Ground-penetrating radar survey for the prevention and elimination of emergency situations

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Abstract. This study analyses the results of a survey of an object in emergency state of a building, identifies the causes of damage, proposes a method for eliminating the consequences, draws conclusions about the possibility of preventing such situations and solutions at all stages of identifying defects. According to the results of a georadar inspection of the underground part of the building, it was found that under the concrete slab there is an air gap zone with a capacity of up to 10–30 mm. In this work, to eliminate the emergency situation, is proposed to utilize a complex solution based on clay and a binder. The work identifies the most effective method for diagnosing the state of bases in case of their discontinuity under the erected construction object. According to the results of the study, the sizes of these zones are determined. A clay suspension fills the voids between the particles of sandy soil and creates conditions that exclude the possibility of further penetration of water into the soil mass. The result of the research allowed to save the object for continued operation.

1. Introduction

The traditional methods of soil research include sounding and test boring with sampling. Regulatory documents indicate the required number and distance between borehole and the depth of the survey depending on the object being built. The situation is similar with test borings. In the conditions of a new construction site, these methods are justified, but if it is necessary to study the foundations of existing objects, considerable difficulties arise due to cramped conditions, the need to damage previously constructed structures (during sounding reinforcement are damaged in densely reinforced structures of foundation slabs). These works are labour-consuming and have limitations on the number of points, due to maintaining the operation capacity of the foundations. In this regard, researchers get a discrete picture of the state of the base. To create a general situation at the facility, one has to apply personal experience and the experience of other researchers in similar conditions, but this assessment will be probabilistic. The radar sounding is deprived of these disadvantages [1-3].

Surface radar sounding (Ground Penetrating Radar (GPR)) is often used to study the structure, identify bearing capacity and detect defects of the base. This method is often used to determine the properties of the soil and to monitor changes in these properties near and under construction. This method not only allows not to break the structure of the soil but also to repeatedly study the same area for a long time to control the dynamics of the changes. This allows to receive a huge amount of digital data that is processed in real time, as a result significantly increasing the accuracy of research and minimizing the probability of error [4-7].
This method does not require significant labor costs and has a low cost, so the method is optimal for many tasks on the study of soil bases. Modern GPR systems are able to accurately determine the location of the "defects" of the base. Moreover, there is a continuous improving of data processing, what leads to an increase in accuracy of the method.

The finite-difference time-domain (FDTD) method is the base for most of existing approaches. The ease of implementation in a computer program and good scalability when compared with other popular electromagnetic modelling methods are the reasons of popularity of this method [7]. The FDTD method has a disadvantage, which is necessity to discretize the volume of the problem space which could lead to excessive computer memory requirements and the staircase representation of curved interfaces. In-depth description of the FDTD method is outlined in [8]. Examples of the application of GPR studies are in the following sources [9-13].

This study analyses the results of a survey of an object in emergency state of a building, identifies the causes of damage, proposes a method for eliminating the consequences, draws conclusions about the possibility of preventing such situations and solutions at all stages of identifying defects.

The construction site has complex hydrogeological conditions. Landing of the building was performed incorrectly, some of the foundations are located at the groundwater level. Execution of construction works led to the creation of pressure movement of groundwater. As a result of groundwater movement, the soil was washed out from under the foundations. As a result, transversal crack associated with its flexure appeared on the foundation plate of the constructed object.

Figure 1 shows the layout of cracks in the foundation plate.

![Figure 1. Layout of cracks in the foundation plate.](image_url)

To control the development of deformations were utilized crack tell-tale. According to them, the progressive development of cracks was revealed. The crack opening width was from 0.5 to 1.5 mm.

The geological conditions of the construction site are presented in table 1. The geologic cross-section is shown in Figure 2.
| Stiff clay | Medium grade, high-silica, medium-density sand | Fine grade, high-silica, medium-density sand | Fine grade, high-silica, high-density sand | Top soil/Filled soil | Soil classification according to Russian all-Union State Standard 25100-2011 |
|-----------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|---------------------|--------------------------------------------------------------------------------|
| 0.257     | 0.210                                         | 0.227                                         | 0.2                                           | 0.107               | Moisture                                                                        |
| 0.423     |                                               |                                               |                                               |                     | Liquid limit                                                                    |
| 0.241     | Water saturated                               | Water saturated                               | Slightly wet                                  |                     | Rolling-out limit                                                               |
| 0.182     | 0.62                                         | 0.57                                         |                                               |                     | Moisture                                                                        |
| 0.86      | 0.9                                          | 0.9                                          | 0.42                                         | 0.94                | Rolling-out limit                                                               |
| <0.7      | 0.1-2.0                                      | 0.04-0.8                                     | 0.04-0.8                                     |                     | Moisture                                                                        |
| 24        | 33                                           | 33                                           | 35                                           |                     | Specified value                                                                 |
| 0.165     | 0.0007                                       | 0.0024                                       | 0.0038                                       |                     | Natural                                                                        |
| 12        | 31                                           | 25                                           | 35                                           |                     | Moisture                                                                        |
| 1.86      | 1.99                                         | 1.95                                         | 1.76                                         | 2.01                | Rolling-out limit                                                               |
| 1.85      | 1.99                                         | 1.95                                         | 1.76                                         | 2.01                | Moisture                                                                        |
| 23        | 33                                           | 33                                           | 36                                           |                     | Specified value                                                                 |
| 23        | 30                                           | 30                                           | 33                                           |                     | Natural                                                                        |
| 0.0776    | 0.0007                                       | 0.0026                                       | 0.0038                                       |                     | Moisture                                                                        |
| 0.0089    | 0.0005                                       | 0.0014                                       | 0.0025                                       |                     | Specified value                                                                 |

Table 1. Geological conditions
According to the results of a georadar inspection of the underground part of the building, it was found that under the concrete slab with a thickness of 400 mm there is an air gap zone with a capacity of up to 10 mm (Fig. 3) along the GPR profile No. 16 of about 12 m long.

According to the GPR profile No. 25, a 30 mm air gap zone was identified (Fig. 4).
According to the GPR profile No. 23 (Fig. 5), numerous zones of soil softening at various depths under the base plate up to 1.5 meters were identified. The presence of a crack in the foundation plate along axis 3 coincides with the zones of soil softening (Fig. 3) 2-4 meters. The crack along axis 7 is caused by 4-6 (Fig. 5). Cracks along the axis from 14 to 17 are caused by the presence of soil softening zones from 8 to 12 m. For additional control, holes were drilled in the foundation plate of the building at three points shown in Figure 1 and the soil conditions were studied by static sounding. As a result, it was revealed:

Point 1 - no cavities;
Point 2 - cavity 100 mm;
Point 3 - cavity 30 mm.

2. Methods

In this work, to eliminate the emergency situation, is proposed to utilize a complex solution based on clay and a binder, what is supposed to lead to achievement of the following goals:

1. Creating a water resistant layer under the foundation slab.
2. Moisture sorption from the water-saturated soil mass.
3. Filling voids in a soil softening layer.
4. Improvement of physical and mechanical characteristics of the soil, increase in bearing capacity and density, porosity reduction.

To simulate the situation, hardening solution was introduced into soil samples. Soil samples with porosity close to the porosity of the strengthening soil were molded into formwork 100x100x100 mm in size. The samples were covered with a lid and a reinforcing solution was pumped into the holes
made on the lid with a syringe. For each composition, 9 samples were made, 3 of which were dismantled on the 7th day, 3 samples on 28 day, and 3 samples on 56 day in accordance with the methods of the authors [14-15]. The compositions of the strengthening composites and the concentration are presented in table 2.

**Table 2. Strengthening compositions and their concentration in the soil.**

| Sample Group No. | Clay soil, % | Lime waste, % | Plasticizer polycarboxylate P-16, % | Water, % | Concentration in soil, % |
|------------------|--------------|---------------|-------------------------------------|----------|--------------------------|
| 1                | 32           | 44            | 2                                   | 22       | 20                       |
| 2                | 38           | 37            | 1.7                                 | 23.3     | 20                       |
| 3                | 46           | 30            | 1.5                                 | 22.5     | 20                       |
| 4                | 52           | 26            | 1.1                                 | 20.9     | 20                       |
| 5                | 60           | 20            | 0.8                                 | 19.2     | 20                       |
| 6                | 72           | 12            | 0.4                                 | 15.6     | 20                       |
| 7                | 79           | 6             | 0.1                                 | 14.9     | 20                       |

After dismantling, the density and humidity of the samples were measured, the destruction of the samples was carried out without drying, the average value for each parameter was calculated for groups of 3 samples.

The test results of the samples for physico-mechanical characteristics are presented in table 3.

**Table 3. The results of the test samples.**

| Sample Group No. | Density, \( \text{g/cm}^3 \) | Humidity, \( \% \) | Strength at 7 days, MPa | Strength at 28 days, MPa | Strength at 56 days, MPa |
|------------------|-------------------------------|-------------------|--------------------------|--------------------------|--------------------------|
| 1                | 1.77                          | 5                 | 1.6                      | 4.3                      | 4.8                      |
| 2                | 1.77                          | 8                 | 1.5                      | 4.1                      | 6.1                      |
| 3                | 1.93                          | 7                 | 1.3                      | 5.2                      | 5.8                      |
| 4                | 2.10                          | 11                | 1.5                      | 5.1                      | 6.0                      |
| 5                | 1.78                          | 13                | 1.3                      | 5.1                      | 5.9                      |
| 6                | 1.75                          | 15                | 1.4                      | 4.8                      | 5.7                      |
| 7                | 1.71                          | 18                | 1.3                      | 4.3                      | 5.3                      |

The graph of strength gain is shown in the figure 6.

**Figure 6. Strength gain of the sample.**
The microstructure of the reinforced soil sample is shown in Figure 7.

3. Results and Discussion

The pumping of the solution should be carried out to refusal. The pumping rate should not exceed 5-10 liters per minute.

Injection from the surface of the foundation plate. The preparation of a clay suspension is carried out in the following order:
1. Adding water in the mixer
2. Adding plasticizer and additives
3. Adding lime waste feed
4. Mixing for four minutes

The volume of the suspension is calculated for each strengthening point according to the equations 1.

\[ V = V_n K_1 K_2 \]  

where \( V_n \) is the volume of the cavity, \( K_1, K_2 \) are the loss coefficients due to the filtration of water from the suspension into the soil and the flow pressure. For water-saturated soils \( K_1 = 1 \), for wet \( K_2 = 1.1 \), for slightly wet soils \( K_1 = 1.2 \) [15].

The obtained results are consistent with the results of studies [16-20].

4. Conclusions

The work identifies the most effective method for diagnosing the state of bases in case of their discontinuity under the erected construction object. According to the results of the study, the sizes of
these zones are determined. To ensure the possibility of further operation of the facility, a method of soil strengthening was proposed. This strengthening technology allows to fill the formed cavity and achieve high water resistance of the strengthened base.

A clay suspension fills the voids between the particles of sandy soil and creates conditions that exclude the possibility of further penetration of water into the soil mass.

The effect of lime waste (slaked lime) on clay soil is caused by aggregation of dispersed clay replaced by calcium of other exchange cations (Na+, K+) by pozzolanic reactions in the interaction of lime with free silica, with the interaction of Ca(OH)2 with CO2 to form CaCO3, which leads to soil cementation.

The proposed method is more effective from economic and technological points of view, compared with the most common method of soil cementation.

The result of the research allowed to save the object for continued operation.

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