

## DESIGN RISKS OF GROUND IMPROVEMENT METHODS INCLUDING RIGID INCLUSIONS

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After an introductory presentation of design approaches the risks involved are investigated. Considered are different ground improvement methods, like soil mixing, vibro compaction and vibro stone columns, as well as pile-like supporting elements, including vibro concrete columns and full displacement columns named rigid inclusions.

The difference in stiffness of the inserted material and the soil determines the design and the risks involved. Three categories with increasing risk are proposed. Ground improvement methods, ductile in compliance with EN 1997-1 and DIN 1054, proved to be extraordinary robust and present only a small risk with regard to a possible variation of soil and material parameters and loads. The design is usually determined by the serviceability limit state.

Risks increase with the application of non-ductile methods with small column diameter, like rigid inclusions, because the ultimate limit state is controlling the behaviour. Namely, in order to mobilize high skin friction, the lower and upper end of the column have to fail during punching in the soil below and the load transfer platform above. Even a small variation in material parameters, system geometry or loads may lead to a complete loss of bearing capacity and progressive failure, resulting in expensive damages of civil engineering structures and time consuming repair works.

### 1. INTRODUCTION

Since the 40's of the 20th century ground improvement methods have been successfully applied to improve the bearing capacity and/or stability and/or deformation characteristics of soft soils for a variety of applications. The involved technologies of ground improvement have won a substantial market share in relation to competitive procedures, such as traditional piling or heavy foundation solutions.

Present requirements for well-positioned ground improvement methods, which represent established professional practice and also reflect respective regulations included in standards and codes, comprise: the involved procedure is based on a well-defined execution process, manageable and controllable in each stage, the procedure is calculable and repeatable, the process involved should allow for optimization of the solution applied in

Compaction		
Static methods	Dynamic methods	
Pre-loading	Compaction by vibrations - using depth vibrator - using vibratory hammer	
Pre-loading with consolidation aid		
Compaction grouting	Impact compaction - drop weight - explosion - air pulse method	
Influencing the ground water		
Reinforcement		
Displacing effect	Without displacing effect	
	Mechanical introduction	Hydraulic introduction
Vibro stone columns	DSM-method	Jet grouting
Vibro concrete columns	FMI-method	
Sand compaction piles	Injections	
Lime/cement-stabilising columns	Freezing	
Compaction grouting		

Figure 1. Ground improvement methods.

relation to expected functional performance, the success of performance of the procedure is verifiable by measurements and/or field tests, the execution time is relatively short (in comparison to the total construction period), an immediate use of the improved ground is possible and cost of application is competitive.

Traditionally, piling or direct exchange of soft soil has been used to bridge or replace layers with insufficient bearing capacity. The aim of modern ground improvement methods is to increase the bearing capacity of the ground in order to bear the loads with compatible deformations. Consequently, not the entire action is taken by the supporting elements, but only the difference between the required and existing bearing capacity without ground improvement, what contributes to the attractiveness and customer’s use of ground improvement. The degree to which the existing ground can be intentionally used to support acting loads, which may vary from zero up to allowable limit, depends on the characteristic of the ground improvement method involved and the design solution adopted.

A systematic overview with classification of the different methods can be found in Figure 1, excluding surcharge, Sondermann and Kirsch [1].

Due to constantly increasing competition and pressure to shorten execution time, the application limits of existing ground improvement methods had to be extended. This resulted in a rapid development and use of alternative procedures in the last years.

## 2. STANDARDS AND RECOMMENDATIONS

The growing importance of ground improvement methods in Europe and world-wide is also reflected by the recent development of normative documents. Standardization committees as well as national and international working groups have compiled and even still work on various recommendations and codes. The most important sets of rules and recommendations, which define current standards for ground improvement measures, include (but are not limited to):

European standard for Deep Soil Mixing, EN 14679,

European standard for Ground Treatment by Deep Vibration, EN 14731,  
 European standard for Vertical Drains, EN 15235,  
 Recommendation 6.9 by EBGEO “Rein-forced embankments on pile-like elements”,  
 Working Group 5.2 of the German Geotechnical Society DGGT,  
 Bulletin for the installation, calculation and quality control of stabilization columns for  
 ground improvement, Working Group 2.8 of the German Geotechnical Society  
 DGGT, Part 2 “Mortar columns” (in German),  
 Amélioration des Sols par Inclusions Rigides, ASIRI, (2011), Ground improvement with  
 stabilising columns, Draft (in French) [2].

### 3. LIMITATIONS AND RISKS OF GROUND IMPROVEMENT METHODS

There is still a research need for a more comprehensive investigation of the limits between different soil improvement methods, pile-like elements and piles. Generally there are the following risks of geotechnical methods:

Serviceability limit states (DIN EN 1997-1): larger settlements and tilting or sliding of a footing.

Ultimate limit states (DIN EN 1997-1): larger settlements, tilting due to eccentric load, punching, failure of column head and toe, bearing capacity failure, slope stability failure and sliding failure.

The risk level of various ground improvement methods can indeed be different! The following three categories with increasing risk level can be identified. In each category the typical risks are:

Category A:

- Larger settlements.

Category B:

- Larger settlements.
- Structural failure (internal failure due to vertical loads).
- Overall bearing capacity failure (external punching failure of column toe or head).

Category C:

- Larger settlements.
- Structural failure (internal failure due to vertical and horizontal loads, buckling).
- Bearing capacity failure (external punching failure of column toe or head).
- Overall bearing capacity failure, slope stability failure.

#### 3.1. Category A (Low Risk)

In definitely true ground improvement methods the columns have to be supported by the surrounding soil in order to keep their shape. Therefore the columns themselves do not have an own failure load. Usually the serviceability limit state (deformations) is decisive in the geotechnical design. All these methods pose a low risk because they are sufficiently

ductile as specified in DIN 1054 “Supplementary rules to DIN EN 1997-1” of the Eurocode 7 and robust. Robustness is here defined as the ability of a system to maintain its function during soil parameter and load variation. It is important to note that the bearing capacity is not exceeded even if the columns are overloaded. Vibro compaction and vibro stone columns, executed with depth vibrators as well as band, sand and gravel drains and sand compaction piles are included herein. The design is done, e. g., with the Priebe method [3] or the Balaam/Booker method [5].

**3.2. Category B (Medium Risk)**

The next, medium risk category includes all methods that involve columns with a diameter equal to or greater than 30 cm, in which plastic deformations are considered with sufficient safety factors against failure load. These are, e. g.,: lime /cement columns installed with the dry method, deep soil mixing with the wet method, vibro mortar columns and vibro concrete columns, and combined concrete /gravel columns like columns with mixed modulus (CMM). The design is conducted, e. g., with DIN 4017, using the Brinch-Hansen approach for the bearing capacity of the column base, and additionally with DIN 1045 for the structural bearing capacity.

**3.3. Category C (High Risk)**

This category includes all pile-like elements with a small diameter (i.e., generally below 30 cm) and material to soil stiffness ratio well above the limit identified in Section 4.

Due to the adopted design negative and positive skin friction will develop along such elements (Figure 2), while the design load is close to the failure load. Even small variations of soil parameters and/or acting loads may easily cause sudden loss of the bearing capacity of the column material or the ground, with all related consequences for the super structure. Care should be taken especially in soft soils and with weak load distribution layers. Consequently, the risk involved in application of such methods of ground improvement is much higher, compared to category A, in particular, and also to B. Therefore the methods ascribed to category C require more attention.

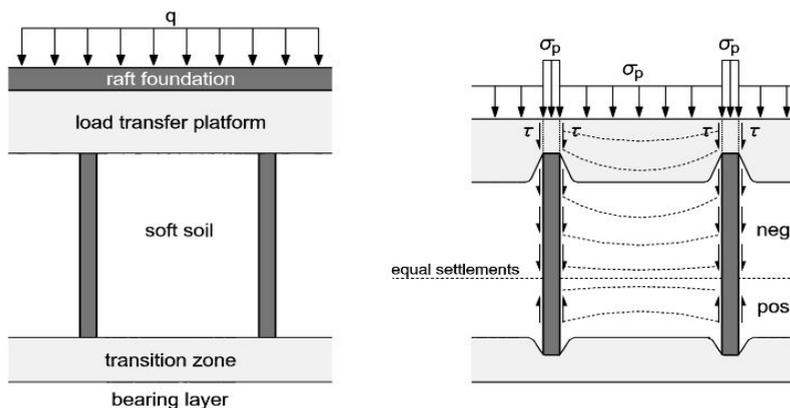


Figure 2. System of category C with stresses and settlements.

In category C there are stabilizing columns installed using dry granular binders, which harden upon contact with the ground water (Combined Soil stabilisation with Vertical columns), columns made of ready mixed wet materials, as well as rigid inclusions like Controlled Modulus Columns (Wong and Muttuvel [9]), made of regular concrete or specific mortar.

All columns are usually unreinforced. Column diameter may vary between the lower limit of 12 to 15 cm, as in the German recommendation [8], through frequently used up to 40 cm. Steel reinforcements in form of single bars or profiles can also be installed in columns with a diameter above 25 cm, but this is usually limited to restricted areas due to cost increase (Wong and Muttuvel [9]).

As outlined in the recommendations for “the installation, calculation and quality control of stabilizing columns for ground improvement” (DGGT, 2002 [8] in Germany, and ASIRI, 2011 [2] in France), the loads are gradually transferred from the soil to much stiffer stabilizing columns. Generally, the supporting system shows a similarity to a “floating foundation” or a “pile-raft” design, the difference being the embedment of the supporting elements, which only slightly penetrate into the underlying bearing layer. This kind of system has significant influence on the load distribution pattern between the columns and the soil.

As specified in DIN EN 1997-1, many calculation methods are based on the assumption of a sufficiently ductile behaviour of the supporting soil-structure interaction system. In DIN 1054 a sufficiently ductile behaviour is assumed if the ultimate limit state is preceded by large displacements. If this ductility is missing, an ultimate limit state with sudden and progressive failure may easily appear. Particularly this risk exists for controlled modulus columns, because the design takes into account that some columns are already partially broken (Wong and Muttuvel [9]). Therefore standard geotechnical calculation methods, well suitable for ground improvement categories A and B, should not be directly applied in category C because of much lower safety level of such systems, which does not comply with DIN 1054 or DIN EN 1997-1 recommendations. Further dedicated research is needed to find out how much the existing partial safety factors of DIN 1054 have to be increased for category C.

Special attention is also required in case of unreinforced slender elements subjected to tensile loads, which can easily break. Such failures have been often observed, although not documented, e.g. during column execution, when influenced by ground heave, as well as after column completion due to associated earth works or heavy vehicles passes. Quite often there is also a danger of column buckling, especially for diameters less than 30 cm, which has to be assessed [2]. Due to the complicated interaction between soil and structure all these methods have to be classified as GK3 according to DIN 1054. The observational method must not be applied due to missing ductility of the system (DIN 1054).

There are certain similarities to the combined piled raft foundation. However, the piles are directly connected to the raft and therefore a punching failure of the column head is not possible. Furthermore the diameter of the piles is much larger than 30 cm resulting in lower risks of the piled raft foundation.

#### **4. INFLUENCE OF THE SUPPORTING ELEMENT TO SOIL STIFFNESS RATIO**

Crucial for the risk assessment of all ground improvement methods considered in this paper and evaluated in the following section is the stiffness ratio between a supporting

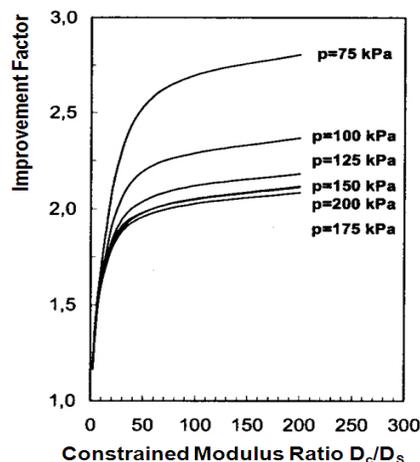


Figure 3. Settlement improvement factor [4].

member, i.e. column or pile-like element, and the soil, which – unfortunately – is often not rigorously taken into account or even entirely ignored.

There are, however, the following exceptions:

In his thesis Kirsch [4] examines the influence of the variation of the constrained modulus ratio between 2 and 200 on the settlement improvement factor which is denoted as the settlement ratio of the unimproved soil to the improved soil. As shown in Figure 3, the settlement improvement factor increases less and less with increasing stiffness ratio and loading stress level. Only below a ratio of ca. 40 to 50 a relevant increase of the settlement improvement factor can be expected. Thus larger stiffness factors are not efficient in terms of soil improvement.

In the EBGeo recommendation [10] for geotextile coated columns there are certain design rules for the horizontal geogrid design above the columns. Below a stiffness ratio (column/soil) of 50 a geogrid is not necessary because of the self regulating system. For an intermediate stiffness ratio between 50 and 75 a geogrid design is recommended in special cases. However, if the ratio is higher than 75 a geogrid must be foreseen. The core of geotextile coated columns is granular but due to the relatively stiff “sock” they may be regarded as transition to cement and concrete columns.

For lime/cement deep mixing columns there are similar approaches. The undrained shear strength of the column  $c_{US}$  should not exceed 150 kPa [6]. Based on the empirical relationship  $M = 50 \text{ to } 150 \times c_{US}$  a compression modulus of  $M = 7.5 \text{ MPa to } 22.5 \text{ MPa}$  can be calculated. Considering the very soft soils in Scandinavia, with compression moduli around 0.3 MPa, average stiffness ratios of 50 can be back calculated.

Summarizing the above findings it can be stated that the stiffness ratio of approx. 40 to 50 between the supporting element and the soil can be regarded as an upper limit for efficient ground improvement methods. This is because any further increase of stiffness of the supporting element is ineffective and does not contribute to acceleration of the settlement and to the increase of settlement improvement factor. It is therefore recommended to decrease

the columns stiffness in soft soils in order to remain below a stiffness ratio column/soil of 50.

The influence of large horizontal forces or earthquake loading has been neglected at this stage of consideration. Also special rigid inclusions, formed with a weak mortar  $UCS < 5$  MPa, should be investigated in more detail.

Moreover, it should be also noted that stiffer supporting elements usually require increased cement consumption. Consequently, the use of less stiffer columns will have a positive effect on the equivalent  $CO_2$  emission, as shown by Zöhrer *et al.* [7].

It would be appreciated if future research could focus on the column to soil stiffness ratio of currently relevant ground improvement methods.

## 5. CONCLUSION AND OUTLOOK

Three ground improvement categories with increasing risks are proposed. True ground improvement methods in category *A*, e.g., vibro compaction and vibro stone columns, are ductile according to DIN 1054 and Eurocode 7. Moreover, they maintain their stability even when variations in soil and material parameters occur, and therefore incorporate only small risks. For the geotechnical design the serviceability limit state is usually a determining factor.

The methods in category *B*, that utilizes columns with a diameter of more than 30 cm, involve an average risk. And the risk of an increased stiffness ratio is here compensated with an increased column diameter.

Methods with non-ductile behaviour in category *C*, that use columns with a small diameter of less than 30 cm, e.g., rigid inclusions, represent a much higher risk because the geotechnical design is usually governed by ultimate limits states. To enable the full development of high skin friction along the columns such supporting systems allow significant punching of the column foot and column head into the soil layers. Thus at least for single and strip footings even a small variation in the mechanical parameters, system geometry or loads may lead to a complete failure with related consequences.

The difference in stiffness between the columns and the soil plays a fundamental role in ground improvement supporting systems. The stiffness ratio of approximately 40 to 50 is regarded as an upper limit for true ground improvement solutions, which account for ground interaction. A further increase in column stiffness is ineffective.

The goal of further research should be the establishment of a reliable limit classification of various ground improvement methods including granular and stiff elements with focus on the column to soil stiffness ratio. In any case, the term 'Ground Improvement' should not be used to undermine the safety level of existing piling standards, nor to countervail certification documents issued by, e.g., the Institute for Bautechnik in Germany and to design full displacement piles (EN 12699) with ground improvement methods.

It is very much appreciated by the authors that the French ASIRI recommendation finally has been changed fundamentally to increase the safety level at least to a certain extent. Generally two cases are distinguished:

- A) If stiff columns like rigid inclusion are necessary for bearing capacity of shallow foundations (global factor of safety without rigid inclusions  $< 2.4$ ) or slope stability (global factor of safety approx.  $< 1.4$ ) they have to be designed according to the local piling

standard. Reinforcement has to be used where the columns are not entirely compressed which means that no tensile stresses are allowed.

- B) If stiff columns like rigid inclusion are not necessary for bearing capacity of shallow foundations (global factor of safety without rigid inclusions approx.  $> 2.4$ ) or slope stability (global factor of safety  $> 1.4$ ) they are designed as ground improvement. Reinforcement is not necessary where the maximum tensile stress according to EC2 is not exceeded.

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