Design of inverted T-shaped Cantilever Wall with a Relief Floor

Conception d'un mur équerre avec dalle de délestage

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ABSTRACT: Cantilever walls are widely used as ground retaining structures. The analytical approach of L-shaped and inverted T-shaped cantilever walls results in reliable designs. This paper proposes and discusses an analytical approach for the geotechnical design of inverted T-shaped cantilever walls with relief floor. This approach combines the analytical approaches of inverted T-shaped walls and of relief floors. The resulting analytical approach is verified by numerical simulations of inverted T-shaped cantilever walls with relief floor for 5m till 10m high retaining structures in unsaturated sandy soils, silty soils and alluvial clayey soils. Finally, rules of thumbs for typical dimensions of the inverted T-shaped cantilever wall with relief floor are given, based on experience, analytical calculations and numerical simulations.

RÉSUMÉ : Les murs équerres sont communément répandus comme structure de soutènement. D'un point de vue de la conception géotechnique, les méthodes analytiques sont éprouvées. Cet article propose et discute une approche analytique pour la conception géotechnique des murs équerres avec dalle de délestage. Cette approche combine l'approche de dimensionnement analytique des murs équerres avec l'effet d'ombre des dalles de délestage. L'approche analytique proposée est justifiée à l'aide de simulations numériques modélisant des murs équerres avec dalle de délestage reprenant des différences de niveau allant de 5m à 10m et ce, dans des sols non-saturés de nature sableuse, silteuse et alluvio-argileuse. En conclusion, des dimensions typiques de murs équerres avec dalle de délestage sont données, basées sur l'expérience, des calculs analytiques et des simulations numériques.

KEYWORDS: inverted T-shaped cantilever wall, relief floor, soil retaining structure, finite element code

1 INTRODUCTION

In recent decades, the number of installations of permanent ground retaining structures is drastically increasing. One of the oldest ground retaining structures are the gravity walls. They have a very easy way of realization and are particularly suitable for retained heights of less than 3m. While they can be designed for greater heights, other types of retaining walls such as L-shaped cantilever walls are usually more economical as the height increases.

L-shaped cantilever walls uses the soil upon the heel to stabilize the horizontal soil pressures. One of the disadvantages of the L-shaped cantilever walls is the high ratio between the horizontal loads due to soil pressures and the vertical soil weight, causing a disadvantageous eccentricity of the forces at the base slab. Therefore, the length of the base slab can amount up to 70% (sandy soils) and up to 120% (alluvial clay) of the retaining height. In most projects, the realization of L-shape structure is not possible due to the lack of required space to excavate up to the rear edge of the base slab level with a reasonable slope.

It is usually more economical to design the L-shaped cantilever wall with a toe at its front side: the inverted T-shaped cantilever wall. This increases the moment arm and reduces the disadvantageous eccentricity of the forces in the base slab. The distance between the front of the stem and the back of the heel of the cantilever wall amounts to 50% (sandy soils) or to 60% (alluvial clay) of the retaining height.

In some cases, it is more economical to further reduce the required space between the front wall face and the temporary slope at the back of the structure. In these cases, a relief floor could be added : the inverted T-shaped cantilever wall with relief floor. In this way, (1) the disadvantageous horizontal soil forces are reduced and (2) the disadvantageous eccentricity of the forces at the base slab could be reduced, generally down to a negligible low value. The distance between the front of the stem and the back of the heel of the cantilever wall amounts only 20% (sandy soils) or to 40% (alluvial clay) of the retaining height.

The construction of the inverted T-shaped cantilever wall with a relief floor itself is in most of the cases of lower economical interest than the inverted T-shaped cantilever wall. Nevertheless, reducing the space between the front of the stem and the heel, increases the available space for the excavation, necessary to reach the level of the base slab. The possible economic benefit may be found in the less expensive temporary excavation method.

The geometry of an inverted T-shaped cantilever wall with a relief floor depends on the conditions of the specific project. Therefore, each realization must be based on thorough geotechnical evaluation of its design, a hydrogeological evaluation, a detailed structural design, an analyses of the construction methodology and a general risk evaluation.

This paper proposes a simplified analytical approach for the geotechnical design of the inverted T-shaped cantilever wall with a relief floor. This simplified analytical approach is checked by numerical simulations for unsaturated sandy soils, silty soils and alluvial clays. Finally, typical dimensions which can be used for predesign estimations are given, based on experience, analytical and numerical calculations.

1 ANALYTICAL APPROACH OF A L-SHAPED WALL WITH A RELIEF FLOOR

The envisaged geotechnical structure is an inverted T-shaped cantilever wall with a relief floor. Figure 1 shows a typical section of this construction with a retaining soil height of 8.6m. The foundation level is 0.8m below ground surface, in order to place it under the frost line. In order to study the behavior of this structure, a brief review of the behavior of L-shaped cantilever walls and the influence of a relief floor is given, before the global analytical approach is proposed.

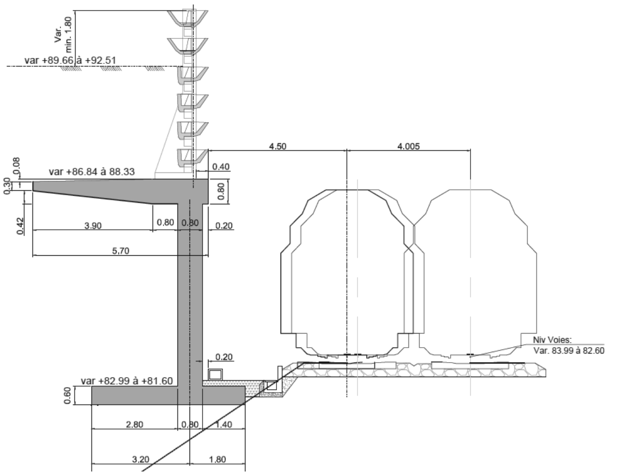

Figure 1. View of the inverted T-shaped cantilever wall with a relief floor of 3.9 m.

1.1 *Geotechnical principle of L-shaped cantilever wall*

The geotechnical behavior of a L-shaped or an inverted T-shaped cantilever wall is quite complex (Figure 2). When the L-shaped wall fails geotechnically, the failure surfaces E-F, A-D and A-C occur. All these failure surfaces have an inclination of $\pi/4$-$\varphi/2$ from the vertical A-B (further called 'virtual back'). All the soil in the block A-C-D can be described as active Rankine soil. The block A-C-F-E deforms and slides downwards simultaneously. The soil pressure distribution in the block A-C-D is symmetrical about the vertical A-B, on which horizontal soil pressures are present. This theory is confirmed by numerical modeling (e.g. Arnold, 2010).

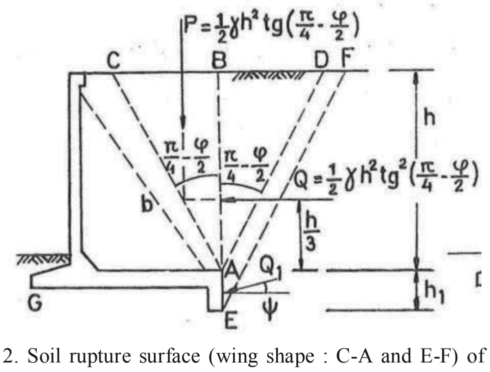

Figure 2. Soil rupture surface (wing shape : C-A and E-F) of a L-shaped cantilever wall (after Vandepitte, 1979).

It is shown that this complex geotechnical behavior of the L-shaped or an inverted T-shaped cantilever wall is equivalent to the following simplified structure (Rouili et al. 2005; Vandepitte 1979). The wall together with the backfill up to a vertical plane above its heel (A-B i.e. 'virtual back') is treated as a monolithic block. Gravity forces, surface loads and horizontal active soil pressures acting at the virtual back may be assumed. This block is checked against sliding, overturning and bearing capacity failures in the ultimate limit state (GEO 2000; Frank et al. 2004).

This approach is mathematically equivalent to the consideration of the wall together with the backfill up to the plane A-C (Figure 3).

It has to be stressed that though the two above approaches are equivalent for the design of the L-shaped or an inverted T-shaped cantilever wall, the wing-shaped soil rupture surface is the only physical failure mode.

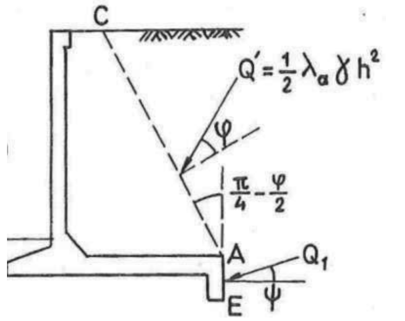

Figure 3. Alternative design rupture surface C-A-E of a L-shaped cantilever wall (after Vandepitte, 1979).

1.2 *Geotechnical principle of a relief floor*

Geotechnical constructions sometimes uses a relief floor. If the relief floor is rigidly build-in in the geotechnical construction, it implies three stabilizing effects (Figure 4):

1. the backfill in the area A'-A-B engenders a stabilizing moment against overturning,
2. a reduction of the total horizontal soil pressure, increasing the safety to sliding,
3. a reduced eccentricity of the global force at the base, increasing the bearing capacity.

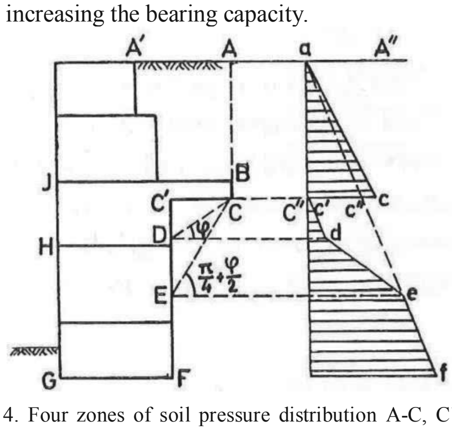

Figure 4. Four zones of soil pressure distribution A-C, C'-D, D-E and E-F. (after Vandepitte, 1979).

Four zones of horizontal soil pressure can be distinguished:

Zone 1 : A-C is not influenced by the relief floor.

Zone 2 : C'-D is totally influenced by the relief floor. The horizontal soil pressure is 0 in C'.

Zone 3 : D-E is partly influenced by the relief floor. The horizontal soil pressures increases linearly from d to e.

Zone 4 : E-F is not influenced by the relief floor. The horizontal soil pressure correspond to the active soil pressure, taking into account the surface level A'A and the present surface load.

1.3 *Simplified analytical approach of an inverted T-shaped cantilever wall with a relief floor.*

The proposed simplified analytical approach combines the theory of the L-shaped cantilever wall and the theory of the relief floor. Two virtual backs are defined : upper virtual back A-B and lower virtual back C'-F (Figure 5).

The wall together with the backfill up to the virtual backs (A-B and C'-F) is treated as a monolithic block. Surcharges and horizontal active soil pressures acting on the virtual backs and gravity forces may be taken into account. On the lower virtual back (under the relief floor level), horizontal soil pressures as described in §1.2 are assumed. This monolithic block is checked against sliding, overturning and bearing capacity failures in the ultimate limit state.

It has to be stressed that the above approach is a simplification of the physical behavior. The physical soil rupture surface does not follow the two virtual backs, but corresponds more with wing-shapes.

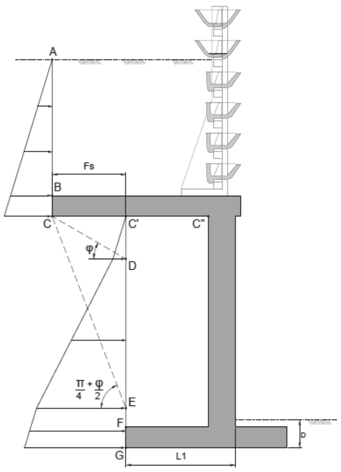

Figure 5. Virtual backs as in the analytical approach of an inverted T-shaped cantilever wall with a relief floor.

2 NUMERICAL SIMULATION OF INVERTED T-SHAPED CANTILEVER WALL WITH RELIEF FLOOR

For the numerical validation of the inverted T-shaped cantilever wall with a relief floor, two-dimensional finite element code PLAXIS is used. The Hardening soil model in plane strain is used to model the soil (Brinkgreve et al. 2002).

2.1 *Simulation of excavation stages*

Accomplishment of physical modeling, including simulation for gravity stresses is followed with the calculation program. Simulation of the entire inverted T-shaped cantilever wall with relief floor is carried out in a sequence of construction stages. In each construction stage a sufficient number of calculation steps are used to obtain an equilibrium-state:

- Stage 1 : initial situation (gravity loading, soil with temporary cohesion)
- Stage 2 : excavation till bottom level of the cantilever wall (soil with temporary cohesion)
- Stage 3 : construction and back fill of the cantilever wall till level of relief floor (soil with temporary cohesion)
- Stage 4 : Construction and back fill of the relief floor till final level (final situation, permanent soil parameters, SLS)
- Stage 5 : Determination of factor of safety using c-phi reduction (ULS).

Table 1. Soil parameters of sandy soil, silty soil and clayey soil, as used in the numerical simulations (the stiffness is expressed at a reference pressure of 100 kPa).

	Sandy soil	Silty soil	Clayey soil
γ_{unsat}	17kN/m^3	18kN/m^3	17kN/m^3
E^{ref}_{oed}	22,30.10^{3}kN/m^2	6.10^{3}kN/m^2	4.10^{3}kN/m^2
E^{ref}_{50}	22,30.10^{3}kN/m^2	9.10^{3}kN/m^2	8.10^{3}kN/m^2
E^{ref}_{ur}	66,90.10^{3}kN/m^2	36.10^{3}kN/m^2	40.10^{3}kN/m^2
m	0,50	0,75	1,00
c'_{temp}	4kPa	4kPa	4kPa
c'_{perm}	0,1kPa	2kPa	4kPa
φ'	30°	25°	22°

The model simulates 100m (length) by 50m (depth) using 4825 elements (15-noded). The elements around the inverted T-shaped cantilever with relief floor are highly refined. The geotechnical behavior is simulated in unsaturated sandy soils, silty soils and alluvial clayey soils (Table 1).

2.2 *Numerical simulation of an inverted T-shaped cantilever wall in sandy soil*

A typical section of inverted T-shaped cantilever wall is simulated (Figure 1), retaining the soil over 8,6 m of height. The used geometry implies a L1 = 3,6m and a Fs = 1,9m (Figure 5). The buried depth of the base slab D is in this case 0,6m. The used type of in situ soil and the backfill soil are in this example the above described 'Sandy soil'.

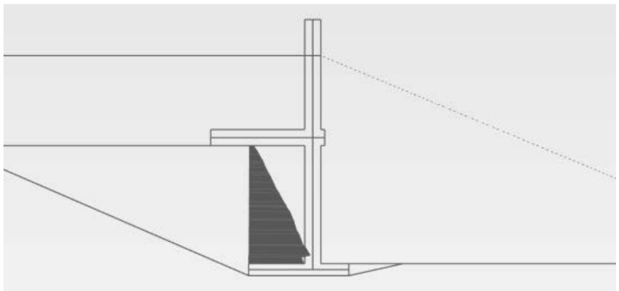

Figure 6. Horizontal effective soil pressures at the lower virtual back up to 61,3kPa at stage 4 (c-phi reduction of 1,20).

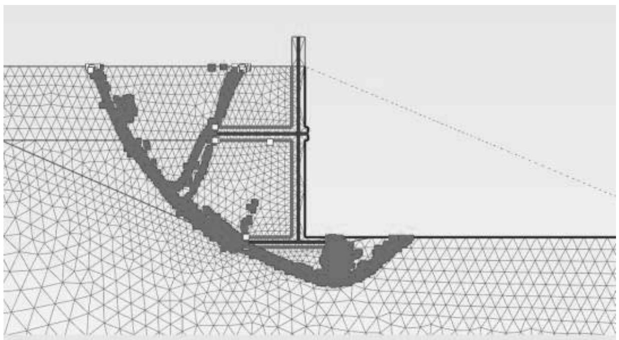

Figure 7. Positions of elements with a Mohr-Coulomb plastic behavior in stage 4 (c-phi reduction of 1,20).

The global geotechnical safety, calculated by the c-phi reduction is 1,20. Figure 7 shows the positions of the elements which are in the plastic zone of the Mohr-Coulomb law. The failure surface underneath the foundation level suggests a failure mode of bearing capacity. As the inverted T-shaped cantilever wall deforms, failure surfaces, inclined at $\pi/4-\varphi/2$ from the vertical, at the upper and lower virtual backs occur. This corresponds with the described failure 'wings' in § 1.1.

The effective horizontal stresses at the upper virtual back increases from 0kPa up to 29kPa. At the lower virtual back, the effective horizontal stresses increases from 2kPa up to 70kPa. Figure 6 shows that the influence of the relief floor isn't total : the relief floor deforms 3cm downwards, causing a small horizontal effective stress (2kPa) at the top of the lower virtual back. The mean effective vertical stress at the base slab amounts to 228kPa.

2.3 *Comparison of the numerical simulation with the proposed analytical approach*

The inverted T-shaped cantilever wall with a relief floor in § 3.2 is compared with the analytical calculation as described in §2.3. The geometry and the soil parameters are similar inputs in both approaches.

Remember that the analytical calculations consider active soil pressures. Therefore, the analytical approach assumes a displacement of the structure. In the numerical simulations, this displacement of the structure occurs only in stage 5 'c-phi-reduction'. When forces in the analytical calculations are compared to those in the c-phi reduction stage of the numerical simulations, it is important to notify that the actual cohesion c' and angle of internal friction of the soil φ' are reduced.

In the analytical approach, the factor of safety is 3,39 for the overturning failure mode, 1,98 for the sliding and 2,14 for the bearing failure mode. Figure 7 suggests that the failure mode of the numerical model is the bearing capacity (c-phi reduction safety factor = 1,20).

Table 2 shows that the difference of the horizontal forces at the virtual backs in the analytical approach and in the numerical simulations is below 8%. The difference of the vertical force at the foundation amounts to 15%.

Table 2. Comparison of the horizontal and vertical forces at the virtual backs and the foundation in the analytical approach and the numerical simulations.

	Anal. approach	Num. simulation
Horizontal force at upper virtual back	57kN/m'	62kN/m'
Horizontal force at lower virtual back	230kN/m'	211kN/m'
Vertical force at foundation	951kN/m'	1117kN/m'

3 PREDESIGN OF L-SHAPED CANTILEVER WITH RELIEF FLOOR

Based on experience, numerical modeling and hand calculations, typical dimensions of reliable inverted T-shaped cantilever walls with a relief floor could be estimated. For sandy soil and a buried depth of 0,8m and 1,3m; the L1 is about 20% to 40% of the retained soil height H; the Fs (as defined in Figure 5) is about 1,5 to 2,5 m (Figure 8).

The level of the relief floor is of less importance for the geotechnical design, as long as the full stress relief is applied on the virtual back of the inverted T-shaped wall. Furthermore, it is good practice to design the level of the relief floor at about the half of the retained soil height.

The type of soil in situ is an important geotechnical parameter, specially for the bearing capacity and sliding failure mode. For inverted T-shaped walls with relief floor, retaining a soil height of 5 m, a buried depth D = 1,3m; the length L1 varies from 1m (sandy soil) to 2m (clayey soil) (Figure 9).

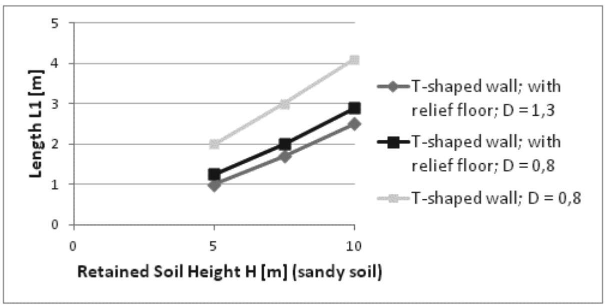

Figure 8. Typical distance between the front of the stem and the back of the heel (L1 [m]) of inverted T-shaped cantilever walls with and without relief floor in sandy soils.

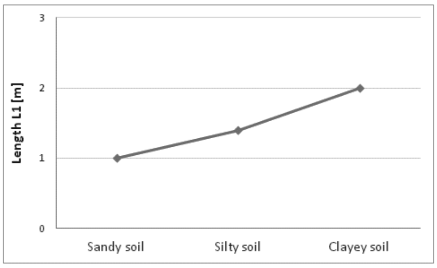

Figure 9. Typical distance between the front of the stem and the back of the heel (L1 [m]) of inverted T-shaped cantilever walls with a relief floor in sandy, silty and clayey soils (retained soil height of 5,0m; buried depth of base slab D = 1,3).

4 CONCLUSIONS

The geometry of an inverted T-shaped cantilever wall with a relief floor depends on the height of the retaining soil, the surcharges, the depth of the foundation base slab, the geotechnical parameters of the soil in situ and of the backfill, the possible length of the toe and so forth.

In the case of unsaturated sandy soils, silty soils and alluvial clayey soils, an analytical approach is proposed and confirmed by numerical simulations. The analytical approach is based on an upper and a lower vertical virtual back. The wall together with the backfill up to the virtual backs are treated as a monolithic block. At the lower virtual back, the horizontal soil pressures are reduced, due to the presence of the relief floor. This monolithic block is checked against sliding, overturning and bearing capacity failures in the ultimate limit state.

For predesign estimations, a typical inverted T-shaped cantilever wall with a relief floor may be considered:

- the distance between the front of the stem and the back of the heel is about 20% to 40% of the retaining soil height,
- the length of the toe is similar to the length of the heel,
- the base slab is buried deeper than the frost line,
- the difference between the length of the relief floor and the length of the heel is about 1,5m to 2,5m,
- the level of the relief floor is about the half of the retained soil height.

Though some general rules of thumbs for the dimensions of an inverted T-shaped cantilever wall with relief floor are given, each realization must be based on thorough geotechnical evaluation of its design, a hydrogeological evaluation, a detailed structural design, an analyses of the construction methodology and a general risk evaluation.

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