

# Value of additional vertical deformations of foundations depending on injection grouting conditions

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**Abstract.** The possibilities of new construction in the center of Saint Petersburg are quite limited by the requirements for preserving the historical center and by the height restrictions, so the construction of underground space is of great importance for the developing city. Investors are ready to deepen basements and to excavate foundation pits in the courtyards of existing buildings to increase usable space, but before starting such works, a number of compensatory measures are required, one of which is strengthening of foundation bed and foundation body of affected buildings.

## 1. Introduction

To increase the usable area in the center of Saint Petersburg and to preserve the historical appearance of buildings, it becomes necessary to develop the underground space using state-of-the-art technologies [1]. At the same time, additional risks for existing buildings have increased due to their natural wear and tear, occurrence of new temporary and short-term loads on foundations and beds, and due to the introduction of dynamic impact from transport. About 250 years ago in designing of buildings, it was not possible to take these factors into account and, in connection with this, many historical buildings go into pre-failure or failure conditions [4]. These above risks are minimized by means of strengthening the foundations and foundation soils in the impact area of new construction.

This paper provides the analysis of the efforts made regarding the injection underpinning of the foundations of an affected historical building due to the construction of a foundation pit in the courtyard of the existing building. In the course of the work, the dependence was found between the injection conditions of grout based on Portland cement M400 into the weak underlying layers of the foundations and additional vertical rise deformations of the building.

## 2. Engineering and geological conditions on reconstruction site

In the city center, a specific feature of the engineering-and-geological section is specific pervasive banded clayey soils that have thixotropic properties (Figure 1), as well as the presence of a ramified groundwater system. Table 1 shows the engineering-and-geological conditions on the site of the reconstruction facility.

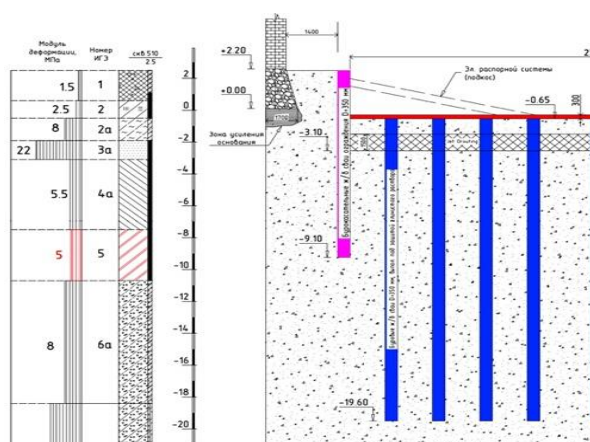
The hydrogeological conditions on the site are characterized by the occurrence of an aquifer of underground water with free surface. Underground water is confined to filled soils (EGE-1) and to sand interlayers in littorina clayey loams and sandy loams (EGE-2/2a). The standing groundwater level is recorded at a depth of 2,0 m from the ground surface. The second aquifer of groundwater is confined to



gravelly and silty sands (IGE-3/3a), the latter serve by discharging underground water of the surrounding area to a river bed located at a distance of 200 meters, as evidenced by screened sands and by decline of the layer base towards the river bed. An artesian horizon is encountered within the depth range of 4,1 – 6,6 meters from the ground surface, a head reaches 4,1 m.

**Table 1.** Physical and mechanical properties of soils.

EGE	Geological Index	$\rho$ , g/cm <sup>3</sup>	$e$	$I_L$	$E$ , kgf/cm <sup>2</sup>	Soil description
EGE-2/2a	m,1 IV	1.48	1.894	3.09	25	Flowing heavy clayey loams with interlayers of silty sand;
EGE-3	m,1 IV	2.00	0.650	-	300	Gravelly sands of medium density, water-saturated;
EGE-3a	m,1 IV	2.00	0.612	-	220	Silty sands of medium-density, water-saturated, with peat impurity and with interlayers of sandy loams;
EGE-4	m,1 IV	1.96	0.772	0.65	90	Heavy silty clayey loams, of soft consistency, fine-stratified.
EGE-4a	m,1 IV	1.91	0.866	1.21	55	Flowing light silty clayey loams, stratified;
EGE-5	lg III	1.78	1.189	1.34	50	Flowing heavy silty clayey loams, banded;
EGE-6	lg III	2.04	0.638	0.52	95	Plastic gritty sandy loams with gravel and pebble up to 5% with lenses of sand with boulders.



**Figure 1.** Engineering-and-geological section.

One of the features of the engineering-and-geological conditions on the site is the presence of a soft layer of the significant thickness that includes littorina and limnoglacial deposits IGE-2/2a/4/5.

### 3. Analysis of survey results

According to the survey results, the foundations of the building are strip rubble-stone foundation on a natural bed. The foundation height is composed of two different materials: the upper part consists of broken limestone on lime mortar, the lower part consists of two rows of cobblestones of igneous rock. In cobblestone-boulder masonry of the lower part of the foundation, there was found strong outwashing of mortar from the cobblestone masonry and the unstable state of stones. Under the bottom of the foundations, there were found longitudinal sleepers - logs 150 mm in diameter. Wood of sleepers is in the satisfactory conditions, but there is decay on its surface.

In view of the above, a decision should be made regarding the most rational way to strengthen the foundation bed and body - injection consolidation using cement-based mortar in various injection grouting conditions. These compensatory measures will make it possible to carry out new construction with the minimum risks near the historical building.

#### 4. Method of operations

The technical and economic efficiency of grouting soft soils is confirmed by many years of practice in Saint Petersburg [3]. The demand for soil grouting technology in strengthening the foundations of existing buildings during their reconstruction or those affected by new underground structures under construction is explained by the absence of dynamic effect on the structures of existing buildings and foundations, by the compact technological equipment and insignificant noise and environmental impacts. Out of the variety of grouting technologies for soil consolidation during the development of underground space in the restrained urban conditions, the most widely used is the technology of injection consolidation of soil in the conditions of impregnation of the pore structure of soil based on cement binder [5].

The method of grouting clayey soils of low permeability is based on obtaining vertical cavities of ruptures filled with cement-sand material of high strength. Soil is reinforced due to the formation of rupture cavities that occur in the soil mass at the initial moment of injection when the discharge pressure exceeds one of the principal stresses in the grouting zone. Under ordinary conditions, this value is the value of one of the principal stresses in the horizontal plane of the injection zone. The rupture plane is formed perpendicular to the minimum principal stress, which determines the horizontal nature of the orientation of the rupture cavities in soil. After they have occurred, the rupture cavities become conductors of injection grouting, and the further pressurized extraction of water from cement-sand material leads to the formation of planes filled with high-strength cement stone.

Soil consolidation operations at the foundation beds were carried out in a residential building of variable number of stores (Figure 2) located at a distance of 1,4 meters from the planned contour of the pit. In this regard, it was decided to comprehensively strengthen the foundations and bed of the building by injection grouting method in the impregnation conditions.

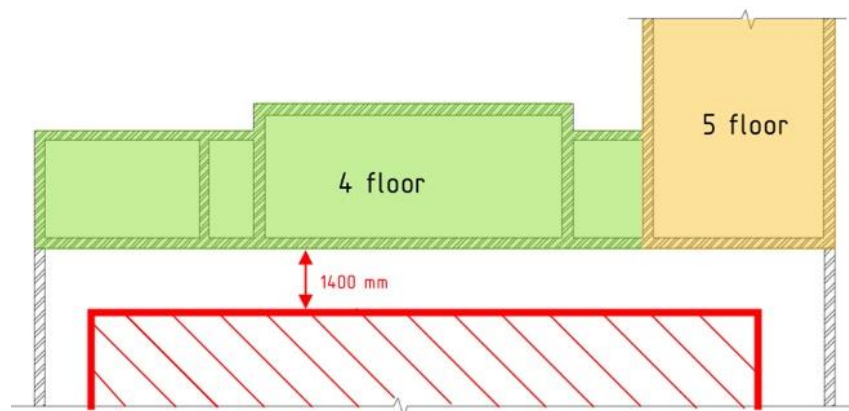


Figure 2. Layout of building.

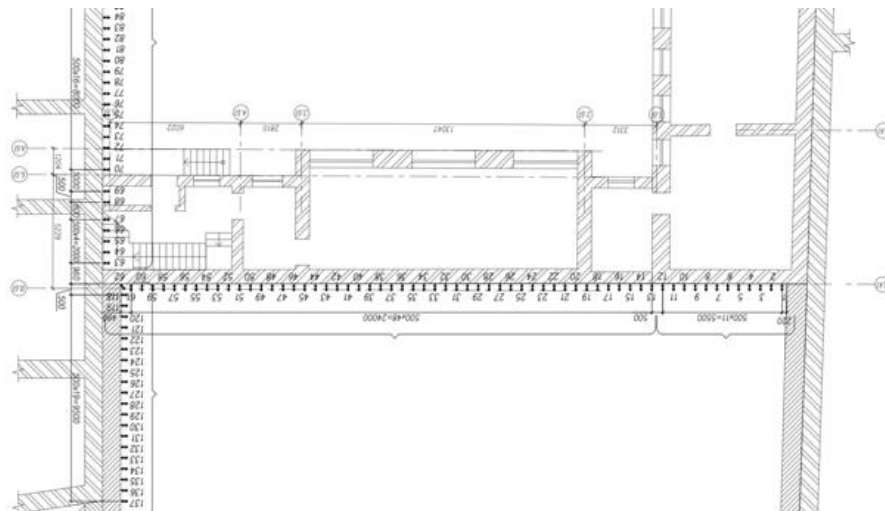


Figure 3. Building underpinning borehole plan.

The foundation under the building is strip rubble-stone foundation on lime-sand mortar; clayey loams of soft and very soft consistency serve as foundation bed. The bed depth (FL) is fixed at a depth of 2 m.

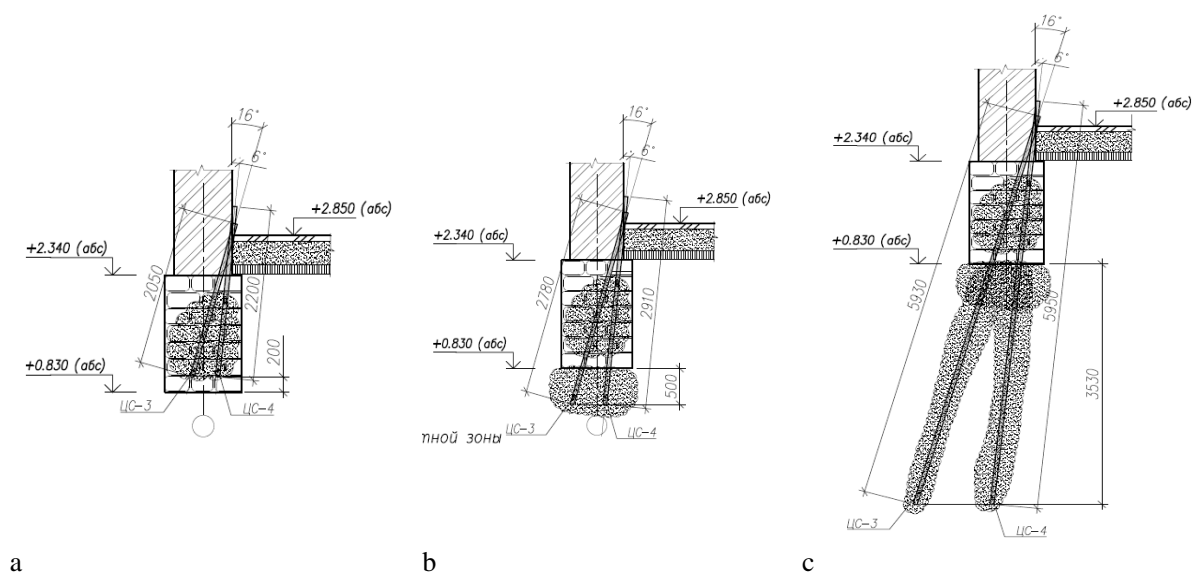
The design provided for the consolidation of soils from September to October inclusive to a depth of 12 m from the foundation bed with cement mortar based on PC400 with a density of not more than 1800 kg/m<sup>3</sup>. According to the design, the spacing of the boreholes was taken to be 500 mm (Figure 3).

The work is carried out in 4 stages:

**Stage I:** The reinforcement of the foundation body by means of constructing boreholes with drilling tools Ø52 mm and injection into foundation masonry (Figure 4a) at W/C = 0.5 and at a pressure no higher than 0.3 MPa. The design volume of grout for Stage I is 150 liters per running meter, the borehole-return-to-thermal-equilibrium time to Stage II is set 2 days.

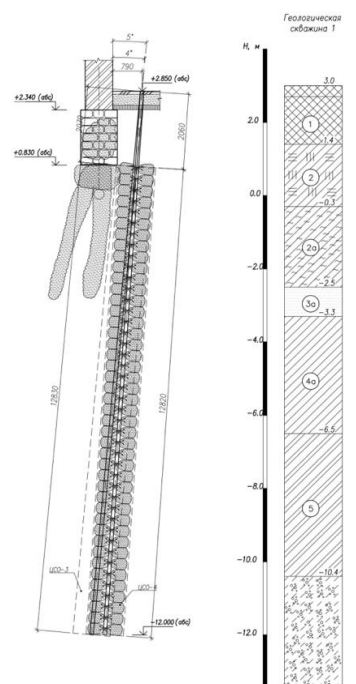
**Stage II:** The consolidation of the contact zone 500 mm below the foundation bed (Figure 4b) represented by flowing heavy silty clayey loams with interlayers of silty sand, by means of drilling the foundation body and supplying injection grout to surface through a metal packer at a pressure no higher than 0.5 MPa and at a flow rate up to 20 l/min. The design volume of grout for Stage II is 200 liters per borehole, the borehole-return-to-thermal-equilibrium time to Stage III is set 1 day.

**Stage III:** The consolidation of foundation soils 3.5 m below the foundation bed (Figure 4c) represented by plastic silty sandy loams by means of drilling the foundation body, the consolidated contact zone and supplying injection grout to surface through a metal packer at a pressure no higher than 0.5 MPa and at a flow rate up to 20 l/min. The design volume of grout for Stage II is 150 liters per running meter, the borehole-return-to-thermal-equilibrium time to Stage IV is set 9 days.



**Figure 4.** Diagram of foundation body consolidation.

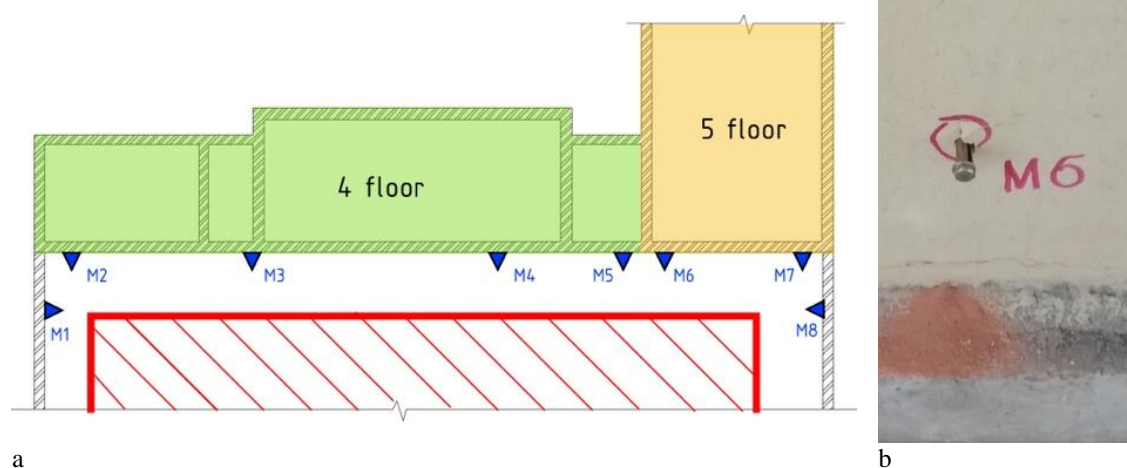
**Stage IV:** The consolidation of the foundation bed using cup-type pipe string technology by means of drilling a borehole Ø112 mm to the design level (Figure 5), filling it with cartridge grout, and setting the borehole-return-to-thermal-equilibrium time to 3 days before the start of the main injection stage. The injection is carried out using injection grout based on cement binder added with CaCL<sub>2</sub> and at W/C = 0.8 from bottom-upwards horizontally with a difference in height of 80 mm, the initial injection pressure is set at 1.5 MPa to break the cartridge, then the pressure is reduced to the operating level of 0.3 MPa, the injection stops at the failure pressure of 0.6 MPa, while the grout flow rate shall be varied up to 5 l/min.



**Figure 5.** Diagram of soil consolidation by method of cup-type pipe string technology.

### 5. Analysis of the monitoring results

Vertical deformations of the building are recorded by a SOKKIA B20 level equipped with an OM5 attachment. The method used for taking geodetic measurements of building settlements is geometric leveling, whose principle is to determine the excess of one point over another using the horizontal sighting beam and vertical rack bars installed at these points. The plan of deformation telltales is shown in Figure 6a, permanent deformation telltales are represented by anchor bolts 8 mm in diameter (Figure 6b) in the amount of 8, which are reliably secured to the pedestal of the building.



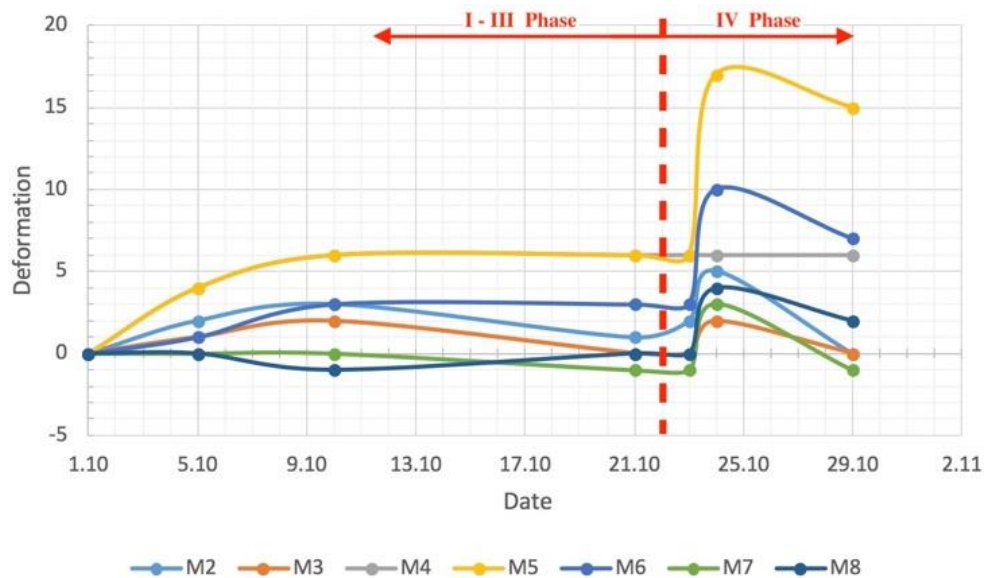
**Figure 6.** Deformation (settlement) benchmarks.

Work on injecting grout were started from the 5-storey portion of the building, the operations were divided into two main stages:

- 1) in the period from 01.10 to 21.10, the foundation body and the foundation-soil contact zone were injected using the technology described above (Stages I-III);
- 2) in the period from 22.10 to 25.10, work was carried out to consolidate the foundation soils using the cup-type pipe string technology (Stage IV).

Let us consider the dependence of the vertical deformations values of the building based on the settlement telltales from the days, on which work was carried out to consolidate the base of the building.

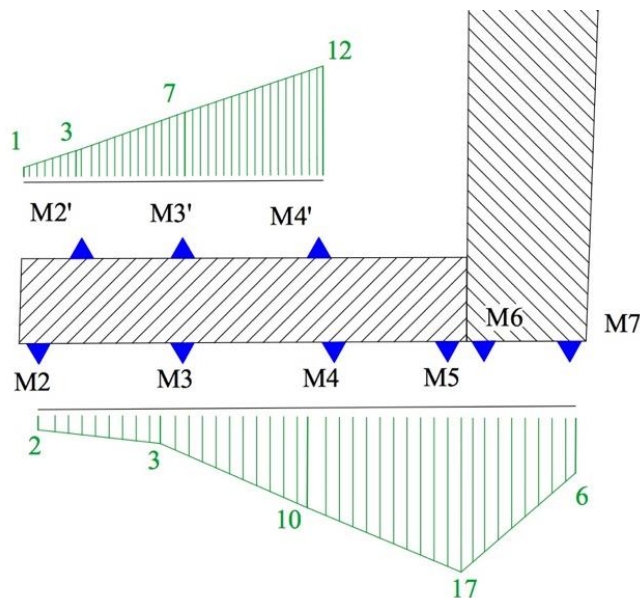




**Figure 7.** Deformation over time.

As it can be seen, figure 7 shows a spike at the time of the beginning of the injection grouting of the foundation soils using the cup-type pipe string technology. At the time of monitoring on 25.10, building rise deformations were recorded as 1.7 cm along M5, which is located at the junction of the 4th and 5th floor sections, as a result of which the injection operations were quickly stopped. The next monitoring cycle was carried out on 29.10, which showed positive dynamics - no vertical rise deformations as a result of the work stopped, but the occurrence of building settlement due to the relaxation of the stress-strain state of the soil mass impregnated with the injection grout.

The consequences of non-uniform rise of building (Figure 8a) led to the opening of existing cracks and the formation of new ones up to 0.25 mm at the level of the 2nd floor at the junction of the building sections (Figure 8b).

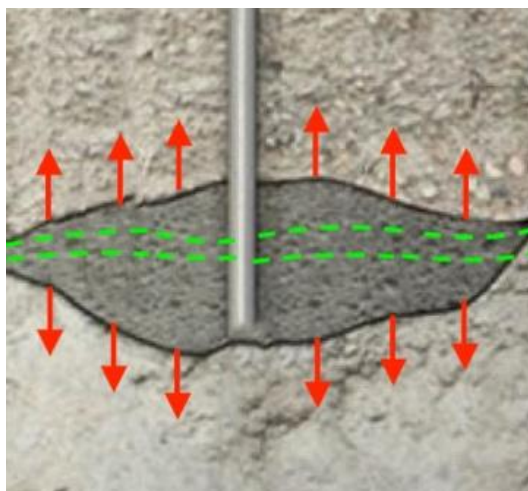


**Figure 8.** Diagrams of rise of deformation telltales and an example of opening of new crack at level of 2nd store.

## 6. Conclusion

According to the analysis results of the operations logs, deviations were found from compliance with the injection failure pressure of injection grout when using the cup-type pipe string technology to consolidate the soil mass to a depth of 12 meters below the foundation bed. As a result of exceeding the failure

pressure (0.6 MPa), hydraulic fracture effect occurs, in which the forces arising in the strip clayey soils become sufficient for non-uniform rise the building up to 1.7 cm. Based on the experience on many sites in the center of Saint Petersburg, it can be concluded that in the operations conditions for injection of soils, it is quite difficult to control the grout injection pressure parameters into the cup-type pipe strings. Due to the specific nature of the of these operations [3], it becomes difficult to catch the moment, at which the pressure exceeds a limit of 6 atmospheres, which results in an uncontrolled rise of the building to be underpinned due to the hydraulic fracture effect (Figure 9).



**Figure 9.** Distribution of injection grout in soil mass in non-compliance with impregnation technology.

During the injection of cement-based grout, due to a size of cement particles, the soil particles begin to shift relative to each other reducing a size of the pore space channels and blocking the further spread of grout in the soil mass, which leads to an increase in the supply pressure and to the transition from the impregnation technology to the hydraulic fracture technology.

This problem is solved by changing the composition of injection grout from Portland cement to finely dispersed cement with plasticizing additive (microcement). As this material has the particle size by an order lower and contains a complex system of additives, it has the high capacity of penetrating into pores of soil compacting and binding soft soil mass. This method of soil grouting with the use of micro-cements in the impregnation conditions has proven itself in soft soil conditions and is the most low-impact method during reconstruction [6].

It is important to pay attention to the selected injection zones. It is necessary to carry out work throughout the entire consolidation element at the same time. Thus, using this building as an example, it was necessary to consolidate soil along the entire length of the building wall at the same time strictly controlling the failure pressure for all injection pump installations. In this case where there is rise or settlement of the building, the risks of the formation of main cracks and the separation of one historic building into separate blocks are minimized.

When examining the foundations of the historical buildings, insufficient attention is paid to the conditions of sleepers, it is recommended that bacteriological and microbiological analysis should be conducted to identify pathogenic microflora. This factor has effect on the rate of wood destruction and, as a result, leads to uncontrolled non-uniform deformation of historical buildings.

To conduct monitoring and early diagnostics of changes in the technical condition of structures of historical buildings, it is recommended that an automated stationary monitoring system should be installed that provides access to data on changes in the stress-strain state of structures with the localization of their hazardous areas and the determination of the level of the building tilt in the automated mode, based on which decisions can be promptly made regarding the adjustment of operation, the reduction of the risk of failure condition occurrence and compensatory measures can be timely taken.

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