E3S Web of Conferences **730**, 05005 (2026) https://doi.org/10.1051/e3sconf/202673005005
Soft Soils 2026

Geotechnical characterization and ground improvement of soft glaciolacustrine clays along the Rail Baltica high-speed railway in Estonia

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Abstract. The construction of the Rail Baltica high-speed railway in Estonia encounters significant geotechnical challenges where the alignment crosses deep deposits of very soft to soft Quaternary glaciolacustrine clays. These soils, characterized by low shear strength, high compressibility, and high sensitivity, pose critical risks to embankment stability and long-term serviceability. This paper presents an in-depth geotechnical characterization of these problematic clays across four key construction sections. The study integrates a comprehensive suite of advanced in-situ testing data, including Multichannel Analysis of Surface Waves (MASW) to establish small-strain stiffness profiles, Piezocone Penetration Tests (CPTU) for detailed stratigraphic delineation and consolidation parameter assessment, and Field Vane Tests (FVT) to determine the undrained shear strength profile. Analysis of this data provides robust, site-specific geotechnical models and establishes the key design assumptions for high-speed railway embankments. The primary design concerns embankment stability (both short- and long-term) and the prediction of total and differential settlements under strict serviceability limits are addressed. Furthermore, the paper discusses and evaluates a range of soil improvement solutions implemented to ensure the railway's long-term performance. These solutions include basal reinforcement with high-strength geosynthetics, accelerated consolidation using surcharge and Prefabricated Vertical Drains (PVDs), and load transfer platforms supported by rigid inclusions or stone columns. The findings offer validated design parameters and practical insights for constructing critical infrastructure on the complex soft clays of the Baltic region.

1 Introduction

Rail Baltica is a major European infrastructure project connecting the Baltic States — Estonia, Latvia, and Lithuania — to the broader European rail network via a new standard-gauge (1435 mm) high-speed railway. In Estonia, the alignment traverses a geologically complex corridor characterized by Quaternary glacial and glaciolacustrine deposits overlying Ordovician and Silurian carbonate bedrock. The design and construction of railway embankments along this corridor present significant geotechnical challenges, particularly where soft to firm glaciolacustrine clays and silts of Geotechnical Unit GU IIabc are encountered.

This paper presents the geotechnical characterization of GU IIabc and the ground improvement solutions adopted for two representative sections: the Harju 2 section (EE DS2 DPS1, Tallinn–Rapla corridor) and the Rapla 4 section (EE DS1 DPS3, Pärnu–Rapla corridor). Both sections were designed under the Rail Baltica Master Design framework by IDOM, with Detailed Technical Design (DTD) prepared by Verston OÜ. The ground improvement solutions discussed include vibro-replacement stone columns (Harju 2), consolidation with and without prefabricated vertical drains (PVDs) (Harju 2 — Aasu viaduct abutments), rigid inclusions (Rapla 4). Both sections have entered active construction, with ground improvement works initiated in 2025. Full railway operations are scheduled to commence in 2030.

2 Geological and geotechnical setting

2.1 Regional geology

The Rail Baltica corridor in Estonia crosses the North Estonian Klint zone and the South Estonian lowlands [1-2]. The Quaternary cover, deposited during and after the last glaciation (Weichselian), consists of a characteristic stratigraphic sequence: glaciofluvial sands and silty sands (GU I), glaciolacustrine clays and silts (GU II), glacial till / moraine (GU III), and locally peat (GU V). Ordovician and Silurian limestones and marls (GU IV) form the bedrock, which is encountered at shallow depths (typically 3–10 m) in the northern sections and at greater depths further south.

Glaciolacustrine deposits (GU II) were formed in proglacial lakes during deglaciation and are characterized by fine-grained, laminated to massive clays and silts [1-2]. Their consistency ranges from very soft to hard depending on stress history and depth. For design purposes, GU II is subdivided into three consistency classes: GU IIabc (very soft to firm), GU IId

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(stiff), and GU IIe (very stiff to hard). The soft subunit GU IIabc is the primary geotechnical hazard along the corridor.

2.2 Harju 2 section (EE DS2 DPS1)

The Harju 2 Design Priority Section 1 (DPS1) covers the alignment from Ülemiste to Kangru, south of Tallinn. The section is characterized by a relatively shallow Quaternary cover (typically 3–8 m) overlying Ordovician limestone. GU IIabc is encountered sporadically along the alignment, predominantly in low-lying areas and former lake basins, often interbedded with glaciofluvial sands (GU I) and overlain by peat (GU V). Embankment heights along the critical sections range from 1.5 m to 7.3 m. Soft soil section of interest from ch. 7+000 to ch. 7+700 given in Fig. 1.

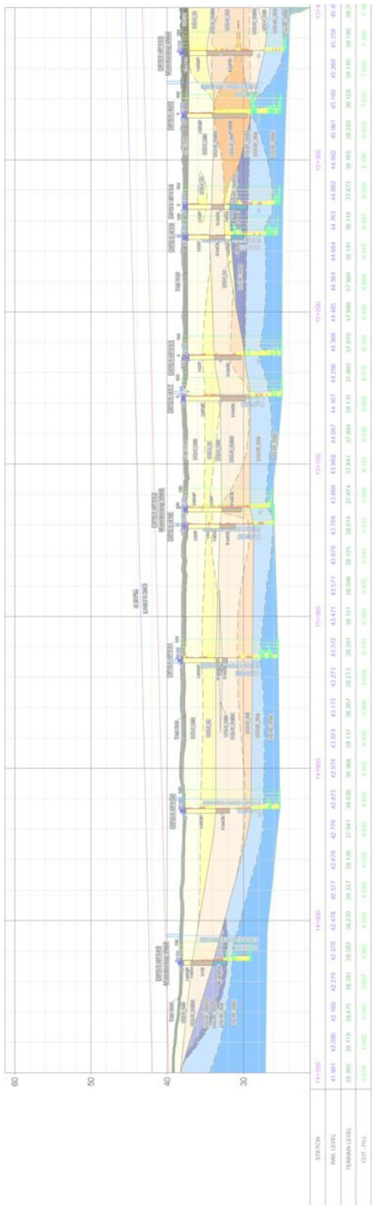

Fig. 1. Geotechnical long section – Harju 2 site.

The ground investigation program for EE DS2 DPS1 comprised 252 percussion drillings, 46 core drillings, 7 CPT/CPTu tests, 206 DPSH-A dynamic probing tests, 12 vane shear tests, and an extensive laboratory testing program including 145 Atterberg limit tests, 843 moisture content determinations, and 25 oedometer tests. Open standpipes were installed at selected locations to characterize groundwater conditions. The groundwater table is generally shallow, at 0.2–1.0 m depth.

2.3 Rapla 4 section (EE DS1 DPS3)

The Rapla 4 Design Priority Section 3 (DPS3) covers the alignment from Kärpla to Alu, in the Rapla County. This section is characterized by a thicker Quaternary sequence, with GU IIabc layers encountered at depths ranging from 0.20 m to 6.80 m (upper occurrences) and 0.40 m to 9.80 m (lower occurrences), with an average individual layer thickness of approximately 1.5 m. Multiple GU IIabc layers are present at some locations due to interbedding with glaciofluvial sands. Embankment heights in the critical sections reach up to 6–8 m. Soft soil section near Aasu viaduct from ch. 14+700 to ch. 15+400 given in Fig. 2.

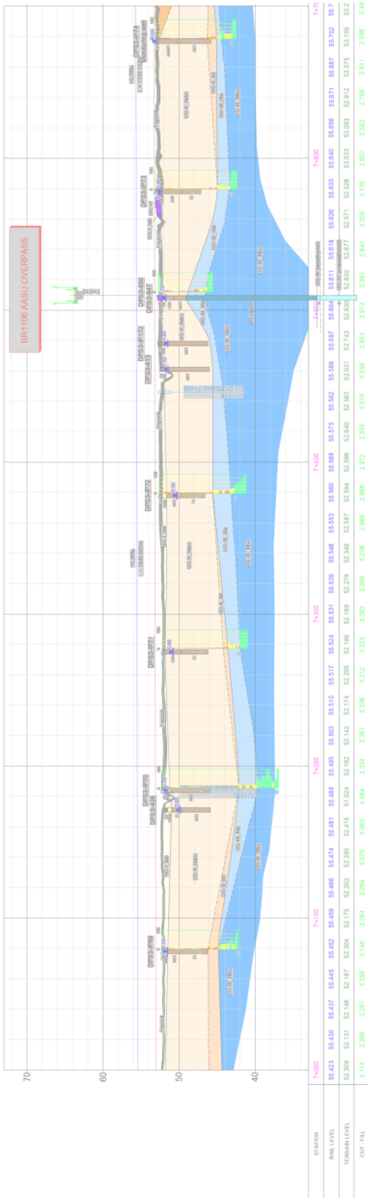

Fig. 2. Geotechnical long section – Rapla 4 site.

The ground investigation for EE DS1 DPS3 included CPT/CPTu tests, DPSH dynamic probing, borehole drilling, laboratory testing, and additional targeted investigations performed in early 2025 to refine the ground model at critical locations. Field vane tests (FVT) were performed at selected locations to directly measure undrained shear strength of GU IIabc.

3 Geotechnical unit GU IIabc — characterisation

3.1 Description and classification

GU IIabc is classified as very soft to firm clay/silt (EN ISO 14688-2:2018 — saCl to siCl) [3]. The unit is normally consolidated to lightly overconsolidated ($OCR \approx 1-2$) and exhibits high compressibility and low undrained shear strength. It is the primary problematic geotechnical unit along the Rail Baltica corridor in Estonia, controlling embankment stability and post-construction settlement design.

In both sections, GU IIabc is identified primarily from CPTu soil behaviour type (SBT) classification [4], borehole sampling, and dynamic probing. The SBTn plots consistently place the unit in zones 1–3 (sensitive fine-grained, organic, and clay), confirming its cohesive, low-strength character. The unit is considered a cohesive material for all geotechnical design purposes.

3.2 Index properties

Key index properties of GU IIabc from both sections are summarised in Table 1.

Table 1. Index properties of GU IIabc - Harju 2 and Rapla 4.

Parameter	Harju 2 Average / Range	Rapla 4 Average / Range	Unit
Moisture content (w)	32 / 8–66	35 / 6–212	%
Liquid Limit (LL)	27 / 18–47	35 / 13–84	%
Plasticity Index (PI)	10 / 5–22	13 / 1–33	%
Particle density (ρs)	2.71 / 2.6–2.80	2.71 / 2.4–2.9	Mg/m³
Fines content (< 0.063 mm)	73 / 38-95	86 / 37-100	%
Classification (Casagrande)	CL–ML (low plasticity)	CL–CI (low–intermediate plasticity)	—

3.3 Strength parameters

Undrained shear strength (cu) of GU IIabc was derived from CPTu [4], DPSH dynamic probing [5], and field vane tests (FVT). The characteristic design values adopted are presented in Table 2.

Table 2. Characteristic strength and stiffness parameters of GU IIabc.

Parameter	Symbol	Harju 2	Rapla 4	Unit
Undrained shear strength (mean)	cu	17–28	21–24	kPa
Effective friction angle	φ'	28	28	°
Effective cohesion	c'	1	1	kPa
Bulk unit weight	γ	19.0	19.0	kN/m³
Undrained Young's modulus ($Eu = \alpha \cdot cu$)	Eu	~17 000	~13 000	kPa

The undrained shear strength shows a wide scatter (0–42 kPa in Harju 2; 0–90 kPa in Rapla 4), reflecting the variable consistency within the unit. For design, the characteristic value is taken as the lower 5th percentile (k5%) of the dataset, consistent with Eurocode 7 (EN 1997-1) requirements. Additional FVT and CPTu investigations performed in 2025 confirmed that c_u > 20 kPa and also allowing a SHANSEP-based strength gain model to be applied for embankment consolidation design [6-8].

3.4 Compressibility and consolidation parameters

GU IIabc is normally consolidated to lightly overconsolidated. Compressibility parameters were derived from oedometer tests and empirical correlations. Key consolidation parameters are summarised in Table 3.

The significant anisotropy in permeability ($k_h/k_v \approx$ 4.5–4.6) is consistent with the laminated fabric of glaciolacustrine deposits and has important implications for the design of prefabricated vertical drains (PVDs), where horizontal drainage is the primary consolidation pathway.

4 Need for ground improvement

4.1 Design requirements

Rail Baltica imposes stringent performance requirements on the railway substructure. The key geotechnical design criteria governing the need for ground improvement are:

- Post-construction settlement: ≤ 1 cm/year and 4 cm over 25 years after ballast placement at the abutment areas.
- Post-construction settlement: ≤ 1 cm/year and 10 cm over 25 years after ballast placement other areas than the abutment areas.
- Total settlement under culverts and structures: ≤ 50 mm.

Table 3. Compressibility and consolidation parameters of GU IIabc.

Parameter	Symbol	Value / Range	Source	Unit
Compression index	Cc	0.21 (meas.); 0.16–0.22 (corr.)	Oed. / Skempton corr.	—
Swelling index	Cs	0.034 (meas.)	Oed.	—
Coefficient of consolidation (vert.)	c_v	5–21 (from CPTu diss.)	CPTu diss.	m²/ year
Coefficient of consolidation (horiz.)	c_h	21–95 (from CPTu diss.)	CPTu diss.	m²/ year
Anisotropy ratio	$c_h/c_v = k_h/k_v$	4.5–4.6	CPTu diss.	—
Vertical permeability	k_v	3.9×10^{-10} – 3.3×10^{-9}	CPTu diss.	m/s
Horizontal permeability	k_h	1.8×10^{-9} – 1.5×10^{-8}	CPTu diss.	m/s
Over - consolidation ratio	OCR	~1 (norm. cons.)	Eng. judgement	—

4.2 Critical speed assessment

The Rail Baltica design speed considered here is 250 km/h, corresponding to $v = 69\ \mathrm{m/s}$. Multichannel Analysis of Surface Waves (MASW) provide Rayleigh-wave phase velocity $c_{R(f)}$ as a function of frequency. This information can be used directly (without conversion to shear-wave velocity v_s) to relate measured surface-wave propagation characteristics to the kinematic loading associated with high-speed traffic [9-10].

A simple kinematic relationship links train speed, wavelength and frequency for a moving load:

$$f \approx v/\lambda \qquad (1)$$

where f is the frequency (Hz), v the train speed (m/s), and λ the wavelength (m).

For $v = 69\ \mathrm{m/s}$, representative wavelengths and frequencies are: λ = 5 m → f ≈ 13.9 Hz; λ = 10 m → f ≈ 6.9 Hz; λ = 15 m → f ≈ 4.6 Hz; and λ = 20 m → f ≈ 3.5 Hz. High-speed passenger trains have characteristic dimensions including axle spacing (typically 2.5-3 m), bogie spacing (approximately 5 m), and car lengths (15-25 m). These physical dimensions correspond to the wavelengths of cyclic loading imposed on the ground as the train passes. These estimates indicate that for 250 km/h the frequency band of interest for train–ground interaction commonly falls within a few hertz up to approximately 15 Hz, overlapping the MASW phase-velocity picks (typically ~5–40 Hz) reported in in-situ tests.

For a descriptive comparison between train speed and measured surface-wave propagation speed, a non-dimensional index can be defined as:

$$\eta(f) = v/c_{R(f)} \qquad (2)$$

where $\eta(f)$ is a non-dimensional index, v the train speed (m/s), and $c_{R(f)}$ provides the Rayleigh-wave phase velocity (m/s).

Values $\eta \ll 1$ indicate that the train speed is far below the measured Rayleigh-wave phase velocity at that frequency; values approaching 1 would indicate proximity to a critical regime in which moving-load effects may be amplified. This index is indicative only and does not replace full coupled vehicle–track–soil dynamic analysis [11-12].

MASW test results from the Harju 2 and Rapla 4 illustrated in Table 4 with the magnitude of η in the relevant band.

Across the reported points and frequencies, c_R values within ~5–15 Hz remain greater than the train speed (69.4 m/s), and η remains below 1.

Sections with η > 0.4 (Harju 2 ch. 14+760-15+143, Rapla 4 ch. 7+180-7+220 and ch. 8+520-8+560) correspond to locations where GU IIabc is thickest and softest. These are precisely the sections where stone columns, rigid inclusions, and PVD treatment were prescribed. The MASW data thus independently corroborate the geotechnical model derived from CPTu and laboratory testing, confirming that ground improvement is both necessary and properly targeted.

4.3 Geotechnical hazards from GU IIabc

Where GU IIabc is present beneath embankments, two primary geotechnical hazards arise.

The high compressibility of GU IIabc (C_c = 0.16–0.22) combined with its low permeability (k_v ~ 10^{-9} m/s) results in large primary consolidation settlements that develop slowly over years to decades. Under embankments of 4–8 m height, total settlements of 200–400 mm are typical, with post-construction settlements exceeding the 1 cm/year criterion without intervention.

For example, at the Aasu viaduct abutments (Rapla 4), maximum projected settlements of up to 397 mm (Abutment A1) and 405 mm (Abutment A2) were calculated without ground improvement.

The low undrained shear strength of GU IIabc (cu = 15–28 kPa) is insufficient to support high embankments without additional measures.

 https://doi.org/10.1051/e3sconf/202673005005

Table 4. Rayleigh phase velocities for soft soil sections in Harju 2 and Rapla 4.

Report / Location	Freq., f (Hz)	Rayleigh phase velocity, $c_{R(f)}$ (m/s)	η = 69.4 / $c_{R(f)}$ (-)
Harju 2 — ch. 14+700–14+760	10	600	0.12
Harju 2 — ch. 14+700–14+760	15	396	0.18
Harju 2 — ch. 14+700–14+760	20	278	0.25
Harju 2 — ch. 14+760–15+143	7	346	0.20
Harju 2 — ch. 14+760–15+143	10	175	0.40
Harju 2 — ch. 14+760–15+143	15	137	0.51
Harju 2 — ch. 15+143–15+590	8	284	0.24
Harju 2 — ch. 15+143–15+590	10	216	0.32
Harju 2 — ch. 15+143–15+590	15	144	0.48
Rapla 4 — ch. 7+180–7+220	6.5	234	0.30
Rapla 4 — ch. 7+180–7+220	10	122	0.57
Rapla 4 — ch. 8+520–8+560	10	153	0.45
Rapla 4 — ch. 6+960–7+000	10	304	0.23
Rapla 4 — ch. 6+960–7+000	15	175	0.40

4.4 Selection of ground improvement method

The selection of the appropriate ground improvement method depends on the thickness and extent of GU IIabc, embankment height, available construction time, and the proximity of structures. Three principal methods were applied along the Rail Baltica corridor in the studied sections:

- Stone columns (vibro-replacement): Applicable where GU IIabc thickness is moderate (< 8 m) and total settlement reduction is the primary objective. Used under culverts in Harju 2.
- Consolidation with PVDs: Applicable where GU IIabc is thick (> 3 m) and sufficient construction time is available for staged loading. Used at bridge abutments in Rapla 4 (Aasu viaduct).
- Rigid inclusions: Applicable where GU IIabc is thick, embankments are high, and strict settlement limits apply. Used extensively in Rapla 4.

5 Case study 1: Harju 2 (EE DS2 DPS1)

5.1 Section overview

The Harju 2 section (Ülemiste–Kangru) is located south of Tallinn. The critical sub-sections for ground improvement are associated with embankments in the chainage range 14+640 to 15+720, where GU IIabc is present beneath embankments of 1.5 m to 7.3 m height, and with culverts CU0460–CU0500 at approximately chainage 14+750–15+143. The ground model in this area is characterised by a thin GU IIabc layer (0.5–2.5 m) interbedded with glaciofluvial sands (GU I) and overlain by peat (GU V) in some locations, with glacial till (GU III) below.

5.2 Stone columns under culverts

Stone columns (vibro-replacement) were designed for culverts CU0460, CU0470, CU0480, CU0490, and CU0500 in the Harju 2 section. These culverts were originally designed on rigid concrete inclusions, but the Detailed Technical Design (DTD) proposed stone columns as a more cost-effective and technically appropriate solution for the moderate GU IIabc thicknesses encountered.

Settlement calculations at the representative section (chainage 15+143, section S08) showed that without ground improvement, total maximum deformations of approximately 190 mm were expected — exceeding the 50 mm limit for culverts. Stone columns were designed according to the Priebe method [13].

The stone columns are installed through the full depth of GU IIabc and penetrate 1 m into the underlying glacial till (GU IIIa or IIIbc), which provides the bearing stratum (Fig. 3.). The area replacement ratio achieved with 600 mm diameter columns at 1.5 m triangular spacing is approximately 14.5%, providing sufficient stiffness improvement to reduce total settlements below the 50 mm design limit. Under the design embankment loading (4–8 m height, corresponding to applied stress of 75–150 kPa), and accounting for stress concentration in the columns (stress concentration ratio $n \approx 3$–5 typical for this area replacement ratio), the maximum column stress is estimated at 375–450 kPa, which remains below the allowable stress of 534 kPa [14]. The bulging resistance check is therefore satisfied for all stone column sections in Harju 2, confirming that the lateral confinement provided by GU IIabc (c_u = 17–28 kPa, q_c ≈ 0.5–1.0 MPa) is adequate to prevent bulging failure at the design loads.

https://doi.org/10.1051/e3sconf/202673005005

Table 5. Stone column design parameters — Harju 2 culverts.

Parameter	CU0460–CU0490	CU0500
Column diameter	600 mm	600 mm
Column spacing (triangular)	1.5 m	1.5 m
Column length	To GU IIIa/IIIbc (1 m penetration into till)	To GU IIIa/IIIbc (1 m penetration into till)
Arrangement	Triangular grid	Triangular grid
Target total settlement	< 50 mm	< 50 mm
Culvert type	Box culvert 1.9×1.9 m	Box culvert 4.7×2.7 m

Fig. 3. Installation of stone columns – Harju 2 site.

6 Case Study 2: Rapla 4 (EE DS1 DPS3) — Rigid Inclusions

6.1 Section overview

The Rapla 4 section includes several critical embankment sections where GU IIabc is thick (up to 9.8 m) and embankment heights reach 6–8 m. The Detailed Technical Design (DTD) was prepared by Verston Eesti OÜ in 2025.

6.2 Design concept

Rigid inclusions are small-diameter concrete columns that transfer embankment loads through the soft GU IIabc layer to the competent underlying glacial till (GU IIIa/IIIbc) or bedrock. Unlike stone columns, rigid inclusions do not rely on lateral confinement from the surrounding soil and are therefore suitable for very soft soils where stone columns would not achieve adequate improvement. A load transfer platform (LTP) consisting of compacted granular fill with two layers of high-strength geogrid is placed between the top of the inclusions and the embankment base to distribute loads and ensure arching.

The main objectives of the rigid inclusion treatment are: (1) to transfer embankment loads to competent strata, thereby reducing settlements to within the design limits; (2) to increase the overall shear resistance of the improved ground, improving slope stability; and (3) to reduce stresses on GU IIabc, limiting long-term consolidation settlements.

The rigid inclusions were installed in four different areas with total quantities of about 300 000 linear meters (Fig. 4.).


Fig. 4. Installation of rigid inclusions –Rapla 4 site.

6.3 Design parameters

The rigid inclusion design was verified using 2D finite element analysis in plane strain conditions. The rigid inclusions were modeled using embedded beam elements. This approach represents each inclusion as a one-dimensional structural element embedded within the two-dimensional soil continuum, allowing accurate representation of discrete column behavior in a computationally efficient 2D framework. The analysis confirmed that the C16/20 concrete class is sufficient to resist the design bending moments and axial forces. Key design parameters are summarised in Table 6.

Table 6. Rigid inclusion design parameters — Rapla 4. S (spacing), L (length), D (diameter).

Section	S (m)	L (m)	D (m)	Max. deformation (mm)
SE-08	1.2	10	0.4	36.3
SE-08.1	1.6	10	0.4	43.7
SE-RI.1	1.5	4.2	0.4	22.6
SE-RI.2	2.0	4.2	0.4	~25

6.4 Geogrid load transfer platform

The load transfer platform (LTP) geogrid design was performed according to CUR 226 methodology [15]. Two layers of geogrid are required in all sections. The design stiffness requirements and proposed materials are summarised in Table 7.

Geogrid anchorage (wrap-around) lengths were calculated according to EBGEO [16] to ensure pull-out resistance exceeds the design tensile force.

Table 7. Geogrid LTP design — Rapla 4 rigid inclusion sections.

Section	Required stiffness J (kN/m)
SE-08 (1.2 m spacing)	1500 (both directions)
SE-08.1 (1.6 m spacing)	3000 (both directions)
SE-RI.1 (1.5 m spacing)	3000 (both directions)
SE-RI.2 (2.0 m spacing)	3000 (both directions)

7 Case study 3: Rapla 4 (EE DS1 DPS3) — Aasu viaduct

The Aasu viaduct (BR1106) abutments (Rapla 4 section, chainages 1+50 to 6+25) are founded on embankments over GU IIabc with thicknesses of 3.6 m (Abutment A1) to 7.0 m (Abutment A2). The original design assumed uniform ground conditions, but additional investigations in February 2025 revealed significant variability in GU IIabc thickness and strength, leading to a revised design with differentiated treatment zones.

The revised design differentiates between sections where consolidation without PVDs is sufficient and sections requiring PVDs to achieve the required post-construction settlement performance within the construction programme. The key design parameters are summarised in Table 8.

PVDs are installed to the bottom of GU IIabc (5–12 m depth from working platform level). A 0.5 m thick drainage layer (sand or sand-gravel, permeability ≥ 0.5 m/day, fines ≤ 7%) is placed at the surface to facilitate horizontal drainage. The consolidation time assumed is 6 months, after which post-construction settlements are reduced to less than 5 cm. The significant permeability anisotropy of GU IIabc (k_h $/k_v$ $\approx$4.5) means that PVDs are highly effective in accelerating consolidation by reducing the drainage path length from the full layer thickness to half the PVD spacing (1.0 m).

For sections without PVDs, the post-construction settlement criterion (< 1 cm/year, < 4 cm/25 years) is met where GU IIabc thickness is limited (< 4 m) and the embankment height is moderate. Geosynthetic reinforcement (geogrids with design tensile strength $T_d = 50 - 750\,\mathrm{kN/m}$) is provided throughout the abutment zones to ensure slope stability and to bridge any residual differential settlements.

The ground model for the abutments was refined based on additional investigations, differentiating GU IIabc into three sublayers with increasing strength and stiffness with depth: IIab ($c_u = 15$ kPa, $E = 3$ MPa), IIbc ($c_u = 35$ kPa, $E = 5.25$ MPa), and IIcd ($c_u = 65$ kPa, $E = 9.75$ MPa). This sublayering significantly improved the accuracy of settlement predictions and allowed optimization of PVD lengths.

8 Discussion

The case studies presented demonstrate the range of ground improvement solutions applicable to soft glaciolacustrine clays (GU IIabc) along the Rail Baltica corridor. The choice of method is primarily governed by the thickness of GU IIabc, the embankment height, the proximity of structures, and the available construction time.

Stone columns are the most economical solution for moderate GU IIabc thicknesses (< 5 m) under culverts and other structures where total settlement must be limited to 50 mm. The Priebe method provides a reliable design framework for this application.

PVDs with staged loading are effective for thick GU IIabc layers (> 3 m) under embankments where the construction programme allows a 6-month consolidation period. The high permeability anisotropy of GU IIabc ($k_h/k_v \approx 4.5$) makes PVDs particularly efficient. The differentiation of GU IIabc into sublayers (IIab, IIbc, IIcd) based on additional investigations significantly improved the accuracy of settlement predictions and allowed optimisation of PVD lengths and treatment zones.

Rigid inclusions are the most robust solution for thick GU IIabc layers under high embankments where strict post-construction settlement limits apply and construction time is limited. The 2D FEM approach provided reliable verification of the inclusion structural capacity and deformation performance. The CUR 226 methodology was used for the design of load transfer platform.

Table 8. Consolidation treatment zones — Aasu vaduct abutments (BR1106).

Ch.	GU IIabc thickness	Treatment	PVD spacing / length	Max. settlement (20 yr)
1+50 – 2+50	3.6 m	Cons. without PVDs	—	185 mm
2+50 – 3+00	3.6 m	Cons. with PVDs	2 m triang. / 6.7 m	397 mm
3+00 – end A1	3.6 m	Cons. without PVDs	—	397 mm
5+00 – 5+50	7.0 m	Cons. with PVDs	2 m triang. / 9.1 m	405 mm
5+50 – 6+00	7.0 m	Cons. with PVDs	2 m triang. / 9.1 m	270 mm
6+00 – 6+25	~5 m	Cons. without PVDs	—	187 mm

A key finding from both case studies is the importance of targeted additional investigations to refine the ground model. The initial characterisation of GU IIabc as a single homogeneous unit was insufficient for detailed design; sublayering based on CPTu and FVT data was essential for optimising treatment solutions and reducing construction costs.

Additionally, targeted field monitoring programme has been implemented to verify design assumptions and validate ground improvement performance.

Settlement Monitoring: Settlement plates were installed at 50 m intervals along all improved sections to provide continuous monitoring coverage of vertical ground movements in Harju 2 site and under Aasu viaduct PVD area.

Pore Pressure Monitoring: Vibrating wire (VW) piezometers were installed at mid-depth of GU IIabc layers in all PVD-treated zones to track consolidation progress. The piezometer data will be used to verify the consolidation parameters against design assumptions and to adjust construction staging when necessary to ensure adequate consolidation before proceeding to the next construction phase.

Lateral Deformation Monitoring: Inclinometers were installed at embankment toes to monitor horizontal ground movements during and 6 months after construction.

9 Conclusions

1. GU IIabc (very soft to firm glaciolacustrine clay/silt) is the primary geotechnical hazard along the Rail Baltica corridor in Estonia, characterised by c_u = 15–40 kPa, C_c = 0.10–0.22, $k_v \sim 10^{-9}$ m/s, and $k_h/k_v \approx 4.5$.
2. Across the reported points and frequencies, c_R values within ~5–15 Hz remain greater than the train speed (69.4 m/s), and η remains below 1.
3. Three ground improvement methods were successfully applied: stone columns (Priebe method) under culverts in Harju 2; consolidation with and without PVDs at bridge abutments; and rigid inclusions (FEM-verified) in Rapla 4.
4. Stone columns (Ø600 mm, 1.5 m triangular spacing) reduced total settlements under culverts to below the 50 mm design limit.
5. PVDs (2 m triangular spacing, 6.7–9.1 m length) reduced post-construction settlements to < 5 cm within a 6-month consolidation period, exploiting the high horizontal permeability of GU IIabc.
6. Rigid inclusions (Ø400 mm, C16/20 concrete, 1.2–2.0 m triangular spacing, 4.2–10 m length) with two-layer geogrid LTP (CUR 226 design) limited maximum deformations to 22–44 mm.
7. Sublayering of GU IIabc into IIab/IIbc/IIcd based on targeted CPTu and FVT investigations was essential for optimising treatment solutions.
8. The DTD refinements (variable pile lengths, C16/20 concrete, geogrid anchorage design) resulted in significant cost savings compared to the Master Design while maintaining full compliance with Rail Baltica design requirements.

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