TECHNICAL NOTE

Deep anchored excavation in sand: a 3D finite-element study

A Berlin-informed adaptation in PLAXIS 3D

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RESULTS AS OF 23 NOVEMBER 2026

MAX. WALL MOVEMENT	MAX. GROUND SETTLEMENT	PEAK WALL MOMENT
38 mm	**23** mm	**756** kN·m/m

Refined mesh. Movements are measured from the end of wall installation (P01), a datum that includes the effect of lowering the water level inside the pit (P02). The peak moment is a strip average over the anchor spacing, reached in the stage excavated to −14.35 m (P07).

1 Purpose and scope

This note documents an independent 3D finite-element study of a deep excavation in sand, retained by a diaphragm wall and prestressed ground anchors. It adapts the published Berlin excavation [B01, B02] to a finite pit with corners and individually modelled anchors. The study asks how large the movements and the wall and anchor demands are, how far they depend on mesh and solver, and how the midspan response compares with the 2D benchmark. It is portfolio work, not a design; its limits are stated once, in the last section.

2 Model basis

The pit is 60 m by 80 m in plan and 16.8 m deep, inside a soil block 300 m by 320 m and 100 m deep (Figure 1). A diaphragm wall 0.8 m thick, an elastic plate with interfaces on both faces, reaches 32 m below ground. The 520 prestressed anchors in 3 rows incline at 27° below the horizontal; each is a tendon over its free length and a grout body over its bond length (Table 2).

The soil is sand described by the Hardening Soil model in layers (Table 1). Layer L3 starts at 40 m below ground, as in the published arrangement [B02]. Parameters follow the original thesis [B01]; the manual's table lists the oedometer and unloading stiffness rows with each other's values, and the thesis assignment is adopted. Common to all layers: unloading Poisson ratio 0.20, reference pressure 100, failure ratio 0.9, cohesion 1. The wall–soil interface factor is 0.67, a study assumption.

The excavation follows 10 phases: initial stresses, wall installation, lowering of the water level inside the pit (P02), and excavation in steps to 4.8 m, 9.3 m,

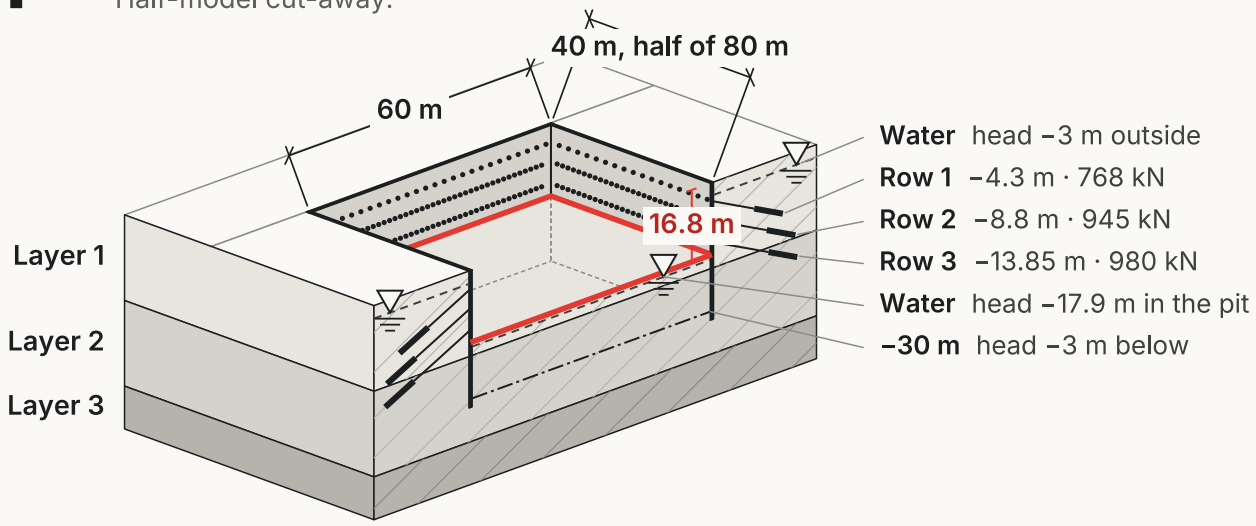
14.35 m and 16.8 m depth. Each anchor row is installed and prestressed once the excavation exposes it, at 768 kN, 945 kN and 980 kN in the successive rows.

Phase codes used below: P00 initial stresses; P01 wall installation; P02 pit water lowered to 17.9 m below ground; P03, P05, P07 and P09 excavation to 4.8 m, 9.3 m, 14.35 m and 16.8 m depth; P04, P06 and P08 installation and prestressing of the successive anchor rows.

Pore pressures are imposed, not computed from seepage: the water level is 3 m below ground outside the pit; once the water is lowered (P02) it is 17.9 m below ground inside the pit above an assumed low-permeability layer at −30 m, and below that layer it stays at the outside level. Excavated soil is dry.

01 MODEL GEOMETRY

Half-model cut-away.



Schematic of the PLAXIS 3D 2026.1 model · Bentley Education licence — Schematic · not to scale

Figure 1. Cut-away of the model with the pit, the walls, the anchor rows and the water levels. The soil layers are L1, L2 and L3.

TABLE 1 **Hardening Soil parameters of the three sand layers**

LAYER	DEPTH, m	$E_{50}^{ref} = E_{oed}^{ref}$, MPa	E_{ur}^{ref}, MPa	φ′, °	ψ, °	c′, kPa	m	K_0^{nc}	γ, kN/m³	EVIDENCE
L1	0–20	45	180	35	5	1	0.55	0.43	19 / 20	**S**
L2	20–40	75	300	38	6	1	0.55	0.38	19 / 20	**S**
L3	40–100	105	315	38	6	1	0.55	0.38	19 / 20	**S**

Evidence codes: **S** source-reported; **D** derived; **P** study assumption. Common to all layers: ν_{ur}, p_{ref}, R_f and the wall-interface factor are given in the text. Depth is below ground.

TABLE 2 **Ground anchors by row**

ROW	HEAD LEVEL BELOW GROUND, m	FREE LENGTH, m	BOND LENGTH, m	SPACING, m	ANCHORS	PRESTRESS, kN
1	4.30	11.8	8.0	2.30	120	768
2	8.80	15.3	8.0	1.35	200	945
3	13.85	15.8	8.0	1.35	200	980

Wall (per metre): EA 24,000,000 kN/m, EI 1,280,000 kN·m²/m. Anchor tendon: EA 315,000 kN. Head level is below ground.

3 Calculation and verification

All calculations use PLAXIS 3D 2026.1 under a Bentley Education licence. A common iterative solver, Picos, was used for every phase and every mesh. Every phase must end with an OK result and the full stage multiplier, and the activation of soil, plates, interfaces, anchors and grout bodies is compared with the input record before calculation; 10 of 10 phases met both conditions. Prestress locks in within 1 kN, and for each of the 520 anchors the tendon force balances the integrated grout skin force, with a largest imbalance of 3.4 % (tolerance 1 %). In each prestressing stage some anchors miss the 1 % balance between tendon force and grout skin force, by up to 3.4 %. Every miss sits where the grout reaches its bond limit locally at the start of the bond length, and refining the mesh does not remove them; in the excavation stages that follow, every anchor balances within 1 %. Of the 28 checks in Table 3, 23 are within tolerance and 5 are not.

The model was solved on 2 meshes of 46,476 and 285,191 soil elements. Wall forces at anchor heads and re-entrant corners are point peaks that grow with refinement, so wall actions are taken as strip averages over 2.3 m of wall, the anchor spacing, outside a corner offset of 4.6 m. Between the meshes the displacement quantities differ by at most 6.3 % (tolerance 2 %) and the wall actions by at most 16 % (tolerance 5 %). 3 of 16 mesh checks exceed their tolerance; those quantities are not treated as converged. The east and west walls agree within 0.39 % and the south and north walls within 0.21 % (tolerance 2 %). See Table 3, and Table 4 for every compared quantity, including the bending moment M11 and the line force of each anchor row. The settlement counted from the end of water lowering (P02) is mesh-sensitive: it changes by 6.3 % between the base mesh and the refined mesh against a tolerance of 2 %, so its refined-mesh value is reported and should be read with that in mind.

TABLE 3 **Verification checks on the refined-mesh run**

CHECK	RESULT	TOLERANCE	OUTCOME
PHASE COMPLETION			
Phases finished with the load fully applied	10 of 10	all	PASS

CHECK	RESULT	TOLERANCE	OUTCOME
SYMMETRY OF PAIRED WALLS AND ANCHOR ROWS			
Largest wall movement, east vs west	0.39 %	2.0 %	PASS
Largest wall movement, south vs north	0.21 %	2.0 %	PASS
Mean anchor force, row 1, east vs west	0.019 %	2.0 %	PASS
Mean anchor force, row 1, south vs north	0.028 %	2.0 %	PASS
Mean anchor force, row 2, east vs west	0.020 %	2.0 %	PASS
Mean anchor force, row 2, south vs north	0.0040 %	2.0 %	PASS
Mean anchor force, row 3, east vs west	0.011 %	2.0 %	PASS
Mean anchor force, row 3, south vs north	0.0010 %	2.0 %	PASS
PRESTRESS LOCK-IN			
Row 1 prestress reached at installation, all 120 anchors (P04)	0 kN	1.0 kN	PASS
Row 2 prestress reached at installation, all 200 anchors (P06)	0 kN	1.0 kN	PASS
Row 3 prestress reached at installation, all 200 anchors (P08)	0 kN	1.0 kN	PASS
ANCHOR EQUILIBRIUM, TENDON FORCE AGAINST GROUT SKIN FORCE			
Anchor force balance, row 1 prestressed to 768 kN (P04)	3.4 %	1.0 %	**FAIL**
Anchor force balance, excavation to −9.3 m (P05)	0.85 %	1.0 %	PASS
Anchor force balance, row 2 prestressed to 945 kN (P06)	2.4 %	1.0 %	**FAIL**
Anchor force balance, excavation to −14.35 m (P07)	0.47 %	1.0 %	PASS
Anchor force balance, row 3 prestressed to 980 kN (P08)	1.9 %	1.0 %	**FAIL**
Anchor force balance, excavation to −16.8 m (P09)	0.33 %	1.0 %	PASS
MESH DIFFERENCE, BASE MESH AGAINST REFINED MESH			
Maximum wall movement, measured from the end of wall installation	1.1 %	2.0 %	PASS
Maximum wall movement, measured from after dewatering	0.13 %	2.0 %	PASS
Maximum ground settlement, measured from the end of wall installation	1.9 %	2.0 %	PASS
Maximum floor heave	1.3 %	2.0 %	PASS
Wall bending-moment peak M22, excavation to −14.35 m (P07)	3.2 %	5.0 %	PASS
Wall bending-moment peak M22, excavation to −16.8 m (P09)	2.7 %	5.0 %	PASS
Wall shear-force peak Q23 near the corners, excavation to −14.35 m (P07)	9.1 %	5.0 %	**FAIL**
Wall shear-force peak Q23 near the corners, excavation to −16.8 m (P09)	3.1 %	5.0 %	PASS
Wall shear-force peak Q13 near the corners, excavation to −16.8 m (P09)	16 %	5.0 %	**FAIL**
Maximum anchor force	0.23 %	2.0 %	PASS

Percentages are differences between paired quantities, changes between the base mesh and the refined mesh, or the imbalance as a share of the tendon force.

TABLE 4 **Mesh comparison, base mesh and refined mesh**

QUANTITY	UNIT	BASE MESH	REFINED MESH	CHANGE, %	TOLERANCE, %	OUTCOME
M11 moment, peak, corner offset 4.6 m (P09)	kN·m/m	343	329	4.2	5	Within
M11 moment, peak, no corner offset (P09)	kN·m/m	−1,195	−1,213	1.5	5	Within
M22 moment, peak, corner offset 4.6 m (P07)	kN·m/m	781	756	3.2	5	Within
M22 moment, peak, corner offset 4.6 m (P09)	kN·m/m	642	625	2.7	5	Within
Q13 shear, peak, corner offset 4.6 m (P09)	kN/m	−372	−321	16	5	**Mesh-sensitive**
Q23 shear, peak, corner offset 4.6 m (P07)	kN/m	−523	−479	9.2	5	**Mesh-sensitive**
Q23 shear, peak, corner offset 4.6 m (P09)	kN/m	−433	−420	3.1	5	Within
Anchor row 1, line force (P09)	kN/m	324	324	0.26	2	Within
Anchor row 2, line force (P09)	kN/m	716	716	0.08	2	Within
Anchor row 3, line force (P09)	kN/m	756	755	0.18	2	Within
Largest wall movement (P01 datum, P09)	mm	38.4	38.0	1.1	2	Within
Largest wall movement (P02 datum, P09)	mm	25.5	25.5	0.13	2	Within
Largest settlement (P01 datum, P09)	mm	23.2	22.8	1.9	2	Within
Largest settlement (P02 datum, P09)	mm	11.8	12.6	6.3	2	**Mesh-sensitive**
Largest floor heave (P01 datum, P09)	mm	35.5	35.0	1.3	2	Within
Largest tendon force (P09)	kN	1,037	1,035	0.23	2	Within

Wall actions are strip averages over the anchor spacing. A quantity that changes by more than its tolerance is marked mesh-sensitive, and the refined-mesh value is the one reported. Wall movements and moments here are peaks along the wall and the ground; the midspan values in the text and in the wall-response and benchmark figures can be slightly lower (25 mm, 750 kN·m/m).

The largest displacement anywhere in the model, 130 mm, is a numerical artefact and not ground movement. It sits on an individual node at the end of an anchor grout body, where the tendon force enters the embedded beam: there the beam moves perpendicular to its own axis relative to the soil beside it, while the nodes next to it follow the soil. Offsets of this kind occur at the ends of many grout bodies; they appear in the phase in which the anchor row is installed and do not change afterwards, and they grow with mesh refinement. The largest ground movement is 44 mm. No grout node enters any reported wall, settlement or heave value, and grout nodes whose perpendicular offset from the soil exceeds 10 mm, with the 2 nearest nodes along the same beam, are left out of the slip figures below.

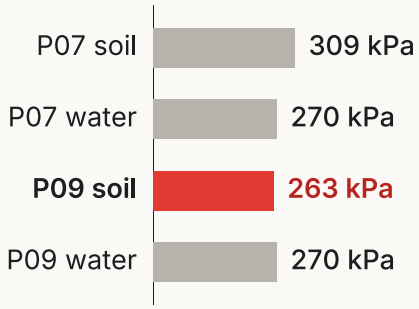
At the low-permeability layer at −30 m (Figure 2), inside the pit, the soil above it weighs 263 kPa in the final phase, against a water pressure of 270 kPa below it. In the phase of excavation to 14.35 m (P07) the ratio of weight to pressure is 1.15. With the partial factors of a verification the final-phase ratio is 0.88, against the 1.11 that such a verification needs. At the end of excavation the soil plug above the low-permeability layer at −30 m weighs slightly less than the water pressure beneath it (ratio 0.97). In the model the walls hold it down by

friction: the base stays in compression throughout, rising to about 100–150 kPa near the walls but only 15–24 kPa on average across the central 25 m. The plug draws 1,040–1,180 kN per metre of wall from friction (base and refined mesh; mesh-sensitive), roughly twice the 570 kN/m the hand check needs with the EN 1997-1 uplift factors. The small margin at the pit centre is the critical point in this model. The raw stress points confirm the picture. None is in vertical tension; the least compressive, 17 kPa, sits at the toe of the south wall. In the first level of stress points, 1.4 m below the layer, the central 25 m averages 33 kPa, consistent with the 21 kPa at the layer plus about 11 kPa for the extra depth. On the refined mesh, six stress points at the wall toe near three pit corners, about 2 m below the layer, were flagged by the tension cut-off; their vertical effective stress was a few kPa at the excavation to −14.35 m (P07) and is at least 37 kPa compressive at the end of excavation.

02 UPLIFT CHECK

Soil weight above −30 m against water pressure below.

A HAND CHECK

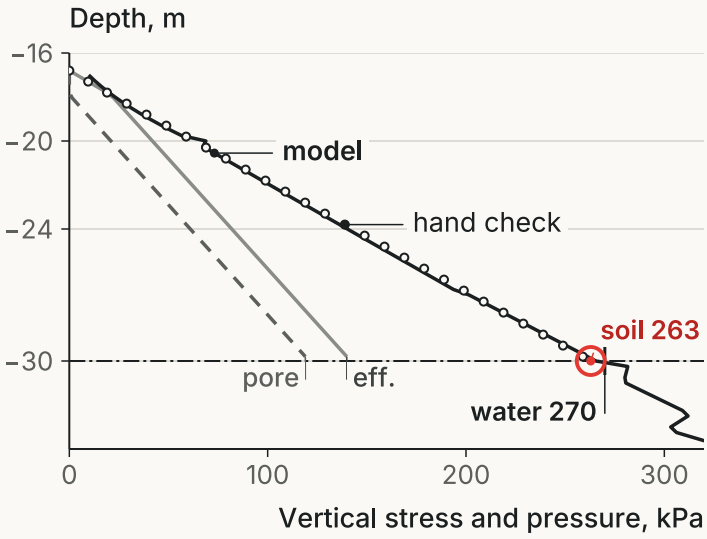


0.97 P09 ratio

1.15 P07 ratio

0.88 P09 with factor 0.9

B STRESS AT THE PIT CENTRE, P09



Computed with PLAXIS 3D 2026.1 · Bentley Education licence Pit centre

Figure 2. Uplift check at the low-permeability layer. Left: hand calculation of soil weight against water pressure in the excavation phases (P07 and P09). Right: total vertical stress at the pit centre from the model (line) and from the hand calculation (circles), with the hand-calculation effective stress and pore pressure in grey.

Wall–plug shear (for information). In the final phase the wall–soil interfaces mobilise 73–81 % of the integrated interface strength (base and refined mesh; mesh-sensitive). The shear includes the wall's own vertical load and is not an uplift safety factor. As a cross-check, the vertical force the wall plates lose between the formation level and the layer agrees with the net interface shear within 0.23 % on the refined mesh; no tolerance was fixed in advance for this check. Adding the wall shear to the soil weight and subtracting the water

pressure leaves a vertical gap of 14 % of the model's mean effective stress on the refined mesh (12 % on the area clear inside the wall faces) and 18 % (16 %) on the base mesh.

4 Results

4.1 Anchor forces

At the end of the final phase the tendon forces range from 719 kN to 1,030 kN, the highest in row 3, against installation prestress of 768 kN, 945 kN and 980 kN. In 171 of the 520 anchors the grout skin reaches its limit locally, within about a metre of the bond start; no anchor is near pull-out, and the busiest uses 26 % of its capacity.

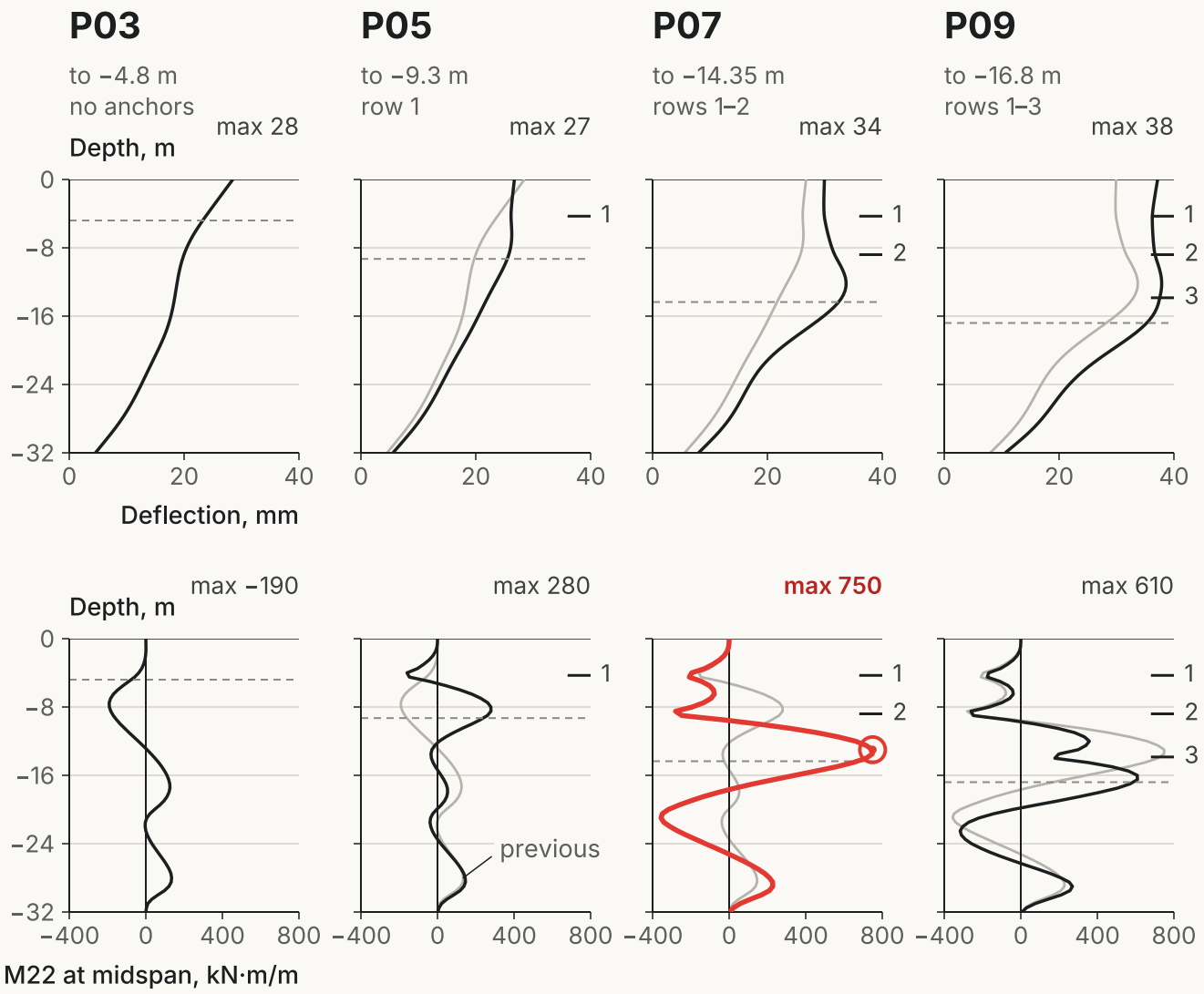
In PLAXIS 3D 2026.1 the relative displacement of embedded beams is reported as nil at every node, so the grout slip given here is derived, not a program result: at each grout node it is the beam displacement minus the soil displacement interpolated at the same point, projected on the beam axis. Where the grout is at its skin-resistance limit the mean axial slip is 1.8 mm and the largest axial slip 4.1 mm, with 63 nodes at grout ends excluded as described above.

4.2 Wall response

Figure 3 shows midspan deflection and the bending moment M22 against depth in selected phases (P03, P05, P07 and P09). The largest wall-normal movement is 38 mm, at 12 m depth on the west wall in the final phase, measured from the end of wall installation (P01). Lowering the water level inside the pit (P02) contributes to this datum; measured from the end of that lowering, the largest midspan movement of the long walls is 25 mm. Deflection is largest in the final excavation stage (P09), while the governing wall action is a strip-averaged M22 of 756 kN·m/m along the wall in the stage excavated to −14.35 m (P07), at 13 m depth on the east wall; at midspan, as plotted in Figure 3, it is 750 kN·m/m. Toward the corners movement falls to 1.3 % of the midspan value at the end of the east wall, and reaches 90 % of it only 24 m from the corner (20 m on the south wall).

03 WALL RESPONSE AT MIDSPAN

East-wall midspan, P01 datum. Red marks the largest moment.



Computed with PLAXIS 3D 2026.1 · Bentley Education licence — East wall · midspan

Figure 3. Midspan wall deflection (toward the pit, from the end of wall installation) and bending moment M22 against depth at selected phases. Red marks the phase with the largest moment.

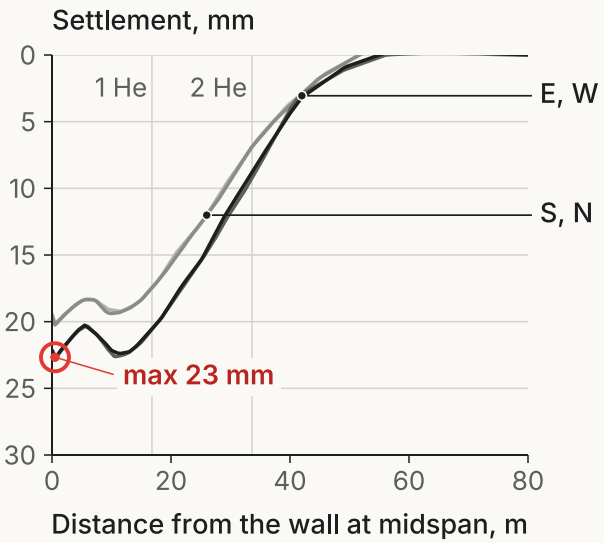
4.3 Ground movement

The largest surface settlement is 23 mm, 0.14 % of the excavation depth, and the trough extends about 44 m from the wall, 2.6 times the excavation depth. The floor heaves by up to 35 mm (Figure 4).

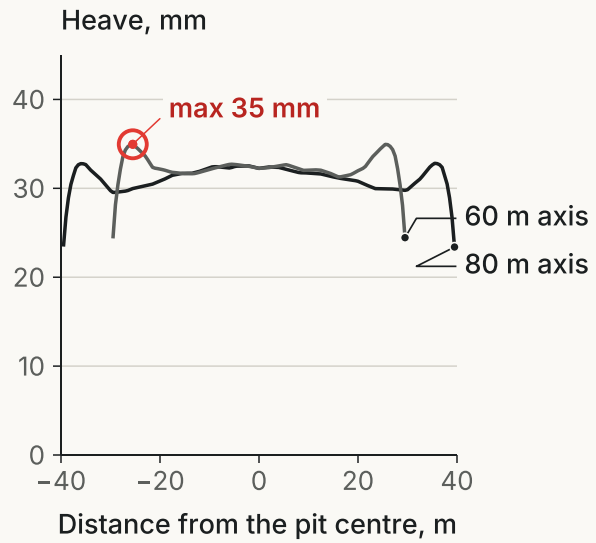
04 SETTLEMENT AND FLOOR HEAVE

Final phase, P01 datum.

A SETTLEMENT



B FLOOR HEAVE



Computed with PLAXIS 3D 2026.1 · Bentley Education licence P09 · P01 datum

Figure 4. Surface settlement against distance from each wall, and floor heave along the pit centre lines. Red marks the peaks.

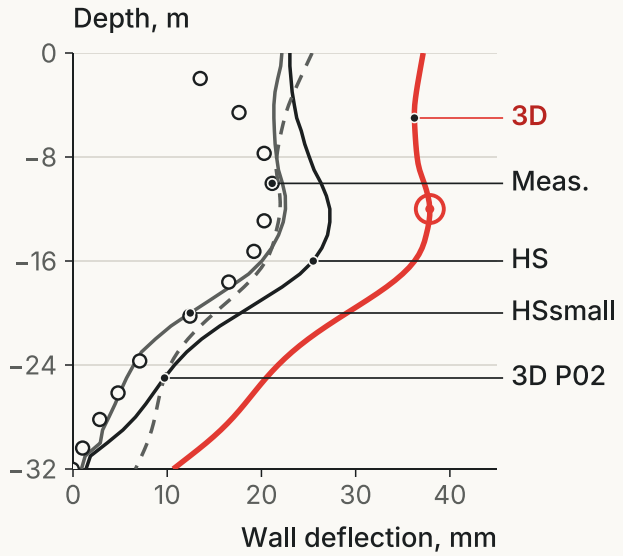
4.4 Benchmark and normalised movements

At midspan of the east wall the 3D deflection is 38 mm from the end of wall installation (P01) and 25 mm from the end of water lowering (P02). The published 2D analysis gives 27 mm with the Hardening Soil model and 23 mm with small-strain stiffness, against 21 mm measured with an inclinometer [B02] (digitised from the manual's figure and compared in Figure 5). The datum of the published curves is not stated, so both 3D datums are shown. From the end of water lowering (P02) the 3D midspan value lies below the 2D Hardening Soil value, consistent with a finite pit moving no more than plane strain; from the end of wall installation (P01) it does not, so the datum decides the comparison. Normalised by the excavation depth, the largest wall movement is 0.23 % and the largest settlement 0.14 %.

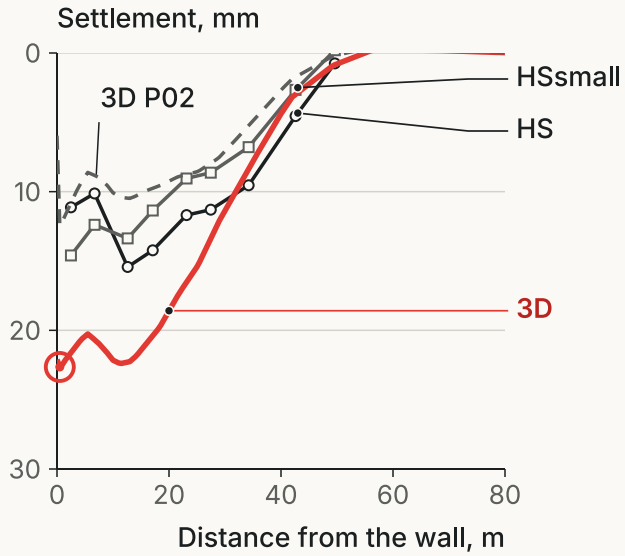
05 BERLIN BENCHMARK

3D midspan against the 2D results and the measured values.

A WALL DEFLECTION



B SETTLEMENT TROUGH



Peak deflection: 3D 38 mm, 2D HS 27 mm, 2D HSsmall 23 mm, measured 21 mm.

2D curves and measured values: digitised from Fig. 17–29 of the PLAXIS 3D 2026.1 Material Models Manual (after Schweiger, 2002), ±1 mm; they show the final excavation step, and their zero reference (datum) is not stated.

3D midspan: P01 datum (solid), P02 datum (grey dashed). A comparison, not a validation: the 3D model lowers the pit water in one step before excavation (about 16 mm).

Computed with PLAXIS 3D 2026.1 · Bentley Education licence P09 · P01 datum

Figure 5. Midspan wall deflection of the 3D model against the published 2D curves and the inclinometer, and surface settlement against the 2D curves. Both displacement datums are shown for the 3D model.

4.5 Bond sensitivity

Every case uses the base mesh and differs only in the grout bond resistance: 250 kN/m, 500 kN/m (the base case) and 1,000 kN/m. Halving or doubling the grout bond limit changes the wall movement, settlement and heave by 2 % or less and the peak wall moment by 5 % or less; even at half the limit the busiest grout body uses only 53 % of its capacity. Table 5 gives the effect on the largest wall movement.

TABLE 5 **Grout bond sensitivity on the base mesh, measured from the end of wall installation (P01)**

CASE	MAX. WALL MOVEMENT, mm	DIFFERENCE, %	COMPARED WITH
Grout skin resistance, 250 kN/m	38.4	−0.079	500 kN/m (base case)
Grout skin resistance, 500 kN/m (base case)	38.4	–	–
Grout skin resistance, 1,000 kN/m	38.3	−0.26	500 kN/m (base case)

5 Scope and limits

This is an idealised finite excavation built from published and assumed inputs and calibrated to no field data. It is not a design, not an assessment of any real project and not a reproduction of the Berlin case: the wall–soil interface strength, the grout bond, the way prestress is applied and the water idealisation are study assumptions, and the datum of the published monitoring curve is not known. Pore pressures are prescribed, behaviour is drained, and there is no seepage or consolidation. Wall forces at anchor heads and corners depend on the mesh and are reported only as strip averages. Mesh agreement is shown for the stated quantities on the meshes used and is not proof of full convergence. The low-permeability layer at −30 m is assumed: the model represents it only through the water pressures (pit water lowered above it, the outside water pressure below), not as a separate soil layer.

6 References

B01 Benz, T. (2007). *Small-Strain Stiffness of Soils and its Numerical Consequences.* Mitteilung 55, Institut für Geotechnik, Universität Stuttgart (ed. P. A. Vermeer). Berlin excavation: pp. 123–126; material data: Table D.4, p. 182.

B02 PLAXIS 3D 2026.1 Material Models Manual (last updated 30 September 2026), section 17.7 "Hardening Soil model and Hardening Soil model with small-strain stiffness: Excavation in Berlin sand", Figure 17–29 (p. 220), after Schweiger (2002) as given in the manual. Curves and measurement markers digitised from the figure (reading uncertainty ±1 mm); the manual states "after the final excavation step" and does not state whether displacements were reset after wall installation.

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