Excavation Pits: Calculation Methods

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Abstract. Three methods in engineering practice are mainly implemented to investigate the behavior of excavation walls. In the majority of the cases beam models with classical supports seem to be sufficient.

For modelling more accurate the deformation behavior of the foot of the wall it may be worth to improve the prediction of the deformation behavior using a subgrade reaction model. In cases of more complex pit geometries and soil conditions a finite element analysis may be more appropriate.

All these three methods of calculation are shortly described in the paper and compared with each other.

With the consideration of bound theorems an attempt is made in the paper to discuss the safety issues. All the presented three methods can be used to calculate the wall deformations. It is demonstrated that even a finite element analysis has limitations in cases of deformation predictions induced due to geotechnical installation processes in the vicinity of the wall. Data from field records may be used to estimate the order of magnitude of wall deformations due to installation processes. As an example of using field data in the wall deformation prediction and FEM in a recent research project the vibroinstallation of uplift piles near to the wall has been used.

The numerical results show quite satisfactorily that the new developed model may serve as a basis for the prediction of wall deformations due to some installation processes.

1 Introduction

In practice, there are essentially three methods available for the calculation of excavation pits - beam model, modulus of subgrade reaction method, finite element method - which are presented and compared with each other in the article. When verifying the ultimate limit state, the question arises about the safety of the individual methods. By means of simplified considerations, it can be shown that the calculated systems can generally be classified as approximately safe. For most standard cases realistic results for the serviceability state are achieved with the available methods. However, with some exceptions, the limits of the procedures are reached when deformations due to installation processes are to be predicted. The current state of technology and science is discussed on the basis of examples.

T. Triantafyllidis (Ed.): *Recent Developments of Soil Mechanics and Geotechnics in Theory and Practice*, LNACM 91, pp. 370–382, 2020.
https://doi.org/10.1007/978-3-030-28516-6_20

2 Design Analysis

Typically, wall constructions are calculated and verified using classical framework models. A special feature are the supports of the bracings and anchors and the earth support.

In the case of unsupported walls, the simplification of Blum has proven successful (Fig. 1). This makes it possible to convert the highly statically indeterminate fixed support in the ground into a statically determined model with two unknowns. The earth resistance E_{ph}, or the mobilised earth resistance E'_{ph} as well as the equivalent force C_h can be determined directly from the two available equilibrium conditions. It should be noted that in the Blum model a vertical tangent is assumed at the fixed support point. Thus, a comparison with the modulus of subgrade reaction method and with finite element calculations yields the highest fixing effect.

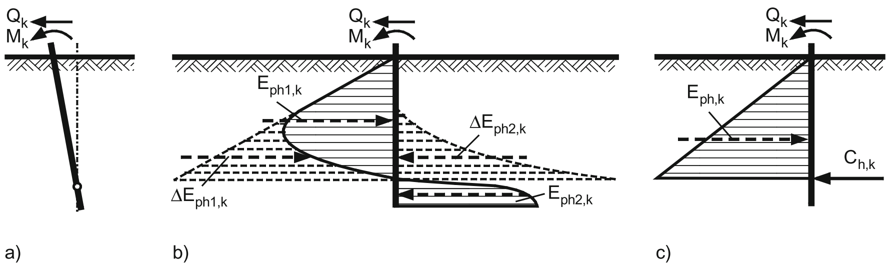

Fig. 1. Blum's simplification [17]: a) wall movement b) supposed earth pressure c) simplified earth pressure distribution.

In general, in the case of one or more supported excavation pit walls with support in the ground, a distinction must be made with regard to the static system between

- free supported walls (Fig. 2a),
- partial fixed walls (Fig. 2b),
- fixed walls (Fig. 2c).

All three systems assume a fixed support at the actual wall embedment length or at the theoretical point of bearing.

With a free support according to Fig. 2a, the wall embedment length is only supported by ground reactions $\sigma_{h,k}$ on the excavation pit side; the support force at the wall base must result from the calculation to $C_{h,k} = 0$. In the case of partial fixed support (Fig. 2b), the ground reaction $\sigma_{h,k}$ and the equivalent force $C_{h,k}$ generate a reversing moment, which reduces the inclination of the bending line at the wall base in comparison with a free support. If the back-turning moment is so large that at the theoretical bearing point C, where the equivalent force $C_{h,k}$ is applied, a vertical tangent of the bending line is reached, this is referred to as a full soil mechanical fixing or a

Blum fixed support. Their special feature is that the fixing moment $M_{C,k} = 0$ at the fixed support must result from the calculation (Fig. 2c). Depending on the degree of utilization of the soil reaction, the wall base can be free supported, partially fixed or fully fixed for the same depth of embedment.

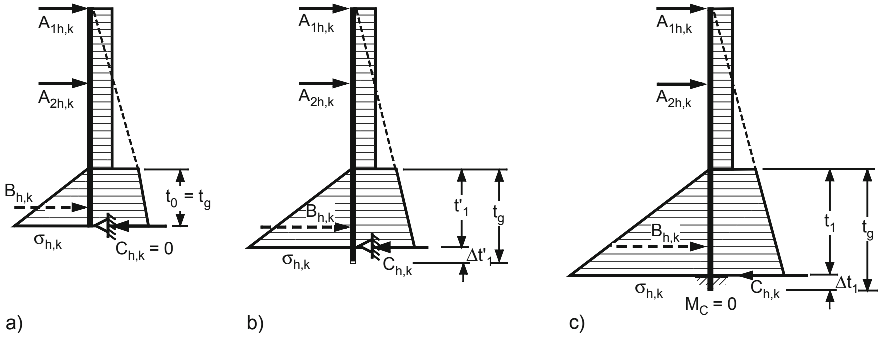

Fig. 2. Earth support for supported excavation walls: (a) Free support, (b) Partial fixed support, (c) Fixed support [11]

- The smallest possible embedment depth t_0 for a free support is obtained when the design value of the soil reactions with the boundary conditions according to Fig. 2a is 100% utilized.
- The smallest possible embedment length t_1 up to the theoretical bearing point with a fixed soil mechanical support is obtained if the design value of the soil reactions with the boundary conditions according to Fig. 2c is 100% utilized.

The support points of struts and anchors are generally assumed to be freely rotatable and immovable. Under these conditions, wall structures such as beams in building construction can be calculated. For details see *Hettler/Triantafyllidis/Weißenbach* [11].

3 Extension with Modulus of Subgrade Reaction Method

If the displacements of the wall base are to be calculated more precisely than with the beam model with non yielding support, the modulus of subgrade reaction method can be used. Here, the soil reaction is replaced by springs that are usually not coupled to each other. The advantage of this method is that the magnitude of the soil reaction and the displacements can be mapped realistically. At the same time, the effort for the static calculation is limited and the influence of different parameters can be clearly recorded. The main difficulty of the method lies in determining the spring characteristics in such a way that the calculated displacements and bending moments come as close as possible to the reality. The following points, among others, must be taken into consideration:

– The actual relationship between displacement and soil reaction is non-linear.
– Depending on the type of wall of design, e.g. parallel movement, rotation about the foot or rotation about the top of the wall, other spring characteristic curves result.
– Due to the arching effect, earth pressure redistributions occur and the spring characteristic curves are actually coupled with each other.
– The initial earth pressure condition has a great influence on the spring characteristics and must be taken into consideration.

In recent years, the working group for excavations from the German Geotechnical Society (DGGT) has also dealt in detail with the modulus of subgrade reaction method and issued Recommendation EB 102 [5, 9]. According to EB 102, paragraph 1, the method may be used for verifying the embedment depth, for determining the internal forces and also for verifying the serviceability limit state.

The approach of the initial stress condition plays an important role. Systematic investigations show, see e.g. Besler [2] and Hettler/Vega-Ortiz/Mumme [13], that the wall toe displacements become much too large without consideration the preloading arising from the weight of the excavated volume of the pit. According to EB 102 [5], the initial stress state may be the earth pressure at rest, calculated from the ground surface (Fig. 3). The idea is that during the excavation, the original at-rest earth pressure is maintained. In order to meet the requirement of the maximum possible limit state, the initial stress condition is limited from the excavation pit floor to the passive earth pressure.

Below the depth z_e the mobilisation of the soil reactions is modelled by subgrade reaction springs. On the earth side, the actions are applied like in the case of non yielding support of the beam.

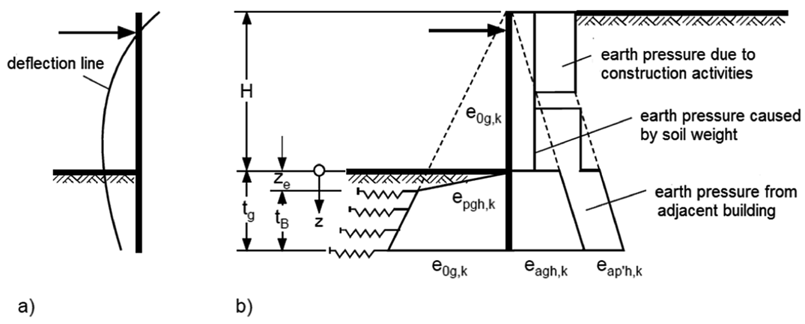

Fig. 3. Subgrade reactive for non-cohesive soil without zero displacement point: (a) wall deformation, (b) pressure diagram [11]

If a large embedment depth and flexible walls cause the wall to rotate backwards with a zero displacement point (Fig. 4a), it is obvious to apply the at-rest earth pressure below the zero displacement point on the earth side as well (Fig. 4b).

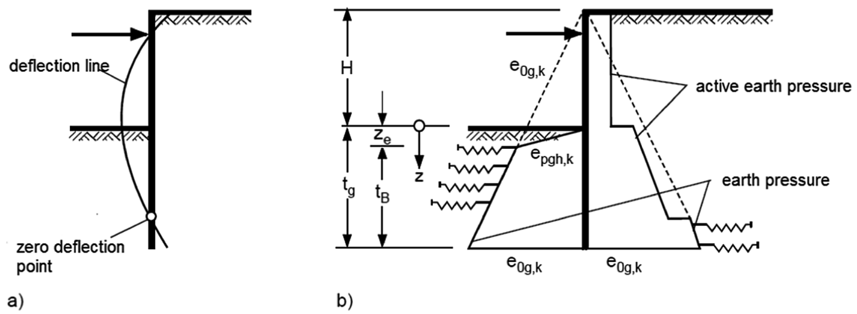

Fig. 4. Subgrade reaction model for non-cohesive soil with zero displacement point: (a) wall deformation, (b) pressure diagram [11]

As shown in Fig. 4a, no vertical tangent can occur at the zero displacement point according to the modulus of subgrade reaction method. In this respect, the fixing effect is less than with the Blum model.

The movement of the wall foot depends very much on the bending stiffness of the wall, the flexibility of the earth support and the embedment depth. Figure 5a, for example, shows the bending line of a simply supported, relatively rigid wall. As the embedment depth increases and the wall becomes more flexible, the deformation pattern changes (Fig. 5b). A backward rotation occurs and the wall toe movement consists of a parallel displacement and a rotation about the toe of the wall. In the case of long, flexible walls, a bending line is obtained as shown in Fig. 5(c).

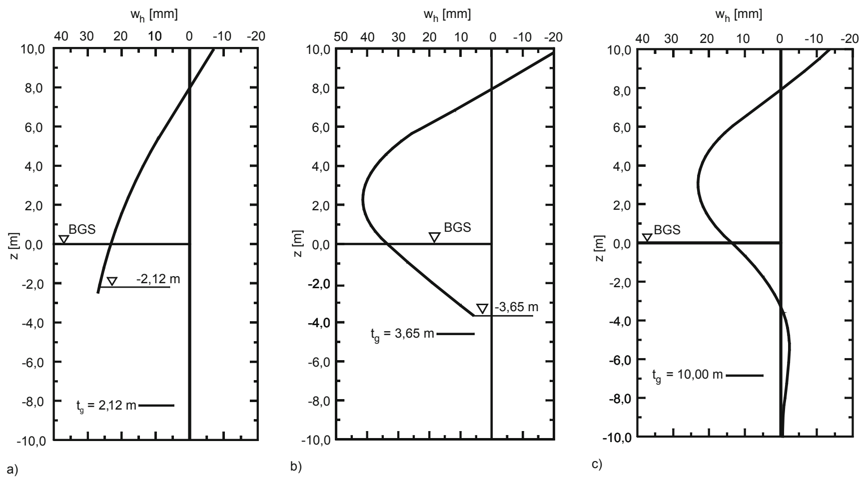

Fig. 5. Different forms of wall movement: (a) relatively stiff wall, (b) flexible wall with reverse rotation, (c) long wall [11].

For further details, including the determination of the subgrade reaction modulus, see *Hettler/Triantafyllidis/Weißenbach* [11].

4 Finite Element Calculations

Numerical calculations using the finite element method (FEM) are much more complex than simple beam models or extended models using the modulus of subgrade reaction method. Following the recommendations of the Working Group for Excavations (EAB), FEM is suitable in the following cases:

- Excavation walls with supporting conditions for which a reliable determination of size and distribution of the earth pressure is not possible, e.g. with strongly deforming walls;
- Construction with difficult geometric dimensions, e.g. recessed or protruding corners, which do not permit a reliable distribution of the earth pressure with conventional assumptions;
- staggered excavation walls with a berm width, which do not allow a reliable determination of the size and distribution of the earth pressure with conventional assumptions;
- Excavation wall designs where a realistic assessment of the effects of excavation, prop or anchor pre-stressing on the earth pressure redistribution and the displacements of the excavation wall is required;
- Constructions, where a realistic recording of the seepage flow and the associated water pressures is required;
- excavation pits next to buildings, pipes, other utility installations or traffic areas;
- exceptionally deep excavations.

In simple cases, classical methods and FEM provide similar results, as the following example in Fig. 6 shows for a wall that is simply propped with a free earth support. The classical beam model with non yielding support, the extended beam model with subgrade reaction and FEM calculations based on hypoplasticity soil model are compared.

In the example in Fig. 6, the support in the FEM calculation was modelled as non yielding. This explains the higher support force compared to the classical model and the increased earth pressures in the support area (Fig. 6a). Apart from that, there is a very good agreement between the active earth pressure assumed according to EAB and the FEM calculation. This also applies to the moment distribution (Fig. 6c). If the wall foot is modelled with non-linear subgrade reaction, the soil reactions in front of the wall in the classical beam also agree practically with the FEM result (Fig. 6a). The wall deformations require a separate discussion (Fig. 6b). Here, stiffness plays a significant role for small strains. In principle, the deformations of the entire terrain caused by the excavation of the excavation pit are added in the FE calculations.

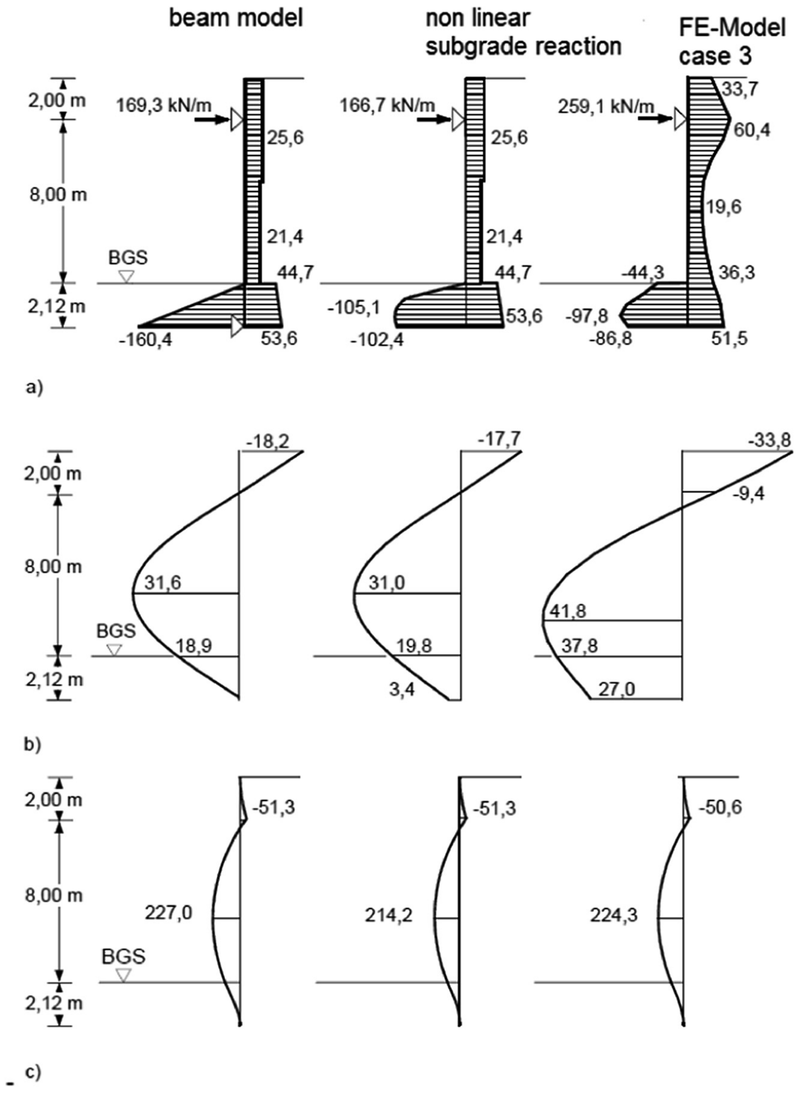

Fig. 6. Comparison of the classical calculation with the FEM for a sheet pile wall with free earth support at the embedment depth t = 2.12 m: (a) Stress distribution [kN/m^2], (b) Bending line [mm], (c) Moment line [kN m/m] [11].

As this example shows, in the standard cases covered by the EAB, the FEM is unlikely to provide any advantages and improvements in the determination of the earth pressure distribution. The FEM can, however, be of importance if the range of validity of the classical earth pressure theory and the empirical basis of the EAB are abandoned. This applies in particular to complex geometry or flexible anchors and flexible walls.

5 Safety Considerations

One of the most difficult tasks is the question of the safety factors of systems.

Brinch Hansen/Lundgren [3] investigate different limit states for an anchored sheet pile wall (Fig. 7)

- Failure with rotation about the top of the wall point
- Rotation about the top of the wall with yielding joint in the middle of the wall and flexible wall toe
- Rotation about the top of the wall with yielding joint in the middle of the wall and fixed at the toe of the wall
- Rotation around the head point with yielding joints in the middle of the wall and in the embedment part of the wall.

and explain: "One could perhaps imagine that it would be necessary - just as for failure mechanisms in the ground - to examine all (or at least some) types of limit state in order to find the critical one. But this is not the case. On the contrary, it turns out that one can design a structure for any chosen type of limit state and thus obtain a safe construction. It can be shown that a logically dimensioned construction subject to earth pressure can actually fail in no other way than assumed in its calculation. This has to do with the fact that the deforming part is relieving stresses and the movement that has begun comes to an end again."

Brinch Hansen/Lundgren [3] justify the explanations with plausibility considerations.

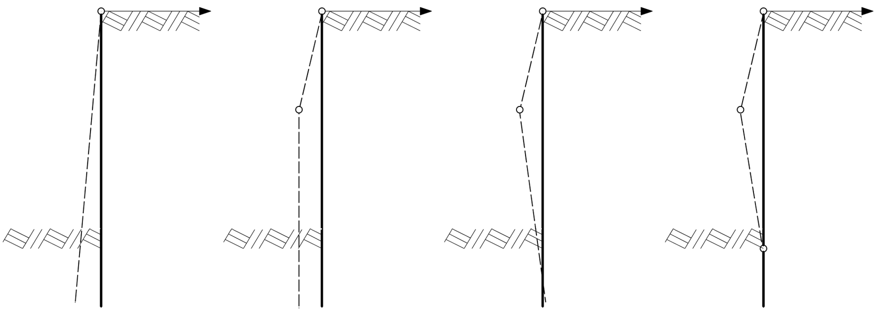

Fig. 7. Types of limit states for an anchored sheet pile wall [3]

From today's point of view, these theories can also be theoretically substantiated with the help of plasticity theory. Collapse loads can be determined within the theory of ideal plastic materials by the analysis of kinematic mechanisms and static stress fields, and upper and lower bounds are obtained see *Drucker/Greenberg/Prager* [4] *Koiter* [14] *and Gudehus* [8].

Put simply, the lower bound theorem is: If a static stress field can be found within the soil that is in equilibrium with the dead weight and the external forces and does not violate the boundary condition at any point, then the external forces form a lower bound for the collapse loads.

The upper bound theorem says: If there is a failure mechanism, for which the work done by the external forces and by the forces from own weight is smaller than the work from plastic deformations in shear zones and shear bands, then the external loads can be classified as the upper bound for the collapse loads, cf. also *Atkinson* [1] and *Powrie* [15].

Strictly speaking, the bound theorems apply only to ideal plastic materials. An important assumption is, among other things, the so-called normality rule, which is generally not fulfilled for soils. Nevertheless, the static and kinematic methods have proved their validity in many applications, especially in earth pressure, and the error made seems to be relatively small. A detailed description and application to soils can be found at *Goldscheider* [6]. As *Goldscheider* can show, the essential assumption for the proof is not the so-called normality condition, but Drucker's postulate.

Transferred to excavation walls, one could classify the calculations on the basis of correctly determined earth pressure distributions in the sense of the static theorem as a solution lying on the safe side, and only one solution suffices. With the realistic load diagrams, the design is further restricted in the EAB. By specifying a load diagram in the calculation and corresponding prestressing of anchors or struts in the design, a more economical design in comparison to any earth pressure approach should normally be possible.

All these considerations assume ductile behavior. In the event of sudden failure, e.g. brittle fracture or loss of a prop caused by collision with an excavator, additional safety measures are required. For this reason, EAB [5] requires increased partial safety factors in the following cases:

- Verification of stability deep slip surfaces in accordance with EB 44, paragraph 10 (Section 7.3) for excavations adjacent to structures,
- Verification of the design against overall failure of terrain in accordance with EB 45, paragraph 7 (section 7.4) for excavation pits adjacent to structures,
- Design of struts according to EB 52, paragraph 14 (section 13.7)
- Design of anchorages for walls in full excavation condition.

6 Determination of Deformations

The regulations of the EAB [5] ensure that, in the case of at least medium-dense non-cohesive soil and at stiff cohesive soil, the displacements of the earth support of a multiple-supported wall are small and correspond in magnitude to the movements and deformations of the remaining excavation pit wall. As a rule, this eliminates the need for special investigations into the size of the deformations and displacements.

A separate serviceability limit state verification may be required in particular

- in the case of construction pits, next to very high buildings, badly founded buildings or buildings in poor structural condition,
- for construction pits with very little or no distance to an existing building,

– for excavation pits alongside structures with high ground water level
– in pits next to structures founded in soft cohesive soil,
– in excavation pits, in proximity to structures which particularly high demands on their deformation, e.g. because of the sensitivity of machines,
– for excavation pits with an anchorage steeper than 35°.

Two cases have to be distinguished when proving serviceability:

– If the deformations of the wall are to be recorded more precisely, but the effects of the deformations on the environment are rather subordinate, the accuracy of the deformation prognoses can be increased by improving the static system, e.g. by recording the flexibility of the anchors, taking into account the pre-deformations in the various construction stages and considering the amount of subgrade reaction in the ground.
– If both the deformations of the wall and those of the surrounding soil are to be determined, numerical investigations, e.g. using the finite element method with consideration of the initial stress state, are required. For further details see *Hettler/Triantafyllidis/Weißenbach* [11].

Even when highly complex FE models are used, the limits are reached when deformations caused by geotechnical installation processes are to be predicted (*Hettler and Triantafyllidis* [12]). Only in isolated cases installation processes have been investigated in the scientific field, e.g. *Grabe and Mahutka* [7] or *Triantafyllidis* [16]. In practice, on the other hand, it is often necessary to include in the deformation prognosis the installation effects of e.g.

– excavation pit walls
– grouted anchors
– Bearing and sealing injection soles
– Basement anchorages

to be taken into account. As long as reliable forecast models are not yet available, it is necessary to carry out an estimation on the basis of measurements in comparable cases. In a contribution to the Baugrundtagung 2012 conference [10] some examples were compiled, see also *Hettler/Triantafyllidis/Weißenbach* [11].

From a research perspective, a DFG research group in recent years has succeeded in producing a complete prognosis model at least for the case of excavations with back-anchored concrete floors and vibrated piles.

The deformations of excavation pit walls due to dynamic installation methods, such as the vibration of piles next to a diaphragm wall [18], can be considered as cyclic creep with the HCA model [19]. The vibration amplitude is set by measurements with the distance to the vibration position of the pile and the time for a penetration of the pile is converted into a number of cycles. *Grandas/Vogelsang/Triantafyllidis* [20] used the sequence of pile installation and the frequency of the vibrator used (34 Hz) as well as the measurements of the particle velocities to determine the geometric radiation of wave attenuation in order to estimate the strain amplitude in all Gaussian points in the FE mesh.

With the HCA model and the simulation of the sequence of pile installation, the deformation curve of the D-wall could be reconstructed for the two published measuring positions of the diaphragm wall at Potsdamer Platz [18] (see Fig. 8), which could not be explained previously by local condensation assumptions and reduction of the passive resistance caused by the vibration processes. Since this model is also used promisingly for other dynamic installation processes, e.g. deep vibratory compaction [21], new possibilities for the estimation of shoring wall deformations due to dynamic effects close the shoring walls open up with the help of the HCA model in combination with FEM analysis.

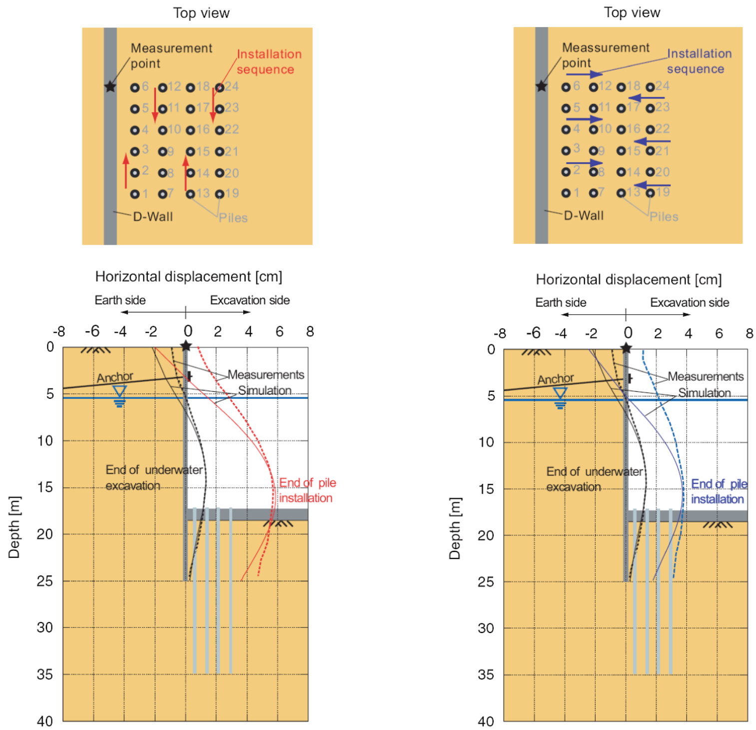

Fig. 8. Simulation of excavation wall deformations with the HCA model, using the example of measurements at Potsdamer Platz in [20], left: Pile construction parallel to the wall, right: Pile construction perpendicular to the wall

7 Further Information

Although a great deal of knowledge about the calculation and construction of excavation pit walls has been gathered over the last few decades, damages also occur again and again - sometimes despite careful planning and execution. It is striking that water effects are often identified as the main cause of damage, e.g.

– ground water drowdown
– ground water under high pressure or artesian conditions
– removing the ground when dewatering the excavation pit
– defects in sealing soles or diaphragm wall joints
– Anisotropy in water permeability
– unstable filter structure

An extensive collection of case histories with damages can be found in *Lutz Wichter* [22].

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