The Effect of Determination of Ground Conditions on Expressway Embankment Foundation

Stanislaw Majer

1 West Pomeranian University of Technology Szczecin, al. Piastów 50, 70-311, Szczecin, Poland

stanislaw.majer@zut.edu.pl

Abstract. Proper identification of ground conditions is one of the most important stages of preparing building documentation. This stage becomes even more important when there are organic soils in the building site. The article discusses a case study of the foundation reinforcement of the expressway embankments with existing thick organic soils layers underneath. This investment was carried out in the "Design and Build" formula. Therefore, the materials made available by the Investor at the stage of preparing the offer determined the method of strengthening the weak substrate by the Contractor. Since the basic criterion for selecting the offer to complete the investment was the price, the choice of the reinforcement method had an impact on the overall cost of execution. This problem concerned about 730 m of an expressway passing through the valley. The height of the embankments was from 3 to 5.5 m, the area of the embankment's base was about 26 500 m² and the average depth of occurrence of weak soils was 10 m. The situation was additionally complicated by the bridge located in the missile of the section, that was based on driven piles. In the described case, the depth of occurrence of the support substrate was determined correctly, inaccuracies occurred when determining the type of organic soils and, above all, determining their state and shear strength. An additional wide range of field and laboratory tests performed during the implementation of the project, commissioned by both the contractor and the contracting party, has changed the method of ground reinforcement. The original Controlled Modulus Columns with a diameter of 40 cm in a triangular spacing with a length of over 90,000 m have been changed to precast reinforced concrete piles with a 40 x 40 cm cross-section in a square spacing with a total length of more than 57,000 m. The head of the columns was finished with a 30 cm C30/37 reinforced concrete slab instead of a transmission layer of aggregate and geosynthetics.

1. Introduction

Low-bearing soils exhibit low compressive strength and high compression. These include organic soils, with organic content of more than 2%. Organic soils exhibit high plasticity, low strength and high compression. These parameters depend primarily on the high hydrophilicity of the organic content [1]. The most common organic soils in the Central European Plain include peat, gyttjas and warp. Peat is a soil formed from the dead and gradually charred parts of plants as a result of the peat process taking place under specific water, air and microbiological conditions. The characteristic feature is the fibrous, porous and high humidity structure and texture. The content of organic substances \( I_{om} \) ranges from 30% to 80%.
Gyttja are Holocene organic lake sediments. Majorly a dark, biogenic lake or swamp sediment composed of plant detritus, in a varying degree of decomposition, containing >5% calcium carbonate. Warps are soils formed by the deposition of mineral and organic substances in the aquatic environment. The presence of those types of soils causes many problems during the foundation of the buildings under construction. In case of the construction of motorways and expressways, it is common that those areas cannot be avoided due to routing and extensive geometric parameters of designed roads. Therefore, it is extremely important to correctly determine the geotechnical parameters of the ground as the basis for designing road embankments.

2. Section parameters, initial geotechnical determination

Analysed case regards a section of the expressway. The investment was carried out in the "design-build" formula. For the needs of the investment, a design and spatial concept was developed together with the geological and engineering documentation prepared within the framework of the project. The geological-engineering documentation was indicated as mandatory in the functional-utility program.

The documentation shows the presence of organic soils on the length of about 730 m of the expressway near the Brodziec River, where a road bridge with a passage for animals has been built. The identification of the remaining organic soils was mainly based on core drilling and macroscopic studies. This allowed to determine the areas with a maximum of 10 m layers of organic soil and the basic parameters such as humidity (\(w_o\)) or the organic content (\(I_{om}\)). In the analysed section 24 boreholes were drilled for determination of organic soils. Samples were taken from the bridge area for two different soil: \(w_o=70.2\%; I_{om}=28.8\%\) and \(w_o=192.8\%; I_{om}=72.4\%\). The strength and deformation parameters for the weak soil layer were not determined.

At the stage of the program-spatial concept, it was planned to use indirect road embankment foundation with the use of concrete columns. The technology of Controlled Modulus Columns (CMC) consists of the following stages:

− execution of the working platform,
− execution of displacement columns,
− execution of the transmission layer,
− execution of the embankment in accordance with the road design.

The load-bearing capacity of individual columns were calculated taking into account the value of the assumed limit resistance in the base of the pile \(q_c\), amounting to 6.3 MPa. This value corresponds to
medium compacted sands with $I_d=0.4$. The columns with diameter of 0.4 m at a triangular spacing of 1.6 m were chosen. Reinforcement was designed for the area of 26,120 m$^2$ using 11,782 columns of total length of 119,122 m.

3. Evaluation of soil-water conditions during the design stage

The construction of the analysed section was carried out in the design-build formula. The General Contractor commissioned additional tests in problematic places, including the analysed section. Additional CPTU probing and laboratory tests were carried out. It was found that the thickness of organic soil layer is higher and amounts to 12.2 m. The value of $I_{om}=67.44\%$ was assumed for peats with undrained shear strength of $S_u=10$ kPa and strain modulus of $M=300$ kPa. The values for warps were assumed as: $I_{ow}=7.02\%$; $S_u=20$kPa, $M=850$ kPa. The values for gyttia were determined as: $S_u=10$kPa, $M=720$ kPa.

On this basis, the Contractor decided on additional tests by an independent unit. Laboratory tests, embankment base contouring, CPTU probes and Electrical Resistivity Tomography (ERT) were carried out. It was found that there are organic sediments, originating from the backwater reservoir, in a form of lake and swampy sediments that are located under the embankment of the expressway. The lake sediments in the studied ground were gyttjas and locally occurring lake muds, which, depending on the content of organic parts, were described as clayey warps or humus dusts. The layers above were formed from peats. Gyttja exhibited a relatively low content of calcium carbonate, which lead to believe that the sediments were formed in a dystrophic environment, poor in oxygen and nutrients. For this reason, the lake chalk, generally characteristic for this type of sedimentation of low peatlands, did not develop.

The parameters of organic soils are presented in Table 1. Physical-mechanical properties of the examined soil layers were determined with Cone Penetration Tests (CPT). Undrained shear strength was determined on the basis of Schmertmann's formula [2]:

$$S_u = \left( q_c - \sigma_{vo} \right) / N_{kt}$$

|                | $I_{om}$ | $w_n$  | $S_u$   | $M$     | $I_L$ |
|----------------|---------|--------|---------|---------|-------|
| Peat           | 21.9-90.6 | 122-583 | 1.2-5.0 | 100-250 | 1.0-1.2 |
| Warp           | 8.4     | 126    | 0.2-10  | 100-600 | 0.796 |
| Gyttja         | 2.0-5.4 | 64-100 | 1.5-9.0 | 100-450 | 0.7-1.7 |

Due to the fact that certain mechanical parameters of organic soils were exceptionally low, the Investor commissioned a geotechnical expert opinion in order to verify soil and water conditions in the analyzed area and to prove correctness of the conducted research and measurements. As part of the expertise, the following tests were carried out:

- 6 test holes - depths from 14.0 m to 15.0 m,
- 10 CPTU probing - depths from 9.4 m to 18.0 m,
- 5 tests with Marchetti DMT dilatometer - depth from 9.0 m to 10.0 m,
- 5 FVT cross probe probing - depths from 7.5 m to 9.5 m.

The CPTU probing was used to determine the undrained shear strength. In accordance with [3] they were not used to determine the deformation parameters. The value of $N_{kt}$ coefficient was determined on the basis of correlations with the results of shear strength tests determined with the FVT cross probe. The $N_{kt}=10$ was assumed for peat, while $N_{kt}=6$ and $N_{kt}=9$ for gyttja in higher and lower parts respectively. The tests with Marchetti DMT dilatometer were performed on the basis of CEN ISO/TS 22476-11 Geotechnical investigation and testing - Field testing - Part 11: Flat dilatometer test. The compression modulus $M$ was determined with the dilatometer module $E_0$ from the formula:
\[ M = R_M E_D \] (2)

Where for gyttja and peat:

\[ R_M = 0,12 + 1,8 \log D \] (3)

In case when RM was lower than 0.85, the value of 0.85 was assumed. The tests carried out confirmed the significantly lowered strength and deformation parameters concurring with previous findings.

4. The expressway embankment foundation

At the concept stage, as already mentioned, the use of Controlled Modulus Columns was planned. This technology is characterized by increased speed of construction, lack of excavated material and small settlements. Therefore, it is frequently used for strengthening the ground for road embankments. However, it has also some restrictions that can be found in the EN 12699:2015-06 - Execution of special geotechnical works. Displacement piles. In case of soils with a shear strength lower than 15 kPa, it is recommended to use the stay-in-place pipe or cover, as there is a risk of concrete mixing with the soil during casting that might cause discontinuities. In addition, according to the Eurocode 7, piles installed in the soil with a shear strength \( S_u < 15 \) kPa should be calculated for buckling.

Due to the fact that the contract for the construction of the expressway includes a guarantee period of 10 years, there was a need for a change in the technology of soil reinforcement under the embankment. The Investor recommended technical and economic analysis of several methods. The deep replacement of organic soils considering the area of at least 55 m and a length of about 730 m at an average depth of 7.0 m, would require replacement of about 281,000 m³ of soil. Additionally, due to the lateral inflow of liquid organic soils, the exchange should be carried out in sealed offcuts.

The use of Geotextile Encased Column (GEC) was also considered. These columns can be used as a reinforcement of the substrate for road embankments, where there are weak-bearing mineral and organic soils, even with large thicknesses. However, the parameters of these soils must guarantee the stability of the entire structure and the lack of buckling of the GEC.

The calculations indicated that the forecasted settlement of embankments may reach 23 cm and horizontal displacements up to 33 cm. Estimated consolidation time depending on the place, e.g. above the column near the embankment edge would be from 200 to 2000 days. In case of consolidation with vertical VD drainage, the maximum settlement should be about 2.0 m, while the service settlement after removal of the overload embankment during the period of use would exceed 10 cm.

Due to existence of the Brodziec river bridge that is based on the precast driven piles right in the middle of the organic soil location, there is a high chance of settlement near the bridge abutments. Technologies characterized by high service settlement and the risk of underestimation of the settlements were excluded from considerations due to the warranty provided by the Contractor. Chosen soil reinforcement method was similar to the method considered in the functional-utility program. The displacement columns were changed to precast driven piles and the transmission layer to a reinforced concrete top plate.

The foundation of the road embankment was designed with precast driven piles of 0.4 x 0.4 m cross-section and total length between 7.0÷15.0 m. The piles were made from concrete of at least C35/45 concrete. A square pile spacing of 2.0 x 2.0 m to 2.4 x 2.4 m was used. A total of 4,458 piles with a length of 57,337 m was used. The precast piles were reinforced with 8Ø12 mm or 12Ø12 mm rebar made from \( f_y = 500 \) MPa steel. Stirrups were made from Ø12mm steel bars. A 30 cm thick reinforced concrete slab was designed at the top of piles over the area of 21,850 m² on a lean concrete base with a thickness of up to 10 cm. Slab materials are listed below:
Ordinary concrete: C30/37 (6550 m³)
Lean concrete: C12/15 (2180 m³)
Rebar: A-IIIN B500SP (750 t).

For the three outermost rows of piles, the rebar in the heads was uncovered at the length of about 0.25 m (Figure 3). The slab was designed with drains in the grid of about 3.6 x 3.6 m. The drains were covered with a geo-textile filtration and separation fabric with a size of about 1.0 x 1.0 m. Drains were made of PP pipe with a diameter of 50 mm and a length of 0.5 m.

Due to the very low strength of the ground, a 1.5 m thick working platform made of non-cohesive soils was designed. It consisted of medium sand reinforced with 2 layers of PES geotextile of 100/50 kN/m strength. The first layer was laid directly on an even layer of sand, the second layer was laid in about half the thickness of the platform (Figure 2). The platform was made from the front without breaking the peat layer. The pile driver of 80 t weight, pressured the working platform with 80*9.81/(2*4.5*0.9)=96.9 kPa. The final acceptance could be only possible by achieving the load capacity of $E_{v2}>40.0$ MPa. The settlement of the platform estimated for extreme cases reached up to 80 cm. The pile driving was performed with use of additional steel plates (Figure 2).

Figure 2. Construction of the temporary platform

Figure 3. Preparation of the piles and reinforcement of the slab

5. Conclusions
The paper presents a case of an embankment foundation of an expressway that was built on very weak organic soils. Determination of strength and deformation parameters for weak-bearing layers turned out
to be crucial for the analysed case. In the case of road investments under the "design-build" formula, the preparation of initial materials at the stage of the functional-utility program has a significant impact on the value of the offer at the tender stage. The organic soils under the constructed expressway were extremely weak. There was a problem with accessing the area with specialist test equipment. Three series of field and laboratory tests were carried out by 3 different contractors to finally determine existing condition and the properties of the weak substrate. The choice of an effective and safe method of reinforcement was influenced by the nearby existing bridge over the Brodziec River (Figure 4).

![Figure 4. The view of the expressway under construction and foundation of the Brodziec river bridge](image)

The chosen method of reinforcement with the use of precast reinforced concrete piles topped with a reinforced concrete slab turned out to be fast (work on the section in question lasted about 3 months without the need for a time extension) and an effective method of reinforcement (it guaranteed no settlement of embankments on the access roads to the bridge over the Brodziec river).

References

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