Seismic response of setback buildings with multiple underground levels

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Abstract. The topic of this paper exceeds the provisions of the present regulations concerning the structural design issues related to the connection or the behaviour of the setback buildings on slopped ground surface. Setback buildings means that the spans progress in a step-like succession from one side of the building along the entire length. Due to the increased number of buildings positioned on sloping ground this paper aims to highlight aspects related to the influence of a variable number of underground levels. This research follows the differences between the loading effects acting on three types of setback buildings that differ by the number of the underground levels (one, two, respectively three), on the length of two spans. The conclusions of the paper refer to the influence of the number of underground levels on the seismic response of reinforced concrete structural elements: columns, beams and walls. The obtained results are compared in the form of internal forces: axial force, shear force and bending moment. The structural modelling and analysis of the buildings have been performed by using ETABS software. In the end these results will show the influence of the number of underground levels in the alteration of the structural elements above ground in terms of material consumption.

1. Introduction
The construction sites considered favourable for the stability of the constructions, with horizontal ground surfaces are less and less, resulting an increased number of buildings positioned on natural ground slopes.

To ensure the general stability of the construction site, the ideal situation is a ground surface with 0° slope that is rarely the real case, especially in the area of large urban agglomerations, which includes also the city of Iași.

In many situations, due to the architecture imposed by asymmetrical shapes, the evaluation of the soil-structure interaction becomes complex, influenced by the variation of the mass and stiffness of the structure. In addition, for buildings located in a seismic zone, the values of internal forces: axial force, shear force and bending moment become significantly higher, regardless of the structural solution chosen.

The structural solutions specific for buildings on a slopped ground surface belong to one of the following categories:

- Setback buildings mean that the aboveground spans progress in a step-like succession from one side of the building along the entire length; in this case the footing is referred to a local 0° slope, upstream being proposed either a retaining structure or an embankment slope work (figure 1a);
• Stepback buildings mean that the underground spans progress in a step-like succession from one side of the building along the entire length (figure 1b);
• Stepback - setback buildings mean that the aboveground spans and the underground spans progress in a step-like succession from one side of the building along the entire length (figure 1c).

The topic of this paper exceeds the provisions of the present regulations concerning the structural design issues related to the behaviour of the setback buildings on slopped ground surface.

2. General data
In order to demonstrate the efficiency of the setback buildings, a case study located in Iași was carried out on a building which has six spans of 4.00 m (SBI), 5.00 m (SBII) and 6.00 m (SBIII), presented schematically in figure 2.

Figure 1a. Setback buildings. Figure 1b. Stepback buildings. Figure 1c. Stepback - setback buildings.

Figure 2. Floor plan – spans of 4.00 m (SBI), 5.00 m (SBII) and 6.00 m (SBIII).
The structure is made of class C20/25 reinforced concrete frame building, reinforced with independent concrete-steel bars BST500C. The columns have constant section along their entire height (50 x 50 cm) and are connected at the floor levels by reinforced concrete beams (30 x 50 cm).

### Table 1. Data for buildings configuration

| Title                | Description               |
|----------------------|---------------------------|
| Type of the building | SB I                      |
|                      | SB II                     |
|                      | SB III                    |
| Occupancy            | residential buildings     |
| Floor height         | 3.00 m                    |
| Spacing in X direction | 4.00 m          |
|                      | 5.00 m                    |
|                      | 6.00 m                    |
| Spacing in Y direction | 4.00 m          |
|                      | 5.00 m                    |
|                      | 6.00 m                    |
| Beam cross-section   | 30 x 50 cm                |
| Column cross-section | 50 x 50 cm                |
| Slab thickness       | 15 cm                     |
| Concrete wall        | 25 cm                     |
| Raft foundation      | 1.00 m                    |
| Floor                | Permanent load            |
|                      | 2.00 kN/m²                |
| Live load            | 2.00 kN/m²                |
| Floor loads          | Permanent load            |
|                      | 2.00 kN/m²                |
| Roof                 | Live load                 |
|                      | 2.00 kN/m²                |
| Snow load            | 2.00 kN/m²                |
| Beam loads           | Dividing walls            |
|                      | 7 kN/m                    |
| Strength class       | C20/25                    |
| Grade of steel       | BST500C                   |

According to Romanian Design Code P100-1 / 2013 “Seismic design code. Part 1. Design provisions for buildings” (amended and supplemented in 2019), the site is situated in the seismic zone with the value of the peak design ground acceleration, determined for average recurrence interval IMR=225 years for ultimate limit state, $a_g = 0.25g$ (figure 3) and the corner period $T_c = 0.7$ sec (figure 4).

![Figure 3. Peak ground acceleration according to P100/-2013.](image)

![Figure 4. Corner period according to P100/-2013.](image)

The structural modelling and analysis of the buildings have been performed by using ETABS software, using a spatial model defined by help of surface finite elements of shell type and linear elements of frame type (beam and column). According to P100-1 / 2013 amended and supplemented
in 2019, for the analysed reinforced concrete structures, the behaviour factor is designed for high ductility class (table 2.). Table 3 presents the relevant data required to consider the soil-structure interaction for this case study.

### Table 2. Behaviour factors

| Type of the structure                        | $q$   |
|---------------------------------------------|-------|
| frame structures, shear wall structures, dual structures | $5 \frac{a_u}{\alpha_1}$ $3.5 \frac{a_u}{\alpha_1}$ $2.0$ |

For common cases, the following approximate values of the $\frac{a_u}{\alpha_1}$ ratio can be adopted:

(a) For frames or dual structures with predominant frames:
   - buildings with one level: $\frac{a_u}{\alpha_1} = 1.15$;
   - buildings with several levels and with a single span: $\frac{a_u}{\alpha_1} = 1.25$;
   - buildings with several levels and several spans: $\frac{a_u}{\alpha_1} = 1.35$.

### Table 3. Data for soil-structure interaction in the local seismic zone for Iasi city

| Title                                      | Description          |
|--------------------------------------------|----------------------|
| Peak ground acceleration, $a_g$            | $0.25g$              |
| Corner period, $T_c$                       | $0.70$ sec           |
| Importance factor, $\gamma_{I,e}$         | $1.00$               |
| Behaviour factor, $q$                      | $6.75$               |
| Soil Type                                  | sandy soil           |
| Angle of internal friction of soil, $\phi$| $25^\circ$           |
| Unit weight of soil, $\gamma$              | $20$ kN/m$^3$        |

The lateral influence of the soil at the basement level is addressed by at-rest earth pressure, which is an assumed state where the soil and the structure develop no displacement (figure 5, table 4). The soil type used for the analyses is non-cohesive with internal friction angle of $25^\circ$ (medium compacted sand).

![Figure 5. Earth pressure diagrams on the inner and outer basement walls.](image-url)
Table 4. Calculation of lateral earth pressure

|                          | Lateral earth pressure on the interior wall:                                      | Lateral earth pressure on the exterior walls:                                      |
|--------------------------|----------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
|                          | \( p = p_{\text{max}} \cdot k_0 \) - at the top where \( p_{\text{max}} = p_{\text{pl}} \) | \( p = 0 \) - at the top                                                          |
|                          | \( p = p_{\text{max}} \cdot k_0 + \gamma \cdot H \cdot k_0 \) - at the bottom     | \( p = \gamma \cdot H \cdot k_0 \) - at the bottom                                  |
| Soil internal friction angle \( \varphi \) | 25.00°                                                                          | 25.00°                                                                            |
| Coefficient of earth pressure at rest: \( k_0 = 1 - \sin \varphi \) | 0.58                                                                             | 0.58                                                                              |
| \( p_1 = p_{\text{pl}} \cdot k_0 \) | 47.78 \( \text{kN/m}^2 \)                                                         | \( p_1 = 0 \) \( \text{kN/m}^2 \)                                                |
| Height: \( H_1 \)        | 2.00 \( m \)                                                                     | Height: \( H_1 \) \( m \)                                                          |
| Height: \( H_2 \)        | 5.00 \( m \)                                                                     | Height: \( H_2 \) \( m \)                                                          |
| Height: \( H_3 \)        | 8.00 \( m \)                                                                     | Height: \( H_3 \) \( m \)                                                          |
| \( p_2 H_1 \) = \( p_{\text{pl}} \cdot k_0 + \gamma \cdot H_1 \cdot k_0 \) | 70.88 \( \text{kN/m}^2 \)                                                         | \( p_2 H_1 = \gamma \cdot H_1 \cdot k_0 \) \( 34.65 \) \( \text{kN/m}^2 \)     |
| \( p_2 H_2 \) = \( p_{\text{pl}} \cdot k_0 + \gamma \cdot H_2 \cdot k_0 \) | 105.53 \( \text{kN/m}^2 \)                                                        | \( p_2 H_2 = \gamma \cdot H_2 \cdot k_0 \) \( 69.31 \) \( \text{kN/m}^2 \)     |
| \( p_2 H_3 \) = \( p_{\text{pl}} \cdot k_0 + \gamma \cdot H_3 \cdot k_0 \) | 140.19 \( \text{kN/m}^2 \)                                                        | \( p_2 H_3 = \gamma \cdot H_3 \cdot k_0 \) \( 103.96 \) \( \text{kN/m}^2 \) |

3. Numerical analysis

A number of nine alternative buildings are analysed in ETABS software, six spans of 4.00 m (SBI), 5.00 m (SBII) and 6.00 m (SBIII), that differ by the number of the underground levels (one, two, respectively three), on the length of two spans (figures 6, 7 and 8). The characteristics of the structure configurations are summarized in table 1.

Figure 6. Building with one underground level.

Figure 7. Building with two underground levels.
4. Results and discussions
The obtained results are compared in the form of internal forces: axial force, shear force and bending moment on relevant structural elements.

The first step is to identify the maximum values of the internal forces. These are extracted from the envelope combination type, which is overlapping values resulting from ten load combinations (8 seismic combinations, one fundamental combination and geotechnical loads combination = ENVE). The maximum values of the internal forces were identified for the column positioned at the intersection of the 5 – F axes (ground floor), for the beams situated between axes 5 – 6 / F (ground floor), 4 – 5 / F (first floor), 2 / G – F (second floor) and for the wall situated between axes 5 / C – D (basement 1), in all nine structural models (figures 9, 10, 11, 12).
4.1. Internal forces in the beams

Figures 13, 14 and 15 show that for each analysed situation, the values of internal forces do not present relevant variations, in sense of increase or decrease.

It is noted that the percentage variation (from three underground levels building to two underground level building and from two underground levels building to one underground level building) for shear forces and bending moments, is between 0.01 % and 7.53 %.
4.2. Internal forces in the column

For the analysed cases (SBI, SBII, SBIII), from three underground levels building to two underground level building and from two underground levels building to one underground level building, it is showing the following conclusions:

- the value of axial forces increases once the number of underground levels decreases and the percentage variation for axial forces is less than 1.00 % (figure 16a);
- the value of bending moments decreases once the number of underground levels decreases and the percentage variation for bending moments is between 4.17 % and 14.19 % (figure 16b).
Figure 16a. Variation of 5 – F axes column axial forces

Figure 16b. Variation of 5 – F axes column bending moments

4.3. Internal forces in the underground wall

For the analysed cases (SBI, SBII, SBIII) the following conclusions are relevant:

(a) the values of M11 moments (figure 17a):
   - from three underground levels building to two underground level building, the values of M11 moments decrease by approximately 22.22 % – 45.71 %;
   - from two underground levels building to one underground level building, the values of M11 moments decrease by approximately 78.57 % – 84.21 %.

(b) the values of M22 moments (figure 17b):
   - from three underground levels building to two underground level building, the values of M11 moments decrease by approximately 16.08 % – 29.29 %;
   - from two underground levels building to one underground level building, the values of M11 moments decrease by approximately 43.75 % – 65.66 %.

Figure 17a. and figure 17b. show that for all nine analysed situations, the values of M11 and M22 moments decreases with the decrease of the number of underground levels.

Figure 17a. Variation of M11 moments for 5 / C – D axes wall
5. Conclusions
The following conclusions can be drawn from the results obtained for the buildings presented above:

- the increase or the decrease of internal forces directly influences the material consumption;
- the number of underground levels is affecting in a small manner the amount of materials required for the superstructure of the building (beams and columns);
- the values of internal forces for underground walls present a decrease which is directly proportional with the number of underground levels; thus, for buildings with the same number of underground levels, the internal forces increase when the values of spans increase; also, for the building with the same spans values (SBI, SBII, SBIII), the bending moments decrease when the number of underground levels decrease;
- the number of underground levels should be optimized based on multiple: required functionality, the expected structural response, availability of the materials required, available budget in terms of cost and time, etc.;
- for the building with one underground level, the maximum values of the internal forces are obtained from a seismic combination, while for the building with two and three underground levels the maximum values of the internal forces are obtained from the load combination including the lateral earth pressures.

References

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