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Geogrid-reinforced soil retaining wall supporting railway lines at Riga Central Station.

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ABSTRACT: Within the framework of the project of "Riga Central Station" which is part of the international railroad system "Rail Baltica", there was a need for construction of a 130 m long retaining wall of 6 m height. The wall is required to carry two tracks of the Rail Baltica connection and located next to existing structures of the local Latvian railway network. Due to the challenging subsoil conditions, consisting of medium to highly compressible soils with only moderate shear strength and varying thickness, the master design considered a concrete cantilever structure resting on piles. Analysis in the detailed design phase, however, showed that this structure could be constructed as a geogrid reinforced fill (MSE) without the need for a deep foundation. The alternative concept included two major stages where the construction of the geogrid reinforced fill – offering high ductility – was carried out first. This phase included the installation of an additional preloading fill to optimize the consolidation of the subsoil. The height of this preload was chosen to represent a significant part of the load expected during the operation of the railway. In the second phase, when settlement became neglectable, a precast concrete facing was installed. The merits of this modified design include simpler and more cost-effective construction without the need for a piled foundation, and the use of precast concrete elements allowing for improved quality, durability and enhanced architectural finish. Furthermore, it is known that the MSE technology significantly reduces the environmental impact. The paper will give insight into the basic concept, and selected aspects of the design especially focusing on the prediction and monitoring of deformations.

KEYWORDS: Geogrid reinforced soil retaining wall, railway, monitoring, preloading, Rail Baltica.

1 INTRODUCTION

The Project of "Riga Central Station" is a part of the bigger railway project Rail Baltica that will integrate the Baltic states within the European railway network. The project consists of the design & build of the station building, railway infrastructure, road infrastructure and integration of these in the city of Riga.

Specifically referring to the "Riga Central Station" the work will include the construction of a 130 m long and 6 m high retaining wall. This is required to carry two tracks of the new 1435 mm passenger connection and located next to the existing 1520 mm tracks of the local Latvian railway network at the same time generating space for landscape architecture at the base of the wall.

Due to the challenging subsoil conditions, consisting of medium to highly compressible soils with only moderate shear strength and varying thickness, the master design considered a concrete cantilever structure resting on piles.

During the detailed design phase however, it worked out that this structure could be constructed as a geogrid reinforced fill (MSE). The merits of this modified approach include simpler and more cost-effective construction without the need for a piled foundation. Furthermore, the use of precast concrete elements allowed concrete works with highest quality resulting in adequate durability and enhanced architectural finish. At the same time, it was possible to significantly improve the environmental footprint of the structure.

The alternative concept included two major stages where the construction of the geogrid reinforced fill – offering high ductility – was carried out first. This phase included the installation of an additional preload to reduce the residual settlement of the track. The thickness of this preload was chosen to represent a significant part of the load expected during the operation of the railway. In the second phase, when settlement became neglectable, a precast concrete facing was installed.

The Rail Baltica project will connect five European Union countries – Poland, Lithuania, Latvia, Estonia and, indirectly, Finland, hence all design work had to follow both the local design criteria as well as Rail Baltica specific requirements that are given with relevant Rail Baltica Design Guildeline (RBDDG-MAN, 2025). Building Information Modeling (BIM) was used to integrate the design within the overall project.

2 GEOTECHNICAL CONDITIONS

The soil in Riga consists of Quaternary deposits of almost 20 m thickness, overlying Devonian sedimentary rocks. The Quaternary soil layers mainly consist of sand deposits but contain a clay ("mud") layer. The rock layer consists of a 6 to 10 m weathered zone at the top with local presence of karst holes. The soil stratigraphy at the location of the MSE retaining wall is indicated in Figure 1.

The master design was based on historical experience and the available soil information. At the start of the Detailed Design phase, a detailed soil investigation campaign was undertaken between October 2019 to July 2020 to allow the derivation of a refined ground model. Special focus at the location of the MSE wall was put on the identification of the Quaternary soil layers and determining their strength and deformation properties.

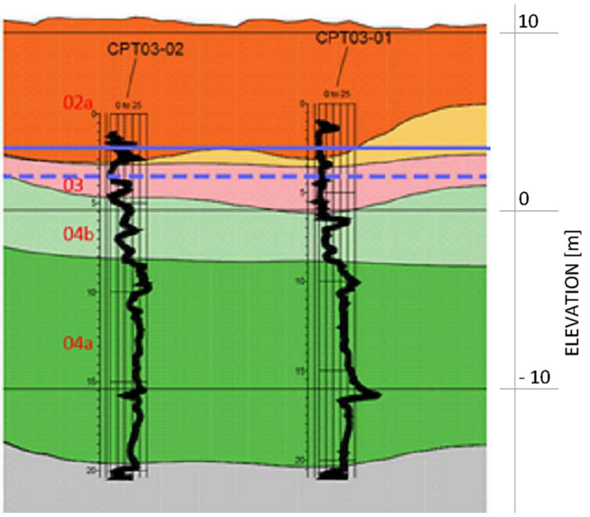

Figure 1. Representative geological section at location of MSE wall

Table 1 shows the representative parameters which have been derived from the soil investigation. The soil parameters have been determined based on correlations with the Cone Penetration Test (CPT) and Pressuremeter Test (PMT) data (strength and stiffness), while stiffness properties are complemented with Oedometer and Dilatometer tests. Special attention is drawn to the clay layer 03, locally containing organic content (generally lower than 5%), which is the main source of settlements for the MSE wall. Due to large variation of the stiffness of this layer throughout the project, lower bound stiffness values were conservatively applied and a sensitivity analysis was carried out in the design. This was of particular importance as the proof of the serviceability limit state was decisive to investigate whether the chosen design concept was feasible within the given serviceability limits and the given timeframe. Similarly, conservative values were considered for the permeability and consolidation coefficient of the clay layer, to safely estimate (the duration of) the consolidation settlement.

Table 1 also provides updated values of some parameters, which are used in a back-calculation of the settlement after the monitoring phase. They correspond to best-estimate values derived from the CPT near the monitoring profile. In this CPT, the combined thickness of the layer 03 is reduced to 0.5m.

Table 1. Representative parameters of the subsoil layers. [Updated values for back-calculation].

Parameter	Unit	Layer Designation				
		Fill	02a	03	04b	04a
Top level	[m CD]	+9.8	+4.1	+2.6	+0.6	-3.0
γ_d	[kN/m³]	17	17	18	17	18
γ_{sat}	[kN/m³]	19	19	18	19	20
E_{oed}^{ref}	[MPa]	60	11 [22]	5	20 [40]	40
E_{y}^{ref}	[MPa]	60	13 [26]	3.4	26 [52]	57.2
E_{ur}^{ref}	[MPa]	180	33 [66]	15	60 [120]	120
ϕ'	[°]	32	28	20	30	34
c'	[kN/m²]	0	0	10	0	0
OCR	[-]	1	1	1	1	1
k	[m/s]	1e-5	1e-5	1e-9	1e-5	1e-5

3 RETAINING STRUCTURE

3.1 *Master Design*

Figure 2 shows the general concept of the soil retaining wall which was adopted during the Master Design. The retaining wall is a classical L–shaped reinforced concrete structure. Due to geometrical constraints the retaining wall had to be designed with a substantial cantilever portion on the upper end. Consequently, the wall thickness and base width of the L-wall are significant and requirements for the foundation are high which means that a piled foundation was required to justify the serviceability limit state of the structure. Full Displacement Piles (FDP) up to the sand layers (04a and 04b) were applied, generating sufficient bearing capacity and allowing to avoid settlements due to the clay layer 03.

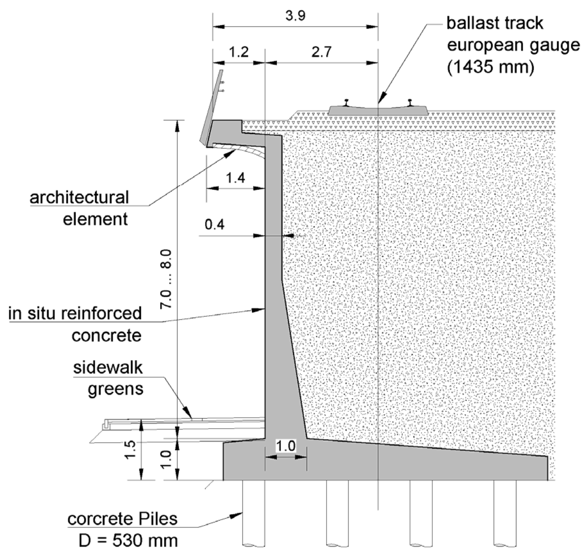

Figure 2. Typical Cross-section of retaining wall (Master Design)

3.2 *Detailed Design*

Figure 3 shows the typical cross-section of the geogrid reinforced soil retaining wall (MSE) which was developed within the Detailed Design and replaces part of the L-shaped wall. The MSE structure is designed as a “passive wall” (Hasslacher et al. 2022). This means that the geogrid reinforced soil body will carry all the load of the track whereas the front facing, which is made of a slim precast concrete panel, will only act as a finishing and protection. Since the facing panel will only be installed after the geogrid reinforced soil structure has been erected to its full height, the structure will be highly ductile during the construction phase. To increase stiffness and shear strength of the facing zone in the final state, however, a section of 1,5 m from the outer surface of the structure was built with broken gravel and blended with hydraulic binder. Behind this zone regular embankment fill was supplied, where compaction of the backfill zone was defined to be min. 98 % of Dpr., compaction in the facing zone had to be min. 100 % of Dpr. In this setup a MSE structure is capable of undergoing several centimeters of settlement without any harm. As only marginal settlement was expected during the operation time and consolidation was planned to be finished safely within the available project timeframe, neither ground improvement nor piled foundation was required. Implementation of ground improvement technologies like vibro-stone columns (VSC) or use of prefabricated vertical drains (PVD) however, would have been an option if the subsoil conditions encountered during excavation were found to be worse than assumed.

Between the geogrid reinforced soil retaining wall and the concrete facing panels, which have a width of 2 m and maximum height of about 6 m, there was left a gap of 150 mm. This gap was designed to accommodate tolerances and deformations which would develop during construction as well as during the period of consolidation. On the top of the structure there was planned to be a precast concrete element which is composed of two parts where the lower part is a concrete block which acts as a horizontal anchorage for the concrete facing panel. This part was installed prior to the installation of the concrete facing panels. Applying concrete grout below the element allowed to compensate for any settlement which had taken place until this moment. Once the facing panels were installed and connected to the anchorage block, the upper part of the coping structure was installed. This element covers the gap between the geogrid reinforced soil structure and the facing panel. It also hosts the cable duct running on top of the retaining wall as well as the maintenance path. The connection between lower and upper concrete elements is provided by means of steel dowels which are locally encased with concrete. The upper concrete elements are equipped with openings, always located at the position of the connection between facing and anchorage block. These are meant to enable inspection of the connection at any time after installation and – if required – to allow minor adjustment of the panel's position. An in-situ reinforced concrete strip foundation was cast to transfer the self-weight of the concrete facing panel down to the subsoil. A steel connection integrated into the panel base and dowels provided in the foundation strip allowed for adjustment at the panel base as long as grouting of those connections was not provided. Backfilling of soil in the construction pit was carried out up to the top level of the strip foundation prior to the installation of the facing panel.

A handrail is installed to protect maintenance personnel or passengers to be evacuated in case of emergency.

Summing up, the construction of the MSE comprised the following major steps:

- Clearance and excavation of the existing ground,
- Preparation of foundation (compaction, levelling),
- Erection of geogrid reinforced soil retaining wall,
- Application of preloading (sand),
- Removal of preloading,
- Execution of an in-situ concrete strip foundation,
- Installation of anchorage block (precast element),
- Installation of facing panel (precast element),
- Installation of coping element (precast element),
- Installation of track, cabling, etc.

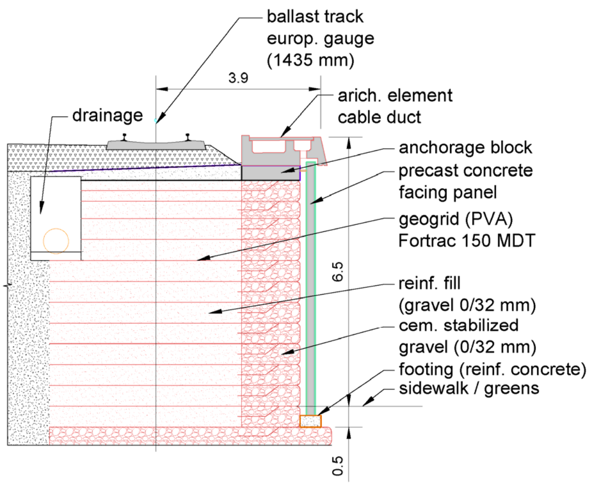

Figure 3. Typical cross-section of the MSE (Detailed Design)

4 DESIGN

4.1 *Ultimate limit state*

There are several national standards and guidelines available to design geogrid reinforced soil retaining structures. As harmonized standardization on the European scale was not (and still is) available at the time of the project, reference was made to the German design guideline EBGEO (2010). The reason to do so was that EBGEO (2010) allows to properly consider the effect of dynamic loading when estimating the long-term design strength and interaction behavior of the geogrid reinforcement. Design calculations involved the analysis of internal, external and compound failure surfaces and resulted in 6 m long reinforcement layers with a vertical spacing of 50 cm. Since the geogrid reinforcement was designed to be in contact with hydraulically stabilized fill-material in the facing zone special consideration had to be taken to prevent geogrid degradation due to hydrolysis. Hence, geogrids from Polyvinyl alcohol (PVA) were chosen because they are stable in alkaline conditions. Geogrid from Polyethylene terephthalate (PET) would not have been appropriate as PET is very susceptible in such (highly alkaline) ambiance conditions.

The design of all other elements (concrete, steel) was carried out based on the relevant European standards.

4.2 *Serviceability limit state*

4.2.1 *General considerations*

An important part in the design verification of MSE structures includes the proof of serviceability. For railroad structures, this is of particular importance as railway tracks allow for small differential deformation only. Limits for the allowable deformation depend on the type of track (ballast or slab track), track geometry (straight, radius or switches) and the design speed at the given location. This railway section consists of a ballasted track and has a (limited) design speed of 80 km/h. Table 2 shows the serviceability limits which had to be justified for the given situation.

Table 2. Deformation criteria as per RBDG-Man

Description	Unit	Value
Settlement of track after commissioning	cm	10
Settlement rate over 25 years	cm/year	1
Differential settlement over length of 15 m	mm	3
Differential settlement over length of 30 m	mm	8

4.2.2 *Finite Element calculation*

Although MSE technology has very successfully been applied for decades, there is still no analytical method available which allows for a dedicated analysis of deformations. Hence, Finite Element Modeling (FEM) was used to predict the deformation of the structure. Two separate models have been developed. The first model focuses on the influence of the MSE construction on existing structures and on the transition to the neighboring track section with L-wall. The second model focuses on the deformation of the MSE as such. In the first model the construction of the MSE was simplified as one single calculation step whereas in the second model various intermediate steps have been analyzed to more precisely model the compaction process and corresponding activation of the geogrid reinforcement layers. Experience in FE-modeling of MSE structures has shown that such detailed analysis is necessary to receive calculation results matching well with the behavior observed on site. Often FE-modeling of MSE results in higher deformation than what is measured in the field.

For both approaches Plaxis 2D Finite Element software was used applying the Hardening Soil model. Figure 4 shows the geometry of the first FE-model.

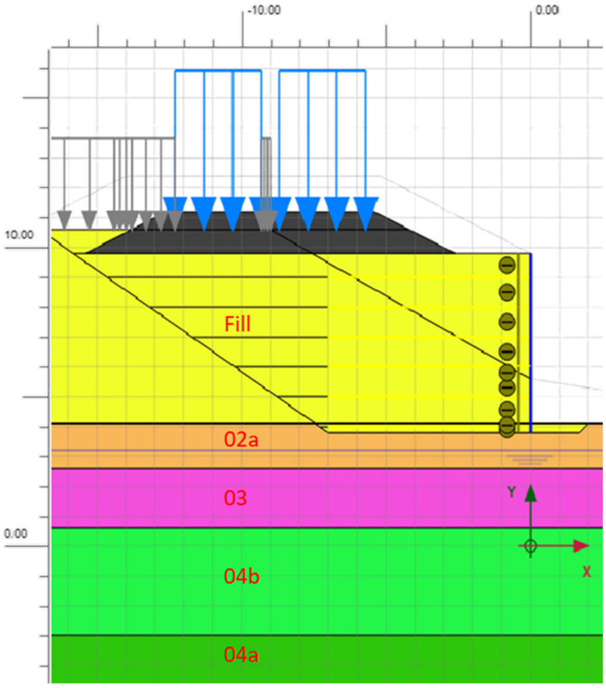

Figure 4. Geometry of the first FE-model in the final situation

4.2.3 *Calculation results*

Figure 5 shows the settlement and vertical stress of the total MSE over time for the most unfavorable cross-section close to the front face at the base of the wall, generated with the second FE-model. Table 3 shows a description of the corresponding calculation steps.

Table 3. Calculation steps and settlement of MSE

Construction Stage	cum. settlement [mm]	vertical stress [kN/m²]
Initial state	0	-
Excavation and compaction of MSE base	0	-
Level 1 of MSE	30	62
Level 2 of MSE	51	80
Level 4 of MSE	56	113
Level 6 of MSE	64	151
Level 8 of MSE	77	181
Level 10 of MSE	100	205
Level 12 of MSE	140	124
Preloading and consolidation to 1 kPa	153	106
Removal of preloading	150	110
Superstructure	168	171
Consolidation 180 days	167	96
Operation 52 kN/m² x 1.46 = 75.92 kN/m²	177	122
Total:	177	

These results were further processed to proof that the client's serviceability criteria were met. In that regard it is important to understand that only those deformation increments are relevant which are developing after the traffic load is applied. Deformation of the structure which is developing during the construction itself could have been compensated prior to commissioning of the railway traffic.

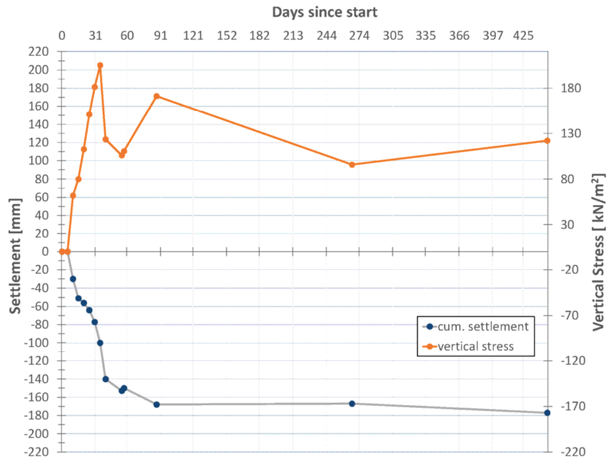

Figure 5. Calculated settlement and vertical stress over time

From Figure 5 and Table 3 it can be seen that the total settlement developing during construction and preloading was estimated to be in the range 18 mm. Furthermore it can be seen, that the immediate settlement induced by the implementation of the final traffic load would result in additional settlement of about 10 mm. Based on these findings it was proven that the deformation limits given with Table 2 (total settlement after commissioning < 10 cm) would be met with considerable safety margin and no ground improvement was required. Figure 6 shows that the calculated settlement rate over time occurs relatively fast and sufficient consolidation time was available during construction.

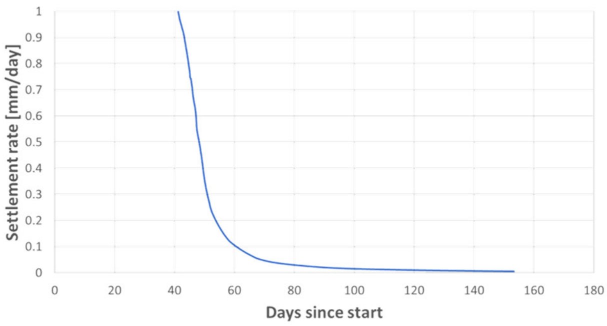

Figure 6. Settlement rate over time

Additional measures were necessary only in the transition zone between the MSE and the L-wall resting on piles. Figure 7 shows the plot of total displacements in vertical direction generated from the first FE-model in a longitudinal cross-section, where x-coordinates < "0" represent the L-wall with a cross-section as per Figure 2 and x-coordinates > "0" the MSE wall with a cross-section as per Figure 3. The calculated (differential) settlement after commissioning at distances of 15 m and 30 m from the transition shows that the serviceability criteria are met by applying FDP piles with decreasing length (increasing toe level) in a 30m long transition zone.

Table 4. Total settlement in transition zone

Distance from interface [m]	Settlement [mm]
0	9.7
15	11.9
30	14.9

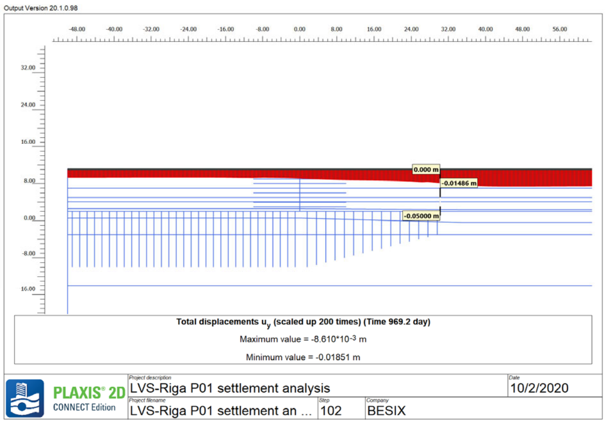

Figure 7. Total vertical displacements in longitudinal direction of the retaining wall (30 m from interface)

5 MONITORING

5.1 *General*

In view of the geotechnical complexity as well as the importance of the time-settlement behavior for the overall schedule of the project, a monitoring program was set up in parallel with the construction of the MSE.

5.2 *Monitoring concept*

The primary objective of the monitoring program was to prove that the estimated settlement and consolidation time were not exceeded. A significant number of standard settlement gauges were installed in totally 8 cross-sections along the wall. Figure 8 shows the arrangement of the gauges in a typical section, with a gauge always located at the bottom of the MSE one near the front of MSE and a second at the rear end of the reinforcement. Latter was considered the main gauge for settlement observation. Additional gauges were installed between the 3rd and 4th reinforcement layer and before placing the last layer (all counting from the bottom of the MSE). The fourth gauge was placed on top of MSE, which is 1.2 to 1.3 m below the top of the rail. Reading of the settlement gauges was carried out at least every week / and after finishing each layer of the MSE.

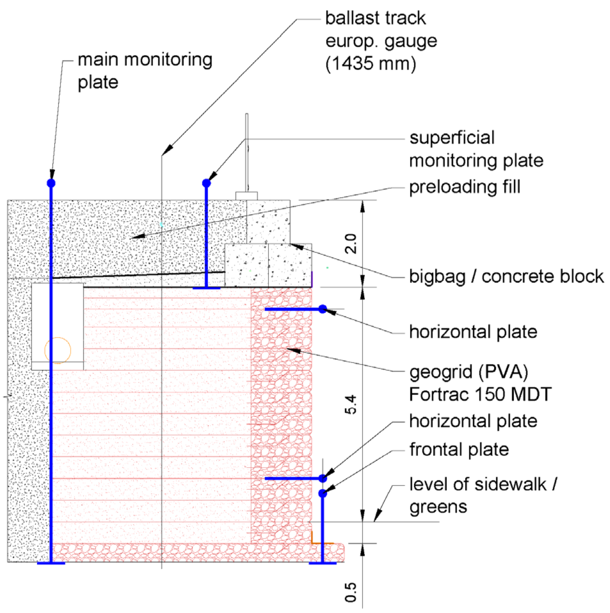

Figure 8. Arrangement of settlement gauges (typical section)

5.3 *Comparison of monitoring and prediction*

Figure 9 shows the time-settlement behavior of the main monitoring gauge at the rear end of the MSE in the cross-section No. 1 which is located close to the transition between L-wall and MSE. Additionally, Figure 9 shows the settlement which was predicted with the first FE-model. Settlement observed in the field is significantly lower than what was estimated during design. The main reason for this discrepancy was the conservative estimation of the thickness and stiffness parameters of the top soil layers. Taking the best-estimate soil profile, as presented in section 2, the thickness of the layer 03 can significantly be reduced and the stiffness of the sand layers (layers 02a and 04b) can be increased. The estimated settlement from this back-calculation is shown in Figure 9 and corresponds much better with the monitoring results. Nevertheless, the ductility of the MSE allowed to deal with the uncertainty of the subsoil conditions without the need for a deep foundation.

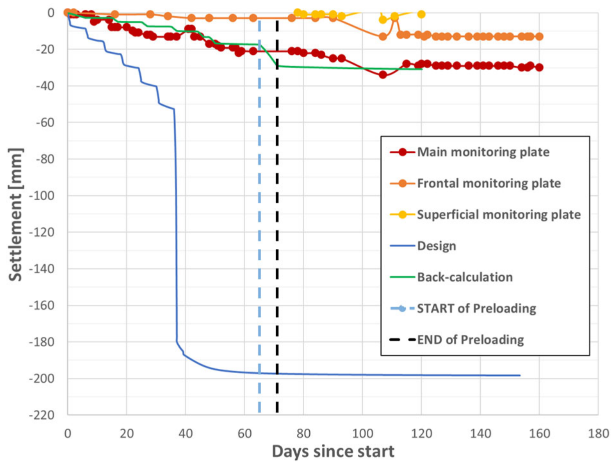

Figure 9. Time-settlement at measurement section 1 (monitoring vs. FEM-calculation)

6 CONCLUSIONS

Within the framework of the Detailed Design of retaining walls at Riga's new central station it has been demonstrated that the concept of preloading and consolidation can be applied not only for embankments with standard slopes but also for geogrid reinforced soil retaining walls. A passive facing system is required to accommodate settlement and consolidation while preventing adverse impacts on the structures. Geogrid reinforced soil structures offer the necessary ductility. To prove the serviceability of MSE, in particular when designing a structure on compressible ground, FEM is an essential and powerful tool. Proper modeling and input parameters, however, can have a significant influence on the output of the calculations. Due to the main objective of the FE-Modelling lower bound parameters were used in the design of the MSE. *This enables safe project planning; however, in the absence of sufficient time and budget for detailed model calibration, it may lead to overly conservative estimates when compared with field measurements.* Nevertheless, the flexibility of the MSE solution in combination with an efficient construction and sufficient consolidation time allowed to deal with the uncertainty of the subsoil conditions without the need for a deep foundation.

7 ACKNOWLEDGEMENTS

Thanks is given to RailBaltica supporting to implement the innovative concept and enable an economic and sustainable approach.

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