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The engineering geological and geotechnical conditions of Gediminas Hill (Vilnius, Lithuania): an update

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We provide an update of engineering geological and geotechnical conditions at Gediminas Hill in Vilnius (Lithuania) from 1955 till 2020, which allows evaluation of the stability of its slopes. Active geological processes are still observed on Gediminas Hill. The latest landslides appeared on March 22, 2004 and on March 8, 2008 on the eastern slope above the hiking trail, as well on February 11, 2016 and February 13, 2016 on the northern part of the slope. The latest landslide (involving ~40 m^3 of soil) took place on March 7, 2017 between the eastern and southern slopes. Eight hydrogeological units were distinguished in 2017. During 2019–2020 many engineering geological and geotechnical investigations have allowed determination of the possibilities and methods of slope stabilization.

Key words. Gediminas Hill, geology, geological conditions, geotechnical investigations, landslide, slope stability.

INTRODUCTION

Throughout history, civil engineers have made many admirable and enduring studies that highlight the merits and of their profession (Buhler, 2016). Each region has its own historical monuments, which have been investigated continuously over decades. For example, many engineering geological and geotechnical investigations have focussed on the tower of Pisa in Italy (Sarti et al., 2012; Squeglia et al., 2018), in Spain – there is the Sagrada de Familia church in Barcelona (Katzenbach et al., 2013; Ladesma and Alnoso, 2017), in Egypt – the Mustafa Kamil Necropolis underground tombs (Hemeda et al., 2015), in Saudi Arabia – the Madâin Sâlih sandstones (Medini and Arbi, 2018), in India – the natural stone sculptures (Sharma, 2019), in Nepal – the Kathmandu Valley (Kumar et al., 2019), and so on.

An important historical monument in Lithuania, included in the UNESCO World Heritage List since 1994 (Mikulėnas et al., 2016), is Gediminas Hill with the remains of the castle (Skuodis and Ng, 2018) and nearby Cathedral of Vilnius (Mackevičius, 2013; Gadeikis et al., 2016). Landslides on the slopes of Gediminas Hill have occurred from olden times up to the present (Kitkauskas, 2001; Morkūnaitė and Česnulevičius, 2005; Satkūnas et al., 2008; Vaičiūnas, 2010; Skuodis et al., 2017; Šadzevičius et al., 2018; Jonaitis et al., 2019). While generally there is a low risk of landslides in Lithuania, according to landslide and risk mapping (Jelinek et al., 2007), Gediminas Hill has been extensively investigated (Katalynas and Vaitkevičius, 2001; Mačiulis, 2005; Vaitkevičius and Kiškienė, 2010; Antanavičienė, 2012; Baubinienė et al., 2015; Markelionis et al., 2017).

The most detailed engineering geological and geotechnical investigations on Gediminas Hill were conducted in 1955–1959 and 1968–1973, with additional investigations in 1980, 1995–1997, and 2017 (JSC Geobaltic, 2020). All these investigations are important, but not all the results can be used in modern engineering geological and geotechnical evaluation. Of the investigations organized in 1959, 44% of the results are doubtful (or not reliable) and from 1973 investigations only 10% are uncertain (or not reliable). Doubtful results are due to several reasons: different normative documents relating to investigations today and in earlier times; average Vilnius city mechanical properties being used if the true values were not determined during earlier investigations, coordinates system discrepancies, and so on. This study updates information on engineering geological and geotechnical investigations realized during

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2019–2020 (JSC Geobaltic, 2020). During these investigations, boreholes (vertical and with inclination of 35–40°) were drilled on the top of Gediminas Hill to collect undisturbed soil samples (the term "soil" here being used in an engineering sense, to include unconsolidated geological deposits). Borehole lengths varied from 31.8 to 57.0 m. The information provided allows updating of existing data on soil layers, their thickness, depth and physical and mechanical properties. A slope stability analysis is made based on that data.

ARCHIVAL RESEARCH – SHORT REVIEW

In 1955, the Cities and Villagies Construction Design Institute carried out geological investigations of Gediminas Hill, on top of which 3 boreholes up to 45 m depth, and a few boreholes on the slopes, were drilled. Unfortunately, the report of these investigations is missing and information about them is found only in the 1973 Engineeering Investigations Institute report. Up to 2019 these 3 boreholes provided the main geological information about the Gediminas Hill lithology. The Gediminas Hill investigations in 1959 focused on investigations of the slopes. These were divided into 6 levels at different altitudes across the whole hill. 87 shallow boreholes of 4–5 m depth were drilled on the slopes, on the basis of which geological cross-sections were compiled. The strata encountered in these boreholes were described lithologically, without determination of mechanical properties, or information about any laboratory investigations.

In 1968–1973 the Engineering Investigations Institute continued the geological studies (1973). These investigations went further than those of 1959, with 79 boreholes drilled up to 10 m depth, and samples for laboratory testing being collected to determine physical properties. Six undisturbed soil samples for investigations of mechanical properties were also prepared. On the path to Gediminas Hill cone penetration tests were made in 2 places. In total, 3 geological cross-sections in different orientations were compiled, including use of information from the 3 deep boreholes drilled in 1955. In these cross-sections engineering geological layers with mechanical properties (cohesion, angle of internal friction, Young's modulus) were delineated. However, mechanical properties described in the 1973 investigations report were determined with indirect investigation methods applied to other Vilnius city studies with similar engineering geology properties of soils.

To check the boundary altitudes determined in all the archival boreholes, the adequacy of their X, Y, and Z coordinates for contemporary coordinates systems was evaluated, by comparing the LKS-94 coordinate projections and their absolute heights at the present surface with the absolute heights given for the boreholes in the investigation reports. One can have high confidence in a borehole if the absolute height difference is <1 m, but where there is >1 m absolute height difference, the borehole was regarded as unreliable and not used in these investigations. Based on the this criterion, 44% of boreholes in the 1959 investigations were unreliable, though only 10% from the 1973 report. Given the amount of unreliable results for 1959, it was decided not to use information from them to constrain the depths of lithological boundaries. And, information from the 1973 investigations were used where the description of soil layers was scant in the 2019–2020 investigations.

Later, in 1980, 1995–1997 and 2017, other engineering geological and geotechnical investigations into individual aspects of the Gediminas Hill design were conducted, though these added little new geological information. The archival data up to 2019 comprises 1089 boreholes of various depth, though descriptions of 470 of them are missing. Information from at least 628 boreholes is reliable, but only 200–300 boreholes are described sufficiently for the information to be used by geologists and/or construction designers. The deepest borehole, drilled in 1955 on the Gediminas Hill top, is 45 m deep. Most of the rest each 12–15 m in depth, with shallow boreholes reaching 2 m. Up to 2018, the Gediminas Hill investigations are listed in 167 documents, while the archival material bibliography comprises 119 documents (https://atviras.vilnius.lt/gedimino-kalnas).

ENVIRONMENTAL CONDITIONS

Gediminas Hill is located in the central part of Vilnius in the area of the National Museum of Lithuania. Absolute heights in engineering geological and geotechnical documentation ranges from 92.7 to 141.0 m (Fig. 1). Slope inclination is mainly 28–33°, but in a few places reaches 43° and rarely 54° (Skuodis and Ng, 2018). The Gediminas Hill investigation area is of one genetic type of relief, with technogenic soil prevailing throughout, the depth of which varies from 0.7 to 7.4 m. Parts of the slopes (the main southeastern slope, and parts of the southern and western slopes) are stabilized with temporary antislide solutions (ballast layers, anchors, steel grids, drainage). The north slope is stabilized with gabions and drainage.

The yearly average temperature is 6.1–6.7°C (lowest recorded temperature –37.2°C, highest recorded temperature 35.4°C), annual precipitation is 610–690 mm (average 658 mm/year), the period with snow coverage is 90–105 days (maximum recorded thickness of snow 52 cm) and duration of sunshine is 1690–1770 hours/year (Skuodis and Ng, 2018). According to prognosis, by 2100 precipitation will increase by 50 mm/year in the Vilnius area. Precipitation intensity will also increase and maximum precipitation quantity may increase by 15%. The largest precipitation increment will be during winter (up to 24%). Due to rising average temperatures, increasing amounts of winter precipitation will be drizzle and sleet. In the Vilnius region, according to RSN 156-94 (1995), the maximum soil freezing depth each ten year period may reach 1.34 and 1.70 m each 50-year period. The Gediminas Hill seasonal soil freezing depth for sandy soil may reach 1.2 m, and for clay 1.5 m.

GEOLOGICAL STRUCTURE AND HYDROGEOLOGICAL CONDITIONS

Geomorphologically, Gediminas Hill is located on the northwestern edge of the Medininkai Highland that is a part of the Ašmena Upland formed during the last Middle Pleistocene Glaciation (Guobytė, 2010). Geologically, Gediminas Hill is made of deposits of several Middle Pleistocene glaciations. According to stratigraphic scheme of the Quaternary currently approved for use by the Lithuanian Geological Survey, the deposits belong to the Dainava Formation (representing the Elsterian 2 Glacial of European stratigraphy), and the Žemaitija (= Saalian Glacial) and Medininkai (= Warthian Glacial) subformations (Guobytė and Satkūnas, 2011; Fig. 2). The Middle Pleistocene deposits are affected by deluvial processes and human activities on the hill slopes (Fig. 3). According to soil permeability criteria, up to 8 different hydrogeological layers may be distinguished in the Gediminas Hill structure (Fig. 4). The physical

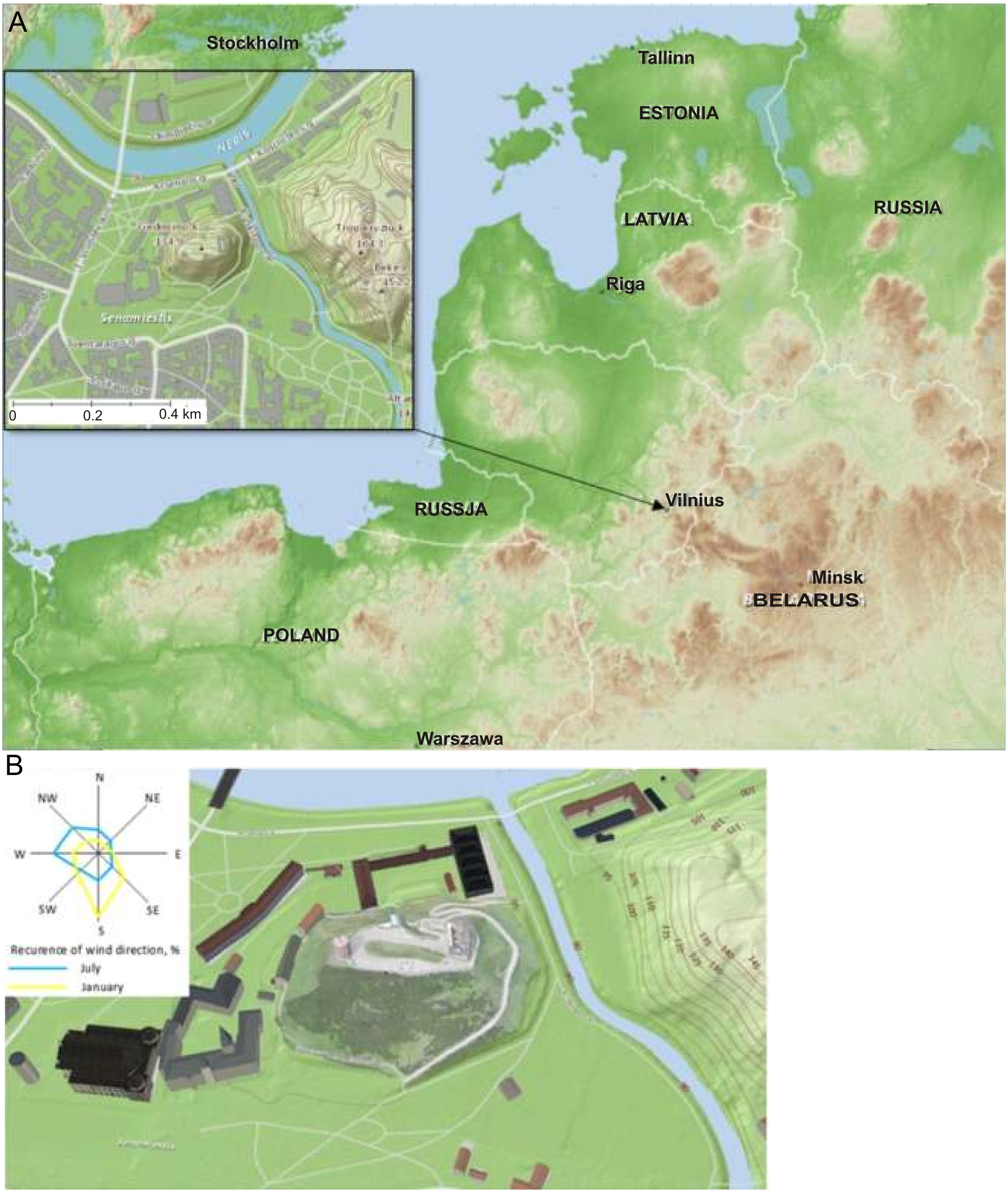

Fig. 1. Relief map: A – general map of investigation site location; B – Gediminas Hill 3D relief and wind directions

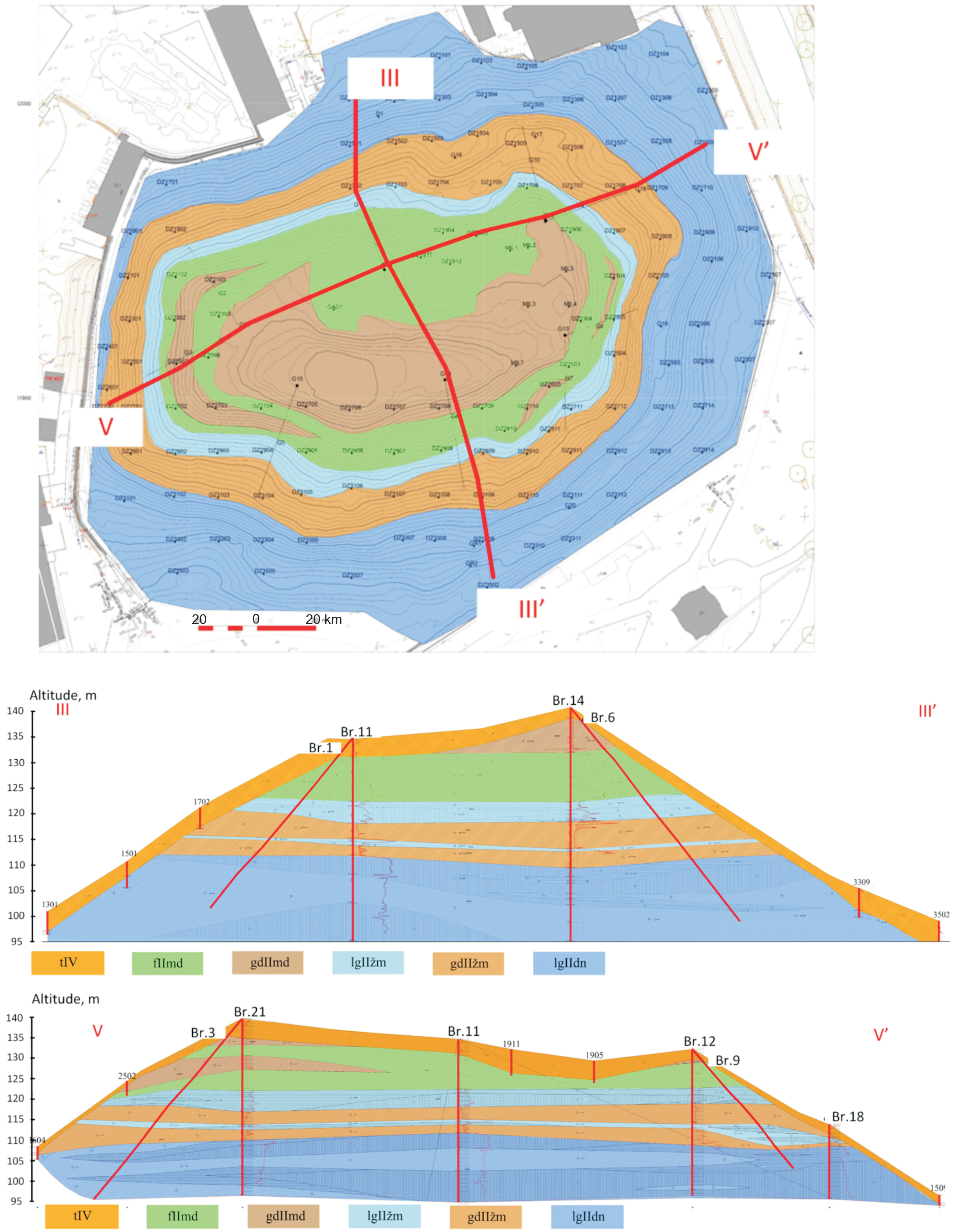

Fig. 2. Geological model of Gediminas Hill

tIV – Holocene technogenic soils; deposits of the Middle Pleistocene Medininkai (Warthian) Subformation: fIImd – glaciofluvial; gdIImd – glacial (deformational till); deposits of the Middle Pleistocene Žemaitija (Saalian) Subformation: lgIIžm – glaciolacustrine; gdIIžm – glacial (deformation till); lgIIdn – glaciolacustrine deposits of the Middle Pleistocene Dainava (Elsterian 2) Formation. Red lines show lines of geological cross-section, while red vertical and diagonal lines on the geological cross-sections represent boreholes

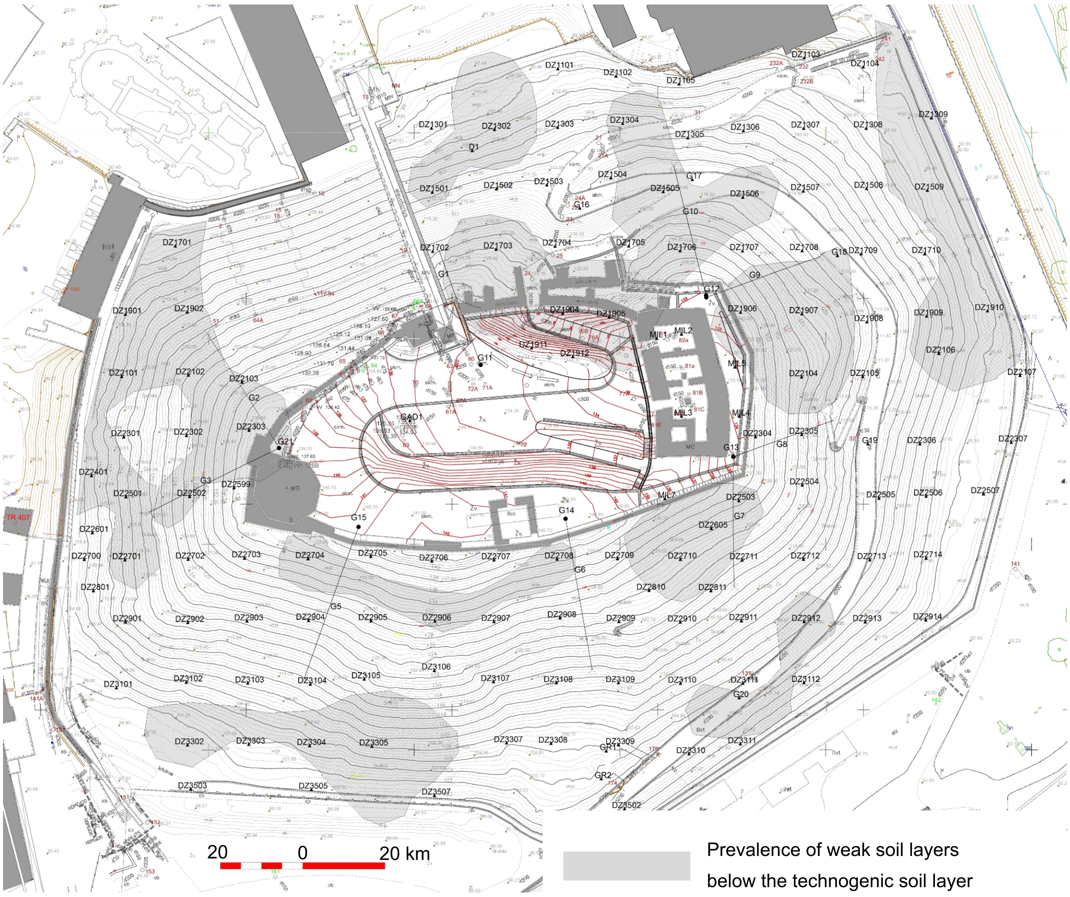

Fig. 3. Weak soil layers beneath the technogenic soil layer

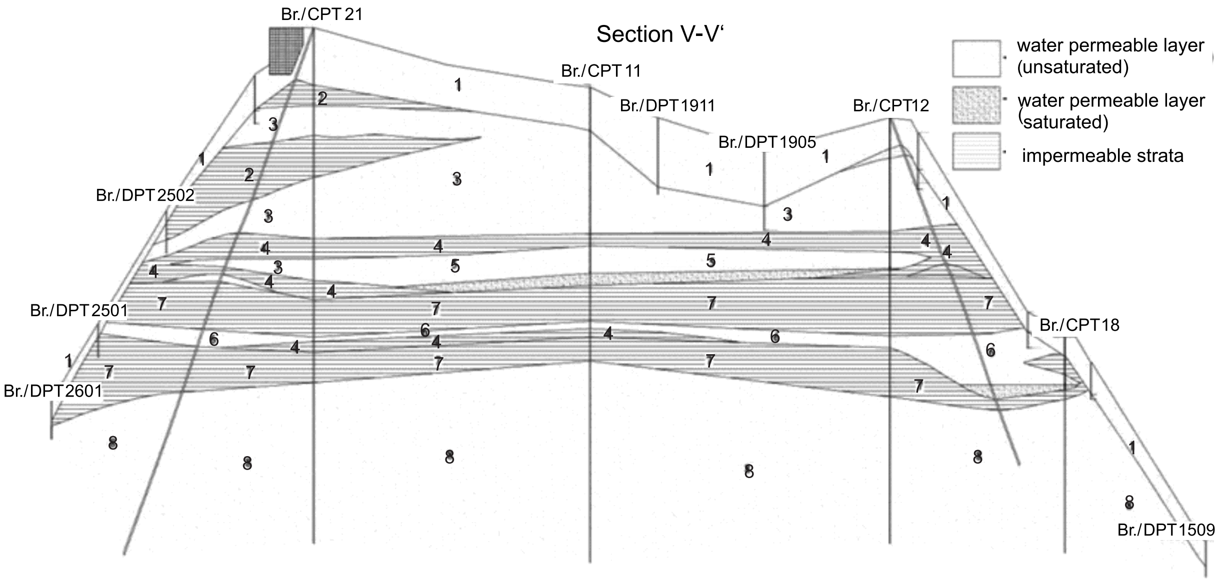

Fig. 4. Schematic hydrogeological cross-section V–V'

1 – tIV – permeable strata (k = 0.4 m/d), 2 – gdIImd – impermeable strata, 3 – fIImd – permeable strata (k = 9m/d), 4 – lgIIžm – relatively impermeable strata, 5 – lgIIžm permeable strata (k = 0.3 m/d,; 6 – lgIIžm permeable intermoraine deposits (k = 5.4 m/d), 7 – gdIIžm – impermeable strata, 8 – lgIIdn – permeable strata (k = 2.3 m/d)

Table 1

Summary of physical and mechanical properties

Stratigraphy Index	Soil layer identification	Soil type	q_t [MPa]	γ [kN/m^3]	ρ [Mg/m^3]	$ρ_s$ [Mg/m^3]	w [%]	w_P [%]	w_L [%]	k [m/d]	φ' [°]	c' [kPa]	c_u [kPa]
tIV-dIV	tIV	Sa, Si, Cl	3.6	17.76	1.81	2.67	9.7	13.4	16.9	1.94	35.3	13.5	-
gdIImd	31	Cl	2.1	21.49	2.19	2.69	12.1	11.0	20.3	-	-	-	71.0
	32		3.6	21.76	2.22	2.69	11.4	12.1	19.9	-	33.8	15.3	-
	33		13.0	22.30	2.27	2.69	11.0	12.1	21.7	-	32.4	48.8	-
	34		0.7	20.51	2.09	2.69	10.3	12.8	18.2	-	44.6	21.1	-
fIImd	41	Sa	6.9	17.46	1.78	2.66	3.7	-	-	8.94	31.6	24.0	-
	42		16.4	19.02	1.94	2.66	10.7	-	-	7.35	38.1	34.1	-
	43		34.8	19.85	2.02	2.67	14.4	-	-	5.91	36.7	36.7	-
	44		-	16.56	1.69	2.66	3.2	-	-	12.1	32.8	11.5	-
lgIIžm	51		26.2	20.12	2.05	2.68	14.9	14.4	18.0	0.11	35.8	30.2	-
	52	Cl-Si	22.1	21.16	2.16	2.68	14.3	14.6	19.9	-	35.1	46.2	-
	53	Cl	10.1	20.09	2.05	2.72	21.2	20.9	38.9	-	14.5	107.0	-
	54	Sa	42.6	20.15	2.05	2.67	15.3	-	-	4.9	39.2	40.9	-
gdIIžm	61	Cl	9.8	22.11	2.24	2.69	11.5	22.0	12.2	-	28.1	76.9	-
	62		3.0	21.78	2.22	2.69	10.9	21.0	10.8	-	-	-	115.0
	63		1.8	21.59	2.20	2.69	15.0	25.8	13.0	-	-	-	81.6
	64		0.6	21.39	2.18	2.70	14.8	26.4	12.2	-	-	-	28.8
lgIIdn	71	Sa	46.9	19.71	2.01	2.67	16.5	19.9	15.7	0.39	37.5	41.7	-
	72	Si	37.2	20.00	2.04	2.68	15.7	20.0	15.8	0.08	33.1	73.1	-
	73	Sa	-	17.19	1.75	2.66	3.3	-	-	1.56	30.4	29.0	-
	74	Sa	57.9	19.86	2.03	2.67	15.7	-	-	1.68	36.9	37.4	-
	1(1973)		-	17.40	1.82	-	-	-	-	-	37.0	0.13	-
	2(1973)		-	17.40	1.82	-	-	-	-	-	38.0	0.09	-
	3(1973)		-	18.40	1.89	-	-	-	-	-	27.0	0.22	-
	4(1973)		-	18.90	1.94	-	-	-	-	-	29.0	0.25	-
	5(1973)		-	20.90	21.40	-	-	-	-		40.0	0.01	-

1 – soil layer identification with (1973) means archival data taken from 1973 investigations; 2 – soil layer identification is the same as in Figures 5–8

Table 2

Summary of Young's modulus measurements

Stratigraphy index	Soil layer identification	Soil type	E [MPa]	E_{oed} [MPa] (at different stress level)							
				25	50	100	200	400	800	1600	3200
				[kPa]							
tIV-dIV	tIV	Sa, Si, Cl	3.6	0.8	1.7	2.6	5.2	10.7	21.5	-	-
gdIImd	31	Cl	21.4	-	-	-	-	-	-	-	-
	32		33.1	2.3	4.8	5.3	8.7	14.1	-	-	-
	33		93.2	3.8	3.1	5.9	9.8	17.3	29.2	-	-
	34		7.3	1.8	2.6	2.4	3.3	6.9	-	-	-
fIImd	41	Sa	30.8	-	-	-	-	-	-	-	-
	42		56.8	3.6	4.2	9.4	18.3	34.8	57.2	93.1	-
	43		96.9	-	3.7	9.2	18.1	30.6	58.6	89.7	-
	44		-	-	-	-	-	-	-	-	-
lgIIžm	51		79.2	2.6	3.9	8.5	14.7	25.7	44.8	67.1	-
	52	Cl-Si	110.7	1.6	3.3	6.8	12.4	20.9	36.8	55.6	-
	53	Cl	79.9	-	-	6.8	9.7	9.3	13.6	-	-
	54	Sa	112.0	0.7	3.6	7.7	15.7	29.8	53.7	84.2	-
gdIIžm	61	Cl	74.2	2.5	4.4	7.2	10.5	15.9	26.2	36.78	-
	62		29.0	-	-	-	-	-	-	-	-
	63		17.5	-	-	-	-	-	-	-	-
	64		6.2	-	-	-	-	-	-	-	-
lgIIdn	71	Sa	119.9	-	3.2	8.6	15.2	28.0	49.0	86.0	110.3
	72	Si	186.1	1.3	3.2	7.1	14.0	24.3	43.4	77.0	135.6
	73	Sa	-	-	-	-	-	-	-	-	-
	74	Sa	139.2	-	2.9	8.1	15.4	24.6	46.7	100.2	-

E – calculated according to CPTU (q_t) results given in Table 1 and mechanical properties of the different layers are characterized separately and are shown in Tables 1 and 2. The soil layers were distinguished using borehole, CPTU and laboratory data.

The Middle Pleistocene Dainava (Elsterian 2) Glaciation left the glaciolacustrine deposits at the foot of the hill. The thickness of these deposits (lgIIdn) reaches up to >15 m. A wide lithological variety is present inside this layer, with fine-grained sand and horizontal bedding predominating. The upper part of this unit is characterized by interlayers (thickness varies from 0.3 to 4.9 m) of fine-grained brown sand, locally silty or clayey, and by interlayers of sandy silt (thickness 0.2–0.6 m). The deposits of the lower part of the unit are represented by interlayers of grey sand (thickness up to 5 or more metres) alternating with silt interlayers (which can exceed 1.8 m). The silt is greenish-grey, coarse, sandy in some places, massive. Interlayers (thickness 0.2–0.3 m) of greenish-grey sandy gravel or a single well-sorted gravel layer of carbonate rocks up to 30 mm across were found in the middle part of the layer. A small admixture of finely dispersed organic matter and a relatively high concentration of black minerals are specific features of this layer.

The glaciolacustrine deposits of the Dainava (Elsterian 2) Formation (lgIIdn) comprise a succession of water-permeable strata. Due to wide lithological diversity, the permeability of the deposits varies from 0.08 to 15 m/d, averaging 2.9 m/d. Groundwater was found only in a single borehole DZ2914, at a depth of 5.05 m (90.05 m absolute height).

The glaciolacustrine deposits of the Dainava (Elsterian 2) Formation are overlain by the Žemaitija (Saalian) Subformation which is divided into advance (the lower part) and retreat (the upper part) deposits. The glacial advance deposits are between 2.0 and 2.2 m thick and are composed of dark grey-brown and brown till, which becomes dark grey, coarse, dense, and massive at the base. Intercalations of sand, clay and gravel are characteristic features of this till layer. The glacial advance and retreat deposits are separated by a layer of glaciolacustrine deposits (lgIIžm), 1.1–1.5 m thick, comprising dense, plastic, massive, dark reddish grey and grey-brown clay (thickness 0.5–0.9 m) in its upper part and fine silty, carbonate-feldspar-quartz, light brownish, grey or brown sand in its lower part. The glacial retreat deposits (thickness from 4.20 to 4.45 m) comprise till: brown in its upper part and gradually becoming grey and then dark grey in its lower part. The till is coarse, dense, massive, locally with light brown spots, and includes gravel.

Glaciolacustrine deposits (lgIIžm) of the Žemaitija (Saalian) Subformation accumulated in a meltwater basin and are 3.65–4.2 m thick. These deposits vary in their particle size distribution and composition. Their lowermost part (thickness 0.2 m) is composed of fine-grained, silty-clayey, dense and massive, carbonate-feldspar-quartz, brown and yellowish-brown sand. This sand is overlain by 0.2–0.4 m thick of dense, plastic, finely layered brown clay. Units of fine-grained and clayey-silty sand (thickness up to 1.1 m), fine-grained sand (thickness up to 1.1 m), and fine-grained silty sand (thickness up to 0.7 m) occur above this clay. Laminated brown sand (thickness from 0.9 to 1.7 m) occurs at the very top of this glaciolacustrine succession.

Two permeable layers are present within the Žemaitija (Saalian) Subformation. The lower of these is developed between two till layers (gdIIžm) of this subformation, while the upper aquifer is present within the glaciolacustrine deposits (lgIIžm). The permeability of the lower aquifer varies from 0.05 to 0.8 m/d, the average value being 0.3 m/d. The upper permeable layer consists of slightly silty clayey sand (fSa) with rare low-plasticity clay-silt inclusions. The permeability of the main lithology varies from 2.6 to 11 m/d, with an average of 5.4 m/d. Due to the undulose geometry of the till layers below and a sharp depression on the eastern slope, a groundwater discharge (source) was formed there.

The highest part of Gediminas Hill is represented by deposits of the Medininkai (Warthian) Subformation (gdIImd). The uppermost part of these deposits is missing, while the thickness of the remaining glacial deposits is 1.3–5.3 metres. A deformational till layer is represented by compacted, massive, reddish-brown till, and locally by morainic sand. The deformation till is rich in sand, silt, and clay beds, also in boulders. An admixture of medium and poorly rounded gravel with clasts 2–50 mm across comprises ~5%. This is the first surface aquitard; with poor permeability, water can move only through it via fractures and permeable lenses or as an initial pressure gradient.

The glaciofluvial sediments (fIImd) of the Medininkai (Warthian) Subformation lie beneath the glacial layer. Their thickness varies from 4.6 m in the northwestern part to 9.8 m in the southern part of the Hill. These deposits are lithologically generally uniform: carbonate-feldspar-quartz brown sand, varying in grain size distribution, locally with gravelly sand or gravel. They are permeable, permeability ranging from 1.0 to 16.0 m/d, average – 9 m/d. Rainfall percolates through them into deeper layers.

The entire natural surface of Gediminas Hill is modified by human activity. The thickness of artificial deposits – technogenic soil (tIV) – varies from 2.4 to 4.6 m. They comprise humus-rich clayey sand and diamicton of various grades, as well as gravel, gravel and brick debris, pieces of carbonate cement, buried cultural layers, etc. The prevalence of weak soil layers exposed below technogenic structures is shown in Figure 3, and a hydrogeological cross-section in Figure 4.

ANALYSIS OF TEST RESULTS

Soil physical and mechanical properties used in slope stability calculations were taken from the latest engineering geological and geotechnical investigations in 2019–2020 (JSC Geobaltic, 2020). During these investigations 6 vertical boreholes and 9 boreholes with an average inclination of 35–40^{o} were drilled at the top of Gediminas Hill to collect undisturbed soil samples. Borehole length varied from 31.8 to 57 m. Close to vertical boreholes, cone penetration tests with pore pressure measurement (11 tests) and without pore pressure measurement (5 tests) were conducted. In order to find the technogenic soil layer thickness on the slopes mechanical drilling by hand (134 tests of average 4.1 m depth) and mechanical dynamic penetration (119 tests of maximum 10 m depth) were performed. Also, 40 pits for evaluation of foundations were dug. In the laboratory 361 particle size distribution tests, 165 water permeability tests, 355 water content tests, 347 unit weight tests, 251 plastic and 231 liquid limit tests, 353 particle solid density tests, 160 direct shear tests, 110 oedometer tests and 14 uniaxial compression tests were conducted.

Mechanical properties were determined for undisturbed samples using direct shear, triaxial and oedometer devices. Undisturbed samples were taken using column boring. Elletarri EK 200 equipment was used for drilling vertical boreholes with a three-section column pipe (with plastic shell), outer diameter – 116 mm, inner diameter – 93 mm, length – 3 m. When drilling in coarse soils "Denison" type equipment was used. After lifting, the soil is removed together with the inner plastic pipe. The pipe is sealed with protective caps. On site the soil left on the boring crown was used only for visual determination of soil type. A detailed description of the soil was made in the laboratory. Part of the soil obtained from the pipe was sent to the laboratory where it was described and classified. The other part was collected in boxes and sent to a storage site.

Based on all engineering geological and geotechnical investigation results, for slope stability analysis each layer soil unit weight γ, effective angle of internal friction φ', effective cohesion c', cohesion under undrained conditions c_u, and Young's modulus was used (Table 1). Accepted masonry unit weight is 30 kN/m^3, possible distributed load on the paths is 10 kPa.

Young's modulus is shown separately in Table 2, where it was calculated from CPTU results given in Table 1 and from oedometer tests. Oedometer test loads applied according to natural soil weight with the possibility of stress increments due to reconstruction of the Gediminas castle remains. More detailed information about the physical and mechanical test results are given in the JSC Geobaltic (2020) Engineering geological and geotechnical investigations report, which can be found in the Lithuanian Geology Survey.

SLOPE STABILITY

Gediminas Hill slope stability was calculated using the Morgenstern-Price method (Zhu et al., 2005) with a polygonal slip surface. The solution of the slope stability problem adopting a polygonal slip surface is based on the determination of the limit state of forces acting on the soil body above the slip surface. To introduce these forces, the slip surface above is subdivided into blocks by dividing planes. Slope stability calculations were conducted with the GEO5 (2020) slope stability program. Morgenstern-Price is a general method of slices developed on the basis of limit equilibrium. It requires a satisfactory equilibrium of forces and moments acting on individual blocks. The blocks are created by dividing the soil above the slip surface into dividing planes. In these calculations the slope utilization factor is defined as the ratio of the destabilizing and stabilizing effects (Bond and Harris, 2008) expressed in %. Slope stability equilibrium is reached when utilization is equal to 100%. If utilization is <100%– slope stability is satisfactory, if utilization is >100%, slope stability is not satisfactory. Calculations were provided according to technical requirement STR 2.05.21:2016 applying third (III) design approach.

The Gediminas Hill slope stability evaluation was made on cross-sections shown in Figure 2 with a worst case scenario, when technogenic soil saturation is 90%. In Figure 2 the northern slope is marked as III, eastern slope – V', southern – III', western – V. The results of slope stability analysis are shown in Figures 5–8 (stratigraphy index and soil layer identification is the same as in Table 1). The utilization factor of slope stability obtained is:

in the northern part – 82.5%,
eastern part – 75.8%,
southern part – 79.4%,
western part – 71.9%.

Calculated slope stability is high enough for such steep slopes, where slope inclination is from 28 up to 57°. Moreover, soil stability is usually not satisfactory for technogenic soil layers, where the formation of shallow landslides is observed. An example of such a shallow landslide is shown in Figure 6, where a distributed 10 kPa load on the path is evaluated.

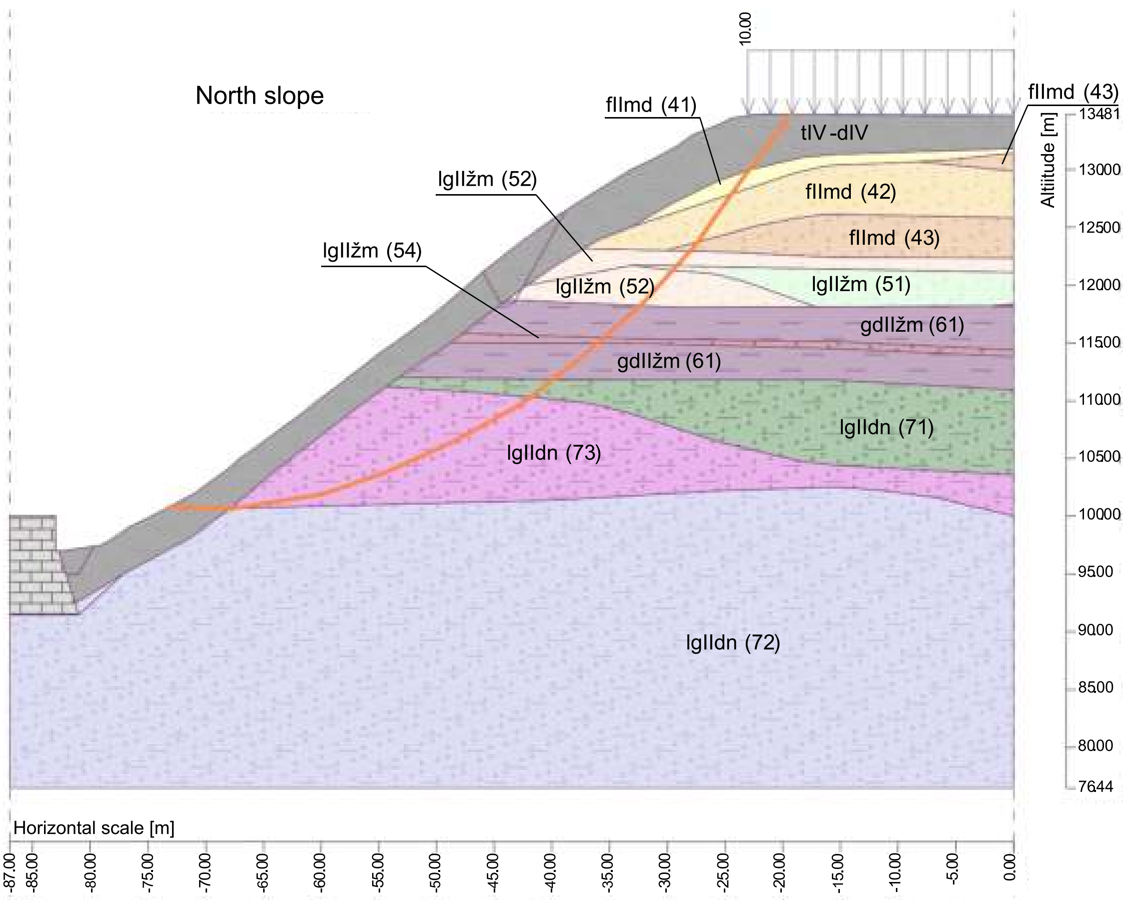

Fig. 5. Northern slope stability analysis

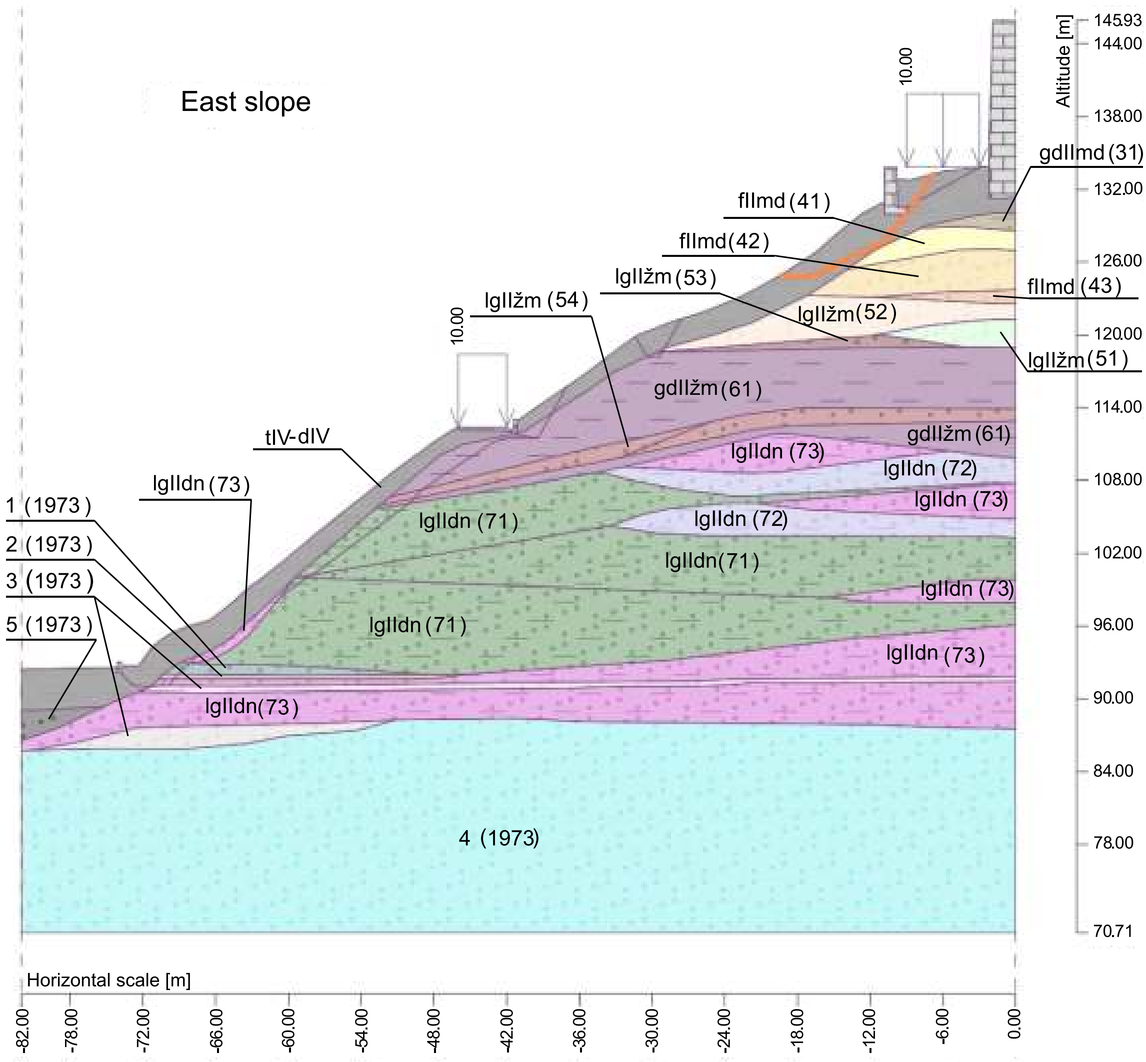

Fig. 6. Eastern slope stability analysis

In recent years, shallow landslides in the techogenic soil layer have appeared on the eastern slope in 2004 and recurred in 2008, and on the northern slope in 2016 (Skuodis and Ng, 2018). These landslides appeared due to extreme weather conditions with very large rainfall. The results shown in Figures 5–8 also show that the natural Gediminas Hill soil layers are stable enough. Also, since 2020, the Gediminas Hill top precipitation water collection and removal system has been completed. This partly helps to collect rainwater from the technogenic soil layer and avoids deeper soil saturation.

CONCLUSIONS

We provide an update of engineering geological and geotechnical investigations of Gediminas Hill realized in 2019–2020, when new results related to geological layers and geotechnical and hydrogeological parameters were obtained. The entire natural surface of Gediminas Hill has been modified by human activity and covered with technogenic soil (tIV). The Middle Pleistocene deposits are affected by deluvial processes and human activities on the slopes of the hill. During this research, weak natural soil layers beneath the technogenic soil were found. Technogenic soil layer thickness varies from 0.6 up to 9.7 m. The thickest technogenic soil deposits are in the southern slope bottom (5.5–9.7 m). The thinnest layer of technogenic soil (0.6–2.5 m) was found on the western slope, around the hill on glacial (gdIIžm) deposits and towards the hill top. In the middle of Gediminas Hill stiff natural soil layers were identified. Low and medium water content is see in the main part of the soil layers, that are characterized by various particle size distributions, with coarse and fine soils.

Six natural soil lithological types were found, namely: tIV – Holocene technogenic weak soils and stiff deposits of the Middle Pleistocene Medininkai (Warthian) Subformation: fIImd –

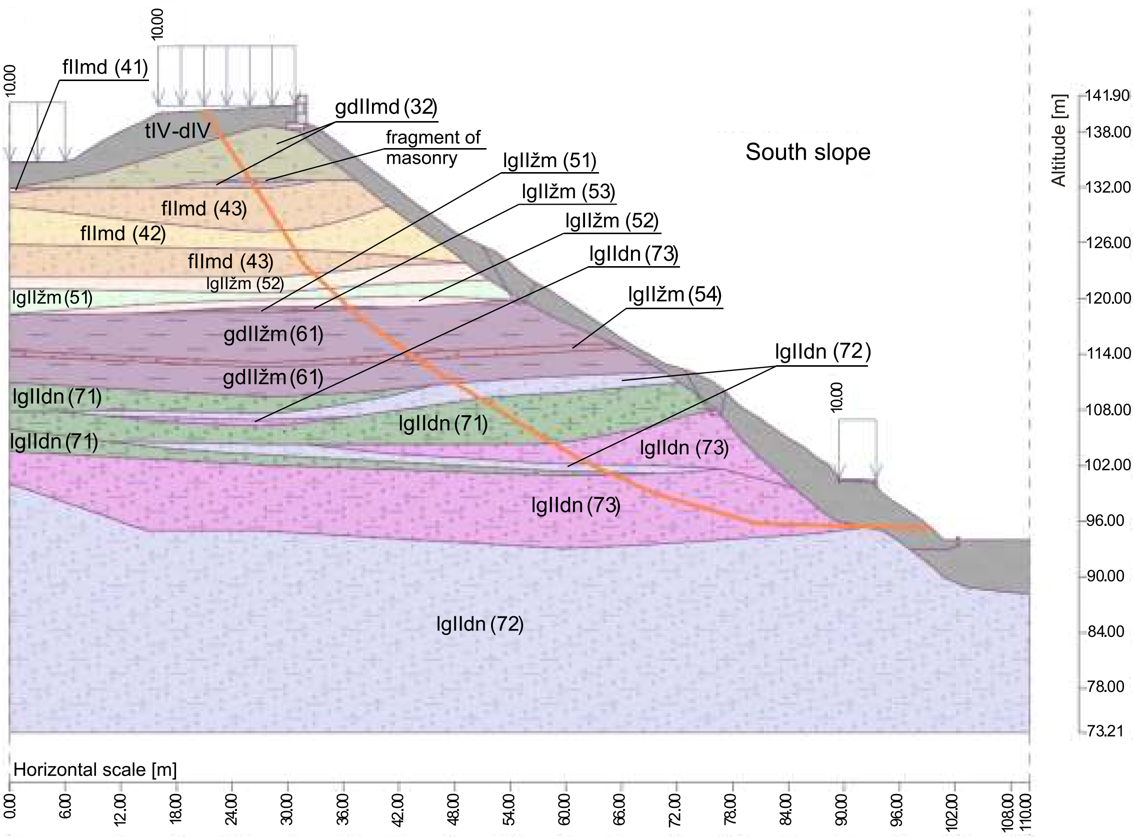

Fig. 7. Southern slope stability analysis

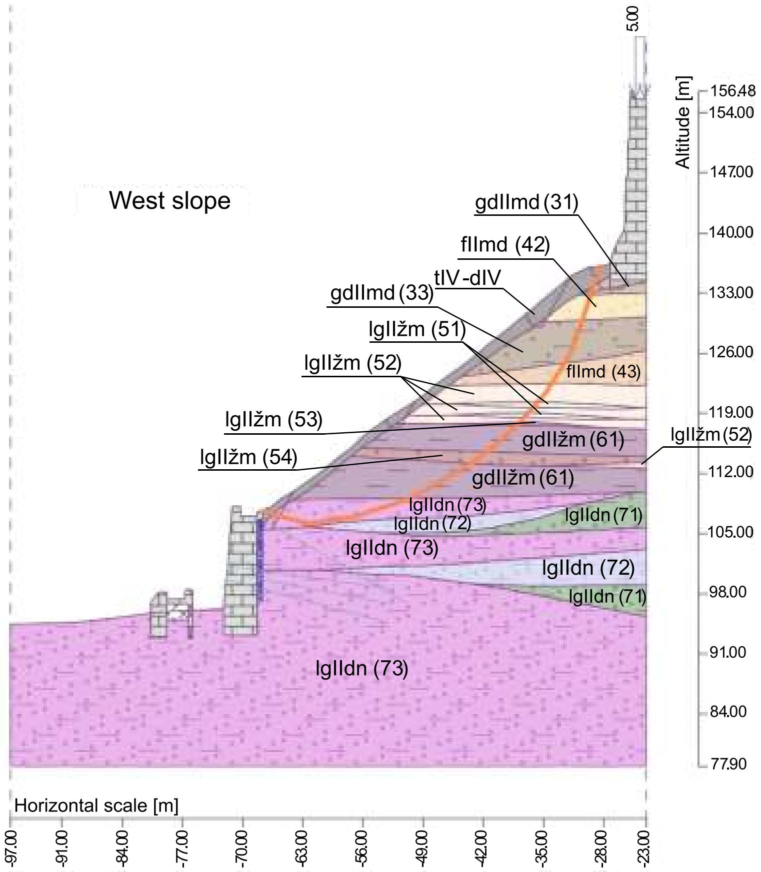

Fig. 8. Western slope stability analysis

glaciofluvial; gdIImd – glacial (deformation till); Žemaitija (Saalian) Subformation: lgIIžm – glaciolacustrine; gdIIžm – glacial (deformation till); lgIIdn – glaciolacustrine deposits of the Middle Pleistocene Dainava (Elsterian 2) Formation. According to permeability criteria, up to 8 different hydrogeological layers were distinguished in the Gediminas Hill structure, with 5 of these being permeable:

tIV (k = 0.4 m/d),

fIImd (k = 9 m/d),

lgIIžm (k = 0. 3m/d, intermoraine k = 5.4 m/d),

lgIIdn (k = 2.3 m/d);

3 are impermeable: gdIImd, lgIIžm and gdIIžm.

Potentially, zones with low slope stability correlate with weak soils, their main concentrations being on the northern slope (at the top and bottom), also on the eastern and western slopes. Detailed slope stability analysis was accomplished with updated engineering geological and geotechnical data. The utilization factors of slope stability were: in the northern part 82.5%, eastern part – 75.8%, southern part – 79.4%, western part – 71.9%. In the eastern part of Gediminas Hill the lowest slope stability utilization was found in the technogenic soil layer. This slope is mostly unstable and shows the largest probability of new shallow landslides if the technogenic soil layer becomes fully saturated. From the Gediminas Hill landslide history, the technogenic soil layer develops shallow landslides after severe precipitation with relatively high saturation levels.

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