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Design methods for geogrid reinforced foundation systems on weak subsoil

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Abstract. Construction on weak subsoil is a reoccurring challenge for engineers nowadays, for which various different solutions are available. Geosynthetics are getting more and more popular and one of their most widely used application is subsoil reinforcement. Several types of geosynthetics can be used, the most well-known are vertical drains and geogrids. Prefabricated vertical drains can be used for accelerating consolidation in oversaturated soils with a high water content as they drain the excess water from soil while also decreasing pore water pressure, optimizing soil bearing capacity and reducing the risk of liquefaction and excess settlements. The main limitation is not significantly reducing total subsidences. Gravel and concrete piles are widely used, and in recent years, rigid inclusions (unreinforced concrete piles) are also getting popular. A common feature of them is that a so-called Load Transfer Platform (LTP) has to be built between the superstructure and the foundation to prevent direct contact with one another. The LTP between them is a stiff, reinforced layer that helps the arching of load. Design of the LTP may be carried out using several design standards, of which the most widely used are Collin's beam method and CUR226. This paper focuses on presenting and comparing these two main design methods, emphasizing their differences and applicability while also considering their limitations.

1 Introduction

Construction under weak subsoil conditions is a recurring problem for nowadays' engineers and they are more and more often forced to find safe ways to build on soft, highly compressible, or even organic soils that may be prone to creep, differential settlements and a prolonged consolidation time. On these low-lying areas that are not suitable for agricultural or other use, transportational infrastructure or windfarm parks (among others) may be built. These establishments involve quite a high load, for which soft soils often have insufficient bearing capacity in themselves, which can lead to one of the many kinds of structural failures, including geotechnical and global stability, equilibrium problems or intolerably large soil deformations and (often uneven) settlements. These conditions all limit the quality or usability of the structure, therefore, they should be avoided or at least minimized. Total replacement of local soil is usually not worth the extra cost, instead, the emphasis is on reinforcing the existing soil when possible. [1]

Every construction is preceded by preliminary investigations with the aim of determining if the structure can or cannot be safely built without altering subsoil conditions. [2] Several

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possibilities are available for designers to do that in a safe way, including but not limited to: soil replacement, dynamic soil compaction, soil injection, horizontal geosynthetic reinforcement, gravel piles and vibro-stone columns, prefabricated vertical drains, rigid inclusion technique, jet grouting and lightweight structural materials. [3] This paper aims to shortly discuss all the applicable methods and put great emphasis on geosynthetic reinforcements and their design methods.

2 Short description of possible solutions

2.1 Simple cases – construction optimization

In simple cases, the solution may be as easy as optimizing the construction process adequately. Subsoil failure may be avoided by slowing down the embankment building and waiting longer times (weeks or months) between constructing each compacted layer. In the meantime, the embankment gradually consolidates and the bearing capacity of subsoil also increases, reducing the risk of failure. This method is very cost-efficient as no special equipment or product is needed, only time and proper planning. [4] However, in most cases the contractor does not have enough time to wait for consolidation.

2.2 Vertical drainage

The process in cohesive soils can take a very long time, however, it can be significantly accelerated with the use of prefabricated vertical drains (PVDs). PVDs are an effective method for improving shear strength of soft soils while also reducing post-construction settlements. With the use of vertical drains the rate of soil consolidation increases by providing a short horizontal drainage path for water to seep into and be transmitted along the length of the drain. The drainage path is usually shortened from the thickness of a soft soil to half the drain spacing thus minimizing consolidation time. [5] Since the 1970s, vertical drains have evolved into being completely polymer based and prefabricated. Nowadays PVDs are applied worldwide to improve foundation of highway and railway embankments, a schematic drawing of their behavior can be seen on Figure 1. [3]

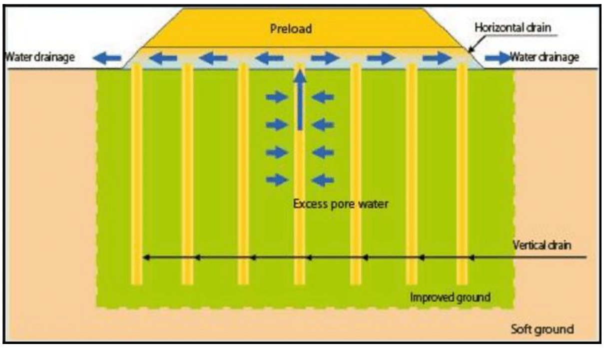

Fig. 1. Behavior of prefabricated vertical drains in soil [6]

2.3 Pile-like reinforcements: stone columns and rigid inclusions

One main limitation of vertical drains is that they cannot reduce total settlements, only bring them forward to before the beginning of construction. While this might be acceptable in many cases, there are also several special design situations when the reduction of deformations is required. Under such strict conditions, different piling systems could be considered. Gravel or stone columns improve soft soils by the installation of load bearing piles composed of compacted, coarse-grained fill. By densifying and reinforcing the foundation soil, increased global stability, reduced settlement and (due to the high discharge capacity of gravel) a significantly shortened consolidation time can be achieved. One crucial drawback is the complete lack of sufficient lateral support of the columns. If the columns are encased in a circular nonwoven geosynthetic fabric or tube, the filter stability between the column fill and the surrounding soil is guaranteed; spreading load is resisted and bulging is reduced. These are the so-called geosynthetic-encased columns (GECs). [3]

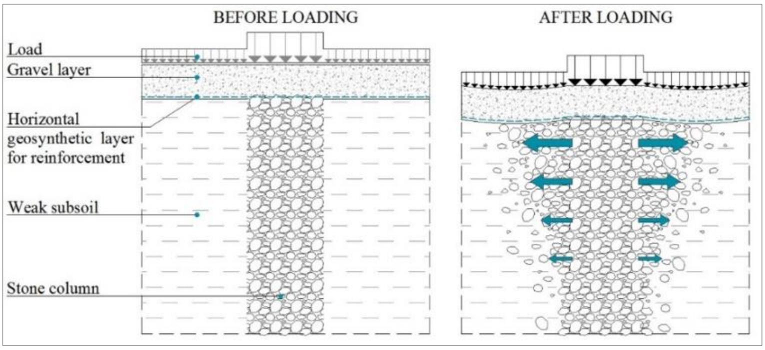

Fig. 2. Undesirable increase in pile diameter due to the loading (“bulging” effect)

Another similar, commonplace method for soil reinforcement is installing rigid inclusion elements. Rigid inclusions are basically unreinforced concrete piles that function more as a soil reinforcement rather than a conventional pile. Their most important role is not simply transferring loads of the superstructure to the high bearing capacity layers below, a major part (often up to 90%) of loads is carried by the weaker upper layers. Rigid inclusions may be considered a transition between shallow and deep foundations and may be used when bearing capacity is low, but not low enough to cost-effectively construct deep foundations. Spacing and length of elements are dependent on foundation soil and structural load, they are able to generally improve subsoil, reduce differential settlements and carry part of load. [7] The elements are only loaded in vertical direction; steel reinforcement is therefore not needed. This may be achieved by installing an intermediary layer between foundation and superstructure - the so-called Load Transfer Platform (LTP). This (normally geosynthetic-reinforced) granular layer is responsible for proper load distribution and economic constructability. [8] In Europe, several design methods are in use, the most important of them are the beam method and the CUR226.

3 Load Transfer Platforms

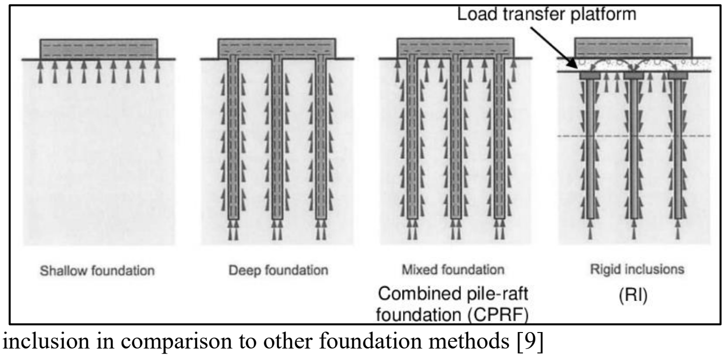

Fig. 3. Rigid inclusion in comparison to other foundation methods [9]

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LTPs are well compacted granular layers with carefully designed thickness and grain size distribution, they can easily be considered the most important part of piled embankments. LTPs break the connection between foundation and superstructure; the purely vertical load distribution breaks due to the arching effect (see Figure 3). For the sake of more efficient behavior, almost exclusively LTPs (with single or multi-layer) geosynthetic reinforcement are used. [10] Number, location and strength of geogrids may vary according to structural load, pile spacing or even the used design method.

A number of different design standards and guidelines are available for designers to choose from, including the German EBGEO, the British Standard BS8006, Collin's beam method and the Dutch guideline called CUR 226. The latter two are the focus of current paper for they approach the same problem in a dissimilar way, yet both are able to produce a safe structural design. The similarities and differences are best showcased through an example later on. Before that, the main principles of each method are given in order to gain a deeper understanding of their mentalities.

3.1 Collin's beam method

The beam method, also known as Collin's method, was first published in 2004. The main principle is imagining multi-layer reinforced LTPs as stiff *soil-beams*: this *beam* provides load distribution between foundation (piles or rigid inclusions) and subsoil. Load distribution may be imagined as a pyramid with a given (usually 35-45°) angle. Each geogrid reinforcement layer carries the weight of soil that is above it, up until the next reinforcement layer. [10] Collin's calculation model is quite simple, however, it may only be used to a limited extent because of the lack of safety factors and consideration of (often large) upper loads.

3.2 CUR226

The Dutch design principle, unlike beam method, approaches the problem by imagining geogrids acting like tensioned membranes. This method is most similar to the German EBGEO (but unique to the Netherlands) as they were published at roughly the same time. [11] Contrary to former methods, CUR226 calculates with the design values of input data from the start. [12] The force distribution is much more complex than Collin's pyramid approach, it is based on concentric arches (2D) and concentric hemispheres (3D) and is shown to be more precise, CUR226 is not yet standardized in Europe, but being fully compatible with Eurocode it has every chance to become more widely used in the future. [13]

3.3 Other methods

A number of design methods may be used apart from the two previously mentioned ones, EBGEO from Germany and BS8006 from Great Britain are both internationally accepted guidelines. EBGEO is based on a similar membrane theory to the Dutch method and uses different safety factors depending on design situation. It goes through the calculation process using characteristic values; design value is the end result. [12] BS8006 is part of the British geotechnical standard and it is often critiqued for not being accurate enough; the result is often overdesigned. Load distribution is calculated as a proportion without a direct equation for geogrid load. With the use of safety factors, a safe design is achievable, however, improving calculation process is needed in the long run. [14]

4 Example project

As previously mentioned, the two design methods are to be compared through an example. For that, an example project is described, where a piled embankment had to be constructed because of the thick peat layer underneath design area. Geometry, soil strata are given and are the same in both designs. A several meters thick organic peat layer was found in the area, thus serious reinforcement and a strong foundation system was needed. Designers eventually decided on constructing a piled embankment with a granular, geosynthetic reinforced LTP. Two different version of those designs are shown here.

4.1 Input data and parameters

The embankment is supported by RI elements with a spacing of 1,40m in both directions. The diameter of elements is 0,40m while the embankment is 3,20m high. Thickness of LTPs is dependent on several different factors but estimating a 1 m thick platform could be a safe staring point in most cases. Physical properties of soil layers have been determined based on the results of CPT tests but are not described in detail here. Most problematic has been the organic peat layer that is approx. between 2 and 6 meters down from ground level. Apart from that, medium or even good quality silty-sandy soils are present in strata.

4.2 Design with beam method

When using Collin's method, initial data includes mostly geometric values like pile spacing, diameter and distance between reinforcement layers. Input data does not include allowable tensile force in any form - the assumed elongation must be decided in a deterministic way. Result of the calculation is tensile force at that elongation (usually 2%) and the appropriate product can be chosen accordingly. Based on design principles, reinforcement layers do not lie directly on each other, they are at 10-25 cm distance vertically. In this particular case, three layers of reinforcement are needed: different EnkaGrid MAX products. It is however worth noting that products were chosen based on the design values of tensile forces and geogrids (using EBGEO reduction factors).

4.3 Design with CUR226

In case of CUR226, input data does not only include geometric properties, but also takes traffic load and subsoil support into consideration. As opposed to the formerly described method, geogrid type (and long-term stiffness) must be decided at the beginning. Elongation is one of the calculative results and the designer is able to decide whether it is in the allowable range or not. Another major difference is Dutch method only using two uniaxial grids that are perpendicular to one another. CUR226 uses various safety and reduction factors, calculates the arc height to determine if full arch is possible in the LTP and makes a clear load distribution between piles, geogrids, and subsoil. The details of the design guideline are, however, not the focus of current paper. Calculation results include long term tensile force which was much higher than in case of beam method design, thus needing stronger geogrids for an equally safe system. Differences are justified by different behavior approaches: it is natural to have larger elongations in tensioned membranes than in case of a stiffened soil beam.

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4.4 Calculation results

Both reinforced cross sections are seen on Figure 5. Differences in geogrid location are easy to observe: the beam method design separates the grid layers with a ~25 cm thick layer of compacted fill, while in case od CUR226, they are both lain on the top surface of rigid inclusions - perpendicular to one another for optimal lead bearing.

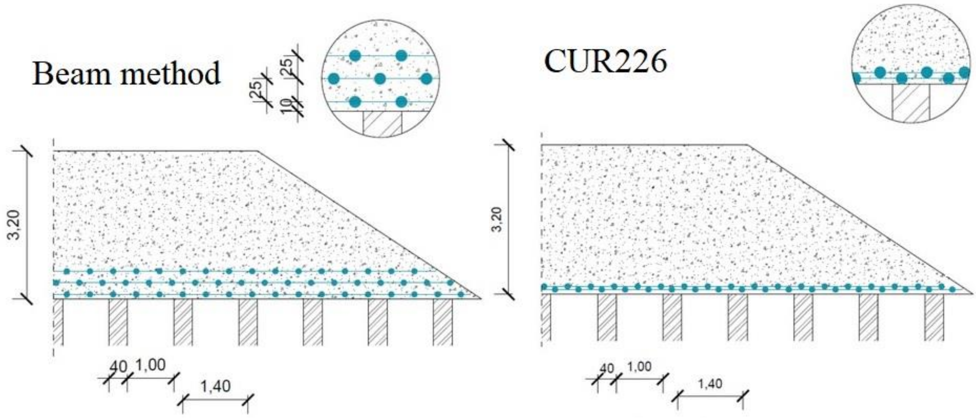

Fig. 4.-5. Reinforced cross section with both design methods

Relevant parameters and quantities of EnkaGrid geogrids used (in both designs) are to be seen in the Table 1. The overall required geogrid quantity for the beam method is higher; they are, however, lower in price.

Table 1. Parameters of geogrids in design

	Beam method			**CUR226**
	MAX 40	**MAX 60**	**MAX 80**	**PRO 180**
Nominal tensile strength [kN/m]	40	60	80	180
LTDS [kN/m]	7,51	11,73	16,89	65,68
Quantity for 5km embankment [m^2]	122 000	128 000	133 000	208 000

5 Conclusion

The main focus of this paper is embankment foundation on soft, compressible subsoil. In the first part, various possible solutions were described, including PVDs and GCEs. Usage of Load Transfer Platforms in piled embankments is increasingly important due to the fact that they make unreinforced piling possible. LTPs may be designed using several different methods, two of which were compared in this paper. Collin's beam method assumes a stiff *soil-beam*, while the Dutch CUR226 is based on the tensioned membrane theory - their different approaches both provide a safe solution. CUR226 is considered a moderner, more reliable theory that is closer to reality while being on the safe side. Lack of safety factors in the beam method has gained international unpopularity as did the fact that results are not dependent on structural load at all. (Outer loads are assumed to be carried by piles alone.) [10] Beam method needs a larger quantity, albeit weaker quality, cheaper geogrids - from an economical point of view, it is more advantageous. The installation is however quite complex with the thin, individually compacted layers between each geogrid. Dutch method is meanwhile much simpler to implement and looking at the big picture, it is the more cost-efficient choice of the two. To summarize, while both methods have advantages, the Dutch guideline is considered moderner and has been proven to work well.

A comparison of a handful of aspects (cost-effectiveness, constructability, partial factors, and others) can be seen in Table 2.

Table 2. Comparison of described methods

	Beam method	**CUR226**
Design approach	stiffened beam	tensioned membrane
Way of thinking	fixed elongation → calculated tensile force	fixed tensile stiffness → calculated elongation
Calculation model	simple	more complex
Complexity of construction	labor-heavy	much simpler
Safety and reduction factors	none at all	factors aligned with Eurocode 7
Required quantity	~ 383 000 m^2	~ 208 000 m^2
Expected cost	lower (cheaper materials)	higher (more expensive materials)
Accuracy	less accurate and modern	more accurate and accepted

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