23 | Review paper I Прегледни научни рад
ISSN 2566-4484 I Doi 10.7251/STP2014250R
pages 250-262

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ANALYSIS OF THE INFLUENCE OF GROUND TYPES ON SEISMIC RESPONSE OF MULTI-STOREY FRAME STRUCTURE

Abstract:

Experiences from previous earthquakes have shown that level of structural damages depends on ground features where the structure is placed. Also, it is noted that reinforced concrete frame structures collapse due to the appearance of “weak floor”, especially when are founded on grounds with lower characteristics. In this paper, the seismic analysis of structure is presented on example of the six-storey RC frame structure, founded on different ground types. The seismic analysis is performed in accordance with European regulations and still valid ex-Yugoslavian code PIOVSP'81. At the end of the paper, a comparison of the results was made, and corresponding conclusions were reached.

Keywords: ground type, seismic design, capacity design, Eurocode 8

АНАЛИЗА УТИЦАЈА КАТЕГОРИЈЕ ТЛА НА СЕИЗМИЧКИ ОДГОВОР ВИШЕСПРАТНЕ РАМОВСКЕ КОНСТРУКЦИЈЕ

Сажетак:

Искуства стечена из ранијих земљотреса показала су да ниво оштећења конструкција зависи од карактеристика тла на ком се објекат налази. Такође, примијећено је да армиранобетонске конструкције доживљавају лом услијед појаве “слабог спрата“, или усљед колапса цијеле конструкције, посебно онда када је објекат фундиран на тлу лоших карактеристика. У овом раду, приказана је упоредна сеизмичка анализа шестоспратне АБ рамовске конструкције која се налази на различитим типовима тла. Сеизмички прорачун је извршен примјеном Европских прописа и прописа ПИОВСП'81. На крају рада, приказано је упоређење карактеристичних резултата и донијети су одговарајући закључци.

Кључне ријечи: тип тла, сеизмички прорачун, метода програмираног понашања, Еврокод 8

1. INTRODUCTION

The seismic response of structure during an earthquake depends on several factors such as material characteristics which the structure is made of, the type of soil where the structure is founded on, the level of area seismicity which the structure is being built in, the structural system which the structure is made of, on non-structural elements, etc. All these factors influence the dynamic characteristics of the structure, which directly affects the response of the structure to earthquake action.

In this paper, the analysis of the influence of ground types is investigated on the seismic response of a multi-storey frame structure. This is performed on example of the six-storey frame structure founded on different types of ground and analysed in accordance with European regulations and still valid ex-Yugoslavian code PIOVSP'81. The effect of ground types is considered with the corresponding response spectrum and in domestic regulation with the dynamic coefficient.

2. MODELING OF STRUCTURE

The numerical example used for this analysis, is a six-storey frame structure, with a total height of 19m. The storey height of the ground floor is 4m, while the height of the other stores is 3m each. The structure is a square-shaped base, with dimensions of 16.5x16.5m. In both directions, a span of structural elements is 3x5.5m.

The class of concrete is C30/37 according to Eurocode 2 [5], which corresponds to the class strength of concrete MB35 according to code PBAB'87 [6]. The reinforcement type is B500.

Columns have rectangular cross-sections. Dimensions of interior columns are 60x60cm, while dimensions of exterior columns are 50x50cm. A rectangular cross-section is adopted for the beams, with dimensions of 40x60cm. The floor slab has 16cm thickness.

Analysis of structure was performed on a 3D model of the structure by using FEM software Tower – Radimpex (Figure 1). Beside this, a cross-sectional ductility analysis was performed in software XTRACT.

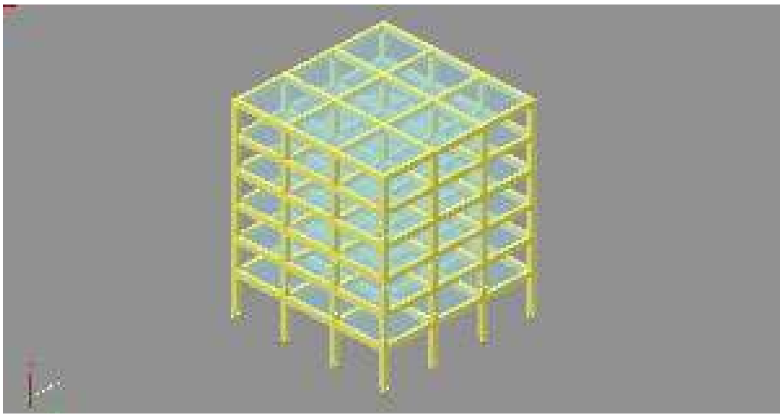

Figure 1 *3D model of analysed structure*

The self-weight load was taken automatically in the software. Additional dead load is uniformly distributed surface unit load, on the floor slabs as well as on the roof. Adopted value of this load is $\Delta g = 2$ kN/m^2. Live load is uniformly distributed surface unit load, on the floor slabs, with the intensity of $p = 2$ kN/m^2.

Considering the location of the structure, the snow load is uniformly distributed surface unit load, with the intensity of $s = 0.75$ kN/m^2.

2.2. Modal periods

According to Eurocode 8 (EC8) [3], the flexural and shear stiffness properties of RC elements should be modeled taking into account the effect of cracking of concrete. The elastic flexural and shear stiffness properties of structural elements are taken to be equal to one half of the corresponding stiffness of the uncracked elements.

In Eurocode 8 [3] the weight of the structure is given by the expression:

$$W=\Sigma G_{kj} + \Sigma \Psi_{ei} Q_{kj} \tag{1}$$

Total weight is calculated as a sum of the dead load, 15% of live load, and 30% of snow load.

The total weight and calculated periods of vibrations for the first 2 modes are given in Table 1.

Table 1 *Characteristics of the structure according to EC8*

Total weight	Period of vibration, the 1. mode	Period of vibration, the 2. mode
17469.4 KN	0.814s	0.814s

It is noted that the European code [3] in seismic design, uses a smaller percent of live load and snow load when compared to code PIOVSP'81 [4]. For seismic design, code POVSP'81 uses total dead load, 50% of live load, and total snow load. PIOVSP'81 [4] does not take into account the effect of cracking by reducing stiffness. According to this code, the greater total weight of the structure, and smaller periods of vibrations are obtained, than in accordance with Eurocode 8 [3], (Table 2).

Table 2 *Characteristics of the structure according to PIOVSP'81*

Total weight	Period of vibration, the 1. mode	Period of vibration, the 2. mode
18586.8 KN	0.588s	0.588s

3. CALCULATION OF SEISMIC EFFECTS ACCORDING TO EUROCODES (EC8) AND NATIONAL REGULATIONS (PIOVSP'81)

3.1. Calculation of seismic forces according to eurocode 8

The analysed building was designed as a high-ductility class structure (DCH), resulting in a greater reduction of seismic forces (higher behaviour factor), higher displacement ductility, and lower bearing capacity.

The structure was located in the IX seismic zone, with the reference peak ground acceleration agR = 0.32g. The analysed building belongs to a group of frame structures. The importance factor of the structure amounts $\gamma 1=1.0$, and the adopted behaviour factor is equal q = 5,85.

According to Eurocode 8 [3], there are 5 ground types: A, B, C, D, and E. They are described by the stratigraphic profiles and parameters given in Table 3. These ground types may be used to account for the influence of local ground conditions on the seismic action. This may also be done by additionally taking into account the influence of deep geology on the seismic action.

Special studies are required for the definition of the seismic effects for sites with ground conditions matching either one of two special ground types S1 or S2. For these types, and particularly for S2, the possibility of soil failure under the seismic action shall be taken into account.

The seismic analysis was performed for the three ground types - ground types B, C, and D.

Table 3 *Ground types according to Eurocode 8*

Ground type	Description of stratigraphic profile	Parameters		
		$v_{s,30}$ (m/s)	N_{SPT} (blows/30cm)	c_u (kPa)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface.	> 800	-	-
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of meters in thickness, characterized by a gradual increase of mechanical properties with depth.	360 – 800	> 50	> 250
C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of meters.	180 – 360	15 – 50	70 – 250

D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil.	< 180	< 15	< 70
E	A soil profile consisting of a surface alluvium layer with v_s values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with v_s > 800 m/s.			
S_1	Deposits consisting, or containing a layer at least 10 m thick, of soft clays/silts with a high plasticity index (PI > 40) and high water content	< 100 (indicative)	-	10 – 20
S_2	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in types A – E or S_1			

3.1.2. Calculation of seismic forces using the lateral force method of analysis (LFM)

Because of its own simplicity, the lateral force method of analysis (LFM) is the most commonly used in calculating seismic forces. Condition for using this method is defined in a way that the structure must vibrate predominantly in the first mode.

The requirement is deemed to be satisfied in buildings which fulfill both of the two following conditions:

- they have fundamental periods of vibration T1 in the two main directions which are smaller than the following values:

$$T_1 \leq \begin{cases} 4T_c \\ 2.0s \end{cases} \tag{2}$$

- they meet the criteria for regularity in elevation.

The considered structure satisfied both conditions.

The seismic base shear force Fb for each horizontal direction in which the building is analysed, shall be determined using the following expression:

$$F_b = S_d(T_1)m\lambda \tag{3}$$

Distribution of the horizontal seismic forces may be calculated using methods of structural dynamnics or may be approximated by horizontal displacements increasing linearly along the height of the building.

For the anylased building, distribution of the horizontal seismic forces was calculated using methods of structural dynamnics.

$$F_i = F_b \frac{s_i m_i}{\Sigma s_j m_j} \tag{4}$$

3.1.3. Calculation of seismic forces using the modal response spectrum analysis (MMA)

Modal response spectrum analysis (MMA) could be used for all types of structures. It shall be used for buildings that do not satisfy the necessary conditions for using the LFM. It is a reference method for calculating seismic forces according to Eurocode 8 [3].

When using this method, the response of all modes of vibration, contributing significantly to the global response, shall be taken into account. The number of necessary modes is determined by fulfilling one of the following conditions:

- the sum of the effective modal masses for the modes taking into account amounts to at least 90% of the total mass of the structure;
- all modes are taken into account with effective modal masses greater than 5% of the total mass. For each mode of vibrations, it is necessary to calculate seismic force Fbi.

$$F_{bi} = m_{ef,i} S_d T_{(i)},\ i = 1,2,..,n \tag{5}$$

If all relevant modal responses are regarded as independent from each other, the maximum value of a seismic action effect may be taken as SRSS – Square-Root-of-Sum-of-Squares method.

$$E_E = \sqrt{\Sigma E_{Ei}^2} \tag{6}$$

3.2. Calculation of seismic forces according to code piovsp'81

Seismic forces were calculated using the equivalent static load method (ESL method). As defined in the code, the total base shear is equal:

$$S = KG \tag{7}$$

The considered building was located on the Montenegrin coast, in the IX seismic zone, and belongs to the second category of structure.

According to code PIOVSP'81 [4], there are three ground categories. The influence of local ground conditions is taken into account when seismic effects are calculated and is given by a dynamic coefficient, which depends on the ground category.

The first ground category represents rocky and semi - rocky soils (crystalline rocks, calcareous rocks, limestone, marl, well-cemented conglomerates, etc.). The second ground category represents very compacted and hard soil, while the third ground category is characterized by soft-to firm cohesive soil.

The building was founded on different ground categories, on the second and on the third ground category.

Seismic forces, for the structure founded on the second ground category, were equal to seismic forces for the building located on the third ground category. It is noted that the effect of the ground category does not exist if the fundamental period of vibration is lower than 0.5s (lower than 0.7s if the considered structure is founded on the 2. and on the 3. ground category).

In accordance with code PIOVSP'81 [4], the distribution of seismic forces was calculated using the following expression:

$$S_i = S\frac{G_i H_i}{\sum_1^n G_i H_i} \tag{8}$$

Code PIOVSP'81 [4] prescribes that for structures with more than 5 storeys, 85% of total base shear is distributed according to the previous expression, and 15% of the total base shear is added as a concentrated force on the top of the structure.

As well as total shear forces, the distribution of shear forces across the structure, for the building founded on the second and on the third ground category, is equal.

4. DIMENSIONING

For the comparison of the results, characteristic cross-sections of the inner frame on the ground floor were dimensioned. The dimensioned cross-sections are shown in Figure 2.

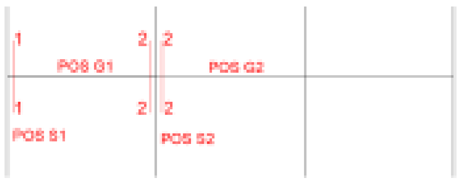

Figure 2 *Characteristic cross-sections of the considered beams and columns*

4.2. Dimensioning according to eurocode 8 (ec8)

Eurocode 8 [3] provides a capacity design procedure for beams and columns, and also defines the rules for the design of critical regions, plastic hinges. By applying the capacity design method defined by Eurocode 8 [3], the aim is to provide such a hierarchy of resistance to different types of fractures and appropriate reinforcement details in critical locations, in order to make the behaviour of RC structure ductile. To achieve the required overall ductility of the structure, the potential regions for plastic hinge formation shall possess high plastic rotational capacities. The non-linear deformations should be the result of bending deformations. In accordance with this, it is necessary to avoid brittle failures and remain in elastic region for the deformations that result in shear and axial force.

In accordance with Eurocode 8 [3], ductile failure shall be provided. For the structure founded on the ground type D, ductile failure could not be provided, but the failure of concrete for beams G1 and G2, so the design conditions were not fulfilled. Increasing the cross-sectional dimensions would be a solution. For the purpose of comparing the final results, dimensioning was continued with the values thus obtained.

Applying the capacity design, the design shear forces of the beams were increased by 55-70%, compared to the shear forces obtained by linear analysis.

The adopted reinforcement of beams G1 and G2, in the considered cross-sections, for the structure on the ground types B, C, and D, is shown in Figure 3.

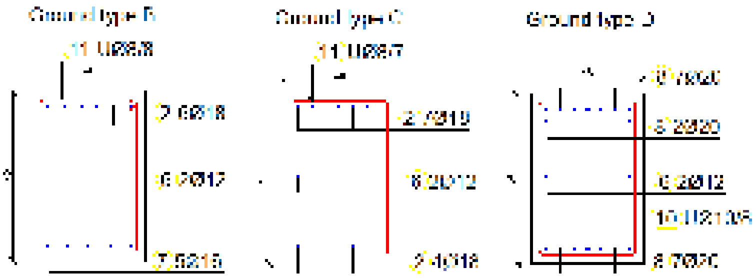

Figure 3 *Adopted reinforcement in beams G_1 and G_2 in considered cross-sections*

For multi-storey RC structures, the basic design objective is to prevent the formation of a "weak floor", i.e. the appearance of plastic hinges at the ends of all columns of one floor. The capacity design is based on providing stronger columns than beams.

Using the capacity design, on average, 50-70% higher values of the bending moments in columns were obtained, compared to the linear analysis.

In order to achieve the required displacement ductility, confining with shear reinforcement is necessary to be applied, due to the negative influence of the axial compressive force on the ductility. Adopted reinforcement in columns S1 and S2 is given in the following figures.

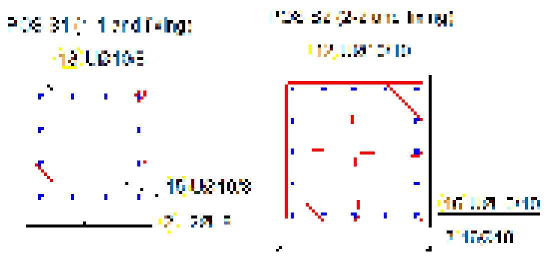

Figure 4 *Adopted reinforcement in columns S_1 and S_2 for the building on the ground type B and C*

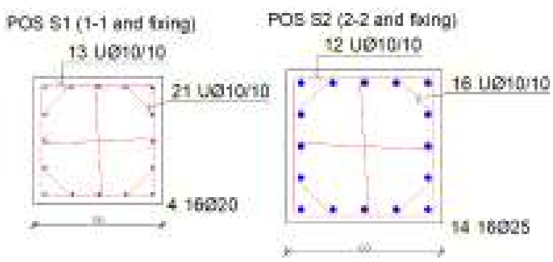

Figure 5 *Adopted reinforcement in columns S_1 and S_2 for structure on ground type D*

4.3. Dimensioning according to codes pbab'87 and piovsp'81

In accordance with the domestic code, the cross-section dimensioning is performed with the effects from the linear analysis.

Adopted reinforcement in considered beams and columns is given in Figure 6.

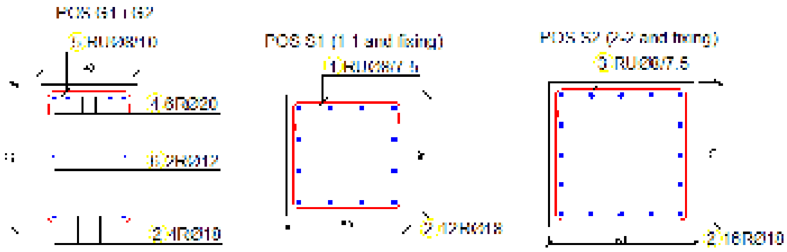

Figure 6 *Adopted reinforcement of beams and columns in considered cross-sections*

5. CROSS-SECTIONAL ANALYSIS OF THE CHARACTERISTIC CROSS-SECTIONS

Analysis of ductility of beams and columns was calculated using the XTRACT (Cross Section Analysis software for Structural Engineers) software package. The XTRACT software is primarily developed for the moment-curvature analysis. The calculation of the moment-curvature relationship is required to determine the nonlinear behavior of the cross-section.

Moment curvature diagrams and interaction diagrams were obtained based on:

- adopted longitudinal and shear reinforcement,
- the stress-strain diagram of unconfined and confined concrete,
- the stress-strain diagram of reinforcement steel B500.

The numerical example of calculation of the moment-curvature diagram and interaction diagram of the column S2, for the structure founded on the ground type B, is presented.

The stress-strain diagram of unconfined concrete C30/37 is shown in Figure 7.

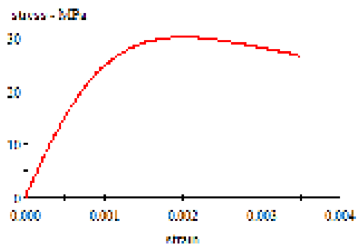

Figure 7 *Stress-strain diagram of unconfined concrete C30/37*

According to Eurocode 2 [5], based on the adopted longitudinal and shear reinforcement of the column, the compressive strength and ultimate strain of confined concrete are given by formulas:

$$f_{ck,c} = \beta \cdot f_c = \min\left(1 + 5\frac{p}{f_c}; 1.125 + 2.5\frac{p}{f_c}\right) f_{ck} \quad (9)$$

$$\varepsilon_{cu2,c} = 0.0035 + 0.2p/f_{ck} \quad (10)$$

The stress-strain diagram of the confined concrete is given in Figure 8.

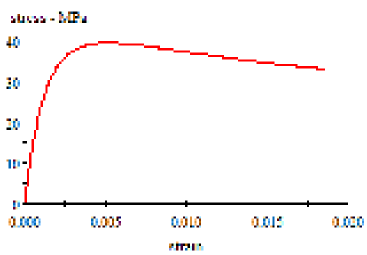

Figure 8 *Stress-strain diagram of confined concrete of column S_2*

The stress-strain diagram for reinforcement steel B500 class C was used for the analysis in accordance with the recommendations of Eurocode 2 [5] and Eurocode 8 [3]. The characteristic yield strength of the reinforcement amounts 500 MPa and the tensile strength is equal 600 MPa. The characteristic strain at maximum force amounts 10%.

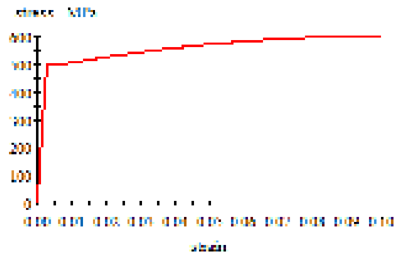

Figure 9 *Stress - strain diagram of steel B500*

Based on these input parameters, the interactions diagram (Figure 10), and the moment-curvature diagram (Figure 11) of the considered column, were formed.

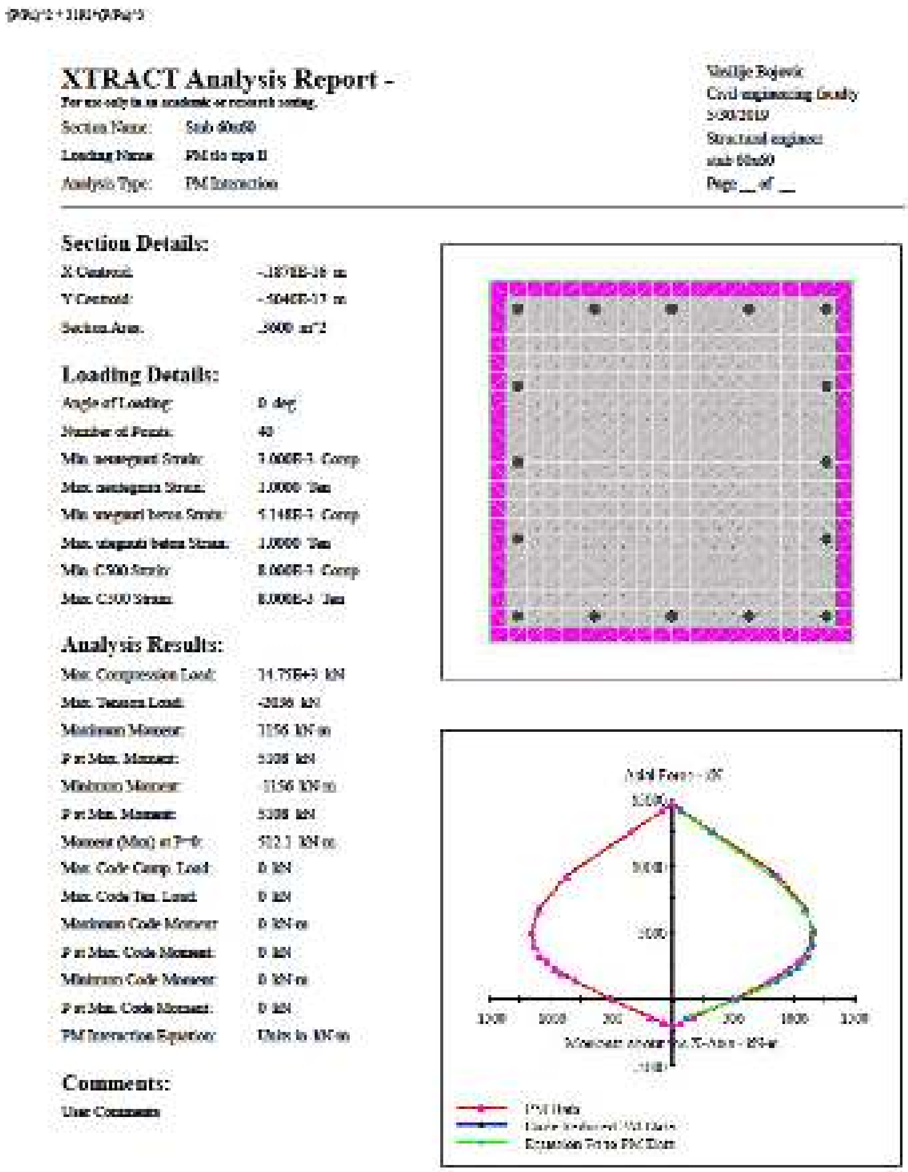

Figure 10. *Interactions diagram of the column S_2*

6. COMPARISON OF THE RESULTS

6.1. Comparison of modal periods

In accordance with Eurocode 8 [3], the calculated fundamental period of vibration for the structure founded on all three ground types, amounts $T_1 = 0.814s$. According to code PIOVSP'81 [4], the fundamental period of vibration is equal $T_1 = 0.588s$.

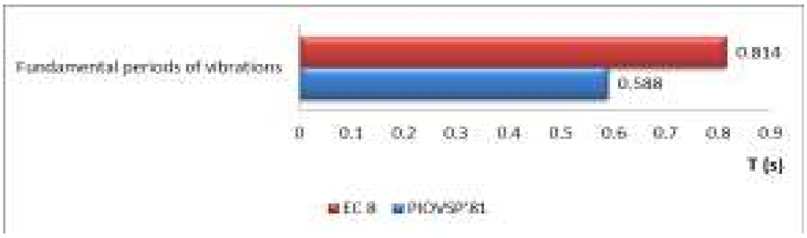

Figure 11. *Comparison of fundamental periods of vibrations according to EC8 and PIOVSP'81*

In Figure 12, a comparison of fundamental periods of vibrations according to codes Eurocode 8 [3] and PIOVSP'81 [4], is shown.

By reducing stiffness in accordance with Eurocode 8 [3], the effect of cracking, during an earthquake was taken into account. The stiffness of the structure was reduced, and the fundamental period of vibration was increased. According to Eurocode 8 [3], the fundamental period of vibrations is higher than according to code PIOVSP'81 [4] for 38.4%.

6.2. Comparison of seismic forces

By comparing the total seismic forces, calculated using the LFM and the MMA, approximately the same values were obtained (Figure 13). It means that the criteria for the regularity of the structure at the base and in elevation are fulfilled, as well as the structure dominantly vibrates in the first mode (the effect of higher modes is insignificant), so the LFM produces satisfactory fluid results.

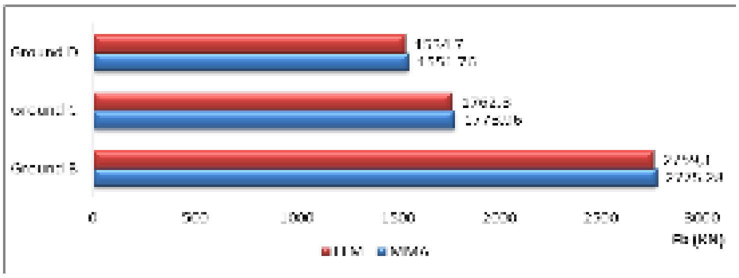

Figure 12. *Comparison of total seismic forces for the structure founded on 3 ground types*

As the total values of seismic forces are approximately equal, their distribution across the structure is approximately equal, so only the LFM was used in the further comparison of the results.

Further charts show a comparison of the total and storey seismic forces. Values of seismic forces, according to code PIOVSP'81 [4] were multiplied with a safety coefficient of 1.3, in order to compare with the seismic forces obtained according to Eurocode 8 [3], by which the coefficient for seismic actions is equal to 1,0.

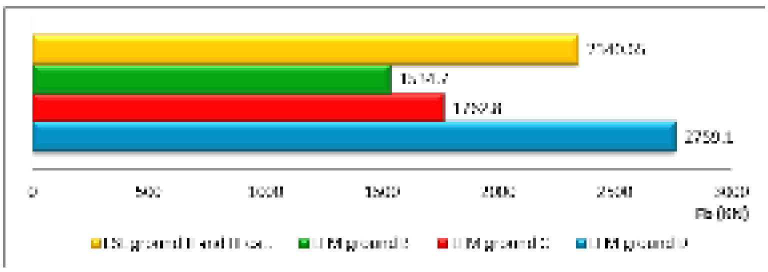

Figure 13. *Comparison of total seismic forces for the structure on 3 ground types*

Depending on the ground category, seismic forces can vary considerably. In analysed case, the seismic forces for the structure founded on the ground type D were higher than seismic forces for the building which was on the ground type B for 79.8%, and 56.5% higher than seismic forces for the structure founded on the ground type C. Using the ESL method, greater seismic forces were obtained than according to Eurocode 8 [3] when the structure was founded on the ground type B and C, and lower seismic forces when the considered building was located on the ground type D.

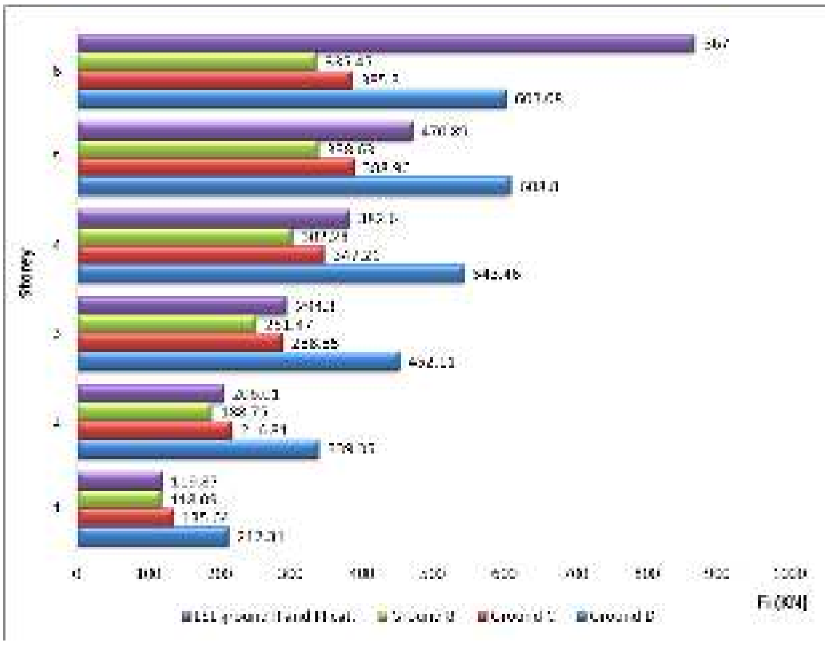

Figure 14. *Comparison of storey seismic forces for the structure on the ground types B, C, and D (LFM and ESL method)*

On the last floor, the seismic force calculated using the ESL method was significantly greater than the seismic force calculated according to LFM, because, according to PIOVSP'81 [4], 15% of the seismic force is added on the top floor for the structures with more than 5 storeys.

6.3. Comparison of total displacements

Figure 16 shows the comparison of total displacements, and Figure 17 presents the comparison of interstorey drifts for the structure founded on the ground types B, C, and D.

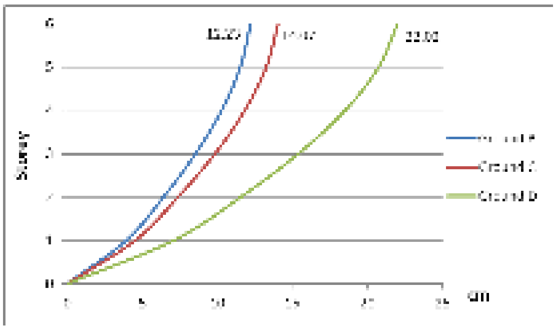

Figure 15. *Comparison of total displacements for the structure on the ground type B, C, D*

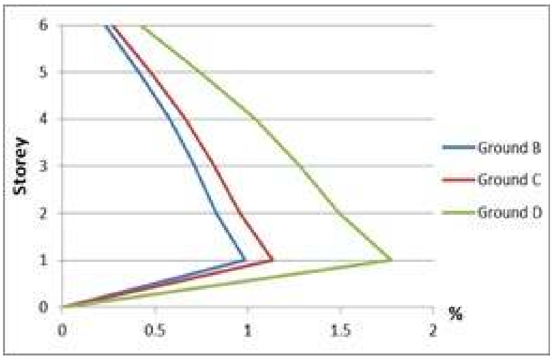

Figure 16. *Comparison of interstorey drifts for the structure on the ground types B, C, D*

Displacement of the top of the structure founded on the ground type D was 80% higher than in case when that building was on the ground type B. Also, the structure founded on the ground type D was displaced 56.5% more than when that building was located on the ground type C.

6.4. Comparison of adopted reinforcement

Comparison of adopted longitudinal and shear reinforcement ratios of the beams is shown in the following figures.

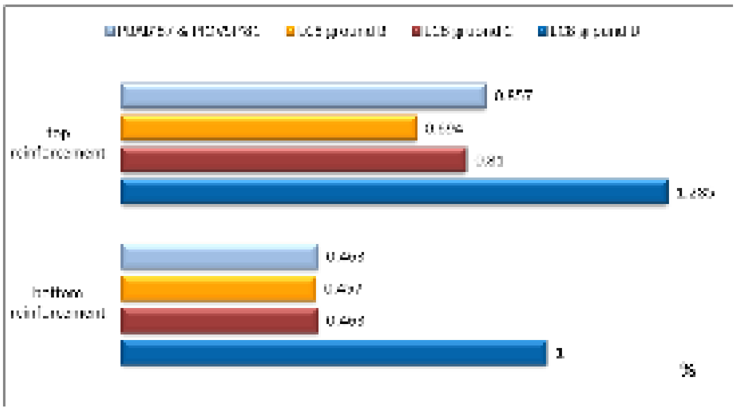

Figure 17. *Comparison of adopted longitudinal reinforcement ratios of beams*

According to PBAB'87 [6] and PIOVSP'81 [4], the reinforcement in the upper zone of the beam is 23% larger than in the corresponding section calculated in accordance with Eurocode 8 [3], for the structure on the ground type B, 5% larger than for a building founded on the ground type C, and 50% lower than for a structure founded on the ground type D.

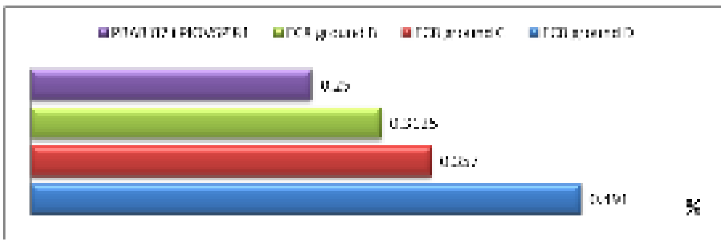

Figure 18. *Comparison of adopted shear reinforcement ratios of beams*

In accordance with Eurocode 8 [3], a larger shear reinforcement, compared to the codes PBAB'87 [6] and PIOVSP'81 [4] was obtained. A 25% larger if the structure was on the ground type B, 42.8% larger if the structure was on the ground C, and 96.3% larger if the building was on the ground type D, then according to codes PBAB’87 [6] and PIOVSP’81 [4].

Comparison of longitudinal and shear reinforcement of the column S2 is shown in the following figures. The longitudinal reinforcement, according to PBAB'87 [6] and PIOVSP'81 [4], and according to Eurocode 8 [3] for the structure on the ground type B and C, was adopted from the condition of the minimum reinforcement ratio.

For the building on the ground type D, 92.7% larger longitudinal reinforcement was calculated when compared to the structure on the other ground types.

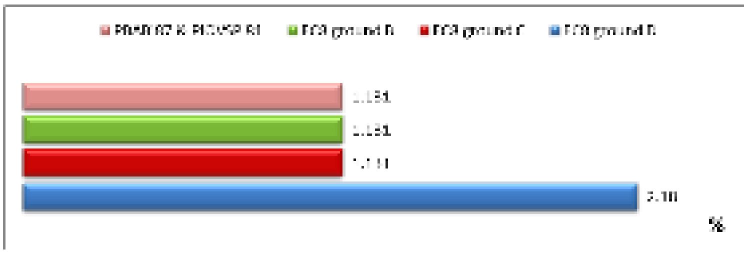

Figure 19. *Comparison of adopted longitudinal reinfocement ratios of the column S_2*

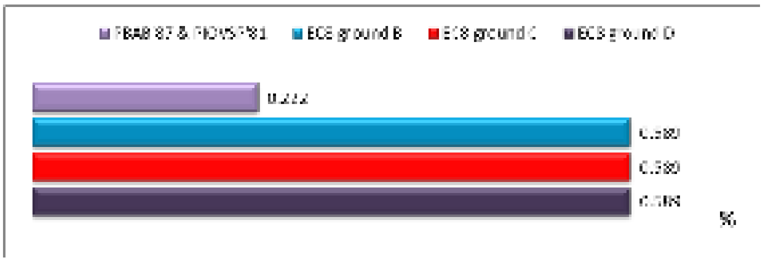

Figure 20. *Comparison of adopted shear reinfocement ratios of the column S_2*

According to Eurocode 8 [3], the stirrups were adopted from the cross-sectional confining conditions, resulting in a 165% larger transverse reinforcement than according to PBAB'87 [6] and PIOVSP'81 [4].

6.5. Comparison of the results calculted using the xtract

The values of the ultimate strain and the curvature ductility of the column S_2 are shown in the following figures.

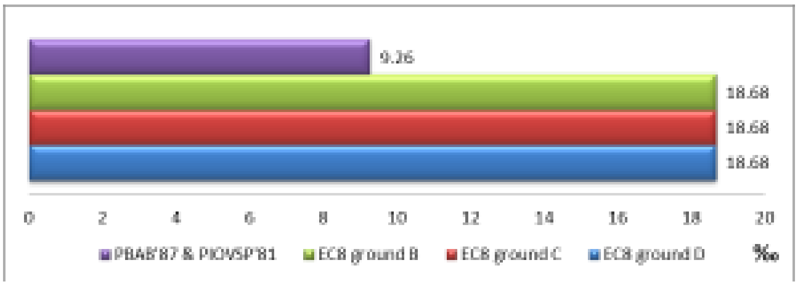

Figure 21. *Comparison of ultimate strains of confined concrete for the column S_2*

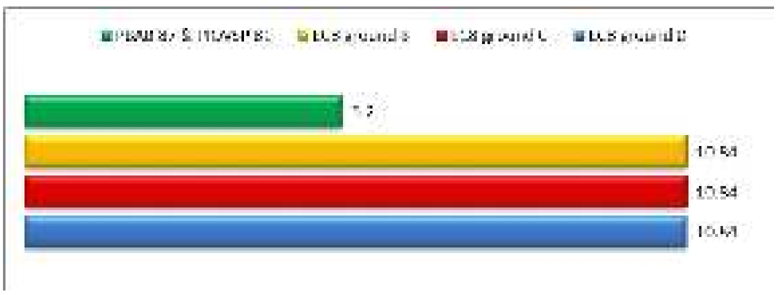

Figure 22. *Comparison of ultimate curvature of the column S_2*

According to Eurocode 8 [3], 102% higher ultimate strain was obtained compared to PBAB'87 [6], and PIOVSP'81 [4].

7. CONCLUSION

Eurocode 8 [3] provides five basic ground types: A, B, C, D, and E, with geological and geophysical parameters that are used in order to select proper parameters. Beside this, it is prescribed that there are two special ground types S1 and S2 where special studies have to be performed for the definition of the seismic actions. In accordance with domestic regulations, there are three ground types and they are given with descriptive geological information.

In accordance with the performed analysis it can be concluded that seismic performance of the structure founded on the ground types B and C, was similar (for the structure on ground type C seismic forces were 15% higher than for the structure on the ground type B). However, when the structure was founded on the ground type D, seismic forces were 80% higher than for the ground type B.

Also, it is concluded that when calculating structure in accordance with Eurocode 8 [3], the effect of changing ground category is better perceived than in accordance with the domestic code. According to code PIOVSP’81 [4], for the structures with fundamental period of vibration lower than 0.5s, there is no effect on the total seismic forces dependent on the selected ground category.

Considering cracked sections, the structure designed according to Eurocode 8 [3], is more flexible than the structure designed according to the code PIOVSP'81 [4].

Designing in accordance with European regulations generally results in slightly smaller longitudinal and much larger shear reinforcement (about 42% for beams and 156% larger for columns) to provide the required ductility of the structure, which is necessary for an adequate seismic performance of the structure.

Based on the analyses performed, it can be concluded that the Eurocode 8 [3] provides good guidelines for taking the ground effects on the performance of the structure and it provides guidelines for detailing for local ductility which is major improvement compared to domestic codes PIOVSP'81 [4] and PBAB'87 [6].

At the end, it can be concluded that type of ground on which the flexible frame structures are founded on, has a great impact on seismic response of the structures during an earthquake. In accordance with this, when designing frame structures in seismic active regions, the additional geotechnical investigations should be performed, local geological conditions should be considered, as well as the effects of deep geology.

LITERATURE

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