Seismic Response of RC Building Structures using Capacity Spectrum Method with included Soil Flexibility

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ABSTRACT:
Capacity Spectrum Method (CSM) is a current design tool to predict peak seismic performance of 2D and 3D structures. The general idea of the method can be extended including the influence of soil deformations on capacity spectrum. The design seismic action is implemented through acceleration-displacement spectrum provided by EN 1998-1. The seismic demands and behaviour factors are then elaborated and studied in order to estimate the role of the of foundation flexibility. For both low-rise and multi-storey R/C frames displacement demands show tendency for decreasing when soil is becoming stiffer. For wall systems considered as 3D structures displacement demands are reduced due to soil stiffening. For 3D structures due to foundation flexibility effects of irregularity may grow up. In this paper, [1] some ideas for extending the existing capacity spectrum procedure are elaborated.

Keywords: capacity spectrum method, pushover analysis, target displacement, soil flexibility, behaviour factor

1. INTRODUCTION

Capacity Spectrum Method is a reliable tool to predict seismic performance and seismic demands of structures subjected to design earthquake. This method, [2] by means of a graphical procedure, compares the capacity of the structure with the demands of earthquake ground motion on the structure. The capacity of the structure is represented by a nonlinear force-displacement curve, sometimes referred to as a pushover curve. The recent advent of performance based design has brought the nonlinear static push-over analysis to the forefront as one of the most simplified procedure for evaluation of structural capacity. The base shear forces and roof displacements are converted to equivalent spectral accelerations and spectral displacements, respectively, by means of coefficients that represent effective modal masses and modal participation factors. These spectral values define the capacity spectrum. The demands of the earthquake ground motion are represented by response spectra. A graphical construction that includes both capacity and demand spectra results in an intersection of the two curves that estimates the performance of the structure due to earthquake action.

The CSM is applicable to a variety of uses such as a rapid evaluation technique for a large inventory of buildings, a design verification procedure for new construction of individual buildings, an evaluation procedure for an existing structure to identify damage states, and a procedure to correlate damage states of buildings to amplitudes of ground motion. As is recommended by the new generation of seismic resistant design codes the method can be used for evaluation of seismic demands and for capacity assessment of newly designed or existing building structures. This procedure is implemented into Eurocode 8 [3] and enables calculation of behaviour factor and peak seismic response of the structure.

During the passed couple of years the Capacity Spectrum Method is under active development. The main goal is to extend the method with inclusion a variety of relevant factors that may influence the structural behavior.

It is already recognized that one of the factor that can significantly affect the seismic response and performance of structure is soil flexibility. Bonev [4] reported the possibility to apply Capacity Spectrum Method to soil-foundation-structure problem and how the method should be generalized including soil influence.

Seismic response of 2D reinforced concrete frames and 3D wall systems using capacity spectrum method which is consider for soil deformation is elaborated. It is shown in FEMA 450 [5] that the wall systems are much more sensitive to soil deformations because the most stiff elements - RC walls dictate internal force distribution. The influence of flexible foundation effects on the calculated target displacement and behaviour factor as results from push-over analysis is further present. In this paper only linear soil properties are taking into account being represent by unit foundation modulus (Winkler's constant).

2. ANALYSIS OF 2D RC FRAMES AND 3D WALL SYSTEMS

The influence of foundation flexibility on the capacity curve and on capacity spectrum method as a whole is studied on 2D RC frames and 3D RC building structure with RC walls as a primary bearing elements, [1,6]. Mathematical modelling of both analysed structural systems were done using SAP 2000 computer program, (Wilson, 2006), [7]. Each structure is modelled with 2D finite elements.

2.1 Numerical Model and Analysis of 2D RC Frames

The object of investigations are 3 storeys and 10 storey single frames. Frames configuration and possible location of plastic hinges are shown on Figure 1. Single footing foundations are used for the first frame and strip foundation is used for the second. Quality of the materials are in accordance to Eurocode 2 and Eurocode 3.

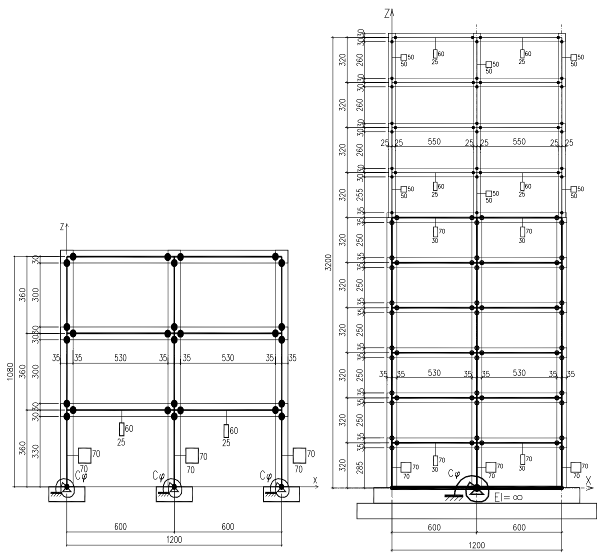

Figure 1. Frame configurations and location of potential plastic hinges

The numerical models of both frames are defined in compliance with:

- Horizontal component of the foundation flexibility is negligibly small and it is neglected.
- Only rocking type of the foundation motion is taken into account. The resistance against such motion is calculated basing on the unit foundation modulus.
- Elastic soil properties are implied during the analysis.
- P-Δ effect is not considered.
- Plane frame systems are considered.

– Structural elements – beams and columns may have plastic hinges at one or at both ends.

The frames are loaded with gravity load and seismic effect is represented through design response spectrum according to Eurocode 8, [3]. The demand spectrum is scaled twice: to 0.27g (*significant damage*) and to 0.40g (*non-collapse requirement*). Design of both RC frames is performed according to EC2 and EC8, considering DCH. Plastic hinges are the source of nonlinearity and the basic constitutive relationship used to simulate development of plastic hinges is moment-rotation.

2.2 Numerical Model and Analysis of 3D Wall System

The model is consisting of RC walls, columns and slabs and its general view is presented in Figure 2.

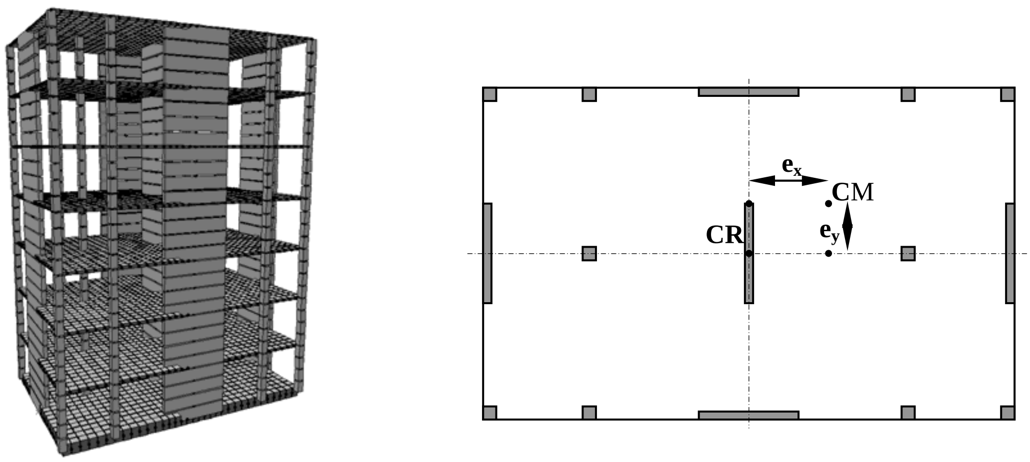

Figure 2. General 3D view of the mathematical model and structural layout

The numerical model used in calculations is defined with compliance of the assumptions listed below:

- Floor slab is treated as a rigid diaphragm in its own plane. The membrane stiffness of the floors is practically infinitely large and the slab may move horizontally as absolutely rigid body. On the other hand the slabs distribute the seismic loads between the walls.
- The vertical loads are carried by shear walls and columns. Lateral loads are carried by the shear walls only. Slab to column connection is not designed as moment resisting. It is assumed that columns are pinned at both ends and could bear only vertical loads.
- Shear walls are modelled by vertical frame elements. The potential locations of plastic hinges are considered at each floor level.
- The structure is symmetric in plan with respect to X- and Y- axis.
- Bending stiffness of the slab is taken into account only to obtain the vertical loads distribution between the vertical elements – walls and columns.
- Single footing under each wall is used. The foundation is supported by soil with vertical resistance. The elastic soil properties are implemented by the unit foundation modulus (Winkler’s constant).
- Loading pattern used for pushover analysis in both X- and Y- directions has the shape of inverted triangle and implies linear force distribution in elevation. Forces are applied in CM for each floor level.
- The calculation of each spring stiffness implies that only rocking motion of the footing is considered.
- Torsion effects due to different disposition of CM with respect to CR are taken into account. The influence of accidental eccentricities is accounted for as a source of torsion.
- Axial forces are remaining constant during the lateral pushover analysis and plastic hinge properties once determined after application of the vertical loads are kept the same.

The potential location of the first plastic hinge is at the base of the shear wall (in the center of the plastic zone). The plastic zone approach is based on distributed plasticity model. The typical constitutive relationship is moment-curvature. Distribution of elastic/inelastic curvature for a simple wall element is shown in Figure 3.

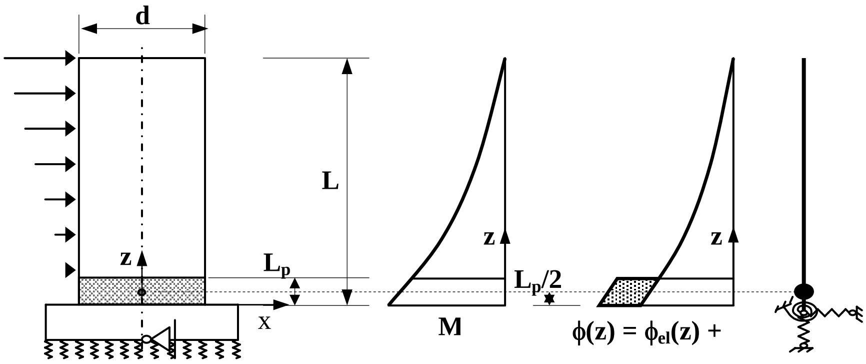

Figure 3. A single wall designed as dissiptive wall

For both 2D RC frames and 3D RC wall structure a series of nonlinear push-over analysis were carried out using SAP2000 computer program, [7]. Lateral load is increased until collapse prevention state is reached. For 3D structure two simplified and independent analyses in each X- and Y- direction are carried out. Two equivalent single degree of freedom systems are used. After that the capacity spectrum method is applied in both orthogonal directions in order to calculated values of behaviour factors, performance points and target displacements with including influence of the foundation flexibility, [6].

3. RESULTS FROM ANALYSIS

3.1 Results from the analysis of 2D RC Frames

As a result of static nonlinear push-over analysis capacity curves for analyzed frame models are calculated considering the influence of the foundation flexibility, (figure 4).

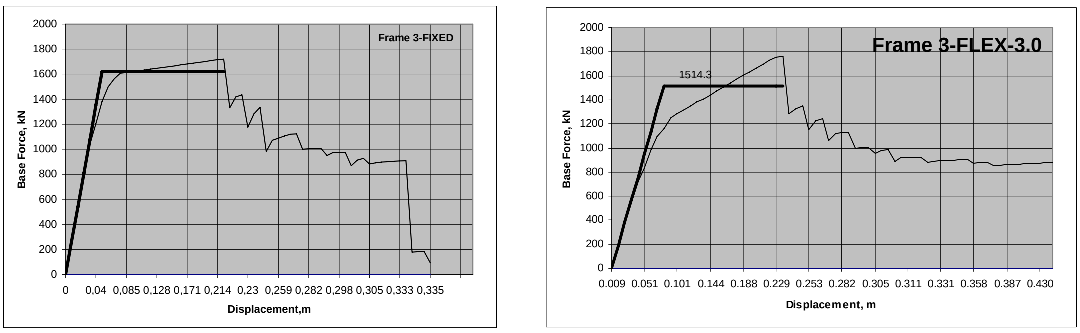

Figure 4. Capacity curve for 2D - RC frame, (3 storey)

Performance point for analyzed frame models calculated considering the influence of the foundation flexibility is shown on figure 5.

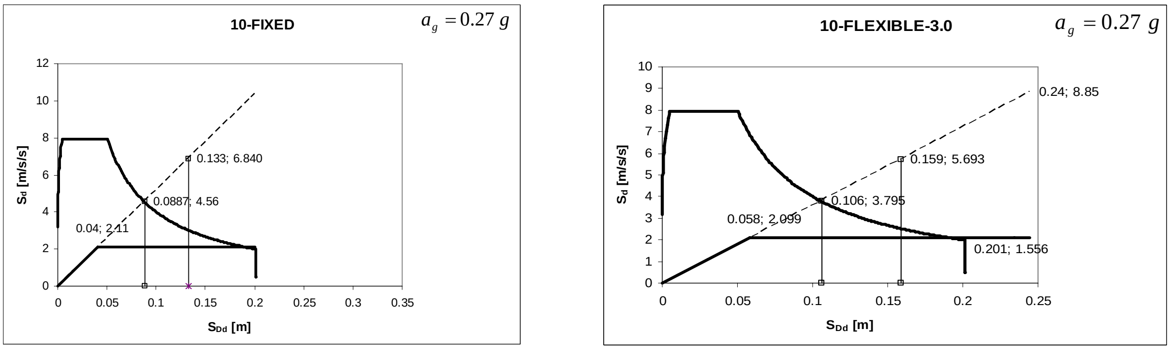

Figure 5. Determination of performance point for 2D - RC frame, (3 and 10 storey)

The results for the calculated behavior factor are presented in Table 1. In general, q behaviour factor decrease for low-rise frames and increase for high-rise frame with moving from soft to stiff soils.

Table 1: Behavior Factor Evaluation

Frame type	Frame abbreviation	Unit foundation modulus, UFM [kN/m³]	Type of foundation	Behavior factor	
				a_g=0,27g	a_g=0,40g
2D – 3 storey frame	3 – FIXED	–	single footing	2.02	3.01
	3 – FLEX – 3.0	3C = 75000	single footing	1.81	2.66
	3 – FLEX – 1.0	1C = 25000	single footing	2.08	3.09
	3 – FLEX – 0.5	0.5C = 12500	single footing	2.33	3.45
	3 – FLEX – 0.3	0.3C = 7500	single footing	2.36	3.47
2D- 10 storey frame	10 – FIXED	–	strip foundation	3.24	4.76
	10 – FLEX – 3.0	3C = 75000	strip foundation	2.71	4.02
	10 – FLEX – 1.0	1C = 25000	strip foundation	2.41	3.59
	10 – FLEX – 0.5	0.5C = 12500	strip foundation	1.99	2.97
	10 – FLEX – 0.3	0.3C = 7500	strip foundation	1.68	2.48

Numerical results for the obtained target displacement are presented in Table 2. The tendency of decreasing the target displacement with moving from soft to stiff soils is obvious for both low and high-rise frames.

Table 2: Target Displacement Evaluation

Frame Type	Frame abbreviation	Unit foundation modulus, UFM [kN/m³]	Type of foundation	Target Displacement, [m]	
				a_g=0,27g	a_g=0,40g
2D- 3 storey frame	3 – FIXED	–	single footing	0.105	0.153
	3 – FLEX – 3.0	3C = 75000	single footing	0.129	0.190
	3 – FLEX – 1.0	1C = 25000	single footing	0.143	0.213
	3 – FLEX – 0.5	0.5C = 12500	single footing	0.147	0.217
	3 – FLEX – 0.3	0.3C = 7500	single footing	0.15	0.225
2D- 10 storey frame	10 – FIXED	–	strip foundation	0.133	0.195
	10 – FLEX – 3.0	3C = 75000	strip foundation	0.159	0.235
	10 – FLEX – 1.0	1C = 25000	strip foundation	0.178	0.264
	10 – FLEX – 0.5	0.5C = 12500	strip foundation	0.213	0.316
	10 – FLEX – 0.3	0.3C = 7500	strip foundation	0.257	0.381

3.2 Results from the analysis of 3D Wall System

The numerical model described above is subjected to monotonically increasing vertical and horizontal loads. Six values of unit foundation modulus are used in calculations: fixed base (infinitely large modulus), 60000, 50000, 40000, 30000 and 20000 in kN/m^3 metric units. After completion of vertical loading procedure the horizontal loading pattern is applied. The effects of accidental torsion are studied considering eccentricity of 15% (large eccentricity and irregular structure) and 0% (regular structure). Selected numerical results are presented further. More detailed information can be find in [6].

Figure 6, (6a and 6b) illustrate that global ductility demand is reduced with increasing the footing flexibility and the initial (elastic) stiffness is reduced due to flexibility. At the same time the base shear strength is relatively slightly influenced by the footing flexibility.

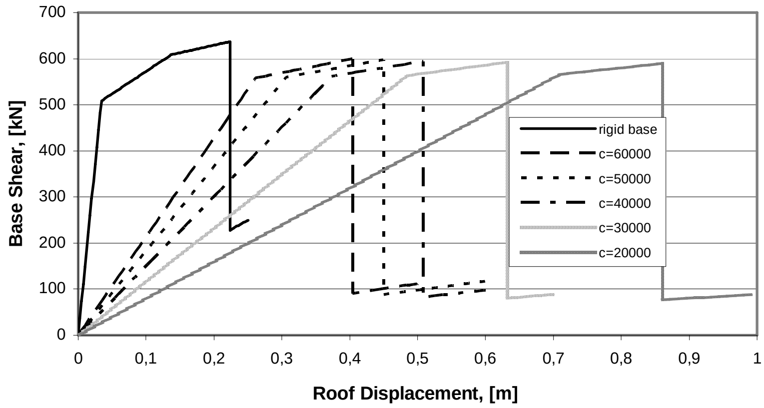

Figure 6a. Capacity curves in X-direction (ecc. 0%) obtained for different Winkler's constants

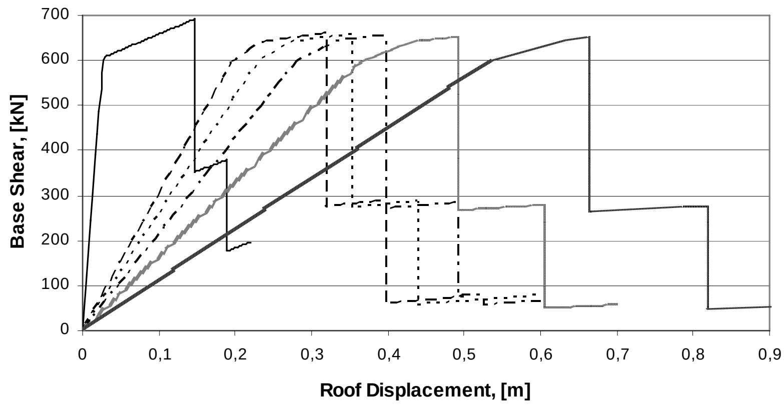

Figure 6b. Capacity curves in Y-direction (ecc. 0%) obtained for different Winkler's constants

Results form the investigations show that the largest values for the behaviour factor could be achieved if the fixed base is considered, (fig. 7). The smallest target displacements are observed in the same case. If the foundations are flexible (fig. 8 and 9) target displacement is increased but the behaviour factor decreases. When the soil is soft and structure reaches the target displacement the global behaviour of the structure may remain completely elastic. This mode of deformation implies that the soil fails before yielding happens in structure. Safe design solutions could be provide if soil deformations are taken into account in capacity curves.

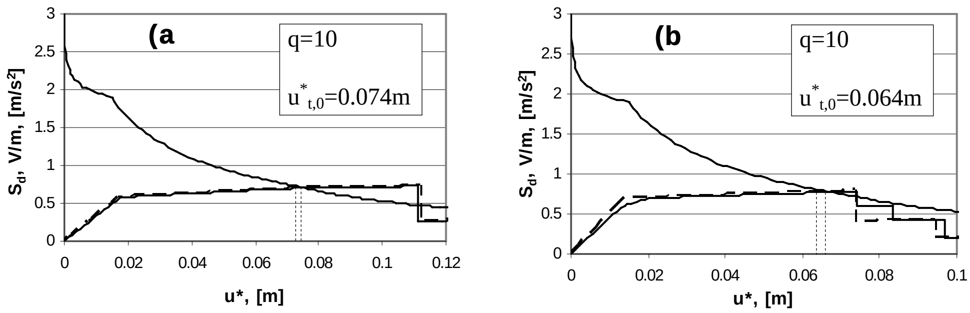

Figure 7. Capacity spectrum method applied to fixed-base structure:
(a) in X-direction; (b) in Y-direction.

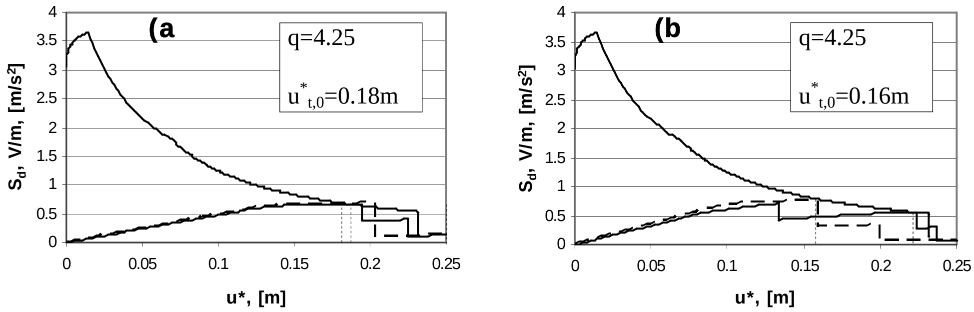

Figure 8. Capacity spectrum method applied to structure with flexible foundations (UFM 60 000 kN/m^3)
(a) in X-direction; (b) in Y-direction.

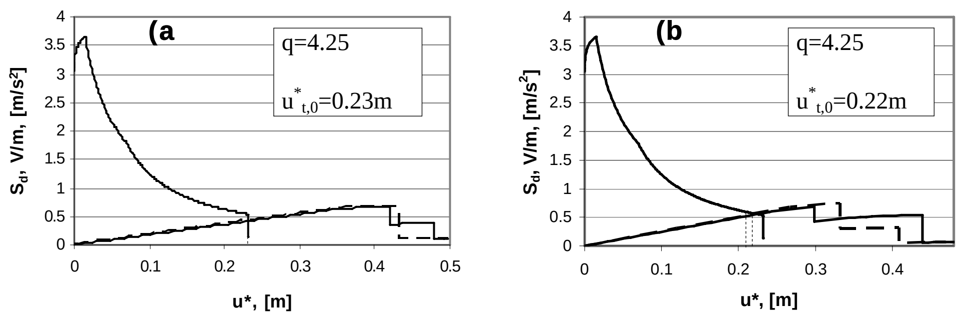

Figure 9. Capacity spectrum method applied to structure with flexible foundations (UFM 20 000 kN/m^3)-
(a) in X-direction; (b) in Y-direction.

4. CONCLUSIONS

Considering the analysis of the numerical results presented above the following conclusions could be made:

- The behavior factor for low-rise frames is decreasing with stiffening of the soil and for for high-rise frames is increasing with stiffening of the soil.
- The foundation flexibility caused by soil deformations influence essentially the capacity curves. The global ductility factor is seriously being reduced due to significant increase of elastic part of deformations. Participation of soil deformation in overall structural deformation is significant with tendency to become more essential in case of plastic soil deformations and foundation uplift.

- Target displacements are increased if the soil is becoming softer. The behaviour factor however shows decreasing tendency for weaker soils which is not on the safety side. Safe design solutions could be expected if soil deformations are taken into account in capacity curves.
- The influence of accidental torsion effects is small considering the elastic behaviour of the structure. More important influence is observed when some plastic hinges yield and when some walls are collapsed. The capacity curves are sensitive to accidental torsion when wall elements yield or collapse occurs.
- The global structure strength is relatively independent of soil stiffness and accidental torsion effects.
- It is concluded that wall systems are sensitive to flexible soil conditions in a large extent. Better results for the structure could be expected if pile foundations are used to decrease the effect of soil deformations.

5. FIELD FOR FURTHER RESEARCH

Some improvements are proposed in CSM in the recent years. The idea is to transform dissipated energy due to inelastic deformations into damping energy dissipated in equivalent linear system. The damping of the new system is called "equivalent damping" and usually is expected to be larger than the usual damping of 5% for the original system. This approach is developed in ATC-40 provisions and explored in a number of recent developments.

N. Priestley (2000) developed the idea to add the soil damping into equivalent damping. G. Mylonakis draws the attention on the fact that structure demands are influenced by the pair of parameters – soil-foundation system stiffness and soil damping. Soft soils imply small stiffness (large demands) but large damping (reduced demands). Stiff soils imply large stiffness (small demands) and small damping (small demand reduction). Finding a good balance between both factors is the purpose of further research work.

ACKNOWLEDGEMENT

The authors are indebted to Ministry of Education and Science of R. Macedonia, National Science Foundation at Ministry of Education and Sciences of Bulgaria, (project grant No. BM-6/2006) and University of Architecture, Civil Engineering and Geodesy – Sofia, Bulgaria, (project grant No. BN-84/2008).

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