Survey of the damaged closely located buildings in the historical part of the Sanaa city (Yemen)

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Abstract. The results of a technical survey of buildings with damage caused by the mutual influence of nearby buildings in the city of Sanaa (Yemen) are presented. The stress-strain state of the foundation is calculated by the finite element method (FEM) using software «Plaxis 3D».

Introduction
In residential and public buildings, built 50 ... 100 years ago, there are significant damage in the form of cracks, unacceptable sediments and tilts. The reasons for this, as a rule, are the base soils deformations caused by the violation of their moisture conditions [3, 5, 8 ... 11]. The development of rheological processes in soils leads to the gradual accumulation of defects, breaking bonds [1 ... 3,5,10,11], including the complete failure of the supporting structures.

A number of methods developed to strengthen the buildings’ foundations [5, 6, 9, 11], increase the rigidity of the building and eliminate roll.

The issues of calculating the bases are considered in detail in [7], and materials and structures in [4, 8, 9], as well as in the works of D.F. Bell (1984), D. Boyl (1986), V.G. Grozdov (2004), D.A. Collins (1984), N.A. Makhutov, V.S. Plevkov (2001 ... 2010) and others.

The surveyed houses of Al-Buheitî, Al-Kibsi, and Al-Maori (Figure 1) are located in the historical district of Daud, the historical part of the Sanaa city, the capital of Yemen. They are the monuments of old architecture, and are notable for the fact that the middle house and the house located on the right banked to each other.

To identify the causes of the roll and assess the deformation danger of closely located houses in summer 2019, a full-scale examination was performed by A.Ya. Al Buheitî. It included: visual inspection, a survey of residents, the buildings’ constructive solution study, deformations measuring, determining the physical and mechanical characteristics of soils, establishing the initial terrain. The features of the inter-house territories’ use over the past 50 years are clarified; the adverse factors are established.
Figure 1. Mutual influence of Al-Kibsi and Al-Maori buildings

The following has been established:

1. The houses were built in the middle of the 19th century, on the rough terrain; Al-Kibi House is located 0.5m higher than Al-Maor House, located on a flatter area.

2. The walls’ material of the considered group of buildings is rubble stone (sandstone), a masonry mortar based on clay. Bearing walls have a thickness of 0.7 ... 1m; floor height 3.5 m; wooden floors.

3. The foundations are also laid out from rubble stone resistant to salt solutions, the laying depth is 1 meter. Masonry mortar between the stones is based on raw clay with sand. The foundation width is 10 ... 20cm wider than the walls’ width.

4. When examining the load-bearing walls of Al-Kibsi and Al-Maori buildings, there were no subsidence cracks, and for this reason the owners did not perform any restoration or the foundations reinforcement.

5. The tilt of the Al-Kibsi house is 0.038 (the deviation of the top of the house at a height of 16m was 0.6m), which is 6 times higher than the maximum permissible values for the ancient monuments in operation. Al-Maori Residential Building also has a significant tilt up to 150mm at the wall top with a building height of 16 meters. These both buildings can be considered in the emergency state according to the Russian standards.

6. The tilt of the Al-Maori house is 0.01 (the deviation of the house top at a height of 16m was 0.15 ... 0.16m), which 2 times exceeds the maximum permissible values of Building Codes 22.133330.2011.

7. The base foundations are sandy with the rock inclusion. The results of soil studies are shown in Table 1 and in Figures 2, 3.
Figure 2. Location of the Sanaa city on tertiary and quaternary volcanic rocks

Figure 3. The structure of the soil’s upper layers and the characteristic sections

Figures 2, 3 show the general picture of the soils’ geomorphological structure in Yemen. Upper and middle quaternary young volcanic rocks are overlain by the black alkali. Not far from the city the tectonic folds, indicating the active seismicity of the area, are observed. In addition, the central
historical part of the city with the buildings under consideration has a significant cultural layer of bulk soils where the foundations’ buried remains can be found. Table 1 below shows the soils’ characteristics from a house under construction, then these data will be used in mathematical modeling of soil deformations.

**Table 1. Foundation soils’ characteristics**

| Physical and mechanical soil characteristics | Soil layers                                                                 |
|---------------------------------------------|-----------------------------------------------------------------------------|
| Soil type                                   | Fine sand gravel with a small amount of cobblestone with clay silt          |
|                                             | Silty FINE SAND with a little gravel                                       |
|                                             | Fine gravel with a small amount of silt                                     |
|                                             | Fine sand clay with a little gravel and silt.                              |
|                                             | Fine sand clay with a little silt.                                         |
| Average layer thickness [m]                 | 2.0 – 5.0                                                                  |
|                                             | 2.0 – 3.5                                                                  |
|                                             | final                                                                      |
|                                             | 2.0 – 3.0                                                                  |
|                                             | 2.0 – 2.5                                                                  |
| Bulk density $\gamma_b = g/ \text{cm}^3$  | 1.83                                                                       |
|                                             | 1.79                                                                       |
|                                             | 1.81                                                                       |
|                                             | 1.58                                                                       |
|                                             | 1.54                                                                       |
| Dry density $\gamma_d = [g/ \text{cm}^3]$ | 1.79                                                                       |
|                                             | 1.73                                                                       |
|                                             | 1.76                                                                       |
|                                             | 1.54                                                                       |
|                                             | 1.5                                                                        |
| Natural humidity [Wc%]                      | 2.44                                                                       |
|                                             | 3.2                                                                        |
|                                             | 3.13                                                                       |
|                                             | 2.86                                                                       |
|                                             | 3                                                                          |
| Angle of internal friction $\phi$, [hail]  | 31.5-42                                                                    |
|                                             | 30.39 – 37.58                                                              |
|                                             | 35.21                                                                      |
|                                             | 25.03 – 26.71                                                              |
|                                             | 30.05                                                                      |
| Specific adhesion, [kPa]                    | 0.02 – 0.096                                                                |
|                                             | 0.072 – 0.138                                                              |
|                                             | 0.039                                                                      |
|                                             | 0.175                                                                      |
|                                             | 0.166                                                                      |
| Poisson’s ratio, $\nu$                      | 0.402                                                                      |
|                                             | 0.441                                                                      |
|                                             | 0.424                                                                      |
|                                             | 0.564                                                                      |
|                                             | 0.499                                                                      |
| Shear rate $f_s = tg \phi$                  | 0.74                                                                       |
|                                             | 0.67                                                                       |
|                                             | 0.70                                                                       |
|                                             | 0.48                                                                       |
|                                             | 0.57                                                                       |

* soil moisture between the houses varied from a water-saturated state to air-dry due to the changes in the operating conditions of houses and inter-house territories.

The section between Al-Kibsi and Al-Buheiti houses was a stone paved alley where rainwater disposing was provided. The passage between the deformed houses of Al-Kibsi and Al-Maori for many years did not have a hard surface, sufficient insolation and ventilation. A little deeper, along the quarter inside there was a terrestrial yard, which contained buried water tanks, water leaks into the ground occurred. At the end of the last century, a tiled room (store) was erected in their place, which completely blocked the lane.

The Al-Kibsi house residents had been observing the deviation for a long time, but only about 20 years ago, the tilt of the Al-Maori house started developing in the direction of the Al-Kibsi house. After building a store between them with a tile floor and shading the area, the soil remained in a water-saturated state for many years. It is known that the soils’ mechanical characteristics, in particular, the specific adhesion and deformation modulus, are sharply reduced. The soils’ condition with reduced mechanical properties is observed both in the aisle and under the foundations of deformed houses adjoining it.

**Technical Survey Results:**
The Al-Kibsi and Al-Maori houses’ nature deformation analysis showed that they turned in the longitudinal direction as the blocks have significantly greater rigidity than the foundation rigidity. As a result, no cracks were found in the houses. In addition, the plasticity of the masonry mortar based on raw clay leads to the deformation energy absorption. Periodic repairs, including plastering, hide the real picture of the houses’ deformation.

The houses were not monitored, so there is no information on the tilt development over time. In future, the deformation rate may increase, the tilt will reach a critical value, leading to a loss of stability and the collapse of the Al-Kibsi house. At the same time, the house of Al-Maori will receive significant damage to the facade from the side of the house of Al-Kibsi (Figure 4).

**Figure 4.** The layout of the surveyed buildings: a, b) the main facades; c) - top view

An important task in this situation is to stop the tilt and straighten the position of the middle building. Below are the recommendations for their implementation. As for the Al-Maori house, here it
is necessary to stop the tilt development by injecting a cement-sand mortar into the base foundation along the facade facing the Al-Kibsi house.

The proposal to eliminate the middle building tilt: taking the weak strength characteristics of the building and the possibility of a sudden collapse, restoration work should be carried out extremely carefully, avoiding any dynamic impacts on soils.

We propose to apply the method of the inclined indented piles - racks developed in the mid-90s by the Penza company Novotekh, together with the Penza State University of Architecture and Construction.

Figure 5. Strengthening foundations with the pressed piles: a) grillage reinforcement scheme; b) factory-made pile parts; c) the grillage exterior

Initially, the foundation walls are strengthened by the repair mortars’ injection. Before their installation, the holes are usually drilled in the building basement with a width of 60 cm and a pitch of 150-250 cm (Figure 5, a). In these holes, metal frames K-2 are installed, to which the girdle frame K-1 grillage is welded and monolithic with concrete of class B15 is applied. After the concrete grill has gained strength with the help of hydraulic advancing cylinder, supported together the grillage into the punched hole in the wall, the pile cylinders prefabricated at the factory with a diameter of 25 and a height of 30 cm at an angle of 10 ° to the vertical start being pressed (Figure 5, b).

The first (lower) cylinder P-1 has a conical sharpening downward. This method allows not only to increase the bearing capacity of the existing foundations, to eliminate the tilt, but also to strengthen the destroyed foundations by the encircling monolithic reinforced concrete grillage (Figure 5).

Finite element study.
The calculation was performed by the finite element method using a software package “Plaxis 3D”.
The data for the base soil calculation is shown in Table 1.
The stress state simulation of the “base-foundation-building” system is performed. As an example, the base soils’ displacements and loads distribution patterns are given (Figure 6).
Figure 6. Mathematical modeling of soil movements at the buildings’ foundations:

a) construction of a calculation model, determination of the buildings’ rotation; b) the bases
soil movements diagrams;

c) zones of maximum soil movements, and zones of weak soil;

d) the buildings’ movements calculation result;

e) stress fields in the soil base.

Analysis of the mathematical modeling results
The program calculations’ results (Figure 6, a-c) showed the maximum displacement of thee soils under the foundation of the middle building’s main face 234 mm, and the minimum value of displacements 40 mm, with a facade width 7 meters, the tilt value was 0.028, which is quite close to the real tilt 0.038. The Al-Buheitii building tilt (Figure 6, c) is close to zero, in reality we also do not see any movements in this building.

Figure 6a shows the calculated movements of the buildings, where the maximum tilt of the middle building was 603 mm. The observation results showed approximately 600 mm.

The calculations showed a tilt of the Al-Maori building towards Al-Kibs by 0.011, in practice its value is 0.01. In fact, the additional settlement of these buildings’ foundations is almost the same. The buildings’ tilt turned out to be different due to different widths, i.e. height to the width ratio.

The stress fields in the base-building system (Fig. 6, e) reflect the involvement of all five soil layers in the work. Maximum voltages are in the contact zone. At the same time, the soil located between the deformed buildings is almost not involved in the work, because it has weak mechanical characteristics.

Summary
1. In the old cities of Yemen, there are many buildings with architectural expressiveness, distinguishing the local flavor, but built without projects, without taking into account the geological conditions. In addition, during operation, the residents make significant functional and design changes.
   2. The reasons for the buildings’ tilt are:
      - local decrease in the soil foundations’ strength due to their systematic soaking.
      - the mutual influence of the neighboring buildings.
   3. Banks of houses exceed (up to 6 times) the maximum permissible values according to Russian standards. Possible loss of stability and the collapse of the average building. Earth vibrations from earthquakes or heavy traffic can speed this process up.
   4. No cracks were found on the deformed buildings’ facades, and the nature of their movements is similar to the rigid bodies’ rotation, indicating their high stiffness compared to the base. The plastic mechanical behavior of the clay-based masonry mortar absorbs the deformation energy of the structural system due to creep. In addition, the periodic maintenance of old houses in Sanaa, plastering masks any weak or cracked areas that are always treated with plaster.
   5. Finite-element modeling made it possible to evaluate the occurrence of roll due to the mutual influence of buildings and the presence of a soil weakening zone. The calculated results correlate well with the observational results.
   6. The recommendations to prevent the collapse of the middle building, the vertical layout of the territory with organized rainwater drainage, to strengthen the foundation of the far-right building by cement-sand mortar injecting or to reduce soil moisture are proposed.

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