Ground improvement by vertical band drains and controlled modulus columns

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Abstract. The company FM Logistic plans to build a warehouse about 40 km at east of Moscow. Total area of the future project is 149 615 m\textsuperscript{2}. Compressive soil layers have been identified by the soil investigations. The main purpose of this article is to illustrate soil improvement solution in order to ensure the bearing capacity and to limit the absolute and differential settlement to allowable values.

1. Introduction
The FM Logistic group intended to build a 72,700 m\textsuperscript{2} logistics platform in Elektrougli (50 km from Moscow), which consists of 7 warehouses and 2 sprinkler tanks. The total area of the building site is 75,700 m\textsuperscript{2}, including highways and landscape area. From a geotechnical point of view, the following criteria were set in the project: operating load on the slab: 50kN/m\textsuperscript{2}; the maximum load on the foundations for individual supports is 2600 kN. Rather stringent criteria in the project were set for the ultimate deformations of the soil foundation, for example: the absolute values of the settlement should not exceed 50 mm, the limiting differential in settlement between two adjacent foundations for the columns should not be more than 25 mm, the permissible residual settlement under the highways was not more than 150 mm. Currently, in the practice of geotechnical construction, a lot of attention is paid to improving soils in difficult engineering and geological conditions \[1\]. Researchers in many countries and research centers have been involved in improving soil foundations \[2\] to \[5\]. The environment of the most significant works on this research topic can be attributed to the work of Jérôme Racinais, Menard France \[6\].

2. Geotechnical conditions
Geotechnical surveys at the construction site were carried out several times by various organizations in 2006, 2010 and 2012. The geotechnical conditions of the construction site were complicated by the presence of large layers of weak soils (flowing clays and peat) with very low mechanical characteristics. Typical geotechnical geological profiles are shown in figure 1. The first geological profile shows that approximately 6m thick very soft clay, including peaty layers, followed by a 1.5 m thick sand layer of good mechanical properties, laying on very stiff clay. The second geological profile shows that approximately 7m thick very soft clay, including peaty layers, laying directly on very stiff clay. The intermediate sand layer has either insufficient mechanical properties or insufficient thickness to play a role as bearing layer. The main calculated physical and mechanical characteristics of the base soils, obtained from the data of the mine and geological surveys, are summarized in table 1. The
The groundwater level at the site was recorded at a depth of 1-2 from the surface of the earth. In figure 3 shows the results of static sounding of soils (CPT tests). Analyzing the presented results of engineering and geological surveys, one can summarize the fact that the construction site is represented by highly compressible soils, which require a special technical solution for the implementation of the construction project.

![Soil profile 1](image1.png) ![Soil profile 2](image2.png)

**Figure 1.** Two characteristic geological profiles.

**Table 1.** Physical and mechanical characteristics of the soils of the construction site.

| Characteristics | 1 (very soft clay) | 2 (peat) | 3 (very soft clay) | 4 (sand) | 5 (very stiff clay) |
|-----------------|-------------------|---------|-------------------|---------|-------------------|
| $E_M$ (kPa)     | 700               | 250     | 700               | 13 200  | 13 000            |
| $\alpha$        | 2/3               | 1       | 2/3               | 1/3     | 1                 |
| $E_y$ (kPa)     | 1 050             | 250     | 1 050             | 39 600  | 13 000            |
| $P_l$ (kPa)     | 100               | 30      | 100               | 1 100   | 750               |
| $C_c$           | 0.315             | 1.2     | 0.315             | /       | 0.266             |
| $C_s$           | 0.0315            | 0.12    | 0.0315            | /       | 0.0266            |
| $e_0$           | 1.135             | 3.0     | 1.135             | /       | 0.99              |
| POP (kPa)       | 50                | 0       | /                 | /       | /                 |
| OCR             | /                 | 1       | 1.5               | /       | 1.8               |
| $\gamma$ (kPN/m$^3$) | 17       | 15      | 17                | 20      | 18.1              |
| $c'$ (kPa)      | 5                 | 2       | 5                 | 1       | 5                 |
| $\phi'$ (°)     | 19                | 15      | 19                | 34      | 31                |
3. Solutions. Proposed approaches for project implementation

As noted above in the article, the construction project included the construction of two warehouses and the arrangement of a parking zone with internal roads for technological needs. Therefore, in the future, we will consider separately the proposed geotechnical solutions for the warehouse section and the road section, taking into account the specified limiting deformations of the subgrade.

3.1. Roads / Parkings

According to the requirements of the project, the maximum settlement of the road surface and parking lot should not exceed 150 mm. To solve this problem in order to accelerate soil consolidation, it was proposed to use vertical band drains (figure 3). In order to accelerate the consolidation of soils, it was proposed to pre-compact the soil base of additional embankments with a height of 1.9 m to 2.85 m, depending on the profile-geological analysis. Pre-consolidation was carried out within 2-4.5 months. Settlement monitoring, consisting of settlement plates, has being implemented to test the soil consolidation. The sequence of work performed is shown in figure 4 and 5. The drains’ length varies from 3.5 m to 6m depending on the depth of clay layers. After 3 months with a 2.85m preloading and a grid of drains of 1.8 m × 1.8 m. The soils have degree of consolidation 77% that gives a preloading settlement of 40 cms. After 4.5 months with a 1.95 m preloading and a mesh drain of 1.8 m × 1.8 m the soils have a consolidation degree of 89% that gives a preloading settlement of 40 cm. And after 2 months with a 2.85m preloading and a mesh drain of 1.5m × 1.5 m the soils have a consolidation degree of 77% that gives a preloading settlement of 40 cms too.

Thus, we can conclude that vertical drains associated with a total temporary surcharge of 2.85 m or 1.95m will limit the residual settlement of the roads and parking’s area to allowable value (less than 150 mm). Thus, for accelerated consolidation of the soil, 22,800 vertical band drains were install on the construction area of 75,700 m.
**Figure 3.** Vertical Band Drain rig.

**Figure 4.** Construction phases on the site with preliminary compaction with embankment 2.85 m high.
3.2. Warehouse

The warehouse includes two foundation types: a central slab and the footings. As developed above two soil profiles are considered, so two analyses for each foundation case. In order to satisfy the project settlement criteria, the ground under the warehouses is reinforced by Controlled Modulus Columns - CMC (figure 6) [3]. The CMC are either anchored 50cm in the 1.5 m sand layer (Soil profile 1, figure 1), or in the very stiff clay whenever good properties are encountered, between 9 and 14m (Soil profile 2, figure 1). For a technical and financial optimization, CMC lengths have been adjusted following the geological conditions encountered on site.

Columns with a controlled module (CMC) with a diameter of 280 mm were arranged over the entire area of the warehouse, filled with well-granulated material. The grid install between the
columns was 1.4 × 1.4 m. On top of the columns, a Load Transfer Platform (LPT) for transferring the load with a thickness of 1.63 m was designed and covered by a monolithic slab with a thickness of 0.2 m (figure 7).

![Figure 7. Under the slab.](image)

The design of CMC has been carried out based on Plaxis finite element calculations [7]. Total vertical displacements do not exceed 4.7 cm and are thus in acceptable range (lower than 50 mm). The maximal effective vertical stress in the CMCs is 2.70 MPa and complies with the strength of the selected concrete of Ultimate Compressive Strength (16 MPa). The additional bending moment in the slab created by the CMC is negligible due to the important thickness of the Load Transfer Platform.

Depending on the load transmitted by the structure, one or more CMC will be installed under the isolated footings. No Load Transfer Platform is needed between the footing and the CMC head; the footing will directly rest on the CMCs. Depending on the geological conditions (see figure 1), two design schemes were proposed. One of them is shown in figure 8. In total, 13 types of supports were designed, taking into account the transfer of allowable pressure to the ground not more than 250 kPa.

![Figure 8. Design scheme for the foundation on CMC for profile 1 (see figure 1).](image)
The determination of the number of CMCs to be installed under such footing is performed thanks to a Menard Excel program based on the Pressumeter theory and on the Combarieu method [4]. The calculation method is well detailed in the French recommendations on Rigid Inclusions ASIRI, which was published in June 2012. As a result of the performed calculations, it was found that calculated settlements do not exceed 1.0 cm, which is fully within acceptable range. Due to very limited absolute settlements, there is no risk of significant differential settlement between two adjacent shallow foundation.

4. Conclusion
Improvement of subsoil by the method of vertical band drains, as well as columns with a controlled module (CMC), has shown its high efficiency in difficult soil conditions represented by weak clays and peat.

The decision made made it possible to significantly reduce the investor's funds in comparison with the known construction methods on these soils, for example, such as long reinforced concrete piles and soil replacement with deep excavation.

The performed analytical calculations, as well as the use of the finite element method, showed that the proposed solutions significantly reduce the deformations of the base, and the calculated settlements do not exceed the limiting values.

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