

3D modelling of ground improved raft foundation

Modélisation 3D de la fondation améliorée du radier au sol

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ABSTRACT: During the past decades, ground improvement has successfully been able to provide competitive and economical technical foundation solutions by increasing the ground bearing capacity, and reducing the settlements. Ground improved raft foundations are accomplished solutions to reduce settlements during the construction and along the life of structures. Nowadays by using three dimensional numerical modelling, the real behaviour of complex foundation systems can be investigated successfully. It is not enough to define the soil properties correctly, creating a perfect model geometry is also important.

RÉSUMÉ: Au cours des dernières décennies, l'amélioration des sols a permis de fournir des solutions techniques concurrentielles et économiques en augmentant la capacité portante du sol et en réduisant le nombre de tassements. Les fondations de radier améliorées au sol sont des solutions efficaces pour réduire les tassements pendant la construction et le long de la vie des structures. De nos jours, en utilisant une modélisation numérique en trois dimensions, le comportement réel de systèmes de fondations complexes peut être étudié avec succès. Il ne suffit pas de définir correctement les propriétés du sol, il est également important de créer une géométrie de modèle parfaite.

Keywords: Raft foundation; combined piled raft foundation; ground improvement; rigid inclusion

1 INTRODUCTION

In this study modelling of raft foundation, combined pile-raft foundation and rigid inclusion ground improvement, the advantage and development of structural solutions are presented. Nowadays, during the calculations, the design method of footings are based on modulus of subgrade reaction (Winkler theory). The soil-structure interaction is replaced by springs, where the settlement is the function of the bearing pressure and spring force. The spring force depends on the load, the load distribution, the stiffness of the structure and the deformation properties of the subsoil. The modulus of subgrade reaction is not

a constant value or a soil property, its value changes from point to point under the footings. Using 3D finite element software, modelling of complex structures with the real subsoil is possible to determine the settlements, deformations and approximate structural stresses. In Hungary the structural elements are designed with special structural engineering software where the input modulus of subgrade reactions are usually calculated with geotechnical engineering software (especially the deformation of the foundation). In this article Plaxis 3D geotechnical finite element software was used to perform the numerical calculations.

2 STRUCTURAL DESIGN

In the following, geotechnical design of raft is introduced through a simple building geometry. This structure is a reinforced concrete frame building where the total sustainability limit state (SLS) load is 140 kPa (only static loads are taken into account in the calculations) and the loads are acting on the location of the pillars. The effect of the structural stiffness is also investigated with three different models where the behaviour of the raft is examined with different building levels (0, 1 or 2 levels) which are shown in Figure 1.

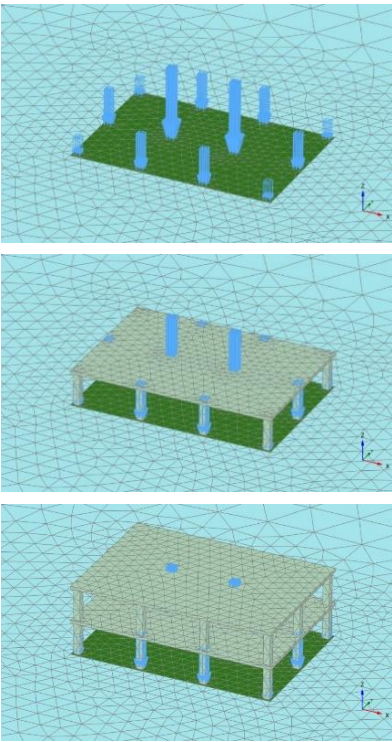


Figure 1. Structural geometries (0, 1 and 2 levels)

The size of the raft is 13.0x19.0m and the pillars are divided into 6.0m grid in x and y direction. The thickness of the raft (v) is 60cm. The raft and the other structural elements are defined with volume elements, and the connections are rigid between them. The subsoil is modelled with only one homogeneous layer to compare the different foundation systems. This is a normally

consolidated (sandy) silt which design properties are defined from some previous Hungarian projects. The silt layer is modelled with HSS (Hardening Soil model with small-strain stiffness) and the reinforced concrete structural elements are modelled with elastic (EL) material model. The properties are summarized in Table 1.

Table 1. Material properties

Properties	(sandy) Silt	Reinforced concrete
Material model	HSS	EL
γ (kN/m ³)	19	25
E (MPa)	-	33·10 ³
ν (-)	0.3	0.2
E_{oed}^{ref} (MPa)	6	-
E_{50}^{ref} (MPa)	6	-
E_{ur}^{ref} (MPa)	18	-
m (-)	0.75	-
c'_{ref} (kPa)	15	-
φ' (°)	24	-
$\gamma_{0.7}$ (-)	2·10 ⁻⁴	-
G_0^{ref} (MPa)	75	-

3 RAFT FOUNDATION

The effect of the structural stiffness on the raft deformation behaviour is shown in Figure 2. The maximum settlements are almost the same in every cases, but on the other hand the relative deformations decrease with take into account the stiffness of the building. Significant effect could be reached by modelling one level above the raft and get a more realistic raft behaviour. It is essential to consider the structural stiffness for economical design.

The modulus of subgrade reaction (C) is calculated with 3 different methods, which are the following:

- Ratio of the bearing pressure and the settlement based on the modelling results.
- Winkler Method based on analytical calculation of the settlement (constant value).

- Modified Winkler Method (in the inner ½ part of the raft 0.8 times, on the edge of the raft 1.6 times).

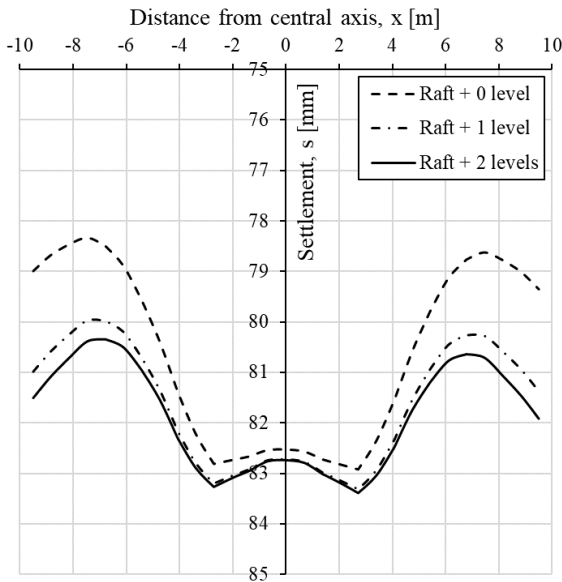


Figure 2. Deformation of raft (Raft foundation)

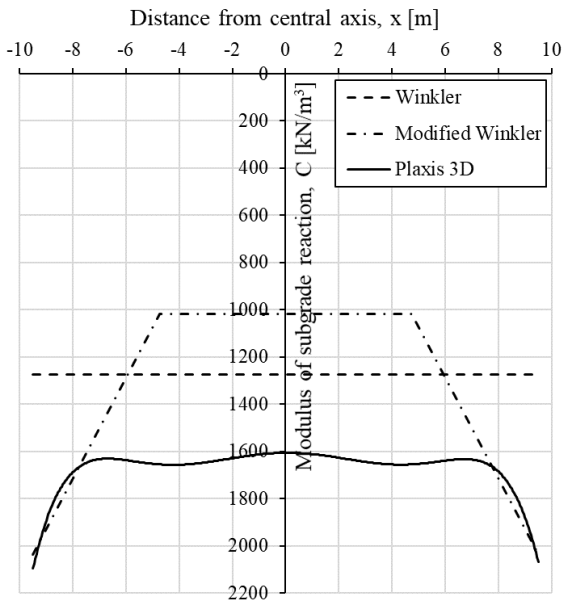


Figure 3. Modulus of subgrade reaction (Raft foundation)

With numerical modelling, the modulus of subgrade reaction is greater than with analytical calculations (Winkler or Modified Winkler Method) because we get smaller settlements with Plaxis 3D modelling. In analytical calculations the limit depths are determined with “50% rule”, which means that the limit depth is where the induced stress equals the 50% of the initial effective stress. The subgrade reaction is almost a constant value with finite element models, it increases by 30% only on the final 2m from the edge of the raft which is a smaller zone than in case of Modified Winkler Method, but the final value at the edge is almost the same. Values from the models, especially the shape of the subgrade reaction distribution are closer to the Winkler theory.

4 COMBINED PILE-RAFT FOUNDATION

The combined pile-raft foundation (CPRF) is a geotechnical composite that combined the bearing effect of both foundation elements raft and piles taking into account interaction between the foundation and the subsoil. The characteristic of the total resistance $R_{tot,k}(s)$ of the CPRF depends on the settlement of the foundation and consists of the sum of the characteristic pile resistances $\sum_{j=1}^m R_{pile,k,j}(s)$ and the characteristic base resistance $R_{raft,k}(s)$. The characteristic base resistance results from the integration of the settlement dependant contact pressure $\sigma(s,x,y)$ in the ground plan area A of the raft.

$$R_{raft,k}(s) = \iint \sigma(s, x, y) dx dy \quad (1)$$

$$R_{tot,k}(s) = \sum_{j=1}^m R_{pile,k,j}(s) + R_{raft,k}(s) \quad (2)$$

$$R_{pile,k,j}(s) = R_{b,k,j}(s) + R_{s,k,j}(s) \quad (3)$$

The bearing behaviour of the CPRF is described by the pile raft coefficient α_{pr} which is

defined by the ratio between the sum of the characteristic pile resistances $\sum_{j=1}^m R_{pile,k,j}(s)$ and the characteristic value of the total resistance $R_{tot,k}(s)$.

$$\alpha_{pr} = \frac{\sum_{j=1}^m R_{pile,k,j}(s)}{R_{tot,k}(s)} \quad (4)$$

The pile raft coefficient varies between $\alpha_{pr}=0$ (spread foundation) and $\alpha_{pr}=1$ (pure pile foundation). Figure 4. shows a qualitative example of the dependence between the pile raft coefficient and the settlement of a CPRF s_{pr} related to the settlement of a spread foundation s_{sf} with equal ground plan and equal loading. The pile raft coefficient depends on the stress level and the settlement of the CPRF.

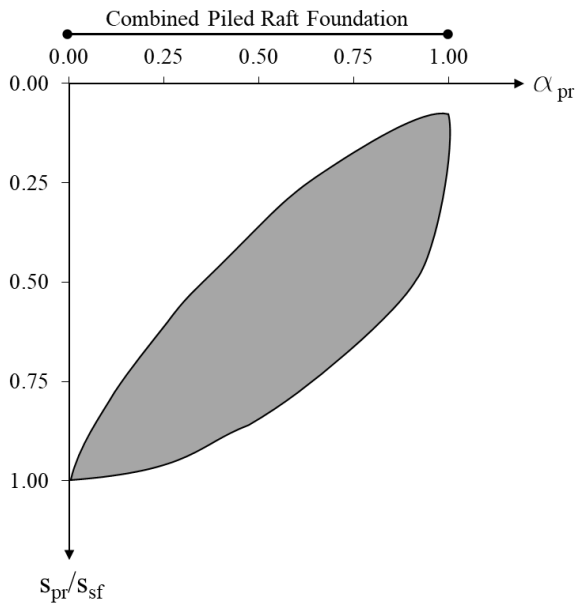


Figure 4. Qualitative example of a possible settlement reduction of a CPRF in function of the pile raft coefficient α_{pr}

The investigated 3D model geometry of combined pile-raft foundation is shown in Figure 5., where under the raft the columns are divided into

3m grids. The 10m long (L) reinforced concrete CFA piles with a diameter (D) of 60cm are located under the raft with rigid connections to that and the pile spacing (R) is 3.0x3.0m or 6.0x6.0m (so just under the pillars in the second case). The average settlement of the raft is around 17.5mm if the pile spacing is 3.0x3.0m and 41.0mm if the pile spacing is 6.0x6.0m. The effect of the structural stiffness is not significant, no remarkable efficiency could be achieved with modelling +1 or +2 levels. The piles provide adequate stiffness to the raft which is enough to analyse the real deformation behaviour of the complex foundation system.

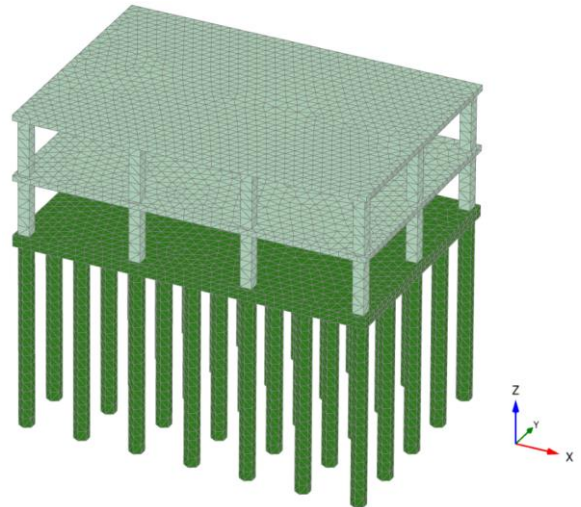


Figure 5. 3D model geometry of combined pile-raft foundation

The pile raft coefficient is $\alpha_{pr}=0.59$ if the pile spacing is 3.0x3.0m and $\alpha_{pr}=0.42$ if the spacing is 6.0x6.0m. The pile raft coefficient is increasing by increasing the number of piles under the raft, at the same time the bearing pressure and the settlement is decreasing.

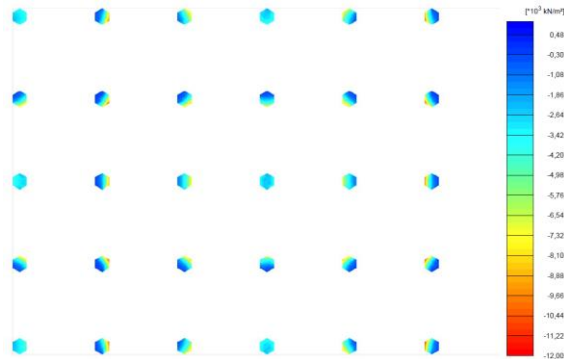


Figure 6. Principal effective stresses on the top of the piles ($R=3.0 \times 3.0 \text{ m}$)

The calculation process of raft's subgrade reaction is the same like in case of simple raft foundation (ratio of bearing pressure and settlement). We reached the smallest average subgrade reaction value in case of raft foundation which is the reason of the large displacement due to the total SLS loads. The modulus of subgrade reaction increases by decreasing the pile spacing. The results are shown in Figure 7. The spring forces, which are acting on the raft are calculated from the normal forces and the settlements of the piles. The smallest spring forces are at the centre of the raft (around 54 MN/m), while the biggest values are near to the edge (around 106 MN/m).

As it can be seen in Figure 8., the biggest bending moments are in that case if the foundation concept is a simple raft foundation, where the structural stiffness has a significant impact on the bending moments, which decreases by 10% due to modelling + 1 level above the raft. At the same building with combined pile-raft foundation the bending moments are almost same, while the settlements are decreasing substantially. The bending moments with rare pile spacing ($R=6.0 \times 6.0 \text{ m}$) are less than with denser spacing ($R=3.0 \times 3.0 \text{ m}$) which is a great advantage in the raft design, on the other hand the settlements are higher which is disadvantage for sustainability limit state (SLS) calculations.

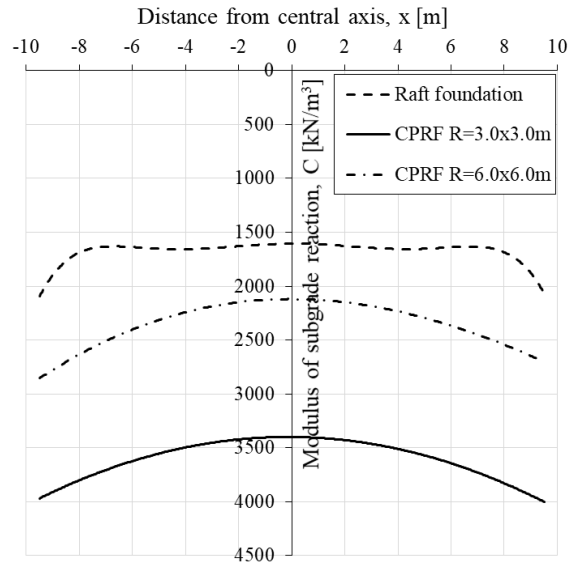


Figure 7. Modulus of subgrade reaction

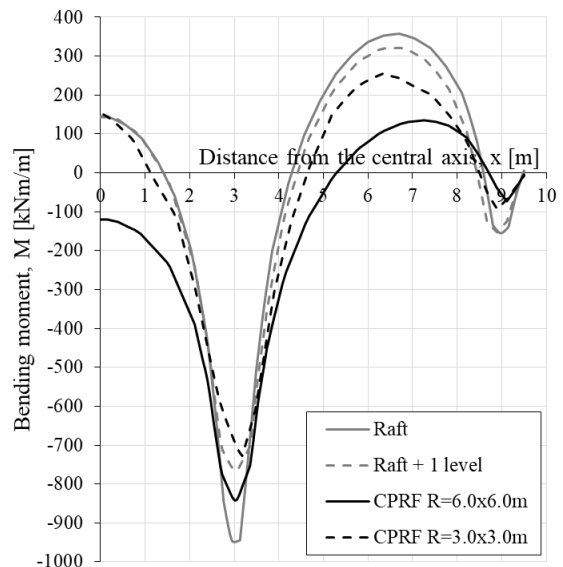


Figure 8. Bending moments in the rafts in case of different foundation concepts

5 RIGID INCLUSION GROUND IMPROVEMENT

Ground improvement through vertical rigid piles is an interesting method for foundations on soft,

compressible soils. Recently, this process has become widespread in Europe against the traditional pile or pile raft foundations.

Rigid inclusion (RI) contain elements that are slender, often cylindrical shape, mechanically continuous and typically vertical. They are laid out according to a regular mesh pattern, which must be adapted both to the nature and geometry of applied loads and to soil conditions. The rigid inclusion concept implies that inclusion caps are not structurally connected to the supported structure. There is a well-compacted, granular load transfer platform (LTP) between the inclusions and the raft. The LTP has a very important role to ensure the transfer of loads to the ends of the piles and to uniform settlements. A minimum load transfer platform thickness is necessary to allow for appropriate load transfer between inclusions and soils, as well as to limit forces within the supported structure. This thickness, often on the order of 40 to 80 cm, proves essential in deriving an optimal design for the supported structure, particularly with the aim of reducing bending moments in the slabs.

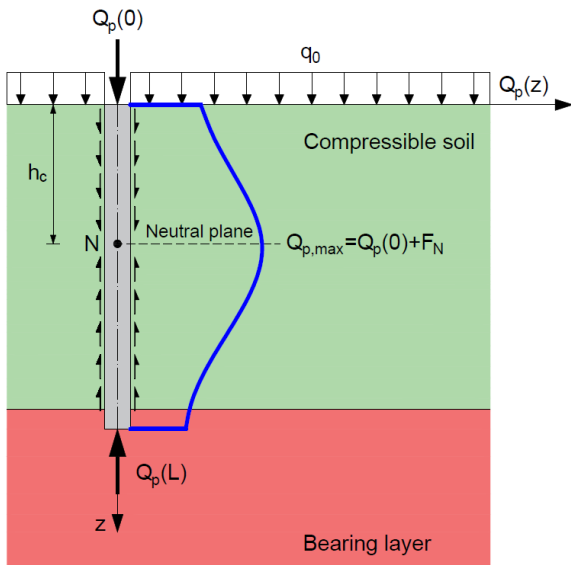


Figure 9. Axial load-distribution inside a rigid inclusion (ASIRI 2012)

The 10m long (L) concrete piles with a diameter (D) of 60cm are located in the soil layer and the pile spacing (R) is 3.0x3.0m (such as the CPRF). The compacted granular load transfer platform of 1.60m thickness is placed over the inclusion head and topped with a raft having a thickness of 60cm or 30cm. The whole structural geometry is almost the same like the CPRF with the exception that there is LTP between the piles and the raft so there are no connections between them.

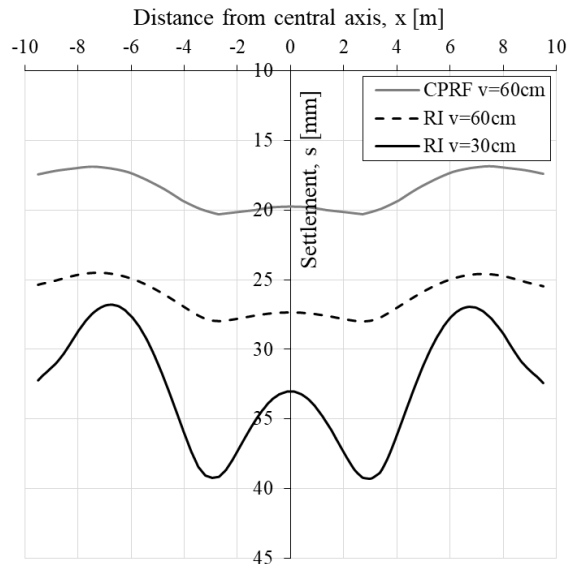


Figure 10. Deformation of raft in case of CPRF and RI

With rigid inclusion ground improvement the average deformation of the raft increases compared to combined pile-raft foundation with 30cm or 60cm, but the bending moments are almost the same if the raft thickness is 60cm. Raft having a thickness of 30cm the bending moments are much higher. These results shows that RI is not so effective if the building is a reinforced concrete frame building, where decisively there are point loads on the raft. This foundation method is efficient if the dominant load is surface load. In that case, when the dominant load is surface load (storage reservoirs, highway embankments or railway embankments for high speed trains), the

effect of the bending moments in the design calculation of the raft is not important so a relative thin raft could be used and the main question is the deformation behaviour analyses of the structure.

6 CONCLUSIONS

Significant effect could be reached by modelling one level above the raft in case of raft foundation and get a more realistic raft behaviour and it is essential to consider the structural stiffness for economical design. The subgrade reaction is almost a constant value with finite element models, it increases by 30% only on the final 2m from the edge of the raft which is a smaller zone than in case of Modified Winkler Method but the final value at the edge of the raft is almost the same. Values from the models, especially the shape of the subgrade reaction distribution are closer to the Winkler theory.

In case of modelling combined pile-raft foundation, the effect of the structural stiffness is not significant, no remarkable efficiency could be achieved with modelling +1 or +2 levels. The piles provide adequate stiffness to the raft which is enough to analyse the real deformation behaviour of the complex foundation system. The modulus of subgrade reaction increases by decreasing the pile spacing. The biggest bending moments are in that case if the foundation concept is a simple raft foundation where the structural stiffness has a significant impact on the bending moments which decreases by 10% due to modelling + 1 level above the raft. At the same building with combined pile-raft foundation the bending moments are almost same while the settlements are decreasing substantially.

With rigid inclusion ground improvement the average deformation of the raft increases compared to combined pile-raft foundation. RI is not so effective if the building is a reinforced concrete frame building where decisively there are point loads on the raft. This foundation method is efficient if the dominant load is surface load.

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