Design of relief boreholes for relaxation of pore-water pressure at the bottom of excavations

Méthode de calcul des forages permettant la détente de la pression interstitielle au-dessous du niveau d'excavation

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ABSTRACT

For excavations in subsoil below the groundwater level a verification against failure by heave has to be carried out. Relief boreholes can be applied at the bottom of the excavation in order to relieve the pore-water pressure. But in this case the well known classical approaches for the verification against failure by heave fail themselves. A calculation scheme on the basis of the finite element method (FEM) is presented to fill this gap. The derived scheme is more flexible than the classical approaches and so it can also be used to design the relief boreholes. Finally, the scheme is illustrated by an example.

RÉSUMÉ

Lors d'excavations au-dessous du niveau de l'eau libre, il est nécessaire de procéder à des vérifications afin d'éviter les ruptures consécutives aux annulation des contraintes verticales. Des forages facilitant la détente de la pression interstitielle peuvent être utilisés. Les approches classiques bien connues et utilisées pour procéder à des vérifications de la stabilité ont montré leurs limites. Une méthode de calcul par la méthode des éléments finis est présenté afin de corriger cette lacune. Ce procédé de calcul dérivé est plus flexible que les approches classiques et en outre permet la conception des forages. Un exemple est donné afin d'illustrer ce méthode de calcul.

Keywords : excavation, design, heave, relaxation, relief boreholes, retaining wall, ultimate limit state, uplift, verification

1 INTRODUCTION

For the construction of excavations various verifications and proofs are necessary. Basically, there are design proofs concerning the retaining wall construction and verifications against failure of the subsoil. According to Eurocode 7 (EN 1997-1) limit state considerations are split up into Serviceability Limit States (SLS) and Ultimate Limit States (ULS). In the following it is focused on those ULS failure mechanisms of the subsoil which only appear in presence of different groundwater levels inside and outside the excavation. Here not only the static behaviour of the retaining wall is affected. In this case additionally some special potential failure mechanisms exist. These failures are namely uplift, heave, internal erosion and piping.

Uplift has to be investigated, if the water pressure is acting upwards on an impermeable soil layer below the excavation level. The weight of the saturated soil has to be proven higher than the acting water pressure underneath the impermeable layer. In this case no seepage of water is assumed. According to Eurocode 7 a rather simple evaluation of the acting soil weight and the water forces is sufficient to prove safety against this failure mechanism. Usually that means, that there is no impermeable layer allowed close to the excavation level. Relief holes can perforate such layers and prevent them from uplift.

Another important failure mechanism to focus on is heave. Here upwards seepage of water occurs due to different water potential heads inside and outside the excavation pit. Along with that, seepage forces are acting on the subsoil. Especially the upward seepage close to the excavation level may lead to heave. Here the seepage forces could be higher than the effective weight of the soil. Along with seepage internal erosion or piping might occur, but this paper will not deal with that.

In practical cases the classical approach from Terzaghi & Peck (1956) is used to prove safety against heave. Here the failure mechanism is simplified to a rectangular body with a certain width depending on the embedding length of the retaining wall. In this approach only soil weight and seepage forces are taken into account. For cohesive soils this approach might lead to too conservative embedding length of the wall since the cohesion is neglected.

For the two potential failure mechanisms 'uplift' and 'heave' relief boreholes can help to find suitable and economical solutions for the construction. The application of relief boreholes at the bottom of an excavation to relax the pore-water pressure is an appropriate measure to improve the geohydraulic situation at the bottom of the excavation. But, to prove safety against uplift or heave, the relief boreholes need to be designed with care with respect to their depth and diameter as well as their distance to the wall and between each other.

The relief boreholes need to have a sufficiently wide diameter. On the one hand the cross section has to be large enough to lead incoming water to the bottom of the excavation. If the diameter is too small the relief boreholes are not capable to relief pore water pressure efficiently. On the other hand the lateral surface area has to be large enough to collect sufficient water for pressure relief.

Also the relief boreholes need to have a certain depth. First, the boreholes prevent an impermeable layer beneath the bottom of the excavation from uplift. Secondly, the boreholes need to be deep enough to avoid upward seepage of water at the bottom of the excavation to prevent heave.

The arrangement of the boreholes in the base area of an excavation has to follow two aspects: first, if the distance between the relief boreholes is too large, in some distance the seepage is not effected by the boreholes any more; second the boreholes need to be somewhat close to the wall since this zone has been recognized as extremely affected by heave. Otherwise, if the boreholes are too close to the wall, high seepage forces might act in centre of the pit, which could cause other failure mechanisms. So the optimum has to be found somewhere in between.

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2 COMPARISION OF MECHANICAL MODELLS

In both cases – 'uplift' and 'heave' – the classical verifications are based on simple comparisons of up- and downward acting forces. Normally, internally or externally acting shear resistances are neglected completely.

For soils with high cohesion it seams to be uneconomic to disregard the cohesion. On the other hand it is somewhat risky to apply the cohesion working with a simple rectangular failure body according to Terzaghi & Peck (1956) since it is not clear if it is suitable also for cohesive soils.

Furthermore, it is not clear, which failure mechanism becomes relevant in the case of excavations with relief boreholes in the subsoil. It does not seem to be admissible to transfer the classical failure mechanisms to these situations.

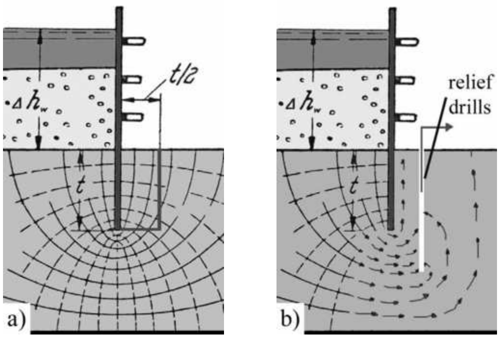

Figure 1 a) Terzaghi's failure body for verification against heave (non cohesive soil, classical seepage situation) b) situation with cohesive soil and seepage effected by relief boreholes

In both cases – cohesive soil and relief boreholes – the classical method fails. Here, numerical simulations on the basis of the Finite Element Method (FEM) appear as a helpful tool, since they present the relevant failure mechanism as a result of the calculation – and do not demand an assumption of their geometry (Perau & Haubrichs, 2006).

3 CONCEPT FOR VERIFICATION

A concept for verification against failure by heave on the basis of the FEM is presented, which takes into account friction and cohesion of the soil. This method can be used to verify geohydraulic situations at the bottom of excavations with and without relief boreholes. It allows to determine the length of relief boreholes as well as to compute the maximum possible excavation depth before these boreholes have to be effective. Additionally, the amount of groundwater that needs to be pumped out of the pit to keep it dry in all construction stages is forecasted.

Calculations are realised, using the FEM according to the ideas from Perau (2005), Perau & Haubrichs (2006), Wudtke & Witt (2006) and Gutjahr & Perau (2006). According to this concept the relevant construction phases are modelled and computed step by step. That embraces computations of the flow-field with characteristic parameters, considering the intrinsic geometric and geohydraulic circumstances (e.g. depth of the retaining wall, relief boreholes, etc.) of each construction stage.

In each stage the respective geohydraulic situation is included by a calculation of the groundwater flow-field in advance of the actual structural analysis. In a second step for each phase the seepage forces are imposed on the structural model. Table 1 displays a typical scheme of calculation.

A level of safety corresponding to the German code of practice (DIN 1054) as a NAD (National Application Document) for the European code of practice (Eurocode 7) had to be realized by the verifications. The definition of a FEM safety factor via ϕ-c-reduction (Brinkgreve & Bakker 1991), which has often proven to be useful, does not succeed in this special case. The reason for this is, that safety against failure by heave is governed by the stabilising action of the weight of soil (Perau 2005). The influence of internal friction and cohesion is less important than in the analysis of the bearing capacity of foundations or the stability of slopes. Therefore the weight of the soil has to be included as a varying factor into the verification of stability. In the presented concept this is realised by a reduction of the soil weight.

Table 1: Typical scheme of calculation

Phase 0:	Initial State: stresses and pore-water pressures before any construction activity
Phase A:	Creation of the retaining wall
Phase B:	Drainage and excavation inside the pit down to a level where additional measures (like relief boreholes e.g.) are not required for stability
Phase C:	Sinking of relief boreholes and filling with drainage material
Phase D:	Drainage and excavation inside the pit down to maximum depth under consideration of additional measures like relief boreholes

The safety concept with partial safety factors under the terms of Eurocode 7 and DIN 1054 demands not only to decrease the stabilising actions (here the weight of the soil) but also to increase the destabilising actions (here the seepage forces). To find easier acceptance the definition of input parameters for the FEM-program follows as far as possible the regulations of Eurocode 7. In verifications against heave, see Eqn. (1), the stabilising weight G'_k has to be reduced by the partial safety factor $\gamma_{G,stb}$; the destabilising seepage force with an upward direction of action S'_k has to be increased by the factor γ_H.

$$S'_k \cdot \gamma_H \leq G'_k \cdot \gamma_{G,stb} \tag{1}$$

The disposable FEM software does not provide the enhancement of seepage forces in a sufficiently transparent way. Hence these forces are calculated always with their characteristic values, which makes it necessary to reduce the weight even further for compensation. The expression (1) is therefore equivalently converted as follows:

$$S'_k \leq G'_k \cdot \gamma_{G,stb} / \gamma_H \tag{2}$$

In this expression the ratio $\gamma_{G,stb}/\gamma_H$ represents the resulting safety factor, by which the weight of the soil (γ and γ') has to be multiplied within the FEM calculations.

In Terzaghi's classical approach for failure due to heave no shear resistances appear. So the German code of practice consequently does not contain any partial safety factors for the shear parameters in the respective ULS. This lack can be filled by considerations on the basis of the ULS concerning slope stability and overall stability of retaining walls. For the concept presented here partial safety factors for shear parameters are evaluated with caution to $\gamma_{\phi/c} = 1{,}4$ and so design values are calculated as follows:

$$\tan\phi_d = \tan\phi_k / 1{,}4 \quad \text{and} \quad c_d = c_k / 1{,}4 \tag{3}$$

A major advantage of FEM-calculations appears in the implementation of the pore water pressure and seepage forces as internal loads on the subsoil and the wall construction. So it can be incorporated in the structural analysis and the verification of safety against failure.

If the results of the FEM-calculations on the basis of design values meet the requirement of a state of equilibrium in all construction stages, the verification against heave is fulfilled. Otherwise the design of the wall or the relief boreholes has to be adapted.

4 DIMENSIONING OF RELIEF BOREHOLES

The relief boreholes must have sufficient dimensions to provide an efficient effect on the geohydraulic situation beneath the bottom of the excavation. Overall, three dimensions have to be determined:

1. A sufficient lateral surface area of the boreholes to realize the inflow of water into the borehole
2. A sufficient and possibly optimised number of boreholes and their respective arrangement in the ground plan of the excavation
3. A certain depth of the boreholes to relieve the pore water, and so to lower the hydraulic potential as well as the hydraulic gradient in a sufficient way

For the first aspect, a sufficient surface area of the boreholes, an approach for the capacity of a single well is chosen (see e.g. Herth & Arndts 1994):

$$q_E = 2\pi \cdot r \cdot h \cdot \sqrt{k_f}/15 \qquad (4)$$

In Eqn. (4) q_E [m³/s] is the capacity of a single borehole, r [m] denotes the radius of the borehole and h [m] is the depth of the borehole beneath the toe of the retaining wall. The last factor in Eqn. (4), containing the square root is the maximum velocity v [m/s] of the inflow depending on the permeability [m/s] of the soil (Herth & Arndts 1994).

In sum all relief boreholes have to be capable to catch the total discharge of water Q [m³/s], which is a result of the steady state groundwater flow simulation. So with n as the number of boreholes Eqn. (5) gives the required radius r [m] of the relief boreholes:

$$r = \frac{15\ Q}{n \cdot 2\pi \cdot h \cdot \sqrt{k_f}} \qquad (5)$$

The second aspect, to optimize the number of boreholes and their arrangement in the ground plan, induces to make sure that a transfer from the real 3-dimensional situation to the idealized axial symmetric simulation is justified. That means the distances a_n [m] between the boreholes have to be small enough, so that they may be modelled as a slot. They should depend on the embedding length t of the excavation wall and the distance between the boreholes and the wall a_b [m]. Therefore the approach in Eqn. (6) is suggested:

$$a_n \leq 1{,}5\ \min(a_b;\ t) \qquad (6)$$

The third aspect, a sufficient depth of the relief boreholes, is a result of the numerical simulation. As described in the previous section, the numerical simulation is meant to result in a state of equilibrium of the acting forces. For this purpose the hydraulic potential has to be lowered enough to prevent a failure by heave. A variation of the depth of the relief boreholes consequently leads to their optimal depth.

A variation of the distance between the boreholes and the wall a_b leads to the optimal distance as well. It has to be small enough to avoid an appreciable upstream of water in this area.

5 EXAMPLE AND PARAMETER STUDIES

To illustrate the concept of verification and its usefulness it is applied to a practical example which is rather simple (Perau & Haubrichs 2006). Figure 2 shows a circular excavation of 20 m in diameter and 20 m in depth. The soil parameters are given in Table 2.

A diaphragm wall retains the surrounding soil as well as the groundwater, which levels outside 19 m higher than inside the excavation. The wall reaches down 2 m into a relatively impervious layer from cretaceous marl. So the embedment depth amounts to t = 3 m in total.

To avoid an uneconomic depth of the diaphragm wall a circularly arranged group of relief boreholes has to be applied in a certain distance (1 m) from the wall (see Figure 2).

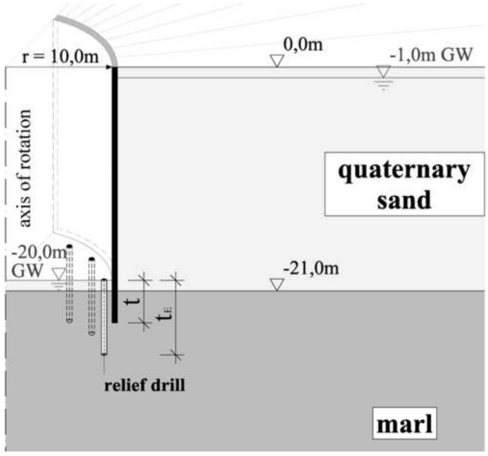

Figure 2. Example: Stratigraphy of the subsoil and geometry of the excavation (embedment depth t = 3 m)

Table 2. Characteristic soil parameters

Parameter	quaternary sand	marl
weight γ'_k / γ_k [kN/m³]	11 / 19	12 / 21
ϕ'_k / c'_k [kN/m²] / $\sigma'_{tension}$ [kN/m²]	35° / 0 / 0	25° / 50 / 0
wall-friction and -adhesion $R = \frac{\tan\delta}{\tan\phi'} = \frac{a'}{c'}$	0,5	0,2
permeability [m/s]	1 x 10^{-3}	1 x 10^{-6}
stiffness modulus [MN/m²]	E_s / E_{sr}	E_s / E_{sr}
σ'=100 kN/m²	50 / 150	80 / 240
σ'=200 kN/m²	70 / 210	90 / 270
σ'=500 kN/m²	110 / 330	130 / 390

This example is modelled in axis symmetry conditions, so the relief holes appear as a concentric thin slot with a relatively high permeability (k=10^{-4} m/s). Since the relief boreholes in the ground plan are only small spots, the shear parameters of the drainage material were chosen as those from the surrounding marl layer. To verify the assumed axis symmetry effect on the drainage the distance of the relief boreholes to each other has to be confined according to Eqn. (6).

The calculations performed with the program code from (PLAXIS 2D 2002) resulted in the following insights:

- the excavation process is safe enough without any measures down to a level of 5 m above the final excavation depth
- from a level 5 m above the final excavation depth additional measures (like relief boreholes) have to be applied
- with relief boreholes reaching down 5 m beneath the final excavation level (t_E = 5 m in Figure 2) all excavation states have the required safety
- since at the final excavation level no failure occurs, a ϕ-c-reduction is accomplished, which leads to the failure plane presented in Figure 3.

Figure 3 shows in detail the subsoil below the excavation´s bottom. Here one finds lines of equal potential head, which have been evidently manipulated by the relief boreholes. Also the Figure clearly points out that the relevant failure plane reaches very deep and so differs completely from Terzaghi's rectangle.

If no relief boreholes were applied, the same calculation scheme would lead to an embedding length of the wall of t = 11,5 m instead of t = 3 m in this example. The Terzaghi approach – by neglecting the shear resistance – yields to t = 16 m (Perau & Haubrichs 2006).

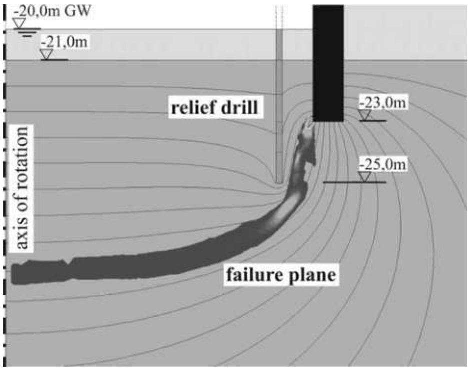

Figure 3. Failure plane beneath the bottom of the excavation

Finally, some results of a parameter study are presented, which show the influence of the internal cohesion of the marl layer. For the situation shown in fig. 2 and the parameters from Table 2 only the cohesion c'_k is varied. According to Table 2 tensile stresses are cut off by input in order to regard possible fissures in the marl layer.

The calculations lead to the following results:

- in case of $c'_k < 30$ kN/m² the proposed relief boreholes do not help, even if they reach very deep,
- in case of $c'_k > 30$ kN/m² the relief boreholes allow to prove the stability against failure by heave if they reach to a certain depth,
- an increasing cohesion (if $c'_k > 30$ kN/m²) leads to a decreasing required depth of the relief boreholes,
- a cohesion from $c'_k = 200$ kN/m² still requires a depth of the relief boreholes from $t_E \approx 4$ m.

Apart from variations of the relief borehole´s length a second group of relief boreholes or a moderate prolongation of the wall could be the right measure to fit the verification against failure by heave.

Fig. 4 shows the failure mechanisms which occur in case of $c'_k = 20$ kN/m². The left hand of Fig. 4 represents the failure mechanism if no relief boreholes are applied. The right hand image represents the situation if relief boreholes are applied with a depth of $t_E = 10$ m. Note that the applied relief boreholes improve the flow field significantly so that the verification in this case is near to a successful result while in cases of missing relief boreholes the verification is far away from it. Fig. 4 shows that potential failure planes are shifted in deeper zones by relief boreholes. In that way more shear resistance and weight from overburden subsoil can be activated.

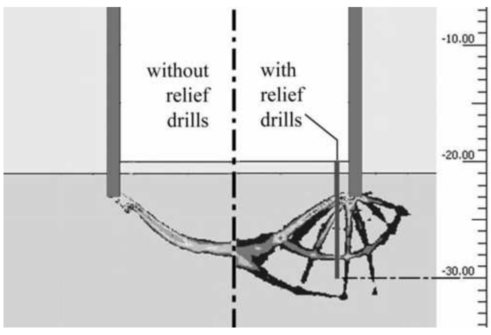

Figure 4. Failure mechanisms beneath the bottom of the excavation (ϕ_k'=25°, $c_k' = 20$ kN/m², $\sigma'_{tension} = 0$) without relief boreholes (left hand) and with relief boreholes, $t_E = 10$ m (right hand)

In an additional study the tensile stresses are not cut off. The cohesion is varied in the same way as before. These calculations lead to the following results:

- in case of $c'_k < 30$ kN/m² the proposed relief boreholes do not help, even if they reach very deep,
- in case of 30 kN/m² > c'_k > 50 kN/m² the relief boreholes allow to prove the stability against failure by heave if they reach to a certain depth,
- an increasing cohesion (if $c'_k > 30$ kN/m²) leads to an decreasing required depth of the relief boreholes,
- in case of $c'_k > 50$ kN/m² the stability against failure by heave is achieved without relief boreholes.

6 CONCLUSIONS

Terzaghi's assumption of a rectangular failure body for the verification against heave is not generally correct. Verifications on the basis of this failure body only lead to good results in case of non-cohesive soils and a simple flow-field geometry, which is not influenced by additional measures like relief boreholes. It does not work for systems with cohesive soils or for manipulated groundwater flow fields.

To improve the geohydraulic situation beneath the bottom of an excavation it is helpful to apply relief boreholes, which normally should reach below the toe of the retaining wall. When relief boreholes are applied the relevant failure planes reach far beneath the toe of the retaining wall. The beneficial effect of relief boreholes can be regarded most precisely by FEM-calculations. This also allows to take into account the shear strength of the soil. Especially from an economic point of view it should be not accepted to disregard the stabilising effects of cohesion and internal friction of the soil.

But when advantage from shear strength is taken into account, a numerical investigation is necessary, since the presented results show potential failure mechanisms, which are totally *different* in shape and extension from Terzaghi's rectangular failure mechanism. The finite element method (FEM) automatically identifies the relevant failure body. Due to this feature it can be used to design reliable and economical structures.

The presented concept for verification against failure by heave or uplift leads to constructions of excavation pits which are optimised in safety and economics. The keys are the realistic approach for the acting seepage forces, the static calculation including shear strength and the openness for every possible failure mechanism.

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