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RETROFITTING INDIVIDUAL FOUNDATION IN BUILDING REHABILITATION

BY

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Abstract. The paper consists of a case study upon the possibility of adding a new floor to an existing building, with its primary focus being on the soil-structure interaction. The negative influence of differential settlements between individual foundations in addition to the supplementary load requires the analysis of the benefit when adding strip foundations into the initial foundation system. The research approach regards the position of the new strip foundations to be considered at three different elevations related to the height of the existing individual foundations. The soil-structure interaction is made in each case with different cross-sections for the strip foundations

The analysis was performed according to the P100-3/2008 Romanian design code and Eurocode 7, using several finite element software. Based on the analysis outputs, conclusions and recommendations will be drawn upon the efficiency of this foundation retrofit solution as part of the building rehabilitation plan.

Keywords: Soil-Structure interaction; foundation retrofit; coefficient of subgrade reaction; FEA.

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1. Introduction

In this day and age, both architects and real estate developers are working towards maximizing every building site available. At present, for buildings in need of functional retrofitting, one viable option to achieve this desiderate consists in adding stories and thus extending the available working space. This method has the advantage of being cost-effective and environmentally friendly but involves adding loads to the existing structure and consequently to the foundation soil. As such, civil engineers are responsible to assess whether such interventions can be performed safely.

The structure, erected in 1999, consists of reinforced concrete frames, reinforced concrete floors and individual foundations and it is located in the North Eastern region of Romania, in the city of Iasi. The building was designed according to the P100-96 code and did not underwent any major retrofitting since then, maintaining its original dimensions and characteristics of the structural and architectural composition.

It is well established in the literature the fact that uneven settlements are to be avoided because they add supplementary stresses to the structural system. The safety of the isolated or individual footings is endangered by the eccentricity produced by the combination of the bending moment and the vertical load. The objective of this paper is to observe the influence of the strip beams, when added to a system of isolated footings as part of a retrofitting method, in relationship with the vertical and angular displacements of the foundation. The study will take into account three distinctive elevations for the beams, each with three different sections.

The key aspect in this design is to account for the uneven settlements and their effects on the superstructure, both in the G+2 levels and G+3 levels cases. From this point forward the authors propose mitigating such shortcomings by adding strip foundations as a way of retrofitting the initially isolated foundations and assess the performance of the intervention.

2. Finite Element Analyses

The geometry of the foundation system both in plan view and cross-sections, and the materials are presented in Figs.1 and 2 and Table 1.

The first step in predicting the building settlements consists in evaluating the modulus of soil reaction also known in the literature as modulus of subgrade reaction, subgrade modulus, subgrade reaction, Winkler's subgrade, k_s value. It is important to take into account that previous research concluded that k_s is not an intrinsic soil property, but instead, it is just a response to a given load over a certain area and depends not only on the deformation characteristics of the soil but also on the size of the contact area between foundation and subgrade (Teodoru and Toma, 2009). In other words, there is no unique numerical value of the coefficient of subgrade reaction for any given soil.

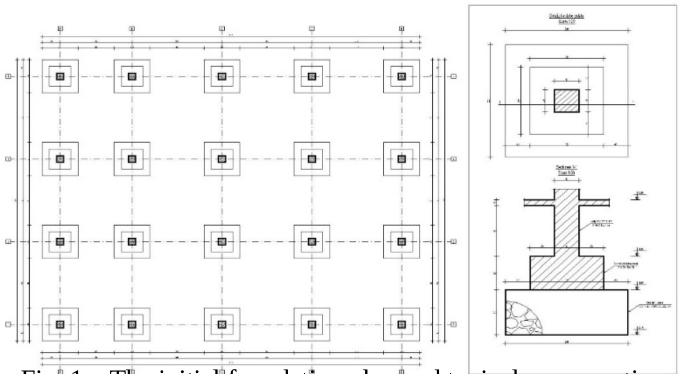

Fig. 1 – The initial foundation plan and typical cross-section.

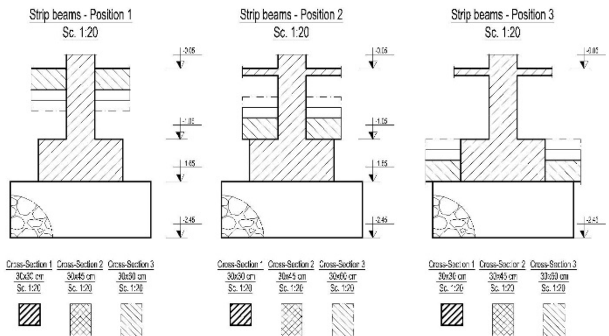

Fig. 2 – The three different elevations for the strip beams when introduced between isolated foundations.

Table 1
The Cross-Section Characteristics of the Strip Beams

Cross-sections of beams, [cm]	Materials used	E, [kN/m²]	I_y, [m^4]	EI_y, [kNm²]
30×30	Concrete C16/20	29,000,000	6.75×10^{-4}	19,575
30×45			2.278×10^{-3}	66,065
30×60			5.4×10^{-3}	156,600

In order to determine the modulus of soil reaction, the authors proposed a numerical analysis following the Plate Load Test (PLT), (Fig. 3). The results of a PLT are presented as applied contact pressure versus settlement curve (Fig. 4).

$$k_s = \frac{p_1}{s_1} = \frac{126.1}{9.066 \times 10^{-3}} = 13{,}909 \text{ kN/m}^3, \tag{1}$$

where: k_s is the subgrade reaction, [kN/m³]; p_1 – the limit pressure of the elastic region where Hooke's law is valid, [kN/m²]; s_1 – the settlement associated with p_1, [m].

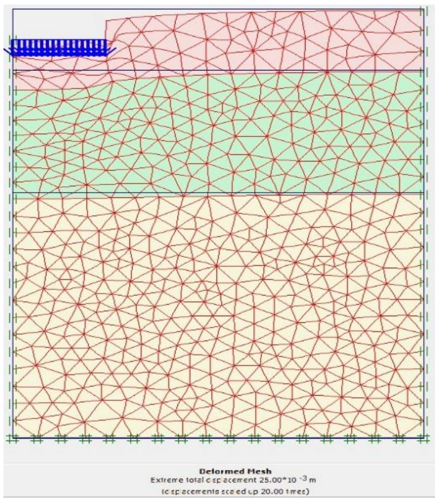

Fig. 3 – FE model applied for the Plate Load Test case.

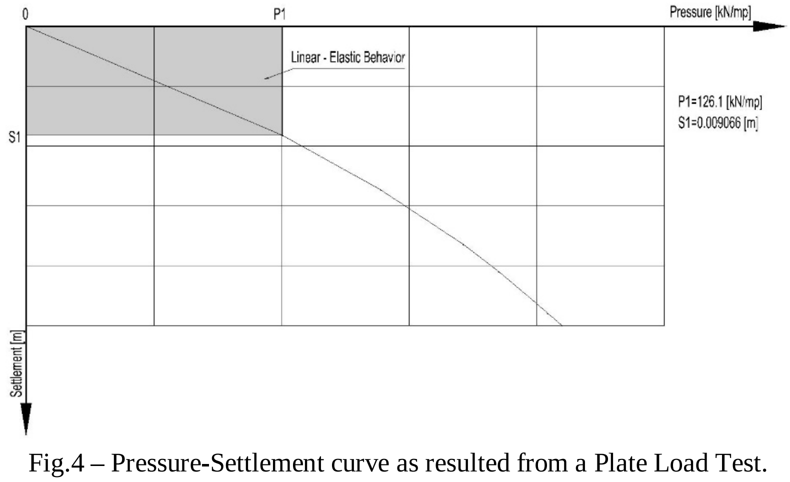

Fig.4 – Pressure-Settlement curve as resulted from a Plate Load Test.

All FE analyses were performed with an axis-symmetric mesh and the diameter of the plate was chosen so as to match the real foundation area. Also, the computation was performed both by means of displacement control and by a prescribed vertical displacement boundary condition applied to the soil surface under the plate. The soil behavior is assumed to be described by the Mohr-Coulomb model.

Having an accurate estimation of the value for the coefficient of subgrade reaction the next step involved assessing the settlements of the structure, both for the initial, G+2 levels and for the extended G+3 levels case. The connection between the columns and the infrastructure is modelled by assigning to the base of each column a spring reaction. The stiffness of the springs along the *z*-axis was computed as follows:

$$R_s = Ak_s = 4.00 \times 13{,}909 = 55{,}636 \text{ kN/m}, \tag{2}$$

where: R_s is the spring stiffness, [kN/m]; k_s – the subgrade reaction, [kN/m³]; A – the area of the isolated footing, [m²].

In Fig. 5, the 3D models considered in the FE software are presented. The settlements range within acceptable values, their effects are showcased in Figs. 6 and 7 where it is illustrated the increased bending moment in the concrete frames.

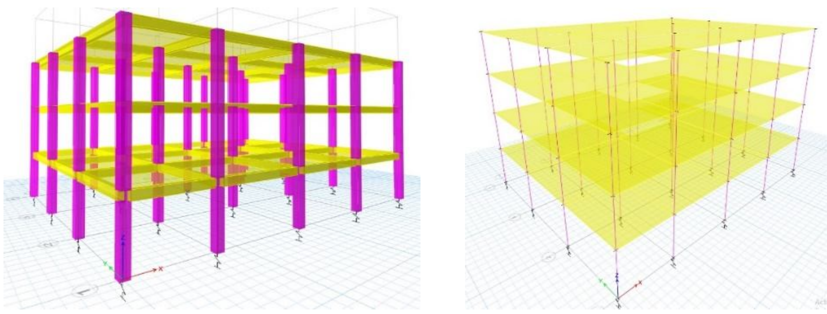

Fig. 5 – 3D model of the G+2 levels and G+3 levels structures.

As a result of the differential settlements, it can be observed an increase in the bending moment with 41% and in the shear force with 30%.

According to Eq. (3), the beam with the highest structural demand, still meets the necessary requirements for the safety degree to sustain the loads (Fig. 7) according to current technical regulations.

$$R_3 = \frac{M_{Rd}}{M_{Ed}} = \frac{94.28}{78.76} = 1.197; \; R_3 = \frac{V_{Rd}}{V_{Ed}} = \frac{100}{82} = 1.219, \tag{3}$$

where: R_3 is safety degree, M_{Rd} – the capable bending moment, [kNm]; M_{Ed} – the effective bending moment; [kNm], V_{Rd} – the capable shear force, [kN]; V_{Ed} – the effective shear force [kN].

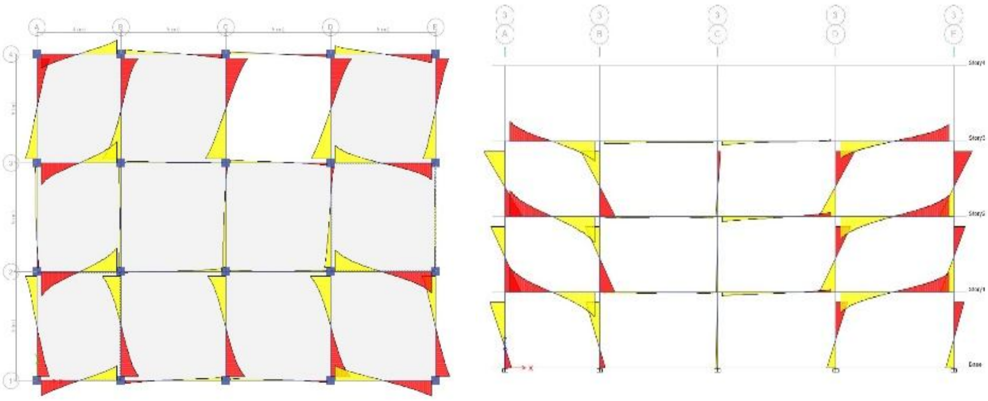

Fig.6 – Supplementary bending moments induced by different settlements: left -Plan view, right – Elevation view.

Fig. 7 – Shear and bending moment diagram for a concrete beam before considering the differential settlements (left) and after (right) (G+2 levels).

The analysis continues with the structure supplemented with the third floor (FE model presented in Fig. 5) and its effects. An increase in the bending moment values of 47.7% and in the shear force values of 38.7% have been noticed (Fig. 8).

According to Eq. (4), the beam with the highest structural demand, still meets the necessary requirements for the safety degree.

$$R_3 = \frac{M_{Rd}}{M_{Ed}} = \frac{94.28}{82.6} = 1.14; \; R_3 = \frac{V_{Rd}}{V_{Ed}} = \frac{100}{83.5} = 1.19. \qquad (4)$$

As it can be noticed from Eq. (4) the existing structural system can take over the additional internal forces developed by the extra level.

However, for the high horizontal forces associated with an earthquake loading scenario, the bending moments carried over to the isolated footings are high enough to induce unacceptable rotations and uneven pressure distribution on the footing.

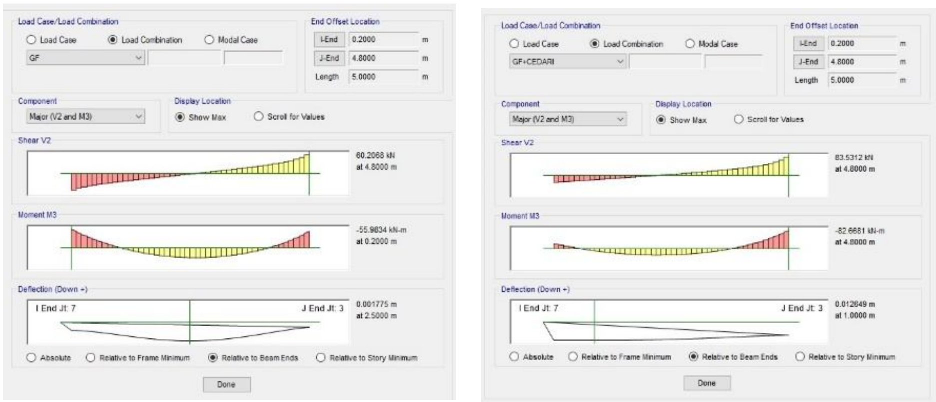

Fig. 8 – Shear force and bending moment diagram for a concrete beam before considering the different settlements (left) and after (right) (G+3 levels).

Thus for each isolated rigid foundation, the vertical force must act within the area defined by Eq. (5) and illustrated in Figs. 9 and 10 for one of the internal columns.

$$k_y = k_z = \frac{W}{A} = \frac{L^3/6}{4} = 0.333 \text{ m}; \tag{5}$$

$$e = \frac{M}{N} = \frac{460}{950} = 0.48 \text{ m}; \tag{6}$$

$$e' = \frac{M}{N} = \frac{29.84}{950} = 0.031 \text{ m}, \tag{7}$$

where: k_y and k_z define the area around the mass center of the cross section of the isolated footing in which if a vertical force acts upon there will be only compressive stresses [m], $W = W_y = W_z$ is the section modulus of isolated footing [m³], A is the area of the isolated footing [m²], e is the eccentricity of the vertical force [m] and e' is the eccentricity of the vertical force when the strip beams are introduced as a retrofitting method.

Without the benefit of the supplementary strip beams as the best retrofit solution when an extra level is added, the safety of the infrastructure of the existing foundation system is not adequately provided.

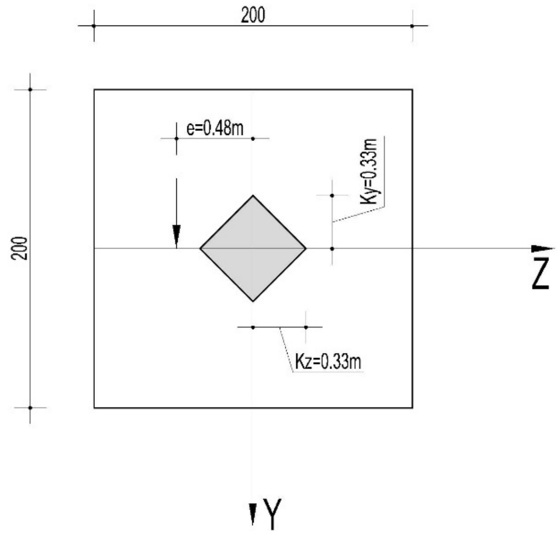

Fig. 9 – The eccentricity of the vertical force before the addition of the strip beams, outside the recommended area.

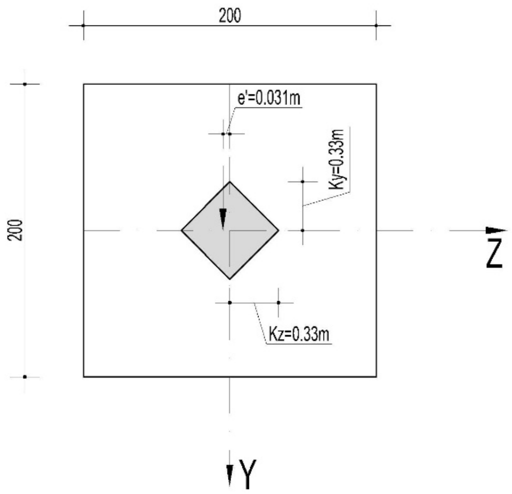

Fig. 10 – The eccentricity of the vertical force after the addition of the strip beams, inside the recommended area.

The reduction of the bending moment onto the footing and of the developed eccentricity as well is the optimum geotechnical benefit when strip foundations are aided with minimum invasive works required.

Regarding the positions of the strip beams in accordance with the variation of their cross-sections, Fig. 11 illustrates the dependency in respect to the bending moments, Fig. 12 displays the dependency in respect to the largest differential settlements and Fig. 13 presents the dependency in respect to the initial footing rotation.

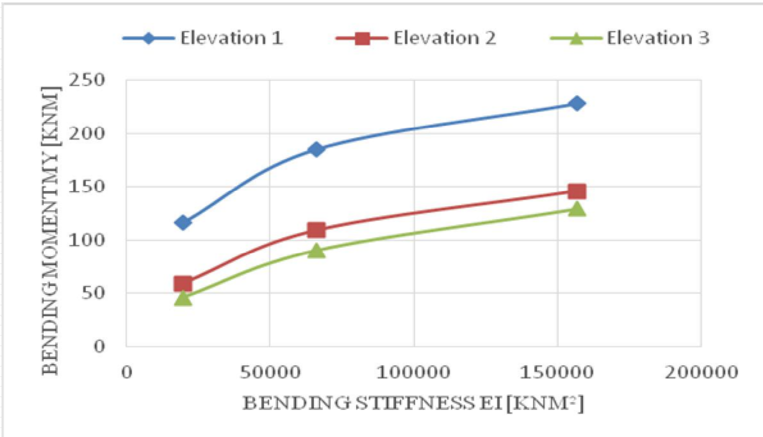

Fig. 11 – The bending moment developed by the strip beams.

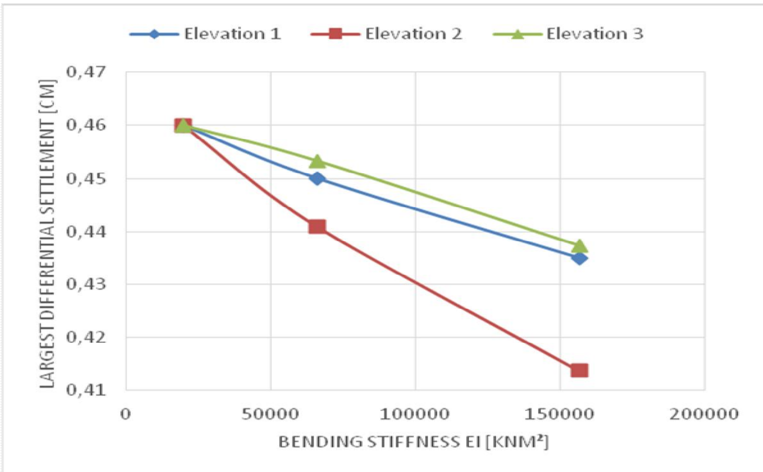

Fig.12 – The influence of the strip beams on differential settlements.

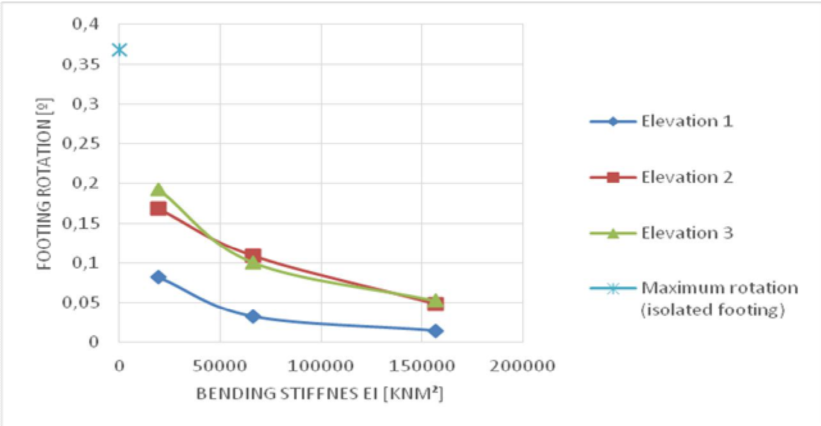

Fig.13 – The influence of the strip beams on the rotation of the initially isolated footings.

The highest position of the strip beams, above the rigid foundation pad and immediately under the ground floor slab, (elevation 1 referred to Fig. 2 – A) and the strongest cross-section (30 × 60 cm) develops the best effect in terms of safety against geotechnical Ultimate Limit State (GEO-ULS). The bending moment developed by the strip beams will decrease the bending moment onto the existing footing and thus, the eccentricity of the vertical force decreases to fit the required area illustrated in Fig. 10.

3. Conclusive remarks

Based on the numerical study on the isolated footings connected with strip beams at different elevations and section properties, the following conclusions can be drawn:

– the most noteworthy benefit of adding strip beams into the initial infrastructure consists in the reduction of the footings' rotation along the y-axis, as shown in Fig. 13. This will lead to a more uniform distribution of the pressure on the footings. The most significant reduction of the rotation is developed by the strip beams in position/elevation 1 and cross-section of 30x60cm (95.9% decrease).

– concrete structures are usually statically indeterminate or hyperstatic. As such, the distribution of the bending moments depends on the ratio between flexural stiffness of adjacent elements. This phenomenon is highlighted by Fig. 11 which shows the relationship between the cross section of the beam (read moment of inertia) and the bending moment. As the height of the beam increases from 30 to 45 and 60 cm, so does the flexural stiffness of the element.

In response to this increase in rigidity, the bending moment acquired from the column increases also and the footing is significantly discharged.

– in regards to the positions of the beams, placing the strip beam at the lowest level and in connection with the plain concrete foundation block will not provide a proper structural interaction. The best results were obtained when the beams were located right below the floor slab. This solution is also the least intrusive and the most cost-effective.

The elastic-perfectly plastic (i.e. Mohr-Coulomb) model is relatively simple, and it is considered the most widely used model among practitioners in geotechnical engineering. This model seems to be accurately enough for some areas of geotechnical problems, however, great care must be taken because it can be misleading in terms of overprediction of soil strength. By consequence, the geotechnical benefit of the strip beam as a retrofit solution by its location according to the analyses above must continue by further research, with more advanced constitutive models.

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CREŞTEREA PERFORMANŢELOR FUNDAŢIILOR IZOLATE CA MĂSURĂ DE CONSOLIDARE A UNEI CLĂDIRI EXISTENTE

(Rezumat)

Lucrarea de faţă constă într-un studiu de caz ce urmăreşte posibilitatea de supraetajare a unei clădiri existente, prin considerarea esenţială a interacţiunii teren-

structură. Efectul defavorabil al tasărilor diferentiate între fundațiile izolate, împreună cu creşterea încărcărilor transmise terenului de fundare de către etajul suplimentar impun necesitatea unei analize a beneficiului pe care grinzile de echilibrare îl pot aduce sistemului de fundare. Acest studiu va lua în calcul patru poziții diferite pe elevație pentru grinzile de echilibrare şi trei secțiuni distincte ale acestora.

Analiza a fost efectuată în conformitate cu principiile normativului P100-3/2008 şi a Eurocodului 7, folosind o serie de analize cu programe de calul cu element finit. Pe baza rezultatelor obținute se vor trage concluzii şi recomandări referitoare la eficiența soluției aleasă de reabilitare a sistemului de fundare.