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THE INFLUENCE OF SUPERSTRUCTURE STIFFNESS ON INTERNAL FORCES DISTRIBUTION IN RAFT FOUNDATIONS

WPŁYW SZTYWNOŚCI NADBUDOWY NA WIELKOŚĆ SIŁ WEWNĘTRZNYCH W PŁYTACH FUNDAMENTOWYCH

A b s t r a c t

The article presents the changes in designing rules of raft foundations according to Eurocodes in relation to structural stiffness of: superstructure–foundations–soil. The results from two numerical models (wall-type and slab-column superstructure) were analyzed. The subject of the analysis was to assess the influence of the raft foundation effective stiffness and Winkler's spring constant on internal forces distribution in the foundation.

Keywords: superstructure stiffness, Winkler's spring constant, raft foundation, Eurocodes

S t r e s z c z e n i e

W artykule przedstawiono zmiany w przepisach normowych przy projektowaniu posadowień bezpośrednich na płycie fundamentowej w odniesieniu do sztywności układu: nadbudowa – fundament – podłoże gruntowe. Przeanalizowano wyniki z dwóch modeli numerycznych (dla nadbudowy ścianowej i płytowo-słupowej) pod kątem wpływu sztywności efektywnej płyty fundamentowej i parametrów podłoża Winklera na dystrybucję sił wewnętrznych w fundamencie.

Słowa kluczowe: sztywność nadbudowy, współczynnik sprężystości podłoża Winklera, płyta fundamentowa, Eurokody

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Symbols

$(EJ)_S$ – approximate value of flexural rigidity per structure width unit of the building structure concerned, [MN·m]
$(EI)_f$ – approximate value of flexural rigidity per structure width unit of the foundation raft and the structure directly bound with it, [MN·m]
E – deformation modulus of the ground, [MPa]
b,l – dimensions of the foundation, $b<l$, [m]
K_R – relative stiffness of the structure acc. EN 1992–1–1:2004, [-]
K_f – stiffness index acc. DIN 4018:1974-09, [-]
h_z – replacement thickness of the raft foundation (taking into account rheology), [m]
E_{cm} – secant elasticity modulus for foundation concrete and superstructure, [MPa]
I_f – moment of inertia of the foundation cross section and the structure directly bound with it (e.g. foundation walls), [m^4]
M_0 – compression modulus of the ground (value reduced for layered ground), [MPa]
E_f – elasticity modulus of concrete in the foundation and superstructure, [MPa]
M_{xx} – bending moments in the raft foundation, [kNm/m]

1. Changes in standard requirements

The requirement to take into account the effect of the superstructure stiffness when determining the value and distribution of internal forces in raft foundation, has until recently, not been included in any Polish standard concerning structural design. The withdrawn standard, PN-81 / B03020 [1] concerning the design of direct foundation of buildings assumed the ground as a homogeneous elastic half-space, and the structure as perfectly elastic, without considerating the overall stiffness of the superstructure–foundation–ground system. Both of these sub-systems (superstructure as the first and foundation–ground as the second) were treated separately, and the active element was the deformable soil. The building, or actually only its foundation is, in this approach, merely a passive receiver of forces transmitted from the ground [2]. As a result, the significant influence of the building's actual stiffness on the behaviour of its elements is omitted, especially in the form of settlement and internal forces generated in direct foundations. Unfortunately, the standard applicable at the same time, PN-B-03264 [3], does not contain any provisions regarding the discussed issue.

The situation radically changed with the introduction of common European Standards in design practice. The provisions of Eurocode 7 [4] repeatedly point at the legitimacy of the use of models enabling the consideration of a full interaction between the structure and the substrate (Chapters 2 and 6) – in the serviceability limit state, clearly preferring FEM numerical models. At the stage of determining interaction values, and the calculation of differences in settlement, the referenced standard directly "requires that the structure stiffness during construction and after its completion should be taken into account." In contrast to no longer valid reinforced concrete standard [3] much more attention is attached to the topic in Eurocode 2 [5], especially in Annex G. The so far applied separation of computational methods used in analyses of the superstructure-foundation–ground system has been validated, among others, in the dependence of the so-called relative stiffness (K_R) of this system.

4 analysis levels were introduced (0 to 3) into structural designs. The most demanding is level 3, which basically means building a model (e.g. FEM) of the entire superstructure-foundation-subsoil system, in order to assess interactions. Unfortunately, as it can be found in numerical analyses and on-site observations carried out by numerous authors [6–9], this level seems to be the most suitable for analyses of buildings erected on raft foundations. The core of the problem is to determine the relationship between: load distribution from the superstructure onto the foundation – stiffness of the whole building structure – distribution of the soil vertical bearing resistance; while maintaining conformity of the displacement of the foundation footing with the soil. Thus only designating the soil vertical bearing resistance distribution allows the determination of internal forces at any raft foundation cross-section. A theoretical development deserving attention is presented in [10].

The relative stiffness quoted above for EC2 is defined by the formula:

$$K_R = \frac{(EJ)_S}{El^3} \tag{1}$$

The structural system under consideration can be regarded as rigid when parameter K_R > 0,5. Literally, this means that the soil stiffness should be less than twice with regard to doubled stiffness of the building and the foundation. As Starosolski noted [11], this is a very conservative limitation, and contains a substantial safety margin. The fulfilment of this criterion is also considered sufficient for the adoption of a linear distribution of pressure under the raft foundation, for which the following condition is fulfilled:

$$\frac{l}{h_z} < 0,55\sqrt[3]{\frac{E_{cm}}{E}} \tag{2}$$

For example, for a raft foundation with dimensions of 30 m × 40 m, situated on ground with a deformation modulus of E_0 = 30MPa, and made of concrete C25/30 (E_{cm} = 31000MPa) the thickness h > 6,2 m which, according to [12] roughly corresponds to the actual thickness of a non-cracked plate h > 8.2 m, or h > 9.3 m for a cracked plate.

The relative rigidity formula (1) is not a novelty in estimating the susceptibility of the brand superstructure-foundation-subsoil system, and is only a small modification of index (K_f) cited by Motak in [6], after an old German DIN 4018:1974-09 standard:

$$K_f = \frac{bl^3}{I_f}\frac{M_0}{E_f} = \frac{M_0 l^3}{\frac{E_f I_f}{b}} = \frac{M_0 l^3}{(EI)_f} \tag{3}$$

Based on the calculated value of K_f, it could be initially determined whether the whole system is rigid ($K_f \leq 1$), elastic ($1 < K_f \leq 100$), or flexible ($K_f > 100$). It can be clearly seen, on the basis of algebraic transformations applied to equation (3) that formula K_f by DIN and K_R by EC2 are similar. The main difference is the replacement of module M_0 determined in a laboratory (by an oedometer); module E, determined in-field (e.g. by a pressuremeter), which stems from the thinking in the new standards – normally E < M_0. In addition, the impact of superstructure stiffness on the stiffness of the entire system was increased, replacing, as introduced by the authors of the article, $(EI)_f$ by $(EJ)_S$ value, – where $(EI)_f < (EJ)_S$ – which further underlined the difference between K_f and K_R. In structures erected on coarse-grain, compacted soils, such as gravels ($M_0 \approx E$), with a flexible superstructure ($(EI)_f = (EJ)_S$), rate $K_f \approx 1/K_R$ can be assumed.

2. Impact of the superstructure stiffness on the distribution of bending moments in a raft foundation for a simple engineering model – qualitative approach

2.1. Adapted numerical models

For a rough estimation of changes in the raft foundation bending moments under the influence of changes in the overall stiffness of the superstructure, two opposing models were analysed. The first model (slab-column type) reflects a flexible structure, while the second (wall type) reflects structure with a rigid superstructure. In both cases, the Winkler model was used, with soil constant elasticity in the vertical direction equal to 5 MPa/m, and in both directions horizontally 0,5 MPa/m. The change in stiffness of the superstructure was simulated by reducing the number of floors, retaining a constant total of vertical loads (load from the reduced section was applied at the highest node of columns/walls, in order to exert the least impact possible on the distribution of bending moments).

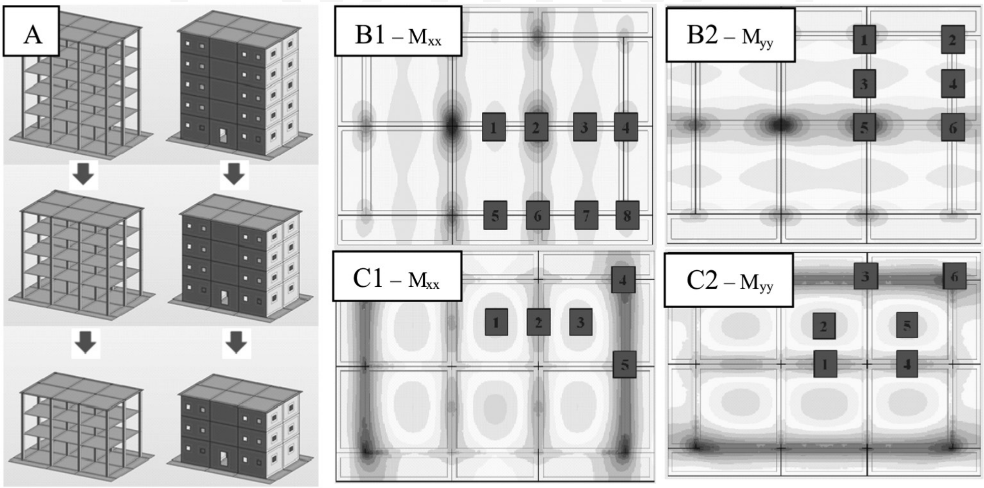

Fig. 1. A) Reduction of superstructure stiffness; B1-2) Location of points on the foundation for flexible superstructure; C 1-2) Location of points on the foundation for a rigid superstructure

The raft foundation with dimensions of 16 × 22 m was analyzed in thickness variants of 50 cm and 100 cm. The height of the buildings was 21m, and floor slabs were 22 cm thick. For numerical calculations, Autodesk Robot Structural Analysis Professional 2014 was used [13] – a popular engineering software for linear analysis of structures.

The analysis was based on tracking changes in moments M_{xx} and M_{yy} at specific points on the raft foundation in both models – the location of points is shown in Fig.1.B1-2) and C1-2).

The concept to modify the superstructure stiffness in the form of a gradual reduction in the number of storeys from 5 to 2 is presented in Fig. 1.A).

2.2. Results obtained

Analysing the results obtained for the slab-column structure (Fig.2.A), one can observe high sensitivity of the model to decrease in the number of storeys. For 50cm thick raft foundations, a more stable trend can be observed, tending to decrease the value of moments in the span. In a variation solution, where the plate thickness was 1m, the change in moment values was much more evident. The largest M_{xx} increase occurred in the span middle lane, while the largest decrease was recorded in the last (edge) span strip. Relative changes in the columns were insignificant, which is associated with a very high value of reference moments at this point. For M_{yy} moments, the largest increase occurred in central columns, while decrease occurred in the last span. However, when analyzing the absolute moment values, regardless of the selected direction, the greatest changes occurred in the column area.

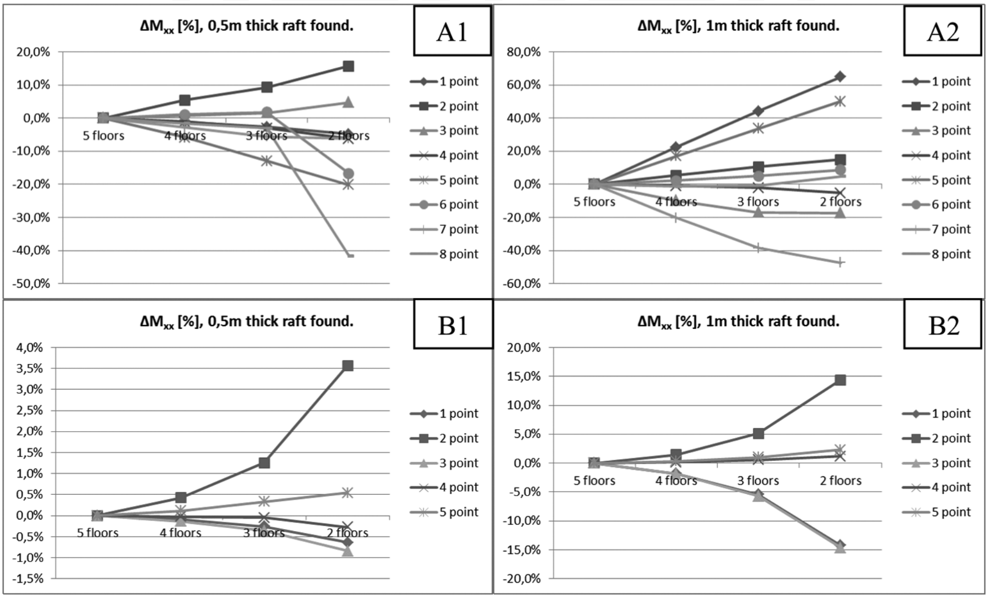

Fig. 2 A) Relative M_{xx} change for flexible superstructure with 0,5m (A1) and 1m (A2) foundation; B) Relative M_{xx} change for rigid superstructure with 0,5m (B1) and 1m (B2) foundation

For the wall construction (Fig. 2.B), changes in the bending moment value with a foundation at the thickness of 50 cm were fully negligible – with a maximum reduction of stiffness, they did not even achieve 6%. Just as before, along with doubling of the foundation thickness, the impact of the superstructure reduction was multiplied. However, due to low absolute values of reference moments, these changes are insignificant.

3. Conclusion

With the increase in the stiffness of a raft foundation, the range of moments stretching lower fibres grows significantly. Based on the above analysis, it can be stated that the building with a wall construction is characterized by high effective stiffness in the foundation, which takes into account the stiffening impact of the superstructure. This justifies the use of solid, reinforced concrete walls in the raft foundation floor, even for structures with framework superstructures. This floor acts as a rigid box that positively influences on the behaviour of the entire structure.

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