*Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)*
*Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5*
*https://doi.org/10.53243/ICSMGE2026-783*

# 2nd generation of Eurocode 7 – Ground improvement

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ABSTRACT: The purpose of ground improvement works is to render the ground suitable for construction when its original properties are insufficient to meet the design criteria required by the specific construction project. Ground improvement techniques are being increasingly applied as an alternative to conventional foundation solutions to optimise construction costs, shorten construction time and reduce $CO_2$-emissions. However, the current Eurocode 7 does not cover ground improvement. This will change significantly with the introduction of the second generation of Eurocode 7, which includes a new clause for the design of such geotechnical works. This paper presents the adopted concept for rigid inclusions. It includes an example of a design case and discusses the level of partial resistance and model factors in comparison to those found for piled rafts in the respective clause.

KEYWORDS: Second generation Eurocode 7, ground improvement, rigid inclusions, piled raft

## 1 CLASSIFICATION OF GROUND IMPROVEMENT AND DEFINITION OF RIGID INCLUSIONS

A wide range of different ground improvement methods are used in practice. Within the framework of drafting the second generation of Eurocodes, a new classification scheme has been developed that considers how ground improvement is applied and modelled (EN 1997-3, 2025). Ground improvement should be classified based on whether the result of treatment is diffused (e.g. global improvement of a zone) or discrete (e.g. with inclusions), and whether an unconfined compressive strength of the improved ground can be measured. Further details can be found in Denies et al. (2024).

The new generation of Eurocode 7 provides a clear definition of rigid inclusions. These are structural elements whose stiffness and strength are significantly higher than that of the ground in which they are installed. To distinguish them clearly from conventional piles, one of the following conditions should be satisfied (see Figure 1):

- structural loads are transferred from the slab, spread foundation or embankment through a Load Transfer Platform (LTP) into the improved ground;
- in the absence of a LTP, there is no structural connection between the rigid inclusions and the slab or spread foundation.

However, if the loads are compression loads only, the concept of rigid inclusions without a load transfer platform corresponds to a piled raft. The second generation of Eurocode7 also provides a definition of this and a design methodology.

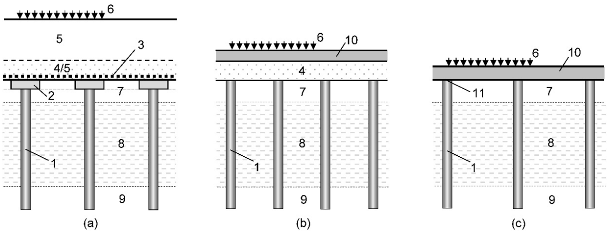


Figure 1. Concepts of rigid inclusions: a) embankment, b) slab or spread foundation with a LTP, c) slab or spread foundation without a LTP. Key: 1 – rigid inclusions, 2 – optional caps, 3 – optional basal reinforcement, 4 – Load Transfer Platform (LTP), 5 – embankment, 6 – load, 7 – working platform, 8 – weak soil, 9 – load bearing ground, 10 – slab or spread foundation, 11 – no structural connection between 1 and 10 (Figure 1c). Figure based on Formal Vote version of EN 1997-3

A piled raft is a combined foundation that incorporates a ground bearing raft and a pile group. According to EN 1997-3, piled rafts are designed according to clause 6, which applies to conventional piles, while rigid inclusions are covered by clause 12. However, as this paper illustrates, the second generation of Eurocode 7 has defined partial resistance and model factors to ensure an equivalent level of safety and reliability when designing both types of foundation. Any changes to these factors, through National Annexes and Nationally Determined Parameters, should take this into account.

## 2 GROUND-STRUCTURE INTERACTIONS

### 2.1 *Rigid inclusions*

Analysis of the interaction between a structure, improved ground and the surrounding ground should be conducted to verify that the ultimate and serviceability limit states (ULS and SLS) are not exceeded. This analysis should consider the stiffness ratio of discrete inclusions to the surrounding ground. For ground improvement the following ULS shall be verified in particular:

- failure of the ground improvement inclusion or zone in compression, tension, bending, buckling or shear;
- failure in the ground due to transverse loading of the improved ground zone;
- uplift or insufficient tensile resistance of the ground improvement zone;
- combined failure in the ground and in the ground improvement inclusion or zone;
- bearing resistance failure below the ground improvement inclusion or zone;
- limit states caused by changes in groundwater conditions or groundwater pressure;
- limit states in load transfer platforms caused by change of load distribution in time in case of cyclic or dynamic loading; and
- failure at the edges of the improved ground zone.

Where rigid inclusions are used to support or retain a structure, the calculation model shall include:

- the consideration of the interaction effects between the ground, rigid inclusions, and the overlying structure, embankment, or LTP; and
- a verification of the structural resistance of the individual rigid inclusions.

The interaction effects for rigid inclusions are similar to those relevant for a piled raft. However, a LTP, if present, also affects the load distribution between the rigid inclusions and the supporting ground. This results in negative skin friction developing in the upper part of the inclusions (see Figure 2).

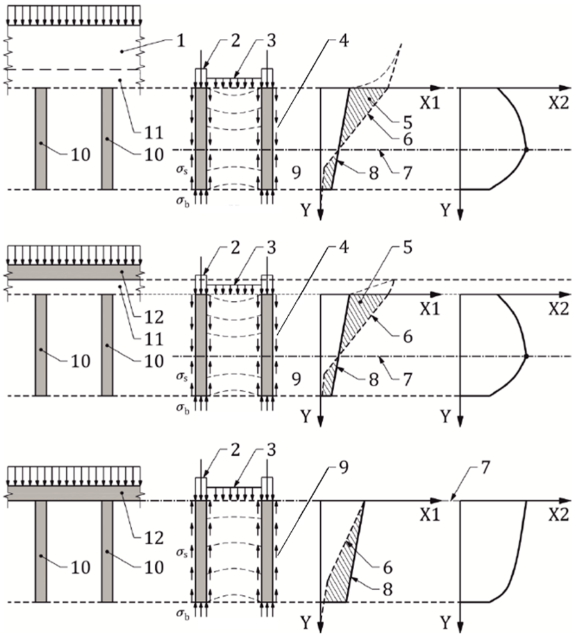


Figure 2. Interaction effects of a ground improvement with rigid inclusions. Key: X1 – settlement, X2 – inclusion axial force, Y – depth, 1 – embankment, 2 – load transmitted to the inclusion, 3 – load transmitted to the ground, 4 – negative skin friction, 5 – differential settlement, 6 – settlement of the ground, 7 – neutral plane, 8 – settlement of the inclusion, 9 – positive skin friction, 10 – inclusion, 11 – load transfer platform, 12 – structure (e.g. slab or spread foundation), $\sigma_s$ – mobilised shaft friction along inclusion, $\sigma_b$ – mobilised tip resistance of the inclusion. Figure based on Formal Vote version of EN 1997-3

### 2.2 *Piled rafts*

The following potential ultimate limit states shall be verified for all piled foundations:

- failure of the ground surrounding the piled foundation;
- failure of a pile group;
- buckling of the pile element;
- structural failure of the pile itself or any of its elements;
- combined failure of the ground and the structural pile element; and
- failure of the supported structure caused by excessive pile movement.

As illustrated in Figure 3, the design of piled rafts shall consider the effects of the following:

- pile-soil interaction;
- pile-pile interaction;
- raft-soil interaction; and
- pile-raft interaction.

In both cases, the structural resistance of the individual bearing elements of the piled raft's conventional piles or of rigid inclusions shall be verified according to the corresponding material's Eurocode or applicable European standard. Clause 12 of EN 1997-3 (2025) also provides partial factors and the design methodology for the structural verification of materials produced by methods such as deep mixing and jet grouting.

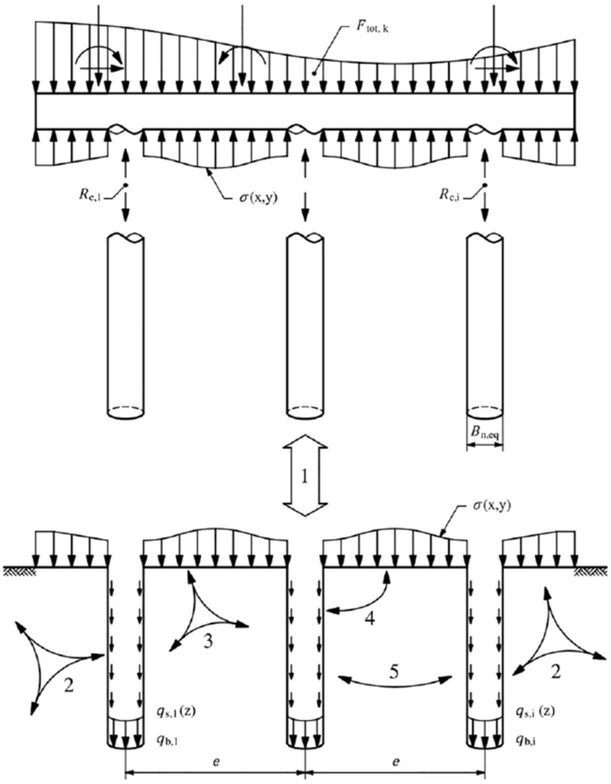


Figure 3. Interaction effects of a piled raft. Key: 1 – interaction between piled raft and ground, 2 – piled-ground interaction, 3 - raft-ground interaction, 4 – piled-raft interaction, 5 – pile-pile interaction, e – distance between piles, $B_{n,eq}$ – pile diameter ($F_{tot,k}$ - total characteristic load, $R_{c,i}$ - vertical force in the column, σ(x,y) - vertical stress in the soil. Figure based on Formal Vote version of EN 1997-3

## 3 DESIGN OF RIGID INCLUSIONS AND PILED RAFT WITH THE FINITE ELEMENT METHOD AND THE LOAD TRANSFER METHOD

### 3.1 *Geotechnical analysis and Limit States of rigid inclusions and piled rafts*

For the geotechnical verification (SLS and ULS) of rigid inclusions, an analysis of the interactions between all elements of the system is required, as specified in Clause 12. In order to achieve this, it is crucial to determine the load distribution between the ground and the inclusions as accurately as possible and to perform a realistic settlement calculation. For this purpose, both the Finite Element Method (FEM) and the Load Transfer Method (LTM) can be employed. These methods have been widely used for unit cell systems (a representative elementary cell of a large area of a ground improvement system using rigid inclusions, for which the assumption of an infinite grid is appropriate) over the past few decades. However, applying them to single footings supported by rigid inclusions is more complex and requires additional considerations as described in recent publications (Bohn, 2015 and Bohn and Vogt, 2018).

FEM analysis for single footings generally requires a detailed 3D model. In LTM models, footings differ significantly from unit cells in that load distribution with depth in the ground must be considered, as must the ground's non-linear response under the footing, in order to make a realistic settlement calculation at all load levels (see Figure 4 and 5).

The non-linear response of the inclusions is common to all variants of the LTM model (piles, inclusions in a unit cell or inclusions under footings).

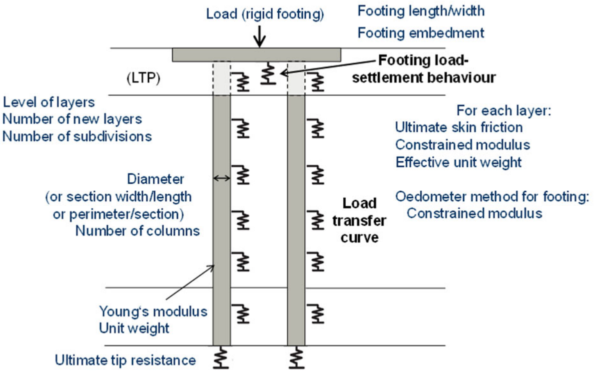


Figure 4. Use of Load Transfer Method (LTM) for single footing supported by rigid inclusions with a LTP, after Bohn (2015)

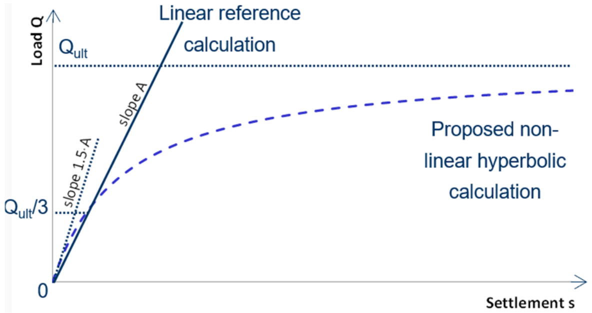
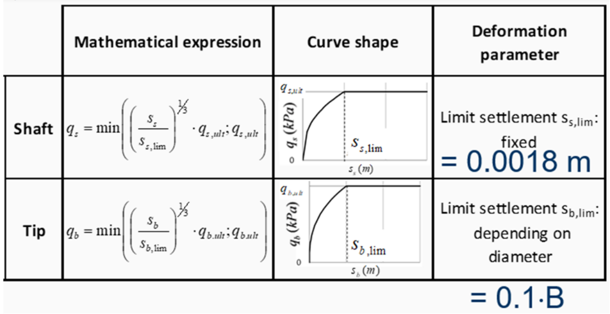


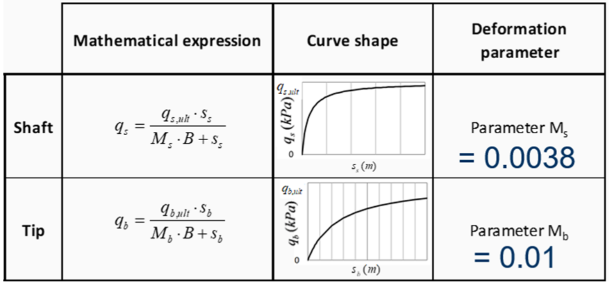
Figure 5. Load-settlement curve of the ground component below a footing for Load Transfer Method (LTM), according to Bohn (2015)

a) Cubic root curves



| | Mathematical expression | Curve shape | Deformation parameter |
|---|---|---|---|
| **Shaft** | $q_s = \min\left(\left(\frac{s_s}{s_{s,\lim}}\right)^{1/3} \cdot q_{s,ult}; q_{s,ult}\right)$ | $q_{s,ult}$<br>$q_s\ (kPa)$<br>$s_{s,\lim}$<br>0<br>$s_s\ (m)$ | Limit settlement $s_{s,lim}$: fixed<br>= 0.0018 m |
| **Tip** | $q_b = \min\left(\left(\frac{s_b}{s_{b,\lim}}\right)^{1/3} \cdot q_{b,ult}; q_{b,ult}\right)$ | $q_{b,ult}$<br>$q_b\ (kPa)$<br>$s_{b,\lim}$<br>0<br>$s_b\ (m)$ | Limit settlement $s_{b,lim}$: depending on diameter<br>= 0.1·B |

b) Hyperbolic curves



| | Mathematical expression | Curve shape | Deformation parameter |
|---|---|---|---|
| **Shaft** | $q_s = \frac{q_{s,ult} \cdot s_s}{M_s \cdot B + s_s}$ | $q_{s,ult}$<br>$q_s\ (kPa)$<br>0<br>$s_s\ (m)$ | Parameter $M_s$<br>= 0.0038 |
| **Tip** | $q_b = \frac{q_{b,ult} \cdot s_b}{M_b \cdot B + s_b}$ | $q_{b,ult}$<br>$q_b\ (kPa)$<br>0<br>$s_b\ (m)$ | Parameter $M_b$<br>= 0.01 |

Figure 6. Load transfer curves of inclusions (or piles) with the Load Transfer Method (LTM), after Bohn (2015), for cubic root curves (a) and hyperbolic curves (b)

The geotechnical ULS verification of rigid inclusions (and piled rafts, for comparison) only applies to structures of limited dimensions. This is because a unit cell system (e.g. one representing large rafts) has, in theory, an infinite resistance.

The design resistance of a rigid inclusion system may be determined as the sum of the resistances of the inclusions and the ground, as shown in equation (1):

$$R_{\mathrm{sys,d}} = \frac{\sum_i^n R_{\mathrm{ri,i}}}{\gamma_{\mathrm{Rd,ri}}\gamma_{\mathrm{R,ri}}} + \frac{R_{\mathrm{g}}}{\gamma_{\mathrm{Rg}}} \tag{1}$$

where:

$R_{\mathrm{ri,i}}$: representative value of the vertical resistance of the $i$-th rigid inclusion, considering group effects if relevant;

n: number of supporting rigid inclusions;

$R_{\mathrm{g}}$: representative value of the vertical resistance of the ground after installation of inclusions;

$\gamma_{\mathrm{Rd,ri}}$: model factor set equal to $\gamma_{\mathrm{Rd,group}}$ for a pile group, equal to 1.0;

$\gamma_{\mathrm{R,ri}}$: partial resistance factor for the rigid inclusion system equal to 1.4;

$\gamma_{\mathrm{Rg}}$: partial resistance factor for the ground after treatment equal to 1.4.

The values of the partial resistance and model factors can be provided in the National Annex, as these are Nationally Determined Parameters (NDPs).

On its side, the ultimate compressive resistance of a piled raft should be determined from:

$$R_{\mathrm{piled-raft}} = \left(\sum_i^n R_{\mathrm{c,i}} + R_{\mathrm{raft}}\right) \tag{2}$$

where:

$R_{\mathrm{c,i}}$: compressive resistance of the i-th pile;
n: number of piles supporting the raft;
i: index that varies from 1 to n; and
$R_{\mathrm{raft}}$: bearing resistance from the raft.

When the Resistance Factor Approach is used, the design resistance of piled rafts may be defined by the overall representative piled raft resistance as follows:

$$R_{\mathrm{piled-raft,d}} = \frac{R_{\mathrm{piled-raft,rep}}}{\gamma_{\mathrm{Rd,piled-raft}} \cdot \gamma_{\mathrm{R,piled-raft}}} \tag{3}$$

where:

$R_{\mathrm{piled\text{-}raft,rep}}$: representative ultimate vertical resistance of the piled raft;
$\gamma_{\mathrm{Rd,piled\text{-}raft}}$: model factor for the piled raft equal to 1.0;
$\gamma_{\mathrm{R,piled\text{-}raft}}$: partial resistance factor on the pile raft's vertical resistance equal to 1.4.

As previously mentioned, the values of the partial resistance and model factors can be amended in the National Annex, as they are NDPs.

Except for the fact that there is no structural connection between the inclusions and the footing, rigid inclusion concepts without load transfer platforms and under compression loads only are, from a geotechnical point of view, the same as piled rafts, but the equations (1) and (3) treat them differently. However, with the current values of the partial factors given in EN 1997-3, the results are identical. Changes to the following factors would lead to different results:

- $\gamma_{\mathrm{R,ri}}$ which, according to EN1997-3, is comparable with $\gamma_{\mathrm{R,group}}$ for a pile group, but is not directly associated with piled rafts in EN1997-3;

- $\gamma_{\mathrm{Rd,ri}}$ and $\gamma_{\mathrm{Rd,piled\text{-}raft}}$ as there is no model factor on the ground component of rigid inclusion systems. $\gamma_{\mathrm{Rd,ri}}$ applies to the inclusions only, thus a value different from 1.0, even if set equal to $\gamma_{\mathrm{Rd,piled\text{-}raft}}$, would lead to a distortion of the results compared to the piled raft results as the factor there applies to the overall system.

For both rigid inclusion and piled raft systems (which work as overall geotechnical systems), and prior to any possible modifications by National Standardisation Bodies (NSBs), the partial resistance factors are independent of the installation method, unlike for piles in Clause 6 (where values range from 1.0 to 1.4 for the Model Pile Method, as opposed to 1.4 for rigid inclusions and piled rafts). Similarly, the model factors are independent of the soil or pile testing methods used to determine resistance, unlike for piles (values range from 1.0 to 1.8 for the verification of axial pile resistance by testing or assisted by testing, as opposed to 1.0 for rigid inclusions and piled rafts). The partial resistance factor of the ground part (or raft part) is in line with the partial factor on the bearing resistance of a spread foundation. The approach for factors for rigid inclusions systems and piled rafts reflects their consideration as overall systems.

To demonstrate the application of suitable calculation methods and geotechnical limit state verifications for rigid inclusion systems in accordance with the 2nd generation of Eurocode 7, this paper presents a simplified theoretical example of a single footing on a single layer of soft soil, supported by rigid inclusions, both with and without a load transfer platform. Both the FEM and LTM methods are used to demonstrate how they model the system's interactions. Some calibration steps are performed in-between them just for comparison. Further details of the examples presented can be found in Bohn (2015).

### 3.2 *Case without ground improvement*

Figure 7 shows the geometry of the theoretical footing and the soil layers, along with all the parameters employed in the FEM analysis. The estimated footing failure load is approximately 4500 kN (500 kN/m²), as determined by methods based on shear parameters, in accordance with the relevant clause for spread foundations (see Figure 8). As is often the case with the FEM method, there is no clear failure asymptote for the footing and for the inclusion/pile tip resistance. This is a disadvantage of the method.

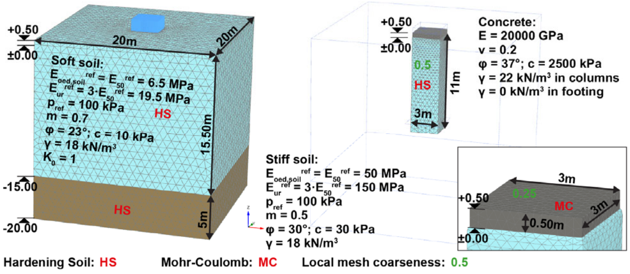


Figure 7. Geometry and parameters for the FEM calculation of the case without ground improvement

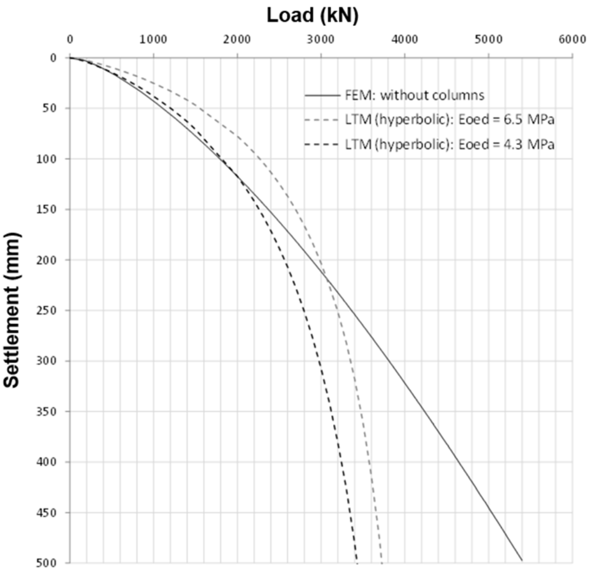


Figure 8. Load-settlement curves of the soil below the footing with FEM and LTM

The soil constrained modulus of 4300 kN/m² in the LTM model is the result of back-calculations until a good agreement with the theoretical FEM model (hardening soil model with $E_{\mathrm{oed}}^{\mathrm{ref}} = 6500$ kN/m² for $p_{\mathrm{ref}} = 100$ kN/m²) in the domain of service loads was found.

### 3.3 *Case with load transfer platform*

Figure 9 shows the geometry of the case with rigid inclusions and a load transfer platform. The non-reinforced concrete inclusions are assumed to have been installed using a displacement drilling technique. According to current design practice, no group effect is expected for the selected inclusion spacing.

A representative load of 1350 kN (150 kN/m²) has been chosen to trigger the usual settlement range of 20 to 30 mm for such improved footings.

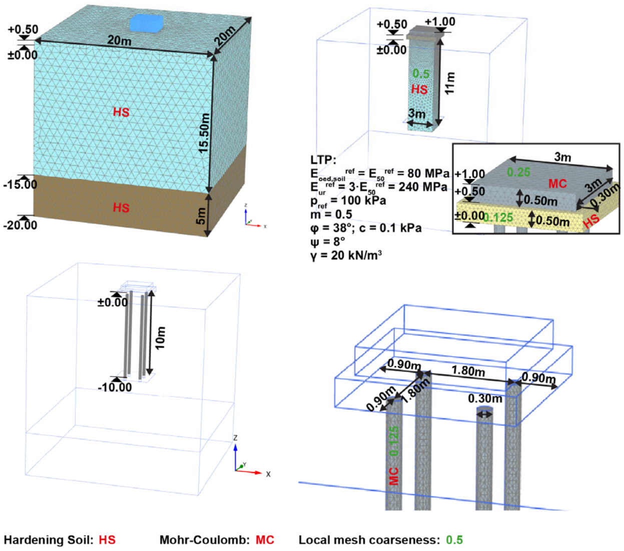


Figure 9. Geometry and LTP parameters for the FEM calculation of a case with inclusions and a LTP

The skin friction and the tip resistance values used in the LTM analysis were determined as average over one-meter segments using an axisymmetric FEM model of the same inclusion, loaded as a single inclusion/pile. The increase in soil resistance under the footing and in skin friction of the inclusion due to the presence of the LTP (which replaces the original soil) is neglected, which is conservative for ULS verifications. The total representative resistance of each inclusion is 393.2 kN. The representative resistance of the footing from the soil area (total area less the area of inclusions) is 4358.6 kN.

Figure 10 shows the settlement and skin friction mobilisation. The stress in the column and in the soil resulting from the applied load are presented in Figure 11.

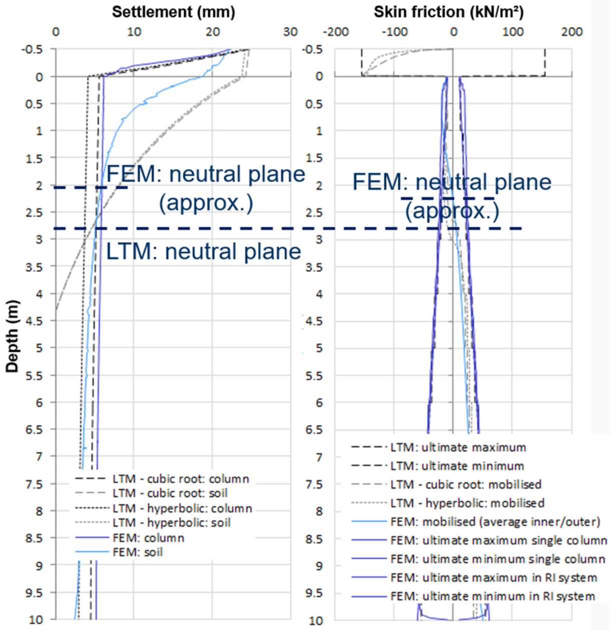


Figure 10. Settlement and skin friction mobilization in the case with a LTP

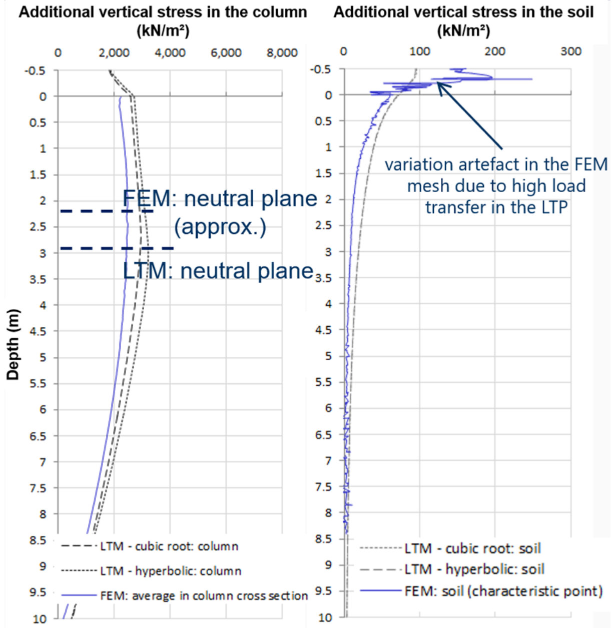


Figure 11. Stress in column and in soil from load in the case with a LTP

The results show the negative skin friction forming in the upper part of the inclusions and the positive skin friction below the so-called neutral plane, where the settlement of the soil and the inclusion are equal. The neutral plane level is slightly different between both methods because the shape of the profile of stress and settlement in the soil are assumed not to be influenced by the presence of the rigid inclusions in the LTM method. For the load in the inclusion, relevant for ULS verifications of the inclusion material, this implies an increase in load with depth down to the neutral plane and a decrease in load below the neutral plane. Both methods deliver very similar results.

The design resistance of the rigid inclusion system is computed below, according to EN1997-3, before any potential amendments by the NSBs. Even for the most unfavourable combination of loads in terms of permanent versus variable loads, the design load would remain below this value, thus passing the geotechnical ULS verification for the system.

$$R_{\mathrm{sys,d}} = \frac{\sum_i^n R_{\mathrm{ri,i}}}{\gamma_{\mathrm{Rd,ri}}\gamma_{\mathrm{R,ri}}} + \frac{R_{\mathrm{g}}}{\gamma_{\mathrm{Rg}}} = \frac{4 \cdot 393.2}{1.0 \cdot 1.4} + \frac{4358.6}{1.4}$$

$$R_{\mathrm{sys,d}} = 4236.6\ kN \tag{4}$$

### 3.4 *Case without load transfer platform (rigid inclusions or piled raft)*

Depending on the type of connection between the inclusions and the footing, the considered system would either fall into the ground improvement clause (for contact only) or the pile clause (for piled raft) of Eurocode 7 in case of a structural connection. The consideration of all interactions in the system is required for piled rafts in the 2nd generation of Eurocode 7 as it is for rigid inclusion systems.

A representative load of 2000 kN (222.2 kN/m²) has been chosen to trigger the typical settlement level of 20 to 30 mm for such improved footings.

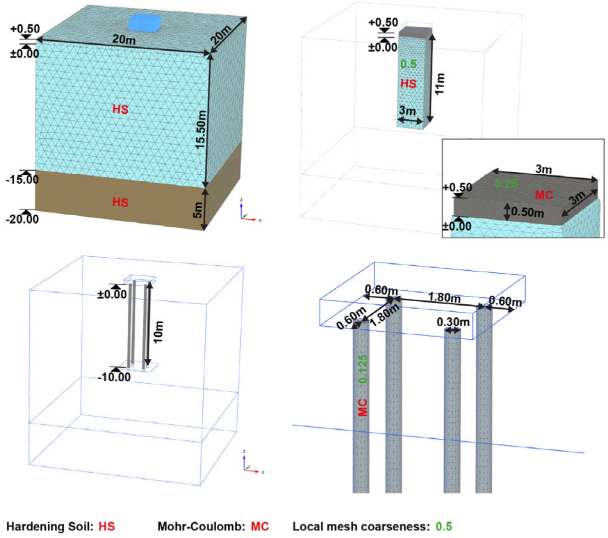


Figure 12. Geometry for the FEM calculation of a case with bearing elements (inclusions or piles) and without LTP

Figure 13 shows the settlement and skin friction mobilisation, which is almost fully utilised in this case. The stress in the column and in the soil resulting from the applied load are presented in Figure 14.

For compression loads only, the results for this case without LTP are equally valid for the rigid inclusion system and the piled raft. The typical interactions between the pile and the raft are visible, with the same settlement in the soil and bearing elements at the top of the system and no mobilisation of friction there, representing the neutral plane. Only positive skin friction is mobilised with depth, which corresponds to a decrease in inclusion load. As for the case with a LTP, there is good agreement between the two computational methods, with the only difference in the soil settlement distribution due to the assumption that the shape of the stress profile from the load in the soil is not influenced by the presence of inclusions.

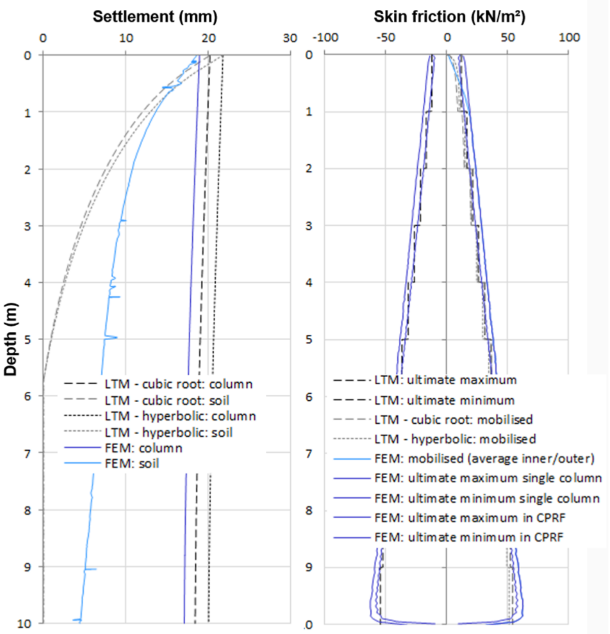


Figure 13. Settlement and skin friction mobilization in case without LTP

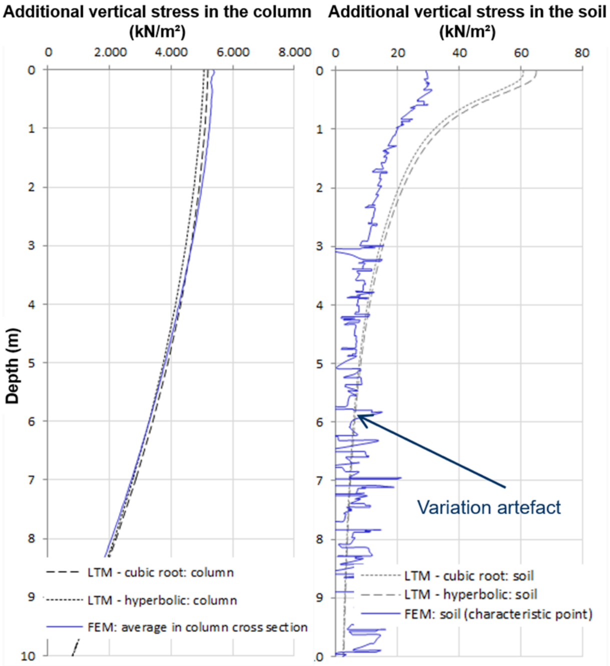


Figure 14. Stress in column and in soil from load in case without LTP

The design resistance of the rigid inclusion or piled raft system is computed below according to EN1997-3 (2025), prior to any potential amendments by the NSBs. Even for the most unfavourable load combination in terms of permanent versus variable loads, the design load would remain well below this value, thus passing the geotechnical ULS verification for the system.

$$R_{\text{sys,d}} = \frac{\sum_i^n R_{\text{ri,i}}}{\gamma_{\text{Rd,ri}}\gamma_{\text{R,ri}}} + \frac{R_{\text{g}}}{\gamma_{\text{Rg}}} = \frac{4 \cdot 393.2}{1.0 \cdot 1.4} + \frac{4358.6}{1.4} \quad (5)$$

$$R_{\text{sys,d}} = 4236.6\ kN$$

$$R_{\text{piled-raft}} = \left( \sum_i^n R_{\text{c,i}} + R_{\text{raft}} \right) \quad (6)$$

$$R_{\text{piled-raft,d}} = \frac{R_{\text{piled-raft,rep}}}{\gamma_{\text{Rd,piled-raft}} \cdot \gamma_{\text{R,piled-raft}}} \quad (7)$$

$$R_{\text{piled-raft,d}} = \frac{4 \cdot 393.2 + 4358.6}{1.0 \cdot 1.4} = 4236.6\ kN$$

However, if the NSBs modify any of the values of the partial resistance or model factors, there may be significant differences in these results, as discussed above (3.1). This would be unreasonable, given that the systems are physically identical under compression loads.

## 4 CONCLUSIONS

The first generation of the Eurocodes contained minimal information on the design of piled rafts and no specific guidance on the design of rigid inclusions. The 2nd generation of Eurocode 7 is filling this gap and provides engineers with a consistent design methodology for both piled rafts and rigid inclusions based on the partial factor concept. The rigid inclusions are now clearly defined, with a distinct feature that clearly differentiates them from piled rafts.

As the design examples presented in this article demonstrate, the partial factors for the geotechnical verification of piled rafts and rigid inclusions, as proposed in the 2nd generation of Eurocode 7, lead to designs with a comparable level of safety and reliability. Any potential changes to these partial factors through National Annexes should bear in mind that an uncoordinated modification of the partial factors related to piled rafts and rigid inclusions would create an inconsistent level of safety resulting in a potential imbalance between the two systems, which cannot be objectively justified.

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