Experience in application of drilled injection piles for building and structure strengthening

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Abstract. The paper presents the experience of building and structure strengthening in Tyumen soil conditions which are often presented by a soft water saturated clay and sand layer of the quaternary period. All buildings mentioned in the paper had uneven settlements due to complex engineering and geological conditions and the wrong choice of foundation type. Thin drilled injection piles with a diameter of 200 mm were used for foundation strengthening. All the piles were installed on the solid soil base during the drilling process regardless of the depth of its location. No rules have so far been approved to calculate the bearing capacity of thin drilled injection piles. That was the reason for defining the drilled injection pile bearing capacity at every facility. The paper describes the methods and test results obtained in the study. It was found out that all piles had unexpectedly high bearing capacity. The paper also contains the results of geotechnical monitoring before and after base building strengthening by drilled injection piles which show the current decrease of settlements and the efficiency of this base strengthening method.

1. Introduction
The southern territory of Tyumen region is characterized in geotechnical structure by soft silt loam clay formations with up to 20-35 m in depth from the ground surface underlain by hard sand or firm clay. The typical geotechnical cross-section of the south of Tyumen region is shown in figure 1.

![Figure 1. Typical geotechnical cross-section of the south of Tyumen region.](image-url)
Surrounding soil is often anisotropic and non-uniform within the foundation active zone. It has the following mechanical properties:

- an internal friction angle: 14 – 22 degrees;
- specific cohesion: 0.02 – 0.05 MPa;
- the modulus of deformation (Young Modulus): 2 – 12 MPa.

Soil conditions of the south of Tyumen region can be classified as complex for building and structure design and construction. Frequently, neglect of these factors causes uneven settlements and tilts of buildings both during their construction and maintenance, which give rise to emergency situations at the facilities.

In conditions of high social tension at the facilities which have limited operation capacity due to their critical state, it is necessary to make quick though reliable decisions which can help stabilize uneven settlements and tilts and provide further safe maintenance of these facilities. Strengthening of existing foundations (strip, piled, slab and pile-slab foundations) by drilled injection piles of Atlant and Normal type is one of the solutions which is successfully applied on the southern territory of Tyumen region.

2. Results and discussions

The main reasons that lead to the development of excessive uneven settlements and tilts of buildings and structures are:

- complex geotechnical conditions;
- design faults (wrong foundation type choice) and construction errors (violation of work production technology);
- no pile support on an underlying layer;
- soft water-saturated silt clay soils with a high content of organic matter in the base;
- strip/slab/pile-slab foundations rested on soft water-saturated clay soils.

Further the paper presents some examples of drilled injection piles application for underpinning residential buildings foundations that have excessive uneven settlements and tilts in the city of Tyumen.

2.1 Drill-injection piles of Atlant and Normal type

Obviously, there are no reliable solutions when choosing a type of foundation. Nevertheless, the principle of foundation construction, when piles are set in a reliable underlying soil (had sand, clay), makes it possible to minimize the risks of uneven settlements and tilts of buildings and structures. However, when reliable soil base layers are located at a depth of 20-35 meters or more from the ground surface, it is difficult to use prefabricated driven piles, so, in this case, it is rational to use drilled and drilled injection piles [1]-[4]. In geological conditions of the south of Tyumen region the drill-injection technology of Atlant-type piles is often used, which is characterized by a loose core injector as a further reinforcement element. The drill-injection technology of Normal-type piles is also used. The latter was developed by the authors of the paper [5]. It is based on the repeated usage of a high-strength core injector due to its extraction after the pile crimping and the following sinking of the reinforcement element into the pile shaft. A general view of the Atlant-type drilled injection pile is shown in figure 2.
Figure 2. The design of the Atlant-type drilled injection pile.

Drilled injection piles of Atlant and Normal types have some advantages, which allow builders to use these technologies successfully for strengthening the existing buildings and structures:

- decrease of foundation settlements;
- possible application in almost any geological conditions;
- wellbore drilling without soil removal, which creates an additional compaction zone around the pile perimeter;
- unlimited depth of drilling;
- no need for pits and trenches;
- no dynamic impact on the soil base;
- small-sized equipment for carrying out pile installation in cramped conditions;
- the possibility of drilled injection piles installation within the prepared site due to a small diameter of the piles made (200-300 mm).

There are some main steps which are taken when installing drilled injection piles:

- wellbore drilling of a required diameter and depth under the protection of the water-cement mortar in the ratio of 1 to 1;
- wellbore crimping by the water-cement mortar with $0.25 - 0.4$ ratio under pressure after the required depth has been achieved.

2.2 Typical examples of excessive building settlements and tilts in Tyumen

After the residential building had been constructed, the deviation of block section no.2 from the vertical, which exceeded the maximum permissible value by more than twofold (figures 3 and 4), was determined in the course of its maintenance. The building is U-shaped in plan and consists of six 9- and 16-floor brick block sections. The foundation of the building is piled-slab. During the geotechnical monitoring differential foundation settlement, which exceeded the maximum permissible value by more than 2.5 times, was also observed.
According to the results of the follow-up survey, the main reasons for defects appearance and development were found:

- complex geological conditions of the construction area (a flood plain part of the Tura river);
- non-stabilized settlements of the soil base;
- design errors (wrong foundation type);
- resting of the combined pile-slab foundation on soft water-saturated clay soils with significant organic impurities (up to 7%);
- violation of technology process in winter conditions, which caused freezing and subsidence of the developing layers.

During the structural survey, it was also found that the slab part of the combined pile-slab foundation did not rest on the soil-base (due to the soil base subsidence). For that reason the load from the above-foundation structures was taken only by the piles whose bearing capacity was insufficient, which caused the development of excessive settlements of block section no. 2.

To stabilize the differential settlements of the block-section under study, it was decided to apply the method of strengthening the existing foundation by the Atlant-type drilled injection piles of 200 mm in diameter which rested on a medium-density saturated sand layer. According to the geological survey, the sand layer was found at a depth of 12.0 m from the foundation slab base.

Before starting work, four drilled injection piles were tested for pull-in and pull-out loading. The results of the static tests are shown in figures 5.
According to the test data, it was found that:

- the bearing capacity of a single drilled injection pile was 630 kN;
- the maximum safe load on the drilled injection pile was 525 kN;
- 50% of the load were perceived by the side surface of the drilled injection pile;
- the load-bearing capacity of the drill-injection pile in material was 650 kN.

During the process of drilled injection piles installation, it was determined that a reliable soil base (a layer of medium-density saturated sand) had a variable depth, which mostly differed from the geological surveys data. Thus, the maximum length of a drilled injection pile for block-section no. 2 was 23.0 m with an average length of 19.0 m. The condition of pile sinking into the soil by no more than 10 cm per hour of continuous drilling was taken as the criterion of a reliable foundation.

Location of the drilled injection piles used for strengthening in the geotechnical cross-section is presented in figure 6.
Totally, 55 drilled injection piles were used for strengthening the foundation of block-section no. 2 in the period from January to February 2019.

Following the results of continuous geotechnical monitoring the stabilization of the reinforced block-section settlements was determined three months after the drilled injection piles installation. The results of geotechnical monitoring is shown in figure 7.

Another facility where drilled injection piles were applied, was a 9-floor panel building with a pile foundation. The building has a L-shaped plan form and consists of three blocks: panel blocks in axes 1-3 and 8-10 are 9-floor sections with dimensions of $13.2 \times 42.0 \text{ m}$ and $13.2 \times 45.0 \text{ m}$, respectively. A block in axes 4-7 is a 9-floor brick-panel corner insert. The building was taken into use in 2008. During the maintenance a progressive abnormal longitudinal and transverse tilt in axes 8-10 was observed. A detailed structural survey revealed the following defects and damages:

- the maximum deflection of the foundation raft in the longitudinal direction was 80 mm, in the transverse direction it was 30 mm;
- the absolute values of the maximum horizontal displacements in the transverse direction were exceeded by more than 2.5 times in regarding to the limit value. In the longitudinal direction that parameter was exceeded by more than 4 times;
- the maximum monthly increment of settlements exceeds 1 mm;
- the differential settlement of opposite corners of the building was 55 cm.

The general view of the building is shown in figures 8 and 9.

![Figure 7. The results of block-section no. 2 geotechnical monitoring.](image7)

![Figure 8. The building with a pile foundation.](image8)

![Figure 9. Horizontal corner deviation from the vertical, cm (the limit values of deviation, cm, are given in brackets).](image9)
The main reasons for the development of the non-normative corner tilts are:
- the lack of piles resting on reliable underlying sandy soil;
- the development of negative friction forces on the side surface of piles to a depth of over 65% from the pile length;
- the presence of soft watersaturated silt-loam soils with a high content of organic matter in the base.

Due to the lack of piles resting on a reliable soil layer, it was also decided to strengthen the foundation by drilled injection piles with their setting on a reliable soil base. The application of drilled injection piles was an important condition for the subsequent building tilt correction by its lifting with a system of jacks. The condition of pile sinking into the soil by no more than 10 cm per half an hour of continuous drilling was taken as the criterion of a reliable foundation.

Before starting work, two drilled injection piles with a diameter of 200 mm were tested for pull-in and pull-out loading. The results of the static tests are shown in figures 10 and 11.

According to the test data, it was found that:
- the bearing capacity of a single drilled injection pile was 850 kN;
- the maximum safe load on a drilled injection pile was 710 kN;
- about 50% of the load were perceived by the side surface of a drilled injection pile;
- the load-bearing capacity of the drilled injection pile material was 950kN.

A significant increase in the load-bearing capacity of the drilled injection pile material (46%) is explained by the application of a new sandy-cement mortar which was developed by the authors especially for making drilled injection piles in the conditions of soft clay soils [6].

The maximum length of drilled injection piles was 33.0 meters under the building corner which had the maximum longitudinal and transverse tilt (figures 9 and 12). In the process of
drilled injection piles making, the difference between the actual position of the medium-density sand layer roof and the geotechnical surveys data carried out earlier was determined.

Figure 12. Location of underpinning drilled injection piles in the geotechnical cross-section.

After installation of 33 drilled injection piles in September, 2019 the building settlements were stabilized. In January-February, 2020 a tilt of the building was successfully corrected and the building returned to its original geometric position.

Strengthening the foundations of the existing buildings by drilled injection piles showed a high efficiency of the method. Thus, the application of Atlant and Normal type drilled-injection piles at these facilities allowed finishing work by underpinning the foundations in a short time and stopping further settlement and tilt development.

It should be noted that all drilled injection piles had significant bearing capacity. With an average diameter of about 200 mm, the bearing capacity of drilled injection piles in the first example was 630 kN, while the bearing capacity of the pile shaft material was 650 kN. In the second case, the bearing capacity of piles was 850 kN, while the bearing capacity for the pile shaft material was 950 kN. Thus, in the first case, the difference between the bearing capacity of the pile in soil base and pile shaft material was 3%, and in the second case it was 10.5%. These values fully satisfy the principle of equal strength in soil base and pile shaft material, which is the criterion of maximum efficiency for pile foundations.

Attention should also be paid to the length-diameter ratio of a drilled injection pile (L/D): in the first case the maximum ratio was 122.5, and in the second it was 165. At the same time, there was no loss of stability of the pile shaft in the soil base under the action of sufficiently high loads. A smooth increase of settlements depending on real loading confirms that fact (figures 5 and 11).

3. Conclusion
Based on the research into strengthening the existing buildings and structures, we can conclude that in conditions of highly-compressible soils on the territory of the South-Western Siberia (south of Tyumen region) underlain by a layer of hard sand (firm clay) at a depth of 20-35m or more from the ground surface the application of drilled injection piles of Atlant and
Normal types is an efficient and reliable solution. So, this type of strengthening provides some benefits:

- stabilization of progressive differential settlements and tilts of buildings and structures;
- transmission of loads to reliable soil base, regardless of their depth;
- the maximum ratio of pile use in soil base and pile shaft material (the criterion of maximum efficiency for pile foundations): \( N_{\text{soil}} = N_{\text{material}} \) (when \( F_{\text{soil}} = 600-900 \text{ kN}, F_{\text{material}} = 800-1150 \text{ kN} \));
- small-sized equipment for pile arrangement in cramped conditions;
- installation of drilled injection piles on hard-to-reach and remote territories with low developed transport infrastructure, as well as in difficult climatic conditions based on minimal material, technical and logistic requirements.

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