Back analysis of settlements beneath the foundation of a sugar silo by 3D finite element method

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In the city of Kaposvár, Southwestern Hungary, a new sugar silo with a diameter of approximately 60 m and a storage capacity of 60,000 tons was constructed in 2013 on the site of Magyar Cukor Ltd. (Figure 1). The purpose of the recent study is to back analyse the foundation performance of the sugar silo. The behaviour of the sugar silo and its settlement were continuously monitored during the filling process by using geodetic methods. This enabled the back analysis of the silo foundation's behaviour. The objective of the analysis presented herein is solely academic. Settlements are computed by means of a finite element model created based on the available soil investigation results and the results are compared with the measured data.

1. Model geometry

The dome-shaped upper structure is connected to the foundation by a circular, vertical wall structure. The stored bulk material is drained from the silo through an underground tunnel.

The most important geometric properties of the silo are as follows (Figure 2):

- top of the base slab:
  ±0.00 or 131.95 m above sea level
- external diameter of the structure: D = 58.34 m
- height of the structure: H ≈ 39 m
- bottom level of the unloading tunnel:
  -4.00 m or 127.95 m above sea level

The load transfer from the upper structure to the subsoil is provided by reinforced piles connected to the beam below the outer walls and to the base of unloading tunnel. At the base of the silo, a 25 cm thick reinforced concrete base slab was constructed.

Rigid inclusion technique was used to improve the deformation properties of the underlying soil layers. Within the outer ring, in the inner area of the silo, the load distribution and load transfer to the rigid inclusions are ensured by an approximately 2 m thick, dense, coarse grained subgrade layer reinforced with geogrids (Figure 3).

The side-to-side distance between the piles varied over the range from 1.5 m to 2.5 m. Parameters of the used piles and inclusions are summarised in Table 1 and their layout is shown in Figure 4.

(a) (b)

Figure 1: Pictures of the sugar silo: (a) Under construction, and (b) After completion

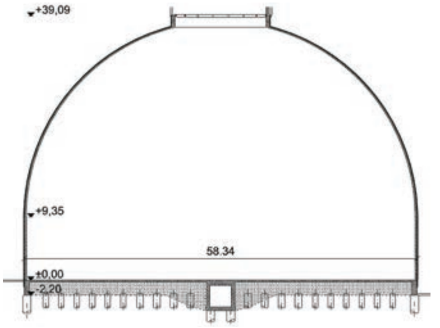

Figure 2: Geometry of the silo

The newly built silo is located on the site of Magyar Cukor Ltd., where other heavy-loaded structures had already been built. These buildings are supported by deep foundation, usually by 16 to 20 m long piles.

2. Soil conditions

In the construction area, two 50 m deep borings were performed with a 180 mm diameter hollow stem auger and sampling was carried out with double wall barrel.

In order to supplement the information gathered from the borings, one Cone Penetration Test (CPTu) and two seismic CPTu were also carried out. Shear wave velocity measurement was performed in every 2 m. The soil exploration revealed that the layers are approximately horizontal in the investigated area.

Table 1: Properties of the used piles

Pile	Notation	Material	Number of piles	Diameter [cm]	Length [m]
C1	🟩	Reinforced concrete	51	100	14.70
C2	🟦	Reinforced concrete	1	100	12.52
C3	⬛	Reinforced concrete	38	120	12.52
C4	🟦	Concrete	4	120	14.95
C5	🟪	Concrete	136	100	14.95
C6	🟥	Concrete	146	80	14.95

Based on these in-situ observations and the subsequent detailed laboratory program, the following soil layers were distinguished:

- 🟩 Mg:Various manmade fill (0.0-2.2 m),
- 🟦 A: Plastic SILT / SANDY SILT (2.2-11.0 m),
- 🟩 B: Firm SANDY SILT / SILTY SAND (11.0-14.9 m),
- 🟨 C: Medium dense - dense SAND (14.9-19.9 m),
- 🟪 D: Firm SILTY CLAY / CLAY (19.9-31.7 m),
- 🟫 E: Stiff, tertiary ("Pannonian") CLAY (31.7 -50.0 m).

The small-strain shear modulus of each layer was obtained from the shear wave velocity measurements of the seismic CPTu-s. Shear strength parameters were determined from simple shear and triaxial tests, while compression characteristics were evaluated by means of oedometer tests.

3. 3D finite element model

The detailed soil investigation results and systematic monitoring of the load and base slab settlements enabled the back analysis of the foundation behaviour. The objective of the analysis is solely academic. The consolidation settlements of the structures are computed (using parameters that fit best to the obtained soil properties) and the results are compared with the measured settlements.

Although the 2D axisymmetric model may be adequate to analyse the settlement of the sugar silo, a three dimensional model is required to calculate the settlement of the basement tunnel and pile foundation. The 3D finite element modelling of the silo was performed using the finite element program PLAXIS 3D AE. Due to the biaxial symmetric geometry of the silo, it is sufficient to implement the quarter of the structure in the model as shown in Figure 5. The geometric dimensions of the model space were selected such that the model boundaries give no effect on the calculation results. For this reason the outer boundary in horizontal direction was placed 30 m from the silo, and the bottom of the model was 50 m depth.

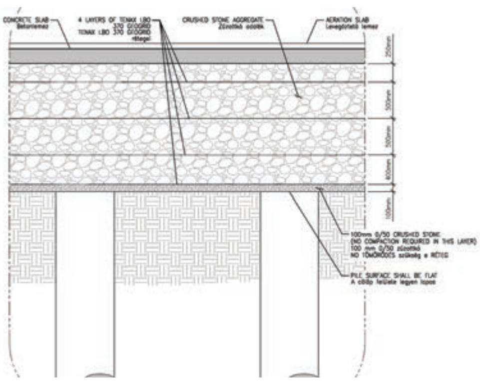

Figure 3: Structural composition of the subgrade

3.1 Soil model and its properties

Creation of the soil model was based on the reported boring logs and cross section profiles. The thickness of the soil layers was set to their average thickness below the studied area. The physical soil properties of each layer have been also assigned as their average value given in the geotechnical report.

The layers were modelled with Hardening Soil with small-strain stiffness (HSsmall) model in order to avoid the overestimation of the soil deformations at larger depths. For each layer, the required stiffness parameters were determined using oedometer tests. The shear modulus at very small strains was computed from the shear wave velocity of the corresponding layer. The assigned values of the different properties for each material are summarised in Table 2.

3.2 Structural elements

For the modelling of structural elements, construction and as-built plans were used in order to form the most realistic geometry. This is important to mention, because during the construction some modifications have been made compared to the design plans.

3.2.1 Piles

Foundation piles were modelled as embedded beams. The base and shaft resistance of the piles were determined using the CPT-based correlations proposed by Szepesházi (2011) (Table 3). A typical CPT tip resistance curve of the area is illustrated in Figure 6. For those piles that are cut in half due to the geometry of the model space (Figure 7), the values of base and shaft resistance were also divided by two.

3.2.2 Plate, interface and geogrid elements

The beam running beneath the shell structure was modelled using 3D solid elements. The walls and the base slab of the unloading tunnel, as well as the base slab of the silo were defined as plates and their thickness was selected based on the construction plans.

For these, structural elements were used to represent concrete. It is also assumed that the concrete behaves as a linearly elastic isotropic material. The relevant properties used for the analysis are shown in Table 2.

Table 2: Material properties

	Fill	Sandy silt	Silty sand	Sand	Silty clay	Clay	Subgrade	Sugar	Concrete
Notation	🟫	🟦	🟩	🟨	🟪	🟥	🟨	🟦	🟦
Depth interval	0 – 2.2	2.2 – 11.0	11.0 – 14.9	14.9 – 19.9	19.9 – 31.7	31.7 – 50.0	-	-	-
Material model	HSsmall	HSsmall	HSsmall	HSsmall	HSsmall	HSsmall	HS	MC	LE
Type	Drained	Drained	Drained	Drained	Drained	Drained	Drained	Drained	Non Porous
γ_{unsat} [kN/m³]	20	19	18	17	20	21	20	8.5	25
γ_{sat} [kN/m³]	20	20	20	19	22	22	20	8.5	25
E_{50}^{ref} [kN/m²]	6000	5950	4850	20000	3850	10600	70000	30000	33.0E+6
E_{oed}^{ref} [kN/m²]	6000	5950	4850	20000	3850	10600	70000	-	-
E_{ur}^{ref} [kN/m²]	18000	17850	14550	60000	11550	31800	210000	-	-
m [-]	0.7	0.75	0.8	0.7	0.65	0.5	0.5	-	-
ν [-]	-	-	-	-	-	-	-	0.2	0.2
c'_{ref} [kN/m²]	1	16.9	9.5	6.8	40.6	71	10	1	-
ϕ' [°]	20	26.9	31.5	31.9	16.9	16.7	40	35	-
$\gamma_{0.7}$ [-]	0.16E-3	0.21E-3	0.25E-3	0.32E-3	0.15E-3	0.25E-3	-	-	-
G_0^{ref} [kN/m²]	231.6E+3	112.8E+3	85.65E+3	129.1E+3	203.3E+3	344.7E+3	-	-	-
K_0^{nc} [-]	0.658	0.5476	0.4775	0.4716	0.7093	0.7126	0.3572	-	-
k_x, k_y, k_z [m/day]	0.8640	0.233E-3	0.527E-3	0.4752	0.0864E-3	0.0104E-3	864	8.64	-

Table 3: Characteristics of the piles

Soil type	α_{sq}	$q_{c,\ average}$ [kPa]	q_s [kPa]	Base resistance [kN]
🟩 MG	0.55	911	16.6	-
🟦 A	0.55	1437	20.8	-
🟩 B	0.55	3061	30.4	-
🟧 C	0.55	16395	70.4	2257 (D = 0.80m) 3016 (D = 1.00m) 4030 (D = 1.20m)

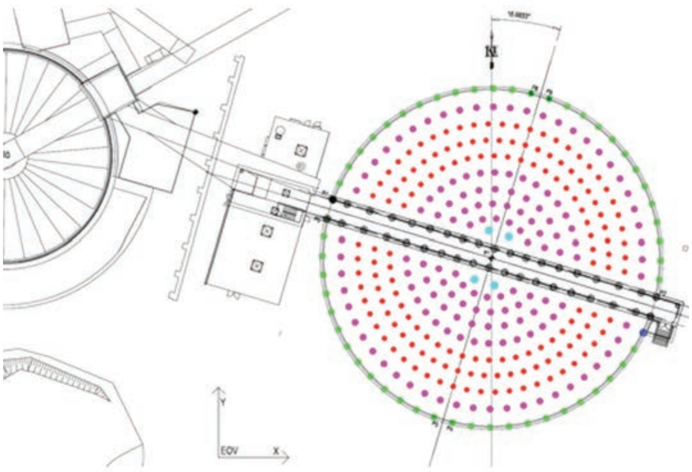

Figure 4: Location of the piles

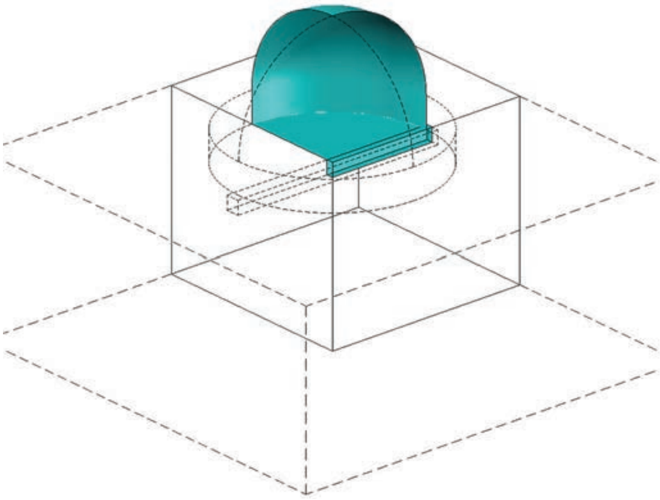

Figure 5: Model space

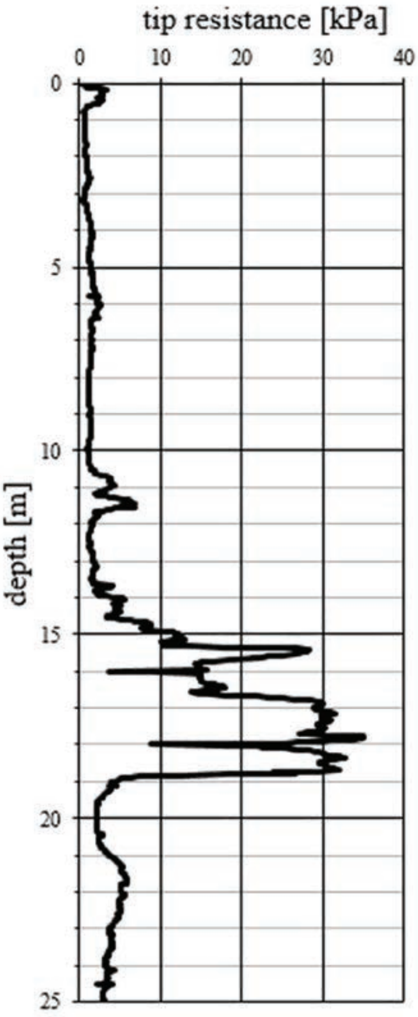

Figure 6: CPT tip resistance

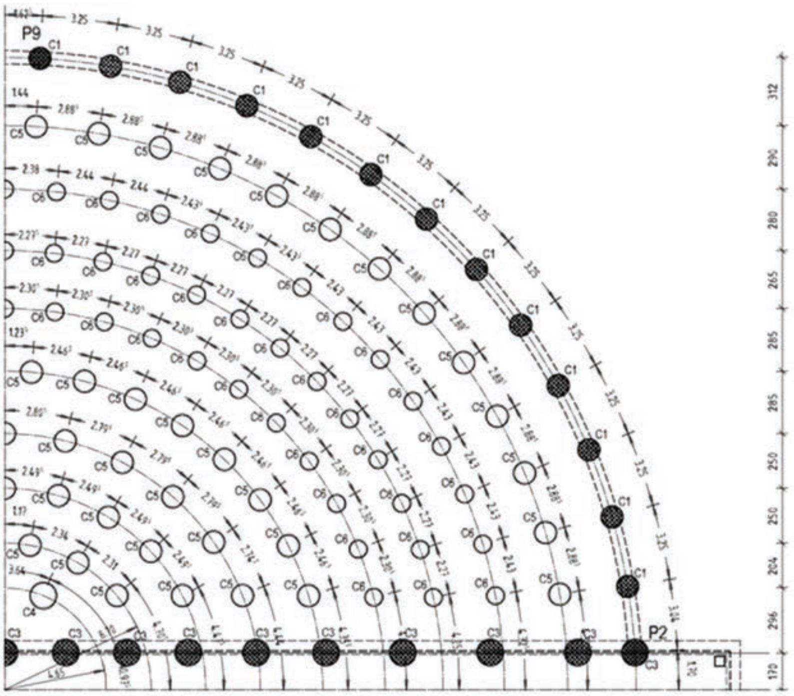

Figure 7: Layout of the piles

The subgrade was assumed to behave according the rules of the Hardening Soil model. The behaviour of the four layers of geogrid strengthening the subgrade was assumed to be elastic with an axial stiffness, *EA*, of 500 kN/m.

At the outer side of the tunnel structure, at the bottom plate and at the upper and bottom side of the silo base, beam interface elements were defined.

4.3 Modelling of the sugar

Instead of considering the effect of stored sugar as a distributed load on the base slab, the sugar was modelled as a granular soil. In this way, the dome-shaped structure could have been involved into the load bearing, so that the load intensities transferred to the bottom plate and to the base slab can portray the real conditions. An interface was defined between the dome structure and the sugar elements to allow sliding between the two materials. The interface parameter was defined based on the sugar properties, and the interface factor, R was taken as 1.0.
Loading and unloading of the silo was modelled as construction stages. Figure 8 shows 4 selected loading stages, for which the geometry of the sugar was calculated using its assigned friction angle value, which was 35°.

5. Results

The construction stages were defined in a way that the model reproduces the recorded loading and unloading history as accurately as possible. The following eleven construction stages have been defined and performed as "consolidation calculation":

1) Filling to 17.000 tons in 3 weeks;
2) Filling to 51.500 tons in 6 weeks;
3) Resting for 6 weeks;
4) Complete unloading in 16 weeks;
5) Resting for 2 weeks;
6) Filling to 17.000 tons in 14 weeks;
7) Filling to fully filled condition in 11 weeks;
8) Resting for 3 weeks;
9) Unloading to 44.650 tons in 14 weeks;
10) Resting for 4 weeks;
11) Unloading to 0 tons in 13 weeks.

The computed vertical displacements and slab settlements are shown in Figure 9. The results agree well to the well-known tendencies, in which the settlements are high in the middle part and low at the periphery. In this particular situation, the rigid supports (i.e. the reinforced piles) directly connected to the tunnel and the outer beam cause further settlement reduction in these areas. Although there were no settlement measurements inside the sugar silo to confirm these, the results seems realistic. To set-up the monitoring system, 8 measuring points were established on edge of the base slab and 10 points on the wall of the tunnel. In the presented model, the development of deformations was studied in 3 points (Figure 10). The comparison between the in-situ observed settlements and those calculated using PLAXIS are shown in Figure 11.

6. Summary

This article discusses the performance of a Hungarian sugar silo's foundation by back analysing the loading-unloading history of the structure. The foundation of the dome-shaped silo is rather complex, it includes traditional piles, but also rigid inclusion ground improvement. Therefore, its behaviour can only be modelled properly with sophisticated 3D geotechnical finite element models.

At the back analysis of the structure, the soil layers were modelled using the HSsmall model, for which the input parameters were obtained from the laboratory (oedometer test, simple shear test) and field tests (seismic CPTu, CPTu) carried out for the geotechnical report of the site. The base and shaft resistance of the piles and rigid inclusion bodies were also derived using the records of CPT. The settlements calculated by PLAXIS 3D were compared with the monitored settlements during the loading-unloading history of the silo, and the following conclusions can be drawn:

- The calculated and the measured settlements are in good agreement; the biggest difference between them is only a few mm (approximately 10%).
- Development of the displacements with time shows slightly different tendencies. The measured settlements are significantly smaller in the first few weeks compared to the calculated ones, but later they accumulate faster than the calculated settlements. The reason behind this observation is unknown yet, but previous works also have shown similar tendencies.
- After the first loading the curves of the measured and calculated displacements have similar shapes.
- The calculated settlements of the 3 selected representative points slightly differ from the measured values (however the behaviour of the settlements are comparable).

Overall it can be concluded that soil behaviour and soil-structure interaction determined by the finite element model are in good agreement with the results of monitoring. This indicates that with the use of HSsmall model and input parameters from proper field and laboratory test program, even geotechnical problems with such complexity can be analysed adequately with finite element method with good accuracy.

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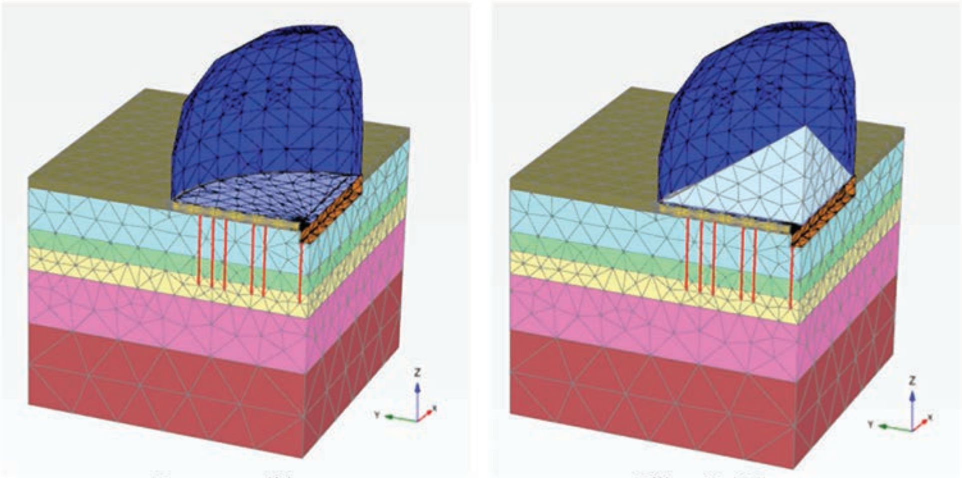
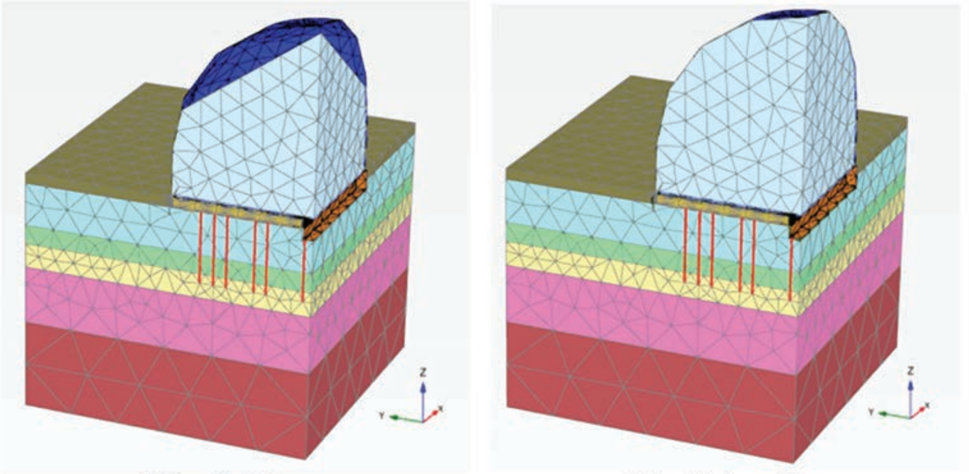


Empty condition

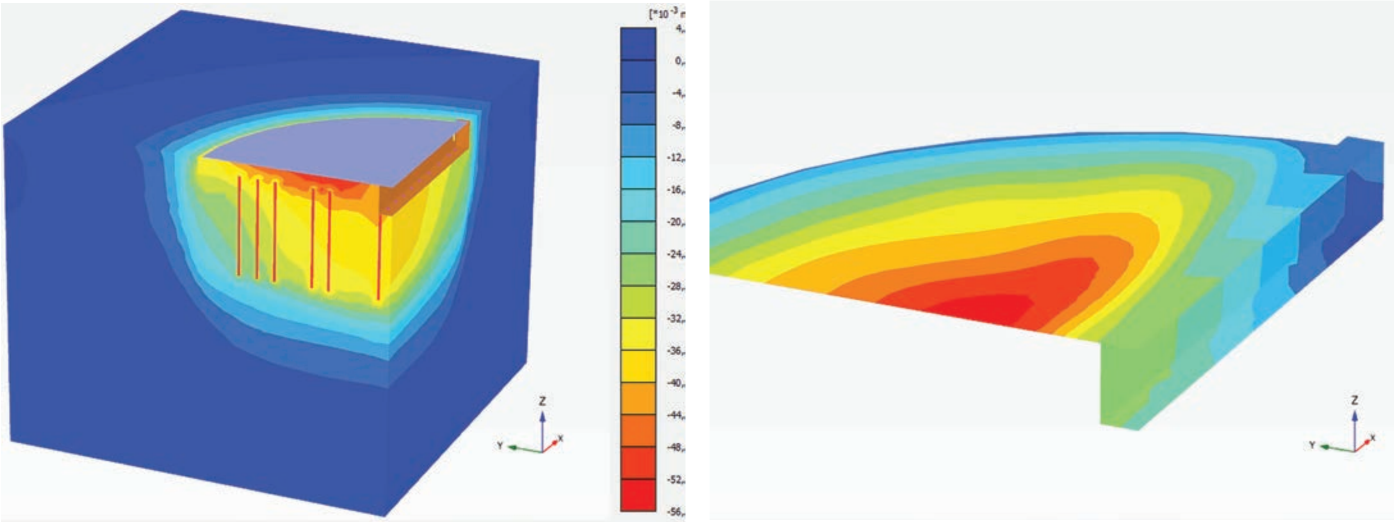
Fill to 17,000 tons



Fill to 51,500 tons

Fully filled condition

Figure 8: Construction stages



(a)

(b)

Figure 9: Full displacement in direction z (a); Displacements of base slab and tunnel in direction z (b) - Displacements in fully filled condition

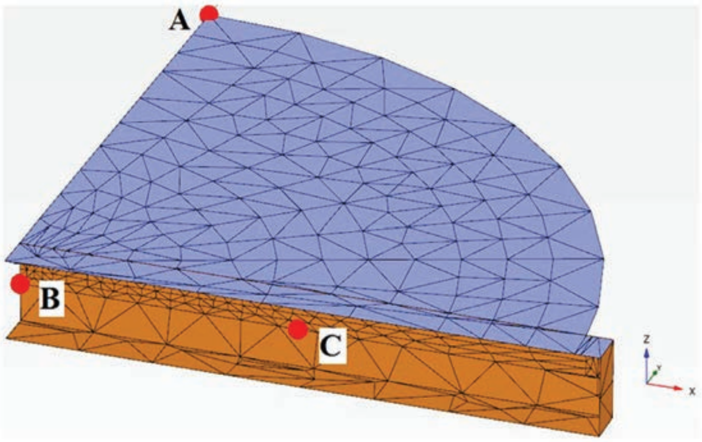


Figure 10: Measuring points of the settlement in the model

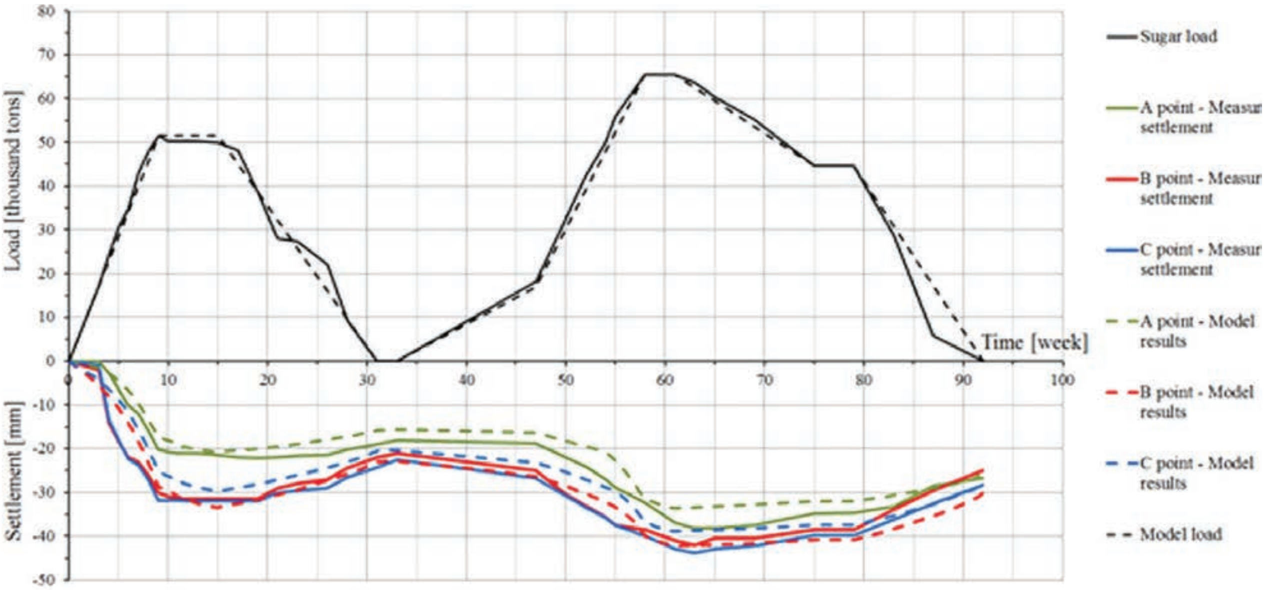


Figure 11: Development of settlements with time