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Analysis of the Behavior of Foundations of Historical Buildings

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Abstract

The article is devoted to the analysis of the behaviour of the foundations of historic buildings. Some basic aspects of foundation engineering are discussed, with an emphasis placed on its development, applied techniques, and materials. Several different approaches and methods for the analysis of foundations of historical buildings are presented. A particular analysis has been focused on an example of a typical stone foundation from the sixteenth century. First, the calculations have been performed using the finite element method, then the bearing capacity and the settlement analysis has been determined according to EC-7. Next, the bearing capacity has been evaluated using simplified analysis. A settlement of the foundation has been also estimated using Kerisel's proposal. The information should allow for a better understanding of the behaviour of foundations discussed in this research, and especially of methods of their analysis. A comparison analysis has been performed and possible directions for further research in this field have been indicated.

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*Keywords:*historical buildings; settlement; bearing capacity; numerical analysis;

1. Introduction

Analysis of the behaviour of the foundations of historic buildings is usually quite difficult or even impossible. Their work can be carried out in many different aspects, taking into account in particular: the kind of foundation and the object placed upon it, the material, the shape and dimensions of the foundation, bearing capacity and settlement

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of foundation and geological substructure conditions. In a wider context, one can also consider a number of other elements such as the level of settling of the foundation, the hydrogeology, groundwater aggressiveness and other physical factors – chemicals that affect the foundation rotation or uneven settling of the foundation, etc.

Studies oriented towards a better understanding of the mechanical behaviour of old structures are still carried out. Some reviews of analytical methods dealing with masonry have been given by Theodossopoulos and Sinha [7] or Valluzzi et al. [8]. Giordano et al. [2] and Lorenco [4] have applied different numerical techniques for the analysis of such structures. Unfortunately, in the literature, there are not many comprehensive studies devoted to foundations of historical buildings [1,3,5,6]. Most of the papers concern the diagnostics and maintenance of particular objects and only a few analyze the mechanical behaviour of old foundations. The issue of the necessity to analyze the foundations of historical buildings and some proposed resolutions have been discussed by Kerisel [3] and Dardzińska [1].

2. Characteristics of foundations of historical objects

Since the beginning of the history of construction the most popular materials were brick, stone and lumber. Brick foundations in ancient times were made initially with sun-dried mud bricks and later with fired bricks. It is obvious that dried bricks cannot be used to make foundations. Their uses in ancient times were due to the lack of alternatives and as a result led to a significant reduction in the durability of objects of this era. Significant differences were noted in the basic physical and mechanical characteristics of fired brick of past epochs versus those produced today. They arise from a different course of forming bricks and a different process of firing. A fundamental change in the method of the manufacture of bricks finally occurred in the mid-nineteenth century, as a result, inter alia, of the invention of the bend press that produced bricks with a pulling method; the use of a vertebral furnace; and the improvement of the drying system.

Stone foundations were mostly used for sacred buildings and public utility structures. Various types of stones were used, depending on the function of specific elements of a building, the available equipment and workmanship, and the geographic location. Often granite, limestone, sandstone, sandstone volcanic tuff, or even marble was used. The majority of stone foundations of historic buildings did not have offsets at all or they were not extended to the bottom. In addition, it would’ve been difficult in the past to find mortar that would be in accordance with currently recommended mortar strength requirements (excluding pozzolan). The fact that such foundations are still effectively supporting many historical buildings should therefore be explained by their oversized measurements. Figure 1 presents the views of a few medieval foundations located in two Polish towns.

a b c

Fig. 1. View of foundations: (a) historical building in Olsztyn at Staromiejska Street;
(b) old granaries at Basztowa Street in Gdańsk; (c) old granaries at Chmielna Street in Gdańsk.

3. Analysis of the behaviour of foundations

3.1. Stresses and displacements – numerical analysis

A properly designed and constructed foundation should be adapted not only to the type of building placed on it or the nature of its use, but also to the geotechnical and hydrogeological conditions of the ground. While analysing each foundation, it is important to verify two basic conditions: the bearing capacity and the limit state of usage, which are included in standards. It should be noted that in the case of exceeding the bearing capacity of the soil, immediate intervention is necessary, aimed at strengthening the substrate or the foundation. Intervention is also necessary in the case of a threat to the stability due to slips of the soil or turning of the soil. As far as the horizontal displacement and settlement, the determination of the limit of their size is often subjective and requires appropriate arrangements. It is essential to determine the maximum stress at foundation and in the subsoil when two normative conditions (the ultimate and serviceability limit states) are verified.

Numerical analysis was performed using the finite element method in Abaqus software. Figure 2 shows a photo and a cross section through the foundation of one of the walls inside the historical building together with geotechnical profile at Staromiejska Street in Olsztyn (Poland).

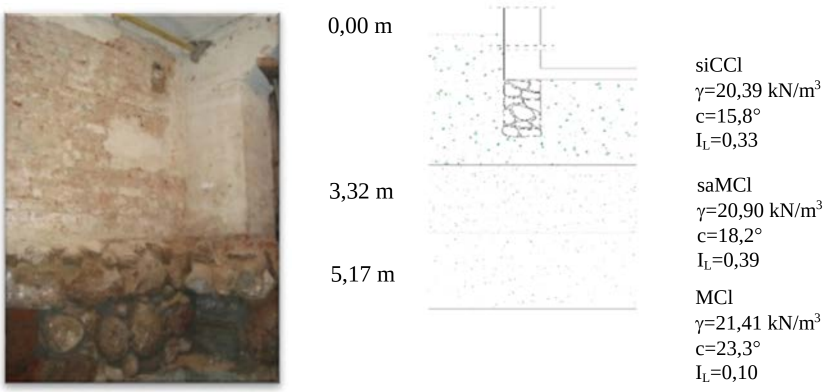

Fig. 2. Cross-section of foundation of historical building at Staromiejska Street in Olsztyn (Poland) together with geotechnical profile.

The foundation of the considered building is a typical stone foundation from the16thcentury. The dimensions of the foundation and its depth vary slightly along the length of the building. The following geometrical properties of the foundation have been assumed in the analysis: width - 0.57 m, height - 0.87 m, depth - 2.20 m. The subsoil underlying the foundation consists of three layers of soil (Figure 2). The geotechnical parameters of particular soil layers have been determined from the data for soils (EC-7 standard and basic relations between soil properties). Thickness of particular soil layers differs from 0.5 m to 2.50 m, which can be seen in scheme of foundation (Fig. 3a). With regard to the serviceability limit state, the most unfavourable fragment of geotechnical intersection has been taken for analysis. The total weight of 171.40 [kN/m] has been applied on the foundation. The foundation itself as well as subsoil has been modelled using solid elements with 6 degrees of freedom at each node (3 translations and 3 rotations). The mesh of the FE model has been created with triangle and quadrangle prisms. The number of nodes is equal to 5827 and number of elements is as large as 3928. Connections between the layers have been modelled as elastic ones.

3.2. Bearing capacity and the settlement of foundation – analysis according to EC-7

The bearing capacity and the settlement analysis according to EC-7 for a considered previously foundation was performed. With regard to the data geotechnical parameter of soil, the ultimate bearing capacity for the subsoil has been calculated as R_d=226,98 kN/m, which can be considered as sufficient, comparing with design load V_d=201.07 kN/m.

The total settlement of the foundation is the sum of the individual layers and it is carried out to the depth of z_{max} (when the limit value of additional stresses is more than 20% of the original). It is seen from calculation according to

EC-7 that the total settlement is equal to 12.63 mm. Comparing the results of the numerical analysis and the normative approach, substantial consistency can be observed.

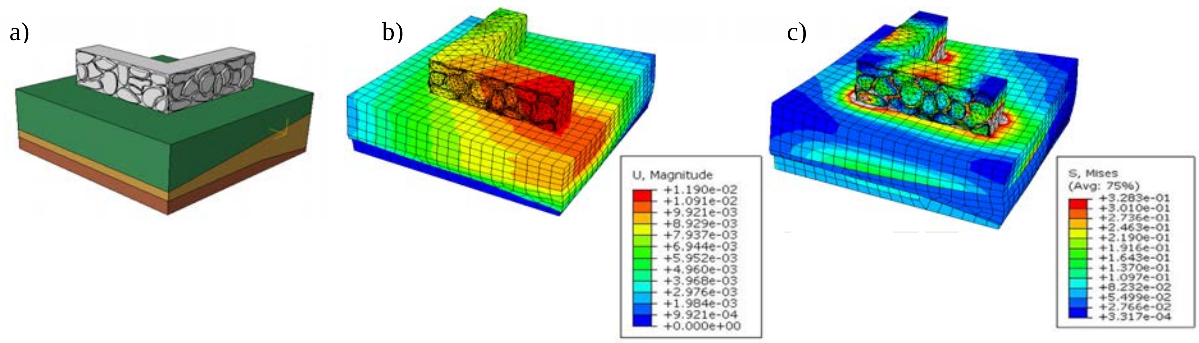

Fig. 3. Subsoil with stone foundation: (a) view; (b) graphical results of settlement of foundation; (c) graphical results of vertical stress at ground.

Graphical results of settlements and vertical stresses in subsoil and foundation, based on FEM, are given in Figs. 3b and3c. The maximum settlement from numerical analysis is equal to 11,9 mm, while the extreme vertical stress beneath the foundation is equal to 328 kPa.

3.3. Simplified analysis

In the case of historic buildings, some parameters, even those most crucial to the analysis, are not always known. It is necessary then to use approximate evaluation. It can be carried out on the basis of the tabular method, recommended in the basic

Table 1. Allowable load unit k_2 [MPa]

Cohesionless soils:	**highly compacted**		**moderately compacted**		**loose**
Thick and medium sands: regardless of the moisture	0.50–0.40		0.40–0.30		0.30–0.20
Fine and silty sands: slightly damp	0.40–0.35		0.35–0.25		0.25–0.15
damp	0.35–0.28		0.28–0.20		0.20–0.12
wet	0.25–0.20		0.25–0.15		0.15–0.10
Cohesive soils:	solid	semi solid	hard-plastic	plastic	soft-plastic
Clay sands, dust, clay, loam	0.45–0.35	0.45–0.25	0.30–0.15	0.20–0.08	0.10–0.00
Organic silts in the form of cylinders with a total thickness <0.5m not occurring directly under the foundation:					0.10–0.00
Peat in the form of cylinders with a total thickness of <0.5 m not occurring directly under the foundation:					0.05–0.00
Bulk land:					
sandy	Such as suitable sands - depending on the degree of compaction				
cohesive	Indicative values: 0.05–0.0				
organic	They are not suitable for direct placement				

Polish geotechnical handbook [8] for the preliminary dimensioning of foundations. Practice has shown that in many cases it can be a very effective method. The permissible loads of the soil are used as a measure of bearing capacity. Their unit values of k_2 were tabulated for foundations of a relatively narrow width (0.6–4.0 m), situated on a level of 2.0 m below the original ground surface. In order to ensure the safety of the building it is required that the stresses in the soil should never exceed these values. The indicative limit values of unit loads (k_2) for several types of ground are shown in Tab. 1.

If the foundation depth is other than H = 2.0 m or the ground is heterogeneous the values in Table 1 must be amended. In the case of considered foundation of building at Staromiejska Street in Olsztyn the value of k_2 factor has been approximated with regard to Table 1 and estimated as equal to k_2 = 0.162 MPa for the underneath silt loam. With regard to the correction for depth of foundation, the permitted unit load is equal to 0.202 MPa. Taking into account the width of foundation of 0.57 m, the bearing capacity of subsoil can be calculated as equal to R=115 kN/m. It is worth mentioning that the tabular method has been applied for the foundation, which is slightly narrower than the recommended 60 cm. The obtained result is almost twice higher than in the case of other methods. Thus, the outcome is on the safe side.

Settlement of historic buildings' foundations can also be performed in a simplified manner. Such a method, for a rigid foundation erected on a layered, isotropic, elastic half-space, was proposed by Kerisel [3]. He showed that the settlement of the foundation could be calculated regardless of its shape, with an accuracy of at least 8%, using the following formula:

$$s = \frac{3.5}{E}\frac{W}{P} \tag{1}$$

where s [mm] – settlement of the foundation, W [kN] – the weight of the object, P [m] – periphery of the object, E[MPa] – the deformation modulus of the ground.

In the case of considered foundation, according to above formula, the settlement is equal to 23,05 mm. The obtained result is almost two times higher than settlements computed using numerical solution and EC-7 methods. Such discrepancy is explained, of course, due to the lack of rigidity of the foundation, where in Kerisel's proposal for monumental buildings, rigidity of the foundation is a basic assumption. However, the approach – similarly as the tabular method – can be regarded as being on the safe side.

4. Conclusions

A thorough analysis of the behaviour of the foundations of historical buildings is difficult and complicated. Several approaches and some more or less exact computational methods are available, and selecting the most appropriate choice is paramount. In fact, it depends on the given case and could not be generalized nor established as a uniform procedure. On one hand, numerical analysis is usually more tedious and sophisticated, but often it is indispensable. Numerical methods using the finite element method seem to be a powerful tool to complete a thorough analysis. The FE models can allow for including rheological models in the analysis. Such analysis should be applied to the buildings of particular importance; when different kinds of foundations' imperfections are observed during *in situ* tests, etc. On the other hand, the application of direct formulas, being the result of a simplified approach, often leads to satisfying conclusions. Practice has shown that such methods, which do not require tedious calculations, can in many cases be a highly effective approach. For example, the results obtained in this paper may give some evidence for the usefulness and advantages resulting from applying the "tabular method" to analyze foundations of historical buildings.

Topics discussed in this paper aim not only to signal the nature of the problem but also to indicate directions for further research in the field of analysis of historical buildings' foundations. The presented methods can be regarded as a step towards solving this issue.

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