International School and Workshop
NONLINEAR MATHEMATICAL PHYSICS AND NATURAL HAZARDS
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Seismic Monitoring and Instrumentation for Earthquake Engineering Application in Bulgaria

Part II

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In-situ dynamic testing and seismic instrumentation of structures

That is an adequate way to:

- check the appropriateness & improve the dynamic models;
- quantify the interaction of soil and structure;
- explain the reasons for any damage to the structure;
- determine the influence of nonlinear behavior on the overall and local response of the structure;
- correlate the damage with inelastic behavior;
- facilitate decisions to retrofit/strengthen the structural systems, etc. .

Why are they necessary ?

DT of structures:

- ✓provides substantial data for their real Dynamic Characteristics (DC);
- ✓ relationships are determined – possibilities to correlate the DC of the models with those of real structures;
- ✓ improvement of the design process in construction;
- ✓ a prerequisite for the optimal Seismic Instrumentation (SI) of structures.

SI of structures:

- ✓the actual response of structures subjected to real earthquake events is recorded;
- ✓valuable empirical data for the bahaviour of structures in the process of their response to EQ loads are accumulated.

What are the benefits?

- Provides possibilities for analysis and evaluation of:
  - ✓ the actual seismic vulnerability of structures;
  - ✓ the efficiency of the current engineering/design practices;
  - ✓ current knowledge and technology (to be corrected).
- Facilitates the "performance-based" EQ engineering.

Building Standard Law of Japan – revised:
"quantitatively evaluate the structural performance for various type of external disturbances including earthquake motion".

Prerequisites: High-grade data of the DT & SI

Obstacle: The equipment for DT & SI is expensive

AMBIENT RESPONSE TESTING OF RC RESIDENTIAL BUILDINGS, INDUSTRIAL AND COMMERCIAL STRUCTURES AND DAM WALLS

The Dynamic Identification (D.I.) through ambient vibration processing is a new branch of experimental dynamics developed during the last decades due to the availability of:

- ✓ highly-sensitive sensors (broad dynamic range);
- ✓ advances in computer technologies.

Advantages of DI to the conventional methods of ED:

- ✓ relatively easy, fast and cheaper experimentation (without disturbing the exploitation of the building)
- ✓ no use of expensive and clumsy actuators (no damages)
- ✓ simultaneously activation of a number of eigenfrequencies (due to the broad band input ambient noise)

METHODS FOR EXTRACTION OF MODES THROUGH AMBIENT VIBRATION PROCESSING

Two independent methods for modeling and identification of DC:

- ✓ The Stochastic Subspace Identification (SSI) - t
- ✓ The Enhanced Frequency Domain Decomposition (EFDD) - f

Time domain modal identification techniques in state space form.:

$$(1) \quad x_{t+1} = Ax_t + Ke_t$$

$$(2) \quad y_t = Cx_t + e_t$$

where x, y, e, A, K, C are: the estimated state vector, the response vector, the innovation, the state matrix (physical information), the Kalman gain (statistical information), the observation matrix.

The modal decomposed transfer function appears as :

$$(4) \quad H(z) = \Phi(Iz - [\mu_j])^{-1}\Psi + I$$

z, μ, Φ and Ψ are: a frequency dependent complex number, the matrix of the eigenvalues of A, the mode shapes matrix and the statistical matrix.

$$(5) \quad \mu_j = e^{-2\pi f_j(\zeta_j \pm i\sqrt{1-\zeta_j^2})T}$$

⟹ natural freq. f_i and the damping ζ_i

RC Residential Buildings

Building "A" (24.10m/11.50m) Building "B" (29.00m/11.50m)

H = +20.00 m

K2 - *High Dynamic Range Strong Motion Accelerograph*

Data Acquisition

Type: 24 bit Digital Signal Processor

No ch.: 12 Channels

Dyn. range : 114 dB @ 200 sps

Freq. resp.: DC to 80 Hz @ 200 sps

Resolution : 24-bit res. @ 200 sps

Sampl. rate: 20, 40, 50, 100, 200, 250 sps

Input range: ± 2.5V

Sensor

Type: Triaxial/Uniaxial EpiSensor FB Accelerometer

Full scale range: ±0.25g

Bandwidth: DC to 200 Hz

Dynamic range: 155 dB+

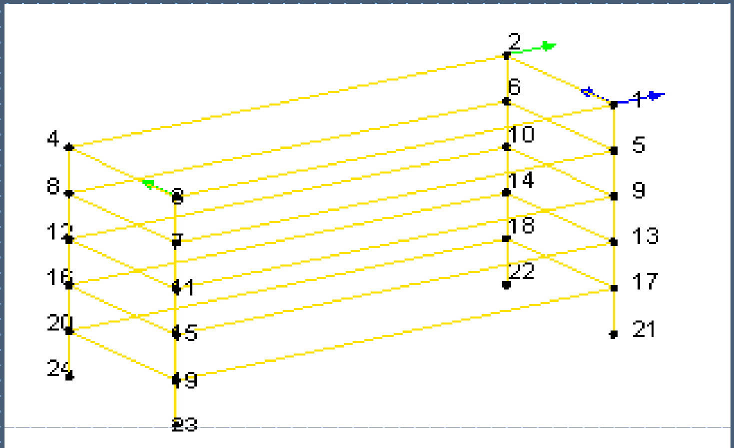
Storage

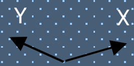
Type: 2 Fully compliant PCMCIA storage slots

32/64 MB Memory Card

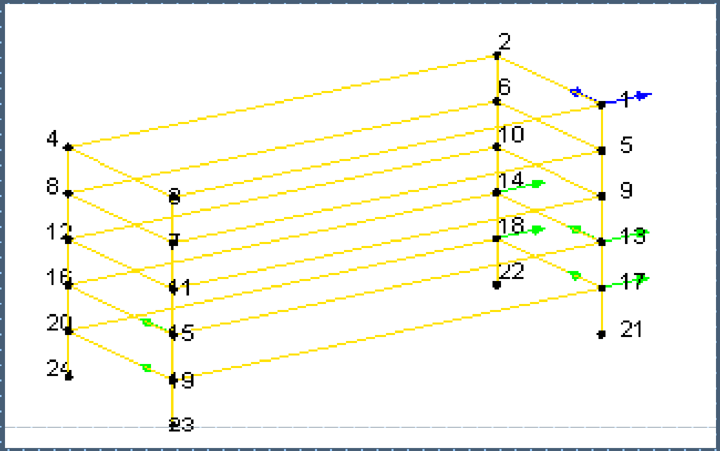
Model of building “B” with 40 DF

Data set 1





Data set 2



Disposition of sensors by data sets (data set 1 and 2)

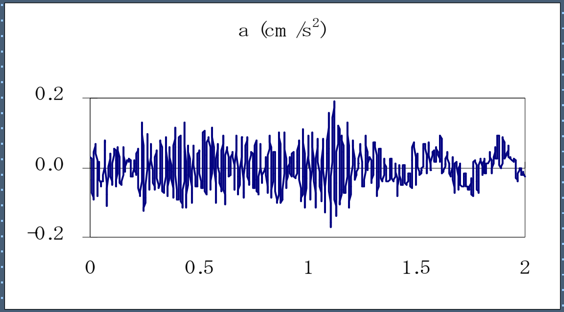
tri-axial sensor in node 1

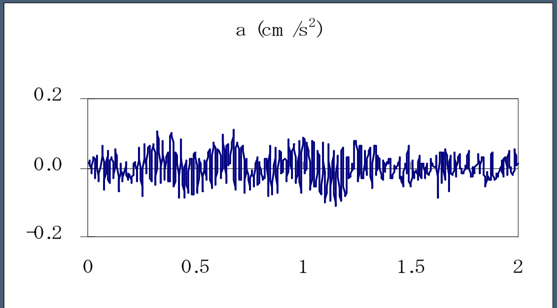
uni-axial sensors in node 13

The observation/measuring and recording points

6 recording sessions (records with t = 875 sec; f < 25 Hz)

sensor 1X



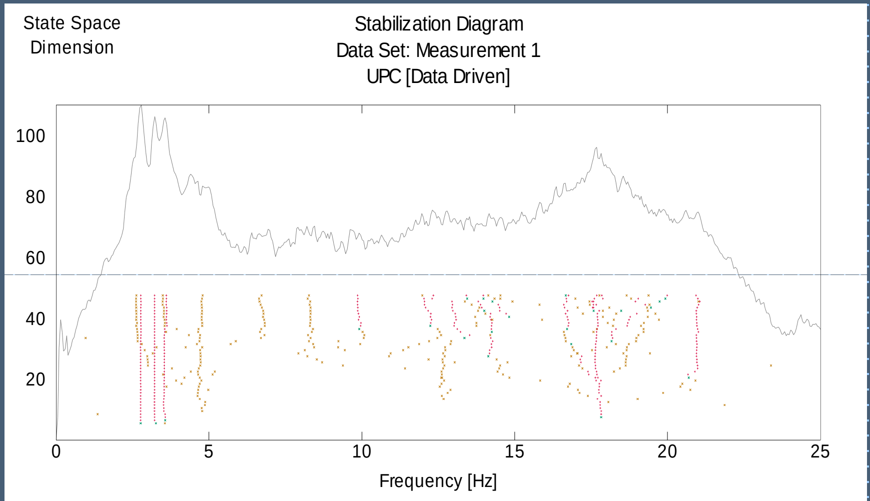


sensor 1Y

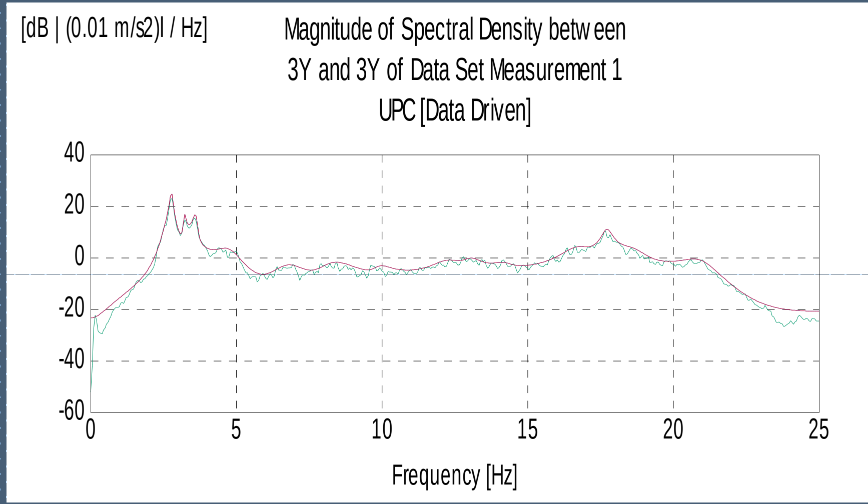
segments of recordings (data set 3)

MODAL IDENTIFICATION IN THE TIME DOMAIN (SSI-UPC)

Range of models dimensions - varied from 10 to 65



Stabilization diagram for data set 1

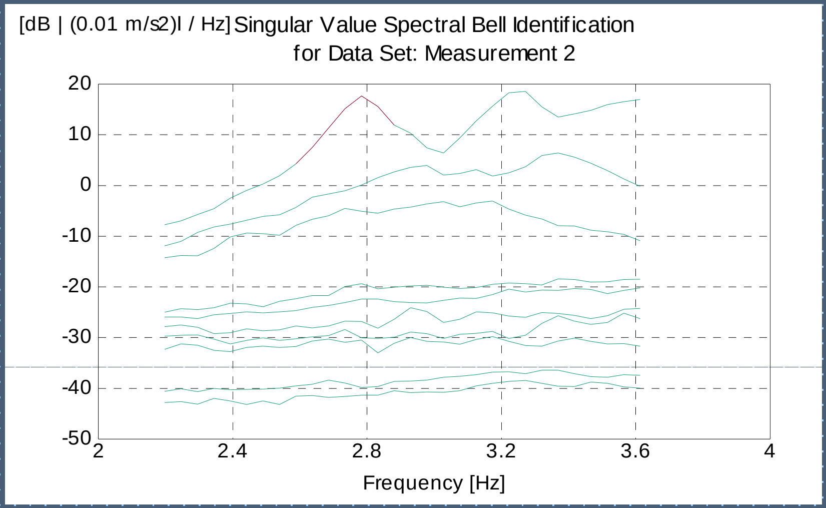


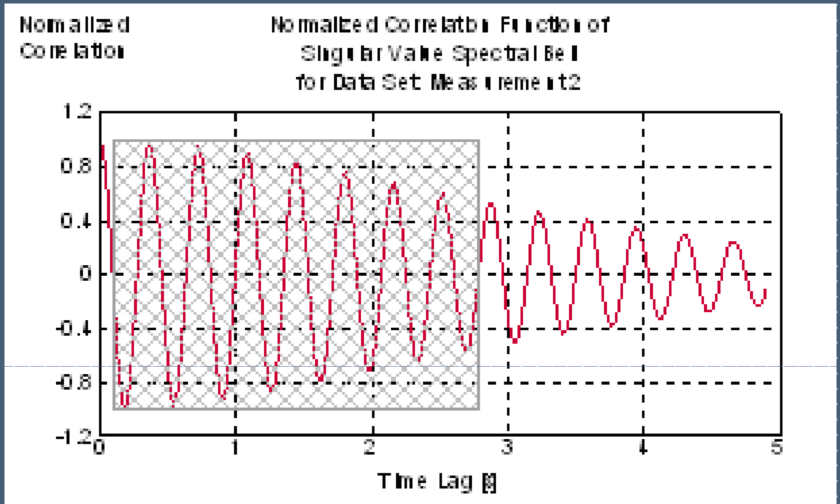
Comparison of the spectral densities for data set 1, sensor 3Y

Optimal approximation for every data set -> representative model.

DC of all representative models are averaged -> final estimate of the DC.

MODAL IDENTIFICATION IN THE FREQUENCY DOMAIN (EFDD)





Spectral bell identification

The corresponding damped vibration of a SDF system

A local maximum is picked out from the graphs of the SVSD -> a spectral bell is outlined by ...-> this spectral bell is transformation in the time domain -> damped vibration trace of a SDF system -> f, ζ.

COMPARISON OF THE RESULTS

Natural frequencies and damping of building “A”

№	N.Freq. by SSI (Hz)	Standard deviation (Hz)	N.Freq. by EFDD (Hz)	Standard deviation (Hz)	Diff. (%)	Damp. by SSI (%)	Damp. by EFDD (%)
1	3.133	0.00429	3.145	0.01006	0.38302	1.573	1.748
2	3.266	0.00703	3.269	0.00678	0.09186	1.373	1.260
3	3.937	0.00553	3.930	0.00131	0.17780	2.192	2.149

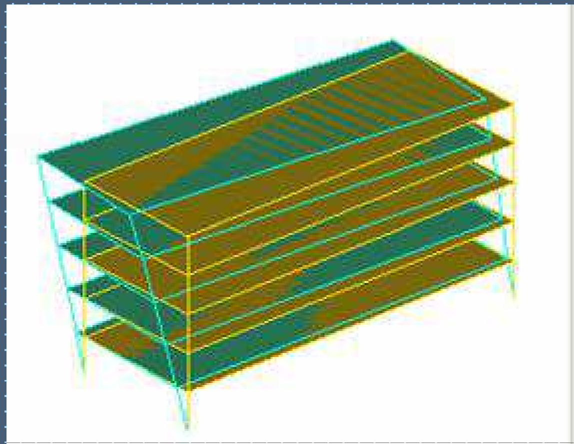
COMPARISON OF THE RESULTS

Natural frequencies and damping of building “B”

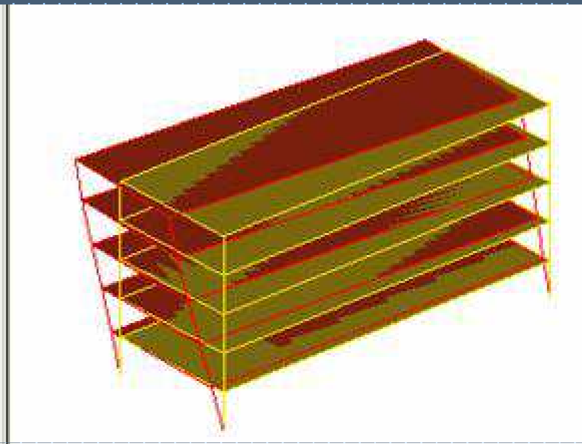
№	N.Freq. by SSI (Hz)	Standard deviation (Hz)	N.Freq. by EFDD (Hz)	Standard deviation (Hz)	Diff. (%)	Damp. by SSI (%)	Damp. by EFDD (%)
1	2.781	0.01104	2.778	0.01289	0.10787	1.448	1.426
2	3.224	0.00549	3.242	0.00630	-0.55831	1.405	1.381
3	3.570	0.03222	3.549	0.01892	-0.58824	2.478	2.481

Natural mode shapes for building "B"

time domain

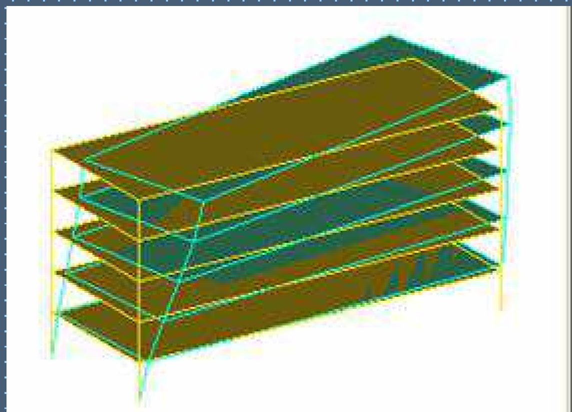


2.781 Hz

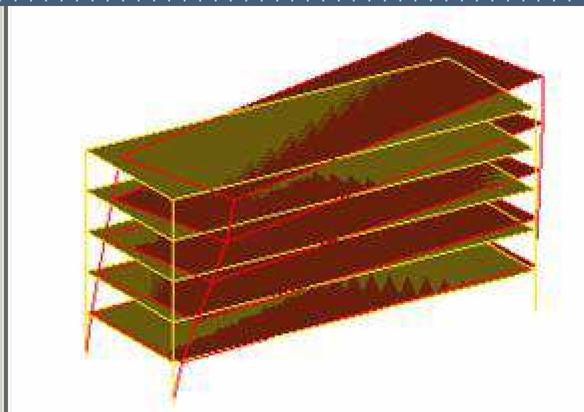


2.778 Hz

frequency domain

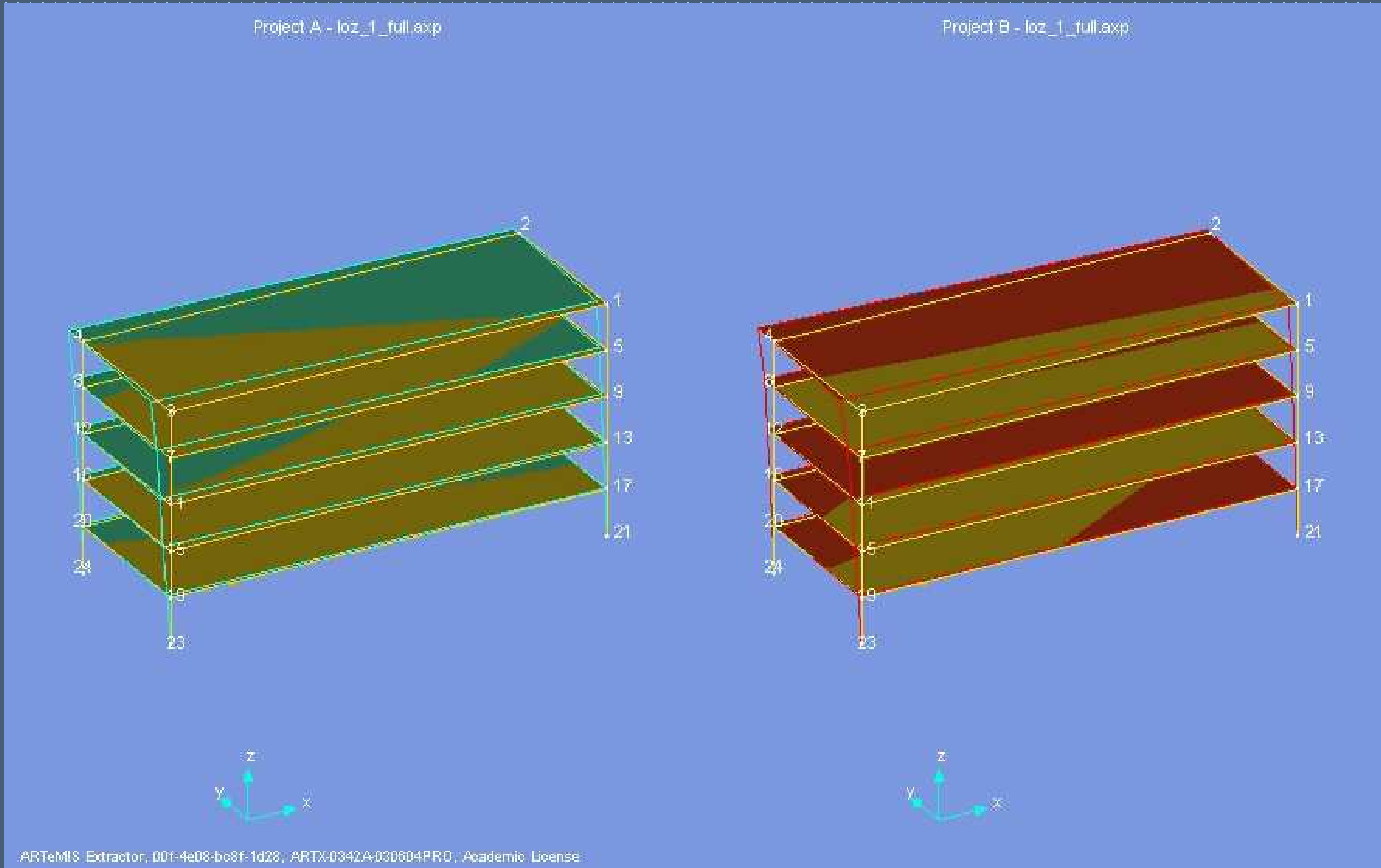


3.224 Hz

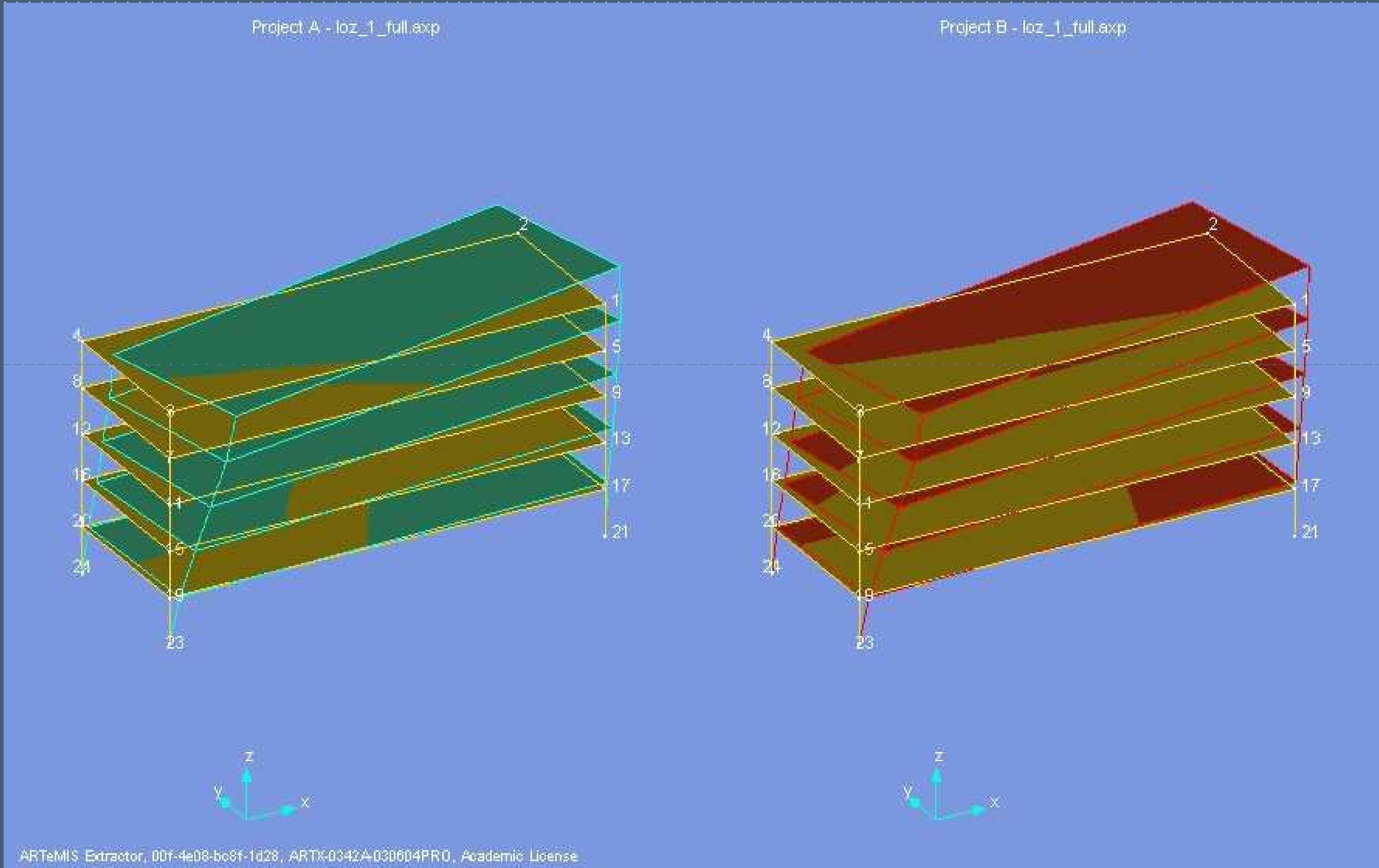


3.242 Hz

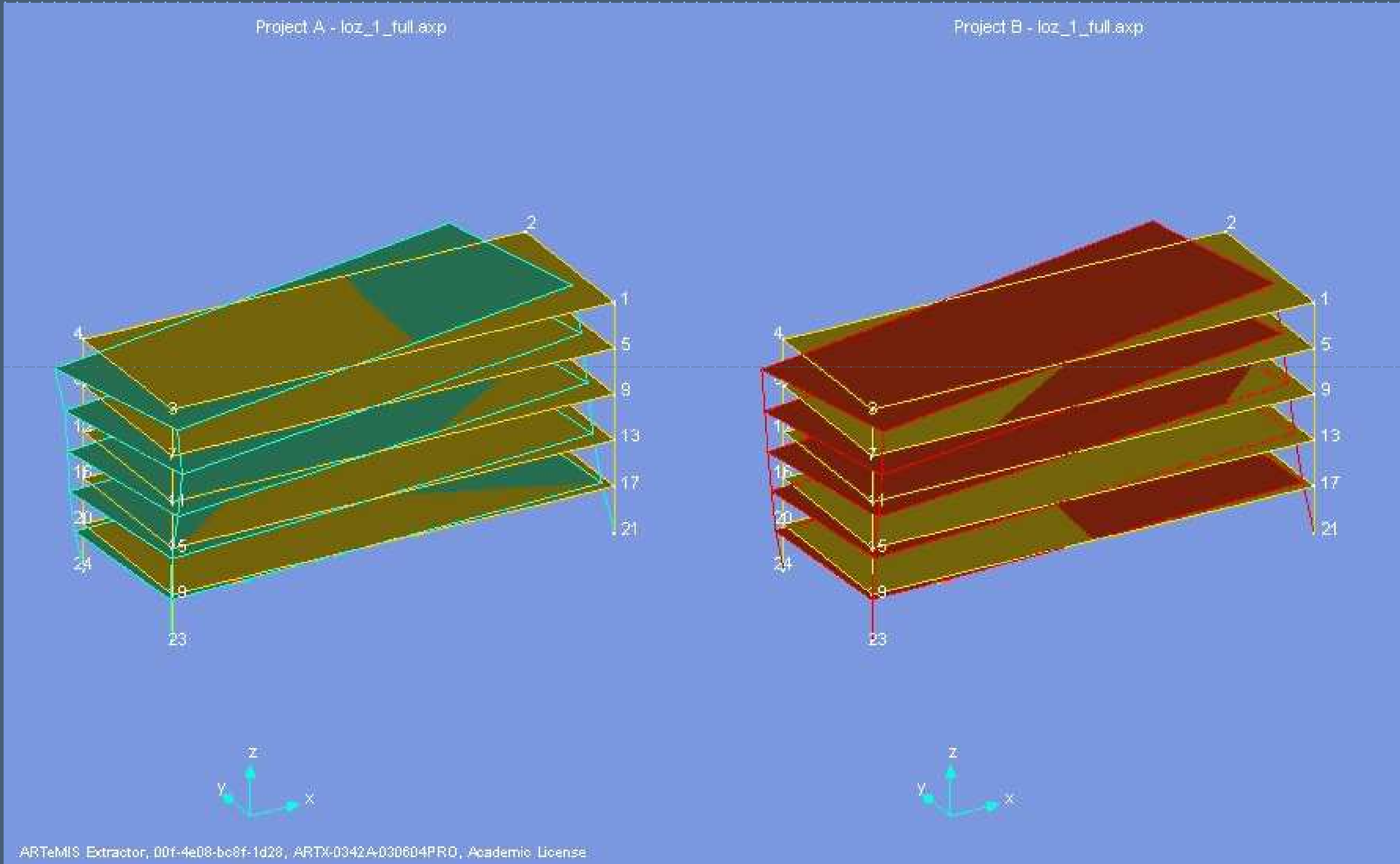
Visualizations of the 1-st mode shape obtained by the SSI and EFDD methods



Visualizations of the 2-nd mode shape obtained by the SSI and EFDD methods



Visualizations of the 3-rd mode shape obtained by the SSI and EFDD methods



PERFORMED

AMBIENT RESPONSE TESTING AND MODAL IDENTIFICATION OF A

RC RESIDENTIAL BUILDING

TO BE

INSTRUMENTED FOR

CONTINUOUS SEISMIC MONITORING

Permanent S I of block "B"

ETNA unit in the basement

Cased ETNA unit at the 6-th floor level

ANALYSIS OF THE RECORDED RESPONSES OF A MONITORED

RC RESIDENTIAL BUILDING

TO WEAK EARTHQUAKES

Sofia Earthquake input:

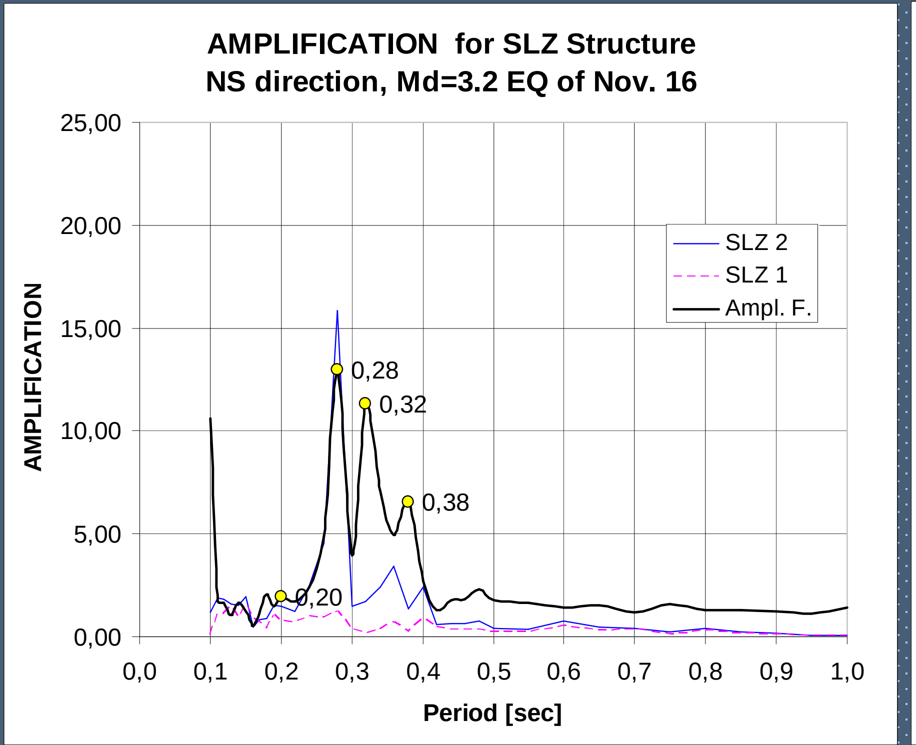
November 15 (EQ# 9, Md = 3.7, depth of hypocenter H = 10 km)

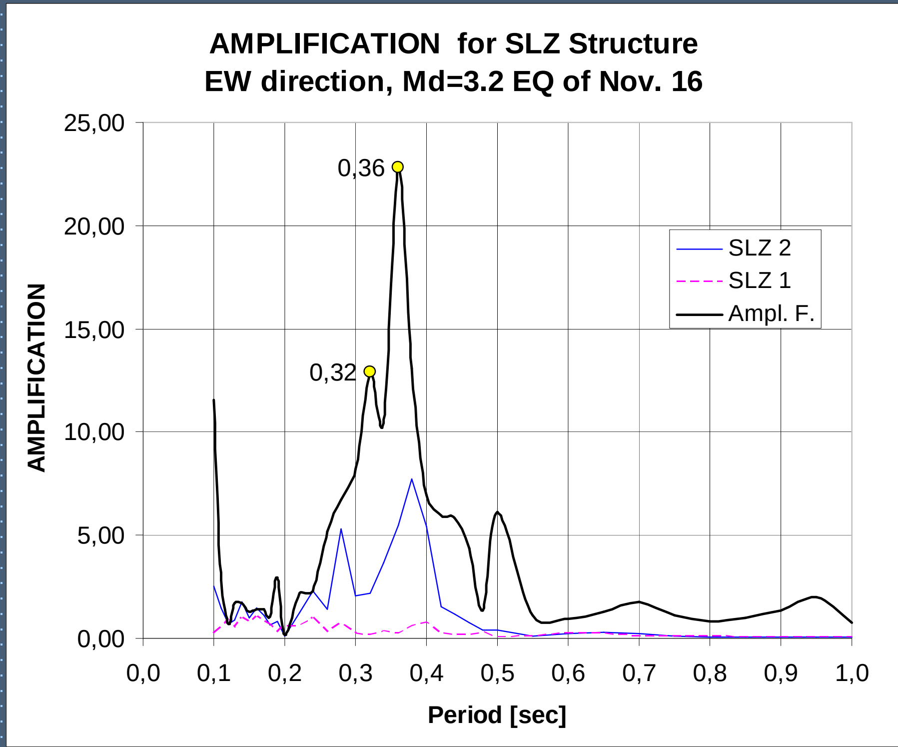
November 16 (EQ#10, Md = 3.2, depth of hypocenter H = 10 km)

Characteristics of recorded structural response to EQ impact

EQ	Station		Epicenter distance	Axis code	Peak Accel.	Peak Sp. Accel.	Predom. Freq.	Order of PSD
#	Code	Cond.	[km]		[cm/s^2]	[cm/s^2]	[Hz]	[g/Hz]
9D	SLZ1	base	3.14	EW NS UD	21.83 42.27 -28.41	203.5	5.4 ÷ 13. 6.2 ÷ 11. 8.8 ÷ 12.	$1.\ 10^{-6}$
9E	SLZ2	top	3.14	EW NS UD	-47.04 -92.14 59.78	425.8	2.5 ÷ 2.9 3.3 ÷ 3.7 9.0 ÷ 10.	$1.\ 10^{-5}$
10C	SLZ1	base	4.75	EW NS V	8.43 15.76 -32.31	27.2	5.3 ÷ 8.6 5.2 ÷ 9.8 7.0 ÷ 11.	$1.\ 10^{-7}$
10D	SLZ2	top	4.75	EW NS UD	21.37 -29.88 60.53	92.6	2.3 ÷ 3.8 3.3 ÷ 4.0 7.2 ÷ 11.	$1.\ 10^{-6}$

The structure's Amplification Spectra for EQ #10 inputs





NS

EW

Comparison of Identified Natural Frequencies of the Structure

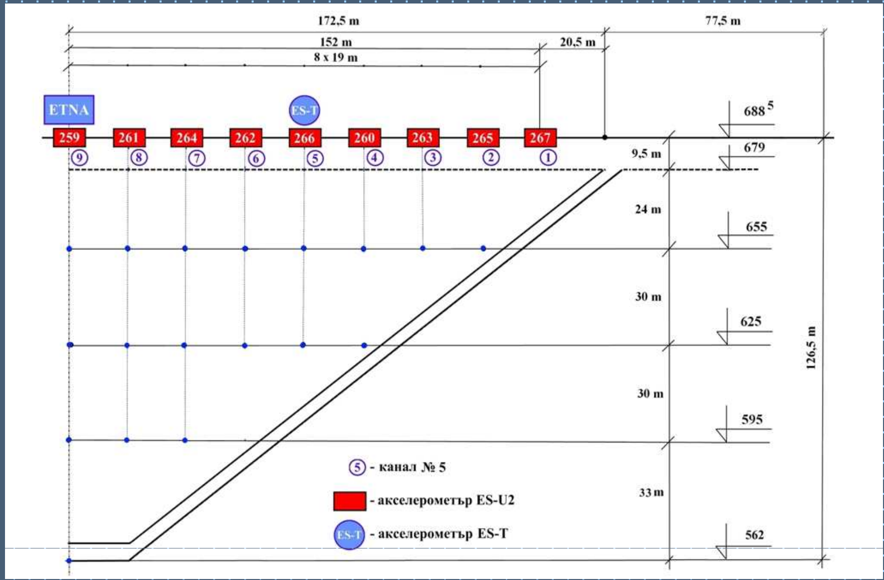
Fn #	From full-scale tests		From EQ #9		From EQ #10	
	Nat. Freq. [Hz]	Nat. Period [sec]	Nat. Period /NS/ [sec]	Nat. Period /EW/ [sec]	Nat. Period /NS/ [sec]	Nat. Period /EW/ [sec]
1	2.78	0.36	0.34	0.38	0.38	0.36
2	3.22	0.31	-	0.32	0.32	0.32
3	3.57	0.28	0.28	-	0.28	-

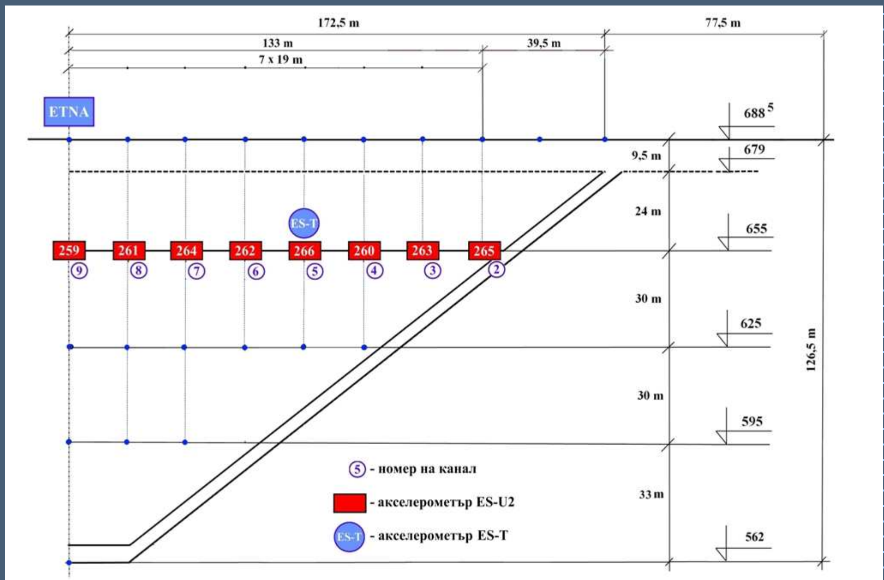
Maximum observed difference in the values of the identified natural frequencies by the two methodologies is within 6 %.

Industrial and Commercial Structures

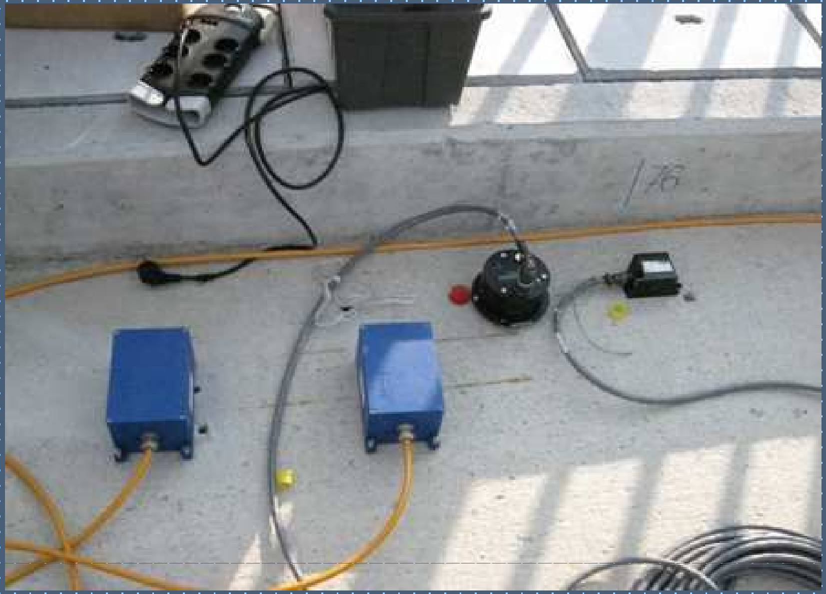
Concrete Dam Walls

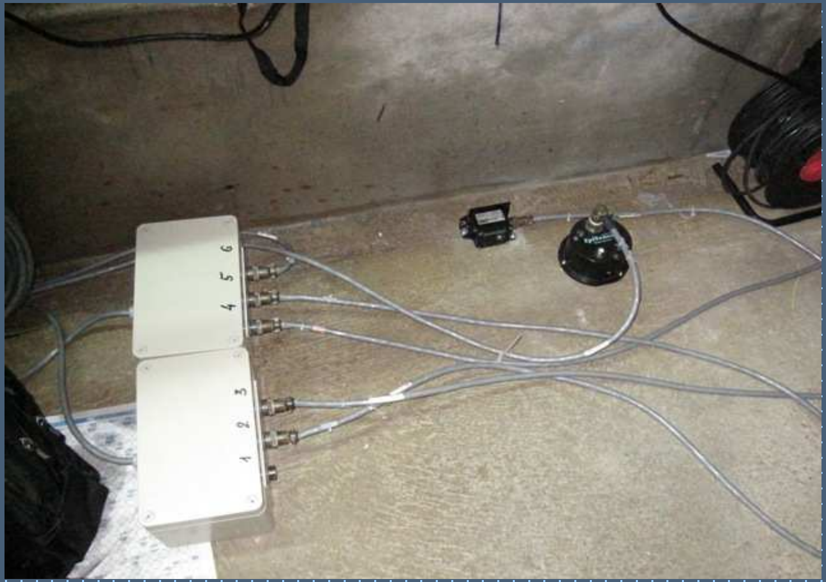
Testing Schemes





Equipment





EXPERIMENTAL PROCEDURES

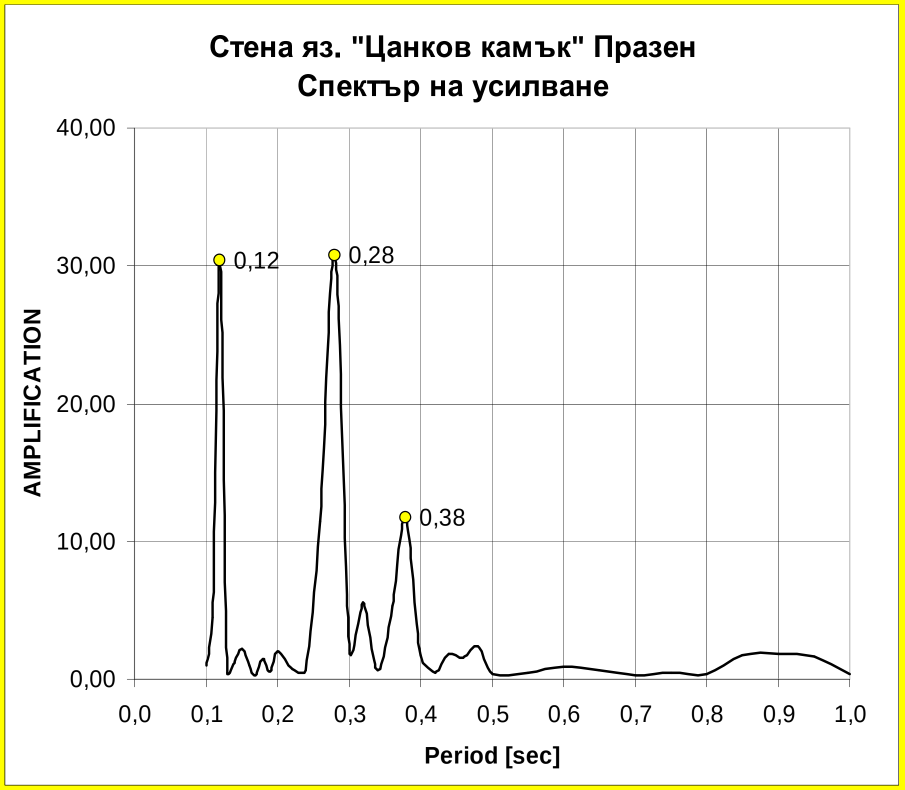
Communication, Calibration and Response Testing

Fixing and Mounting

Checking Compliance

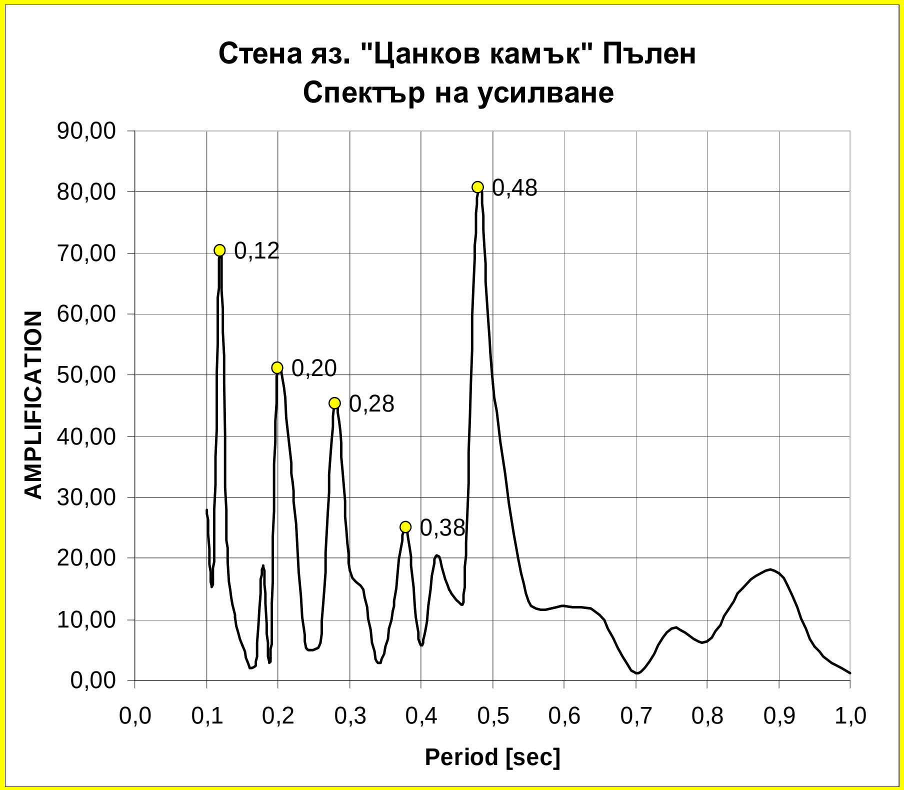
Amplification Spectra within the Dam's Wall

EMPTY



2.63 Hz, 3.57 Hz and 8.33 Hz

FULL



2.08 Hz, 2.63 Hz, 3.57 Hz, 5.00 Hz, 8.33 Hz

Perspectives

Focusing of the continuous seismic monitoring in urban regions and areas with higher earthquake hazard (including seismic instrumentation of buildings and structures) is a prerequisite for solving not only engineering problems (analysis, design, construction etc.), but also for effective prevention policies and earthquake protection of the population.

Every moderate earthquake to strike makes a warning that we need to put more effort to assess, retrofit and strengthen especially the existing older building stock.

The latest trends of structural health monitoring is a proper tool to enhance and speed up this process.

Final Remarks

Proper selection of parameters for generation of the design earthquakes is a major problem in seismic risk assessment and earthquake resistant design of structures.

Acquired data from the SGM monitoring play a key role for consistent solution of the seismic action problems for buildings, engineering structures and life-line systems.

Final Remarks

The availability of local strong-motion records is an indispensable tool for adequate earthquake resistant design of local structures to meet the safety requirements of the lately enforced Eurocode-8.

The seismic action on structures and their dynamic characteristics are key issues of adequate model analysis and safe design. Hence an integrated data bank compiled from analyzed seismic records and ambient vibration response testing offers a relevant background for advanced seismic analysis of structures, providing improved quality of their design and enhancing their safety and reliability.

THANK YOU
FOR
YOUR KIND ATTENTION

National Institute of Geophysics, Geodesy and Geography,
Bulgarian Academy of Sciences