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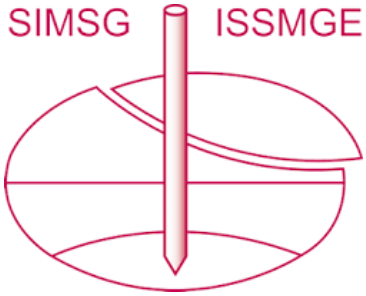

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Vertical geotechnical barrier erected by compensation grouting

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ABSTRACT: Compensation grouting is usually applied to reduce deformations, caused in soil by tunneling. Cement mortar is injected through a system of horizontal injectors into the soil between the tunnel and the footings of the building to be protected. The paper describes compensation grouting technique in a vertical plane for preserving the soil stress-strain state under the footings of the existing building if a new building is being constructed nearby.

1 VERTICAL GEOTECHNICAL BARRIER

When deep pits are excavated ($h > 5$ m) then in order to protect the nearby buildings the footings and/or the soil base shall conventionally be strengthened. An alternative protective technique is erection of a vertical geotechnical barrier with the help of compensation grouting that does not affect the footings of the existing buildings. The authors propose to set up such a barrier by driving a row of vertical injectors to the design depth to intercept the propagated stress-strain state (SSS) change in soil. Prior to construction cement mortar is injected one time through injectors. The protected structure settlements and soil SSS are monitored during underground structure erection, and if any changes are registered then cement mortar is additionally fed through injectors until the soil SSS restores, i.e. compensation grouting technique is applied.

Recently, compensation grouting has been used successfully for tunneling in order to limit soil settlements (Mair, Harris, Love, Blakey and Kettle 1994; Harrs, Menkiti, Pooley and Stephenson 1996; Schweiger and Falk 1998). This technique was initially implemented in Vienna and in London, and now it is applied world-wide. In order to discriminate between the two techniques of compensation grouting we will define compensation grouting in vertical and inclined plane as geotechnical barrier operation, while the one in horizontal plane will remain compensation grouting.

1.1 *History cases*

Vertical geotechnical barriers are recommended in the following cases:

- between footings of existing buildings and the excavated deep pit in congested urban build-up areas;
- to reduce existing buildings footings deformations caused by nearby construction activities;
- between footings of existing buildings and tunnels outside the building footprint.

For the past five years in Moscow a wealth of experience in analysis, design and construction of geotechnical barriers has been accumulated. It was for the first time when in 1998–2000, due to construction of the Third Transport Ring and reconstruction of the Ryzhsky Railway Station Square, NIIOSP developed a technique to prevent existing building footing settlements. Analysis of the nearest footing settlements, caused by pit excavation, yielded 32.5 mm that exceeds admissible values as per Moscow regulations. In order to prevent the above settlements a vertical geotechnical barrier was designed to intercept soil deformations, induced by underground pedestrian passage and a sewer conduit construction activities (Petrukhin, Shuljatjev and Mozgacheva 2001). With the geotechnical barrier present, the analysis predicted 3.4 mm settlement of the footing nearest to the pit and 1.7 mm settlement of the next footing. The measured settlements of the footing nearest to the site, after the underground crossing had been constructed, did not exceed 3 mm, while footings along the next axis had negligible additional settlements (less than 1 mm).

In 2003 a vertical geotechnical barrier was designed to reduce deformations of the existing building of the Clinical Hospital due to nearby construction of new building with a 4.5 m deep underground space. The minimum distance from the pit edge to existing building was 1.2 m. Mean spread footing pressure on soil base of the building under construction was 350 kPa. According to FME analysis (PLAXIS) the settlement of the nearest existing building footings should be 35 mm due to the new building impact with no protection while the geotechnical barrier between the spread footing and the existing footings should limit settlements to 10 mm. Currently, new building

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construction is over. The monitoring data demonstrates good coincidence with analytical data.

A geotechnical barrier was erected at the Russian Federal Property Fund (RFPF) in 2004 to protect a nearby building against the impact of a 10.4 m deep pit to be excavated and a retaining structure to be erected. The erection of a geotechnical barrier at the site is described in detail below.

1.2 *Specific features of geotechnical barrier construction*

Compensation grouting mode depends on soil properties, grout composition, SSS history, boundary conditions and injection rate. Special attention shall be paid to time-dependent compensation effect maintenance.

Conventionally, compensation grouting is applied to low-permeability soils. However, it is necessary, once in a while, to perform compensation grouting in sands. If such is the case then sands shall be specially pregrouted to fill in voids.

Prior to geotechnical barrier execution the injectors are driven into the soil in a vertical (or an inclined) plane. Fill-in and compensation grouting are effected by injecting small volumes (25–30 liters) of 1:2 water–cement ratio grout through holes in the injector, spanned at 30 cm from each other. The process is repeated multiple (up to 10) times at the same location. The main requirement is to inject the specified amount of grout at the specified point into the soil mass. It is necessary to maintain the specified injection pressure level. Depending on the injection point depth from the surface and on the number of the prior injection cycles the injection pressure shall be adjusted accordingly. When the Ryzhsky Railway Station Square was reconstructed the initial injection pressure was 0.2 . . . 0.5 MPa, while the pressure was higher, if 5 or more injections had already been made. It was not possible to do 10 injections at low points, because the hydrofrac pressure limit was higher than the strength of the hoses (1.5 MPa).

Such injection procedure prevents for potential displacements of footings, caused by soil deformations or by mechanical leaching, as well as reduction of horizontal stresses in soil medium.

When a geotechnical barrier is erected it is necessary to monitor the behavior of nearby buildings, the soil mass and the structure under construction, because the monitoring data is the basis for making decisions whether it is feasible to go on with additional injection cycles.

2 GEOTECHNICAL BARRIER ERECTION CASE

Consider practical experience of construction of the Russian Federal Property Fund (RFPF) in Moscow. The site is surrounded by 12 buildings (Figures 1, 2). Most nearby buildings belong to historical urban development and have shallow footings at 1.5 . . . 3.5 m depth from the ground surface. The footings sit on upper quaternary sediments. The initial survey showed satisfactory condition of the buildings. The buildings are situated at 2.1–12.0 m from the retaining structure.

2.1 *Site geotechnical conditions*

The site is located on ancient alluvial terrace of the Moskva river. The following geological strata occur top-down on the site:

– *Stratum-1:* 2 m thick fill, consisting of sand with construction waste, concrete fragments and rubble, moist, loose.

Figure 1. Overall view of the construction site.

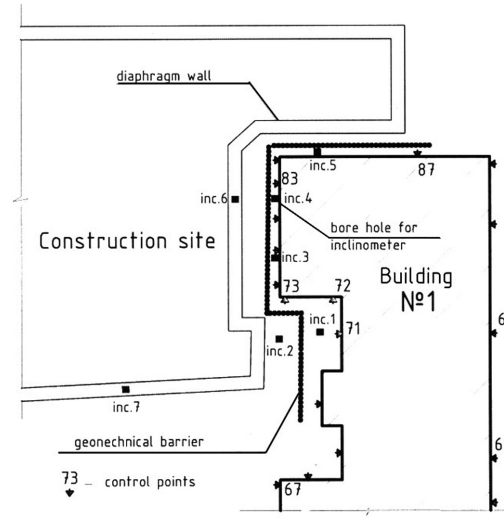

Figure 2. Layout of monitoring points.

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– *Stratum-2:* 2.8 . . . 8.2 m thick upper quaternary sediments, consisting of silt to medium grain size sands, loose to dense, moist to water-saturated. Plastic sand loam seams occur occasionally.
– *Stratum-3:* 6.8 . . . 13.5 m Jurassic sediments, consisting of hard plastic and plastic clays with seams and pockets of sand, sand loam and clay loam.

Bore holes showed super Jurassic aquifer with ground water table at 147.05 ÷148.00 m altitudes, the confining beds are alluvial sands, the aquifuge consists of Jurassic clay sediments.

2.2 *Construction site*

The would-be 6-storey RFPF building has a complex 120 × 60 m layout, with 10.4 m (141.8 m altitude) deep basement (3 storeys). The cut-off (anti-seepage) structure will be a 260 m long, 17.5 m deep and 0.6 m wide diaphragm wall. The retaining structure is supported by two rows of struts. The procedure for trench excavation involved application of bentonite slurry. Concrete was placed with the help of the vertically displaced tube technique (VDT).

RFPF construction includes several stages. At first the existing before construction building on the site was demolished. It was a 6-storey cast concrete building, having a basement (one underground storey). After dismantling the structure (including the footing and the basement) the site was leveled. In compliance with the project design prior to diaphragm wall erection a vertical geotechnical barrier was executed between the nearest building and the designed diaphragm wall.

At this stage injectors were driven into soil and the first grouting cycle was performed, i.e. fill-in grouting (30 liters at 0.5 MPa at each point). After a vertical geotechnical barrier was completed the next grouting cycle (compensation grouting) was carried out in accordance with the monitoring data. In spite of injection pressure increase it was not possible to inject grout at each point at the bottom. After compensation grouting cycle soil was excavated from the pit and a strutting system was mounted. It was initially planned to excavate the pit in three stages: the first two following the installation of struts tier by tier (to 0.5 m below the tiers), while the third one was planned all the way down after the 2nd strutting level completion. In fact, excavation was performed in two stages in order to optimize the earth works, in view of already completed protective geotechnical barrier between the pit and the nearest building and already executed additional compensation grouting. The first cycle of excavation was made to 5.5 m depth from the ground surface and the second to the design depth. This alternative excavation and struts installation plan was supported by respective analysis.

2.3 *Computer simulation*

Diaphragm wall geotechnical analysis was performed with the help of PLAXIS FEM, 8 software. There was analyzed stagewise excavation (for 3 and 2 stages), followed by struts installation, with the account of buildings, located very near the diaphragm wall (2.1 m). As is known, the analysis yields design settlements, generated by the soil base SSS change under footings due to retaining structure displacements in the course of pit excavation. The analysis does not account for technological settlements, appearing during underground structure retaining wall and strutting system construction operations. Such settlements could be assessed qualitatively on the basis of construction know how for similar conditions. The design and construction experience prompts that such settlements may be as great as 40% of the total settlements of buildings, located nearby the construction site (Shuljatjev and Mozgacheva 2004).

Analyses, for no-protective-measures case, showed that the design settlement of the building footing nearest to the construction site will be 19 mm (Figure 3), i.e. greater than the allowable limit for the buildings of the historical area as per Moscow regulations. Besides, the technological settlements of the footings of the building, located at 2.1 m from the excavation, could be 20 . . . 25 mm [5], i.e. the total settlement should be 39 . . . 44 mm.

In view of the foregoing, an analysis was performed, allowing for the geotechnical barrier between the retaining structure and the building footings. The analysis simulated the following stages:

1. The analyzed zone loading by soil weight proper and determination of in-situ soil mass SSS.

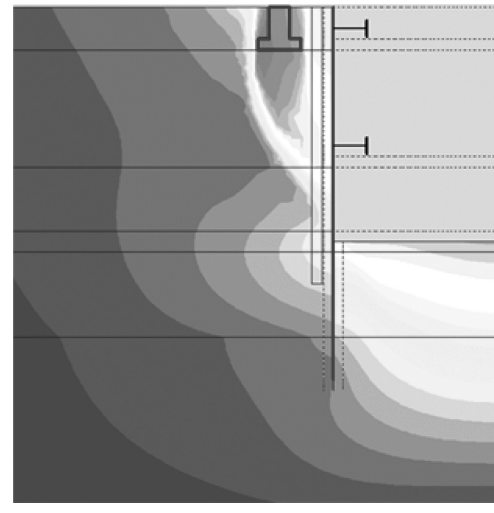

Figure 3. Total settlements of the building N1 without geotechnical barrier.

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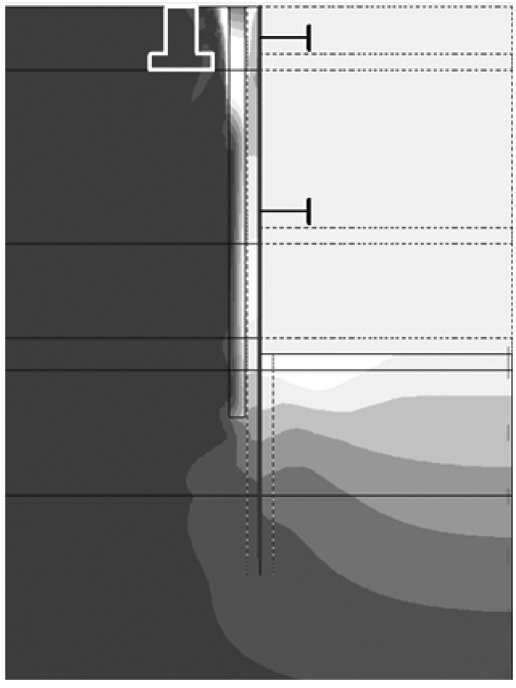

Figure 4. Total settlements of the building N1 after erection of geotechnical barrier.

2. Simulation of the mass SSS change induced by the protected building footing loading.
3. Simulation of soil mass SSS variation due to the geotechnical barrier erection, taking into account the first stage of operations (fill-in grouting).
4. Simulation of soil SSS variation due to erection of retaining structure, strutting system installation and pit excavation (two soil excavation stages).
5. Simulation of soil SSS variation during the second geotechnical barrier grouting (compensation grouting).

The analysis yielded 6.9 mm settlement of the footing nearest to the construction site at the final stage of operations (pit excavation up to the design depth and execution of the 2nd injection cycle, i.e. compensation grouting) (Figure 4). At the intermediate stage (excavation to the design depth without further compensation grouting) the analytical settlement was 13 mm.

On the basis of the performed analysis a detailed project design of the geotechnical barrier was elaborated. The project design envisaged driving of 12 m long injectors into the soil (10 m deep grouting zone) spanned at 0.5 m. The geotechnical barrier axis is located at 1 m distance between the protected building footing and the diaphragm wall. Fill-in grouting as per the project design shall be carried out before the diaphragm wall trench excavation operations start-up.

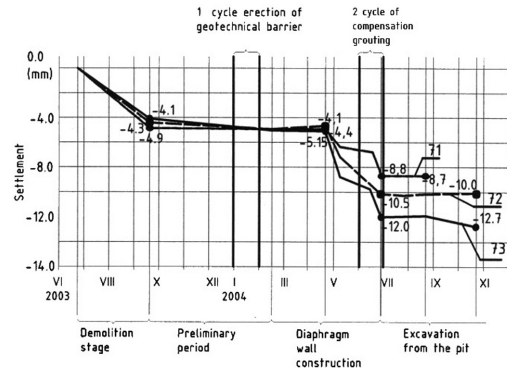

Figure 5. Time – settlement diagram at settlement control points 71, 72, 73.

Thereafter, it was planned to carry out a number of compensation grouting cycles in accordance with the monitoring data.

Notably, when a vertical geotechnical barrier is erected, the diaphragm wall bending moments and plane displacements take place. Respectively, the diaphragm wall reinforcement was designed with the allowance for the barrier influence.

The percentage of injected grout, consumed to fill in soil pores and the one to compact and to displace soil is an essential issue. During grouting process PLAXIS simulation soil expansion percentage rate is introduced. Herein, we assumed 5% at fill-in stage and 3% at compensation grouting stage for geotechnical barrier execution. The obtained displacement values of the retaining structure and those of the footing nearest to the pit were compared with the monitoring results.

2.4 *Monitoring results*

Monitoring was performed during construction operations: nearby building settlements (geodetic leveling); vertical deformations of soil layers in bore holes and plane soil displacements (with the help of inclinometers); plane retaining structure displacements (using inclinometers) and ground water table. All surrounding buildings had ∼2 mm settlements during the whole length of monitoring cycle (from 26 June, 2003 to 21 October, 2004). Nearest building N1 had maximum footing settlement (−12.7 mm). At the demolition stage settlements of the building N1 were 4.1 . . . 6.1 mm. Maximum technological settlement, generated by diaphragm wall construction, was 8.3 mm (Figure 5).

A decision was made, based on footing settlements measurement data, to perform the second grouting cycle (compensation grouting). Cement grout was injected by small portions (30 liters) with 2.0 MPa pressure. The Figure 5 shows that after the second grouting cycle the settlements tend to stabilize. Some

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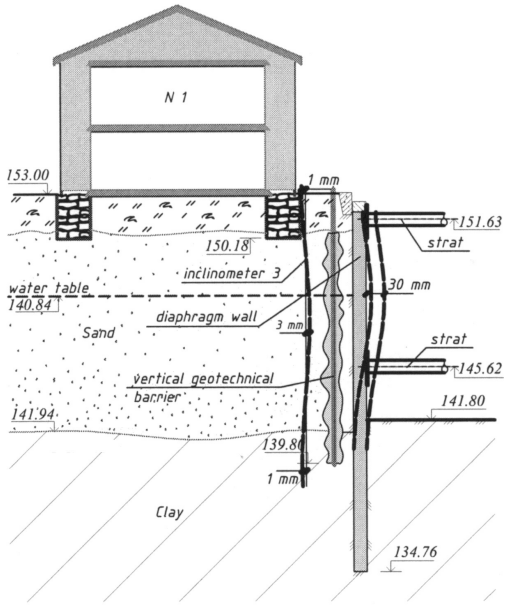

Figure 6. Excavation profile near building N1.

of the control points had a minor (up to 0.5 mm) rise after injection. Settlements of building N1 footings were also measured during pit excavation, and with the help of inclinometers plane deformations of soil and the retaining structure were measured as well. The registered footing settlements, generated by excavation of soil from the pit, were from 1.2 to 4 mm that coincides with analytical data. Diaphragm wall displacement towards the pit was 30 mm (it was 31.7 mm from the analysis). Maximum soil mass displacement, measured in bore hole for inclinometer 3, located between the geotechnical barrier and the footing of the building (Figure 6), was 3 mm. Hence, monitoring data proves geotechnical barrier effectiveness.

Monitoring data was also used to evaluate the injected grout volume that filled voids, compacted and displaced soil. In fact, a converse problem was solved to determine the volume expansion percentage rate of the soil adjacent to the geotechnical barrier, using actual retaining structure displacements and soil mass displacements by varying soil volume expansion percentage until the analytical values of the protected building footing displacements and those of the diaphragm wall coincided with monitoring data. This parametric study showed that only 16% of the injected grout actually compensated soil displacements and compacted soil while the rest filled in the voids and pores.

CONCLUSIONS

1. The proposed geotechnical barrier erection enables, to a large extent, preservation of neighboring buildings during underground construction and may be recommended for large-scale implementation.
2. When a vertical geotechnical barrier is designed with the help of above technology, just a portion of the cement grout (∼16%) compensates displacements and compacts soil.
3. Geotechnical barrier erection also affects the retaining structure. Therefore, geotechnical barrier and retaining structure shall be designed jointly.

REFERENCES

Mair, R.J., Harris, D.I., Love, J.P., Blakey, D. and Kettle, C. 1994. Compensation grouting to limit settlements during tunnelling at Waterloo Station. *Proceeding Tunnelling. 94*, London, Institution of Mining and Metallurgy, Chapman and Hall, pp. 279–300.

Harrs, D.I., Menkiti, C.O., Pooley, A.J. and Stephenson, J.A. 1996. Construction of low-level tunnels below Waterloo Station with compensation grouting for Jubilee Line Extension. *Symposium on Geotechnical Aspects of Underground Construction in Soft Ground*, London, R.J. Mair and R.N. Taylor Eds, pp. 361–366.

Schweiger, H.F. and Falk, E. 1998. Reduction of settlement by compensation grouting – Numerical studies and experience from Lisbon underground. *Proceeding of World Tunnel Congress-98 on Tunnel and Metropolises*. San Paulo, April, A. Negro and A.A. Ferreira Eds., Vol. 2, pp. 1047–1052.

Petrukhin, V.P., Shuljatjev, O.A. and Mozgacheva, O.A. 2001. Monitoring of a building behavior during compensation grouting operations. *International Geotechnical Conf.*, St. Petersburg, 2001. (In Russian.)

Shuljatjev, O.A. and Mozgacheva, O.A. 2004. "A vertical geotechnical barrier erected by compensation grouting technique". *International Geotechnical Conf.*, Astana, 2004. (In Russian.)

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