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EURO 2008 STADIUM KLAGENFURT – PREDICTION, MONITORING AND BACK CALCULATION OF SETTLEMENT BEHAVIOUR

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ABSTRACT: The new Klagenfurt stadium and the adjacent gymnasium and soccer academy comprising a capacity of 32,000 spectators were constructed from 2006 to 2007 for the European Soccer Championship EURO 2008. The ground properties are predominated by saturated soft clays, silts and sands. The underlying bed rock was found in different depths, thus, the thickness of soft soils varies from about 30 to 80 m. The ground was improved by installing stone columns using the vibro replacement technique up to about 18 m, thus homogenizing the ground conditions in the upper layers. Nevertheless, large settlements in the range of up to 15 cm were predicted due to the large foundation area and high loads affecting the ground up to about 60 m. During construction and current long-term settlement measurements have been performed to record the time-dependent deformation behaviour of the ground. Moreover, a well instrumented field trial was carried out during construction. The instrumentation consisted of multilevel-piezometers, multilevel-extensometers and earth pressure cells as well as a horizontal inclinometer. Semi-analytical and numerical simulations using constitutive models were performed to calculate the settlement process and final settlements. Actual settlement measurements show both consolidation and probably creeping behaviour of the soil as well. Calculations based on a sophisticated constitutive model have been applied in order to take into consideration the observed soil deformations.

1. Introduction

In 2008 the European Soccer Championship took place in Austria and Switzerland. Klagenfurt was one of the venues amongst others in Austria in particular in Salzburg, Innsbruck and Vienna. The new so called Wörthersee Stadium was situated near the center of Klagenfurt in the vicinity of the Wörthersee, a large glacial lake in Carinthia.

The project consists of the stadium oval with the integrated west building and three (temporary) canopied grandstands for 31,000 spectators. A new soccer academy building and a multifunctional gymnasium is directly connected to the oval. The stadium was designed in a way that the upper standings of the three grandstands can be deconstructed after the European Championship to a reduced size for 12,000 spectators. The characteristic form remains but the loads are significantly reduced.

Originally a bored pile foundation was designed for the west building due to the unfavorable ground conditions. Alternatively a shallow floating raft foundation on stone columns installed with the vibro replacement technique was executed. For the foundation of the girder and column structures of the three grandstands, the soccer academy building and the multifunctional gymnasium the ground was improved by stone columns as well as the ground beneath the highly loaded sections of the access ramp on the south west side of the stadium. Due to the unfavorable ground conditions settlements of about maximum 20 cm were predicted so that the deformation compatibility of the particular structures had to be carefully taken into consideration.

Fig. 1: EURO 2008 Stadium Klagenfurt.

2. Ground conditions

Prior to construction ground exploration and soil investigation was performed in two phases. Rotational core drillings and dynamic probing heavy (DPH) and moreover, seismic investigations to determine the interface between soft soil and bed rock revealed the following soil structure on the site of the stadium [1], [2], [3]:

Beneath the topsoil young unconsolidated sediments consisting of medium to coarse (gravelly) sands and silt (loam) are deposited up to a depth of 10 to 12 m below surface. Loose to medium dense sands predominate with increasing depth. These layers are underlain by young unconsolidated lake deposits consisting of medium dense silty fine sands followed by silty and clayey lake deposits up to 30 to 48 m beneath surface. Horizontally layered (very) soft clayey silts predominate and alternate with thin layers of silty fine sands and fine sandy silts. These lake deposits rest on sands and the ground moraine, the depth of the underlying bed rock consisting of sound quartz phyllite varies in a wide range below surface from about 31 in the north to about 60 m in the south.

The groundwater table was explored in the drillings in a depth of about 2.3 m. The groundwater level fluctuates seasonally in a range of about 2.5 m in average. The groundwater is near the surface, thus influencing the soil conditions significantly.

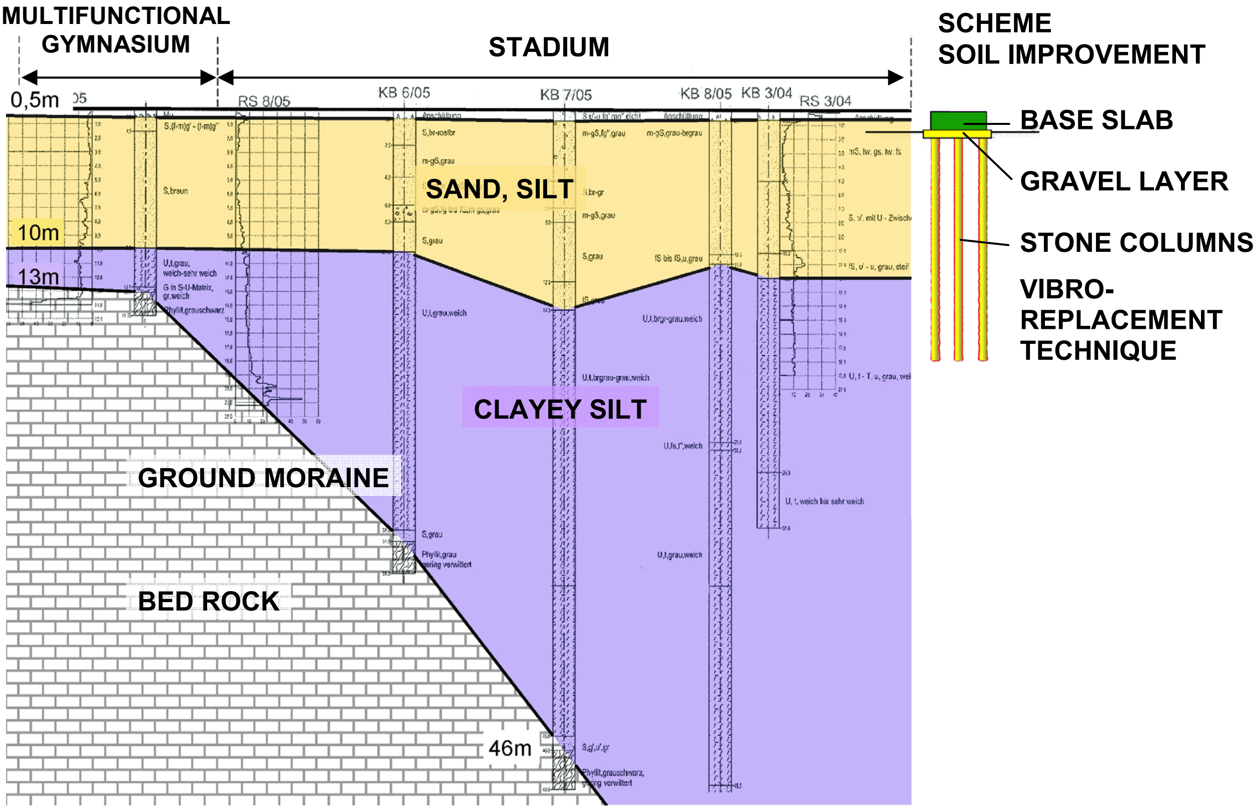

Fig. 2: Ground conditions at the site of the stadium (schematic).

3. Soil improvement and foundation concept

Beneath all structures (west building, girder and column structures of the three grandstands, the soccer academy building and the multifunctional gymnasium, various single foundations) the ground was improved by installing stone columns and was thus prepared for the shallow foundations. The stone columns comprise a length of about 10 to 18 m below surface and were arranged taking into account the calculated foundation pressures and the soil interfaces found during installation. Thus, it was intended to homogenize the ground conditions on the one hand and to minimize the settlements and differential settlements on the other hand. Moreover, it was intended to accelerate the consolidation process in the ground through the highly permeable stone columns [4].

In addition the liquefaction potential of the collapsible soil in the upper layers was reduced to increase the seismic soil resistivity in a case of an earthquake. This could be achieved by improving the shear parameters and increasing the overall permeability of the ground. Moreover, the compactable soil was improved around the stone columns by the vibratory installation process using the bottom feed vibrator technique. For drainage and load distribution a gravel layer was filled above the improved ground with varying thickness for the respective structure. The reinforced concrete slab of the west building was extended by a cantilever comprising a length of about 2 m in order to improve the pressure distribution due to the non-uniform loads beneath the raft foundation. Additionally, at the rear of the west building a preloading was applied to anticipate a specific portion of the expected settlements. Settlement measurements revealed that up to about 12 cm of settlements occurred from the preloading fill. Differential settlements between the west building and the adjacent (temporary) grandstands were taken into account by superelevating the raft foundation of the west building. In the area of the outer stairs in the northwest the soil was preloaded by a demolished building. The maximum allowable soil pressure was limited to 115 kN/m² since no deep ground improvement could be performed there. Soil exchange with recycled concrete aggregate was carried with a thickness of 100 cm. In the lower part of the access ramp in the southwest of the oval the ground was not improved.

The 10.5 m high ramp adjacent to the west building was filled on ground improvement by stone columns for following reasons:

- Reduction of settlements to minimize deformations which could affect the west building;
- Acceleration of settlements by increasing the overall permeability of the ground to reduce the residual consolidation settlements to a minimum for the incorporated concrete structures, like transformer room, retaining walls and the bridge structure;
- Increase of shear strength of the soil to avoid local ground failure due to quick filling procedure;
- Providing sufficient safety against mechanical ground failure of structures which are incorporated into the ramp (especially the transformer room and the retaining structures).

A preloading in the front area of the ramp anticipated a considerable portion of predicted settlements. The preloading fill was removed after defined settlements occurred and the concrete structures were constructed. In defined areas of the multifunctional gymnasium with lower loads (playing field, access area) soil exchange was performed instead of stone columns. The base slab of the gymnasium was filled with concrete at the latest date after completion of the structure to minimize differential settlements between the structure and the base slab.

Ground improvement was checked by following test procedures:

- Dynamic probing heavy (DPH) before and after installation of stone columns to verify the improved properties of the ground;
- Dynamic load plate tests with the Light Falling Weight Device (LFWD) to check the bearing capacity and stiffness of the gravel fill layers and the exchange soil layers;
- Roller integrated Continuous Compaction Control (CCC) with vibratory rollers to check all fill layers and the formation layers of the foundations (e.g. raft foundation).

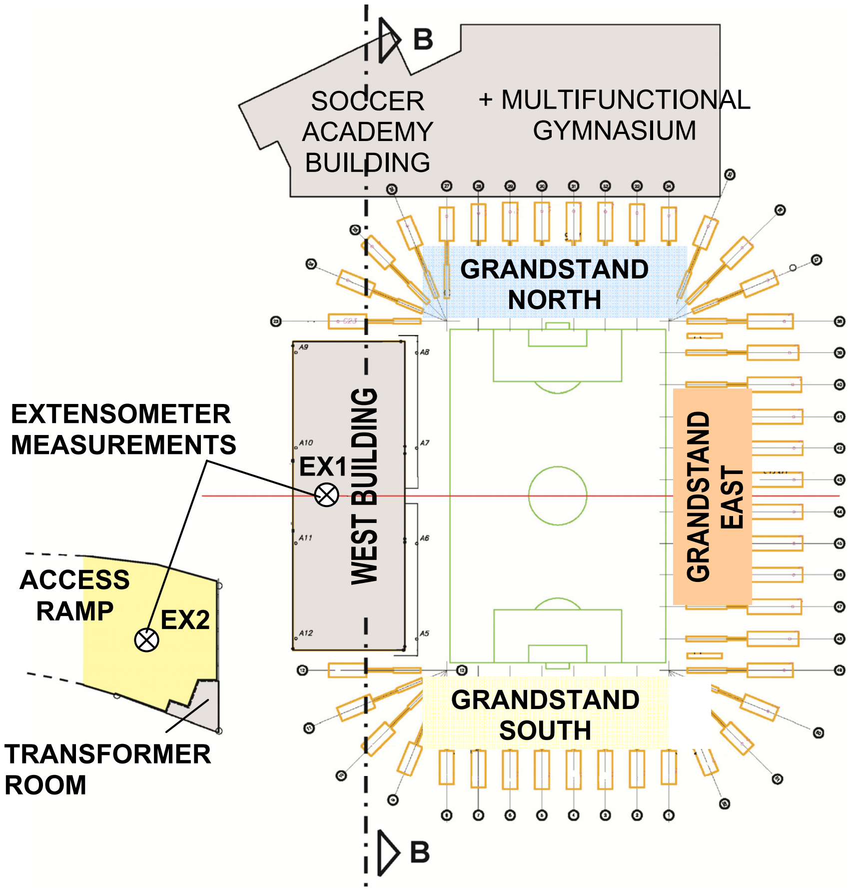

Fig. 3: Layout of foundation scheme of several structures of the stadium.

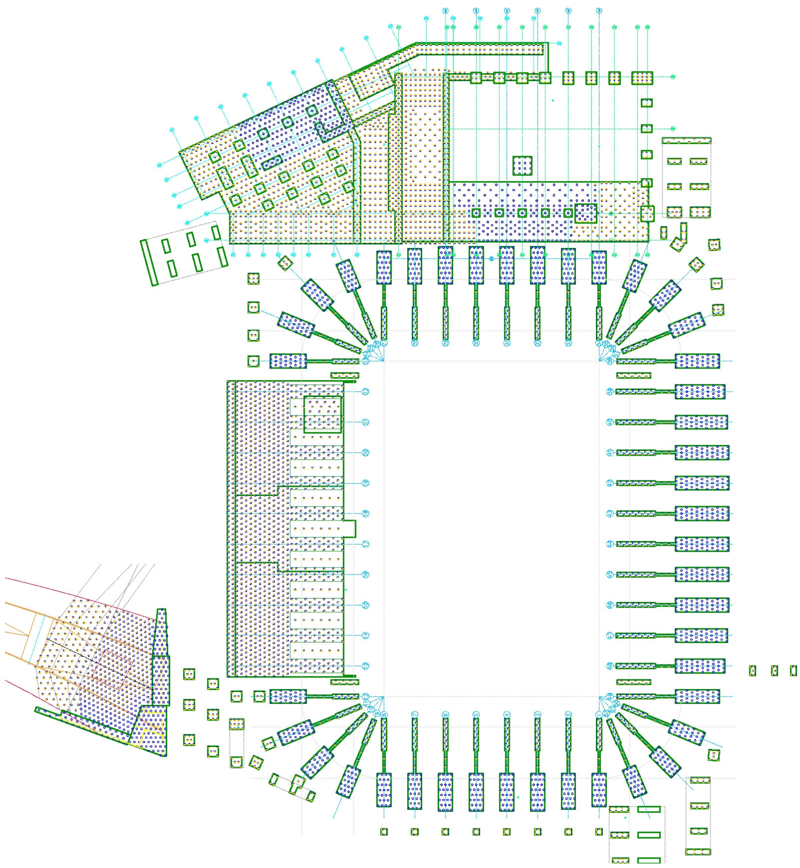
Fig. 4: Layout of executed stone columns.

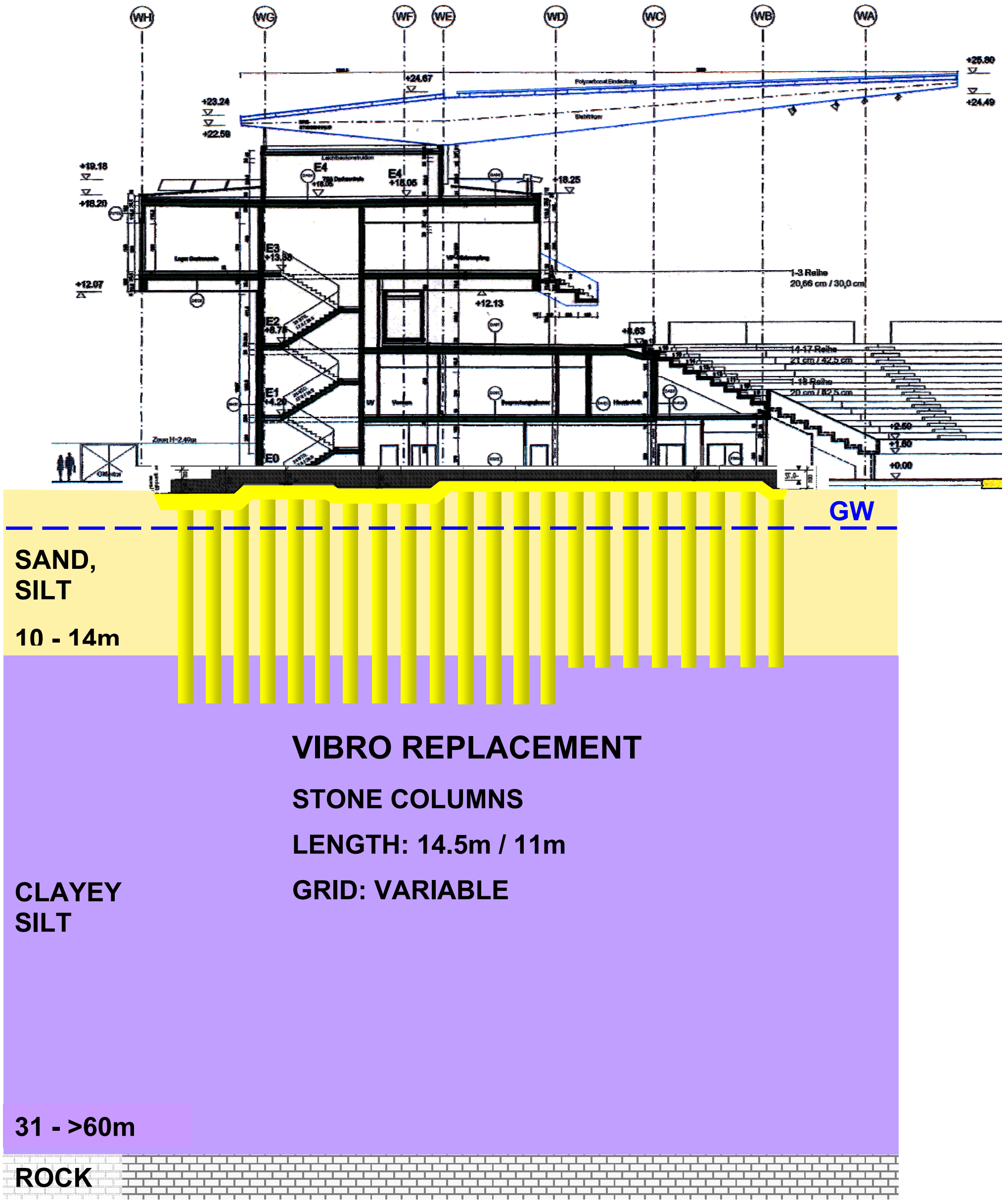

Fig. 5: Cross section of the west building, raft foundation and stone columns.

4. Prediction of settlement behaviour

The deep soil improvement with installed stone columns caused an increase of the bearing capacity of the ground, compaction of the soil by activating the self compaction potential of the soil, a homogenization of the ground properties and an acceleration of consolidation settlements by increasing the overall permeability. Below the stone columns lake deposits comprise relatively homogeneous conditions but long-term settlements of about 3 to 6 cm after completion were predicted by the consolidation process and possibly by a creeping process as well. Due to the permeability and the stiffness of the soil it was assumed that he consolidation process will take some years.

In the design phase of the foundation concept settlement calculations were performed in order to predict the settlements and differential settlements for each building. In Table 6 the total settlements including the consolidation process are presented.

Tab. 1: Predicted settlements (expected values) for the west building taking into consideration soil improvement with stone columns and an extended slab [4].

	s	Δs	length	inclination	
	[mm]	[mm]	[m]	[%]	[-]
corner SW	150	-	-	-	-
corner NW	130	-	-	-	-
corner NE	80	-	-	-	-
corner SE	90	-	-	-	-
outer side W	-	20	101	0.02	1/5050
side N	-	50	34	0.15	1/680
inner side E	-	10	101	0.01	<1/10000
side S	-	60	34	0.18	1/567

Settlement calculations revealed that settlements along the outer side in the west of the west building will be significantly larger compared to the inner side in the east because of the non-uniform load distribution. Moreover, the calculation results showed that the settlements in the north would be smaller than in the south of the west building. On the one hand the rock bed is not so deep below surface in the north than in the south and on the other hand the settlements of the access ramp affected the southern part of the west building as well. For this reasons an additional preloading fill was installed in the south of the west building.

The differential settlements within the west building were estimated to about 9 cm, nevertheless the derived angular rotation of the west building was within the limits. Thus, by means of the large dimensions the serviceability of the building was not affected by the differential settlements.

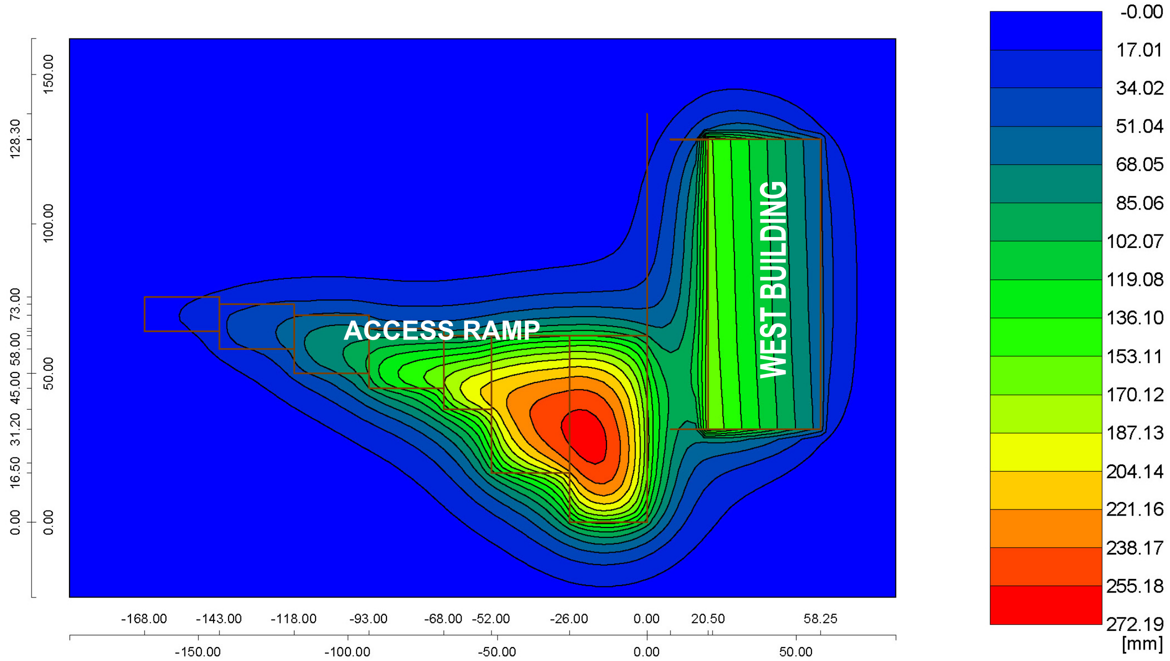

Fig. 6: Calculated total settlements and determination of the mutual influence of west building and access ramp.

5. Monitoring of settlements

Settlement monitoring during the various construction sequences was performed in order to provide a continuous observation of the settlements of the ground. Measurement points for long-term settlement monitoring have been installed at the west building, the girder and column structures of the three grandstands, and the transformer building.

At the west building currently the settlements amount up to maximum 14 cm at the outer side (east) and up to maximum 7 cm (west). In comparison to the last settlement measurements a remarkable increase of the settlements was observed in the southwestern corner of the stadium.

Results of the progress of settlements over time reveal that the outer and the inner sides of the west building settle unequally. In the period from March 2007 to December 2009 (about 33 months) the inner side settled for about 1.5 cm while the outer side settled for about 7 cm. Moreover, the southwestern corner (about 7 cm) is stronger affected by the ramp than the northwestern corner (about 5.5 cm). As expected the settlements are influenced by the superposition of the deformations of the west building and the ramp.

Progress of settlements over time and the evaluation according to Sherif [11] show that the settlements decay already at the inner side but until now not at the outer side. According to the evaluation according to Sherif about 80% of the total settlements occurred so that about 20% are still to be expected in the future.

In spite of the differential settlements between the outer and the inner side of the west building the maximum gradient of the VIP box in the upper floor is in a range of about 0.2% according to the measurements. Thus, the serviceability of the building is not affected by the differential settlements.

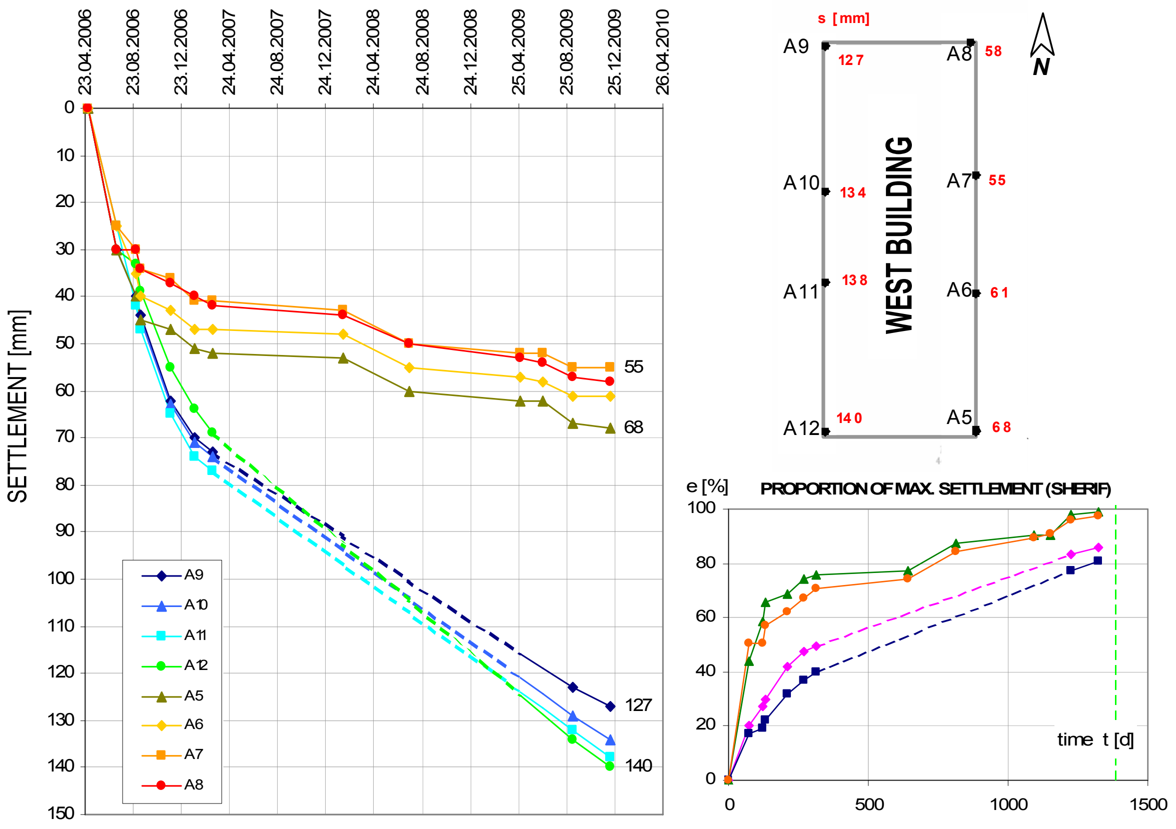

Fig. 7: Geodetic settlement measurements for the west building, position of the measurement points and prediction of final settlements according to Sherif.

The differential settlements at the girder and column structures of the three grandstands are in a range from 0 to 0.8 cm. Only between the structures G11 and G12 and between G23 and G24 adjacent to the west building the differential settlements are larger as expected due to the influence of the west building. However, different deformations can be taken into account by readjusting the tension rods of the bracings. Differential settlements are limited to 2 cm only at foundations of girder and column structures with fixed bracings consisting of tension and pressure rods (so called K bracings). Actual measured values are however far below this limit values.

Settlement measurements show that total settlements have only marginally increased. However, it is expected that certain additional consolidation settlements occur.

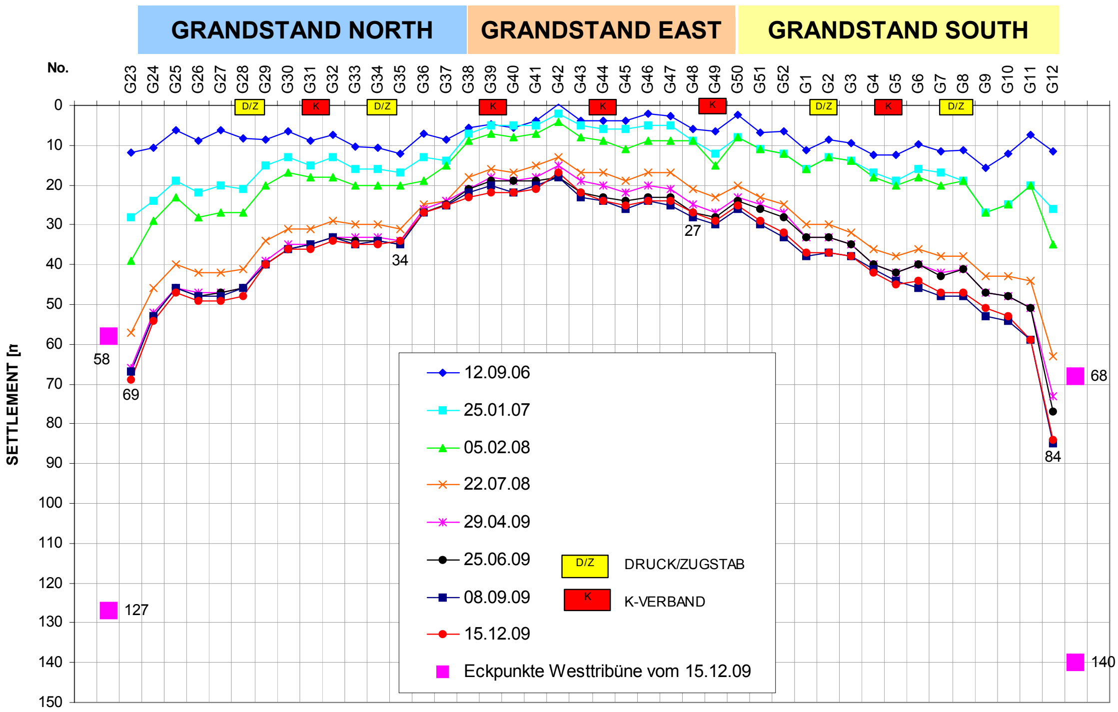

Fig. 8: Settlements over time at the girder and column structures of the three grandstands.

Measured total settlements at the ramp show maximum values of about 18 cm. By means of the influence of the west building additional settlements occur at measure point SP34. Additional settlements at measure point SP36 are caused by the loads on all sides and the extensive settlement influence of the access ramp. The prediction of the final settlements according to Sherif has revealed that about 80% of the total settlements have occurred up to the present.

In a large scale well instrumented field trial consisting of multilevel-piezometers, multilevel-extensometers and earth pressure cells as well as a horizontal inclinometer the performance of the floating stone column foundation was investigated. The measurements give valuable insight into the installation process of stone columns and the evolution of pore water pressures and settlements over time beneath the 10.5 m high access ramp [5]. In Figure 11 results of extensometer and multilevel-piezometer measurements are presented revealing the effect of increasing the over-all permeability in the zone of the stone columns. Pore water pressures decrease rapidly after completion of stone columns installation thus accelerating consolidation settlements in the ground. Below the stone columns the permeability of the ground is low so that pore pressure and consolidation settlement take a long time presumably some years.

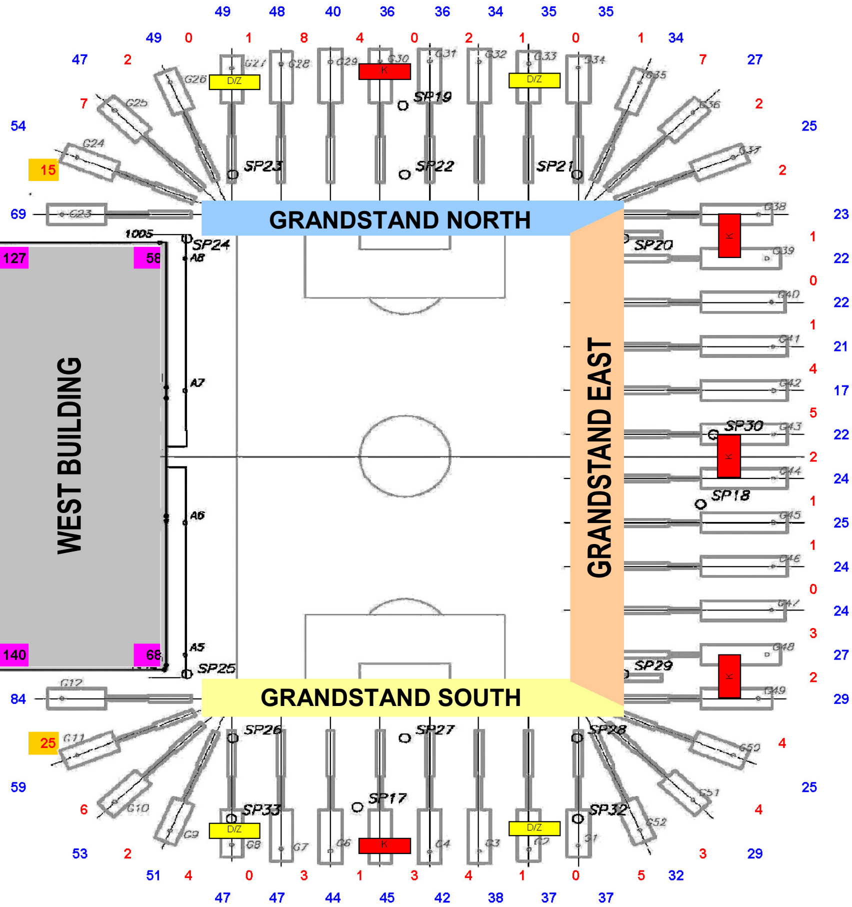

Fig. 9: Geodetic settlement measurements (blue; unit: mm) and differential settlements (red; unit: mm) between the girder and column structures of the three grandstands; measurement campaign of December 2009.

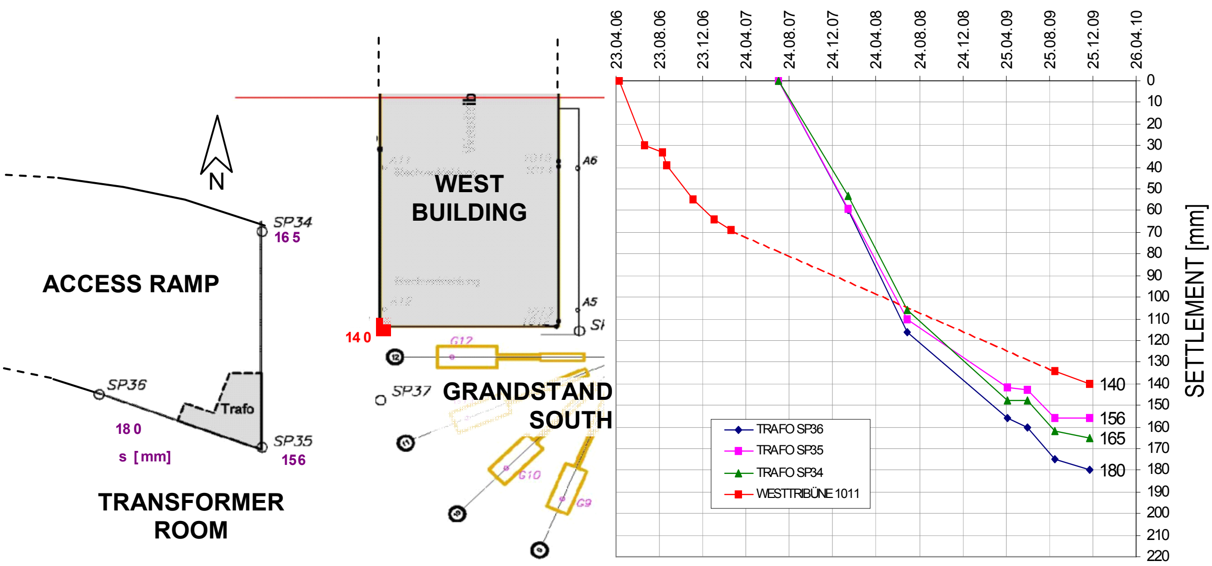

Fig. 10: Geodetic settlement measurements at the access ramp and comparison with measured settlements at the southwestern corner of the west building.

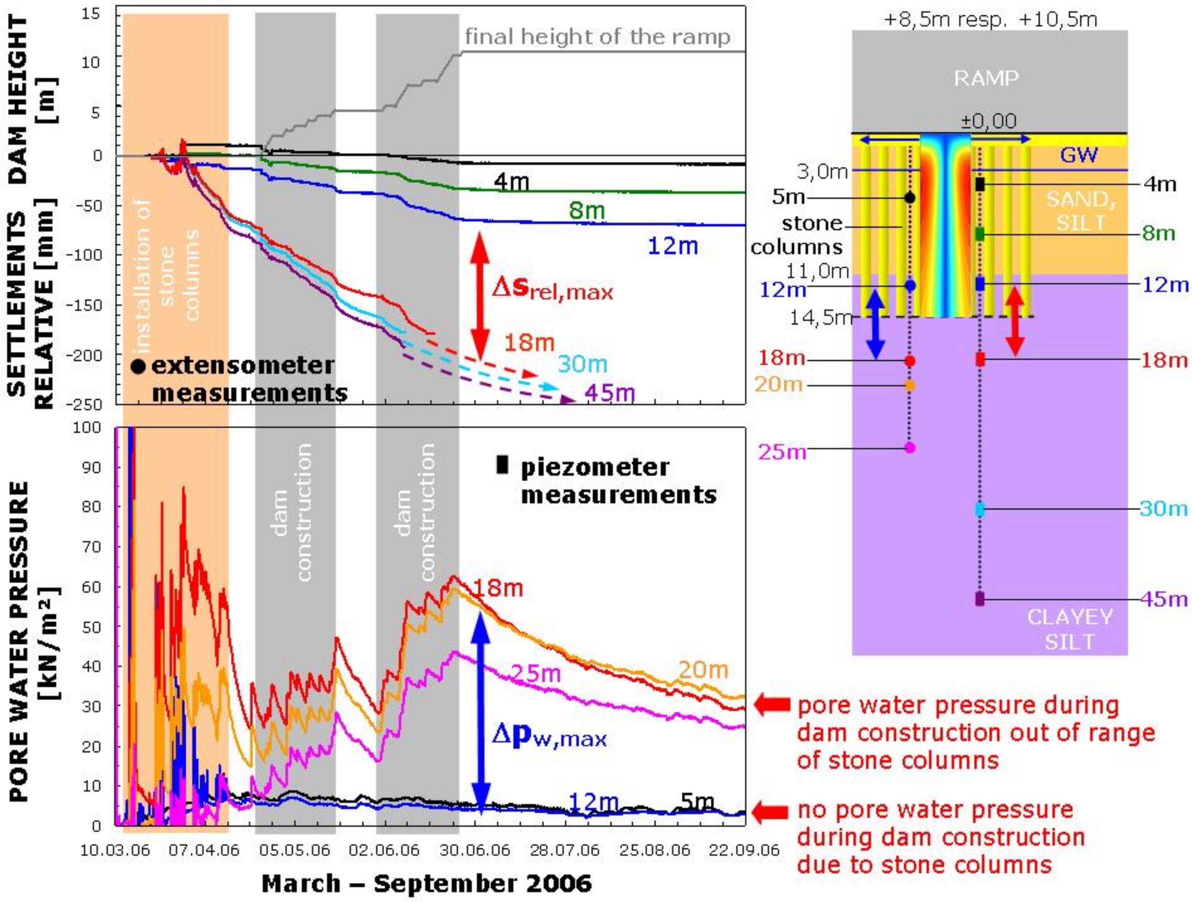

Fig. 11: Results of the large scale field trial to investigate the performance of the floating stone columns foundation beneath the access ramp [5].

6. Back analysis of settlements of the west building

A series of finite element analyses have been performed for this project and comparison of field measurements with 2D analyses employing different constitutive models has been presented in [6] for the heavily instrumented trial field set up in the area of the ramp. Thus these results will not be repeated here but results from back analysis of the settlement behaviour of the west building will be discussed in the following. In addition to the settlement measurements shown in Figure 9 an extensometer has been installed at the west building (location see Figure 3) and these measurements will be considered too.

6.1. Short description of numerical and constitutive models

Considering the ground conditions a 3D model would be required to capture the inclined layers of soil in detail. However, for this preliminary study a cross section through the middle of the west building is taken postulating plane strain conditions (see Figure 12). The stone columns are modelled as “walls” with depths of 14.5 m on the left side and 10.5 m on the right side respectively. The space between the stone columns is 0.9 m. Figure 12 also shows the different soil layers according to Figure 2. It is noted that for simplicity the layers are assumed as horizontal. The rock (Quarzphylit) is not modelled, because its influence on the settlement behaviour can be considered negligible. Around the stone columns a zone is introduced in which the material properties have been adjusted. In this sand layer (“Sand dense”) the stiffness has been increased due to significant compaction of the originally loose sand during the installation of the columns.

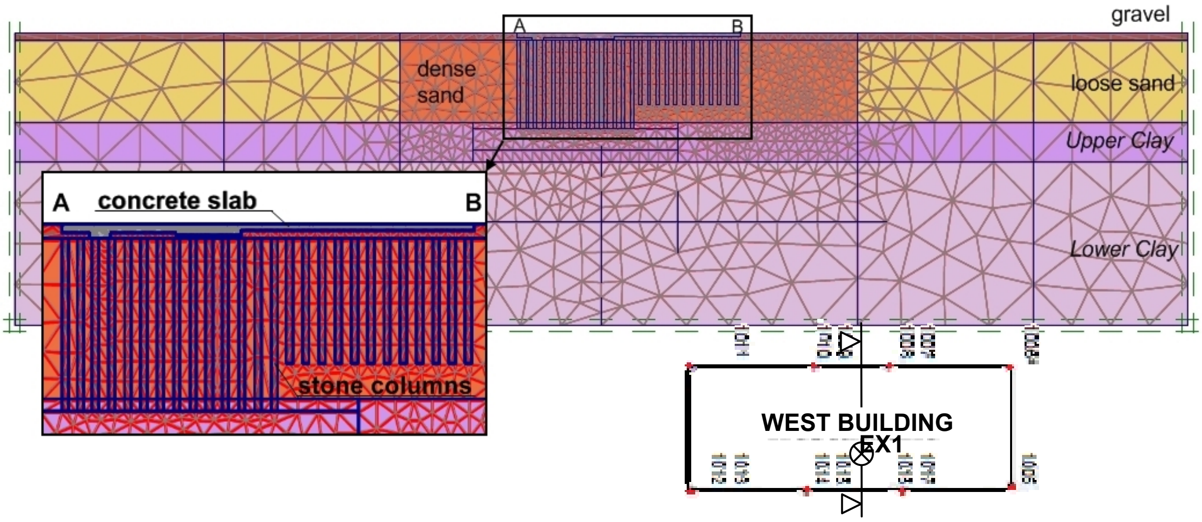

Fig. 12: Cross section and 2D numerical model

The Soft Soil Creep model (SSC) is used for this study which is an extension of the so-called Soft Soil model, both available in model library of the finite element code Plaxis [7]. The Soft Soil Creep model is based on the approach proposed by Bjerrum and Janbu [8, 9] and considers time and strain rate effects. Thus the total strain consists of a time independent elastic part and a time dependent visco-plastic part. The creep effects are introduced by the modified creep index μ^*, which is related to the creep index C_α. The constitutive parameters required for the SSC model are the modified compression index λ^*, the modified swelling index κ^*, the modified creep index μ^*, the friction angle φ', cohesion c', dilatancy angle ψ, Possions's ratio ν and coefficient of earth pressure at rest $K_0,^{nc}$. These parameters can be determined by standard triaxial and oedometer tests. A detailed description of the model can be found in [10]. The Soft Soil Creep model is used for the clayey silt layers, for all other soil layers and the stone columns the Plaxis Hardening Soil model [7] is used. The parameters are summarized in Table 2.

Tab. 2: Material parameters for soil layers

	k_x	k_y	γ	γ	c	φ	ψ	ν	κ^*	λ^*	μ^*		OCR	$K_{0,nc}$
	[m/s]	[m/s]	[kN/m²]	[kN/m²]	[kN/m²]	[°]	[°]	[-]	[-]	[-]	[-]		[-]	[-]
Upper Clay	2.6E-9	7.9E-9	16	19	10	22.5	0	0.2	0.0053	0.028	0.0009		1.3	0.617
Lower Clay	2.4E-8	2.3E-7	16	19	10	22.5	0	0.2	0.005	0.026	0.00085		1.3	0.617
	k_x	k_y	γ	γ	c	φ	ψ	ν	E_{50}^{ref}	E_{oed}^{ref}	E_{ur}^{ref}	m	OCR	$K_{0,nc}$
	[m/s]	[m/s]	[kN/m²]	[kN/m²]	[kN/m²]	[°]	[°]	[-]	[kN/m²]	[kN/m²]	[kN/m²]	[-]	[-]	[-]
Loose sand	1E-5	1E-5	18	21	0.1	27.5	2	0.2	16000	16000	80000	0.55	1	0.538
Dense sand	1E-5	1E-5	18	21	0.1	27.5	2	0.2	40000	40000	120000	0.65	1	0.538
Stone columns	1E-5	1E-5	20	23.5	0.1	35	5	0.2	25000	25000	75000	0.3	1	0.426
Gravel	1E-5	1E-5	20	20	0.1	35	0		35000	35000	105000	0.5	1	0.426
Concrete slab	-	-	25	-	-	-	-	0.2	3E7	-	-	-	1	-

6.2. Results

Results from the numerical back-analysis are compared to the measurements of points (1007/1008 (A10) - 1009/1010 (A11) and 1014/1015 (A6) - 1016/1017 (A7)) according to Figure 7. These data correspond to the simulated vertical displacement of points A and B (Figure 12). Furthermore, available extensometer measurements (EX1) are taken into consideration. The results for vertical displacements versus time are illustrated in Figure 13. The calculated vertical displacements in point A agree very well with the measurements of 1007/1008 and 1009/1010. Also the measurements obtained form of the extensometer in 4 and 8 m depth can be reproduced very well. However, vertical displacements in point B are too high compared to measured values. The reason for this discrepancy is not yet clear and needs further investigations. It is likely that the load in this section has been overestimated.

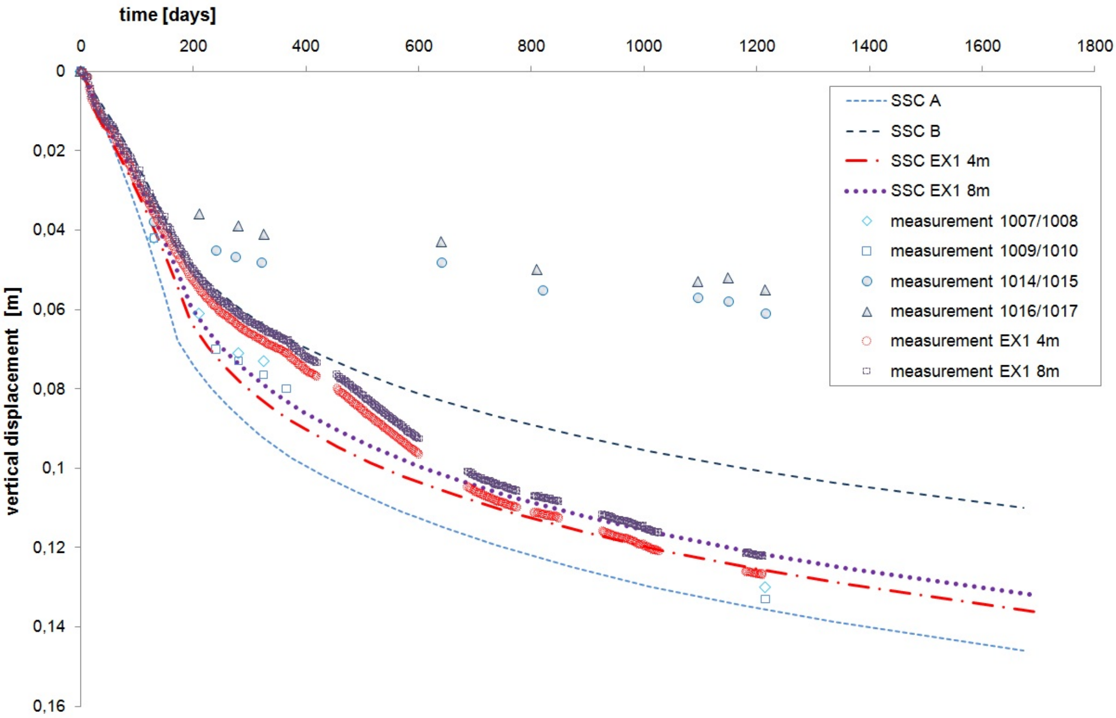

Fig. 13: Results of back-calculation using SSC model: vertical displacements

7. Conclusions

This paper presents the settlement behaviour of the new stadium in Klagenfurt which was built from 2006 to 2007 for the European Soccer Championship EURO 2008. Due to the unfavourable soil conditions consisting of unconsolidated lake deposits underlain by moraine and the bed rock in varying depth large settlements were predicted and significant differential settlements were expected due to non-uniform loads which had to be taken into account for compatibility requirements between adjacent structural elements. Ground conditions were improved and homogenized up to 18 m by installing stone columns using the vibro replacement technique. Long-term monitoring of settlements and a well instrumented field trial have been carried to document the time-dependent settlement process and to investigate the performance of the floating stone column foundation. Back analysis using the Soft Soil Creep model (SSC) was performed to calculate the settlement process and final settlements. Results compare well with measurements from the extensometer and agree with measured settlements of the foundation slab at the west side. Agreement on the east side is less satisfactory and one possible reason for this could be that the load has been overestimated in this part of the foundation.

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