AROS – THE NEXT LEVEL, 3D MODELLING OF SWELLING ANCHORS

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KEYWORDS

Swelling, Anchors, 3D finite element modelling, High plasticity clay

ABSTRACT

”The Dome” is a semi-subterranean art installation designed by the world-famous American artist James Turrell and is a part of the expansion project ”The Next Level” of ARoS Aarhus Art Museum in Denmark. The Dome is a 40 m wide hollow half-sphere skyspace construction extending approximately 9 m below and 10 m above the ground surface. The Dome will become the largest skyspace in the world within a museum context.

The excavation of the large soil mass and the large swelling potential of the underlying very high plasticity Palaeogene clay has led to significant geotechnical design challenges for the foundation.

The foundation is secured using swelling anchors with a free length in the swelling zone and an anchoring zone under the swelling zone to absorb the swelling force on the foundation corresponding to the unloading of the soil.

This article describes the development of a 3D finite element model in PLAXIS 3D using the incorporated linear interpolation between several geotechnical boreholes. Furthermore, different approaches to model the swelling anchors are compared, including “fixed-end anchors” and “node-to-node anchors” with the anchoring zone modelled by embedded beams. Finally, the swelling of the Palaeogene soils is modelled with two different approaches. The first approach uses a predefined swelling phase, while the second approach applies time-dependent consolidation phases in full depth. The latter examines the difference between applying different oedometric modulus E_{oed} and the coefficient of permeability k. The different modelling methods are compared by their influence on the size of the swelling of the ground surface and the anchor forces.

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1. INTRODUCTION

The light art installation “The Dome” is designed by the world-famous American artist James Turrell. It is a semi-subterranean construction extending approximately 9 m below and 10 m above the ground surface. From the inside, The Dome is a 40 m wide hollow skyspace, and seen from the outside, it is a 10 m high perfectly round grass-covered hill. The Dome is a part of the expansion project “The Next Level” of ARoS Aarhus Art Museum in Denmark and will become the largest skyspace in the world within a museum context.

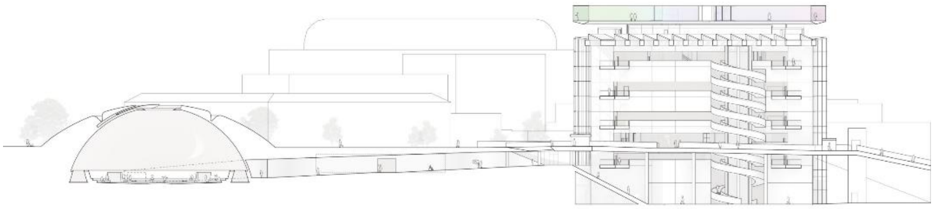

Figure 1: Cross-section through The Dome and ARoS Aarhus Art Museum, ref. [1].

To construct The Dome, a large soil mass must be excavated. As The Dome is a relatively light and hollow structure, the very high plasticity Palaeogene clay will consequently experience a large unloading. This can potentially give rise to swelling problems for The Dome under the assumption of sufficient water flow.

To avoid potential damage to the construction due to swelling, the direct foundation along the edge of the Dome is anchored to counteract the swelling force corresponding to the unloading of the soil. The swelling anchors are designed with an anchoring zone below the swelling zone. The swelling zone is defined as the penetration depth for the swelling based on the permeability of the soil and the design life of the structure.

The floor in the centre of The Dome is allowed to rise. For the same reason, the floor in The Dome is made of paving stones, which enables a relatively uncomplicated restoration.

The focus of the article is to describe different modelling methods with regard to the swelling issue and swelling anchors. The methods are compared by their influence on the size of the swelling of the ground surface and the anchor forces.

Site Geology

The overall geological stratigraphy at the site can be described as 1.5 to 3.4 m of topsoil under which a thin layer of Late Glacial clay was encountered. The Late Glacial clay overlies Glacial deposits of clay till and meltwater sand. The primary Glacial deposit is meltwater sand in one half of the site, whereas clay till dominates the other half of the site. From about 12.2 to 18.4 m below the ground surface, the Palaeogene clays are encountered, consisting of marine Oligocene clay and marine Eocene clay. In general, the Palaeogene clays have a very high plasticity index and are fissured.

2. METHODS

A one-dimensional method is applied to address the swelling issue and give a crude estimate of the size of the swelling before advanced models are initiated.

In PLAXIS 3D, different modelling methods regarding the swelling anchors and swelling of the Palaeogene clay have been applied. The methods are compared by the size of the swelling of the ground surface and the anchor forces. The following methods are addressed:

1. Plastic calculation phases with drained materials and swelling anchors modelled as Fixed-end anchors.
2. As method 1 with swelling anchors modelled as Node-to-Node anchors and embedded beams.
3. Consolidation phase in full depth with the swelling anchors modelled as Node-to-node anchors and embedded beams.
4. As method 3 with a different oedometric modulus, E_{oed}.

3. 1D ESTIMATION OF THE EXPECTED SWELLING

To assess the extent of the swelling issue before advanced models are initiated, an estimation of the expected swelling is made based on the expressions presented in ref. [2]. As the swelling process needs an inflow of water to occur, the calculation is based on one-dimensional consolidation theory and rectilinear drainage compared with measurements of swelling from a site.

The extent of the swelling zone can be estimated by $n = 2 \cdot \sqrt{c_k \cdot t}$, where c_k is the coefficient of consolidation (m²/s) and t is the time corresponding to the lifetime of the building (s). With a service life of 100 years and a coefficient of consolidation of $c_k = 5 \cdot 10^{-9}$ m²/ s, a thickness of the swelling zone of n ≈ 8 m is obtained.

An estimation of the expected swelling is based on $\delta_{1D} = -H \cdot Q_{swell} \cdot \log(\sigma'_{after}/\sigma'_{before})$, where H is the size of the swelling zone, Q_{swell} is the swelling ratio, and σ'_{before} and σ'_{after} is the vertical effective stress in the middle of the swelling zone before and after excavation, respectively. The expected swelling of the Dome is calculated to δ_{1D} = 210 mm, as σ'_{before}= 290 kPa and σ'_{after} = 125 kPa, corresponding to an unloading from excavation of 9.3 meters of soil.

This estimation of the swelling assumes the foundation is constructed directly on top of the Palaeogene clay. This is a conservative assumption and not the case at the site, as the geotechnical boreholes present a variating top level of the Palaeogene clays from about 5.3 to 11.5 m below the foundation level.

4. THE PLAXIS 3D MODEL

The following sections describe the general input for the PLAXIS 3D model, which is applied in all four methods unless otherwise stated.

Stratigraphy

To model the stratigraphy in PLAXIS 3D, the geotechnical boreholes made in or near the modelled project area are modelled using the "borehole" function. The location of each individual borehole is modelled directly from the Autodesk Revit file for the foundation plan, on which the location of the boreholes is indicated. The location of the boreholes is shown in Figure 2. PLAXIS 3D has formed the geological model by interpolation between all the geotechnical boreholes. The model is stopped at a depth where the unloading corresponds to less than 20% of the in situ vertical stress.

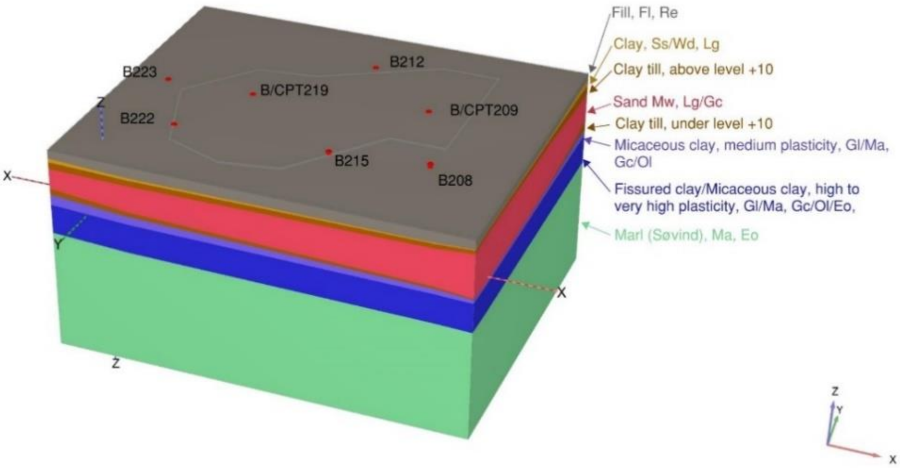

Figure 2: The soil stratigraphy modelled using interpolation between the soil layers.

Constitutive Models

All soil materials are modelled as drained with the Mohr-Coulomb constitutive model, which was applied instead of more advanced models due to simpler calibration and time constraints in the design phase. Further, it is assumed that all soil materials are normally consolidated with $K_0 = 1 - \sin(\varphi')$, Poisson's ratio of $\nu = 0.30$, and apply "Tension cut-off" with a tensile strength of 0 kPa.

Table 1 lists the deformation parameters for the materials with swelling potential. The oedometric modolus, E_{oed}, is calculated based on the expression, $E_{oed} = \ln(10)\, \sigma'_a / Q_{swell}$ from ref. [3], as the swelling ratio, Q_{swell}, must be converted to be applied in a Mohr-Coulomb material model.

The deformation parameters for the micaceous clay and fissured clay are based on swelling tests, whereas no swelling tests were performed for Søvind Marl. The Søvind Marl is located far below the foundation level, therefore, it is uncertain whether a sufficient water inflow for the Marl to swell will occur. Therefore, deformation parameters for both loading and unloading are given. For unloading, the parameter Q_{swell} is assumed to be similar to the one for the fissured clay and converted to E_{oed} using the expression in ref. [3]. The oedometric modulus for primary consolidation is estimated based on experience from the area using $E_{oed} = 10\ MPa + 150 \cdot \sigma'_a$, where σ'_a is the lowest vertical effective stress.

Table 1: Deformation parameters for the soil layers with swelling potential.

Soil type	Q_{swell} [%]	c_k [m²/s]	E_{oed} [MPa]
Very high plasticity micaceous clay and fissured clay	7	$5 \cdot 10^{-9}$	5.5
High plasticity micaceous clay	1.5	$5 \cdot 10^{-9}$	25
Søvind Marl, primary consolidation	-	$5 \cdot 10^{-8}$	34.8
Søvind Marl, swelling ratio	7	$5 \cdot 10^{-8}$	5.4

The oedometer modulus for primary consolidation (loading) is applied in methods 1 to 3, and the parameters for secondary loading (unloading) are applied in method 4.

Geometry and mesh

An excavation pit is made consisting of anchored sheet pile walls, although the sheet pile wall itself is not modelled in PLAXIS 3D, as it is not of interest in determining the number of swelling anchors and the size of the swelling. However, the excavation sides formed by the sheet pile wall are retained by limiting the horizontal displacements to $u_x = u_y = 0$, where the z-axis is the vertical axis.

It is assessed that the model size is sufficient thus, the boundary effects do not affect the results of the swelling under the foundations or the 3D effects of the ground anchors. It should be noted that due to the retained sides (instead of sheet pile walls), it has been possible to limit the model approximately to the area of the excavation pit.

The models are meshed using 10-noded tetrahedral elements, which are the standard elements in PLAXIS 3D. Initially, a convergence analysis was made, showing that the calculated swelling in the centre of The Dome remains constant if the element mesh is discretized as coarser or finer than the medium mesh setting. Therefore, a slightly finer "medium" element mesh is used.

5. METHOD 1 – PLASTIC PHASES WITH FIXED-END ANCHORS

The first method in PLAXIS applies plastic calculation phases, a predefined swelling phase together with swelling anchors modelled as Fixed-end anchors.

Plastic calculation phases in PLAXIS are an elastoplastic deformation analysis where time effects are not considered.

A Fixed-end anchor is a point element [4] where the free length and grouted length are not directly modelled. These are represented by an equivalent length.

The swelling anchors are strand anchors with five strands, each with a cross-sectional area of 150 mm². The grouted length of the anchors is 10 m and is located below the swelling zone, yielding a free length of 17.2 m. The equivalent length, $L_{equvialent}$, is the free length and half of the grouted length.

Phases modelling

In the PLAXIS 3D model, swelling is only allowed to occur when construction is finished. This is a simplification where any swelling that may occur during construction is neglected.

The predefined swelling phase is controlled by a surface at the upper level of the Palaeogene clay, where the displacement in the vertical direction is retained ($u_z = 0$) until the foundations, swelling anchors and loads from the building are applied. Hereafter, the retained surface is released, and swelling can occur. Excavation and construction stages are modelled as plastic, allowing swelling to full depth of the model.

Results from the first method

Figure 3 shows a cross-section through The Dome with the calculated swelling for the first method. The maximum displacement occurs at the centre of the Dome, with a vertical upward displacement of approximately 263 mm. It should be noted that the swelling is considerably lower at the foundations, which is caused by the applied loads and the swelling anchors. The maximum anchor force is calculated to 702 kN in the fixed-end anchors.

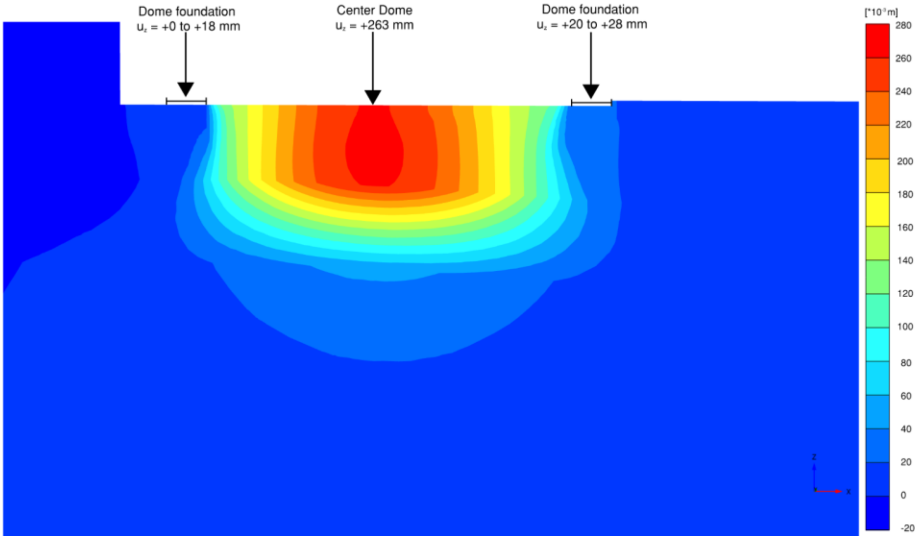

Figure 3: Cross-section through The Dome and calculated swelling for method 1.

6. METHOD 2 – PLASTIC PHASES WITH NODE-TO-NODE ANCHORS AND EMBEDDED BEAMS

The second method applied in PLAXIS is similar to the first method, however, the modelling approach for the swelling anchors is different. In the second method, the swelling anchors are modelled using a combination of node-to-node anchors and embedded beams.

The node-to-node anchor represents the free length of the swelling anchor, while the embedded beam represents the grouted length. The connection between the node-to-node anchor and the embedded beam is automatically set to free to avoid unrealistic loss of axial force in the connection point [4]. The node-to-node anchors are modelled as in the first method.

The embedded beams are modelled as linear elastic with a stiffness based on the stiffness of the five strands, as it is assumed that the grout will crack upon loading of the anchor and, therefore, not contribute to the axial stiffness. An embedded beam is modelled without any width, and the weight is therefore calculated as the difference between the weight of the grout and the weight of the surrounding soil. The grouted length transfers the axial force to the soil through skin friction, which is assumed to be constant for the entire length of the grouted zone. Field tests have yielded a bearing capacity of the swelling anchors of 725 kN.

Results from the second method

The maximum displacement appears at the centre of the Dome, with a vertical upward displacement of approximately 271 mm. The maximum anchor force is calculated to be 667 kN in the node-to-node anchors.

7. METHOD 3 – CONSOLIDATION PHASES WITH PRIMARY CONSOLIDATION

In the first and second methods, a surface at the upper level of the Palaeogene clay was used to control when swelling was allowed to occur, thereby only allowing swelling in the final phase after construction was finished. In the third method, this surface is removed, and all phases are modelled as consolidation phases, where swelling can occur, assuming sufficient water flow to the soil layers with swelling potential.

Each construction phase has a consolidation time of 25 days, except for the last phase, where the consolidation time is 100 years, corresponding to the construction lifetime. The coefficient of permeability, k, of the soil layers with swelling potential are estimated based on ref. [2], $k = c_k \cdot \gamma_w / E_{oed}$, where c_k is the coefficient of consolidation (m^2/s), γ_w is the unit weight of water (10 kN/m^3), and E_{oed} is the oedometric modulus.

For the third method, the oedometric modulus of Søvind Marl is based on primary consolidation. The parameters used to estimate the coefficient of permeability for the soil layers with swelling potential and the estimated coefficient of permeability are given in Table 2.

Table 2: Parameters used for estimation of the coefficient of permeability for the soil layers with swelling potential.

Soil layer	c_k [m^2/s]	E_{oed} [MPa]	k [m/day]
Micaceous clay	$5 \cdot 10^{-9}$	25.6	$1.688 \cdot 10^{-7}$
Fissured clay	$5 \cdot 10^{-9}$	5.5	$7.855 \cdot 10^{-7}$
Søvind Marl	$5 \cdot 10^{-8}$	34.8	$1.240 \cdot 10^{-6}$

Results from the third method

The maximum displacement appears at the centre of The Dome with a vertical upward displacement of approximately 69 mm. The maximum anchor force is calculated to 546 kN in the node-to-node anchors.

8. METHOD 4 – CONSOLIDATION PHASES WITH UNLOADING STIFFNESS

The fourth method is similar to the third method, but instead of estimating the coefficient of permeability based on primary consolidation, the swelling ratio, Q_{swell} of 7 %, is applied.

The coefficient of permeability for the Micaceous clay and Fissured clay is the same as for the third method. The estimated coefficient of permeability is given in Table 3.

Table 3: Parameters used for estimation of the coefficient of permeability for the soil layers with swelling potential.

Soil layer	c_k [m²/s]	E_{oed} [MPa]	*k* [m/day]
Søvind Marl	$5 \cdot 10^{-8}$	5.4	$7.935 \cdot 10^{-6}$

Results from the fourth method

The maximum displacement appears at the centre of the Dome, with a vertical upward displacement of approximately 65 mm. The maximum anchor force is calculated to 532 kN in the node-to-node anchors.

9. COMPARISON OF 3D METHODS

The four methods are compared by their influence on the size of the swelling of the ground surface at the centre of The Dome and the force in the swelling anchors, which is summarised in Table 4.

Table 4: Swelling at the centre of The Dome and anchor force for each method.

	Method 1	Method 2	Method 3	Method 4
u_z - Center of The Dome [mm]	263	271	69	65
Anchor force [kN]	702	667	546	532

The modelling approach of the swelling anchors is compared in method 1 and 2.

From Table 4, it appears that method 1, applying fixed-end anchors, yields a lower swelling at the centre of The Dome and a larger anchoring force than method 2, which uses a combination of node-to-node anchors and embedded beams.

The difference can be caused by the displacement required to activate the full shaft resistance of the grouted zone. In method 1 (fixed-end anchors), the resistance is active without any displacement, as the grouted zone is not modelled, whereas displacements are required to activate the shaft resistance of the grouted zone in method 2, which is modelled using embedded beams. The difference in swelling corresponds approximately to the displacement required to activate the full shaft resistance, according to [5] and [6].

In methods 1 and 2, all materials are modelled as drained and the construction stages as plastic phases, where swelling of the Palaeogene clays is allowed to the full depth of the model and not an 8 m swelling zone as estimated in the 1D approximation in section 3. When the construction stage is modelled as plastic phases, the coefficient of permeability of the soil layers and the time aspect is therefore neglected in the calculations, yielding an overestimation of the swelling and associated anchor forces.

The construction stages for methods 3 and 4 were changed from plastic phases to consolidation phases to account for the coefficient of permeability of the soil layers and include the time aspect. Including these parameters reduces the swelling zone of the Palaeogene Clays. These changes have yielded a large reduction in swelling at the centre of The Dome and lower anchoring force between method 1-2 and method 3-4, as shown in Table 4.

From Table 4, it should be noted there is only a small difference between methods 3 and 4. The difference between methods 3 and 4 is the applied stiffness of Søvind Marl, with the odometer modulus for primary consolidation and the swelling ratio, Q_{swell}, respectively. The change in stiffness is also associated with a change in the coefficient of permeability. As expected, the lower stiffness and higher coefficient of permeability reduce the swelling of the Palaeogene Clays.

10. COMPARISON BETWEEN 1D ESTIMATION AND PLAXIS 3D

A comparison of the PLAXIS 3D models with consolidation phases has been performed, comparing the expected swelling calculated to the 1D calculation, see Table 5. In PLAXIS 3D, a phase without swelling anchors and foundation loads has been performed to compare with the 1D calculation.

Table 5: Calculated swelling in the centre of The Dome without swelling anchors and foundation loads.

	1D	Method 3	Method 4
Swelling in the centre of The Dome [mm]	210	214	419

Method 4 applies the swelling ratio, Q_{swell}, for the Søvind Marl, which is associated with a higher coefficient of permeability compared to method 3. This leads to a larger swelling zone compared with method 3, where the stiffness of the Søvind Marl is based on primary consolidation, thus, the swelling contribution of the layer is limited. The 1D calculation does not have any contribution from the Søvind Marl, as it assumes a swelling zone of 8 m, which corresponds well with method 3.

Comparing the calculated swelling in the centre of The Dome listed in Table 5, it is indicated that the swelling zone is overestimated by method 4. Assuming that the 1D calculation is reasonable as it is compared with measurements of swelling from a site. The results from the PLAXIS 3D model with method 3 are shown in Figure 4.

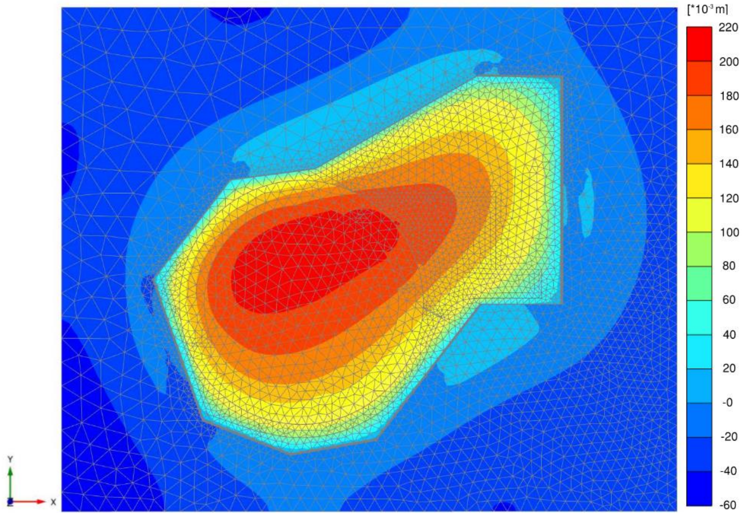

Figure 4: Swelling calculated in PLAXIS 3D for method 3 in the situation of full excavation in The Dome before implementing the foundations, loads, and swelling anchors.

Figure 4 shows that the swelling of the excavation closest to the sheet pile wall is affected by the "boundary effect" as there is no excavation and thus no heave on the other side of the sheet pile wall. Therefore, the calculated swelling decreases from the centre of the excavation towards the sheet pile wall. As the expected swelling by the 1D calculation did not take the "boundary effect" of the sheet pile wall into account, it must be compared with the calculated swelling in the centre of the excavation, which was calculated to 214 mm in PLAIXS 3D. This indicates a good correlation between the PLAXIS model method 3 and the 1D calculation. The minor difference might be due to the "boundary effect" and a minor difference between the applied water table, which was assumed to be at level +9.0 in the 1D calculation and at level +11.0 before excavation in the PLAXIS 3D model.

11. CONCLUSION

This article describes the development of a PLAXIS 3D model using the incorporated linear interpolation between several boreholes.

In PLAXIS 3D, different modelling methods have been applied to the swelling anchors and swelling of the Palaeogene clay. The methods are compared by the size of the swelling of the ground surface in the centre of The Dome and the anchor forces.

The two modelling approaches of the swelling anchors yield close to the same swelling at the centre of The Dome and anchor force. However, method 2 with node-to-node anchors and embedded beams represents the most realistic behaviour since displacement is essential to activate the shaft resistance.

The different approaches to modelling the swelling of the Palaeogene soils distinguish between plastic phases and consolidation phases in full depth. When the construction stage is modelled as plastic phases, the coefficient of permeability of the soil layers and the time aspect is neglected, yielding an overestimation of the swelling and associated anchor forces.

When different stiffnesses of Søvind Marl, primary consolidation or swelling ratio are applied, the lower stiffness and higher coefficient of permeability increase the swelling of the Palaeogene Clays.

The complexity of the PLAXIS 3D model is increased from methods 1 to 4. The PLAXIS 3D model with method 3 exhibits a good correlation with the 1D estimation when results are compared before the installation of the swelling anchors, foundations, and loads. Therefore, it is also expected that method 3 provides the best predictions for swelling when swelling anchors, foundations, and loads are active in the calculations. Method 3 shows that the centre of The Dome will swell approximately 69 mm over the lifetime of the structure, corresponding to 100 years.

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