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A laboratory study of the soil around injection-expanded wells: physical and mechanical characteristics changes

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Abstract: The article is devoted to the description of the physical processes occurring in the soil when cement mortar is injected into the ground under pressure. The paper determines the reason for the lack of knowledge of such kinds of changes in the soil's physical and mechanical properties around a well expanded by the injection. The article presents the author's own results in the variability of the physical and mechanical properties of the soil during ground hardening by the injection, in time and in orientation. The differences over time in sand and clay characteristics are also presented.

Keywords: injection, ground characteristic change, cement mortar, ground strengthening

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Introduction

These days, the construction industry in Belarus is facing the challenge of dealing with increased loads on the foundations and grounds of civil and industrial structures. It can be noted that the structural material characteristics are predetermined and their strength and durability are mostly guaranteed during the entire existence of the building, but the soils are a dynamic system, of which the physical, mechanical and deformation characteristics change in time and space from the effects of cyclic changes in the environment due to vibration, dynamics and changing loading methods for overhead structures, etc.

One of the methods that allows the improvement of the characteristics of the soil, stabilizing and reinforcing them, is the method of injection into the ground

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under pressure of different kinds of mortars. This method, due to its simplicity, has become widespread in the countries of Eastern Europe, namely the Republic of Belarus and is used during the reconstruction and modernization of existing buildings and structures. This method is also used to increase the bearing and reduce the ground deformability, as well as to prevent dangerous geological processes such as precipitation, subsidence and suffusion.

1. Current knowledge of the issue

Two types of drilling injection technology are distinguished in Western European countries (Hanna, 1982; Hulla, 2002; Wiłun, 2007): 1) classical, when a cavity in non-cohesive granular soil is created by drilling, followed by the injector introduction and cement mortar (solite) is pumped under pressure into wells and cavities in the soil; 2) jet-technology, in which hydraulic erosion of the soil occurs with a water-air mixture with high energy, followed by filling the formed cavities with a mortar. The choice of one or the other method depends on the geological properties of the field and the goals of the injection (Kubanski, 2007).

The creator of the classical method of soil injection is considered to be Berigni, who in 1802 successfully pumped, under pressure, injected cement mortar in order to fill voids in soils. Until the mid-1950s, injection soil stabilization was considered an operation where the soil around the well was impregnated with cement mortar, which resulted in the formation of a new "soil-cement" material. Based on this assumption, injection grouting was used both to fill large voids in rock masses and to reduce seepage under dams.

This assumption about impregnation was refuted by Cambefort, who was the first to analyze the results of experimental excavations of injected bodies, carried out both in rocky and non-rocky soils. He showed that injection pressure only compressed the soil, and did not impregnate all the ground pores.

Classical bored injection technology is a kind of bored technology (Nikitenko, 2007a) and includes the following main operations (Ihnatov, 2012b):

1) well or cavity creation in soils (both with ground removal and displacement into the surrounding environment). Boring methods are determined mainly by the nature of the soil layers;
2) reinforcement immersion (if it is necessary);
3) injection into the well or into the ground voids of a cement or cement-sand mortar under low pressure. This leads to the surrounding soil pressing well border displacement to the sides and to the cavity and well cross section increases (Al' Masri, 1998; Nikitenko, 2007b; Povkolas, 2001). As a result, a very uneven surface is obtained, which provides good adhesion between concrete and the surrounding soil. There is also the soil density increase around the well, and as a result, a change in the physical and mechanical properties of the mass surrounding the cavity, the pile and anchor contact resistance is shared and frontal resistance increases.

Thus, the main feature of the classical injection technology is in the formation of a cement (concrete) body in non-rocky soils. These soils must be characterized by small pores and a sufficiently low filtration coefficient. So, in such soils, well expansion and surrounding soil compaction takes place, or hydraulic fractures occur.

A small number of studies have been devoted to a targeted study of the variability of soil properties around injection-filled cement mortar wells and cavities both under pressure and without it. Most of the studies were aimed at determining the shear resistance of the soil along the drilling body (most often an anchor or pile) and the frontal resistance in front of it. The generalization of available results from studies of the variability in soil properties due to their injection pressure testing is difficult for a number of complex reasons (Nikitenko, 2007a):

– the experiments are fragmented with low repeatability due to the technical impossibility of digging out full-scale injection reinforcement elements, parts of anchors and piles in various soils, and also because of the high cost of performing experimental work in the field;
– physical processes occurring during the injection of cement mortar into the soil and methodological complexity of large-scale modelling in laboratory conditions;
– physical and mechanical characteristics of the sampled soils are given incompletely or not given at all;
– there is no information about the design of the reinforcement element, the anchor and the pile, as well as the manufacturing technology;
– there is no description of the methodology for conducting experiments.

The materials presented in this article provide the results of a comprehensive study of the characteristics of soils around the injection body.

2. Experiment description

The author with his supervisor prof. M.I. Nikitenko developed a technique and carried out, in the laboratories of the department "Geotechnics and Ecology in Construction" BNTU laboratory, large-scale experiments in order to study changes in the soil's physical and mechanical properties during injection expansion. After the well injection expansion, excess moisture from the cement slurry is squeezed out into the surrounding soil. Soils, common to the territory of Belarus, were used for the experiments: sands of medium density ($\gamma = 16.5\text{-}16.7$ kN/m^3, W = 0.7%, Pdmin = 1.5 MPa) and sandy loam ($\gamma = 19.1\text{-}19.2$ kN/m^3, W = 12.7-13.0%, Pdmin = 3.5 MPa).

Cylindrical containers (tanks), with a diameter of 750 mm and a height of 0.9 meters (Fig. 1), were used in order to study the variability of soil properties during the introduction of cement mortar into a well. A plastic well-former, with an outer diameter of 110 mm, was placed in a cylindrical container. After laying the soil in the container, an injection cement slurry (mortar) was extracted and pumped with an injection pressure of 150 kPa. Cement grade M 400 was used for the experiments. The water-cement ratio of the poured mortar was equal to 0.5.

Based on the results of injection under pressure, it was found that the ratio of the total volume of injection in the well to the its initial volume was equal: for sandy loam 1.24-1.27, for medium sand 1.19-1.23.

Technological breaks lasting 7, 14 and 28 days were conducted in order to let the cement mortar harden. The injected bodies were excavated after these technological breaks. Sampling was carried out to determine the density and moisture content of the soil. Dynamic probing of the soil, around the injection body and below it, was conducted at 5 levels (with a step of 150 mm) around the injection body and below it. Samples for the density and moisture were taken with an increment of 50 mm in the radial deviation. Soil dynamic sounding was also carried out with increments of 50 mm in spiral rotation.

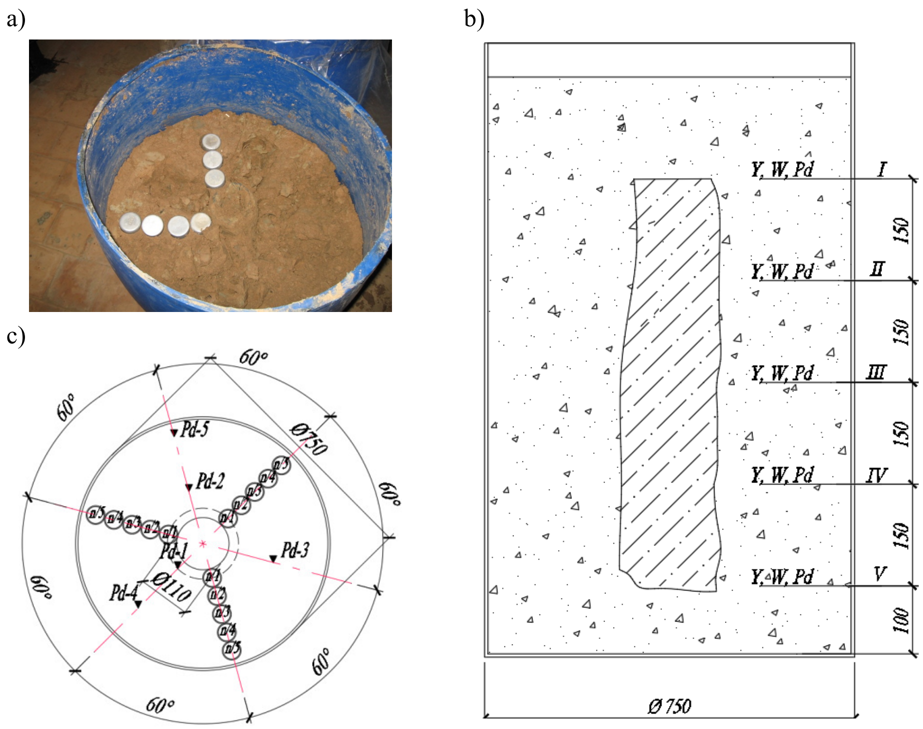

Fig. 1. Locations of the selected soil samples: a) the experiment photo, b) in height, c) in plan; I-V – sample location level; n/1-n/5 – sampling sites for determining soil moisture and density; Pd-1-Pd-5 – dynamic sounding locations (*own research*)

3. Results

3.1. Ground moisture change during and after injection

According to the results of the laboratory studies, it was found that on the 14th day the moisture content of sandy soils in the experimental cylindrical containers (tanks) became equal throughout the volume of the soil. At the same time, for sandy soils, the highest humidity was found in the lower part of the formation of the injection body due to the filtration properties of the soil and the penetration of water unbound by cement under the action of gravity dropping to the bottom of the experimental tank (Fig. 2).

Differences in humidity remained in the sandy loam even after 28 days: for example, the moisture content of sandy loam near the injection body on day 28 exceeded the total moisture content of the soil mass by 1.0-3.5% (Fig. 2). Such water ratio differences change the consistency of clay soil from solid to plastic or fluid. The increased humidity of the clay soil was especially notable on the first day after the injection. This is explained by the fact that for cement hydration it is necessary that the water-cement ratio be in the range of 0.22-0.25, while the injected cement mortar had W/C = 0.5. The excess moisture penetrated into the pores of the soil, thereby changing its consistency, leading to a decrease in the resistance of the soil to shear along the lateral surface.

a) b)

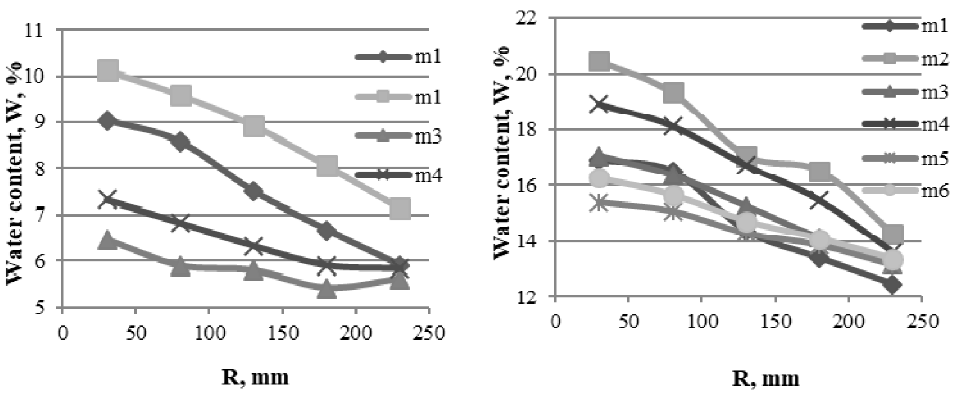

Fig. 2. Sand and sandy loam moisture change in the radial description after injection: a) sand moisture change, b) sandy loam moisture change; m1 – change at the level II on the 7th day, m2 – change at the level V on the 7th day, m3 – change at the level II on the 14th day, m4 – change at the level V on the 14th day, m5 – change at the level II on the 28th day, m6 – change at the level II on the 28th day (*own research*)

3.2. Bulk density and porosity coefficient change

The research results showed that the change in the sandy loam density in the radial direction was in the range of 22.1-18.6 kN/m^3, the porosity coefficient was 0.45-0.63; for medium sand this change was: for density 18.5-16.5 kN/m^3, porosity coefficient – 0.6-0.75 (Fig. 3).

Based on the results of our studies, the main graphical dependences were determined for density changes during injection of the cement mortar.

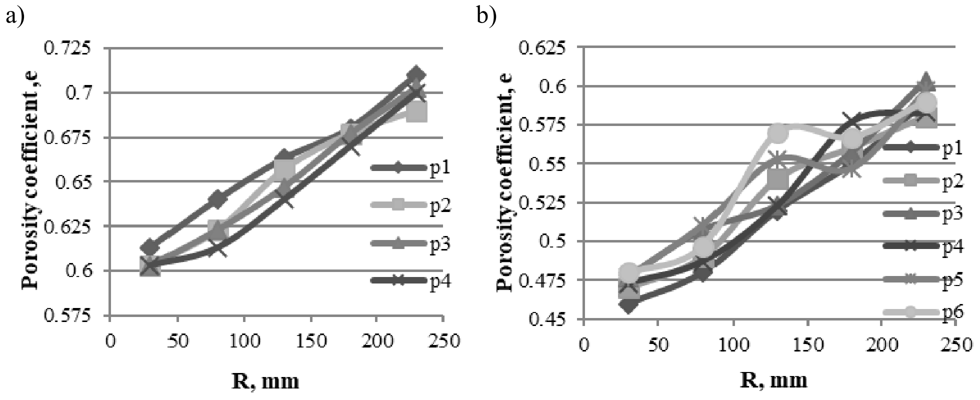

Fig. 3. Sand and sandy loam porosity coefficient change in the radial description after injection: a) sand porosity coefficient change, b) sandy loam porosity coefficient change; p1 – change at the level II on the 7th day, p2 – change at the level V on the 7th day, p3 – change at the level II on the 14th day, p4 – change at the level V on the 14th day, p5 – change at the level II on the 28th day, p6 – change at the level II on the 28th day (*own research*)

3.3. Sand filtration coefficient change

The filtration coefficient of various soils varies depending on the assessment and decision, mainly of the granulometric composition of soils.

The conducted studies have confirmed that the experimental clay soil retains water and its filtration coefficient value tends to be zero. This is due to the fact that the clay soil has very low permeability due to the high prevalence of very small pores with a high degree of dispersion and a high prevalence of the propagation of forces associated with water (Antonenko, 1999).

With the well and cavity expansion, the sand and clay soil density also changes in a radial way. Due to this change, there is also a change in the coefficients of porosity and filtration. Taking into account the change in the ratio of soils in radial terms from the axis of the well, we carried out laboratory studies of the sandy soil filtration coefficient depending on its porosity coefficient and density. According to the results of the laboratory studies, non-linear changes depending on the porosity coefficient of the sandy soil filtration coefficient was revealed (Fig. 4).

According to Figure 4, it can be seen that due to compaction, an intensive decrease in the water permeability of the soil occurs and the dispersion of the values of the filtration coefficient decreases.

3.4. Probing resistance and strength characteristics

The study of changes in the mechanical properties of the soil was carried out indirectly by the soil resistance to dynamic probing around injection bodies. The use of standard methods for determining the strength characteristics of soils in this experiment, from our point of view, is more difficult, since for laboratory studies it is required to take samples with standard rings in fairly large amounts.

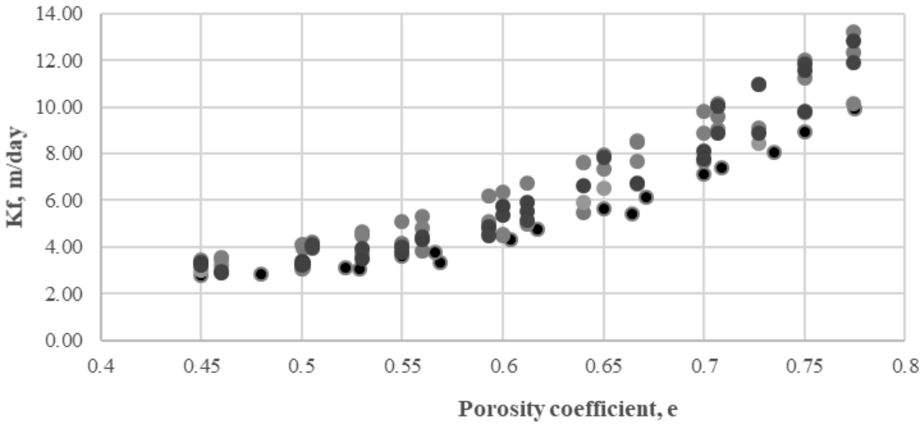

Fig. 4. Sandy soil filtration coefficient change ranges (depending on the porosity coefficient) (*own research*)

In accordance with the sounding resistance change, there is also a change in the strength characteristics of the soil, i.e. angle of internal friction and cohesion.

Soil resistance to dynamic probing was determined using a standard densitometer according to (STB 1377-2003, 2003) with a conical probe diameter of 16.0 mm with an angle at its tip of 60°. The angle of internal friction and cohesion were determined from the obtained values of the probing in accordance with (TKP 45-5.01-17-2006, 2006).

The dynamic sounding soil resistance change graphs and the sands and sandy loam strength characteristics changes are presented in Figure 2.

The medium sand conditional dynamic resistance change at the boundary of the injection body in the period of 7-14 days is no more than 2.0 MPa, which indicates a stabilized state and the invariance of the values of the angle of internal friction and cohesion. However, in the radial direction, there is a significant decrease in the resistance to dynamic probing: from 6.6 MPa at the boundary of the injection body to 2.0 MPa at a distance of 250 mm from it (in the natural state). This change corresponds to a decrease in the angle of internal friction from 35.5° to 33°, and shows an adhesion from 1.2 to 0.0 kPa. In this case, the cohesion in the sand near the injection body is due to the cementation of its fractions.

Sandy loam conditional dynamic resistance changed from 3.6 MPa on the 7th day to 10.6 MPa on the 28th day, so the angle of internal friction changed from 27° to 28°, and the cohesion from 30 to 35 kPa. The sandy loam conditional dynamic resistance of the radial direction on the 28th day at the level of the center of the injected body changed from 10.7 MPa (at the border of the injected body) to 4.2 MPa at a distance from it. This change corresponds to a decrease in the angle of internal friction from 29° to 28°, cohesion – from 40 to 36 kPa. The increase in resistance to dynamic probing for sandy loam in the period of 7-28 days after the installation of the injection body corresponds to the nature of the fluidity index change (Fig. 5).

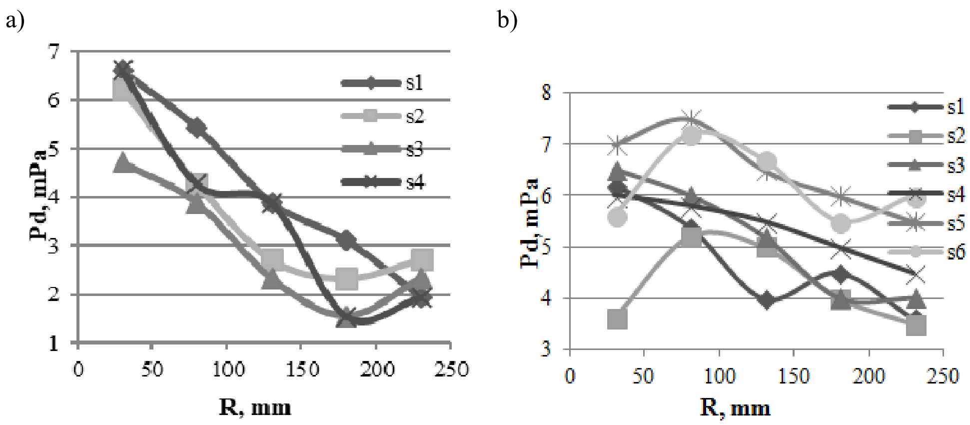

Fig. 5. Sand and sandy loam sounding resistance change in the radial description after injection: a) sand sounding resistance change, b) sandy loam sounding resistance change; s1 – change at the level II on the 7th day, s2 – change at the level V on the 7th day, s3 – change at the level II on the 14th day, s4 – change at the level V on the 14th day, s5 – change at the level II on the 28th day, s6 – change at the level II on the 28th day (*own research*)

Conclusions

The conducted laboratory studies results show that soil around wells and cavities are compressed with injection of cement mortar. At the same time it was found that the soil's physical and mechanical characteristics changed mostly due to the volume of the cement injection mortar, and not due to the high pumping pressure.

There is a fairly rapid (no more than 14 days) excess moisture drainage from the water-cement mortar to a unique W/C = 0.23-0.27 in highly filtering sandy soils. Also there is excess moisture density redistribution in the ground, so high mortar W/C does not greatly influence the sands.

There is a transition of sandy loam from a solid state to a plastic state on the contact of the injection or poured cement body due to low filter characteristics in the initial period. Zones with high moisture in the soil move into a more strengthened state due to the water redistribution in the volume over time (Ihnatov, 2012a).

The soil is an open system, so over time, redistribution of excess moisture from the injected cement mortar occurs and it acquires the same moisture in the entire volume around the injection body. For clay soils, this period is not less than 30 days, for sandy soils – 10 days.

Thus, knowledge of the injection value and the ground's initial characteristics can help us determine the porosity coefficient after the injection, and as a result, the new physical and mechanical characteristics of the reinforced ground.

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