BULETINUL INSTITUTULUI POLITEHNIC DIN IAȘI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iași
Tomul LX (LXIV), Fasc. 3, 2014
Secția
CONSTRUCȚII. ARHITECTURĂ

SPECTRAL ANALYSIS FOR AN ASYMMETRICAL STRUCTURE CONSIDERING SOIL STRUCTURE INTERACTION

BY

CERASELA PANSELUȚA OLARIU[*] and MIHAELA MOVILĂ

“Gheorghe Asachi” Technical University of Iași
Faculty of Civil Engineering and Building Services

Received: June 19, 2014
Accepted for publication: July 14, 2014

Abstract. In civil engineering, problems which deal with the effects of the structural asymmetry are more frequently encountered. Besides the fact that the majority of the design provisions recommend that the structure should be symmetrical in plane as well as in elevation, there are various situations in which asymmetrical structures are designed. The torsional response of these types of structures can be influenced also by taking into consideration the soil structure interaction effects.

The main analytical method used to determine the behavior and the failure mechanism of elements or of the entire structure is the finite element method (FEM). Soil structure interaction can be modeled in various ways, but the most frequently used are the lumped models and the finite element models.

This paper presents a FEA performed in a computer assisted environment on an asymmetrical structure considering the influence of soil condition taking into account the provisions of the Romanian and European design codes.

Key words: finite element analysis; structural asymmetry; torsional response; soil conditions.

---

[*] Corresponding author: *e-mail*: olariucerasela@yahoo.com

1. Introduction

Most design codes have provided detailed provisions for structure asymmetry and torsion-resistant design (Stefano De M., 1997). However, the destruction of numerous asymmetric buildings in earthquakes like: Bucharest 1977, Mexico City 1985 and Kobe 1995 made researchers realize that soil-structure interaction (SSI) can substantially change the seismic performance of asymmetric structures. It is necessary to incorporate the flexibility of foundation soil into calculation. For a realistic approach, multi-storey models were used to study asymmetric structures response.

A structure must have a high strength and stiffness to torsion for a proper behavior to the seismic action, besides the strength and stiffness to lateral loads. Single storey models are more appealing to researches because they are suitable to obtain general information about the torsion behavior of asymmetrical structures, even though in the last years, multi-story models were used to study the response of asymmetric structures (Anechitei, 2010).

The main analytical method used to determine the behavior and the failure mechanism of elements or of the entire structure is the finite element method (FEM).

The most encountered effects of considering soil – structure interaction during an analysis is a decrease in the overall stiffness and an elongation of the overall structural period, which in general decreases force demand and increases displacement demand on the structure (Olariu *et al*., 2011).

Soil-structure interaction can be modeled in various ways, but the most frequently used are the lumped models and the finite element models. A common assumption considers the foundation soil stiffness applied as a set of elastic springs in one or more support points of the structure. There are different equations which define the foundation stiffness taking into account the geometry of the foundation-soil contact area, the properties of the soil beneath the foundation and the characteristics of the foundation motion. The paper uses the relationships depending on the bed coefficient of the soil offered by (Negoita *et al*., 1985). These stiffnesses allow the estimation and the control of the foundation impedances, foundation soil damping and natural frequency of the structure (Davidovici, 1999).

Soil-structure interaction effects are salient for foundation soils defined by seismic shear wave velocities smaller than 800 m/s, because they tend to increase or decrease the structural response compared to the fixed base support. Sometimes, for soils with seismic shear wave velocities greater than 800 m/s structures can be considered as fixed at the base (Johnson, 2003; FEMA 450).

This paper presents a FEA performed in a computer assisted environment on an asymmetrical reinforced concrete structure considering the influence of soil condition. In order to assess the importance of considering soil conditions in structural analyses of asymmetrical structures two situations were considered for the model, namely the fixed base case and the flexible base one. The results from the dynamic modal and seismic analysis were compared being a source of information for the behavior of asymmetrical reinforced concrete structures considering the SSI effects.

2. Structural Description of the FE Dynamic Model

The considered structure is a 3-D reinforced concrete frame designed according to the Romanian Seismic design code P100-1/2012. The frame has 2 levels the first one having a 4 m height and the second one a 3 m height. At the ground floor level the bay has the following dimensions: 6 × 6 m on longitudinal direction and 5 m on the transversal one and at the top floor only a 6 m span on longitudinal way and 5 m on transversal way. The beams have a 0.30 × 0.40 m cross-section with a reinforcement ratio of 0.9% and the slabs have a 0.15m thickness. The columns are not constant along the height, their cross-section varies from the bottom floor to the top floor, namely from 0.45 × 0.45m at the first level with a reinforcement ratio of 1.12% to a 0.40 × × 0.40 cm cross section at the top level with a reinforcement ratio of 0.8%. The total weight of the structure is 70.32 KN and it was assumed a live load of 2 KN/m^2. From the geometrical point of view it is an asymmetrical structure (Fig. 1).

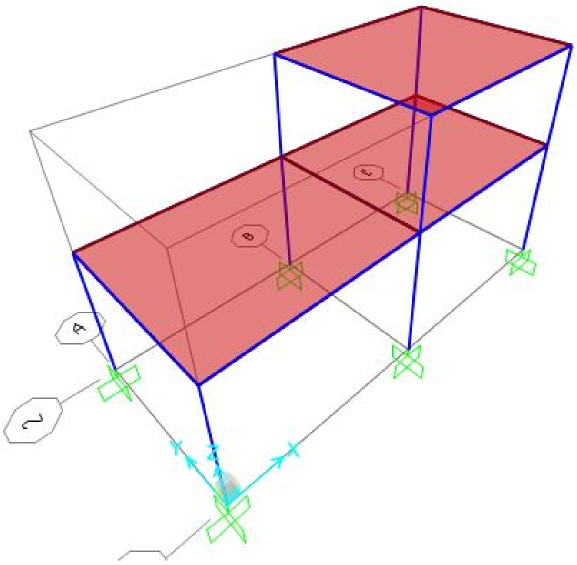

Fig. 1 – Structural model.

Table 1 presents the material properties used for the structure.

Table 1
Material Properties Used for the Structure

Materials	E MPa	ν	$f'c$ MPa	fy MPa	fu MPa
Concrete, C20/25	30×10^3	0.2	20.5	–	–
Longitudinal reinforcement, PC 52	210×10^3	0.3	–	355	570
Shear reinforcement, OB 38	210×10^3	0.3	–	235	360

In order to model soil-structure interaction elastic springs were considered. The foundation is made from reinforced concrete. The three types of soils considered were characterized through elastic compression coefficients, denoted with c_z, as it follows:

a) loose sand and clayey sand, clay and sandy clay with a bed coefficient, c_z = 10,000,000 N/m^3 (noted as the support no. 1);

b) gravel, sand and clayey sand, clay and sandy clay with a bed coefficient, c_z = 40,000,000 N/m^3 (noted as the support no. 2);

c) gravel, sand and clayey sand, clay and sandy clay plastic stiff, with a bed coefficient c_z = 80,000,000 N/m^3 (noted as the support no. 3) (Stanciu *et al.*, 2006).

These types of soils correspond to class B, C and D soil type according to the SR EN 1998-1:2004 standard. The values of the spring's stiffness were computed based on the bed coefficient and on the computational relationships provided by (Negoiță *et al.*, 1985). The spring stiffness's were computed for translational displacement, namely k_x, k_y and k_z and for rotational displacement on the x and y direction, $k_{\theta x}$ and $k_{\theta y}$ and finally for torsion, k_t (Table 2).

Table 2
Elastic Springs Stiffness's

Elastic spring	k_x, k_y N/m	k_z N/m	$k_{\theta x}, k_{\theta y}$ Nm/rad	k_t Nm/rad
Elastic 1	28,000,000	40,000,000	26,600,000	19,950,000
Elastic 2	112,000,000	160,000,000	106,400,000	79,800,000
Elastic 3	224,000,000	320,000,000	212,800,000	159,600,000

3. Dynamic Simulations and FE Analyses

The modeling of the structure has been done for the FE simulations and dynamic including seismic analysis within elastic linear domain using a finite element computational environment. All the dynamic simulations have been performed within the finite element software environment of SAP 2000, *vs*.14.2.3, (SAP 2000, 2010).

Four modeling hypothesis were considered in the modeling process taking into account the soil-structure interaction aspects. Therefore, a model of the structure with fixed support (Case fixed) and then with elastic supports computed based on the bed coefficient (Case support no.1 to no.3).

The methodology used for dynamic simulations considered two computational analysis cases. The Modal Analysis procedure has been applied in order to evaluate the dynamic characteristics, the Eigen Frequencies and the Mode Shapes (Chopra, 2006). The second method consisted of Spectral Analysis considering the Eurocode 8 Response Spectrum and P100-1/2012 Response Spectrum corresponding for Iasi region (SR EN 1998-1:2004; P100-1/2012).

According to the Romanian Seismic Code P100-1/2012 the elastic response spectrum in absolute accelerations for horizontal ground movements is computed with the following relation:

$$S_e(T) = a_g \beta(T)\,, \tag{1}$$

where: a_g is the peak ground acceleration and for Iaşi it is considered to be 0.25 g; $\beta(T)$ is the normalized response spectrum of absolute accelerations.

The elastic normalized response spectrum, $\beta(T)$, of the absolute accelerations for the horizontal ground motion with the conventional critical damping ratio $\xi = 0.05$ and depending on the corner periods are computed with the following relations:

$$0 \le T \le T_B \qquad \beta\left(T\right) = 1 + \frac{\left(\beta_0 - 1\right)}{T_B} T\,, \tag{2}$$

$$T_B < T \le T_C \qquad \beta\left(T\right) = \beta_0\,, \tag{3}$$

$$T_C < T \le T_D \qquad \beta\left(T\right) = \beta_0 \frac{T_C}{T}\,, \tag{4}$$

$$T_D < T \le 5\text{ s} \qquad \beta\left(T\right) = \beta_0 \frac{T_C T_D}{T^2}\,. \tag{5}$$

where: β_0 is the maximum dynamic amplification factor of the horizontal ground acceleration and it is $\beta_0 = 2.5$, T – the period of vibration for a single degree of freedom model, T_B, T_C, T_D – the corner periods of vibrations.

Iaşi is characterized by a corner period of vibration $T_C = 0.7$ s.

Fig. 2 represents the elastic normalized response spectrum $\beta(T)$ for a critical damping ratio of $\xi = 5\%$ and the seismic and foundation soils conditions in Romania.

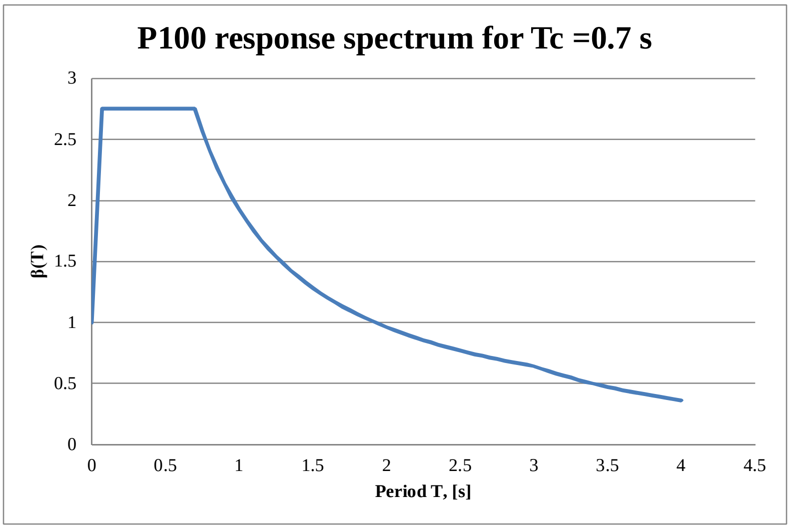

Fig. 2 – Elastic normalized response spectrum for a corner period T_C = 0.7 s (P100-1/2012).

4. Processing of the FEA Results

4.1. Modal Analyses Results

Using Modal Analysis procedure in free vibration, a number of 3 modes of vibrations have been analyzed, in order to ensure a minimum mass participation factor of 91% upon both directions of axes. Table 3 presents the results for the first three modes of vibrations, the third one being for torsion.

Table 3
Modal Analyses Results

Mode of vibration	Period of vibration, [s]			
	Case fixed	Case support no.1	Case support no.2	Case support no.3
1st Mode	0.246	0.405	0.303	0.277
2nd Mode	0.232	0.364	0.282	0.259
3rd Mode	0.184	0.291	0.223	0.205

From the modal analysis results it can be noticed that the soils stiffness influence the overall response of the structure. Therefore, the periods of vibration are increasing in average with 12% for support no. 3, 18% for support no. 2 and 39% for support no.1 compared to the fixed support case. This implies a great overall flexibility of the soils-structure system as the soil type has smaller stiffness. This increase of the period of vibration for the support no.1 case is due to the *D* soil class characteristic, according to the Eurocode 8 classification.

For all the assumed cases is noticed an increase of the structural flexibility when the soil conditions are taken into account by the means of soil-structure interaction.

Apart from this it can be noticed that the structural asymmetry plays an important part in the modal analysis. The highest period of vibration for the torsion is recorded for the support no. 1, which can imply that the structural asymmetry and the soil-structure interaction have a great influence upon the torsional response of the structure.

4.2. Response Spectrum Analyses Results

Sap2000 software environment offers to the user the possibility to perform Response Spectrum analyses based on the implemented Eurocodes in the database, namely Eurocode 8 or to apply a Response Spectrum defined by the user.

For the considered model with fixed and a flexible supports two types of Response Spectrum analyses were applied, namely the Eurocode 8 (EC8) and the normalized response spectrum from Fig. 2 corresponding to P100-1/2012 Romanian Seismic Design Rules.

Table 4

Spectral Analysis Results in FEA

FE Model	Accelerations, [m/s^2]	Velocities, [m/s]	Displacements, [m]
EC 8 Response spectrum			
Fixed, *X*	0.133	0.0047	0.000172
Fixed, *Y*	0.13231	0.005	0.000196
Support no.1, *X*	0.082	0.0046	0.000267
Support no.1, *Y*	0.0896	0.0057	0.000369
Support no.2, *X*	0.09857	0.0042	0.000185
Support no.2, *Y*	0.10155	0.0047	0.000224
Support no.3, *X*	0.11344	0.0044	0.000183
Support no.3, *Y*	0.11197	0.0047	0.000208
P100 Response spectrum			
Fixed, *X*	3.75343	0.1354	0.00499
Fixed, *Y*	4.02157	0.1555	0.006093
Support no.1, *X*	3.36992	0.1941	0.011265
Support no.1, *Y*	3.85547	0.2477	0.015966
Support no.2, *X*	3.56919	0.1572	0.007043
Support no.2, *Y*	3.96741	0.1888	0.009095
Support no.3, *X*	3.64469	0.1475	0.006083
Support no.3, *Y*	3.99358	0.1739	0.00767

Both of them were applied on *X* and on *Y* direction in order to identify the maximum responses in terms of displacements, accelerations and velocities.

Table 4 presents the results of the Response Spectrum analyses for all the studied cases.

Based on the Response Spectrum results in displacements presented in Table 4 some graphs were created in order to compare the fixed with the springs support cases both on *X* and *Y* direction. Figs. 3 and 4 display comparisons performed for all cases considering the two types of response spectra.

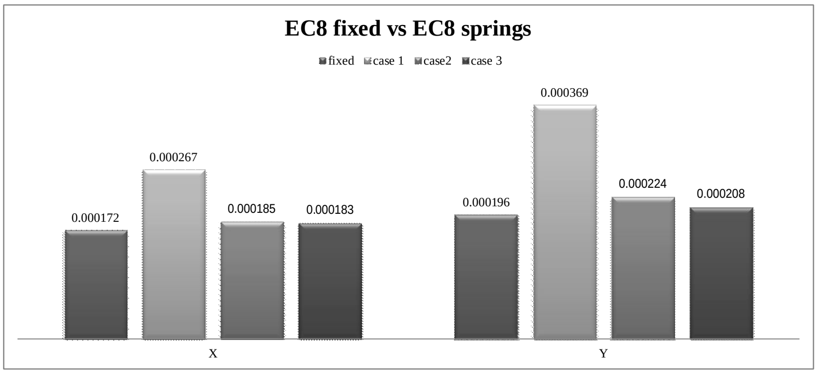

Fig. 3 – Displacement comparison for all cases based on EC8.

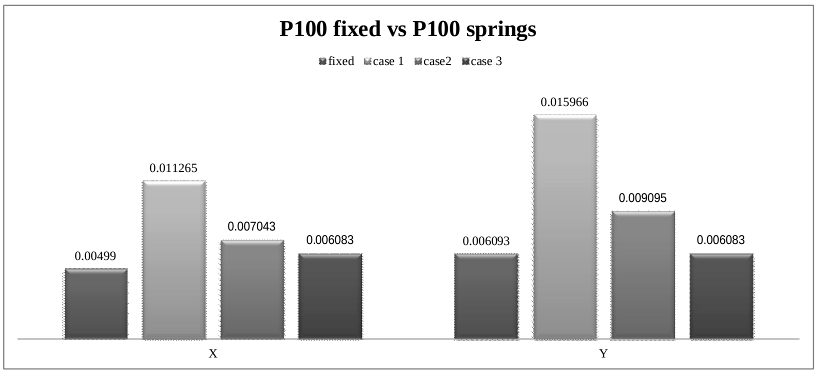

Fig. 4 – Displacement comparison for all cases based P100.

From Figs. 3 and 4 it can be noticed that the maximum responses are recorded for all cases on the *Y* direction. This was expected because the soil structure interaction increases the values of the overall structural displacements. Therefore on the relevant axis, namely *Y*, the highest displacements values are recorded for the situation with soil structure interaction.

There can be noticed a maximum percentage difference between the results obtained for the EC 8 and the P100 response spectrum of 43%, in favor of the P100. This can confirm the idea that the Romanian regulations offer higher structural responses in comparison to the European deign codes. This can be due to the fact that there are specific parameters defined for the response spectrum in accordance with the national seismic records.

Another aspect to be noticed is that the values for both P100 and EC8 for the Support no. 3 are similar to the ones for the Fixed case. The highest values in terms of displacements are encountered for Support no1, followed by Support no 2.

5. Conclusions

This paper presents the results of a dynamic and seismic analyses performed on an asymmetric structure taking into account the effects of soils conditions. The aim of this study was to observe how the soil condition and structural asymmetry interfere on the torsional response of a structure. As for modeling soil-structure interaction there were considered three types of soils and a rigid base situation.

The numerical results for the FE models which consider soil-structure interactions are higher than the ones with the rigid supports. Therefore, they highlight the importance of considering the soil conditions when analyzing an asymmetrical structure.

After performing the analyses it was noticed that soil-structure interaction has a considerable influence in the overall response of the structure but mainly in the modal analyses results. Therefore, the periods of vibration as well as the displacements are decreasing proportionally to the enhancement of the soil stiffness.

After processing the FEA information it was established that the cases with spring supports have increased values of the periods of vibrations than in the rigid base situation. This is an important aspect in identification the areas exposed to some structural damages during repetitive earthquake actions.

Based on the results of the Response Spectrum analyses it was noticed an increase of accelerations, displacements and velocities, identified for the models with elastic supports. Also, comparing the displacements results highlights that on the Y axis, the higher values are encountered, because this axis is the relevant one. Although the differences in numerical experiments obtained in simulation based on EC8 and P100 Response Spectra, the values of displacements, velocities and accelerations, based on the Romanian Code Response Spectrum input can be considered more realistic since they are in accordance with relevant specific parameters of the site location as corner period, peak ground acceleration and soil type.

From the torsion response point of view, it can be noticed that the presence of springs stiffnesses interfere on the torsion period of vibration increasing it as the stiffness of the foundation soil system decreases.

Finally, one can conclude that the simulations which consider the soil structure interaction are recommendable to be used in the process of modeling an asymmetrical structure, exposed to repetitive extreme seismic loading.

REFERENCES

Anechitei M., *Efectele torsiunii asupra răspunsului seismic al structurilor*. Ph. D. Diss., 2010.

Chopra A.K., *Dynamics of Structures* (third edition). Prentice Hall, NJ, USA, 2006.

Davidovici V., *La construction en zone sismique*. La moniteur, 1999.

Johnson J.J., *Soil Structure Interaction*: *Statement of the Problem*. Earthquake Engng. Handbook, CRC Press, Chapter 10, pp. 10-1/10-29, 2003.

Negoiţă Al., Pop I. *et al., Inginerie seismic.* Edit. Did. şi Pedag., Bucureşti, 1985.

Olariu C.P., *Influence of Soil Conditions Upon the Behavior of Certain Structures*. Ph. D. Diss., "Gh. Asachi" Technical Univ. of Iaşi, 2011.

Stanciu A., Lungu I., *Fundaţii*. Vol. **I**, Edit. Tehnică, Bucureşti, 2006.

Stefano De M., Rutenberg A., *A Comparison of the Present SEAOC/UBC Torsional Provisions with the Old Ones*. Earthquake Structures, **19** (1997).

* * * Computer & Structures Inc., 2010. SAP 2000 Software, v.14.2.3, CSI Berkeley, USA.

* * * *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*. Fema 450, Part 1-15, Washington, D.C., 2003.

* * * P100-1/2012 Seismic design Code Part 1 Regulations for structural design

* * * *Proiectarea structurilor pentru rezistenţa la cutremur*, Partea 1. Eurocod 8, SR EN 1998-1-2004, 15 decembrie 2004.

ANALIZA SPECTRALĂ A UNEI STRUCTURI ASIMETRICE CONSIDERÂND INTERACŢIUNEA TEREN-STRUCTURĂ

(Rezumat)

În ingineria civilă se întâlnesc în mod frecvent probleme ce tratează efectele asimetriei structurale. Cu toate că majoritatea normelor recomandă ca structurile să fie simetrice atât în plan cât şi în elevaţie, există situaţii în care sunt proiectate structuri asimetrice. Răspunsul la torsiune a acestor tipuri de structuri poate fi influenţat şi de efectele interacţiunii dintre terenul de fundare şi fundaţie.

Metoda elementului finit este principala metodă analitică utilizată pentru determinarea comportamentului şi a mecanismelor de cedare a unor elemente structurale sau a întregii structuri. Interacţiunea dintre terenul de fundare şi fundaţie poate fi modelată în mai multe situaţii, însă cele mai des utilizate modele sunt cele cu mase concentrate sau cele modelate cu ajutorul metodei elementului finit.

Acest articol prezintă analiza cu ajutorul metodei elementului finit a unei structuri asimetrice luând în considerare influenţa condiţiilor de teren.