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Principles to calculate and verify continuous foundations consolidations

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Abstract

An analysis of the causes leading to degradation in historical buildings appears as one of the indispensable stages in adopting the consolidation solution. A correct evaluation of the degradation causes, but also the trigger mechanism evaluation constitutes the elements leading to right measures for building consolidation. The paper presents an analysis of the consolidation solutions design methods, for the foundation ground, based on principles of Eurocode 7 – geotechnical design. The geotechnical design principles analysis shows that the main demand for the consolidation solutions is related to the serviceability limit state, the deformation limit state, namely differential settlement restriction for different foundation sections. This principle imposes a detailed analysis of deformations and displacements and of its maximum or admissible values for different ground types and structure types. There are presented briefly the main design methods for settlements, applicable to the historical buildings geotechnical design. According to the design principles mentioned earlier, a design diagram for plane dimensions of shallow consolidations (continuous ones) is drawn, starting from settlement condition. Using the relationship between the maximum allowed settlement and differential settlement established according to settlement measurements from literature, the value of the maximum effective settlement can be set up for different ground types and different foundation stiffness. With the help of these graphs, it is possible to find the necessary width of underpinning for different allowable pressures on foundation ground.

Rezumat

Pentru alegerea soluției de consolidare a unei construcții, una dintre etapele indispensabile este analiza cauzelor care au condus la degradarea construcției istorice. O evaluare corectă a cauzelor degradărilor, precum și a mecanismului de degradare, constituie elementele unei consolidări corecte a clădirii. Lucrarea prezintă o analiză a metodelor de calcul a soluțiilor de consolidare pentru terenul de fundare, bazate pe principiile Eurocode 7 – Proiectarea geotehnică. Analiza principiilor proiectării geotehnice arată că cerința principală pentru soluțiile de consolidare este legată de starea limită de exploatare, starea limită de deformație, în special restricții legate de tasările diferențiale pentru diferitele secțiuni ale fundației. Acest principiu impune o analiză detaliată a deformațiilor și deplasărilor și a valorilor lor maxime admisibile pentru diferite tipuri de pământ și structuri. Sunt prezentate în lucrare principalele metode de calcul ale tasărilor, aplicabile proiectării geotehnice în cazul construcțiilor istorice. Conform cu principiile de proiectare menționate anterior, s-a trasat un grafic de proiectare pentru dimensiunile în plan ale consolidărilor fundațiilor de suprafață continue, pornind de la condiția de tasare. Folosind relația

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dintre tasarea maximă admisibilă și tasarea diferențială stabilită din literatură, pe baza unor măsurători efectuate, poate fi determinată valoarea tasării maxime efective pentru diferite tipuri de teren și diferite rigidități ale fundației. Cu ajutorul acestor grafice determinate, este posibil să se determine lățimea necesară a consolidării, pentru diferite valori ale presiunii admisibile pe terenul de fundare.

Keywords: Continuous foundations, consolidation width, settlement based calculation, historical buildings

1. Introduction

Settlements are the visible expression of stresses and deformations in to the earth massif, caused by construction loads. They materialize in structures degradations: architectural degradations: visible cracks in bricks masonry, floors, coating, stiff structures tilting; structural degradations, localized in the structural elements of the building, due to large differential settlements, which may conduct even to structural collapse (by columns buckling, displacement of structural masonry) or combined degradations, with architectural and structural aspects.

Engineer's ideal is to realize a building with zero settlements. But this is practically impossible, due to variety, no uniformity and compressibility of the foundation ground. Soil stratigraphy variation; imply the variation of soil parameters (E, γ,φ c etc.), both vertical and horizontal direction. The presence of soil lenses, stiff or soft, with different characteristics, implies also soil parameters variation.

Different loads values along the foundation, when the foundation bears on a compressible layer of soil, produce in time differential settlement. Realizing the building in different stages, or the addition of supplementary parts (very common situation for historical buildings), after a long period of time from the initial part erection, may produce differential settlements. The demolishment of an existing heavy building, and the erection of a new light building, may produce in time settlements due to soil decompression by different compressibility characteristics. Execution of a partial embankment may have the same effect.

For historical building foundation verification or for the design of the consolidation solution, the main criteria considered are to determine foundation surface in order to have acceptable values for settlements and deformations.

Accepting the deformations verification criteria prior to the pressures one, is justified by the fact that those buildings, by their structure, by the materials that have been used and by their shape are sensitive on deformations and unable to undertake and attenuate differential settlements and rotations. This is the reason why it is accepted as design method – the method corresponding to serviceability limit state as ultimate limit state.

Limit states which leads to a failure mechanism in the soil are verified according Eurocode 7[8, 9], using numerical and analytical methods. When a limit state is defined by deformation considerations, deformations are calculated using known methods or supposed using prior experience. Many design models assume the foundation ground-structure system has sufficient ductility in order to undertake loads. Any ductility modification, in the decreasing way, may lead to an ultimate limit state characterized by a sudden failure

2. Foundation movements and deformations

Burland & Wroth [2] proposed a set of definitions of displacements that are presented in Fig. 1.

- Rotation (θ) – defined as the gradient change for a line joining two reference points,
- Angular strain (α) – positive for upward concavity (sagging) and negative for downward concavity (hogging),
- Relative deflection (Δ) – the displacement of a point relative to the line connecting two reference points,
- Deflection rate (Δ/L), L – being the distance between two reference points defining Δ,
- Relative rotation (β) – the rotation of the line joining two foundation points.

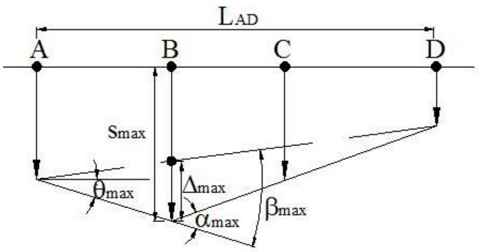


Figure 1: Definitions of foundation movements

Annex H of Eurocode 7 (SR EN 1997 in Romania) [8, 9], defines limit parameters for foundation movements and deformations. The values are quoted after Burland et all. [1]:

- For open framed structures, in filled frames and load bearing or continuous brick walls: maximum relative rotation are between 1/200 and 1/300, to prevent the occurrence of SLS in the structure,
- For the majority of structures, the maximum acceptable relative rotation is β=1/500 for SLS and β=1/500 for ULS.

Seco E. Pinto [7] summarizes the allowable deformations for shallow foundations, considering the type of soil in Table 1:

Table 1: Allowable settlements for shallow foundations (in mm)

Allowable settlements for foundations	Burland et all (1977)	Skempton & MacDonald (1956)	Eurocode 7
Total settlements in sands	25	40	50
Differential settlements in sands	20	25	20
Total settlements in clays	45	65	Higher values
Differential settlements in clays	25	40	Higher values

For the design and verification of foundations it is necessary to settle allowable value for deformations. Any movement of a foundation can lead to deformities in the building superstructure that bear on the foundation and therefore limiting its value will avoid any degradation in the superstructure.

Stanciu & Lungu [10] admits that the selection of the allowable displacements and deformations values must consider the following factors:

- The confidence in defining the allowable deformation value,
- The occurrence and frequency of earth movements,
- Type of work,
- Type of foundation
- Type of construction materials,

- Type of soil,
- The deformation type,
- Construction destination,
- The necessity to ensure that there are no problems with the installation in the building.

A threshold value for a particular deformation is the value of the deformation to which the serviceability limit state (such as cracking walls etc.) may occur in the structure. This threshold value is determined during the design and verification of the structure.
Foundation movements must be considered both as the whole, total foundation movements and the movements of different parts of the foundations, differentially. It is also considered the effect of neighbouring foundations and fillings, when calculating the increased stresses in the ground and its influence on soil compressibility. Foundations movements must not have certain limit values, to achieve an ultimate limit state or serviceability limit state.

Considering foundation system and structural system stiffness, it is possible to define multiple levels of foundation analysis and verifying the appropriate limit states [2]:
Level 0 - which allows linear contact pressure distribution. Admitting level 0 of analysis, the following conditions must be fulfilled [8,9]:

- Contact pressure does not exceed the design resistance values, both STR and the GEO.
- At STR limit state - structural system is not affected by significant settlements or differential settlements.
- At GEO limit state - structural system has sufficient plastic deformation capacity, so that differences between settlements do not affect the design.

For Level 1 - the contact pressure can be determined taking into account the relative stiffness of the foundation and soil, resulting deformations can be assessed to ensure they are within acceptable limits. The following conditions have to be fulfilled:

- There is a prior experience which proves that the existing structure is not likely to be affected by ground deformation,
- At GEO limit state – structural system has adequate ductile behaviour.

Level 2 – take into account the influence on the structure of the ground deformations. Structure is analysed under the strains imposed by the foundation deformation, to determine the redistribution of loads that are applied on foundations. If resulting redistribution are significant (> 10%) level 3of analysis is adopted.
Level 3 - full interactive method is applied which takes into account the structure, foundations and the soil.

3. Foundation plane surface design considering maximum allowable settlement value

Determining consolidation width by allowable settlements method is a logical approach to historic buildings, their ability to undertake non uniform deformations being almost inexistent, due to materials and constructive solutions used (stone or brick walls without concrete belts etc.).
Considering Eq. (1) indicated by Eurocode 7 [8, 9], it is possible to calculate total settlement for a foundation, on cohesive or uncohesive soils. This equation is based on the theoretical relations from theory of elasticity:

$$s = p \cdot B \cdot \frac{f}{E_m} \tag{1}$$

where p = soil pressure, laniary distributed on the foundation bottom; B = foundation width; f = settlement coefficient; and E_m = design value of linear deformation modulus.
If the allowable settlement for a foundation placed on an uncohesive soil is s_{adm} =2cm, and the

allowable settlement for a foundation placed on a cohesive soil is s_{adm}=5cm, it is possible to determine the value of foundation width, according to Eq. (2), for different values of linear deformation modulus and effective pressures at the foundation bottom:

$$B = \frac{s_{adm} \cdot E_m}{f \cdot p} \qquad (2)$$

In order to determine settlement coefficient it is possible to use graphs as given by Schultze et all.[6] and also by German norms. Settlement is calculated for a characteristic point on the foundation surface.

The values of the f coefficient are given as a function of (z/B) and (L/B) ratios, where z – is the depth of the incompressible layer, B – is the foundation width and L – is the foundation length.

Because most of the historical buildings have continuous foundations, the analysed case is for a continuous foundation, having (L/B)>10. The most significant values for (z/B) ratio are 2, 3, 4 and 5, and therefore the study was performed for these values.

With the z/B and L/B ration, it is possible to determine the settlement coefficient f. The coefficient values, obtained from [4, 5] can be found in Table 2.

Table 2: Settlement coefficient f

z/B	(L/B)>10
2	1.0403
3	1.2808
4	1.4553
5	1.5923

Form literature and case studies [4, 5], the maximum soil pressure on the foundation bottom is between 150 and 250 kPa for a normal historical building. Considering a maximum allowable settlement s_{max}=2cm for an uncohesive soil, it is possible to determine the necessary foundation consolidation width, for different values of linear deformation modulus.

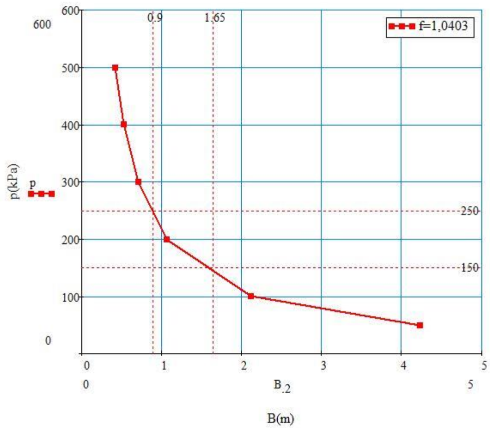
Table 3 and Table 4 summarize the necessary foundation consolidation width, obtained from the Fig. 2 a, b and c.

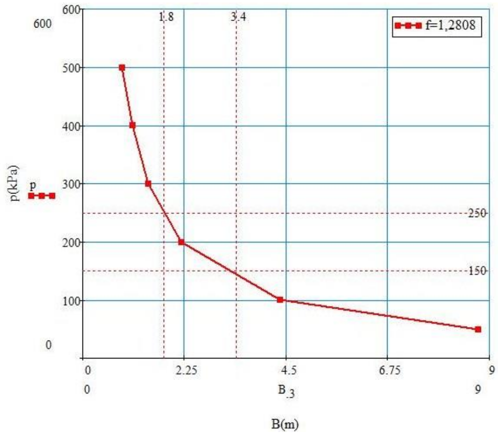
Table 3: Foundation width B, for p=150kPa

E_m[kPa]	f	B[m]	E_m[kPa]	f	B[m]	E_m[kPa]	f	B[m]
11000	1.0403	1.65	28000	1.0403	4.25	50000	1.0403	7.50
	1.2808	1.30		1.2808	3.40		1.2808	6.00
	1.4553	1.20		1.4553	3.00		1.4553	5.30
	1.5923	1.05		1.5923	2.75		1.5923	4.90

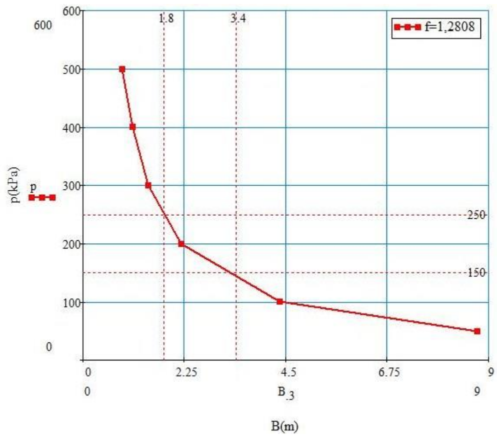
Table 4: Foundation width B, for p=250kPa

E_m[kPa]	f	B[m]	E_m[kPa]	f	B[m]	E_m[kPa]	f	B[m]
11000	1.0403	0.90	28000	1.0403	2.35	50000	1.0403	4.00
	1.2808	0.75		1.2808	1.80		1.2808	3.30
	1.4553	0.65		1.4553	1.65		1.4553	2.80
	1.5923	0.60		1.5923	1.50		1.5923	2.60





a. p-B variation, for E_m=11000kPa and f=1.0403. b. p-B variation, for E_m=28000kPa and f=1.2808.



c. p-B variation, for E_m=50000kPa and f=1.2808

Figure 2. p-B variation for the allowable settlement s_{max}=2cm

Considering a maximum allowable settlement s_{max}=5cm for a cohesive soil, it is also possible to determine the necessary foundation consolidation width, for different values of linear deformation modulus.

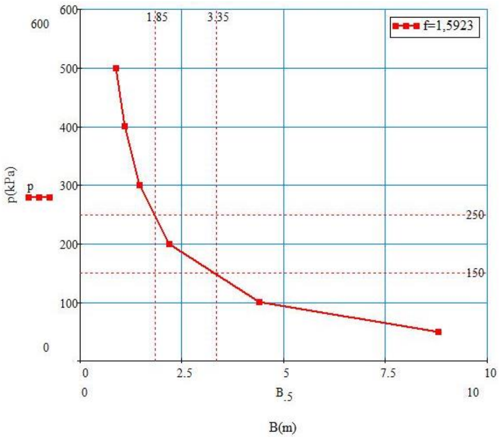
Table 5 and Table 6 summarize the necessary foundation consolidation width, obtained from the Fig. 3 a, b and c.

Table 5: Foundation width B, for p=150kPa

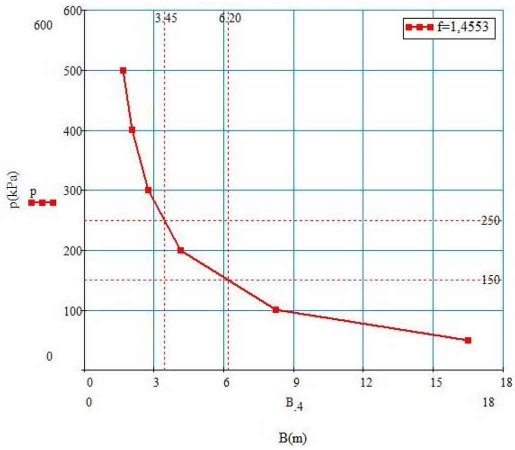
E_m[kPa]	f	B[m]	E_m[kPa]	f	B[m]	E_m[kPa]	f	B[m]
14000	1.0403	5.80	24000	1.0403	8.75	32000	1.0403	8.50
	1.2808	4.10		1.2808	7.20		1.2808	7.20
	1.4553	3.75		1.4553	6.20		1.4553	6.20
	1.5923	3.35		1.5923	5.70		1.5923	5.65

Table 6: Foundation width B, for p=250kPa

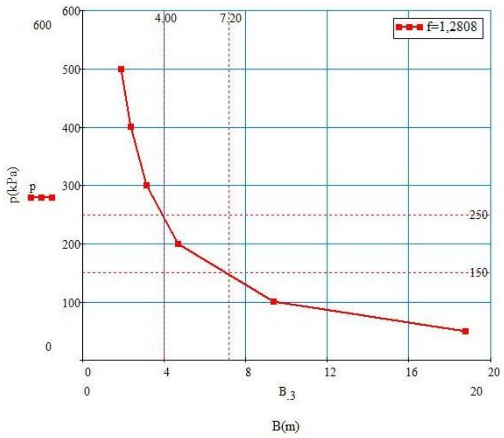
E_m[kPa]	f	B[m]	E_m[kPa]	f	B[m]	E_m[kPa]	f	B[m]
14000	1.0403	2.80	24000	1.0403	4.75	32000	1.0403	4.75
	1.2808	2.25		1.2808	4.00		1.2808	4.00
	1.4553	2.00		1.4553	3.45		1.4553	3.45
	1.5923	1.85		1.5923	3.20		1.5923	3.15



.a. p-B variation, for E_m=11000kPa and f=1.5923.



b. p-B variation, for E_m=28000kPa and f=1.4553.



c. p-B variation, for E_m=50000kPa and f=1.2808

Figure 3. p-B variation for the allowable settlement s_{max}=5cm

4. Conclusions

Maximum allowable deformation value is related to the occurrence of an ultimate limit state or serviceability limit state. Settlements, differential settlements and relative rotations shall be determined such as to avoid the appearance of a limit state. Settlements computation must consider the following aspects: soil parameters variation, loads distribution, construction technology and structure stiffness.

On the emergence of a deformation state into the soil massif it can be found the soil volume deformations. The factors influencing these volume changes are: external action type and intensity, loading velocity and duration; the size and the stiffness of the loaded area; soil structure type and the values of structural soil indexes (porosity, oedometric modulus etc.); the saturation degree and the water elimination possibility and, last but not least, the loading history.

Therefore, a possible method to estimate the continuous consolidation width or to verify an existing foundation width, considering the settlements criteria, may be the one presented above. The method may be extended on many values of linear deformation modulus or settlement coefficient *f*.

The behaviour of a historical building is a balance between simplicity and safety. This type of construction presents difficulties generated by design approaches, due to physical and mechanical characteristics of materials, often unknown. For these reasons models that analyse safety design must be based on simple models or intuition.

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