Using the method of vertical reinforcement for design of the soil base

Konstantin Stepanischev and Vitalii Sidorov
Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

Abstract. In this paper, the method of vertical reinforcement of the base with reinforced concrete elements is considered, applied at a real site in Ekaterinburg. The construction site is characterized by difficult engineering and geological conditions due to the uneven occurrence of eluvial and rocky soils of variable thickness, as well as the presence of specific soils within the soil massif. The imperfection of the normative documentation, based on the lack of knowledge of this method, makes it difficult to design these foundations under load. Frequent comparison with structures typical for traditional pile foundations leads to problems when justifying this method in local authorities of state expertise and sometimes does not take into account the uniqueness and economic efficiency of this topic. The advantages and disadvantages of this method are highlighted when using it in the design of a real object.

1. Introduction
Progressive construction, due to the growth of the population and the requirements of the modern world for the development of underground and aboveground space, inevitably has a significant impact on the existing ground conditions of construction areas. The growth of the number of storeys, respectively, and an increase in load on the foundation soil, the use for construction sites with weak and saturated specific primers, the presence of local areas with lenses and layers of soils having low strength and deformation characteristics, almost always are inclined to the choice of expensive types of foundations (pile, deep foundations) and eliminated the possibility of use as a basic foundation on natural ground (foundation slab). In this regard, the urgency of searching for alternative, optimal and cost-effective solutions for ground bases and foundations according to these design conditions is increasing. One of the ways to do this is to reinforce the soil mass with vertical reinforcing elements.

Currently, the use of vertical reinforcement on real construction sites has a number of difficulties and disadvantages, based on insufficient knowledge and little experience in designing and building on reinforced soil massifs. The lack of regulatory documentation and the design and construction methods used, which are typical for well-studied traditional pile foundations, do not reflect the distinctive feature of reinforced foundations under load and the economic benefits of their use. When using more cost-effective solutions, difficulties arise when justifying and choosing the optimal reinforcement parameters.

This article describes a real construction object designed on a reinforced ground base made of driven reinforced concrete piles. The article describes the identified advantages and disadvantages of the vertical reinforcement method for construction conditions in Ekaterinburg.
2. A review of the literature and normative documentation
The development trends of modern foundation engineering are sought to find optimal and cost-effective solutions for ground base and foundations. One of the promising areas in geotechnics is the reinforcement of soil massifs with different elements of variable stiffness.

In the current regulatory documents up to 2016, the topic of soil reinforcement was considered only indirectly, and only in the updated edition of SP 22.13330.2016 [4] were reflected some fundamental points characteristic of many areas of geotechnics, which do not consider in detail the uniqueness of this topic. However, this section left many questions regarding the design and construction of these arrays.

The use of the base reinforcement method has a long history, confirming and proving the possibility of using this technology on real construction sites, and is aimed at improving the existing characteristics of the subgrade.

In SP 22.13330.2016 [4], soil reinforcement refers to a method of transforming the properties of a soil massif by introducing special elements into it that improve deformation and strength characteristics, and is subdivided by the nature of the arrangement of reinforcing elements, by the material of the elements, by the method of work. As such elements in modern practice, vertical reinforced concrete elements, represented by piles of different types, are very often used.

A vertically reinforced base is a system of interaction of groups of vertical elements with a soil mass. The device of reinforcing elements in a soil environment can be carried out both by driving reinforcing elements and by installing them in pre-fabricated wells (bored and rammed piles). At the same time, the rigidity of the reinforcing elements is much higher in comparison with the surrounding soil mass [2,3,4].

The technology of vertical reinforcement is much more economical than vibration-impact soil hardening technologies (ramming, vibro-rolling), and slab foundations on vertically reinforced foundations are more economical than pile and deep foundations. The method of vertical soil reinforcement makes it possible to strengthen ground bases of slab foundations to the predetermined required soil properties (E, φ, c). Reinforcing elements are improved the deformation properties of the base, interacting with the soil along the lateral surface and at the level of the tip [5,6].

The transfer of loads from the structure to the ground base is carried out through an intermediate ground cushion made of a layer-by-layer compacted material (for example, sand, PGS, granite rubble) [7,8]. It should be noted that the working conditions of the reinforced soil massif differ from the both bases of pile, slab and shallow foundations.

Despite the advantages of this type of foundation, the topic of vertical soil reinforcement remains open, has difficulties and requires detailed study for large-scale use in open areas.

Below is a description of the actual construction site in Ekaterinburg, where the method of vertical reinforcement from driven reinforced concrete piles of variable length was applied.

3. Search optimal design solutions for foundations
The construction site is located in Ekaterinburg within the mountainous and hilly terrain of the Central Urals. The overall smoothed terrain is broken by deeply cut river valleys.

The territory is characterized by the occurrence of eluvial and rocky soils. A characteristic feature of these soils is their uneven location within the site both in depth and in plan, which is confirmed by the results of engineering and geological surveys. The boundary between soils can rise to the earth's surface or sink to a depth of several meters.

According to the report on engineering and geological surveys, specific soils are developed on the construction site, represented in the section by bulk and eluvial soils.

The conditions of occurrence and distribution of these soils are reflected in the characteristic engineering-geological section shown in figure 1.

Bulk soils are man-made formations – mostly displaced soils, the degree of compaction – weight-not caked.

Specific features of eluvial soils are included:
- their significant heterogeneity in depth and plan due to the presence of soils of different degrees of weathering with a large difference in their strength and deformation characteristics;
- reduction of strength and deformation characteristics during their long stay in open pits or when the territory is flooded.

Eluvial soils have fairly high strength characteristics and are represented by loamy and sandy soils. At the same time, semi-solid eluvial loam (IGE-2) has low deformation characteristics. The modulus of deformation of IGE-2 is 14 MPa.

The conducted studies for rock soils have shown that these rocks have low strength characteristics, weak and medium-grained, and strongly cracked. The uniaxial compressive strength ranges from 0.4 to 9.2 MPa, depending on the engineering and geological elements.

![Figure 1. Characteristic engineering-geological section](image)

The calculation results of the slab foundation on the natural base have shown that the uneven occurrence of eluvial soils, their variable capacity across the construction site, as well as the uncertainty of the roof rock has a significant influence on deformations of building’s foundations and their design. These prerequisites predetermined the choice of the type of foundation for this construction object.

Two types of foundations were considered as an alternative: a pile foundation and a slab foundation on an artificial bases made of driven reinforced concrete piles.
The reinforced base with piles was a "structure-reinforced base" system. This base was included the device of vertical elements in the form of reinforced concrete driving piles from 4 to 6 m long, on top of which an intermediate (distribution) sand cushion with a thickness of 1000 mm was arranged.

The pitch of the piles in the transverse and longitudinal directions was 1, 5x1, 5 m. The scheme of the reinforced base with vertical reinforced concrete elements is shown in figure 2, 3.

**Figure 2.** The scheme of the pile field for the method of vertical reinforcement of the ground base with vertical reinforced concrete elements, applied on a real site in the city of Ekaterinburg.

**Figure 3.** Geotechnical model of reinforced base
Due to the lack of geological data, namely a small number of wells in the conditions of uneven and unpredictable occurrence of rock and eluvial soils on the construction site, the design organization decided to make a trial immersion of piles to correct and optimize the initial design decisions.

The results of the trial driving of the piles confirmed the unevenness of the soil occurrence within the entire construction site and identified the zones of possible adjustment of the pile lengths and spacing. During subsequent tests of the piles with static and dynamic loads, the nature of the behavior of the piles under load was revealed (the piles behaved like end-bearing pile). The absence of residual deformations in the typical diagram «load-settlement» indicated the elastic operation of the piles under load, which was confirmed by a large number of pile tests.

In three-dimensional modeling of two variants of a soil bases, interacting with a pile foundation and a slab foundation on a reinforced bases, the calculation results confirmed the possibility of their use at the construction site. However, in the case of using a pile foundation, made of end-bearing pile, large bending moments were formed in the foundation slab and the supporting aboveground structures of the building, which greatly affected the economic part of the project (it was necessary to use additional reinforcement of the structures).

All of the above prerequisites determined the choice of a slab foundation on a vertically reinforced bases, made of driven concrete piles.

4. Analysis of the use of a vertically reinforced base on a real site in Ekaterinburg

Using the vertical reinforcement method on a real site in the city of Ekaterinburg showed the possibility of using this type of ground base on a site with complex engineering and geological conditions. In this case, the deformations caused by the uneven occurrence of rocky and eluvial soils and obtained from the results of numerical modeling turned out to be less than the limit values and did not affect the operational suitability of the building as a whole (Figure 4). This is the most important result that design organizations are striving for and all current regulatory documents are directed.

Despite such a positive effect, the method left many contradictions in substantiating this type of basis in the state examination bodies. The uniqueness of the methodology, based on the possible economic effect and ease of use, was complicated by experts' references to a well-known and studied pile foundation made of driven piles. A slab foundation on a vertically reinforced foundation was considered as a pile foundation without connecting the reinforcing elements into a foundation slab, which resembled a hinge joint. The length of the piles was taken depending on the depth of the piles in solid soil layers while ensuring the required bearing capacity, the step was taken no more than 5-6 pile diameters. The only difference was the presence of a buffer layer of soil in the form of a sand cushion, located between the foundation slab of the building and the pile heads.

All these methods, on the one hand, simplified the design methods and understanding of the work of the reinforced base under load, but at the same time negatively affected the economic part of the project (with the possible use of a pile foundation, a reinforced base was used with the same number of piles, their pitch and lengths with an intermediate sand cusion).

If we turn to the definition of reinforced foundations, we can find that the reinforcement of the soil with any elements is necessary to increase the load-bearing capacity and reduce the deformability of the soil base, which implies a way to increase the strength and deformation characteristics of the soils themselves to certain values that ensure the integrity and safety of the building. This means that when using certain reinforcement parameters, you can achieve this condition at the lowest cost.

Not always a re-reinforced base in the form of a pile foundation, subjected to the requirements of the norms, brings favorable results. In many cases, the use of a pile foundation leads to huge reserves due to small deformations of buildings at much higher limit values.

When we are using a reinforced base, it becomes possible to obtain optimal parameters for the subgrade, in which the soil will be included in the work most fully with the least amount of reinforcing elements. Many studies in the case of vertical reinforcement with reinforced concrete piles show the possibility of using a rarer pile spacing, reaching the value of 9-11d piles, which is almost twice the requirements typical for the design of traditional pile foundations [2,3,5,9]. The regulated length of the
piles according to SP 24.13330.2011 [1] can be replaced by the optimal one with the required strength gain and reduction of deformations of the reinforced base. Also, the zonal arrangement of reinforcing elements with an increase or decrease in the pitch of the piles in the case of occurrence of more durable or low-strength base soils, their local application makes it possible to apply reinforcement where it is necessary, without being tied to the building foundation.

At the same time, it is necessary to take into account the distinctive work of vertically reinforced massifs from alternative options for bases and foundations. The presence of a buffer layer of soil (soil cushion) as a distribution layer, variable stiffness of reinforcing elements and soil, the work and interaction of neighboring cells of reinforced base under load undoubtedly has a significant impact on the formation of an excellent stress-strain state of a solid soil base from other types of foundations.

Based on the totality of the materials considered, the number of studies in this area and the identified problems, the topic of base reinforcement can be characterized as relevant at the present time, but requiring development and modernization. Additional research is needed to scientifically confirm the data and other possibilities of vertical soil reinforcement to achieve the most optimal, safe and beneficial effect with the further inclusion of the results in the main regulatory documents.

![Figure 4](image.png)

**Figure 4.** Isofields of vertical displacements of a soil base located in Ekaterinburg, for the case of using a slab foundation on a reinforced base made of driven reinforced concrete piles of variable length.

5. Conclusion
The method of vertical reinforcement of the soil base with vertical reinforced concrete elements has a wide perspective when it is implemented on real construction sites. Despite its ease of use and an established mechanism for the production, manufacture and arrangement of the main elements, the economic effect (in the case of using a larger pitch of elements, and, accordingly, a smaller number of reinforcing elements, a shorter pile length), this method has difficulties when justified in local authorities of state expertise. Insufficient justification in the current regulatory documentation and the use of design methods similar to traditional pile foundations often do not make it possible to use the method of vertical reinforcement in the construction of buildings in full, which is associated with a low level of knowledge and entails economic losses during its application.
Existing literary sources on this topic indicate the distinctive features and purposes of this method in comparison with pile foundations. The aim of the vertical reinforcement method is to improve the building properties of soils to predetermined values at which the serviceability of the building is ensured. At the same time, it is possible to strengthen the required part of the subgrade provided that relatively equal characteristics are achieved within the massif due to the reinforcement parameters. These parameters include the step, the length of the element, the thickness of the distribution layer of soil (cushion).

This article describes a real construction site in Ekaterinburg with the justification of the chosen methodology for designing a reinforced base. A comparison was made of two typical options for foundations - a pile foundation and a slab foundation on a vertically reinforced base of driven reinforced concrete piles. The choice of a reinforced base is due to the presence of unevenness and unpredictability of the occurrence of eluvial and rocky soils, in which the piles (according to the results of test driving) work as end-bearing pile and have a significant impact on the main bearing structures of the building (in the case of a pile foundation). A flexible base, created by the use of a sand cushion, reduces bending moments in the foundation slab and the building’s bearing structures.

The topic of vertical reinforcement is a promising direction in geotechnics and requires detailed consideration before large-scale application on real construction sites. It is necessary to study in detail the unique and characteristic features of this method with their further inclusion in the main regulatory documents.

References
[1] SP 22.13330.2016 «SNIP 2.02.01-83* Osnovania zdani i soorugenii «Aktualizirovannaya redaksiya» 2016.
[2] Mirsoyapov I T, Popov A O 2008 Izvestia KazGASU Experimental basic research the work of the reinforcement maccife 2, 10 75-80.
[3] Nipun Insoog, Suriyavut Pra-ai, Chaisit Pengjan, Palinee Sumitsawan, and Orianne Jenck 2020 International Journal of GEOMATE Investigation of physical model on soft soil reinforced by rigid inclusions under cyclic loading 19 37-43.
[4] Gorbunova M A, Kleveko V I 2020 Master's Journal Analysis of methods of strengthening of the soil foundation by using vertical and horizontal reinforcement 1 149-155.
[5] Popov A O 2015 Ingenerno-stroitelnii jurnal Settlement calculation of clay bed reinforced with vertical elements 4 19-27.
[6] Kravcov V N, Yakunenko C A, Lapatin P V 2015 Vestnik Polockogo Gosudarstvennogo Universiteta Research of vertical reinforced by soil-concrete micropiles slab foundations’ ground bases and testing results in industrial practice 16 40-47.
[7] Marinichev M B 2015 Nauchnii jurnal KubGAU Practical implementation of vertical reinforcement for nonhomogeneous bases as a method to reduce non-uniform deformability of subsoil and compensate seismic loads to upper structure 64 1-15.
[8] Safin D R 2008 Izvestia KazGASU Study of deformability of vertically reinforced water-saturated argillir soil bodies 2, 10 81-84.
[9] Hou Juan, Zhang Meng-xi, Dai Zhi-heng, Li Jia-zheng, Zeng Feng-fan 2017 Geotextiles and Geomembranes Bearing capacity of strip foundations in horizontal-vertical reinforced soils 1 29–34.