Nonlinear Mathematical Modeling of Seismic Base-Isolation System Based on the Concept of "Floating-Sliding" Structure (ALSC)

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SUMMARY:
Within the frame of the Macedonian-Slovenian scientific cooperation, the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) from Skopje, Macedonia and the Slovenian National Building and Civil Engineering Institute (ZAG) from Ljubljana, Slovenia, a bilateral project entitled: Development and Application of Seismic Base-isolation System for Reservoirs and Buildings Based on the Concept of »floating-sliding« Structure (ALSC), is under realization. The objective of the project was to perform complex analytical modeling of the non-linear response of structural systems base-isolated by the »ALSC« system. In this paper, the simplified mathematical modelling of the nonlinear response of the integral system: structure-ALSC system-elastic springs-dampers, is presented. By this modeling, an optimization of the response parameters such as: transmissibility factor, friction-sliding coefficient, degree of »floating«, damping coefficient and stiffness of the centering springs is performed. The experimental results obtained from the shake-table tests of the church model to the scale of 1/3.5 by harmonic and earthquake excitation, were used for verification of the optimization procedure.

Keywords: Base-isolation, sliding concept, up-lifting pressure, centring springs

1. DESCRIPTION OF THE ALSC SYSTEM

ALSC or almost lifted structure concept is a concept of reducing lateral forces in structures in the event of an earthquake by adding a layer of pressurized liquid (water) between the structure and the ground. As much as 90 % of the weight of the structure is carried by the pressurized liquid. The structure has to be built on a specially designed concrete foundation, which has a special compartment for the liquid. On the edge of this special foundation structure, there is special seal, which prevents leaking and also reduces friction. The foundation slab is placed in a restraining basin, which limits the maximum displacements, and there are springs around the structure, which move the structure into the initial position after horizontal loads subside. The foundation structure is not fixed to the ground.

The friction force at the contact surface is defined by the following equation:

$$F_{fr} = \mu N \text{, where:}$$
$$N = G - L, \quad L = p\, S \;;$$

For $L = G$ the floating state is achieved by $N = 0$ and $F_{fr} = 0$.

F_{fr} = friction force;
μ = friction coefficient at the contact surface;
N = active compressive force;
L = uplifting force produced by the liquid;
G = weight of the structure;
p =liquid pressure;

S = contact surface between the sliding and the fixed plate.

In the event of an earthquake, the system starts to slide very quickly. The frictional forces that develop are relatively small due to the low coefficient of friction and, more importantly, due to greatly reduced normal forces. Extensive testing of the system was performed at IZIIS in Macedonia. A model of a church was built to the scale of 1:3.5 and tested on a shaking table.

2. DESCRIPTION OF THE TESTED MODEL AND EXPERIMENTAL PROGRAM

The model of the church is presented in Figure 1, where the restraining basin (light gray), springs (yellow) and the sliding foundation structure (green) can clearly be seen. The mass of the model is about 19 tons including the foundation plate. The dimensions of the church model are: 2.6 x 4.0 x 3.5 m.

Figure 1. The physical model of the church to the scale of 1/3.5 on the shaking table

The scheme of the structure and the locations of displacement transducers and accelerometers is shown in Figure 2.

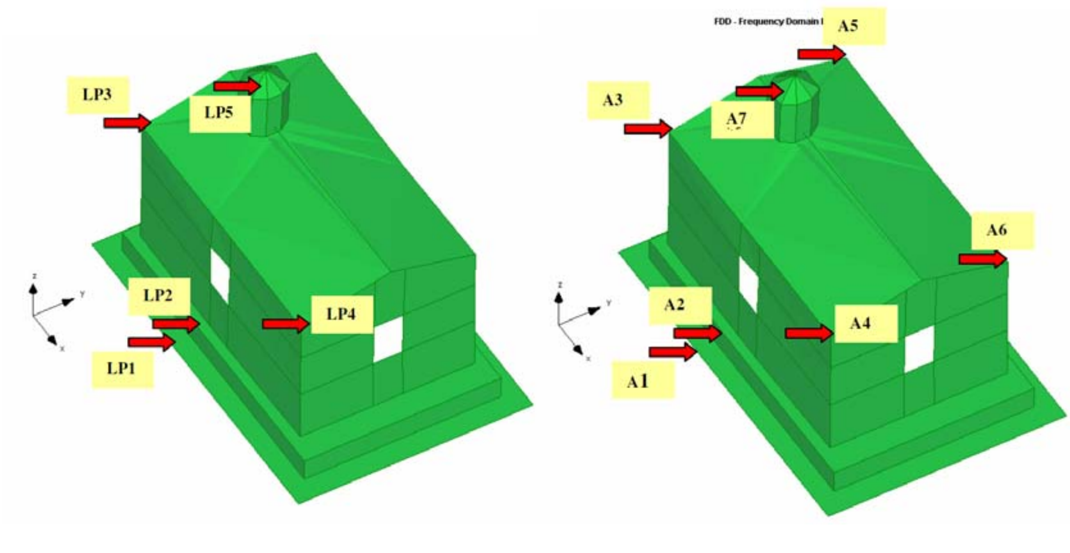

Figure 2. Scheme of the structure and the locations of the measuring devices. LP denotes the displacement transducers, A denotes the accelerometers

The experimental program consisted of tests on the shaking table. First, the ALSC system was tested in a series of earthquake runs with an increasing intensity. No damage occurred in the model during the testing despite peak ground accelerations of up to almost 2.0 g.

After the ALSC testing, the model was fixed to the ground and tested as a fixed base, i.e. normal system. Again, a series of tests with increasing amplitudes was performed. Heavy damage occurred at peak ground accelerations of 0.4 g, as will be described in more detail in the subsequent text.

2. MODELING AND NUMERICAL ALGORITHM

A single degree of freedom system was used to model the dynamic response of the structure. The rationale behind this decision is that, once the ALSC system starts sliding, the system is almost isolated from the ground and the structure is practically rigid. This is confirmed by observations during experiments as well as by analysis of the measured response. Interestingly, even the response of the fixed base system can be modeled using this model for as long as the model is in the elastic range.

The governing equations in the case of the fixed system are:

$$M\,\ddot{u} + C\,\dot{u} + K\,u = M\,\ddot{u}_g \tag{2.1}$$

Where:

M … mass
C … damping
K … stiffness
u … (relative) displacements
u_g … absolute displacements of the ground

The mathematical problem is solved using the Newmark's time integration scheme with the trapezoidal rule. The accelerations in each time step are constant, the velocities are linear and the displacements are quadratic. The initial conditions of the system are complete stillness ($u_{t=0} = \dot{u}_{t=0} = \ddot{u}_{t=0} = 0$). Standard viscous damping is taken into account.

In the case of the ALSC system, friction is also considered. The governing equations that are shown above are expanded to include this phenomenon. Constant friction is assumed. The direction of the friction force is opposite to the direction of velocity.

$$M\,\ddot{u} + C\,\dot{u} + K\,u \pm \mu\,N = M\,\ddot{u}_g \tag{2.2}$$

The solution algorithm is again based on the Newmark's time integration scheme with the trapezoidal rule. In order to correctly determine the moment when the frictional force changes direction, the time of $\dot{u} = 0$ is calculated exactly and the time step size is adjusted. It is assumed that sliding is active from the beginning of the analysis (there is no sticking phase).

3. NUMERICAL SIMULATIONS

3.1. Model with ALSC Base-isolation

The series of earthquake excitations using the ground motion recorded during the 1979 Petrovac Montenegro earthquake N-S component was used to simulate earthquake action (Fig.3). A list of ground motion intensities is presented in Table 1. In an attempt to model the structure, the following data was used:

Mass	18658.9 kg
Stiffness	2.96278 x 10^6 N/m
Damping ratio	0.20
Friction coefficient	0.05
Normal force	0.1*G*

The mass of the structure was known and the stiffness was calculated using known natural periods, which were obtained by spectral analysis of oscillations of the structure due to ambient vibrations. The normal force *N* was calculated from the pressure of the liquid (and the effective area).

The damping and friction coefficient were obtained essentially by trial and error, but taking into account the assumption of low friction, which was observed during the testing. Simulations showed that damping coefficient could be quite reasonably determined from the tests. The friction coefficient, on the other hand, is quite low and has little effect on the response.

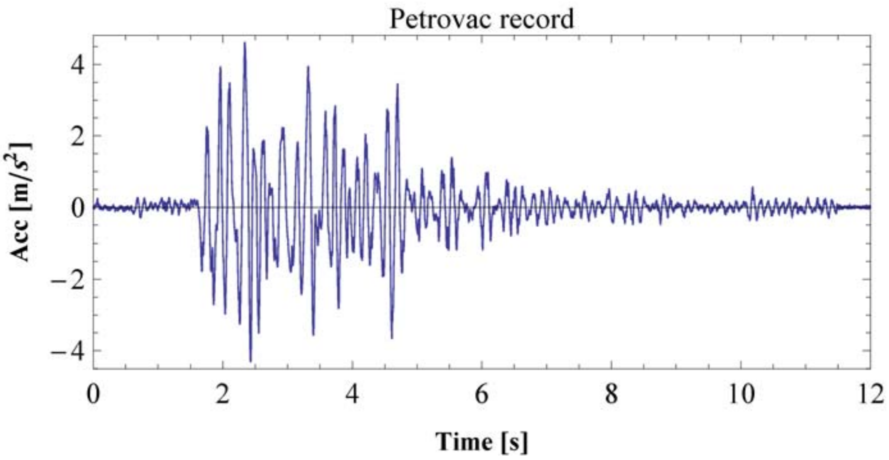

Figure 3. Montenegro 1979-Petrovac earthquake N-S component record compressed 3.5 times, input peak acceleration 0.4g-experimental results

Table 1: Base isolated model- series of harmonic and earthquake excitation tests

test no.	Type of excitation	Span of the table	Acceleration (% g)					Relative displacement basin-sliding plate (mm)
			Basin	Sliding plate	Top of wall	Dome	Simu-lation	
1	Harm. 5Hz	80	0.80	0.15	0.12	0.20	0.15	7.0
2	Harm. 7Hz	40	0.60	0.15	0.16	0.22		3.0
3	Petrovac	50	0.22	0.20	0.18	0.15		3.5
4	Petrovac	100	0.45	0.25	0.18	0.20		6.0
5	Petrovac	200	0.80	0.25	0.25	0.30	0.35	15.0
6	Petrovac	300	1.20	0.32	0.35	0.38	0.50	20.0
7	Petrovac	400	1.50	0.25	0.22	0.28	0.48	35.0

The relationship between input acceleration, response acceleration-versus relative displacement between the basin and the sliding plate is given on fig.4. It is obvious that no damage occurred because the response acceleration is drastically reduced.

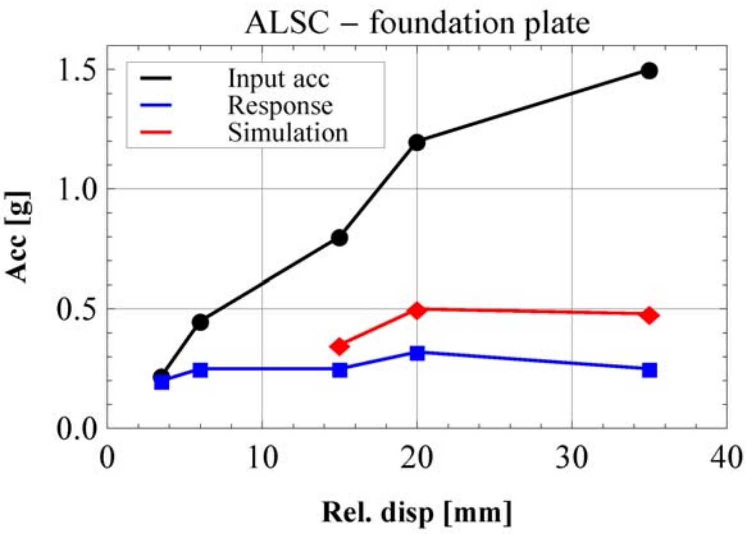

Figure 4. ALSC model: Input and response acceleration versus relative displacement between the basin and the sliding plate

The results in Fig. 4 show that the simulation overestimates the response accelerations, and is thus on the safe side from an engineering view. Detailed analysis of the response of the system shows, that such simulation is a rather crude approximation (Figs. 5 and 6). Nevertheless, the model gives reasonable estimates for a designer and should be regarded as such. In order to obtain better time history response results, the complexity of the model should be increased by taking into account the rotation of the structure, which would cause un-even normal forces along the contact. Moreover, full contact formulation and 3D modelling of the structure could be used. This, however, is not the aim of this paper. Despite the crudeness of the simulations, an essential characteristic of the system, i.e. almost constant response acceleration could be obtained with increasing input acceleration.

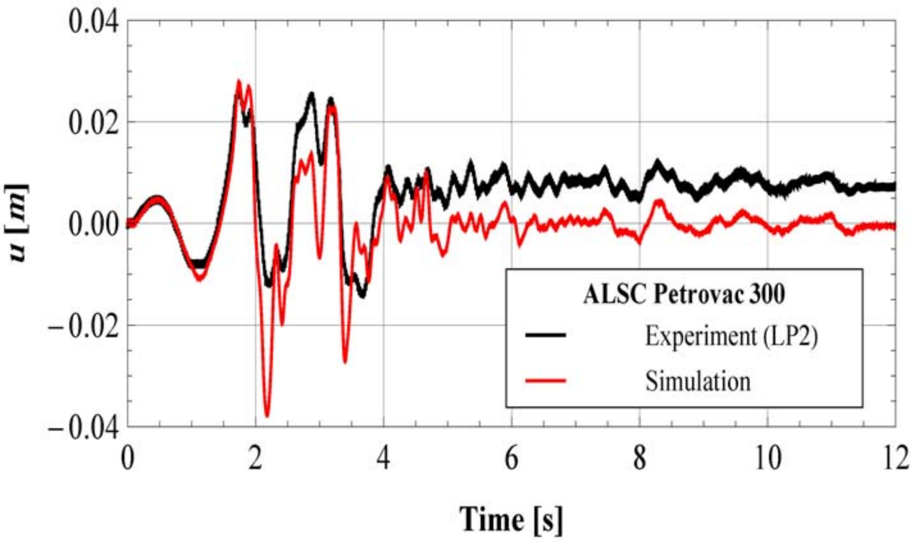

Figure 5. Comparison of absolute displacements by experiment and numerical simulation of ALSC during Petrovac 300 test run

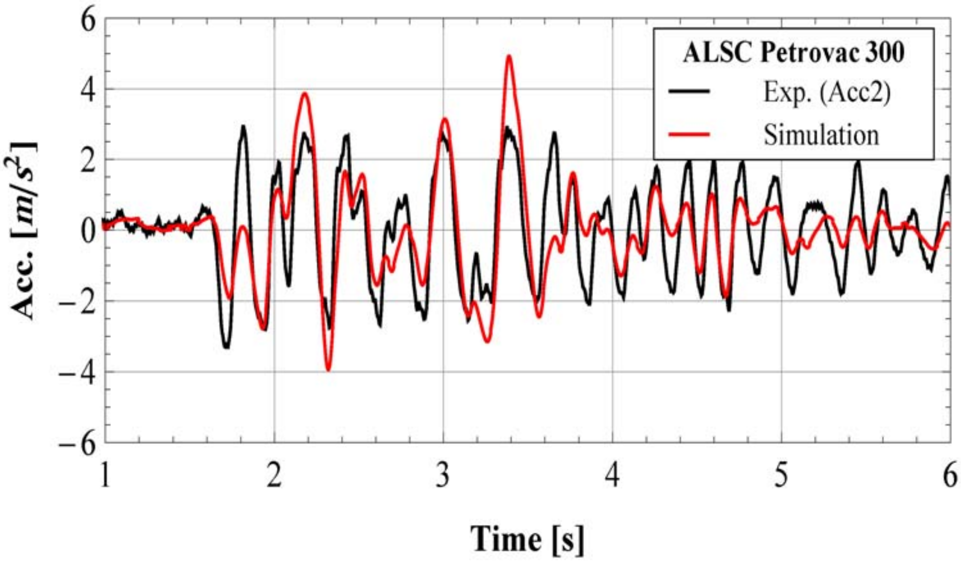

Figure 6. Comparison of absolute accelerations by experiment and numerical simulation of ALSC during Petrovac 300 test run

3.2. Fixed Base Model

The list of test runs and ground motion intensities is presented in Table 2.

Table 2. Fixed base model, earthquake excitation: Petrovac record

Test no.	Span	Response of the fixed base model					
		Acceleration (g)			Relative displacement (mm)		Comment
		Base	Top of the wall	Dome	top of the wall	Dome	
3	20	0.10	0.18	0.25	0.2	0.5	
4	30	0.15	0.25	0.38	0.25	0.7	
5	40	0.20	0.30	0.45	0.4	1.0	
6	50	0.25	0.38	0.55	0.5	1.2	
7	60	0.27	0.42	0.60	0.7	1.5	
8	70	0.32	0.50	0.70	0.8	2.0	
9	80	0.38	0.55	1.0	1.0	3.0	
10	90	0.40	0.60	1.5	1.1	13.0	collapse of the dome
11	100	0.45	0.65	/	2.0	/	
12	120	0.50	0.70	/	2.5	/	
13	150	0.60	1.0	/	3.0	/	
14	180	0.70	1.2	/	8.0		heavy damage to the openings and cracks in the walls

Figure 7. Fixed base: Failure of the tambour-Petrovac, input acc: 0.45 g

Figure 8. Fixed base: Cracks in the walls and arches-Petrovac, input acc: 0.7g

The relationship between input acceleration versus relative displacement at the top of the dome is given in Fig. 9. The graph clearly shows that damage happens at the input acceleration of 1.0 g and relative displacement of 3 mm.

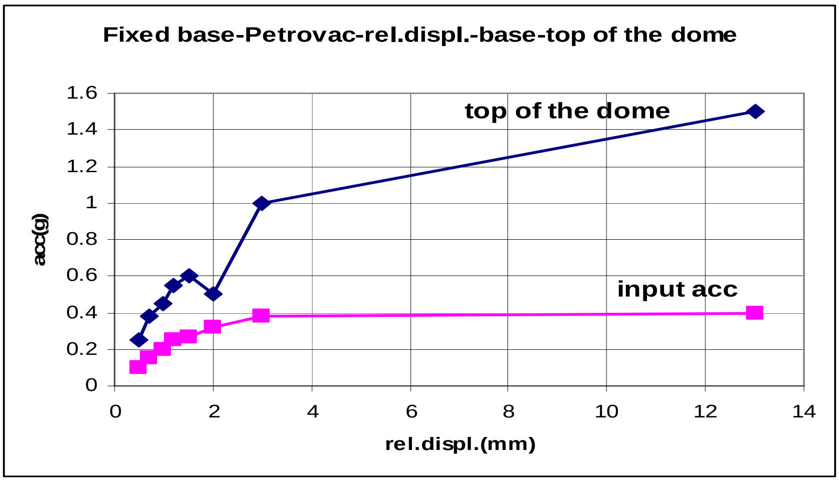

Figure 9. Fixed base-experimental results: input acceleration, response acceleration -versus relative displacement at the top of the dome

The numerical simulation is made for test number 10 (presented in Table 2). Input data for this test was obtained similarly as in the ALSC case. They are:

Mass	16326.5 kg
Stiffness	6.57157 x 10^7 N/m
Damping ratio	0.25
Input acceleration	0.4 g

The results are presented in Figs. 10 and 11. As can be seen, a very good correlation is obtained both for displacement and acceleration time histories.

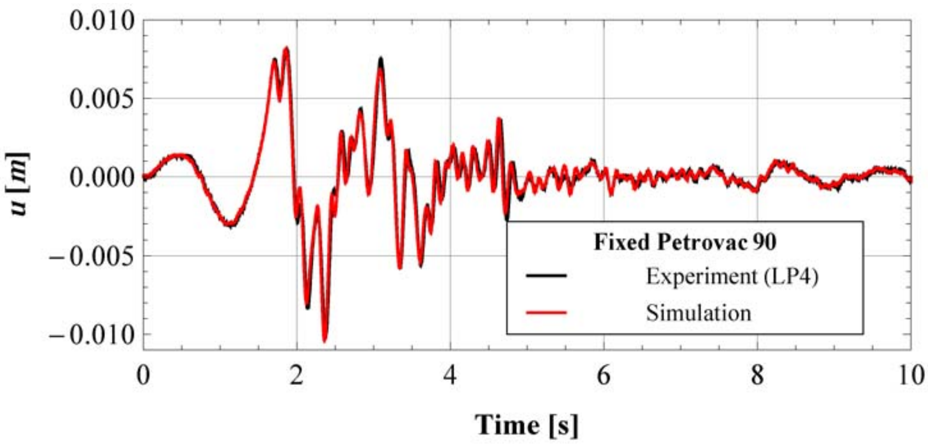

Figure 10. Fixed case: absolute displacements – experiment and numerical simulation

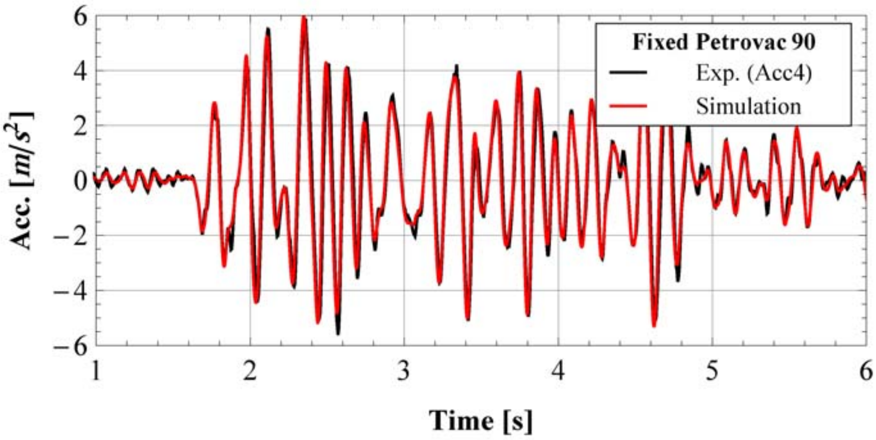

Figure 11. Fixed case: absolute accelerations – experiment and numerical simulation

4. CONCLUSIONS

An experimental program of 1:3.5 scaled model of a church is presented. The test program is first performed on the ALSC system, and then on the fixed system. Results show the ability of the ALSC system to reduce the seismic demand of the structure.

Both systems – the ALSC and the fixed system are modeled numerically. The attempt to model the dynamic response of the ALSC using a simplified SDOF model with friction shows, that such model can give a rough estimate of the seismic demand, which is adequate for engineering practice and design. If better correlation between experiments and simulation is to be obtained, more sophisticated models should be used.

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