Monitoring of the foundation of an existing RC building and some modelling approaches

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ABSTRACT: The monitoring of the foundation of an existing RC building during and after its extension is presented. The existing building consists of a two-storey RC frame structure designed for gravity loads only which is extended by a seven-story steel structure with seismic braces and passive energy systems (twenty-one viscous wall dampers – fourteen in longitudinal direction and seven in transverse direction) in both main directions. Additional strengthening systems such as RC jacketing and steel braces in-filled into the existing RC gravity frames are executed. The existing spread footings of the building are combined into a foundation slab and monitored by application of pressure cells and custom made settlement gauges capable to measure in-depth settlements of the soil. The main objective of the monitoring system is to obtain the stress-settlement relation at the base of the foundation and to compare some analytically calculated settlements with the actual ones. Moreover the affected zone under the foundation base and the actual coefficient of vertical subgrade reaction could be determined. Some modelling approaches which take into account the soil-structure interaction are also studied. A conception for further work is presented together with some conclusions about the soil-structure interaction effect and the effectiveness of the strengthening.

1 INTRODUCTION

This paper represents a real project which is under construction. An existing building (a hotel constructed in the 60s of the last century) located in Sofia, Bulgaria is studied. The structure is a two-story RC frame designed for gravity loads only.

The building is extended by a seven-story steel structure which has seismic braces in both main directions and a number of viscous wall dampers. The RC structure below is strengthened for horizontal seismic action by steel braces which are in-filled into the existing RC gravity frames. RC jacketing is also applied to the existing gravity load resisting only columns. The existing spread footings of the building are combined into a RC foundation slab and monitored. The presented study is focused on the monitoring conception and the modelling approaches for the particular project. The view of the existing building is presented in Figure 1.

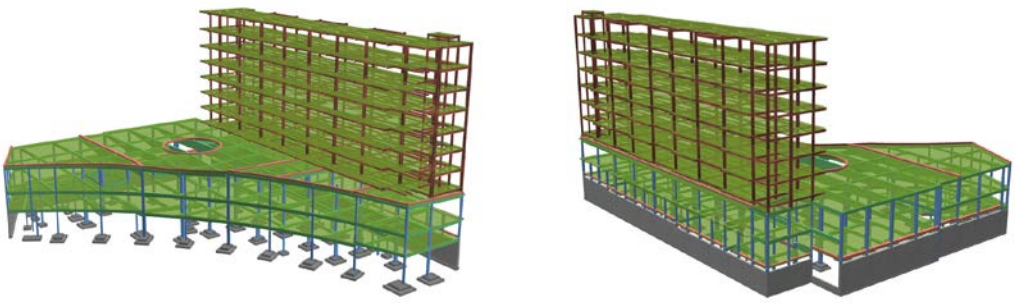


Figure 1. Model presenting the existing RC frame structure and its steel structure extension.

2 STRENGTHENING AND EXTENSION

2.1 Strengthening of the existing structure

The strengthening of the two-story part of the hotel in terms of earthquake induced loads is performed by means of in-filed steel braces which are introduced to the existing RC frames (originally designed for gravity loading only) of the building. As the existing part of the hotel is located next to other hotel facilities and due to functional requirements the possible locations for introducing the in-filed steel braces were limited. The main columns were strengthened by RC jackets (self-compacted concrete was used) in order to bear the gravity loads. The existing spread footings were combined into a RC foundation slab and set to monitoring (Fig. 2).

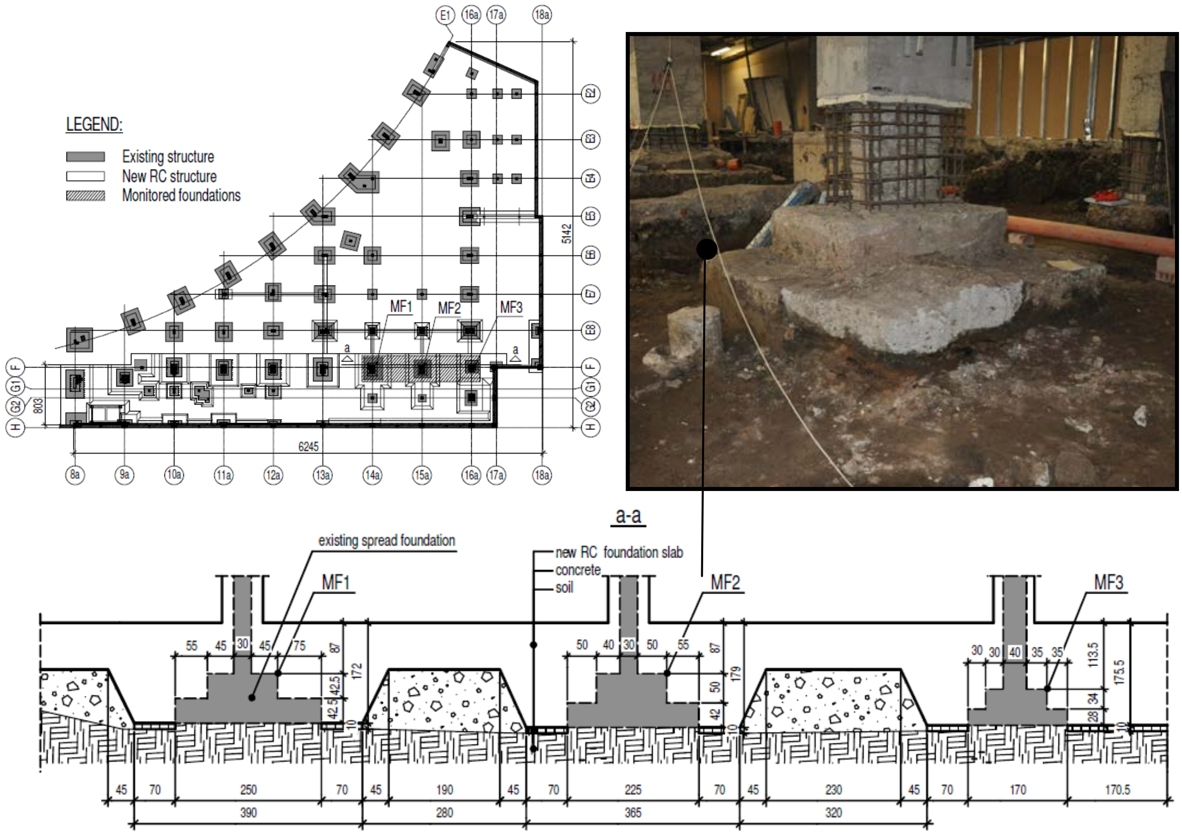


Figure 2. Foundation plan of the RC slab and a section showing the monitored foundations (unit – cm).

2.2 Steel structure extension and application of viscous wall dampers (VWD)

The existing structure is extended by a seven-story steel structure. Twenty-one passive energy dissipating devices (VWD) were added to the seismic braces of the steel structure extension – fourteen in longitudinal direction and seven in transverse direction. The purpose of such devices is to obtain both goals – reduction of the seismic displacements which avoids pounding to the existing neighbouring buildings and seismic effect reduction from the steel structure extension to the existing two-storey RC building.

3 MONITORING OF THE FOUNDATIONS

The main objective of the monitoring system is to check during and after the extension of the building whether the foundation's behaviour is similar to the behaviour from the FEM analysis. It is important to check if: 1) the stress redistribution at the base between the new RC foundation slab and the existing spread footings is as expected; 2) excessive settlements are being generated. To make this possible two separate systems for monitoring of the contact stress at the foundation base and in-depth settlements of the soil are developed. The stress measuring devices are conventional pressure cells and the settlement measurement gauges are custom made and developed by the authors.

Three of the existing spread foundations combined with the new RC foundation slab are being monitored. The contact stress at the foundation's base is measured in eight points whereas the settlements are measured in twelve points. The monitored points are situated in way that they could correspond with each other and the stress-settlement relationship could be defined.

3.1 Contact stress monitoring by application of pressure cells

The contact stress is monitored by application of pressure cells which have been calibrated by the supplying company. The pressure cells have 1 MPa compression capacity which is six times more than the maximum calculated base pressure.

Three devices have been installed under the existing spread footings and the other five are located next to them but under the new RC foundation slab (Fig. 3).

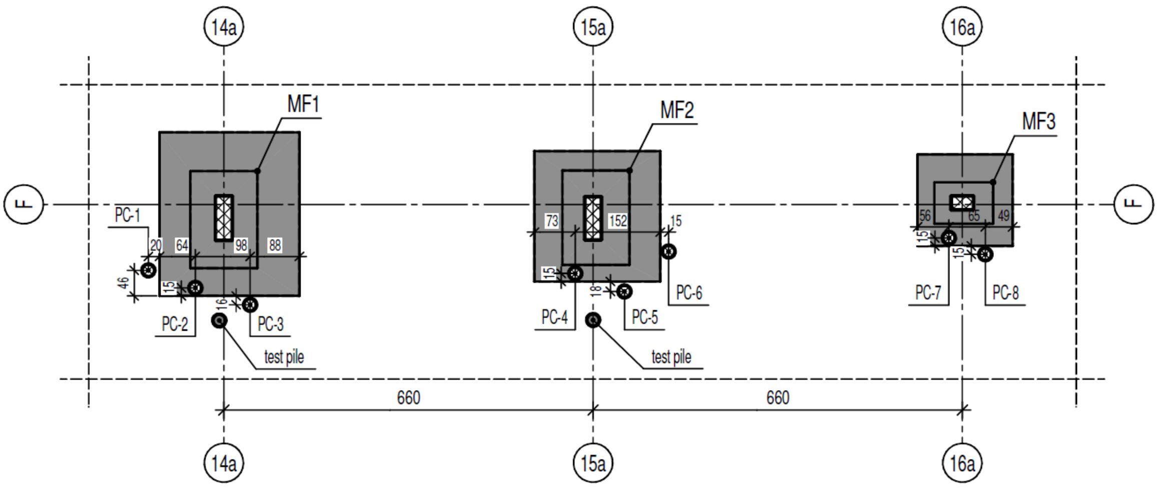


Figure 3. Plan view of the pressure cells (PC) location (unit – cm).

The interpretation of the results was made according to Lazebnik (1997) and the installation procedure was as follows:

1. A hole slightly bigger than the size of the pressure cell's pad was dug under each monitored spread foundation to uncover its base (three holes in total);
2. The uncovered bases were scorched and the burnt soil was scraped (Fig. 4);

Figure 4. Scorching of the base and installing of a pressure cells below an existing spread footing (MF1).

3. A quartz sand layer (about 2 cm thick) was laid in the holes and around the zones of the other five monitored points to prevent excessive local settlements under the pressure cells pads after the increasing of the vertical load due to the extension of the building (Fig. 4);

4. An in place calibration of all of the pressure cells was performed and the zero readings were recorded taking into account a barometric correction;
5. Three of the pressure cells were installed under the base of the existing spread foundations and the gap between the base and the quartz sand layer was filled with slightly expanding (around 3-5% volume change) self-compacted concrete to ensure good contact (Fig. 4). After that the other five pressure cells were installed and covered with self-compacted concrete;
6. All of the pressure cells were connected to a junction terminal switch box allowing the readings to be taken manually by a read out unit. The initial reading was taken when the expansion of the self-compacted concrete ended;

3.2 In-depth settlement monitoring by application of custom made gauges

The settlement measuring system allows multiple in-depth points under the base of the foundation to be monitored and consists of two parts – a fixed part and a free part regarding the global settlement of the building (Fig. 6). The fixed part consists of three steel stands which are supported by two test piles located near to the monitored spread foundations. The test piles settlement is considered negligible. The free part is the building itself and nine steel poles screwed down in the soil.

Four points' settlement at varying depth chosen beforehand for each of the monitored spread foundations is measured – one at the base and three others in the range of the affected zone under the foundation (Fig. 5).

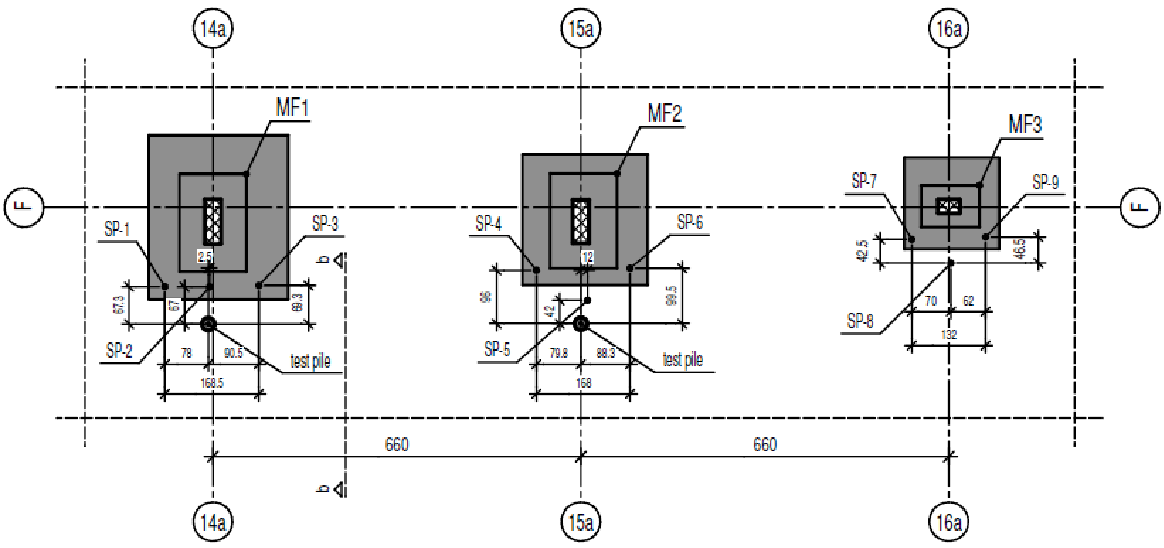
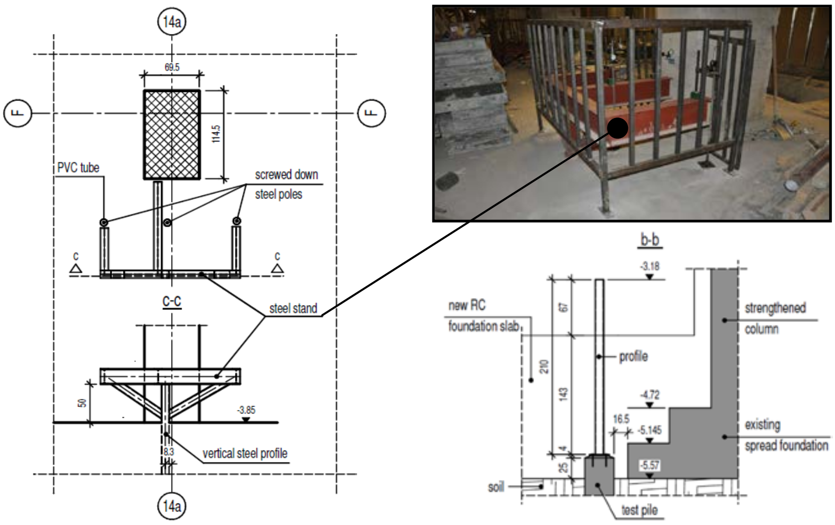


Figure 5. Plan view of the settlement measurement gauges (SP) location (unit – cm).

The preparation for setting the system was as follows:

1. Steel profiles with square hollow section were encased in PVC tubes and anchored to the test piles in order to isolate the fixed part of the global system from the new RC foundation slab. The encased profiles pass vertically through the new RC foundation slab and one steel stand for each profile was attached to their upper end;
2. Each monitored spread foundation was bored by a diamond drilling rig in two or three places (seven in total) as shown in Figure 5;
3. Three steel rods for each monitored spread foundation were hammered down to different depth in each of the monitored points. Seven steel rods were located in the borings and three were located next to the monitored spread foundations. After that, the steel rods were pulled out by a hydraulic system and replaced by PVC tubes with slightly smaller diameter than the rods' diameter. The tubes pass vertically through the new foundation slab. The fact that the soil at the site is cohesive made it possible for the PVC tubes to reach the same depth as the steel rods;

4. Three steel poles (SP) for each monitored spread foundation were inserted in the PVC tubes and screwed down for additional 5 cm below the previously reached depth (Fig. 6) so that they could be reliably attached to the soil and hence follow the settlement. The PVC tube encasing allows the free movement of the SPs.
5. As it can be seen on the photograph in Figure 6, three dial indicators for each monitored spread foundation were set on the steel stands and linked to the steel poles in order to measure their settlement. Three additional dial indicators (one for each monitored spread foundation) were set on the steel stands and linked to the columns above the foundations. In that way, the settlement of the base of the foundation could be measured.



Steel pole	Single footing	Depth from foooting base *[cm]*
SP-1	MF1	245
SP-2		130
SP-3		25
SP-4	MF2	235
SP-5		130
SP-6		20
SP-7	MF3	235
SP-8		130
SP-9		25

Figure 6. Conception of the settlement measuring system and depth of monitored points (unit – cm).

4 BUILDING MODELS

The strengthening strategy and the building's seven-storey extension are numerically studied. For this purpose a model of the building was developed. The dynamic analysis of the building is performed using SAP 2000, version 15.1.0. The focus of the study was to understand the seismic behaviour of the structure as well as the effects of the considerably increasing vertical loads due to the building extension.

The idealization of the building is performed by the elements from the library of SAP 2000: frame elements (for columns and beams), link elements (for SSI and VWD) and shell elements (for walls and slabs). Three models of the building are studied – one model which does not consider the soil-structure interaction (SSI) and two other commonly used spring-dashpot/spring models (before and after combing the existing spread foundations in a RC foundation slab) which do. In that way the structure's behaviour is more realistically captured because of the SSI effect.

The properties of the springs and dashpots were ascertained assuming a cohesive soil immediately beneath the foundation. Soil parameters of the affected zone beneath the foundation base consistent with findings from geotechnical investigations at the site were used for the SSI analysis and are as follows: 1) soil mass density, ρ_s, is 2028 kg/m^3; 2) Poisson's ratio of the soil, ν, is 0.35; 3) Young's modulus of the soil, E, is 25000 kN/m^2.

4.1 Fixed base model

Firstly an analysis of fixed base model (with joint restraints at the base for all three translations and rotations) was performed. The influence of the VWD as well as the behavior of some structural elements such as columns, beams and steel braces were studied (Fig. 7).

4.2 Uncoupled spring-dashpot model

The "uncoupled spring-dashpot" model was developed for the SSI analysis considering a strengthened and extended structure without combining of the existing spread foundations. The prerequisite for this model is the assumption that the spread foundations are rigid with respect to the supporting soil. A set of nine springs' dynamic stiffness (three translational, two rocking and one torsional) were determined together with their corresponding dashpot coefficients in order to take into account the dynamic stiffness and the damping of the soil-foundation system in the seismic analysis. Another set of nine springs' static stiffness was introduced to the model used for the vertical loading analysis. To define the stiffnesses and coefficients the procedures set out by FEMA-356 (2000) and NIST GCR 12-917-21 (2012) were used and summarized in Table 1 for one of the monitored spread footings (MF1).

Table 1. Summary of the springs' stiffness and radiation damping coefficients for MF1.

Degree of Freedom	Static Stiffness			Dynamic Stiffness and Equivalent Viscous Damping	
	Gazetas (1991); Mylonakis et al. (2006)	Pais and Kausel (1988)	Fema-356	Pais and Kausel (1988)	
	[kN/m; kN-m/rad]	*[kN/m; kN-m/rad]*	*[kN/m; kN-m/rad]*	*[kN/m; kN-m/rad]*	*[kN-sec/m]*
Translation along z-axis	$K_{z,emb,1}$ = 120630	$K_{z,emb,2}$ = 138960	$K_{z,emb,3}$ = 125120	$K_{z,emb,dyn}$ = 138880	$C_{z,emb}$ = 3030
Translation along y-axis	$K_{y,emb,1}$ = 154410	$K_{y,emb,2}$ = 151470	$K_{y,emb,3}$ = 159540	$K_{y,emb,dyn}$ = 151470	$C_{y,emb}$ = 2130
Translation along x-axis	$K_{x,emb,1}$ = 152080	$K_{x,emb,2}$ = 149310	$K_{x,emb,3}$ = 157270	$K_{x,emb,dyn}$ = 149310	$C_{x,emb}$ = 2060
Torsion about z-axis	$K_{zz,emb,1}$ = 150090	$K_{zz,emb,2}$ = 719810	$K_{zz,emb,3}$ = 477210	$K_{zz,emb,dyn}$ = 717790	$C_{zz,emb}$ = 13370
Rocking about y-axis	$K_{yy,emb,1}$ = 81990	$K_{yy,emb,2}$ = 610390	$K_{yy,emb,3}$ = 347950	$K_{yy,emb,dyn}$ = 608840	$C_{yy,emb}$ = 32200
Rocking about x-axis	$K_{xx,emb,1}$ = 90610	$K_{xx,emb,2}$ = 566500	$K_{xx,emb,3}$ = 271610	$K_{xx,emb,dyn}$ = 565530	$C_{xx,emb}$ = 28960

To implement the "uncoupled spring" model in SAP2000 the soil and foundations were idealized by frequency-independent linear type links in all six degrees of freedom. Two ways to introduce the link elements to the SAP2000 model were examined and gave similar results. The first one was to model the spread foundations by shell elements (with body constraint assigned to each footing area – one body joint constraint for each footing) and assign the link element as an area. The second one was an approach which introduces the link element as a lumped joint link without modelling the spread footings.

4.3 Bed of springs models

The "bed of springs" approach was adopted for two independent SAP2000 models. One of them was used for the design of the new RC foundation slab (the slab being idealized by shell elements) and the other – for evaluating the condition of the existing spread foundations supporting the strengthened and extended structure. In the "bed of springs" model a set of closely spaced springs is used to model the soil-footing behaviour. The soil is idealized by a bed of vertical springs that captures the vertical and rotational behaviour, and two horizontal springs that capture the horizontal behaviour.

The two models were developed analogically. A single spring in two perpendicular directions of the RC slab were used to model the horizontal stiffness of the foundation and the stiffness of those springs were defined using the formulas developed by Gazetas and Tassoulas (1987). To model the bed of springs a coefficient of vertical subgrade reaction was determined by application of some classical procedures and assigned as compression only area springs to the shell elements. A summary of the determined coefficients are presented in Table 2.

Table 2. Coefficient of vertical subgrade reaction of the RC slab determined by various procedures.

	Method			
	Bozhinov (1982)	FEMA-356 (2000)	Milev (2013)	Design of Highway Bridges in Japan (2003)
Coefficient of subgrade reaction *[kN/m³]*	10040	16240	18050	24300

For the seismic analysis the coefficient of vertical subgrade reaction was multiplied by two as recommended in some Japanese design codes. Conservatively two analyses for each model were performed using the lowest and highest calculated values of the coefficient of vertical subgrade reaction.

5 ANALYSIS AND RESULTS

5.1 Spectral seismic analysis and dynamic time-history analysis

The results from the fixed base model's analysis were used for the design of the structural elements of the superstructure whereas the "bed of springs" model's analysis results were used for the design of the new RC foundation slab. The output data from the analysis of the "uncoupled spring-dashpot" model was used only for quantifying the beneficial effect of the SSI on the structural behaviour.

Two different types of FEM analysis are performed as follows: 1) linear spectral seismic analysis; 2) linear time-history analysis. Those types of analysis were performed for vertical loading and seismic excitation and were applied to all three type of models: with and without consideration of the SSI.

The modal time-history dynamic analysis is performed in order to determine the system's response to seismic excitation. The Bulgarian elastic seismic response spectrum for the area of Sofia according to Eurocode 8 is applied for the study. The time-history analysis of the structure is performed by using several artificial base acceleration functions which fit the applied spectrum for the calculations.

The first two modes of vibration for the fixed base model are presented in Figure 7 and their vibration periods are respectively T_1=1.406 sec and T_2=1.091 sec.

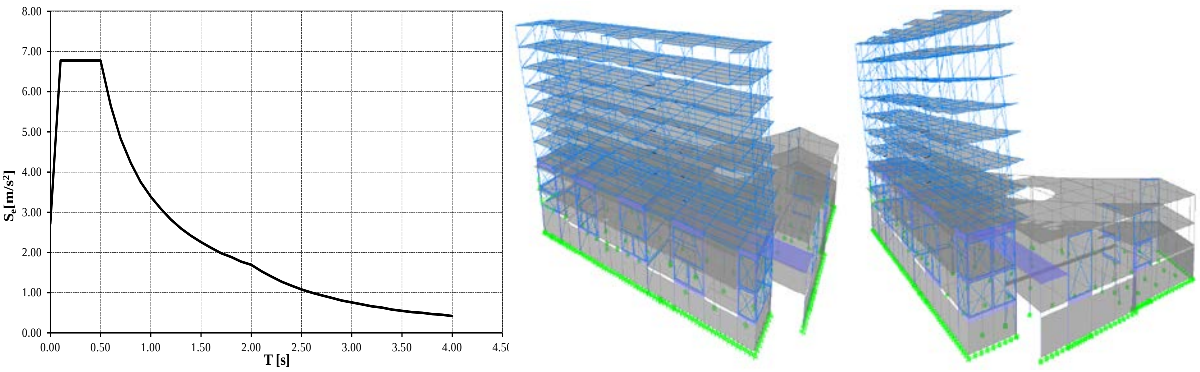


Figure 7. Elastic seismic response spectra for Sofia, Bulgaria (soil type C) and first two modes of vibration.

5.2 Influence of the soil-foundation-structure interaction on earthquake response

The first two vibration periods from the spectral seismic analysis of the "uncoupled spring-dashpot" model increased compared with the fixed base model and are respectively T_1=1.575 sec and T_2=1.188 sec. On the other hand the base shear decreased by 5÷10%. This is explained by the fact that the idealized smooth elastic design spectra implemented in Eurocode 8 attains constant acceleration for periods from 0.1 s to 0.5 s (for soil type C) and thereafter decrease monotonically with period (Fig. 7).

As a consequence consideration of SSI leads invariably to smaller accelerations and stresses in the structure and its foundation. Moreover a part of the energy of the vibrating flexibly-supported structure is dissipated into the soil through wave radiation (a phenomenon with no counterpart in fixed base structures) and hysteretic action leading to an effective damping ratio.

Eurocode 8 allows the SSI to be taken into account even if it has favourable impact on the behaviour of the structure. As keeping the existing spread footings foundation conception was not adopted the beneficial SSI effect on the superstructure was not taken into account in the design.

6 FURTHER WORK

6.1 Stress – settlement relationship

As the project is still under construction the results from the monitoring system are currently being evaluated. The stress-settlement relation at the base of the foundation and the in-depth settlements of the soil will be used to verify the following: 1) depth of the affected zone below the foundation base; 2) base contact stress; 3) in-depth distribution of the vertical stress in the soil; 4) in-depth settlements of the soil; 5) actual coefficient of vertical subgrade reaction.

6.2 SDOF model and laboratory determining of dynamic properties of soil

A 3D finite element model in the program system ABAQUS comprising the entire SFS system, taking account of material (soil represented as continuum) and geometric nonlinearities (uplifting and P–Δ effects) is to be developed in order to study the SSI in details. An equivalent SDOF representation of the MDOF structure is going to be adopted. Soil behaviour is to be modelled through the encoded in ABAQUS FE environment nonlinear kinematic hardening model with Von Mises failure criterion and associated flow rule which is considered appropriate for clay under undrained conditions. This model requires the following parameters of the soil: 1) soil strength: undrained shear strength of the clayey soil; 2) small-strain stiffness: maximum shear modulus or shear wave velocity; 3) shear modulus versus shear strain and damping ratio versus shear strain curves. The above mentioned soil parameters could be determined by a cyclic triaxial apparatus capable to measure the P and S wave velocity. Such apparatus is available at the University of Tokyo and tests of soil samples from the building site are currently being performed.

7 CONCLUSIONS

Due to the complexity of the presented project and the questionable real behavior of the existing spread foundations during a seismic excitation it was decided to combine them in a RC foundation slab. Moreover the RC foundation slab transfers the loads more reliably to the supporting soil and prevents the structure from unexpected uneven settlement effects. To verify the foundation behaviour considered in the design a monitoring system for measuring both – stress and settlements was installed. The study presented herein allows the following conclusions to be drawn:

- The numerical verification of the solution by means of linear FEM analysis represented a satisfactory structural response of the building after its strengthening and extension;
- From economical point of view it is advisable to take into account the beneficial SSI effect in the seismic design for some structures;
- The passive energy dissipating devices (VWD) are a very efficient method for seismic extension of low rise RC buildings with steel structures and reduce considerably the displacements (by 30÷60%) compared with the same structure without VWD which also helps to avoid pounding to the neighbouring buildings. Moreover they reduce considerably the internal forces in both structures – the existing one and the strengthening one (by 35÷65%) which allows some reduction of the strengthening system as well as a better seismic response of the extension building.

8 REFERENCES

FEMA-356. 2000. Prestandard and Commentary for the Seismic Rehabilitation of Buildings. Virginia: ASCE.

Gazetas, G. & J. L. Tassoulas. 1987. Horizontal stiffness of arbitrarily shaped embedded foundations. *Journal of Geotechnical Engineering*, 113(5): 440-457.

Lazebnik, G. & G. Tsinker. 1997. *Monitoring of Soil-Structure Interaction: Instruments for Measuring Soil Pressures*. United States of America: Springer.

NIST GCR 12-917-21. 2012. Soil-Structure Interaction for Building Structures. Gaithersburg: NIST.