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Load bearing capacity of large-size, circular excavation walls without horizontal supporting systems

Comportement de grands parois de la fouille circulaire sans étrésillage ou bien sans ancrage anuscrit

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ABSTRACT

For large-size, circular excavation walls without horizontal supports it is very important to make the right decisions with regard to their construction, load-bearing capacity, stability and execution. Excavations with depths of approximately 50 m and diameters of nearly 60 m in difficult subsoil conditions have been executed rarely. This article describes the marginal conditions for the construction, the calculation as well as the determination of the load-bearing capacity, stability, the execution, the accompanying measurements, and the derivations from these results on the load-bearing capacity of the circular excavation walls.

RÉSUMÉ

Il est importante de trouver la décision correct pour les grands parois de la fouilles circulaire sans étrésillage ou bien sans ancrage à l'égard de la construction, le comportement à l'appui, la stabilité et l'exécution. Fouilles d'une profondeur d'environ 50m et d'un diamètre d'environ 60m dans des circonstances de sous sol difficiles son rarement été effectuées. Cette publication décrit les conditions fondamentales sous lesquelles la construction, la dimensionnement, la définition du comportement à l'appui, la stabilité, l'exécution, les mesures paralleles et les vérifications resultantes des mesures par rapport au grands parois de la fouille circulaire.

1 INTRODUCTION

For the stability and the avoidance of excessive deformations of large and deep excavations with vertical walls, some lateral support is commonly required to cope with the horizontal earth and groundwater pressures from the surrounding soil. Nowadays, the standard support is by external bracing in the form of tieback anchors. Internal bracing is less common and, within this paper, not indicated because of the large horizontal dimension of the excavation considered.

Usually, external bracing consists of a considerable number of tieback anchors which often require tricky installation procedures. Such bracing, however, may not be required if the horizontal earth and groundwater pressures can be accommodated directly by the members of the excavation wall and by the resistance of the soil immediately beneath the foot of the excavation. Relevant in this regard are the bending and normal stiffness of the members and the stiffness of the soil in horizontal direction. In the standard case of large and deep excavations with parallel walls, the required dimension of the supporting members will become enormous which, generally, makes this solution uneconomical. A different situation, however, arises when the walls of the excavation are not anymore (sub-)parallel but somehow circular in shape. In this case adjacent wall segments can generate self-supporting effects of considerable magnitude (Fig. 1). In this situation the excavation wall acts predominately as a cylindrically-shaped shell in which the forces from the lateral earth and groundwater pressures are compensated by compressive ring forces which are generated in response to radial loading. Of course, such mechanism can only prevail if the excavation wall is sufficiently thick and consists of a material of sufficient strength and stiffness.

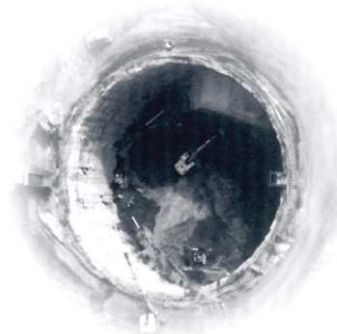


Figure 1. Aerial view of a circular excavation wall

This paper aims at delineating the principal requirements on the design and construction of such a circular-shaped excavation. It is shown that performance monitoring is essential for both construction control and validation of the design assumptions.

2 SYSTEM

Geotechnically, the system considered is a special case of an excavation with vertical walls. All horizontal loads from the earth and water pressures are accommodated solely by the walls of the excavation and the soil layers beneath the excavation floor. There is no provision for external or internal bracing. Figure 2 depicts the loads acting from the outside onto the cylindrical shell of the wall and the reaction forces developing within the shell acting in normal and circumferential directions.

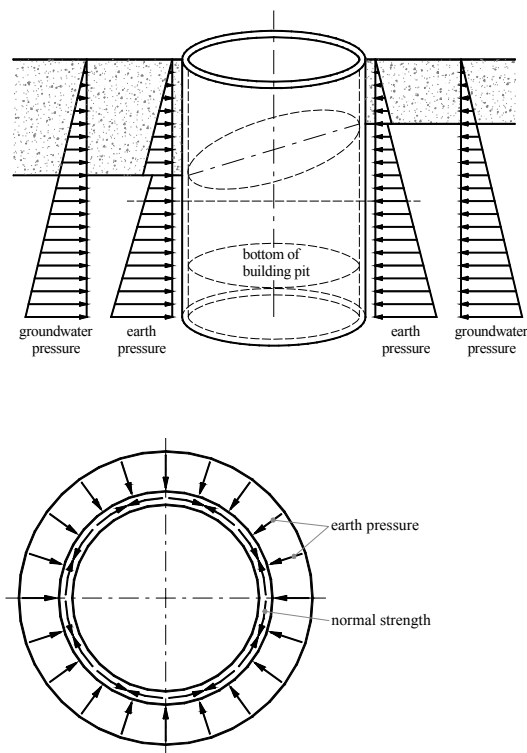


Figure 2. System of the cylindrical excavation wall

From Fig. 2 it becomes evident that the reaction forces vary over the height of the wall. This variation has to be carefully considered, particularly if there are inhomogeneous soil conditions along the wall's circumference.

3 ANALYSIS AND DESIGN

3.1 State of the art

In the analysis and design, large, circular-shaped and non-braced excavations represent a special case. Generally, it is quite conservative to assume that in such excavations the horizontal earth pressures are of identical magnitude than in straight excavations and to select the dimensions of the circular wall members accordingly. Note that this statement holds only for excavations with a diameter which is significantly greater than the respective depth. For a diameter-to-depth ratio of ≤ 1 , a three-dimensional earth pressure distribution in accordance with the classical theory and under consideration of the displacement constraints of the excavation wall has to be considered.

In accordance with Weißenbach et al. (2003), earth pressure assumptions can be made in dependency of the lateral stiffness of the excavation wall member as follows:

a) for non-yielding systems (intersecting bored piles, diaphragm walls):

$$E = E_o \dots E'$$

with E_o = earth pressure at rest (upper boundary value)

$$E' = 1/2 \cdot (E_o + E_{a,r}) \text{ (lower boundary value)}$$

and $E_{a,r}$ = spatial active earth pressure

b) for approximately non-yielding systems (strutted bored pile walls, sheet pile walls):

$$E = E' \dots E_{a,r}$$

c) for slightly yielding systems (strutted soldier pile walls):

$$E = E_{a,r} \dots E \text{ (Beresanzew, 1958)}$$

d) for yielding systems (non-braced cantilever walls):

$$E = E \text{ (Beresanzew, 1958)}$$

In accordance with the modified disc element theory („Ele-

mentscheibentheorie“ after Walz and Hock, 1987) a so-called ring stress factor K_y has to be considered for the determination of the spatial active earth pressure. Hereby, the value of $K_y = 0.5$ is associated with the upper boundary and that one of $K_y = 1.0$ with the lower boundary earth pressure.

It should be mentioned that in 1996, the above specifications were adopted in the Suggested Methods of the Working Group “Excavations” of the German Geotechnical Society (*Empfehlungen des Arbeitskreises “Baugruben”, EAB*). They are part especially of the Suggested Method EB 173 on “Circular-shaped excavations” („*Baugruben mit kreisförmigem Grundriß*“) and much of what is delineated below follows the specification of EB 173. To take account of any unforeseen deviation from the radial symmetry of the excavation wall (geometric imperfections), which in the geotechnical engineering practice is quite common, or of any inhomogeneities in the foundation soil, simplified load assumption procedures are suggested. An example is an earth pressure which is radially acting onto the wall and which is distributed along the circumference of the wall according to a cosine function.

3.2 The approach to analysis and load cases

In the following, the analysis and design of circular excavation walls are delineated with particular reference to the analytical methods and load cases to be selected. Remarks are made on the earth pressure configuration and on the deformation reaction behaviour of the subsoil. This is considered necessary as, so far, there were not too many projects on large, (near) circular-shaped excavations such as a polygonal array of slurry trenches or a large excavation with a closed ring of intersecting bored piles. As a consequence, there is relatively limited in-depth experience on the actual behaviour, in particular on the stability of such geotechnical structures.

For a realistic analysis of the deformational response to excavating large circular soil structures without any internal or external bracing it is essential to incorporate the entire structure within the analysis. For this purpose, the Finite Element computational method is an obvious choice. An alternative is the Bedding (or Subsoil Reaction) Modulus Method (“*Bettungsmodulverfahren*”). This relatively simple method can be reasonably employed even in inhomogeneous subsoil conditions and/or with an imperfect construction geometry of the excavation wall. The inhomogeneity of the soil can be either in horizontal (i. e. in circumferential) and/or in vertical (i. e. in axial) direction of the excavation wall.

The application of the bedding modulus method results in displacements of the excavation wall both in radial and circumferential direction. The magnitude of the displacements depends on the stiffness of the soil and that of the wall. In general, they vary from point to point along the circumference of the excavation wall. Different radial displacements in direction of the excavation (or in the opposite direction, i. e. against the soil) are connected with a different degree of reduction (or increase) of the earth pressures. Consideration of the subsoil reaction is always required in the analysis of large circular excavations with the only exception of constant radial displacements along the entire circumference. This special case applies only to homogeneous soil conditions along the circumference of the excavation and to a perfectly circular excavation structure. Both conditions have to be jointly fulfilled for a homogeneous earth pressure distribution and an equal subsoil reaction performance.

In the design it is assumed that the excavation is a cylindrical hole. External actions to be considered are traffic loads and both earth and water pressures. Like in the analysis, the design has to take account of differing earth pressures resulting from inhomogeneous soil conditions as well as construction features with imperfections such as construction tolerances and local deviations. In the design, generally three cases have to be considered

as follows (Figs. 3, 4 and 5):

- Case 1: Ideal circular excavation under earth and groundwater pressure (Fig. 3).
- Case 2: Elliptic pre-deformed system under earth and groundwater pressure (imperfection due to non-perfect construction procedures: 1st order geometric imperfection) (Fig. 4).
- Case 3: Circular excavation with tolerance of adjacent panels of a diaphragm wall or adjacent bored piles under earth and groundwater pressure (2nd order geometric imperfection) (Fig. 5).

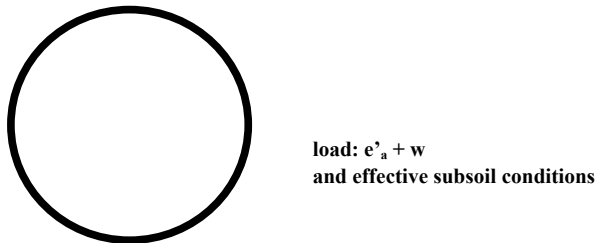


Figure 3. Ideal circular excavation under earth and groundwater pressure

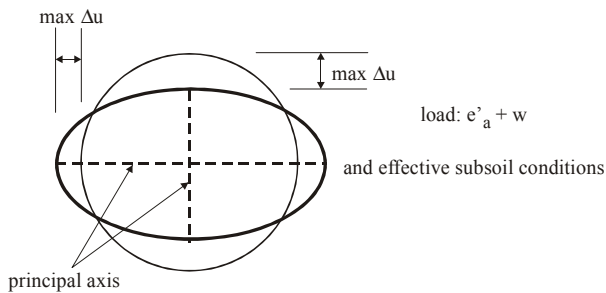


Figure 4. Elliptic pre-deformed system under earth and groundwater pressure (imperfection due to non-perfect construction procedures: 1st order geometric imperfection)

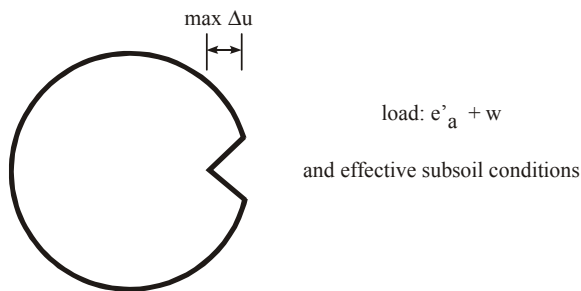


Figure 5. Circular excavation with tolerance of adjacent panels of a diaphragm wall or adjacent bored piles under earth and groundwater pressure (2nd order geometric imperfection)

Case 1 represents the situation of perfectly homogeneous soil conditions all along the circumference of the excavation. It results in the trivial radial symmetric case showing equal circumferential compressive stresses and equal radial displacements for all midpoints of the wall.

Case 2 (1st order geometric imperfection) has to be considered for both homogeneous and inhomogeneous soil conditions

along the wall's circumference. Deviations of the excavation from the ideal circular shape can lead to radial displacements which, from point to point of the wall, can differ significantly in their magnitude, even under initially isotropic earth pressure conditions. The differences can be so pronounced that some parts may be displaced in direction of the excavation and others towards the soil.

Case 3 (2nd order geometric imperfection) has to be considered along identical lines as in Case 2.

All three cases are based on the assumption that initially the active earth pressure E' or the respective spatial active earth pressure $E_{a,r}$ are prevailing, respectively. The order of magnitude of the earth pressure, to be considered in the design, depends on the subsoil conditions, the deformability of the excavation wall and the depth-to-diameter ratio of the excavation. Note that the deformability of the wall depends not only on the stiffness of the wall members (notably their deformational modulus and dimension) but also on the overall geometry of the members as a complete system. In geotechnical projects the highest stiffness is achieved by a closed-form array of diaphragm walls or of intersecting bored piles. In a perfect circular excavation, the Suggested Method on the design of excavations of the German Geotechnical Society (EAB-100, 1996) considers such a configuration as even a rigid structure. In this case and for the initial stage, the load $E_{a,r}$ resulting from the spatial active earth pressure can be determined by means of the above-mentioned modified disc element theory. It hereby is not anymore necessary to refer to the overly conservative assumption of an active earth pressure. In flexible or non-perfect geometric conditions, the load E' due to an increased spatial active earth pressure is decreasing, in line with radial displacements in direction of the excavation, down to the value $E_{a,r}$ of the spatial active earth pressure. Those parts of the wall, which show outward displacements (i. e. towards the soil), are subjected to a load increase from E' (related to the increased spatial active earth pressure) to E_0 (related to the earth pressure at rest).

Generally, the zones of relatively low earth pressures tend to be subjected to displacements towards the soil which, in turn, generate some subsoil reaction leading to an increase of the earth pressure towards the value of the earth pressure at rest. In Figs. 6 and 7 it is shown how to specify the earth pressures and the bedding pressures in asymmetric load configurations due to inhomogeneous subsoil condition along the circumference of the excavation for both geometrically perfect and non-perfect systems.

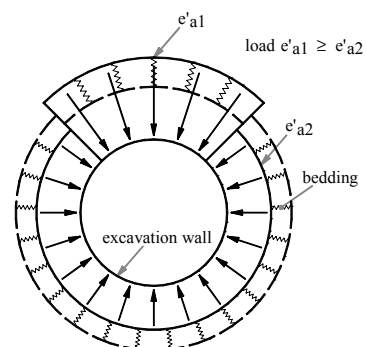


Figure 6. Earth pressure and bedding pressure under asymmetric load (plan view)

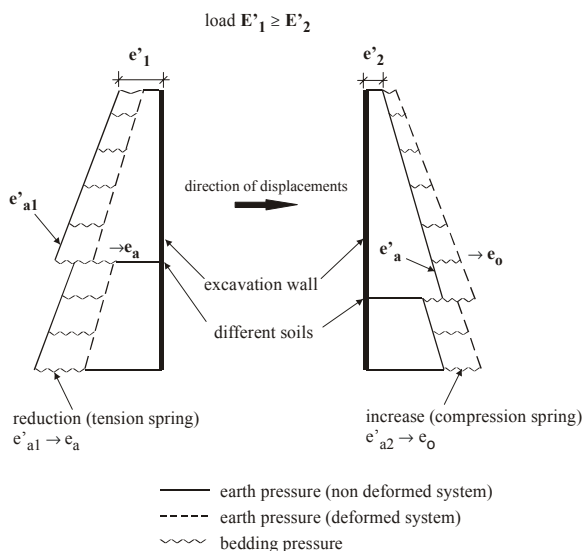


Figure 7. Earth pressure and bedding pressure under asymmetric load (cross section)

3.3 Earth pressure and bedding

For circularly shaped excavation walls the following principles can be considered to be valid:

1. In line with the fundamental interdependency between earth pressure, earth pressure at rest and earth resistance, the bedding conditions are both displacement and stress dependent (Fig. 8). The bedding modulus has to be determined accordingly. This is irrespectively of the fact that, according to the pertinent earth pressure theory, only order of magnitude estimates of the displacements can be given which are associated with a certain level of earth pressure. The bedding is principally resisting any displacements. The shear stresses at the wall-soil contact are limited by the friction angle of the soil.

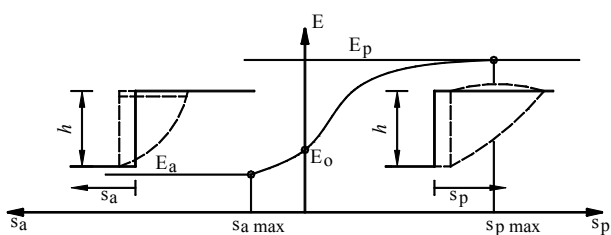


Figure 8. Interdependence between the earth pressure (active E_a , respectively passive E_p) and the displacement (s) of the excavation wall

2. Due to the construction and excavation processes there generally will be a certain reduction of the natural earth pressure in the vicinity of the excavation. The earth pressure will tend towards the level of the increased spatial active earth pressure E' . Note that the construction process in the form of either interconnected slurry trench segments or intersecting bored piles unavoidably creates some disturbance in the soil. The effect is also enhanced by a certain degree of shrinking of the concrete wall members.
3. Along the circumference of the excavation there can always be some inhomogeneous soil conditions which will lead to asymmetric loading. This condition is to be superimposed with the effects from the geometric imperfections as described in the Cases 2 and 3, which constitutes the least favourable conditions.

4. The relevant earth pressure and the state of bedding are to be delineated as follows:

- For non-yielding excavation walls (diaphragm walls; intersecting bored piles): The force associated with the increased spatial active earth pressure E' represents the lower bound of the forces to be considered. For the above-mentioned Cases 1 and 3, no additional comparative analytical studies are required, if the soil is homogeneous along the circumference of the wall.
- For the Case 2, the calculation of the section forces has to be based on a spring-bedded system which is deformed under the action of the increased spatial active earth pressure E' . In this case, as well as in the case of inhomogeneous soil conditions along the circumference of the wall, the tension springs of the bedding are to be inactivated. Alternatively, the magnitude of the increased spatial active earth pressure may be adjusted iteratively in such a way that, when superimposing the tension forces from all actions, the lower bound limit is never violated.

When adopting the above principles, the capacity and the deformational behaviour of large cylindrically shaped and unsupported excavation walls can be properly analysed and evaluated.

4 PERFORMANCE MONITORING - OBSERVATIONAL DESIGN METHOD

As mentioned before, so far only limited experience has been gained with large circular and non-braced excavations. In accordance with EC 7 and DIN 1054, this situation strongly suggests the employment of the Observational Design Method. This method is based on the monitoring of loads and deformations at relevant locations of the structure in course of construction and on a systematic comparison between measured and calculated values. The procedure provides the basis for the verification of the analysis and design. Any deviation from the anticipated conditions is to be carefully judged with regard to the stability of the excavation. A suitable monitoring program for large excavations includes the monitoring of the displacements at discrete points over the depth of the excavation wall and within the adjacent soil. All three independent displacement components in X, Y and Z direction are to be measured. The acting earth and porewater pressures at the soil/wall contact and within the soil are to be monitored in a similar mode. The program should also include monitoring of the heave of the excavation floor and of the settlements of the ground surface behind the excavation wall. All monitoring data have to be related to the construction stage and to the actual groundwater levels as determined in observation wells located inside and outside of the excavation.

In general it is recommended to carry out the following measurements:

1. Geodetic measurements (absolute and relative)
 - Such measurements are to be carried out well ahead of construction (for provision of a reliable reference base) and intermittently during all relevant stages of the construction:
 - a) Measurement of the position of the upper rim of the excavation wall in 3-D (location and height).
 - b) Measurement of the displacements of the walls. This requires setting up of surveying targets at the outer side of the wall and a comparison of the actual measurements with earlier reference measurements.
 - c) Measurement of the heave of the excavation floor by levelling.
 - d) Measurement of the settlements of the ground surface behind the excavation rim.

2. Geotechnical measurements within the excavation wall and at the wall/soil contact
 - a) Displacement measurement in X and Y direction by means of combined vertical inclinometer / extensometer probes
 - b) Measurement of the soil / wall contact stresses over the depth by means of total pressure cells
3. Geotechnical measurements in boreholes (i. e. in the soil)
 - a) Displacement measurement in X, Y and Z direction in the soil by means of combined vertical inclinometer / extensometer probes
 - b) Measurement of the earth pressure acting in the soil in vertical and horizontal direction.

Walz, B. and Hock, K. (1987): *Berechnung des räumlichen aktiven Erddruckes mit der modifizierten Elementscheibentheorie*. - Forschungs- und Arbeits-Ber. Grundbau, Boden mech. & Unterirdisches Bauen Univ.-GH Wuppertal, Nr. 6.

Weißbach, A., Hettler, A. and Simpson, B. (2003): *Stability of excavations*. - Geotechnical Engineering Handbook, Vol. 3, pp. 273-407, Berlin (Ernst & Sohn).

Such monitoring system allows an early recognition of any substantial deviation of the actual conditions from the anticipated stability and deformational behaviour of the excavation wall and the adjacent soil. An example of the horizontal displacements as measured at the top of a large-diameter pumping shaft with diaphragm walls is presented in Fig. 9.

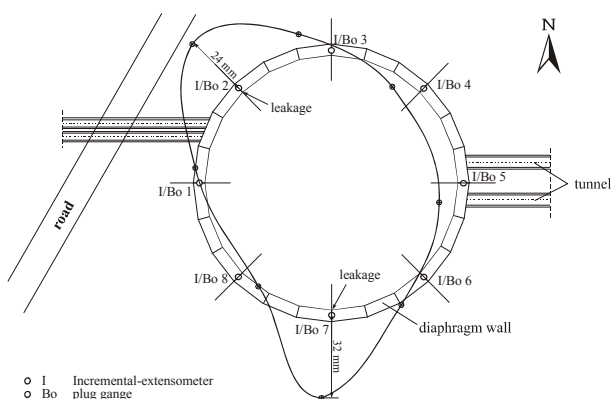


Figure 9. Horizontal displacements of the top of a diaphragm wall (Placzek & Londong, 1994)

5 SUMMARY

This paper describes an approach by which the stability and the deformational behaviour of the walls of large cylindrical, non-supported excavations can be adequately described and analysed. Various load assumptions are delineated and the spatial active earth pressure distribution determined in line with the modified disc element theory. Following the author's experience, the load assumptions presented in this paper are generally on the safe side. At the current state of knowledge, performance monitoring is essential. Still nowadays, large circular and non-braced excavations represent a special geotechnical problem. Despite the procedures presented within this paper, some gaps remain in our knowledge and experience with these structures. Further research on this topic is therefore justified.

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