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German national report on 'braced excavation in soft ground'

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SYNOPSIS: In this national report, the calculation methods and types of construction commonly used in Germany for braced excavations in soft ground are presented. Information is given on experiences made with projects carried out mainly in Southern Germany.

1 SOFT GROUND OCCURRENCE

There are two main regions in the Federal Republic of Germany (FRG), where normally consolidated soft ground is found with the following geological description:

a) Sea Silt: young, mostly very rich, soft clay, to be found in the costal areas and in the marshes of the rivers Ems, Weser and Elbe. The sea silt contains organic components. Its consistency is mainly soft, water content is up to over 100%, drained shear parameters are φ' = 15-20° and c' = 5-15 kPa, its undrained shear strength is c_u = 10-30 kPa.

b) Lacustrine Clay: silty clay to sandy silt in the Lake Constance and South Bavarian lake area. They often have thixotropic properties. The consistency is soft to very soft, water content is up to 25-50%, drained shear strength φ' = 22,5-25° and c' = 0 kPa, undrained shear strength is c_u = 10-40 kPa.

The main emphasis of the following report lays on experiences with braced excavations in lacustrine clay, because these soft grounds are found in a great amount also in urban areas. On the other hand, these experiences also apply to sea silt in many respects.

2 EXCAVATION TYPES

When excavating soft ground, the wall types preferred are sheet pile walls and bored diaphragms. Tie-back anchored or braced systems are used depending on regional subsoil layering. The following systems are preferably used:

a) Depth of open cut up to 4 m approximately and homogeneous soft ground as well as small plan dimensions: Within the excavation walls, a cut of 2 or 3 meters in width each, is made with unbraced slopes during one working day, beginning at the narrow end of the excavation, and a bracing strip of blinding concrete (0,2 - 0,4 m thick) is made under the foundation level of the future building. The strip of blinding concrete can be made of drained concrete, if there is water occurrence. During this state, the loads acting from outside on the side walls in the range of the excavated strip have to be carried over to better supported areas by horizontal beams along the side walls. Through continuous casting of the strips, a bracing footing slab is obtained in the height of the foundation level. The side walls are approximately twice as long as the excavation depth.

b) Depth of open cut from 3 to 6 m and homogeneous soft ground: To begin with, the side wall is supported by a berm using a top-down construction, and the foundation slab of the building or its ground floor is made in the central region of the total future excavation. As a second step, an intermediate bracing is carried out against the foundation part accomplished in the central region, the berm is removed and the bracing slab elongated to the excavation sides. Thus, a continous lower bearing is constructed for the wall. If the excavation is not very deep, the upper bracing can usually be omitted, or, for greater depths, a new bracing following the progress of the construction must be installed.

c) Deep excavations in homogenous soft ground: Prior to start of excavation, a bracing foundation slab is cast underneath the final foundation level, for example using the HDI (high pressure injection) method. The excavation and further bracing of the side walls is carried out as a top-down construction with struts.

d) Excavations in soft ground with sand or gravel layers on top: These conditions often require a tie-back anchoring in the sand or gravel layer. In this case, the anchorage must be made very long, so that a sliding of a major part of the cohesionless layer, including the anchorage, on the soft clay into the excavation is prohibited.

3 CONSTRUCTION RULES AND DESIGN

3.1 General

Special codes of practice or standards for excavations in soft ground are not available. The German recommendations of the Committee for excavations (EAB 1988) deal with excavations in soft ground only in regard to an increased factor of safety against earth resistance (factor of safety FS > 2,0) in order to reduce deformations of the lower end of the wall. In the following, the basic elements are given for the evaluation of the relevant soil parameters and earth pressure assumptions in Germany.

Further recommendations for construction also are given.

3.2 Undrained Shear Strength

The undrained shear strength c_u for excavation calculations in normal consolidated soft ground is mainly determined by vane tests in situ. It has turned out to be useful to refer c_u to the effective stress σ_{vc}', under which the soil is consolidated (consolidation stress), because c_u usually increases with increasing depth and thus with increasing effective stress σ_{vc}'. In the Constance region (Scherzinger 1991), the relation c_u/σ_{vc}' with 0,22 to 0,26 has been measured and thus corresponds well with the equation

$$c_u/\sigma_{vc}' = 0,23 \pm 0,04 \qquad (1)$$

found out by Jamiolkowski et al. (1985).

If there are preloads (for example adjoining buildings), the equation (1) must be replaced by the formula (linear regression)

$$c_u = c_{u0}(z=0) + m \cdot \sigma_z'(z) \qquad (2)$$

which depends on depth.

Figure 1 gives examples of results of vane tests.

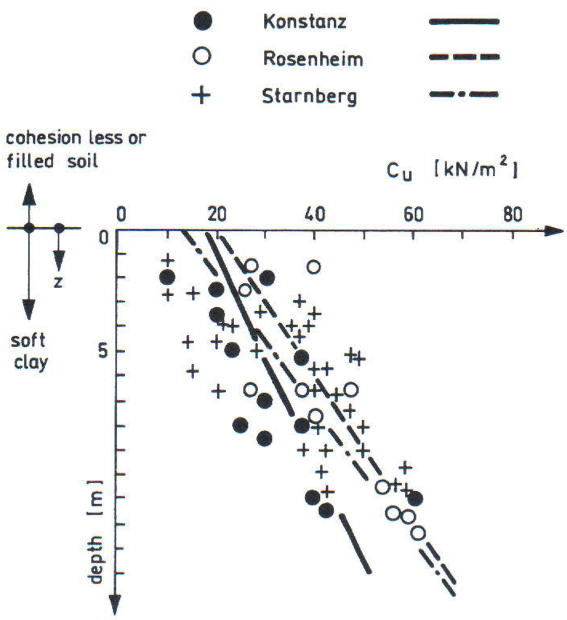

Figure 1: Results of vane tests on lacustrine clay in the Southern part of Germany (Examples)

The different strain velocities at tne side wall and vane tests are taken into account by using a reduction factor μ_R, dependent on the plasticity index, according to Bjerrum et al. (1972). The anisotropy of soft ground is taken into account in regard to the undrained shear strength c_u by a further reduction factor μ_A when extension stresses occur (passive earth pressure against the wall), in accordance with Bjerrum et al. (1972), and is also considered in order to reduce deformations. This becomes noticeable especially when comparing the various stress states behind and before the side walls. An assumption by Scherzinger (1991) is given in Chapter 3.5.

3.3 Calculation of Earth Pressure at Rest

The earth pressure at rest ($e_o = \sigma_x$) can be calculated for a horizontal ground surface by the generally known formula

$$\sigma_x'(z) = K_0 \cdot \sigma_z'(z) \qquad (3)$$

For normally consolidated soft ground, a constant ratio of the effective main stresses

$$\sigma_3'/\sigma_1' = K_{0(NC)} \qquad (4)$$

can be given, when lateral strain is not allowed, or when the ground is cohesionless.

Scherzinger (1991) determined the ratio of the effective main stresses from triaxial tests on lacustrine clay in the Constance area ($I_p \approx 20\%$), corresponding well with the ratio determined by Lee and Jin (1979):

$$K_{0(NC)} = 0,24 + 0,31 \log I_p \ (\%) \qquad (5)$$

For the lacustrine clay, an average value $K_{0(NC)} = 0,6$ is often assumed by experience.

3.4 Calculation of Active Earth Pressure

The active earth pressure ($e_a = \sigma_x$)

$$\sigma_x(z) = \sigma_z(z) - 2 \cdot c_u \qquad (6)$$

depends also on the depth, when c_u increases with the depth, according to Chapter 3.2. Using the ratio c_u/σ_{vc}' according to Eq. (1) or derived from Eq. (2), which can be described by the quantity

$$\lambda = c_u/\sigma_{vc}' \qquad (7)$$

the Eq. (6) can be written as follows:

$$\sigma_x(z) = \sigma_z(z) - 2 \cdot \lambda \cdot \sigma_{vc}' \qquad (8)$$

For completed consolidation, the stress σ_{vc}', under which the ground was consolidated, equals the effective stress σ_z'. The wall stress, including the water and traffic loads, can be given in a simple manner by the total earth pressure coefficient $K_a^T(z)$ which varies with the depth z:

$$K_a^T(z) = 1 - [2 \cdot \lambda \cdot \sigma_z'(z)/\sigma_z(z)] \qquad (9)$$

In order to simplify the earth pressure determination, it has proved to be appropriate and sufficiently exact, if the total coefficient of active earth pressure is determined in the mid-height of the layer depth $K_a^T(z = d/2)$ and if K_a^T is considered to be constant throughout the wall height. This applies if the layer height d in question is not too great. The earth pressure is thus given by

$$\sigma_x(z) = \sigma_z(z) \cdot K_a^T(z=d/2) \qquad (10)$$

For lacustrine clay, alternatively, an effective coefficient of active earth pressure

$K_a' = 0,45 - 0,50$ is often used. In this case, the loading caused by water pressure is to be considered separately.

3.5 Calculation of Passive Earth Pressure

The passive earth pressure ($e_p = \sigma_x$)

$$\sigma_x(z) = \sigma_z(z) + 2 \cdot c_u \qquad (11)$$

also usually depends on the depth, according to Eqs. (1) and (2). The calculated value c_u is diminished by the factors μ_R und μ_A corresponding to Chapter 3.2, according to Bjerrum et al. (1972). Scherzinger (1991) suggests for undrained shear strength c_u, obtained by laboratory tests or vane tests, for extension (passive earth pressure) and for limiting the deformation, the following value:

$$\text{cal } c_{uE} = 0,25 \cdot c_u \qquad (12)$$

In soft ground, a support of the wall by passive earth pressure with a tolarable deformation cannot be obtained. Therefore the loads acting on a side wall have to be carried nearly completely by bracing elements. An example of this is given by Katzenbach et al. (1992). Furthermore, it must be considered that the values in Eq. (12) for c_{uE} do not require further security factors in the earth pressure calculation (FS = 1,0). As for active earth pressure (Chapter 3.4), an effective coefficient of passive earth pressure can alternatively be calculated. For the lacustrine clay, $K_p' = 1,3 - 1,5$ (FS = 1,0) is taken.

3.6 Total Stability of Excavation Construction

The total stability of the excavation construction in soft ground depends on the failure mechanism which can develop according to the type of excavation construction. For bodies of soil sliding down on circular slip surfaces, base failure has to be investigated according to EAB, EB 9 (1988). Further analytical investigations have to be performed according to Terzaghi (1943) and Weißenbach (1978).

Especially for excavations in soft ground, the stability analysis by rigid block mechanisms (figure 2) are recently preferred (Scherzinger, 1991). See also the Kinematic Elements Method (Gussmann, 1986).

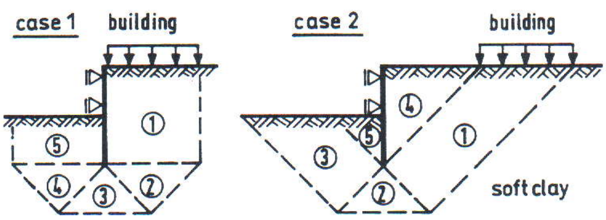

Figure 2: Total stability analysis of a braced excavation in soft ground using the rigid block method by Scherzinger (1991)

3.7 Ground Movements and Settlements

When bored diaphragms are made in lacustrine clay next to existing buildings, settlements of up to 2 cm by pile production alone have been observed, practically independent of the boring method. The casing should be inserted at least 3 m ahead in the soft clay.

The smallest ground movements occur when placing the sheet pile walls by the squeezing method. Driving by vibration in thixotropic or sensivitic lacustrine clay leads to liquefaction effects with considerable settlements behind the side wall.

Settlements as a result of displacement of the side wall or stress redistribution have been observed in soft clay behind the walls up to a distance of about 5 times the excavation depth.

4 IMPORTANT PROJECTS AND MEASUREMENTS

Regarding the technical execution of soft ground projects in Germany, difficult and important projects have been published for example by Gudehus (1986), Gudehus et al. (1987), Goldscheider (1988), Goldscheider et al. (1990). Two difficult excavations in soft clay with extensive supervision by measurement techniques will be described by Kempfert et al. (1993). Figure 3 demonstrates, in an exemplary way, a project of a braced excavation in Starnberg, with an upper strut and a bracing underneath the excavation bottom level by a high pressure injection slab (HDI), anchored downwards using injection piles with small diameters (micropiles).

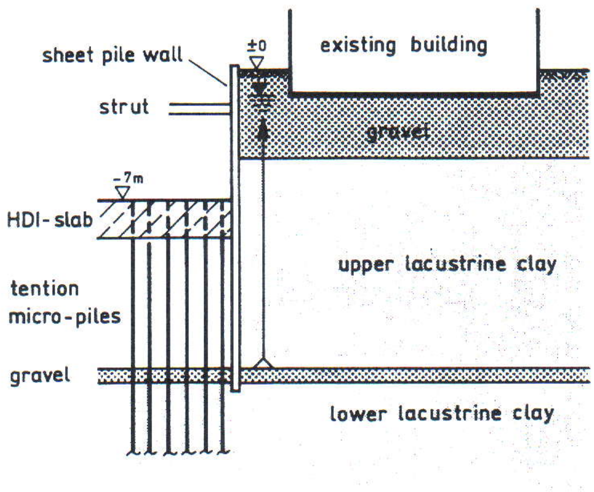

Figure 3: Example of a project carried out with a strutted sheet pile wall, high pressure injection slab (HDI) and injection piles (Katzenbach et al., 1992)

The above-mentioned literature also includes results of measurements on braced excavations in soft ground. Preference was given to inclinometer measurements, strut load measurements and settlement measurements at the neighbouring buildings. Detailed rules of practice on measurements in excavation constructions are also given in the EAB (1988).

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