# Comparison of the safety concepts for soil reinforcement methods using concrete columns

## Comparaison des concepts de sécurité pour les méthodes de renforcement de sol avec colonnes en béton

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ABSTRACT: The rigid inclusion concept is a soil reinforcement method using concrete columns with a small diameter compared to usual piles. The load bearing behaviour of such systems is presented in comparison to pile foundations and to combined pile-raft foundations. The safety concept developed in the French recommendations ASIRI for rigid inclusions is divided in two domains depending on the use of the columns, either to enhance the bearing capacity (analogy to piles) or only to reduce the settlements. The safety factors considered for the bearing capacity are compared with those in pile standards (Eurocode 7) and with those in different recommendations for similar reinforcement systems. The particular sensitivity of columns with small diameter is highlighted.

RÉSUMÉ : Les inclusions rigides sont une méthode de renforcement de sol avec colonnes en béton de diamètre faible par rapport aux pieux usuels. La répartition des charges au sein d'un tel système est présentée en comparaison avec les pieux et les fondations mixtes. Le concept de sécurité développé dans les recommandations ASIRI pour les inclusions rigides se divise en deux domaines d'utilisation, soit comme augmentation de la portance (analogie avec les pieux), soit uniquement comme réduction des tassements. Les facteurs de sécurité considérés pour la portance sont présentés en comparaison avec les normes de pieux (Eurocode 7) et avec différentes recommandations pour des systèmes similaires. On insiste sur la sensibilité particulière des colonnes de faible diamètre.

KEYWORDS: rigid inclusion, soil reinforcement, safety concept, Eurocode 7, column diameter, sensitivity

## 1 INTRODUCTION

One of the existing soil reinforcement methods with concrete columns is the so-called „rigid inclusions" method, which has experienced a fast development in the last years, in particular in France (Briançon et al. 2004). This technique consists of a soil improvement method using in general non-reinforced concrete columns with a column diameter of 25 cm up to 80 cm with a soil displacement method. The rigid inclusions are in general separated from the structure by a granular load transfer layer (Figure 1).

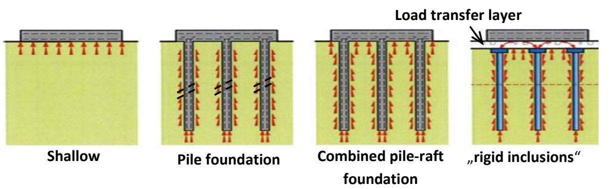


Figure 1. Rigid inclusions system in comparison with usual foundation systems

To some extent, these columns can be compared to usual piles. But in the case of rigid inclusions, the bearing capacity of the soil itself is taken into account in the design, like for combined pile-raft foundations (CPRF), which leads to considerable savings of concrete in the columns and of steel reinforcement in the foundation slab.

The technique with rigid inclusions is employed as well under shallow or raft foundations (e.g. industry halls, water tanks) as under embankments (e.g. high speed railway lines).

The French recommendations of the national research project ASIRI („Améliorations de Sols par Inclusions RIgides"), which have been published in 2012, provide a harmonization for the (in particular numerical) calculations (Jenck et al. 2004), for the safety requirements and for the execution of rigid inclusions. The initial point of the safety theory is the European standardization, that is the French applications of the Eurocode 7 for the geotechnical safety checks, in general based on the pressuremeter design theory in France (Frank 2009), and the Eurocode 2 for concrete. Two different application cases are distinguished in ASIRI: the rigid inclusions can be either used to guarantee the stability of the structure or only as settlement reducers. These different application cases either in analogy to foundations systems or to soil reinforcement methods are reflected in the recommended safety concept in ASIRI.

## 1 LOAD BEARING AND DEFORMATION BEHAVIOUR OF RIGID INCLUSIONS

Rigid inclusions can both be embedded in a bearing layer or – in the general case – designed as floating elements in a compressible soil. The applied load from the structure on the system is distributed between the soil and the column heads. A so-called efficiency of the system can be defined from this load distribution as the ratio of the total load in the column head to the total vertical load. This definition corresponds to the pile-raft-coefficient for CPRF (Hanisch et al. 2002). The load distribution depends on different factors, in particular the rigidity of the foundation and of the soil, the thickness of the load transfer layer, the spacing between the columns and the rigidity of the columns (Okyay 2010).

The interactions between soil and columns in the case of a vertical load are presented in Figure 2. A negative skin friction affects the upper part of the columns due to the separation between slab and columns and because of the compressibility of the soil to be improved. This leads to a reduction of the load in the soil over the depth and to an increase of the force in the columns until the depth where the differential settlement between soil and column is equal to zero. Below this neutral plane, the force in the column is transferred to the soil through positive skin friction and tip resistance, like for usual deep foundations.

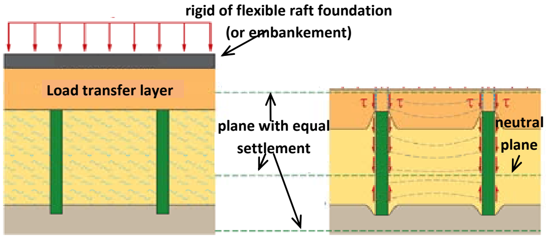


Figure 2. Load bearing and deformation behaviour of rigid inclusions

Horizontal loads can be supported by such systems as well, for example in the case of horizontally loaded isolated footings or when reinforced columns are used as nails against slope failure.

## 2 SAFETY CHECKS IN THE FRENCH RECOMMENDATIONS ASIRI

The usual applications of rigid inclusions are the following:

- Under large embankments or raft foundations to reduce settlements
- At the border of embankments (slope) and potentially of raft foundations against slope failure, or to reduce settlements
- Under isolated footings against failure of bearing capacity or sliding, or to reduce the settlements

First of all, the load distribution in the system without inclusions has to be determined, using the usual calculation methods for foundations or slopes. If the safety according to the French standards against failure of bearing capacity, sliding or slope failure in the ultimate limit state (ULS) is not guaranteed without columns, the subsequent safety checks correspond to the so-called „domain 1“ (Figure 3). Otherwise the columns can be used only to reduce the deformations („domain 2“). The required calculation of the load distribution with columns has to be carried out using comprehensive numerical models or using one of the recommended simplified models in ASIRI.

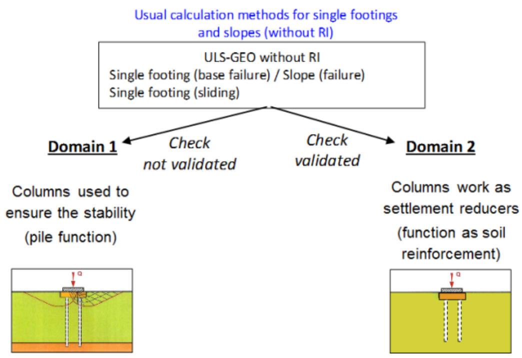


Figure 3. Classification in domain 1 and 2 in ASIRI

In the domain 1, the safety checks are carried out in analogy with the French Eurocode 7 application standards for deep foundations in addition to the standards for isolated footings and slope stability. The favorable action of the columns is taken into account by reducing the foundation load on the soil. Then, the checks of bearing capacity for the foundation or the slope are carried out normally with this reduced load. Besides, the bearing capacity of the columns has to be checked as well against ultimate limit states (ULS) against serviceability limit states (SLS) under the neutral plane (Figure 2), just like for piles after the French standard for deep foundations. The structural capacity of the columns, which are in general not reinforced, has to be verified by means of a limitation of the compression and shear stresses in the column section in the ULS and SLS. The compatibility of the calculated vertical and horizontal deformations has to be checked in SLS.

In the domain 2, the columns are considered as pure settlement reducers. Therefore, no check of the bearing capacity is required in this domain, like in the design philosophy of the CPRF-guideline (Hanisch et al. 2002) or in the case of the so-called “creep piles”. Only SLS-checks have to be carried out here.

In both cases, compatibility verifications have to be done after the checks, in particular to verify the compatibility of the stresses in the load transfer layer.

## 3 COMPARISON WITH STANDARDS AND RECOMMENDATIONS

In this section, the recommended safety checks in ASIRI for the domains 1 and 2 are compared with the French and German piling standards and with recommendations for similar piles or columns systems, i.e. the German CPRF-Guideline (Hanisch et al. 2002) and the German guideline for stabilizing columns "Merkblatt für die Herstellung, Bemessung und Qualitätssicherung von Stabilisierungssäulen zur Untergrundverbesserung" (CSV-Merkblatt, DGGT 2002).
Only the persistent load situation (BS-P in Germany) is considered here. The partial safety factors for the actions in this load case are the same in all regulations, that is 1,35 (respectively 1,5) for the permanent (respectively variable load) in the case of foundations, and 1,0 (respectively 1,3) for the slope stability.

### 3.1 *External bearing capacity (GEO)*

In ASIRI, only the domain 1, where the columns are necessary for the stability, is concerned by the safety checks in the ULS (Table 1). The verifications correspond to those of the French application standard of Eurocode 7 for compression piles (with a diameter of usually 1 m up to 3 m), in general with the use of empirical resistance values from pressuremeter tests (Table 2). The favourable effect of the columns in the checks of the footing or the slope is taken into account by reducing the total load by the force taken in the columns. After ASIRI, no pile loading test has to be done in the design phase for the determination of the bearing capacity. However, loading tests have to be carried out in the execution phase according to ASIRI to verify the previously determined bearing capacity.

In the CPRF-guideline (Hanisch et al. 2002), no distinction is made between a use as “settlement reducer” or as “resistance increaser”. The maximum characteristic resistance is defined here from the load-settlement curve of the global system, and divided by a safety factor to obtain the design value (Table 3). The bearing capacity of the piles themselves has not to be verified, since the whole system made of the slab, the piles and the soil has already to be stable. In the CSV-guideline on the contrary the bearing capacity of the single columns always has to be checked, with the additional assumption that the total applied load from the structure is taken by the columns (here diameter 12 cm up to 20 cm), which is on the safe side.

Table 1. Partial safety factors – ASIRI ULS-GEO

| ULS-GEO (BS-P) | ASIRI (France) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Domain 1 | | | | Domain 2 | | | |
| | Isolated footing | | Slope | RI | Isolated footing | | Slope | RI |
| | Failure | Sliding | | | Failure | Sliding | | |
| **Partial safety factor for resistance** | $\gamma_{R;v}$ x $\gamma_{R;d}$ = 1,4 x 1,2 = 1,68 | $\gamma_{R;h}$ x $\gamma_{R;d}$ = 1,1 x 1,0 = 1,1 | $\{\gamma_{\varphi'} = \gamma_{c'}\}$ x $\gamma_{R;d}$ = 1,25 x (1,1 bis 1,2) = 1,38 bis 1,5 | $\{\gamma_b = \gamma_s\}$ x $\gamma_{R;d1}$ x $\gamma_{R;d2}$ = 1,1 x 1,15 x 1,1 = 1,39 | / | / | / | / |
| **Remark** | load reduction due to RI (Slope only drained here model factor for reinforced soils depending on the sensitivity towards deformations) | | | like piles under the neutral plane empirical values (pressuremeter method) | no stability check | no stability check | no stability check | no stability check |

Table 2. Partial safety factors – Eurocode ULS-GEO

| ULS-GEO (BS-P) | Eurocode 7 Germany | | | | Eurocode 7 France | | | |
|---|---|---|---|---|---|---|---|---|
| | Isolated footing | | Slope | Piles | Isolated footing | | Slope | Piles |
| | Failure | Sliding | | | Base failure | Sliding | | |
| **Partial safety factor for resistance** | $\gamma_{R,v}$ = 1,4 | $\gamma_{R,h}$ = 1,1 | $\gamma_{\varphi'} = \gamma_{c'}$ = 1,25 | $\gamma_b = \gamma_s$ = 1,4 | $\gamma_{R;v}$ x $\gamma_{R;d}$ = 1,4 x 1,2 = 1,68 | $\gamma_{R;h}$ x $\gamma_{R;d}$ = 1,1 x 1,0 = 1,1 | $\gamma_{\varphi'} = \gamma_{c'}$ = 1,25 | $\{\gamma_b = \gamma_s\}$ x $\gamma_{R;d1}$ x $\gamma_{R;d2}$ = 1,1 x 1,15 x 1,1 = 1,39 |
| **Remark** | | | only drained here | with empirical values | with pressuremeter method | | only drained here | with empirical values (pressuremeter method) |

Table 3. Partial safety factors – Recommendations ULS-GEO

| ULS-GEO (BS-P) | CPRF-Guideline (Germany) | | | CSV-Guideline (Germany) | | | |
|---|---|---|---|---|---|---|---|
| | Combined pile-raft foundation | | Slope | Isolated footing | | Slope | Columns |
| | Failure | Sliding | | Failure | Sliding | | |
| **Partial safety factor for resistance** | $\gamma_{R,v}$ = 1,4 | $\gamma_{R,h}$ = 1,1 | / | / | | $\gamma_{\varphi'}$ x $\lambda_{pV}$ = 1,25 x 1,15 = 1,43 | $\gamma_{sp}$ = 1,25 bis 1,4 |
| **Remark** | as global system | | / | not taken into account | | only drained here $\lambda_{pV}$ against chain reaction of columns | Assumption: total load in the columns; depending on number of load tests (in execution phase) |

According to the French application standards of Eurocode 7, safety checks for the resistance have to be carried out in the SLS as well. This has been adopted in ASIRI for the domain 1. Therefore a so-called "pile creep load" has been defined in the French standards as 70% (for displacement piles) of the total resistance as a reference in the SLS. The safety against failure of beraing capacity of single footings also is increased in comparison with the ULS. In the domain 2, only the compatibility of the displacements has to be investigated. In the German application standards of the Eurocode 7, only the limits of deformation have to be controlled in the SLS.

## 3.2 *Internal structural capacity (STR)*

The safety factors for the maximum compression in the section of the rigid inclusions in the ULS and SLS are similar to those for piles in Eurocode 7 (with reference to Eurocode 2 for the concrete). The safety factor for the resistance in ASIRI is up to approximately 2 to 11 depending on the limit state, the execution type, the slenderness of the column and the quality controls. In order to avoid very small column diameters, the mean compression stress in the section is in all cases limited to 7 MPa in the ULS (domain 1). Adapted values have to be considered for domain 2 (SLS).

Although the rigid inclusions are not used as tension piles, tension stresses can develop in the section resulting from bending moments. In the domain 1, the columns have to be reinforced in the same way as piles according to Eurocode 2 as soon as tension stresses appear in the section. On the other hand, in the domain 2 tensile stresses up to the characteristic value of the tensile strength of the concrete are allowed. If this value is exceeded, the columns have to be reinforced as well.

The internal resistance can be particularly endangered in the case of unreinforced columns with very small diameter (Wehr & Sondermann 2011). For this reason, no shear stresses are allowed in ASIRI for unreinforced columns with a diameter smaller than 30 cm (cp. 40 cm for conventional piles). Buckling effects have to be analysed also for these small diameters and for very soft soils (pressuremeter modulus EM smaller than 3 MPa). The minimum allowed diameter in ASIRI for unreinforced columns is 25 cm.

In the CPRF-guideline (Hanisch et al. 2002) the internal resistance has to be checked in the same way as for conventional pile foundations.

According to the CSV-guideline (DGGT 2002), a safety factor of 2 has to be considered for the mean compression, in comparison with 2 up to 6 for the maximum compression stress in the ULS and 7 MPa for the mean compression stress in ASIRI. According to this guideline, the buckling has to be checked only in soft layers with an undrained cohesion smaller than 10 kPa. This is not in accordance with the present state of the art for slender piles: buckling effects can already appear for soils with greater undrained cohesion (Vogt et al. 2005 and Eurocode 7 - DIN 1054 - 2010).

### 3.3 *Sensitivity of columns with small diameter*

Two different design philosophies exist concerning the check of the bearing capacity of the column in the case of column diameters greater than 25 cm. The philosophy can be either without safety check (ASIRI in the domain 2 or CPRF-guideline, where the system is checked as a global system including slab, piles and soil), or with safety check in accordance with the piling standards (ASIRI in the domain 1). For smaller column diameters with a load transfer layer there is no recommendation for the use as pure settlement reducers, use which namely is only applicable for systems with a sufficient ductility and possibilities of load redistribution (flexible connection between piles and slab or relatively large column diameter).

A special attention must be paid to the particular sensitivity concerning the internal resistance of columns beneath the load transfer platform under horizontal loadings. Horizontal loads from the structure lead to shear, bending moments and thus possibly tension in the column section. Though the concrete design is regulated uniformly and with an adequate safety factor for all diameters, the particular importance of the interactions between the structure and the system made of soil and columns is not completely described in the current state of the art, in particular for very slender elements and under special temporary loading cases.

On the safe side, it can be assumed that the total horizontal load is taken by the columns, but this may lead to an uneconomical design. Furthermore, any execution imperfections in the position of the columns (eccentricity), in the column diameter or in their inclination can have a considerable influence in the case of small column diameters and induce undesigned shear stresses, even in compliance with the given tolerances. Attention must be paid to the execution stages too, where the top of the columns can be particularly endangered due to heavy vehicle traffic.

## 4 CONCLUSION

The soil reinforcement method with rigid inclusions is a soil stabilization system with columns which are separated from the structure by a load transfer layer, and which work either by analogy with a pile foundation or with a conventional soil reinforcement technique. The distinction between two application domains 1 and 2, either for an increase of the bearing capacity (1) or for a settlement reduction (2) reflects this difference. In the domain 1, the safety checks are similar to those for conventional pile foundations. In the domain 2, only SLS checks have to be carried out, including a control of the internal resistance of the columns.

The use of such column systems in the domain 2 corresponds to the design philosophy of the CPRF-guideline (Hanisch et al. 2002), in which no verification of the bearing capacity of single piles has to be done, and where only the stability of the global system and of course the structural capacity have to be checked.

In the CSV-guideline (DGGT 2002), a higher safety level than in ASIRI and in the CPRF-guideline is considered for the external resistance for the relevant small diameters. Indeed, the bearing capacity of single columns must always be carried out with the assumption of the total load in the columns, and the approach as settlement reducer without safety check for the single columns is not permitted for those diameters.

The internal resistance of columns with small diameters can be particularly threatened because of the significant influence of potential imperfections in the execution in this case. In the current state of the art of the soil-columns-structure interactions, an increased safety level should be taken into account for columns with small diameters under horizontal loads.

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