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INFLUENCE OF SOIL CONDITIONS ON BUILDING VULNERABILITY

BY

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Abstract. Seismic risk assessment of structures is one of the key elements in estimating and reducing losses that may appear after earthquakes. Building vulnerability quantifies the damages a structure can handle under a known seismic load. Usually, structures are considered to be fixed at the base in the design process, but researchers have highlighted the importance of considering the actual soil conditions in the analysis. In this paper, a nonlinear static analysis (pushover) is performed in SAP 2000, for a reinforced concrete 2-D frame resting on different types of soils. Comparisons between capacity curves, vulnerability curves and between the failure mechanism have been performed. From these comparisons, it was possible to extract some observations concerning the soil condition influence upon building vulnerability and seismic risk for a RC frame.

Key words: vulnerability; seismic risk; soil conditions; failure mechanisms; RC frame.

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1. Introduction

In civil engineering, seismic risk assessment is a critical element for estimating and reducing social and economical losses that may occur after earthquakes. Seismic risk assessment of a structure consists of several components such as: assessment of building capacity, hazard definition and plotting the vulnerability curves.

Building vulnerability quantifies the damages that a structure can handle under a seismic load with a known intensity. The response of a structure subjected to seismic loading is complex and it depends on various parameters that sometimes are difficult to estimate. These parameters are: precise characteristics of ground motion, the deformation limit of the structure, strength of materials, the state of the elements and of the entire structure, soil – structure interaction and others. Most of these factors can be estimated but rarely the values are precise.

Structures are generally assumed to be fixed at the base in the analysis process. This assumption has a great influence on estimating the real behavior of the structure. It is known that taking into consideration the real soil conditions lead to more exact results (Dutta, 2002).

One of the main 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 (Kwon & Elnashai, 2007).

Usually, during earthquakes, support failures may appear which can significantly reduce the usability of structures even though it may not lead to collapse. Therefore, considering soil–structure interaction in seismic analysis can be essential in order to prevent the structure to reach critical states.

This paper studies the influence of soil conditions in the behavior of a reinforced concrete frame. The best way to highlight the soil–structure interaction (SSI) effect is to compare the responses of a structure having fixed base and flexible base. For this purpose several analysis were performed for the considered structure having both types of supports – fixed and flexible. In the next sections of this paper, some theoretical aspects are presented which are used in the analysis.

2. Theoretical Background

The structural response of a building during an earthquake depends on the characteristics of the soil motion, the nature of the foundation soil and on the structural system particularities.

In most of the SSI analysis the foundation soil is considered linear elastic. Due to the complex nature of soils many uncertainties arise when various aspects of the foundation soils are defined and modeled in order to perform the analyses (Fillaurant, 2002).

Depending on the stiffness characteristics and on the propagation velocity of the seismic wave, foundation soils are the main pawns in performing a correct seismic design.

SSI 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, 2003).

There are various types of models for SSI, but the most frequently used are the lumped models and the finite element models. One of the most common assumptions considers the foundation soil stiffness applied as a set of elastic springs in one or more support points of the structure.

There are different relations 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 frequency independent foundation stiffness relations given by Newmark-Rosenblueth, which are provided in Table 1. These stiffnesses allow the estimation and the control of the foundation impedances, foundation soil damping and natural frequency of the structure (Davidovici, 1999).

Table 1
Spring Constants for a Rectangular Surface Mat Foundation

Movement	Foundation stiffness
Vertical	$K_V = \frac{G}{1-\nu}\beta_z\sqrt{A}$
Horizontal sliding	$K_h = 2(1+\nu)G\beta_x\sqrt{A}$
Rocking	$K_\theta = \frac{G}{1-\nu}\beta_\theta a^2 b$
Torsion	$K_t = \frac{1+\nu}{4}G\beta_x\left(a^2+b^2\right)\sqrt{A}$

In Table 1 G is the effective shear modulus of the soil, ν –Poisson’s soil ratio, A – foundation aria, a – foundation length and b – foundation width; β_z, β_x and β_θ are coefficients that depend on the Poisson’s ratio value and on the value of the ratio between the foundation dimensions.

On the other hand, the evaluation of the expected physical damage of a building which quantifies the average loss, having as a starting point a seismic hazard scenario and the structural vulnerability, can be performed through: damage probability matrices, vulnerability functions and fragility curves (Benedetti & Petrini, 1984; Whitman *et al.*, Hong, 1974; Barbat *et al.*, 2010).

The capacity curve is the graphical representation of the relation between the shear force at the base of the structure and the deformation at the top under a uniformly increasing load until it reaches collapse. In this paper the capacity curve was obtained through performing a nonlinear static analysis in SAP2000. The structural performance is computed according to the equal displacement approximation described in ATC-40, shown in Fig. 1.

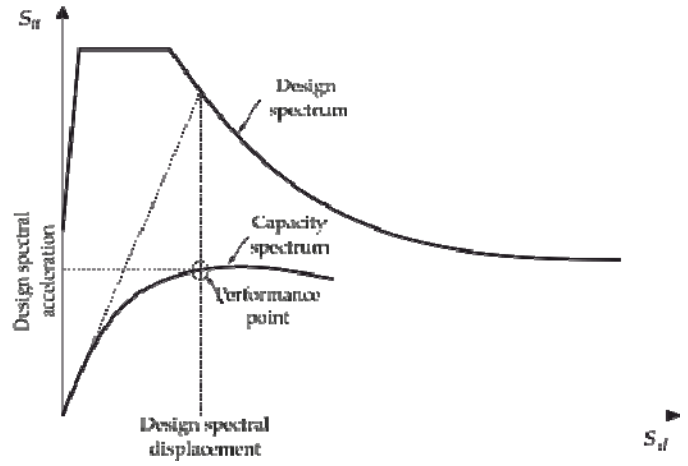


Fig. 1 – Graphical representation of the equal displacement approximation method for the performance point evaluation.

Vulnerability assessment by means of fragility curves became a more frequently used procedure. Thus, for each damage state, *ds*, the corresponding fragility curve is completely defined, by plotting on the ordinate the probability, $P[d > ds]$, and on the abscissa the spectral displacement. Fragility curves have a lognormal distribution. In order to compute the fragility curve for a damage state, *dsi*, the following equation is used (Barbat *et al.*, 2008):

$$P\left[dsi|Sd\right]=\Phi\left[\frac{1}{\beta_{dsi}}\ln\left(\frac{Sd}{\overline{Sd}_{dsi}}\right)\right], \tag{1}$$

Where: Sd is the spectral displacement, $\overline{Sd}_{dsi}$ – the average value of the spectral displacement at which the building reaches a certain threshold of the damage state *dsi*, β_{dsi} – the standard deviation of the natural logarithm of the spectral displacement of the damage state *ds* and Φ – the standard normal cumulative distribution function.

For the slight damage state a $0.7dy$ value was considered for the average spectral displacement, for the moderate damage state the yielding displacement was considered, *dy*, for the severe damage state the following eq. $dy + 0.25(du - dy)$ was used for the average spectral displacement, and for the collapse fragility curve the ultimate displacement was used, *du* (Milutinovic & Trendafiloski, 2003).

The evaluation of the vulnerability curves uses the mathematical probability for the damage index, $M\xi$, computed with the following relation (Sobol, 1983):

$$M\xi = \sum_{i=1}^{n} xi \cdot pi\,, \tag{2}$$

where xi is the damage state and pi – the probability for the corresponding damage state. The sum of the probabilities is equal to 1. In order to compute the average damage index the following equation is used:

$$\frac{1}{N}(\xi_1 + \xi_2 + ... + \xi_N) \approx M\xi\ . \tag{3}$$

The paper studies the influence of soil conditions in plastic hinges development and on failure mechanism occurrence. Plastic hinges are dissipative zones for the seismic energy.

3. Case Study

3.1. Description of the Structural System

The considered structure is a 2-D reinforced concrete frame designed according to the Romanian Seismic design code P100-1/2006. The frame has 6 levels each having a 3.6 m height and 3 bays with the dimensions 4.8 × 2.7 × × 4.8 m. The columns are constants along the height and they have a 0.5 × 0.5 m cross-section and a reinforcement ratio of 1.5%. The beams have a cross-section of 0.4 × 0.5 m with a reinforcement ratio of 0.9%. Table 2 presents the material properties used for the structure.

Table 2
Materials Properties

Materials	E, [MPa]	v	$f'c$	fy	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

The structure capacity was evaluated in SAP2000 assuming a fixed base and a flexible base. The total weight of the structure is of 891.911 kN and it was assumed a live load of 2 kN/m.

In order to model the elastic support, elastic springs were considered. The foundation is a rectangular surface mat, made from reinforced concrete having the dimensions 12.9 × 12.9 m and a 0.6 m depth. As for the foundation soils four different types of soil were considered, characterized on the shear wave velocity according to the site classification provided by SR EN 1998-1:2004. The properties of the chosen foundation soils are shown in Table 3.

In Table 4 are given the foundation stiffness for each foundation soil type which was computed with the formulas presented in Table 1 using the properties presented in Table 3.

Table 3
Properties of Different Foundation Soils Used in Analysis

Soil name	Shear wave velocities m/s	Soil type according to SR EN 1998-1:2004	Poisson's coefficient, v	Unit weight, γ kN/m^3	Elastic modulus E, [MPa]	Shear modulus G', [MPa]
V150	150	D	0.45	19.62	4.804940	1.656876
V300	300	C	0.40	20.00	13.757818	4.913506
V600	600	B	0.35	22.00	23.534400	8.716444
V900	900	A	0.30	25.00	37.807740	14.541438

Table 4
Spring Constants

Soil name	k_h, [kN/m]	k_v, [kN/m]	k_θ, [kNm/rad]	k_t, [kNm/rad]
V150	61,983.727	8,510,618.373	3,233,452.063	2,578,678.020
V300	140,560.875	111,978.811	34,877,960.140	5,847,683.800
V600	251,982.808	183,367.161	57,113,238.460	10,483,114.770
V900	423,340.826	2,486,045.866	88,474,909.770	17,612,036.730

3.2. Results and Discussions

Based on the modal analysis the frequencies and the natural period of the structure were obtained for each supporting assumption. The nonlinear static analysis leads to capacity curves. The equal displacement approximation method and the design spectrum for Iaşi were used to compute the performance points. Table 5 consists in a synthesis of the results from the modal analysis and the values of the displacements corresponding to the performance point, highlighting the influence of soil conditions upon the overall results.

In Fig. 2 is represented a comparison between the capacity curves. It can be noticed that the foundation soil flexibility leads to more ductile structures but also to smaller bearing capacity. The difference between the limit displacement at the top of the structure computed for the structure having a soil type V150 (soft soil) and the displacement for the fixed base situation, is of 45 mm. A comparison is performed by SAP2000 between the material strengths and structure tensions, the analysis ending when one of the strengths is overcome by an effort.

Table 5

Modal Analysis Results

Soil name	Period, [s]	Frequency Hz	Spectral displacement for the performance point, [cm]
V150	0.528	1,892	9.52
V300	0.416	2,399	7.56
V600	0.393	2,541	7.28
V900	0.348	2,870	6.58
Fixed	0.341	2,903	6.44

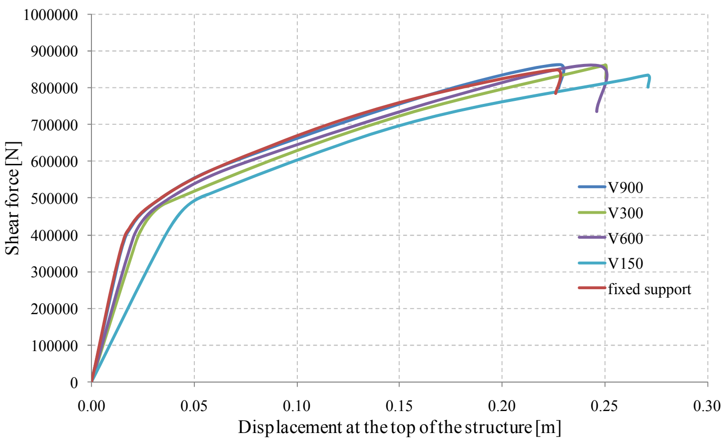


Fig. 2 – Comparison between capacity curves.

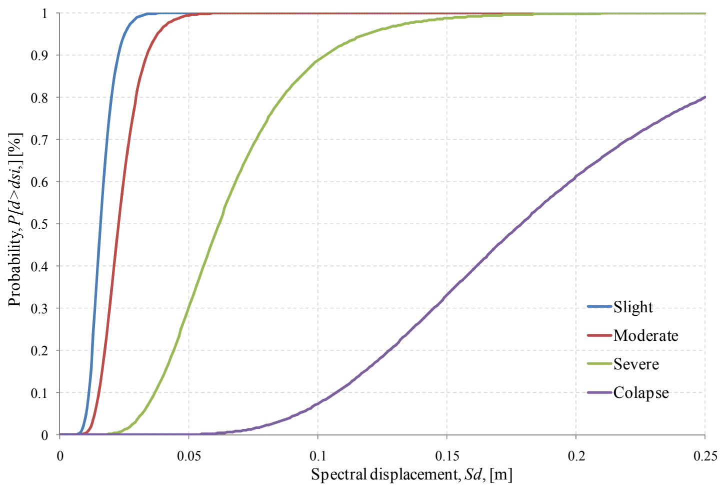


Fig. 3 – Fragility curves for V300 flexible support.

Based on the damage states described in § **2** for each capacity curves the corresponding fragility curves were calculated. Fig. 3 displays the fragility curves obtained for the V300 flexible support case for the foundation soil (randomly chosen). Usually, these are used to determine the damage index for the performance point spectral displacement value. The probabilities of the damage states are introduced in relation (2) and vulnerability curves are plotted.

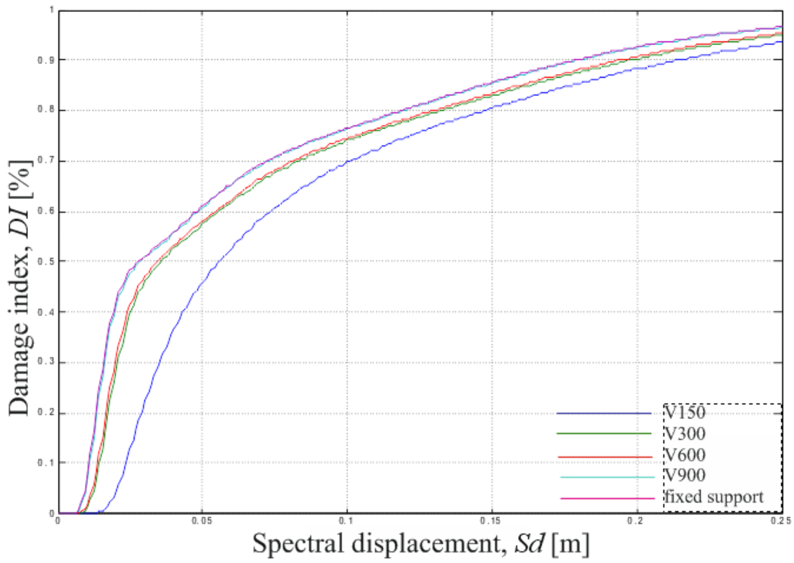
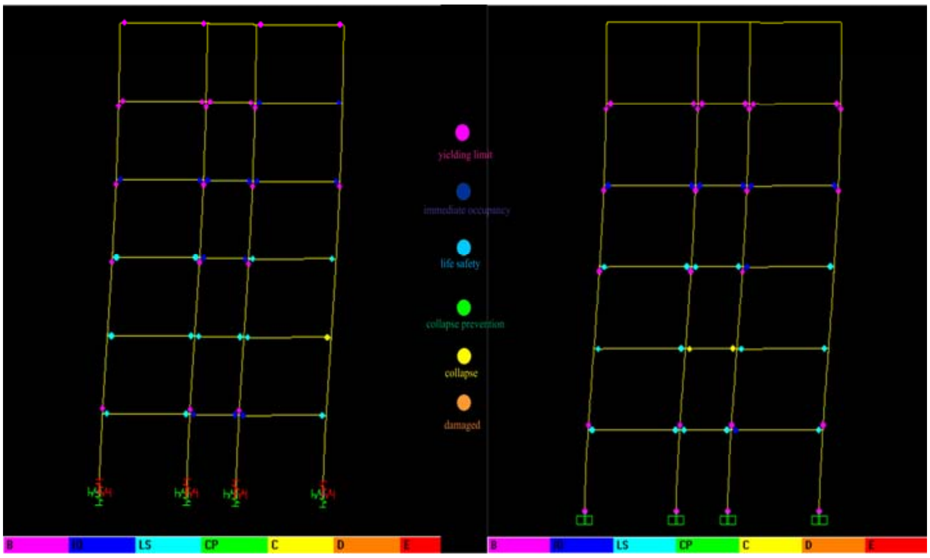


Fig. 4 – Comparison between vulnerability curves.

Fig. 4 shows a synthesis of vulnerability curves for all the studied cases. It is noticed an increase of the damage index along with the stiffening of the foundation soil. Thus, for a spectral displacement of 5 cm, the damage index increases with 17%. These results show that the fixed base assumption is the worst case scenario for vulnerability curves, but it doesn't provide precision for structural design only covering values for all supports situations.

Another essential difference in the behavior of the structure having different foundation soils was noticed in the failure mechanism.

Fig. 5 presents two different failure mechanisms. Although in both cases the failures occur at the second floor beams, the position within the beam differs. Also, the number of plastic hinges is larger for the V150 foundation soil and is smaller for the fixed base assumption. The failure mechanisms for V150 and V300 are similar, respectively for V600 with V900 and with the fixed base.



a *b*

Fig. 5 – Plastic hinge development: *a* – V150 flexible support, *b* – fixed support.

4. Conclusions

This study shows that taking into account the foundation soil in building vulnerability analyses provides results closer to the real behavior of a structure but less covering as in the conservative assumption of the fixed base. Special attention should be taken in choosing the right type of support because even if it doesn't lead to collapse it can cause severely damage to the structure, influencing its exploitation ability.

On the other hand, from the modal analyses it can be noticed the importance of considering soil structure interaction as it affects the natural period of the structure and its frequencies.

According to the performed nonlinear static analyses for the fixed and flexible base situations, changes in the location of occurring of the plastic hinges in the structures depending on the foundation soil type were noticed.

Therefore, from this study it can be concluded that taking into consideration the real foundation soil conditions in vulnerability assessment and seismic risk analyses leads to a better insight on the manner of plastic hinges development. The results obtained taking into account the foundation soil conditions are less covering for the vulnerability analyses.

In order to reach some generally valid conclusions it is recommended to perform some other detailed analyses.

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INFLUENȚA MEDIULUI DE FUNDARE ASUPRA VULNERABILITĂȚII STRUCTURALE

(Rezumat)

Evaluarea riscului seismic al structurilor reprezintă unul dintre elementele esențiale pentru estimarea şi reducerea pierderilor ce pot să survină în urma cutremurelor. Vulnerabilitatea structurală reprezintă mărimea degradărilor pe care o structură le poate suporta sub o acțiune seismică cunoscută. În practica proiectării, în analizele structurale obişnuite, se consideră că acestea au reazem fix, însă cercetările din domeniu au evidențiat importanța considerării condițiilor reale de fundare. În lucrare se efectuează o analiză statică neliniară (pushover) în SAP2000, pentru un cadru plan din beton armat considerând diferite medii de fundare. S-au realizat comparații la nivelul curbelor de capacitate, curbelor de vulnerabilitate şi la nivelul mecanismelor de cedare extrăgându-se o serie de observații privind influența condițiilor de teren asupra vulnerabilității şi riscului seismic pentru o structură în cadre din beton armat.