Using blast energy as an effective technology to provide subgrade stability in road construction

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Abstract. Drilling and blasting technology is considered to be one of the most efficient and cost-effective ways to increase the bearing capacity of soft soils which form the subgrade of road embankments. This study investigates blast energy as a means of creating vertical sand drains in a section of Moscow-Saint-Petersburg Motorway M-11 (construction 2018) which crosses the Kolomenka River and is located in a swampy area. Geophysical and geological engineering tests were conducted, they included monitoring of pore pressure modification in soft soils as well as geodetic monitoring of settlement levels. The findings showed that the applied technology quickly allowed a large bulk of sandy soils (more than 500 thousand cubic meters) to compact in the subgrade of the road as a result of generation of excessive pore pressure. No other technology could have been used due to the presence of an embedded bulk of soft soils and swampiness of the site. Decreasing deformations of the subgrade and CPTU data revealed that the subgrade of the road embankment was compacted. This fact was also confirmed by geophysical tests. Drilling and blasting technology is very effective from an ecological and economic perspective in comparison with other technologies. In addition, this study highlights the importance of preserving swamp systems in order to protect river sources.Keywords: blast energy, drilling and blasting technology, subgrade stability, Moscow-Saint-Petersburg Motorway M-11, soft soil

1 Introduction

The high-speed motorway M-11 "Neva", which connects Moscow and St. Petersburg, pertains to the facilities characterized by presence of structurally unstable soils of different genesis in geological profile. The project for an alternative route of the existing motorway Moscow-St. Petersburg M-10 "Rossiya" had been developed for many years. In the early 1970s the initial concept of the alternative route was included in the master plan of development of Moscow and Moscow region. Then the idea of the alternative route reemerged in the early 2000s as the traffic intensiveness of M-10 "Rossiya" reached 150,000 cars per day at the standard capacity of 40,000 cars a day, it exceeded the standard capacity minimum threefold. The average traffic speed at approach to Moscow was 10 km/h maximum. Such a traffic led to the increase of the level of air pollution in the area (3-5 times)

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according to the Russian sanitary standards. In May 2005 there was the public hearing and the project obtained the required permissions and approvals which constituted the basis for construction of the high-speed motorway M-11 “Neva”. The new highway solved many problems of the Central and North-West federal districts and their most congested areas that was mainly associated with unloading of the existing motorway M-10 “Rossiya” and improving environmental condition of the area.

Engineering-geological conditions of the route are characterized by a considerable complexity, many sections caused certain problems of their engineering development due to the presence of thick peats as well as clay deposits (soft plastic to liquid consistence) in the geological profile. One of these sections is located in Tver’ region of the Russian Federation in place of the Kolomenka river crossing. The present paper deals with the features of development of this area for construction of an approach embankment to the bridge crossing.

2 Materials and methods

The section is a part of the high-speed motorway Moscow-St. Petersburg (fig.1). In administrative terms it belongs to Bologovo district of Tver’ region in place of the route crossing with the River Kolomenka across which it was foreseen to build a bridge located within its up to 200-m-wide flood area, it is annually flooded and consists of hillocks coved with dense grass and partly with cane. Within the flood area, especially near the water edge there are spots of drown rough areas as the district pertains to the zone of excessive humification, plain, with relative elevations, characterized by unsatisfactory surface discharge.

According to engineering-geological zoning the construction site is located within the engineering-geological region of the second order – Moscow tectonic depression, in terms of hydrogeology it belongs to Moscow artesian basin. Engineering-geological conditions of the bridge crossing are characterized by a considerable difficulty caused by swampiness of the site and deposition of soft soils (in terms of construction) of various genesis in the profile.

To evaluate engineering-geological conditions of the construction site of the bridge across the River Kolomenka in order to make optimal decisions for selecting a location of the designed facility a complete set of engineering investigations was gradually implemented, in their course the set tasks were gradually solved.

At the initial stage of works, which included drilling wells on both banks of the river and static probing, the main goal was to identify the subgrade bedrock. The wells which found peat from the surface and at a shallow depth identified that glacial deposits gIIIv at the depths 39,0 - 41,0 m are underlain by limestone of the Carbon age (fig. 2).

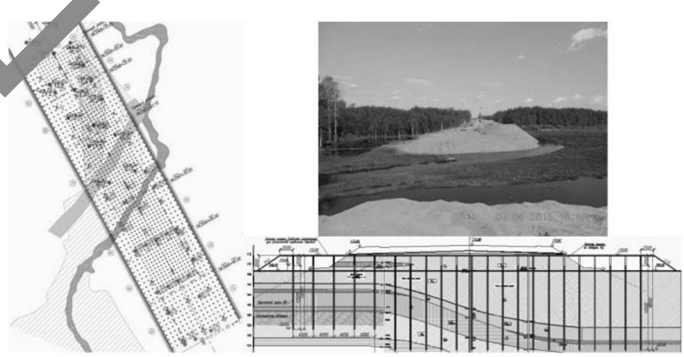

Fig.1 The plan, section and view of the area of bridge crossing of the River Kolomenka where works on stabilization of the motorway (M-11) subgrade were implemented.

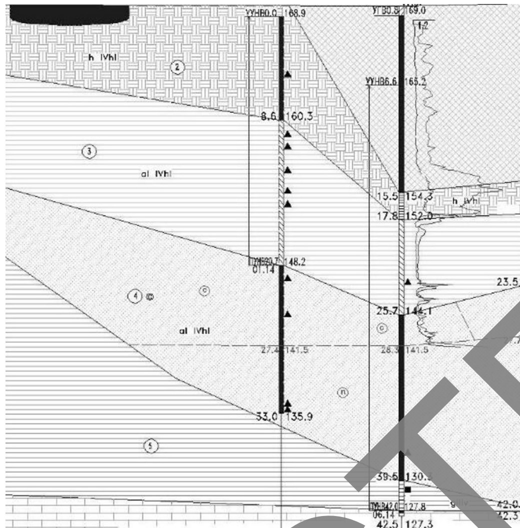

Fig. 2. Engineering-geological profile: 2 – peat layers, 3 – liquid-plastic loams, 4 – sands of different grain size, 5 – clayey sands underlain by limestone.

During the subsequent stages of work geological profile of the area of bridge crossing was specified, additional investigations were conducted in order to make more detailed evaluation of engineering-geological profiles and physical-mechanical properties of soils as there had been found an inconsistency of data on soil stratification and the results of previous investigations.

The implemented works identified that Quaternary and Carbon age deposit were encountered in the studied area down to the depth 46,0 m (fig. 3).

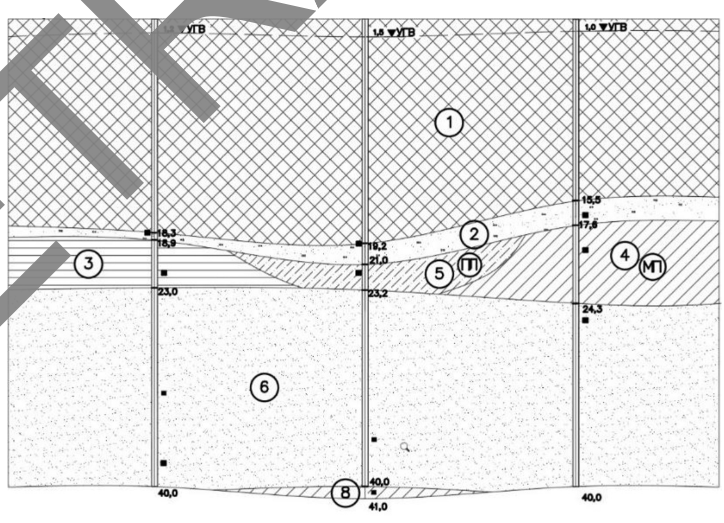

Fig. 3. Engineering-geological profile of the area across the River Kolomenka: 1- filled soils tIV, 2- peat; peated sands - hIII-IV; 3- liquid clay, and liquid and liquid-plastic loam - lgIII-IV; 4- loams lgIII; 5- clayey sands gIII; 6- sands of different grain size (lgII-III); 7- clayey sands (gII); 8- loams (g II). Limestone was not encountered.

Modern deposits are represented by anthropogenic filled soils: medium-grained sand and peats (tIV) encountered everywhere; swamp deposits – peats (hIVhl), which were opened under filled soils and from the surface. Alluvial deposits (alIVhl) pertain to the flood land of the River Kolomenka, they lie under anthropogenic and swamp deposits and they are represented by clay soils (with admixture of organic substances and without admixtures); medium-grained sand with interlayers of sand of different grain size and density.

The major part of the profile consists of modern and Upper Quaternary deposits represented by biogenic suites (hIII-IV) (peat, peated sands) and lacustrine-glacial clays and loams (lgIII-IV).

Under alluvial deposits most of wells opened Upper Quaternary deposits: lacustrine-glacial loams (lgIII) and glacial clay soils (gIII) with inclusion of gravel, pebble and boulders, interlayers of clay, loam and clayey sand, sand in some places.

There are also Upper and Medium Quaternary deposits: lacustrine-glacial sands of different grain size (lgII-III); Medium Quaternary fine-grained sands (f,lg IIms); glacial clays, clayey sands and loams (g IIms) in the profile.

The base of the opened profile is represented by carbon fissured limestones (C1).

Physical-mechanical properties of soils in the construction site of bridge crossing were studied at all stages of works according to the existing regulatory documents.

In the site of bridge crossing ground waters belong to Quaternary and carbon deposits, they are hydraulically connected with each other and water in the River Kolomenka representing a unified aquifer. In modern Quaternary deposits represented by peat and filled medium-grained sand they are unconfined. They are fed due to infiltration of precipitation and snow melting. In the site they were opened in the depth range 0,0-6,4 m. Confined waters were opened in the depth range 31,5-39,2 m in modern alluvial and Upper Quaternary sands and carbon limestones. They have hydrocarbonate-sulfate calcium-magnesium composition. As regards a degree of aggressive influence of water on concrete of W4 grade, they were evaluated as non-aggressive; as for reinforcement of RC structures – as mildly aggressive at periodical wetting and non-aggressive – at constant wetting.

3 The results and discussion

Construction of a one-span bridge with approach embankments was initially planned above the riverbed of the River Kolomenka. During engineering development of the site certain difficulties occurred due to inaccurate investigations. At the stage of construction of pile footing it was found out that piles did not provide the required bearing capacity, it was identified at test pile driving under a bridge abutment to the depth which significantly exceeded the design one ("piles fell down"). Difficult engineering-geological conditions of the site showed impossibility of making a pile field in the area of the existing riverbed.

The design documentation was adjusted; it was decided to transfer the riverbed. Hence, there emerged an issue of transfer of bridge location to an area with the smallest thickness of soft soils (by 150 m aside from the initial design location).

As regards the site of the previous riverbed it was necessary to implement a set of works connected with construction of the approach embankment to the bridge.

The results of evaluation of engineering-geological features of the bridge site showed that the major part of the profile consists of clayey deposits of different consistence lying in the form of tongue lenses and interlayers under peats and filled soils. Their presence together with peat was the root cause of problems, which had emerged at engineering development of the site and had manifested in deformation of soil bulk where they had maximum thickness. Filling an area for the pile field with sand of up to 20 m thickness caused unfavourable processes in these soils subjected to a considerable load of the upper bulk. Meanwhile there was a partial extrusion of peats and clay soils of liquid and liquid-plastic constituency sideward and their partial consolidation. In some sections there was identified a considerable peat compaction and, consequently, its large settlement. There was also an intensive subsidence of the embankment with heave of residual peat towards the riverbed and along the sides of the platform, according to geodetic observations the maximum settlement was about 114 cm [1].

In order to make a decision on providing stability of the subgrade of road embankment there was conducted an evaluation of composition and physical-mechanical properties of peats, peated sands and clayey deposits which characterized them as follows:

Peats and peated sands (tIV) of thickness 0,5-2,5 m were opened by wells in different parts of the site under filled soils (sands of different grain size up to 25.0-m-thick). Relative content of an organic substance (I) in them varied in a small range reaching 40 and 50 %, it witnessed on a border physical state of the tested samples. Therefore, highly peated sands (I = 0,41) and peats (I = 0,50) are close to each other by their state that was confirmed by the obtained data (table 1).

Table 1. Summary table of physical properties of peats and peated sands

Indicators of physical state	Peat	Peated sands
Natural humidity, unit fraction	1,59…2,72	1,60...2,92
Density, g/cm^3	1,03…1,09	1,07…1,28
Density of dry soil, g/cm^3	0,28…0,44	0,27…0,49
Density of mineral part, g/cm^3	1,65…1,96	2,08…2,48
Porosity index, unit fraction	3,45…5,61	3,84…6,61
Water saturation degree, unit fraction	0,90…0,92	0,92…1,00
Full humidity ratio, unit fraction	1,76…3,01	1,61…3,18

The main difficulties of the site in terms of engineering development were caused by presence of soft clay soils in the profile which varied in locations throughout the site as per the area and depth. At their evaluation the main attention was paid to studying alluvial deposits (alIVhl) as well as lacustrine-glacial deposits (modern and Upper Quaternary, Upper Quaternary), which occupy a considerable part of the section.

The analysis of the obtained results show that clay alluvial and lacustrine-glacial deposits have a considerable humidity, which in many cases exceeds 0,40 reaching 0,70. They are characterized by liquid-plastic and liquid consistency (liquidity index > 0,75 and > 1,00) and only in some cases – soft plastic (liquidity index is 0,56…0,61).

Evaluation of strength and deformation properties of lacustrine-glacial (lgIII-IV) clay deposits obtained as a result of shear and compression tests showed that they have a small strength and a significant compressibility. For liquid clays and liquid loams the angle of internal friction (φ, degrees) is 8,89 at cohesion (C, MPa) – 0,007, the strain modulus (E0, MPa) – 2,524.

Therefore, the soils, which comprise the site profile, are characterized by the high natural humidity, small density as well as considerable differential deformability-compressibility that demonstrates impossibility of using them as the subgrade of embankment with improvement of construction properties.

Based on the analysis and evaluation of engineering-geological features of the area of bridge crossing, their influence on the workflow at different stages of its engineering development, there were made the conclusions on the necessity to compact loose water saturated sands, reinforce organic and soft clay soil, and select measures for these purposes.

The global practice of construction knows a number of technologies allowing to maintain a stable state of the subgrade. The issues of improvement of physical-mechanical properties of subgrades of soil structures are stated in many research publications, they are largely summarized in the engineering literature [2, 3]. Experts of the chair “Underground structures, soils and foundations” of St. Petersburg State Technical University under supervision of prof.

V.A. Florin and prof. P.L. Ivanov have been working on subgrade soil consolidation using blasting technology since 1949. This method of soil consolidation was successfully used in construction of various facilities in Russia and abroad [4, 5].

The staff of the chair "Subsoils and foundations", Emperor Alexander I Petersburg State Transport University was involved in solution of the problem associated with increasing bearing capacity of soils of the subgrade of the approach embankment in the area of the former riverbed of the Rived Kolomenka in the framework of research and development. In order to accelerate consolidation of soft soils and compaction of loose sands design documentation was elaborated and approved, research and development work for creating the stable subgrade of the approach embankment in difficult engineering-geological conditions was implemented. This method proved to be one of the most efficient and cost-effective ways of accelerating consolidation of peats, and liquid and liquid-plastic clay sands as well as compaction of loose sands based on forming vertical sand drains using blasting technology. The method is based on one-by-one or group blasting of charges causing liquefaction and consolidation of non-cohesive soils or forming a sand pile drain in cohesive soils with their consequent consolidation [6, 7].

Therefore, in order to stabilize the embankment on saturated non-cohesive soils there was used the technology of reinforcement of a soft bulk under the subgrade of the road embankment and compaction of sand of the road bed which was accompanied with creation of vertical sand drains using blast energy that supposed acceleration of consolidation of soft organic soils as well as compaction of loose sands.

The period of workflow on stabilization of the subgrade of the road embankment lasted for 2,5 years (3 stages), it included the following types of investigations:

1) engineering-geophysical investigations including electric prospecting, seismic prospecting, georadiolocation profiling, monitoring of changes of pore pressure in the bulk of sand and clay soils;

2) geodetic monitoring comprising plan-elevation definition of displacement of deformation marks, values of total accumulated settlements, laser scanning of the site surface;

3) engineering-geological investigations: sampling, static probing to specify geological structure of the area;

4) inclinometer measurements: boundaries of sliding of the soil bulk were defined with a help of well inclinometer.

Geodetic observations of elevation position of settlement marks installed along the axis of the subgrade and cantledge berms allowed evaluating: 1 - values of deformations; 2 - rates of deformation development; 3 - deformation differences.

As a result of geodetic survey, it was recorded that the subgrade settlement occurred at a higher rate during the workflow, its stabilization was observed in breaks between the main stages of blasting works (fig. 4).

Also, comparing the third stage of the workflow with the previous two one could mention that in the period of blasting works a settlement rate equals the period of stabilization.

Geodetic observations proved the efficiency of works, there was reached a balance between loads of embankment weight and bearing capacity of the subgrade in the site of the workflow.

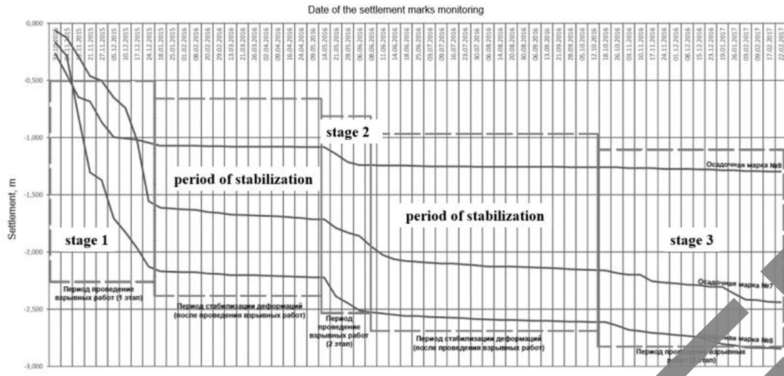

Fig. 4. The results of graphs of settlement development of soil benchmarks in the subgrade of the road embankment.

The goal of implemented geophysical investigations was a quality assessment of a degree of consolidation of soils in the embankment subgrade according to the subgrade stabilization technology using blast energy on the basis of change of physical parameters – velocities of elastic wave propagation [1, 8]. The works [9, 10, 11] are devoted to research of change of strength and deformation properties of disperse soils in the course of geophysical investigations.

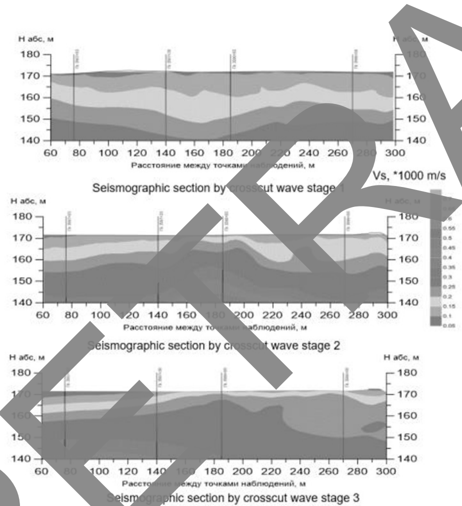

Fig. 5. Seismographic sections along transversal waves (S-waves) built based on the results of the first, second and third stages of works. They show changes of humidity in soils.

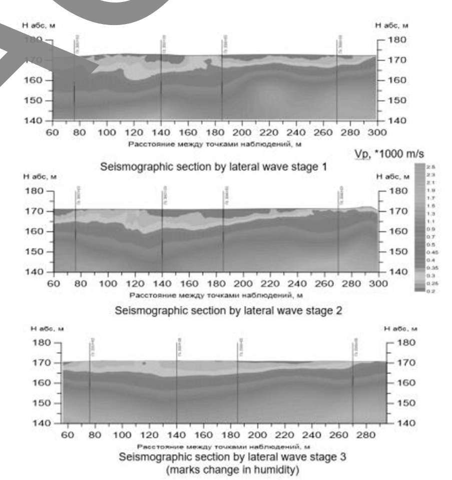

Fig. 6. Seismographic sections along longitudinal waves (P-waves) built based on the results of the first, second and third stages of works. They show changes of density in soils.

Profile 1, along which seismographic sections were made, represents a section located 24 m to the right along the axis of the subgrade in the direction Moscow – St. Petersburg.

Rate sections made according to the results of seismic prospecting works (length 240 m) characterize spatial distribution of rates of elastic S-waves (fig. 5) and P-waves (fig. 6) throughout the depth. The analysis of sections showed that a rate of propagation of P-waves is defined by composition and humidity, humidity almost does not influence a rate of propagation of S-waves but it influences on a density of soil structure. As the soil composition has not virtually changed at different stages of investigations based on the given profiles one can make quality assessment of a degree of soil consolidation under the action of blast energy.

4 Conclusion

Comparison of rate sections at the first, second and third stages was made based on the results of geophysical investigations, it shows that there were changes in sections both in nature and values of rate distribution. Comparison of changes observed in seismographic P-waves and S-waves allows to make a conclusion at the quality different level that conducting blasting works, first and foremost, leads to redistribution of soil particles and consolidation of the embankment subgrade within intervals of sections controlled by increasing rates of S-waves. Changes of humidity regime of soils is secondary and it becomes visible at the second stage of blasting.

Differences in distribution of values of rates of seismic waves are firstly explained by changes of humidity and density of soils. After completion of blasting in some intervals of sections subjected to blasting there was an increase of rates of P-waves and S-waves which witnesses on the occurred consolidation of soils and a decrease of their humidity.

Therefore, comprehensive investigations in the area of the bridge crossing of the River Kolomenka in order to substantiate construction of the approach embankment provided detailed studying of the engineering-geological section and identifying a more accurate location of the roof of strong deposits of the subgrade, and defining a depth of structurally unstable soils. The proposed blasting technology made a considerable contribution in timely commissioning of the motorway Moscow-St. Petersburg.

Compared to the widespread nowadays technologies of strengthening soft soils in the subgrade of embankments of transport infrastructural facilities such as peat replacement (replacement of soft soil by sandy soil) [12], construction of a piled field of bored or vibro-driven piles [13], jet grouting [14], making sandy drain piles [15] the proposed technology has the following advantages:

1. It provides 3-5 time reduction of time and resources for mobilization, preparatory stages of works and implementation as the thickness of the operational sandy layer, on which a light drilling rig rests, is only half a meter.

2. The technology employs rather simple, available and cheap equipment (a drilling rig, dumpers, a loader, a bulldozer), sand without special requirements to its quality as well as explosives produced only in Russia.

3. The technology provides a real opportunity to accelerate a speed of construction of facilities of transport infrastructure, side access roads and sites which are located at least in 30% of cases in areas with prevailing soft soils (swamps, marshes) and structurally unstable soils (loesses, seasonally frozen and permafrost soils, karst).

4. The technology guarantees preservation of landscape of adjacent areas, ecological balance of unique water systems located almost just beyond borders of a construction site (preservation of lakes and swamps as natural sources and filters of rivers).

5. Consolidation of soils in the subgrade of embankments occurs 3-5 time quicker compared to the alternative methods that is highly important for transport facilities.

6. Finally, consumption of sand difficult to be delivered in remote and rough locations together with cheapness of other resources guarantee 3-5 times reduction of a price of works as per the developed technology compared to the alternative methods.

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