Part of the blocks and lumps in the sea bottom originates probably already from the times of Peter I.

The blue clays of the Lontova Stage are mainly of semi-hard to hard consistency, less frequently tough-plastic, and they are very sensitive to leaching, worsening of foundation conditions.

Soft graptolite argillites and sandstones have a very low strength, even worse than most of the Quaternary deposits. The Quaternary cover consists of glacial, glaciolacustrine and marine deposits. The thickness of Quaternary deposits is greater in the central part of the bay and is reducing towards the shoreline both east and west of the bay. The bedrock is covered by purplish grey loamy or sandy loamy till, which contains fragments of crystalline rocks and nests of sandstone and blue clay. The thickness of till is variable ranging from 2 to 7 m. Consistency of till is soft to hard plastic.

In the greater part of the study area a complex of soft clayey soils (sandy loam, loam and clay) of glaciolacustrine origin overlies the till surface. Marine deposits are represented mainly by mud and organic rich silt. During repeated dredging the upper part of mud and silt may have been removed.

The results show that the greater part of the deposits remaining under the harbour constructions has poor engineering geological properties. Especially poor are the geotechnical properties of sea mud, both varieties (with loam and sandy loam) are liquid by consistency and tixotrophic. The natural moisture of mud with high organic matter content is 33–43% and plasticity index 7–12.

CONCLUSIONS

The Paldiski Northern Harbour has good navigation facilities but the widening of the harbour is complicated due to its small area and bad engineering-geological foundation conditions. Under the planned wharf embankment a complex of weak clayey soils occurs on the sea floor, which should be covered with filling material in order to guarantee the stability of the quay, wharf and piers. The ice-push has great danger, to prognosticate it is very difficult.

During the Soviet occupation the Paldiski Northern Harbour was a closed naval port. After the retreat of Russian troops from Estonia in 1995 the sea floor and land area of the harbour were strongly polluted. For the time being the residual pollution has been more or less liquidated, but during the implementation of the project environmental monitoring is highly needed.

ACKNOWLEDGEMENTS

The authors thank Dr. Saulius Gadeikis and Dr. Jonas Satkūnas for constructive reviews.

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PALDISKI ŠIAURINIO UOSTO (ŠIAURĖS VAKARŲ ESTIJA) GEOLOGINĖS SĄLYGOS, EKOLOGINĖ SITUACIJA IR PLĖTROS GALIMYBĖS

Santrauka

Straipsnyje pasakojama Paldiski šiaurinio uosto istorija, aptariamos dugno nuosėdų geotechninės savybės, substrato uolienų geologija ir ekologinė situacija. Paldiski uostai retai užšala, yra gilūs ir gerai apsaugoti nuo iš jūros pučiančių vėjų. Per 300–400 metrų nuo kranto Paldiski šiaurinio uosto dugno gylis siekia net 20 metrų. 1718 m. šį uostą įsteigė Rusijos caras Petras Pirmasis. Sovietinės okupacijos metais uostas tapo uždaras. Rusijos kariuomenę išvedus iš Estijos 1995 m., uosto teritorija buvo palikta labai užteršta. Didelių pastangų dėka teritorijos užterštumas buvo likviduotas. Pastaruoju metu planuojamos naujos statybos siekiant išplėsti uostą. Šį uždavinį labai apsunkina sudėtingos inžinerinės-geologinės sąlygos, kurias lemia labai kaitus dugninių nuosėdų storis ir litologinės sudėties įvairovė.

Raktažodžiai: dugninės nuosėdos, inžineriniai-geologiniai rodikliai, palaidotas slėnis, praeities tarša