INTERNATIONAL SCHOOL AND WORKSHOP
Nonlinear Mathematical Physics and
Natural Hazards

SEISMIC MONITORING OF STRUCTURES –

A TOOL FOR URBAN SEISMIC HAZARD REDUCTION

Dragi Dojcinovski
dragi@pluto.iziis.ukim.edu.mk

Institute of Earthquake Engineering and Engineering Seismology
University "Ss. Cyril and Methodius" in Skopje
Skopje, Macedonia

Sofia, November 28 – December 02, 2013

Contents

Data on the ground motion during earthquakes to which structures are exposed and behavior of structures are fundamental for seismic hazard evaluation, definition of design parameters and criteria and for all other dynamic investigations in earthquake engineering. Without such data all investigations and analysis that follow would be based on assumptions.

Strong motion instrumentation of structures has been utilized since 1940’s. Throughout the world, strong motion instrumentation networks have been installed on buildings, monumental and historic structures, bridges, dams, tunnels, pipelines and power plants as well as free field and soil deposits.

The installation of networks for recording of strong earthquakes and the results which are obtained from them, has become an increasing need in the earthquake engineering.

It has considerable contribution to the overall activities for seismic risk reduction of existing urban space and for the minimizing of the damages resulting from disastrous earthquakes.

- Seismic monitoring of structures is one of the activities within; the scope of the seismology and earthquake engineering, which, lately, has been paid considerable attention.

- The main objective in seismic monitoring of structures is to facilitate response studies that lead to improved understanding of the dynamic behaviour and potential for damage to structures under seismic loading.

SEISMIC MONITORING OF STRUCTURES

One of the main purposes of the strong motion instrument network is providing of data on the dynamic behaviour of structures under the effect of earthquakes. The strong motion instruments installed on the structures enable obtaining of basic data on its behaviour during an earthquake, i.e., making decisions about further exploitation or the need for repair of the structure immediately after the occurred earthquake.

The seismic monitoring of structure mainly refers to engineering aspects of the structure. The instruments are located at characteristic points of the base and the structure and the possibly obtained records are an invaluable source of data for verification of the mathematical model of the structure and its behaviour under the effect of a real earthquake.

The expected output should be in form such that can provide information on the intensity of an earthquake immediately after its occurrence. Based on this, a decision should be made regarding further exploitation of the structure. For instance, if the structure is designed for a = 0.25 g, and the maximum amplitude of recorded ground acceleration is less than this value, a decision can be made, with a great reliability, for further exploitation of the structure with no particular repair or strengthening. However, when the recorded acceleration is greater than 0.25, it is desirable, in case when there are no visible signs of damage, to perform a special study and define the stresses and strains in the structure caused by the forces from the recorded earthquake.

As a result of this understanding, design and construction practices can be modified so that future earthquake damage is minimized.

Data are used for :

a) hazard reduction,
b) improvement of codes,
c) identification of seismic response characteristics of structural system.

PROJECT FOR SEISMIC MONITORING

The seismic instrumentation of the structures should provide exact information on the seismic input and the structural response during the earthquake. The distribution of the instruments is therefore of crucial importance.

Their number varies depending on several parameters:

- seismological and geological characteristics of site;
- foundation conditions;
- type of the structure;
- geometrical shape of structure

Seismic monitoring of structures is planned, designed, carried out and organized for each structure individually. Seismic monitoring project is based on:

(1) Seismic regime of the micro- and the macro-region;

(2) Dynamic and strength characteristics of the local soil;

(3) Mode of foundation;

(4) Type and dynamic characteristics of the structure;

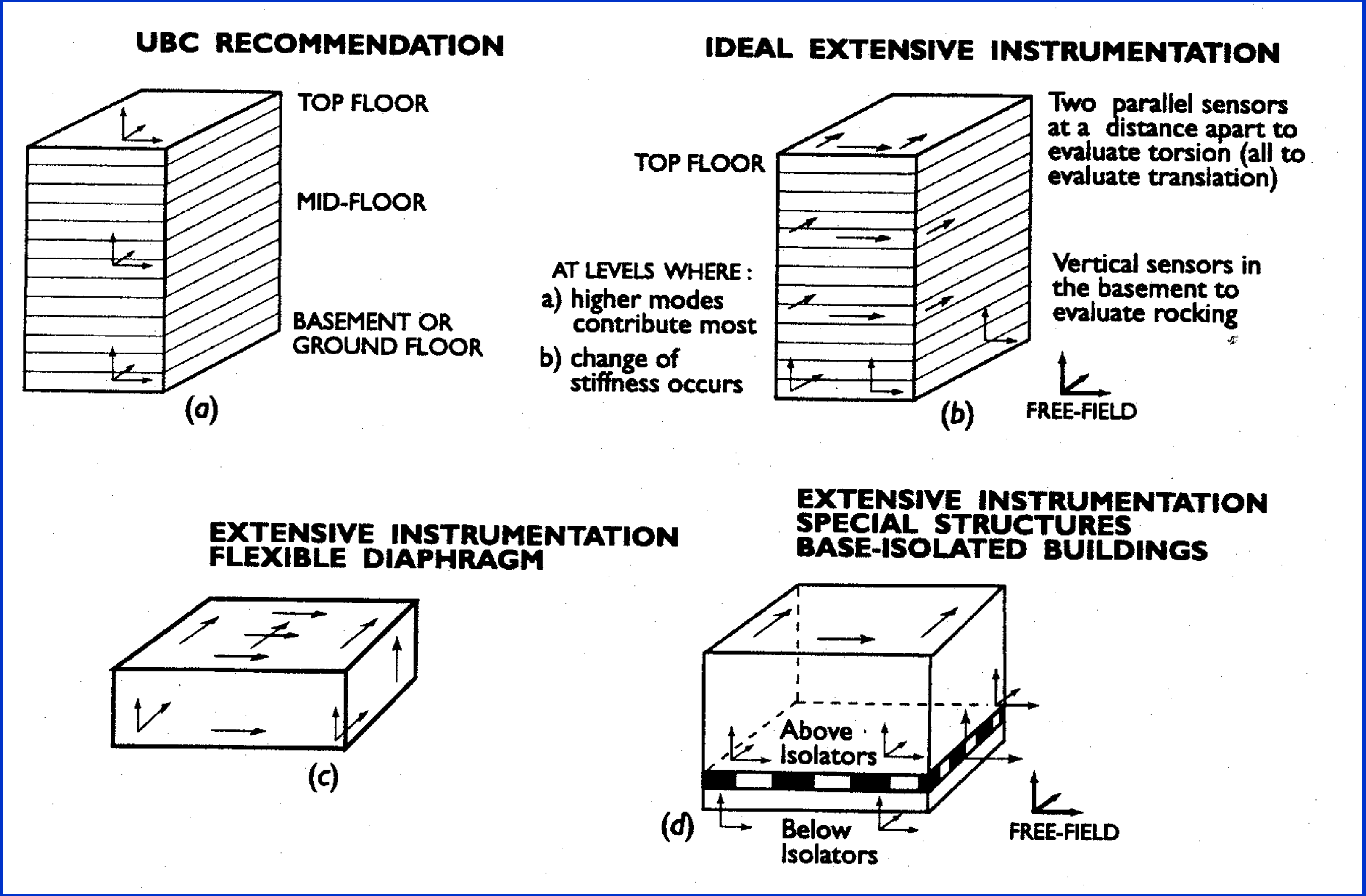
(5) Soil-foundation-structure interaction; and

(6) Geometrical shape of the structure.

All components have effect upon the dynamic characteristics and the dynamic behavior of the structures, so that concept is also based on results from dynamic analyses of the mathematical model and the experimentally defined values of dynamic characteristics of the structure:

1) Natural frequencies,
2) Damping capacity of the structure,
3) Vibration mode shapes of the structure.

It is necessary to establish an optimal system of seismic monitoring instruments that will enable to obtain practically usable and compatible data in case of an earthquake.



Typical Instrumentation Schemes

(taken from M.Celebi)

Data obtained by seismic monitoring network can serve for multiple purposes:

1) verification of previous computations and analyses,
2) analysis of the stress state and level of safety of the structure after the earthquake effect, and
3) optimization of the process of design of future structures.

FORMER YUGOSLAV STRONG MOTION NETWORK

The strong motion instrument network installed (1972) on the territory of former Yugoslavia was one of the largest in Europe. It consisted of over 250 accelerographs type SMA-1 and about 130 seismoscopes type WM-1.

Scientific-research project entitled :
"Installation of Strong Motion Instrument Network on the territory of Yugoslavia".

Institute of Earthquake Engineering and Engineering Seismology (IZIIS) in Skopje

Californian Institute of Technology (CALTECH) in Pasadena until 1975 and

United States Geological Survey (USGS) from Menlo Park until 1979.

Table 1. Distributions of instruments

Instruments	Location	
	Accelerographs	Seismoscopes
On bed rock	28	28
On characteristic soil	63	99
On structure	162	12
Total	253	137

Map of Strong-Motion Instrument Network on the Territory of Former Yugoslavia

MACEDONIAN STRONG MOTION NETWORK

It consisted of over 129 accelerographs and about 54 seismoscopes type WM-1.

All the activities related to this instrument network were carried out by the scientific and professional collaborators of the Strong Motion Laboratory in IZIIS. Scientific-research in this field was also carried out simultaneously resulting in a number of bulletins and reports as well as numerous papers and presentations at scientific meetings.

BASIC CONCEPTS OF THE NETWORK

The basic concept of the Macedonian strong motion network enables obtaining of basic information required for predicting the dynamic response of various types of structures, improvement of codes for aseismic design, understanding of the ground amplification effects as well as for better investigation and perceiving of consequences caused by earthquakes.

For this purpose, strong motion networks in Macedonia were developed with corresponding density in most active regions and with lower density in the regions with lower seismic activity, in order to study the following seismological and earthquake engineering aspects:

(1) earthquake source mechanism,

(2) wave propagation path,

(3) effect of local topography,

(4) free-field soil response at different soil conditions,

(5) site amplification factors, and,

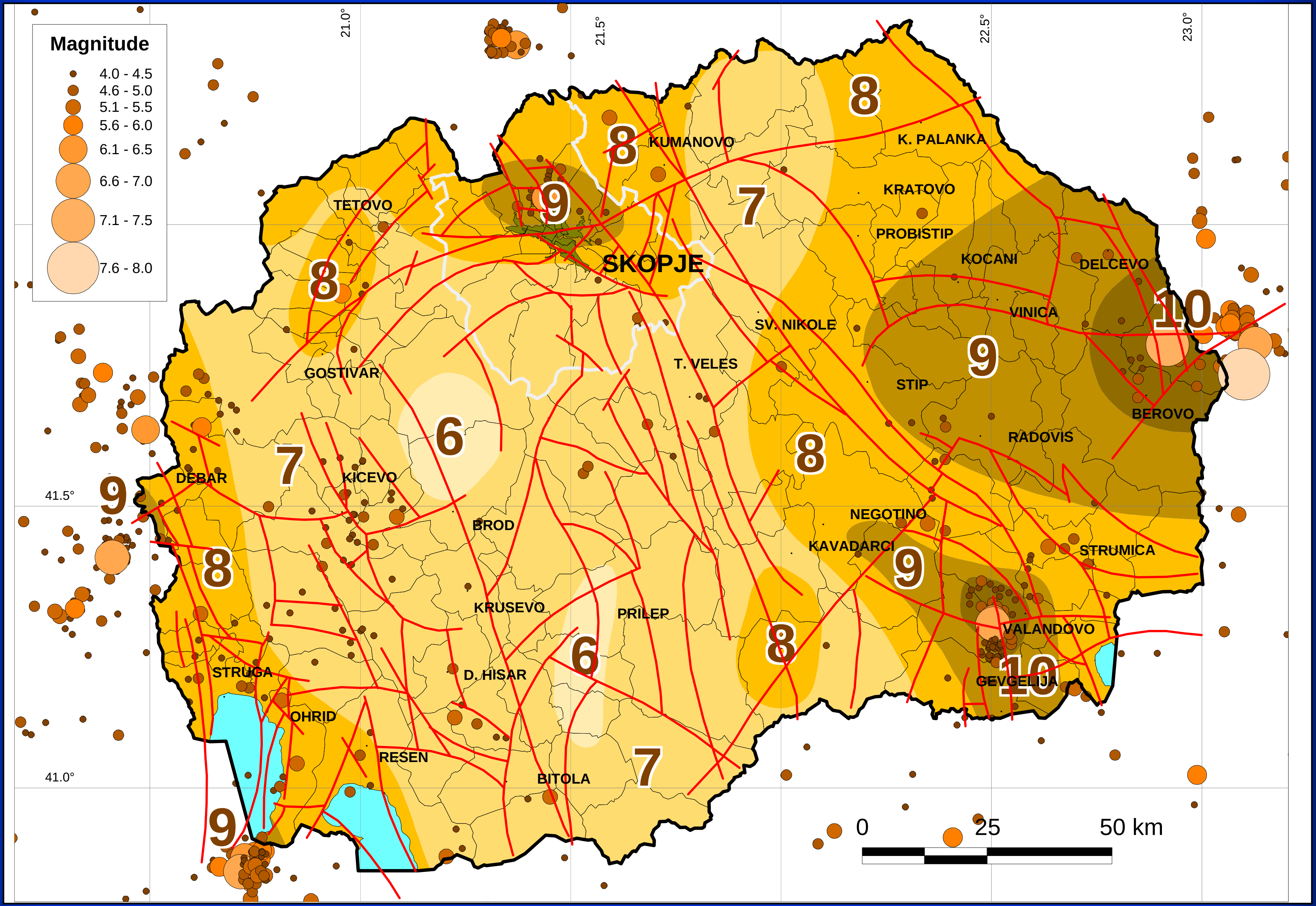
(6) structural response of different types of buildings and structures including soil-structure interaction.

The selection of detailed locations for establishment of these instruments makes it possible to obtain records on :

1) bedrock ,
2) on a surface of characteristic soils (alluvial and diluvia sediments ,
3) on structures (multistory buildings, dams, etc.).

The instrument distribution, of both accelerographs and seismoscopes was made following this basic concept.

Seismotectonic and Maximum Observed Seismic Intensity Map



TECHNICAL REGULATION FOR SEISMIC MONITORING OF DAMS IN MACEDONIA - REQUIREMENTS

GROUP	DAM HEIGHT [m]	MIN. NUMBER OF INSTRUMENTS		
		SEISMOLOGICAL STATION		STRONG MOTION INSTRUMENT
		THREE COMPONENTS	SINGLE COMPONENT	
1	H > 60	1	2	4
2	60 < H > 40	1	-	3
3	H < 40	-	-	2

Table 2. Distributions of instruments

Instruments	Location	
	Accelerographs	Seismoscopes
On bed rock	9	9
On characteristic soil	16	34
On structure	104	11
Total	129	54

Location	Bornhole
3	8

Table 3: Instrumented structures

Structures	Number of Instrumented Structures	No. of Instruments	
		Accelerographs	Seismoscopes
High-rise buildings	11	32	4
Dams	13	52	7
Bridges	3	20	/
Total	**22**	**104**	**11**

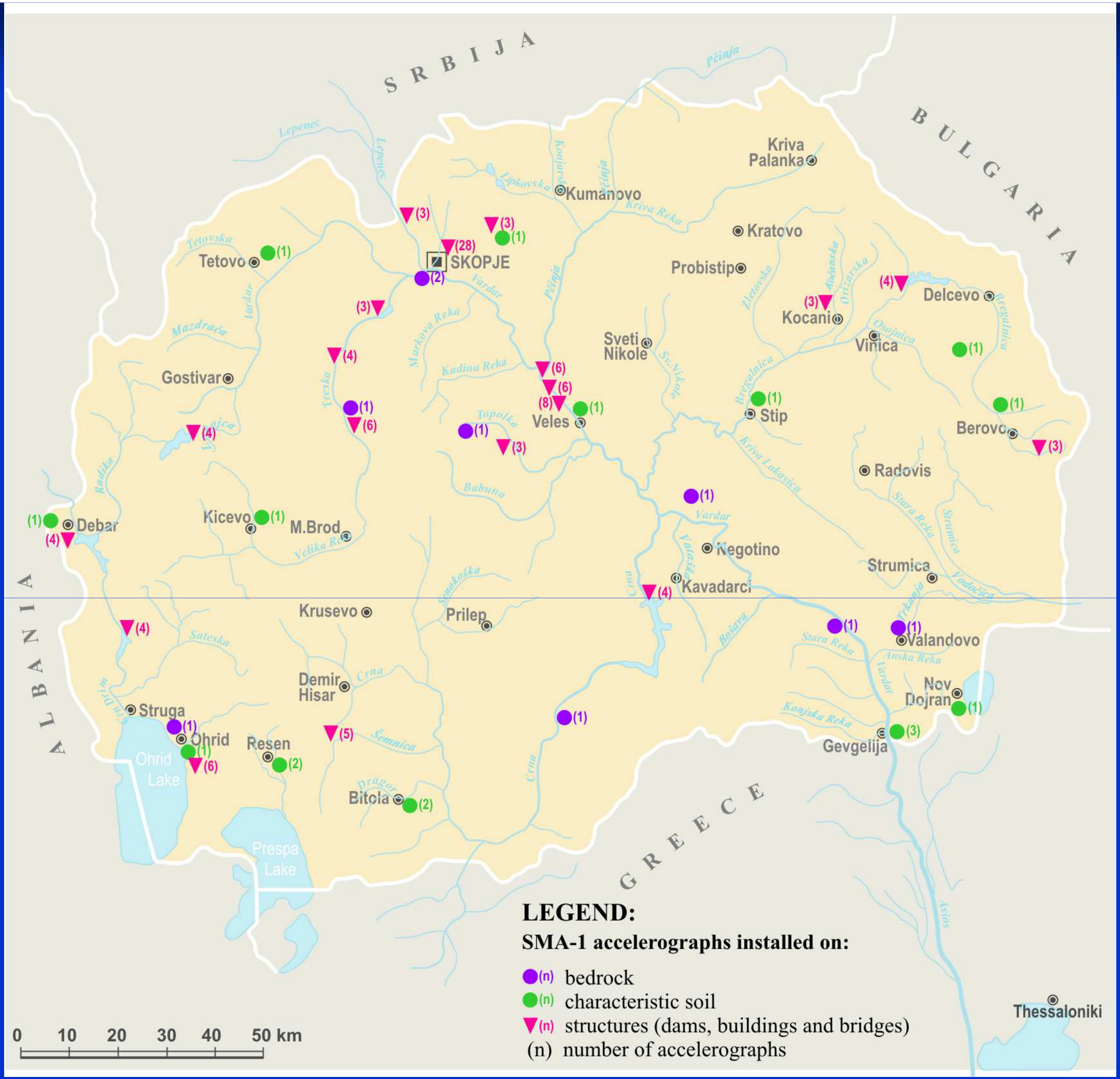
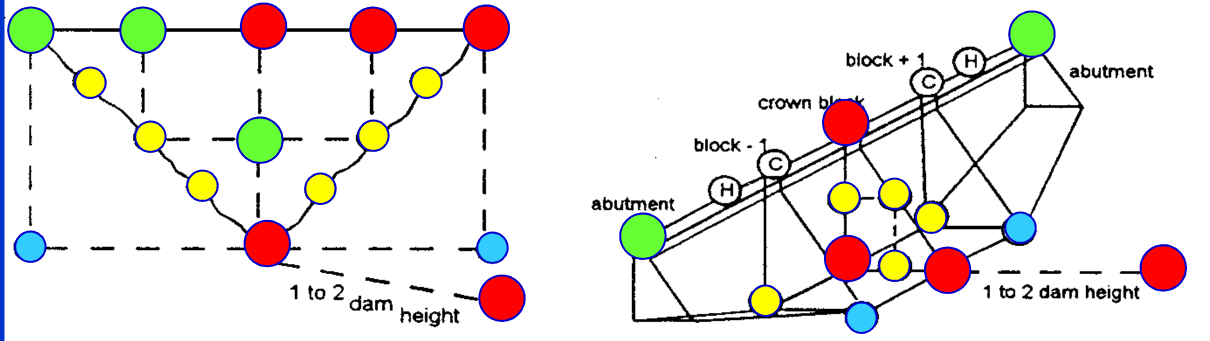
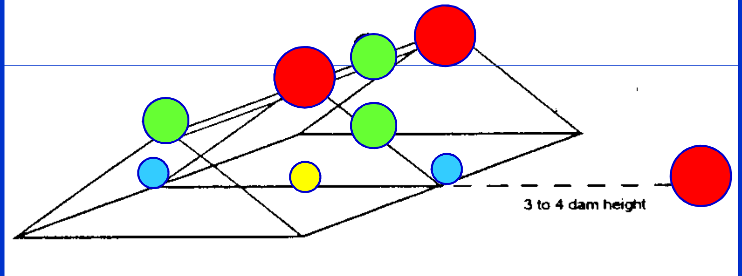


Fig. 1. Strong-Motion Network on the Territory of Republic of Macedonia

Instrumentation of dams





a. Arch dams;
b. Gravity dams;
c. Embankment dams.

A - minimal observation of the excitation and of the response of the dam is obtained
B & E - more detailed observation.
D & G – effective input motion.
F – wave propagation (galleries in the foundation).
H - (crest instruments at the quarter points) - three-dimensional response of the dam
C or B - provides for the free-field motion.

(taken from G.R.Darbre)

Investigation prior to constructed of dam:

- local network of seismological stations - seismographs,

  (at least 2 years prior to the beginning of construction of the dam and should continue to the end of filling of the reservoir, i.e., for a minimum of 5 years after putting the dam into effect).

- Instruments for recording of strong earthquakes – accelerographs

  (basic data on its behaviour during an earthquake, i.e., making decisions about further exploitation or the need for repair of the dam immediately after the occurred earthquake.)

The parameters for elaboration of a seismic monitoring project can be classified into two groups:

- **Parameters implicitly defined in the Book of Regulations on Seismic Monitoring involving general technical regulations;**
- **Parameters determined by the individual characteristics of each structure.**

The second group are defined for each structure, could be defined on the basis of:

- **Seismic regime of the micro- and the macro-region;**
- **Dynamic and strength characteristics of the local soil;**
- **Mode of foundation;**
- **Type of dam and dynamic characteristics of the dam;**
- **Soil-foundation-structure interaction;**
- **Geometrical shape of the dam**
- **Dam lake capacity;**
- **Area of the dam lake.**

Data obtained by means of the seismic monitoring equipment may serve for multiple purposes, first of all, they are very useful for:

(1) verification of previous computations and analyses;

(2) analysis of the stress state and level of safety of the structure after the earthquake effect and

(3) optimization of the process of design of future structures.

INSPECTION PROCEDURE:

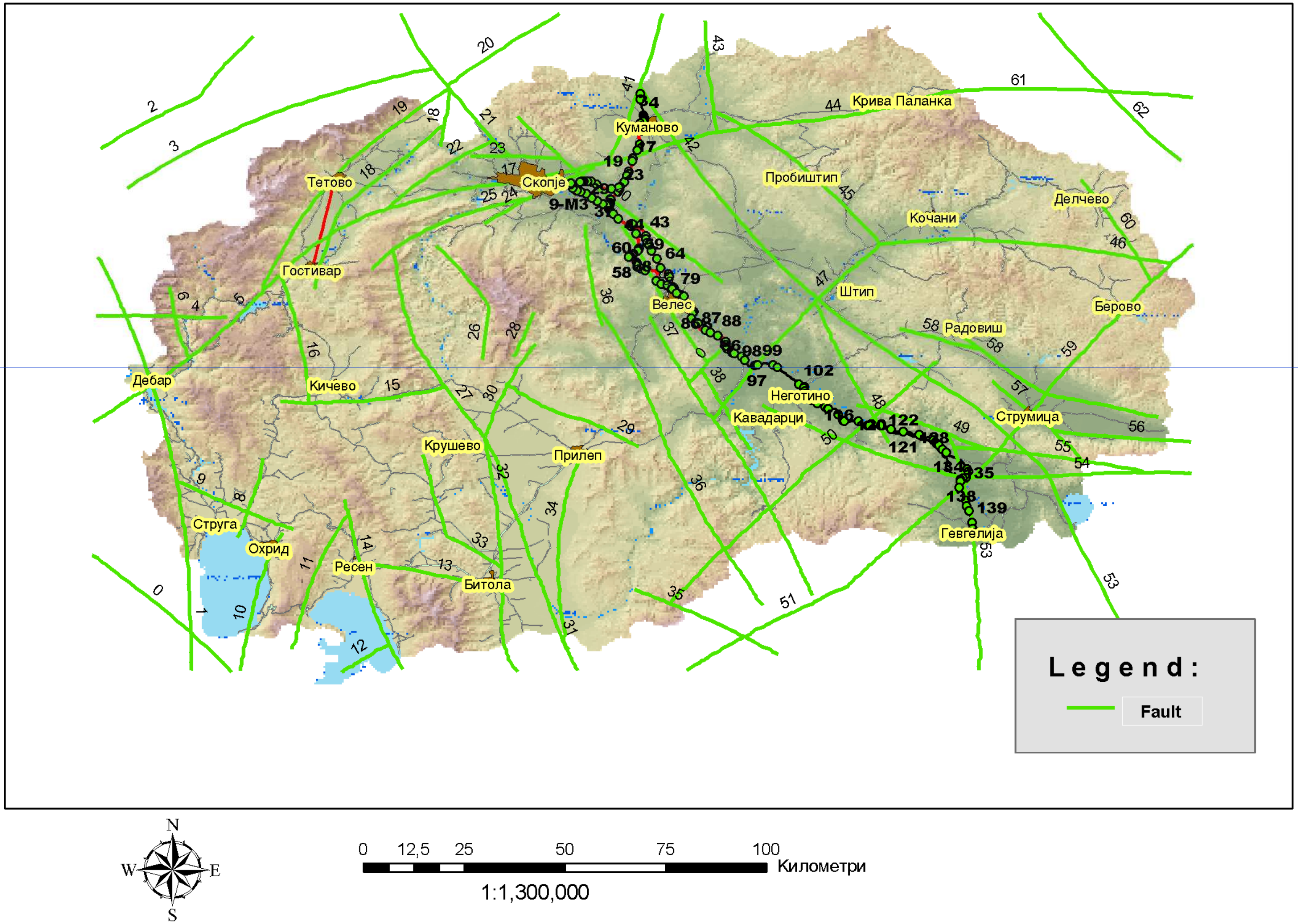
- **an immediate inspection by the dam operator (dam tender), and**
- **followup inspection(s) by dam engineering professionals.**

IMMEDIATE INSPECTION FOLLOWING EARTHQUAKE

If an earthquake is observed at or near a dam,

- **with a Richter magnitude of 4.0 or greater within a 25km radius,**
- **with a Richter magnitude of 5.0 or greater within 50km,**
- **with a Richter magnitude of 6.0 or greater within 80km,**
- **with a Richter magnitude of 7.0 or greater within 125km,**
- **with a Richter magnitude of 8.0 or greater within a 200km radius from the site**

Seismic Monitoring of Bridges

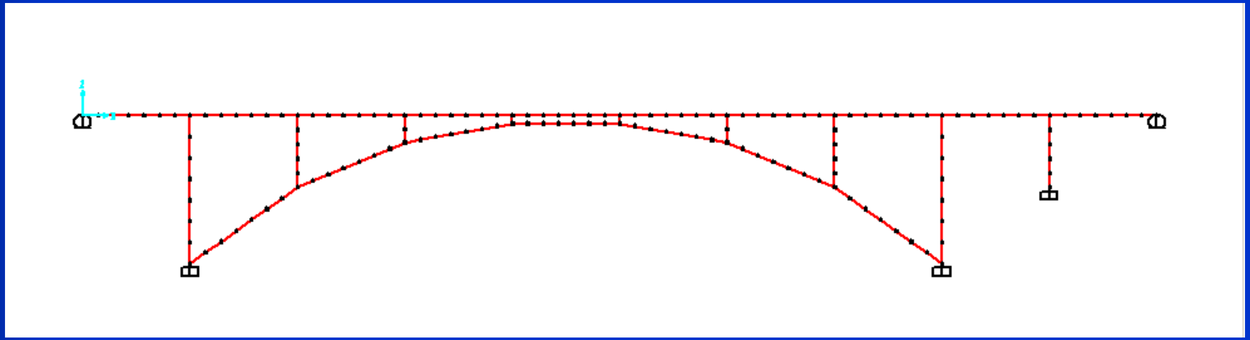


Seismic Monitoring of Bridges

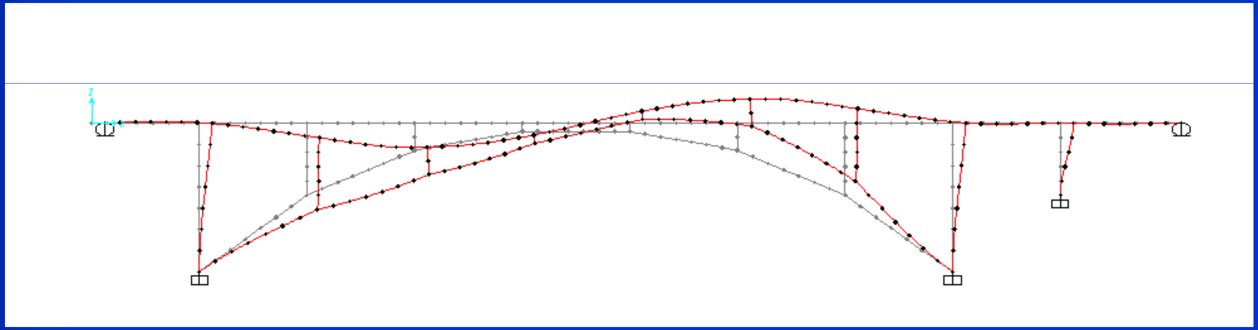
Number of instruments:

- Structural system;
- Length of bridges;
- Different in geological and topological characteristic of foundation.

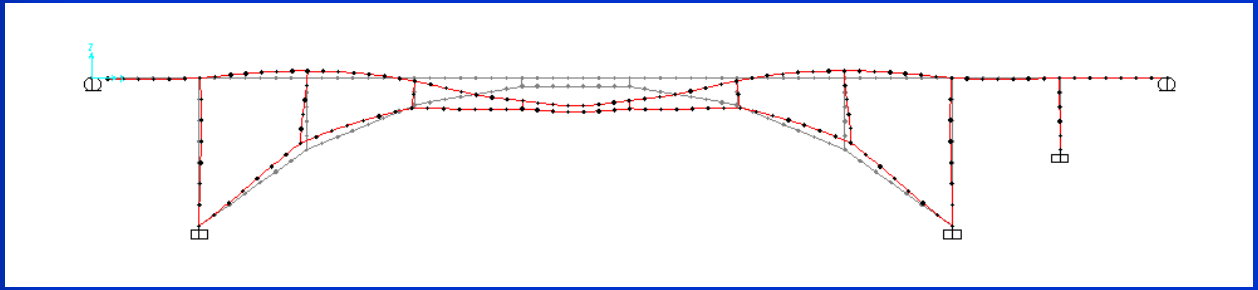
Location of instruments is defined according to modal analysis of the bridges using SAP2000



Matematical model

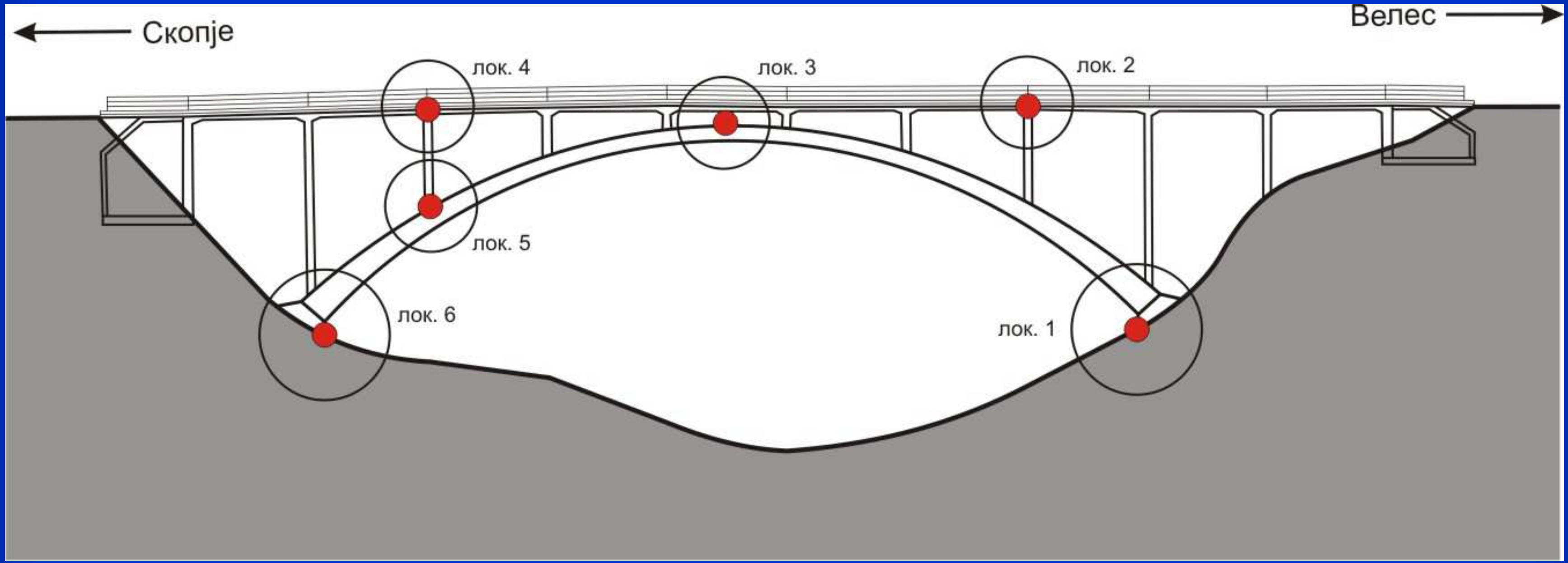


1st mode



2nd mode

Seismic Monitoring of Bridges



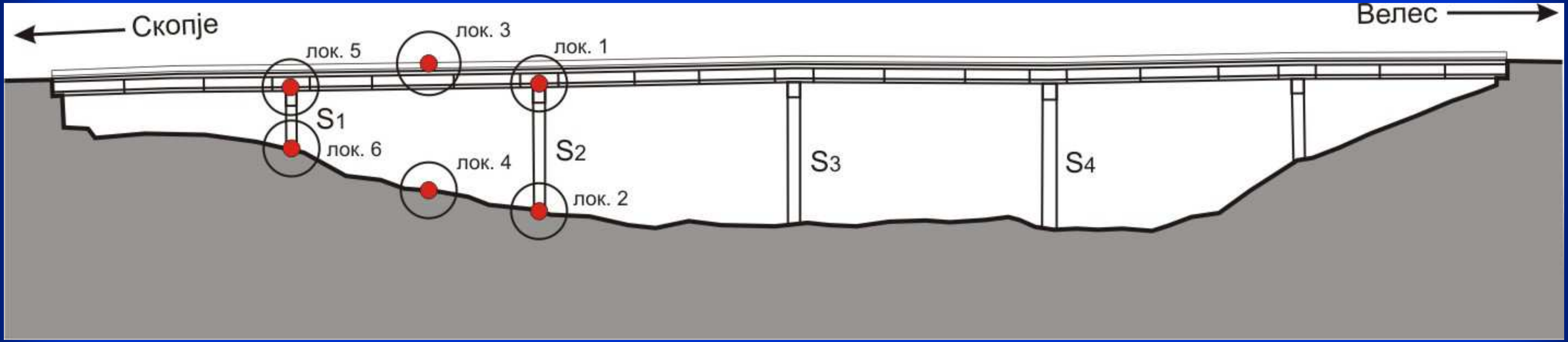
Viaduct Arch Bridges;

High motorway: M-1 right line km 56+022 km,

Total length L=42 m

Seismic Monitoring of Bridges

Seismic Monitoring of Bridges



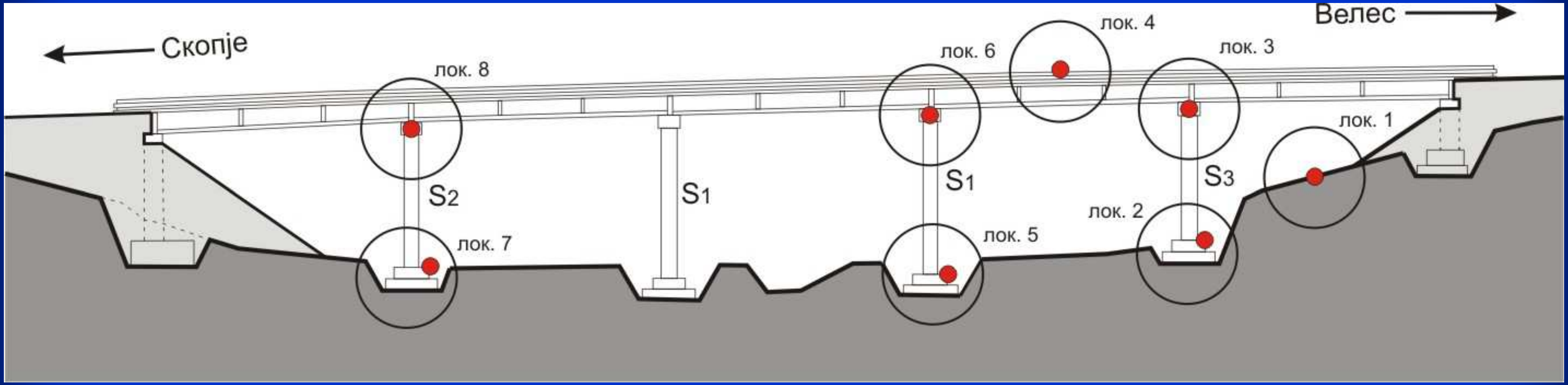
Viaduct Veterski dol;

High motorway: M-1 right line km 52.01km,

System: Continuous beam with 6 span L=112.4m

Seismic Monitoring of Bridges

Seismic Monitoring of Bridges



Viaduct : Durutovec

High motorway: M-1 right line km 68+504 km,

System: Simple beam with 5 spam L=130 m

Seismic Monitoring of Bridges



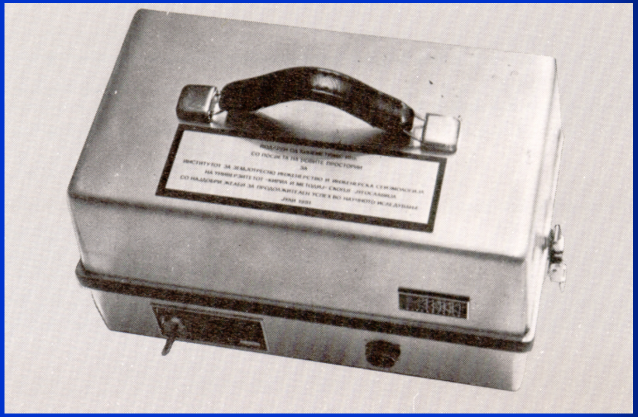



Seismic Monitoring of Bridges

Monitoring and recording Strong Motions

I - GENERATION:

- The first (the oldest) generation of accelerographs, which is still used, is based on application of analog optic recorders in different configurations, out of which the most present is the variant of accelerographs with a wide film track. These accelerographs use accelerometers with a natural frequency of up to 25 Hz, which globally does not satisfy the criteria pursuant to the rulebook.
- The processing of the records is a time consuming and costly process.
- The maintenance is relatively costly, while the producers' support regarding spare parts is very poor.

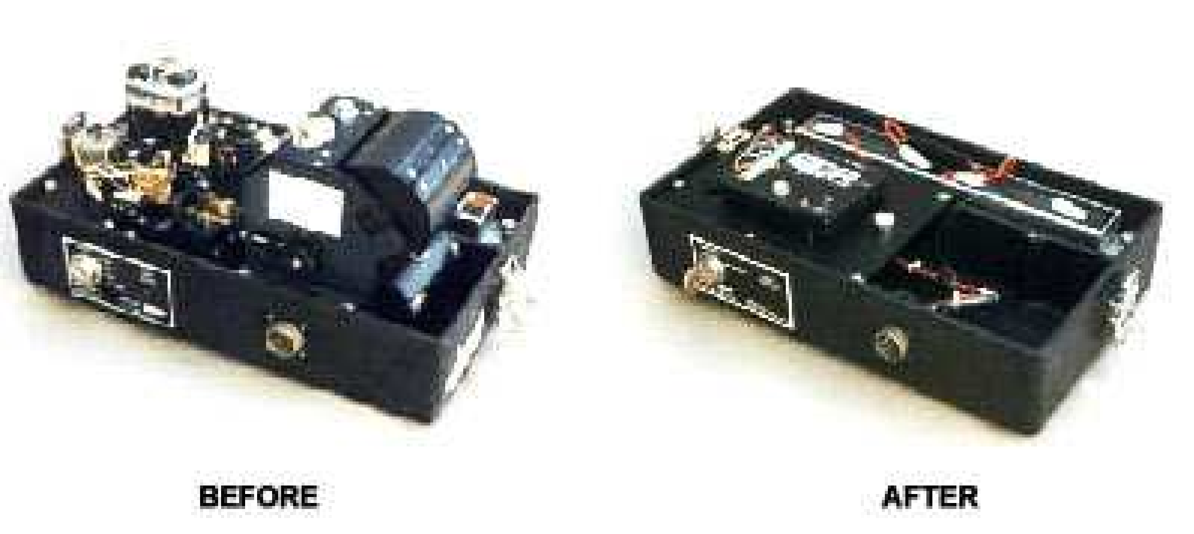


Instrument No. 5000, Juli 1981, present from Kinemetriks

Monitoring and recording Strong Motions

II - GENERATION:

- **The second generation of accelerographs is characterized by two important technological improvements in respect to the first one. An analog magnetic tape is used as a recording medium and accelerometers of higher natural frequency of up to 50 Hz are incorporated.**
- **The processing of data is carried out by a costly computerized equipment.**
- **The maintenance is relatively costly, while the support of producers regarding supply of spare parts is very poor.**



Monitoring and recording Strong Motions

III - GENERATION:

- The third generation of accelerographs has only one important technological improvement in respect to the second one. Instead of analog magnetic cassettes and tapes, there are digital magnetic cassettes and tapes.
- Data processing is carried out by a costly computerized equipment.
- Maintenance is relatively costly, while the producers’ support as to supply of spare parts is very poor.

Monitoring and recording Strong Motions

IV - GENERATION:

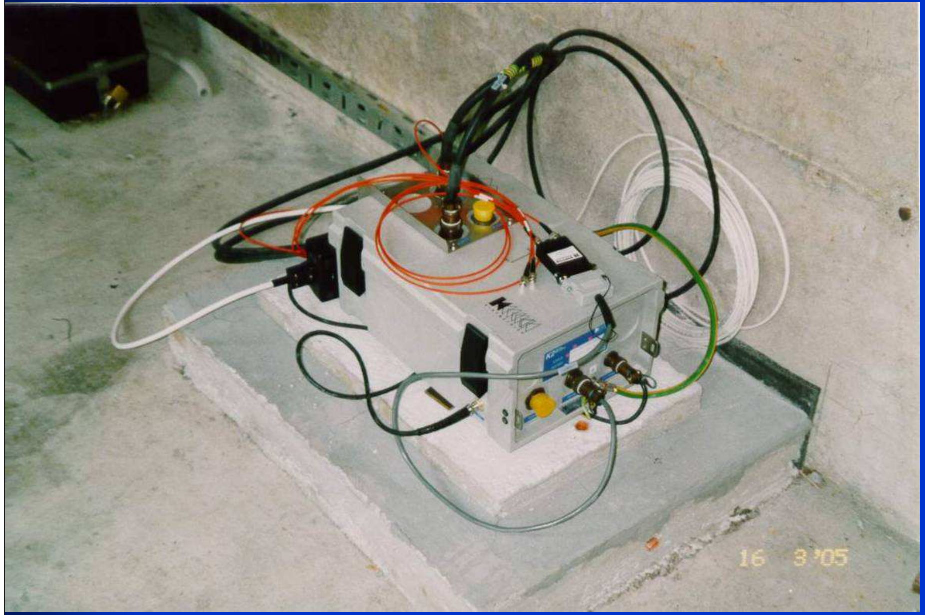
The fourth generation of accelerographs (solid state accelerographs) is characterized by important technological innovations. This generation of seismic instruments is based on application of the microprocessing technique. Important technological improvements made in this type of accelerographs compared with the previous three generations include:

- The control part is sophisticated, based on application of computer programmes and corresponding algorithms;
- The seismic starter represents a software algorithm, whose parameters are simply programmed and controlled;
- The recording medium can be any of the media that are applied in computers;
- The maintenance and the control are almost automatized and very much simplified;
- The access to data (calibration records and accelerogramems) is direct and simple (under programme control of a portable PC);
- No additional data conversion is needed;
- Archiving of original records is in the form of computer datafiles and is much simpler in respect to archiving of original records from other types of accelerographs;

The processing of data is carried out by a low cost computerized equipment.

Maintenance is relatively cheap, while the support of producers regarding supply of spare parts is very good.

Monitoring and recording Strong Motions



Real Time Strong Motion Network

- 3D Real Time Strong Motion Network in Ohrid (1976)
  - 9 in Boreholes
  - 4 on Free Field
  - 6 on Structure

- Real Time Strong Motion Network (2010)
  - 13 GURALP Instruments covering territory of RM

Real Time Strong Motion Network – 3 D Ohrid Network

Commencement 1976

Realization in three phases:

- Phase I (1980 – 1985):
  - Investigations: (Geotechnical, Geophysical, Hydrotechnical)
  - Installation of the entire array
- Phase II (1986 – **1988**):
  - Testing (excitations, field forced vibration, frequency range 2 – 40 cpc)
- Phase III (1989 – …….):
  - Exploatation of the network
  - Several earthquakes (M = 5.0 – 5.5; Albania, Greece, Macedonia)

Real Time Strong Motion Network – 3 D Ohrid Network

The Ohrid Lake Three Dimensional Strong Motion Array (OhL-3DSMA) covers the Ohrid region and consists of an 57-channel network of three axial accelerographs FBA-3 and FBA-3DH, three-axial seismic starters TS-3 and DSA-3 recorders. Regarding the goals and expected results, as the most suitable location was chosen the eastern part of the City of Ohrid.

The network consists of five individual set of instruments that are connected to a standard time code receiver.

Individual systems are located:

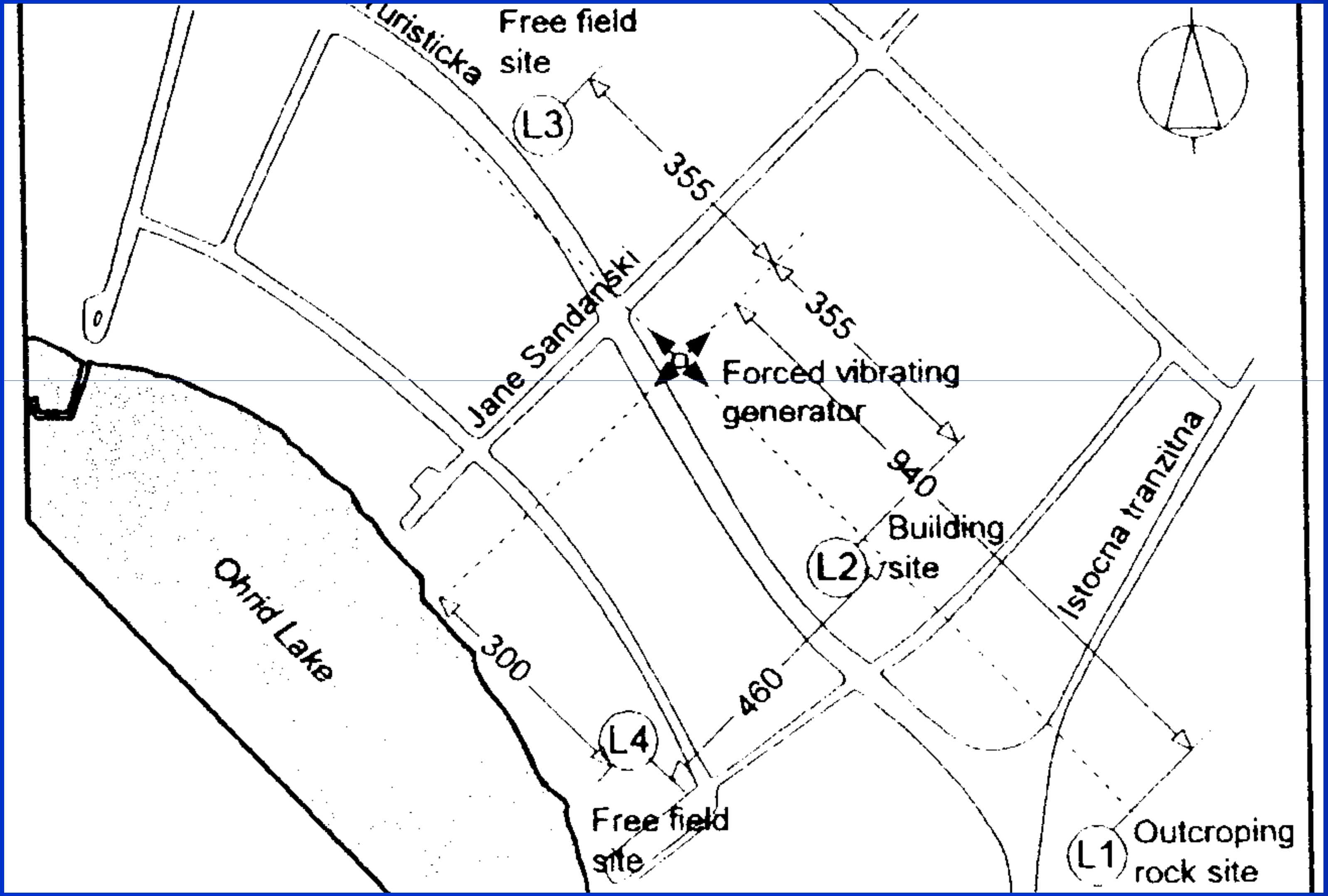
- bedrock (1),
- characteristic soil (3) and
- building (1).

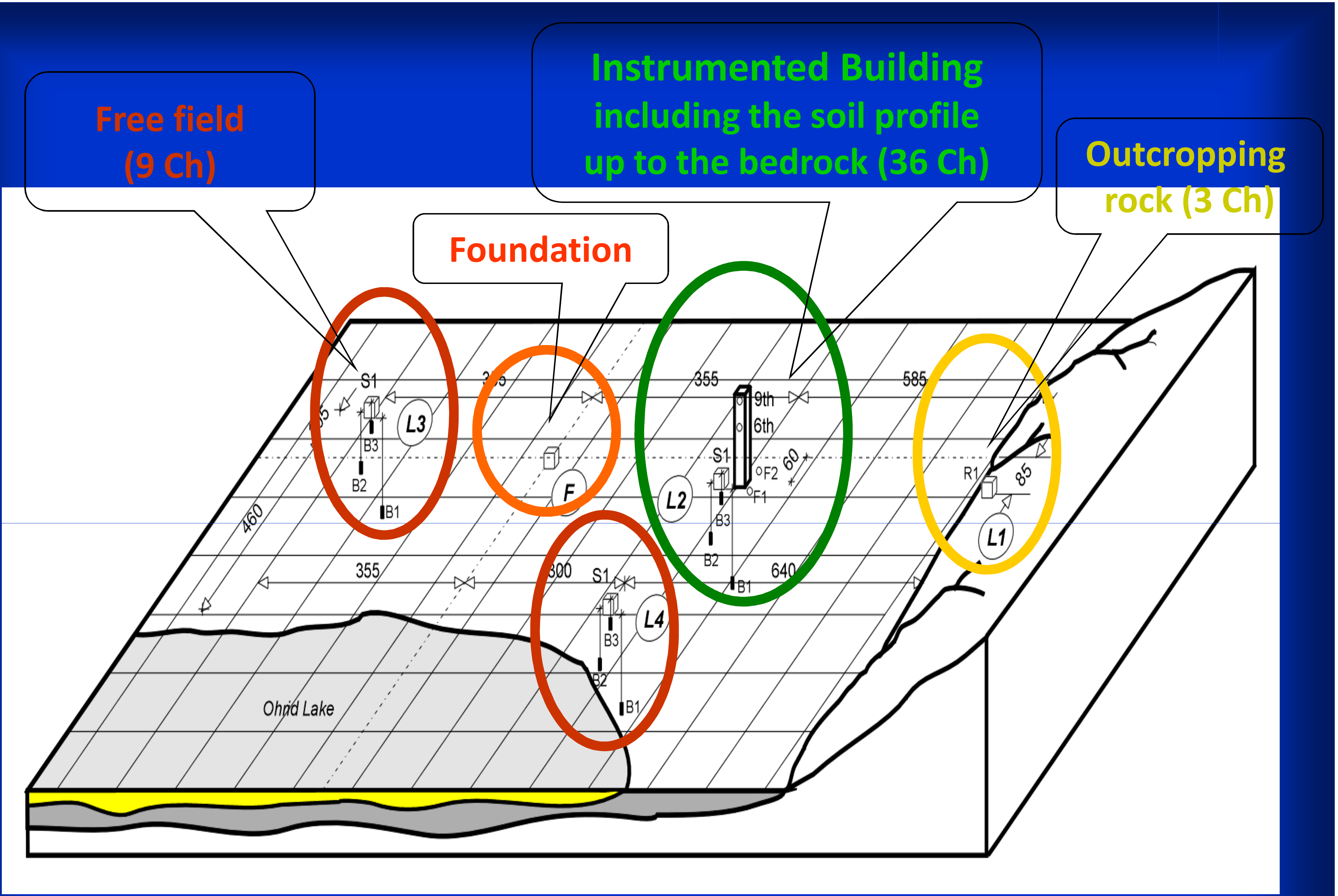
Real Time Strong Motion Network

Ohrid Lake Three Dimensional Strong Motion Array

Real Time Strong Motion Network

Ohrid Lake Three Dimensional Strong Motion Array





Free field
(9 Ch)

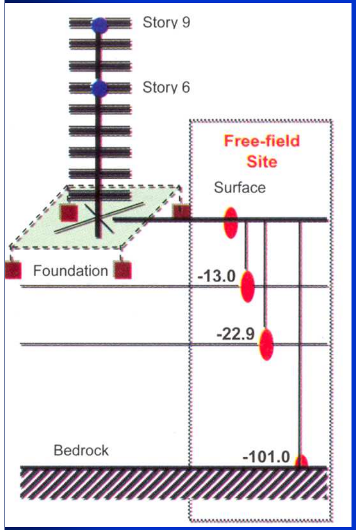
Foundation

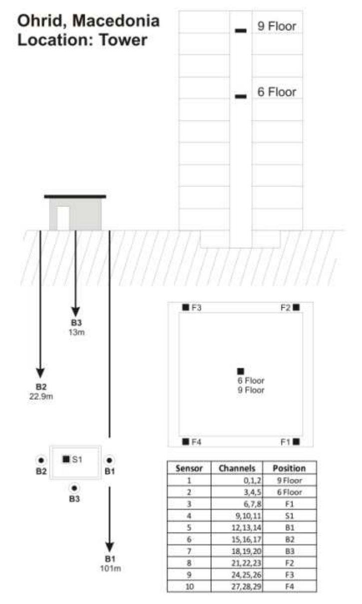
Instrumented Building including the soil profile up to the bedrock (36 Ch)

Outcropping rock (3 Ch)

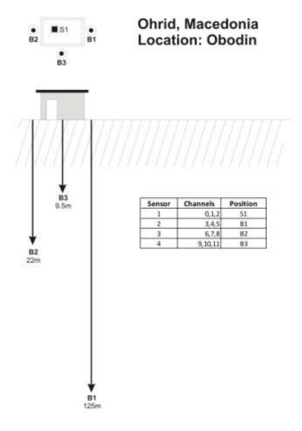
DENSE 3D STRONG MOTION ARRAY

OHRID LAKE VALLEY





Sensor	Channels	Position
1	0,1,2	9 Floor
2	3,4,5	6 Floor
3	6,7,8	F1
4	9,10,11	S1
5	12,13,14	B1
6	15,16,17	B2
7	18,19,20	B3
8	21,22,23	F2
9	24,25,26	F3
10	27,28,29	F4



Sensor	Channels	Position
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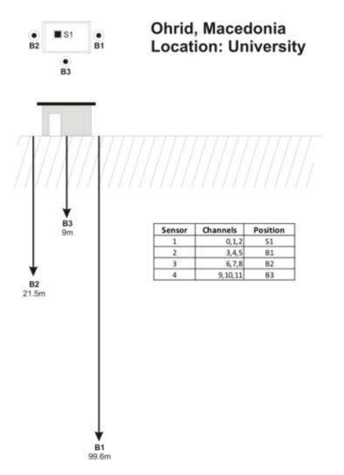
4	9,10,11	B3



Sensor	Channels	Position
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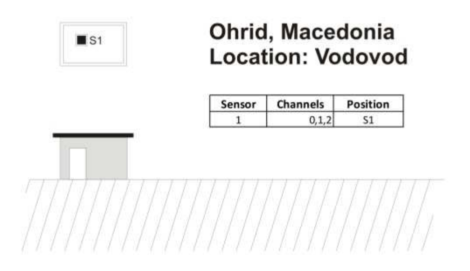
3	6,7,8	B2
4	9,10,11	B3

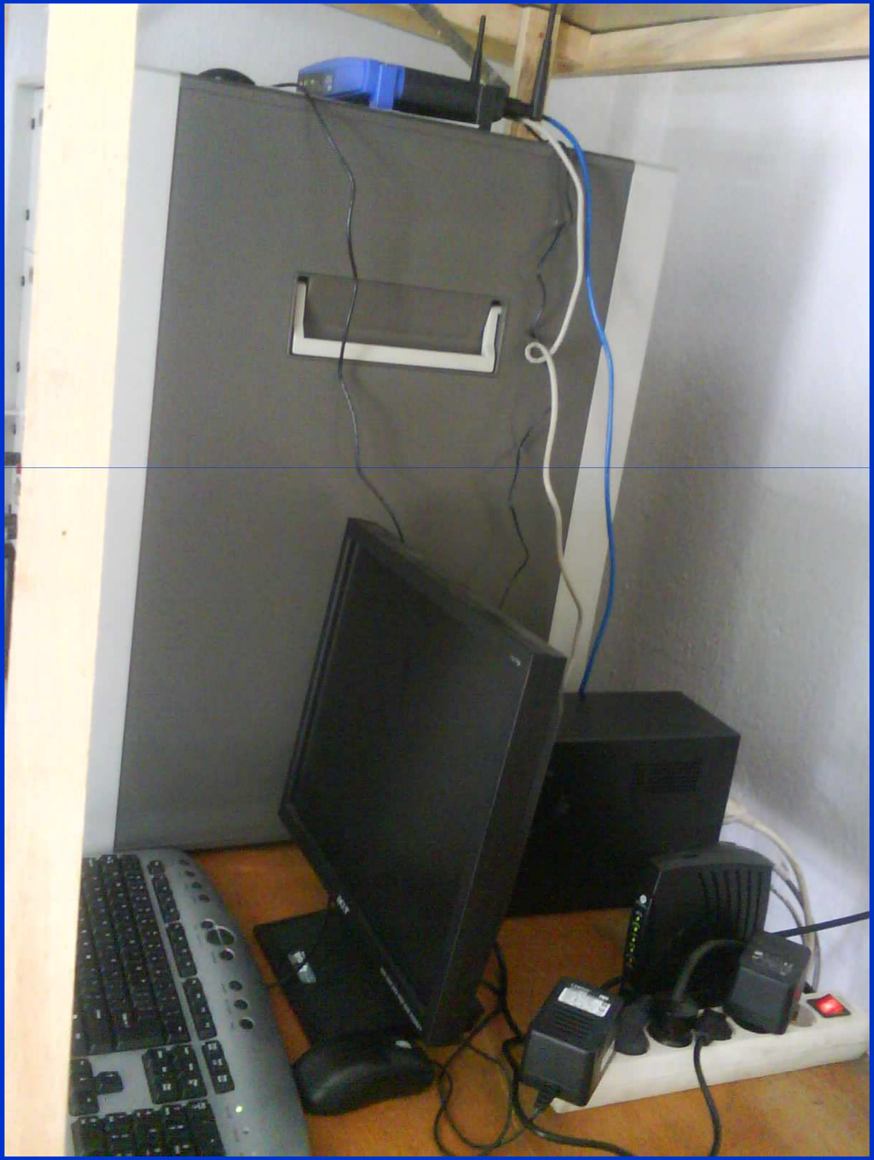


Sensor	Channels	Position
1	0,1,2	S1

	Location -1	Location - 2	Location -3	Location -4
Site Type	**Instrumented Building**	**Free - field**	**Free - field**	**Rock - outcrop**
Instrument Position				
Building	**2(6-th and 9-th story)**	**-**		**-**
Foundation	**4**	**-**		**-**
Surface	**1**	**1**	**1**	**1**
In-profile	**2 (-13.0 and -22.9m)**	**2 (-9.5 and -22.0m)**	**2 (-9.0 and -21.5m)**	**-**
Bedrock	**1(-101.0m)**	**1(-125.0m)**	**1(-99.6m)**	**-**
Total Number of instruments	**10**	**4**	**4**	**1**

Real Time Strong Motion Network

Ohrid Lake Three Dimensional Strong Motion Array



Real Time Strong Motion Network

Ohrid Lake Three Dimensional Strong Motion Array

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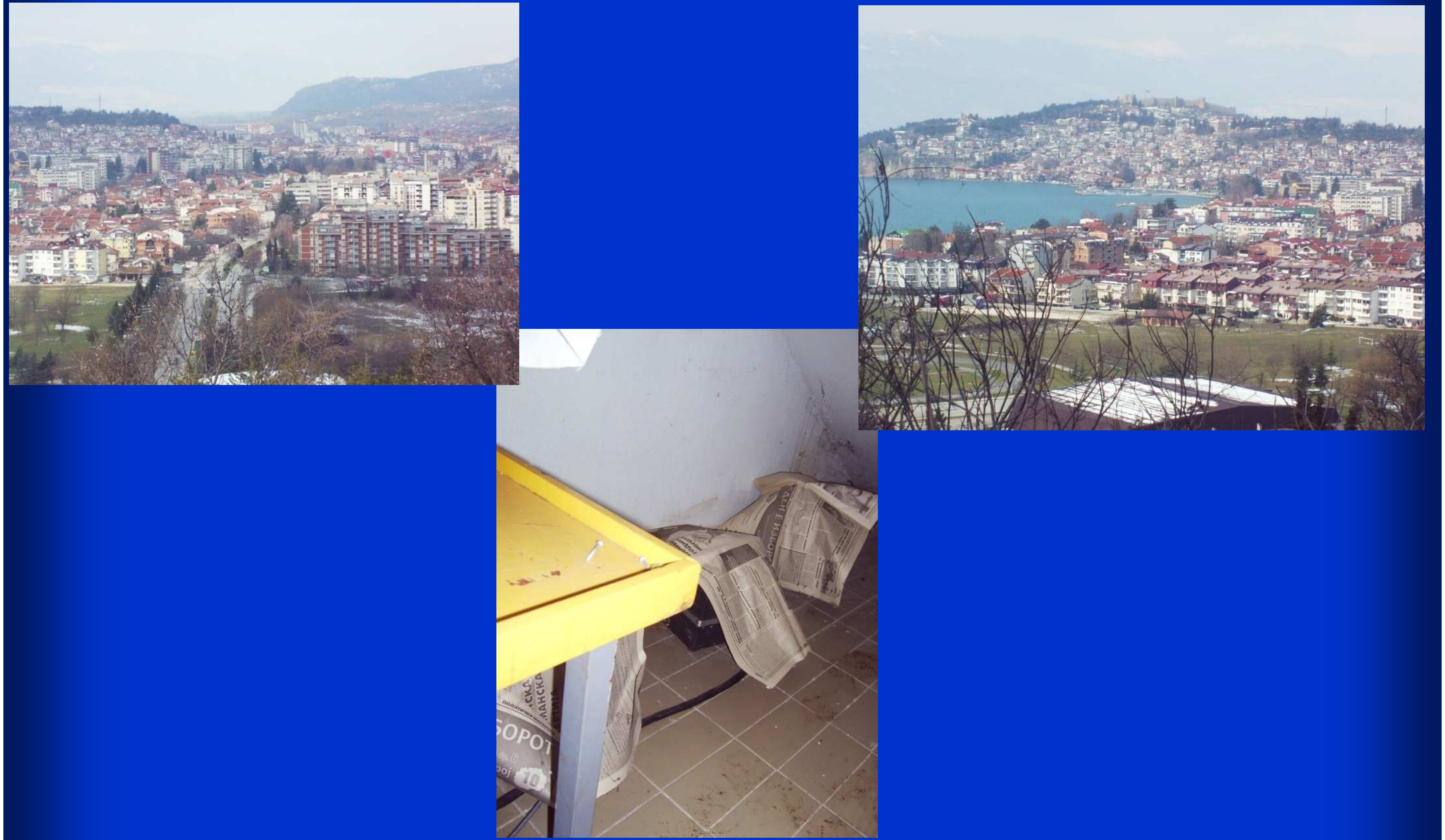

Real Time Strong Motion Network

Ohrid Lake Three Dimensional Strong Motion Array

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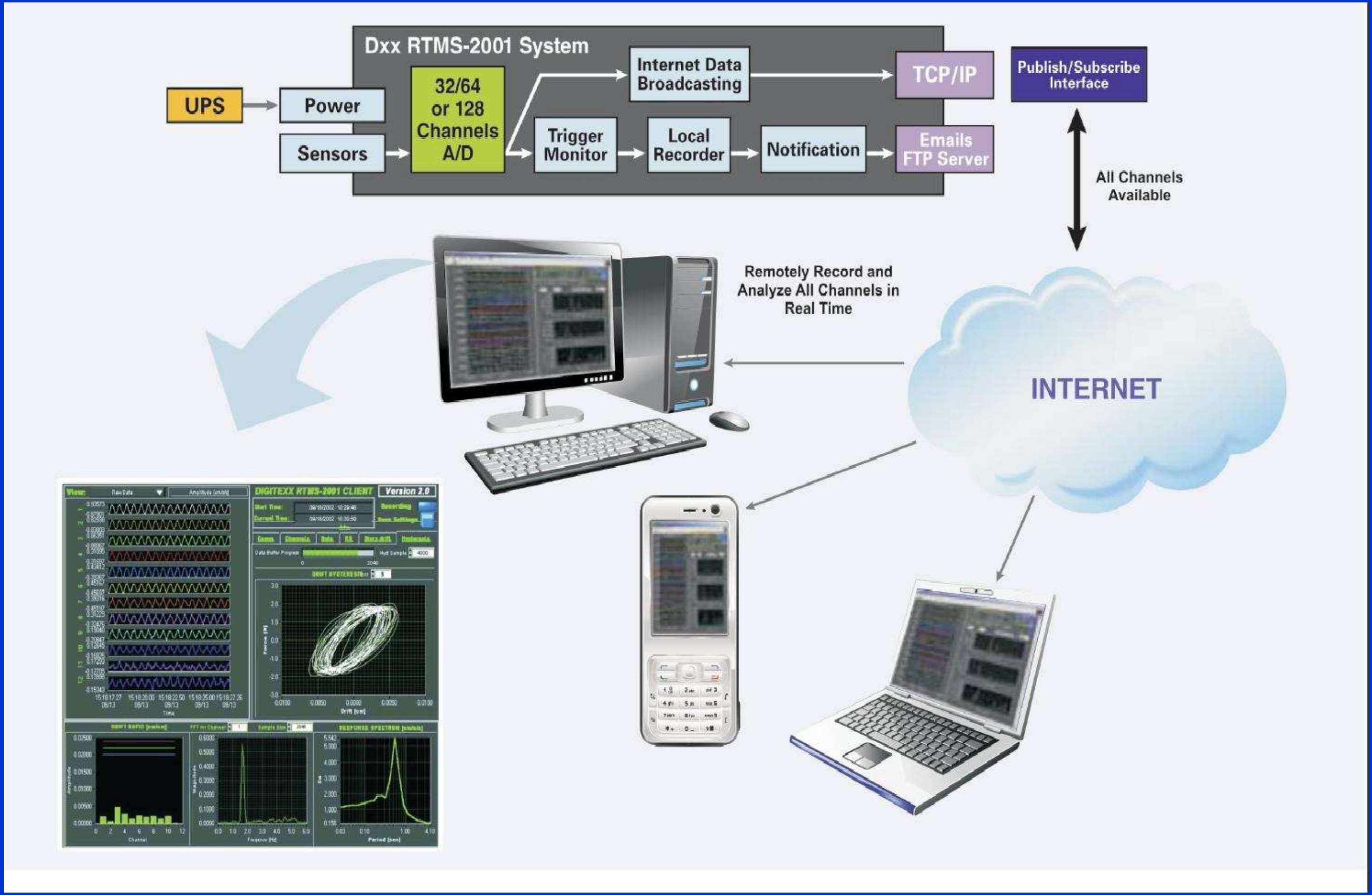
Real Time Strong Motion Network

Ohrid Lake Three Dimensional Strong Motion Array

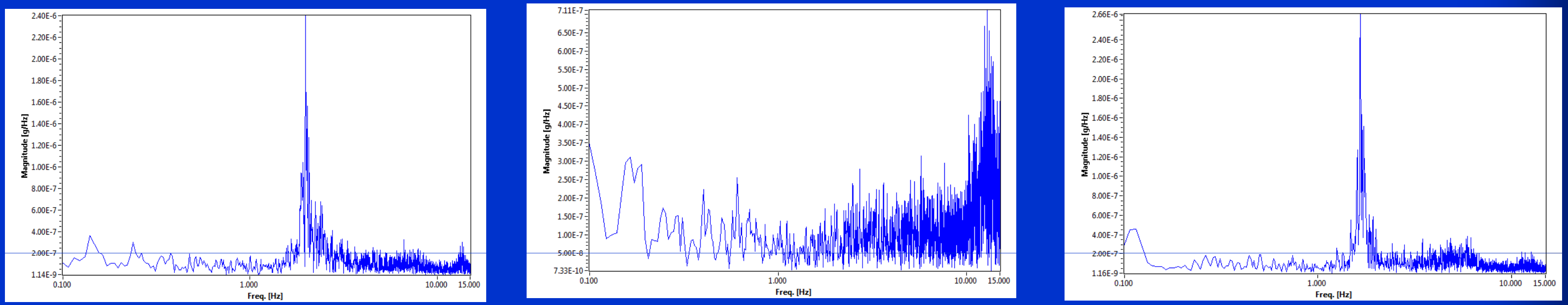
- Architecture of the multi-channel system



Real Time Strong Motion Network

Ohrid Lake Three Dimensional Strong Motion Array

- ❑ Fourier spectra for Ch1-Ch3: 9 floor (components: X-direction, Z-vertical, Y-direction)



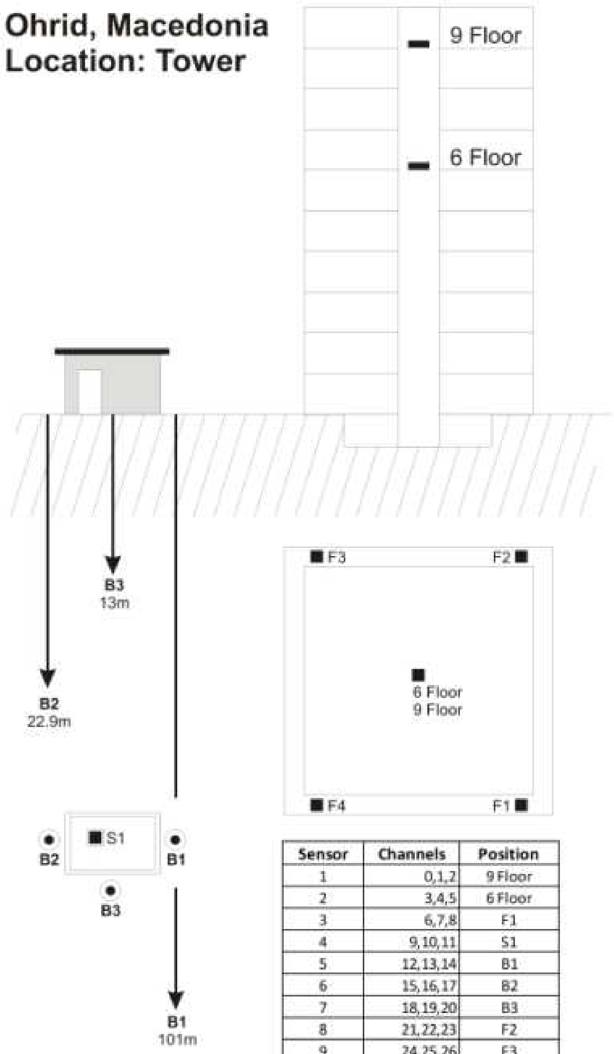
- ❑ Comparison of results from ambient vibration measurements from 1985 and 2010

Location	Component	Dec.1985	Jun.2010
9-th Floor	P1	2,08	1,98
	P2	1,76	1,65
6-th Floor	P1	2,08	1,98
	P2	1,76	1,65

Real Time Strong Motion Network

Ohrid Lake Three Dimensional Strong Motion Array

Ohrid, Macedonia
Location: Tower



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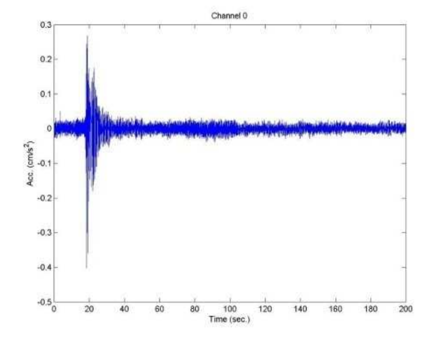
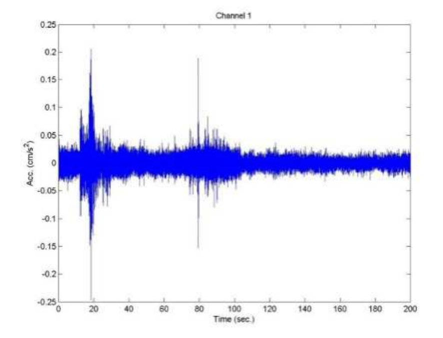
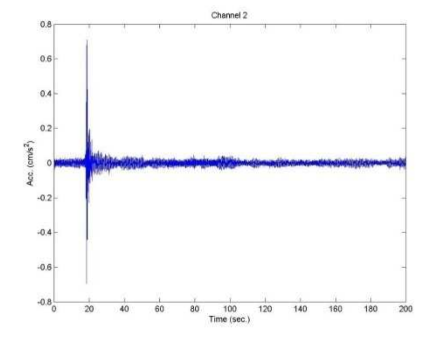
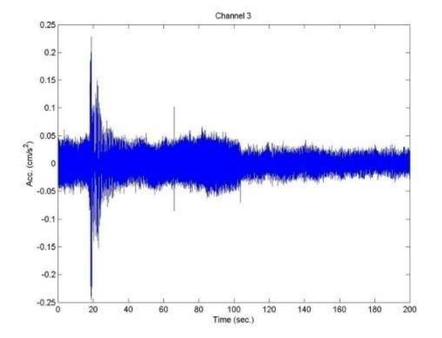
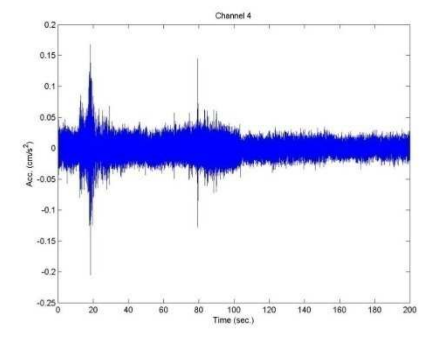
6	15,16,17	B2
7	18,19,20	B3
8	21,22,23	F2
9	24,25,26	F3
10	27,28,29	F4

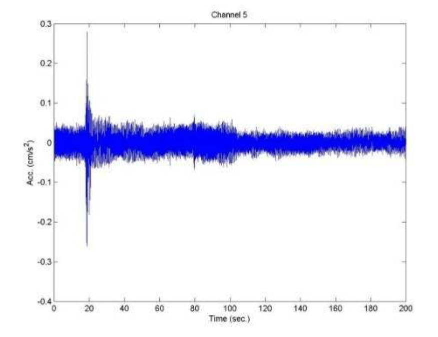








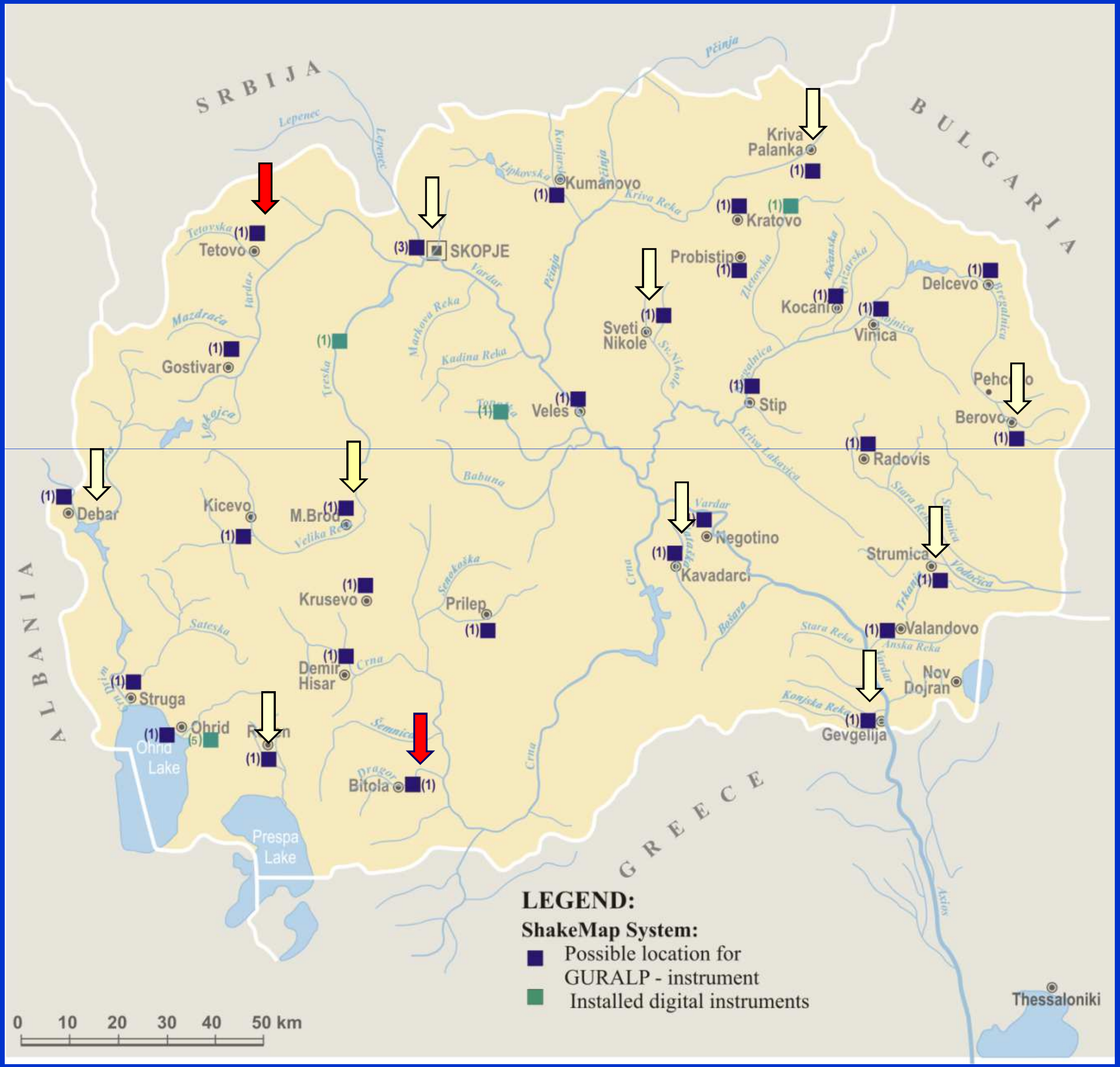




Real Time Strong Motion Network

- ☐ UKIM-IZIIS in colaboration with CMC (Crisis Management Centre) started an iniative to implement the Shake Map system in Republic of Macedonia
- ☐ CMC provides location for the instruments (GURALP) with necessary infrastructure (electric power, internet connection) in its premises throughout Republic of Macedonia
- ☐ UKIM-IZIIS chose 13 locations and installed GURALP instruments, as part of the ShakeMap System Network
- ☐ Definition and realization of two centers (one in UKIM-IZIIS, one in CMC Headquaters) for data acquisition and presentation

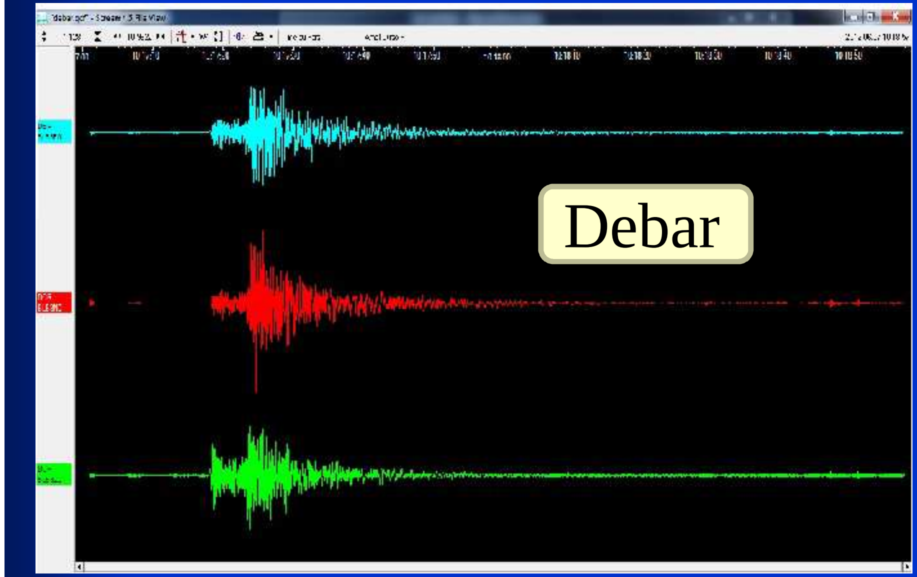
Real Time Strong Motion Network



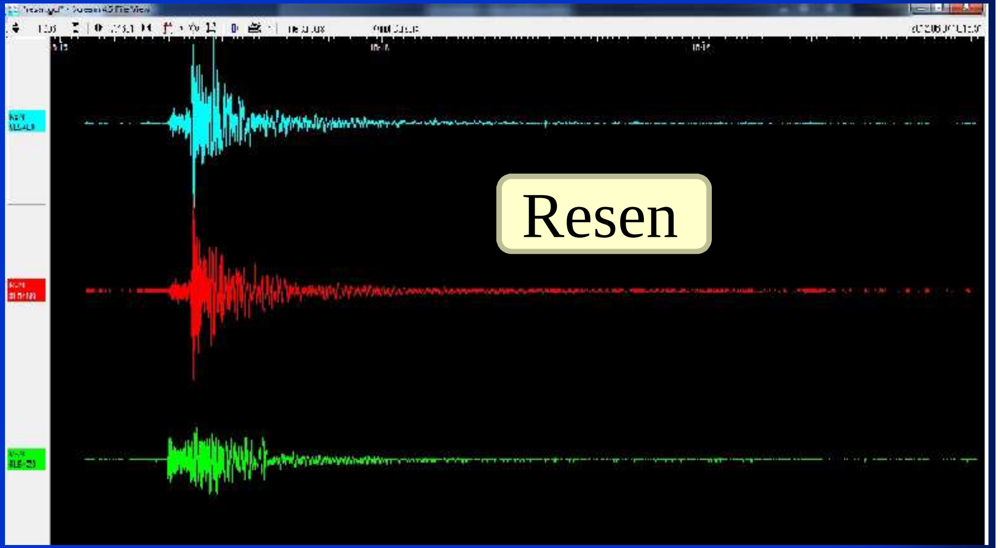
Real Time Strong Motion Network

- **Responsible authorities** for search and rescue operations wants rapid information on areas affected;
- **Government and Emergency** Management need to know the likely financial impacts;
- **Consulting Engineers** need to know the effects on structures and how close to design limits the structure has endured;
- **Earthquake Engineers** want to know the parameters of the shaking;
- **Seismologists** want to know the details of the fault system that caused the event;
- **Media** want to know how the Public will be affected;
- **Business Leaders** need to know the likely affect on their multiple locations and campuses and the safety of their structures

Ohrid, Macedonia, 2012-06-07 10:17:14 (UTC);
Lat: 41.30; Lon: 20.90; ML 4.3

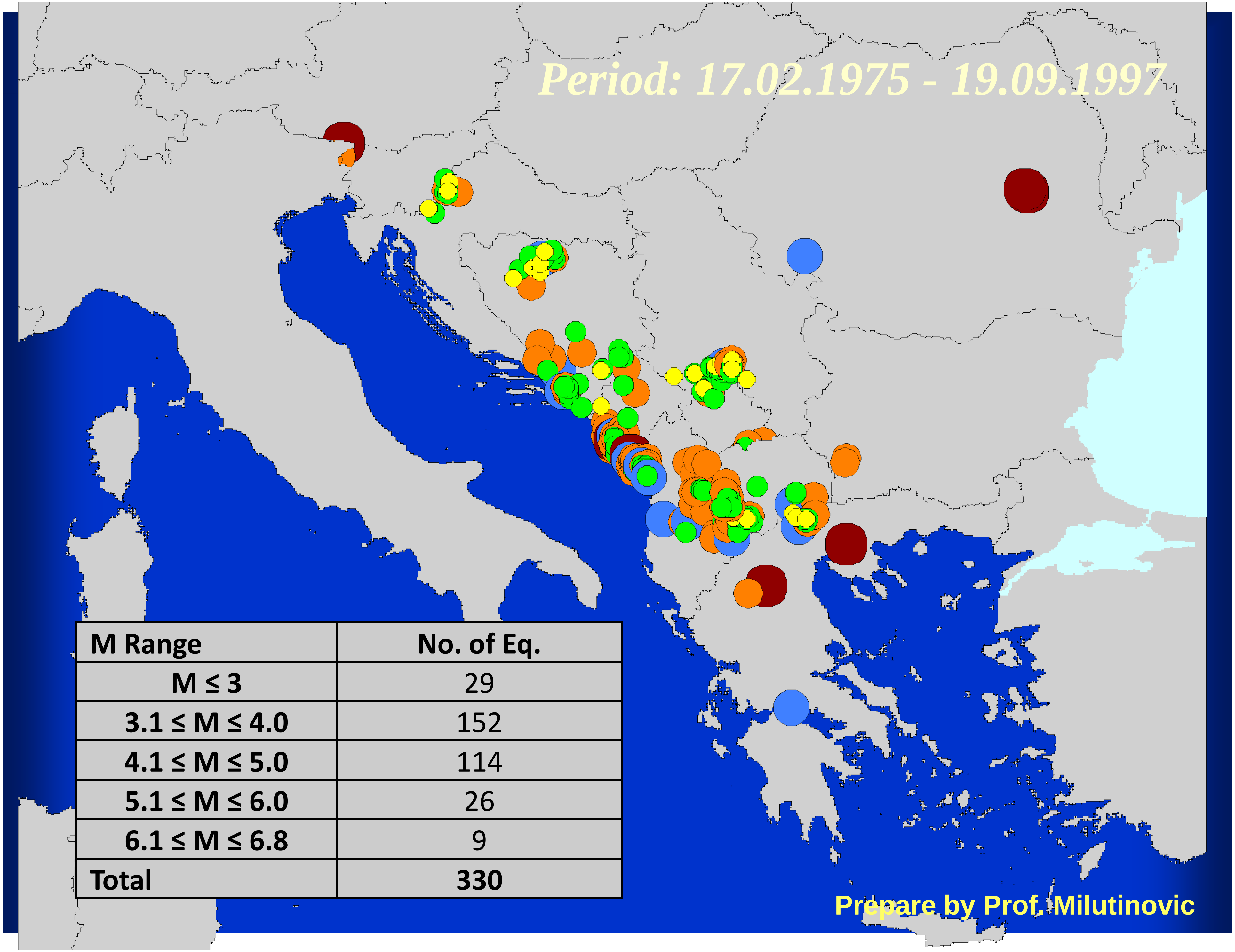


Debar



Resen

Period: 17.02.1975 - 19.09.1997



M Range	No. of Eq.
M ≤ 3	29
3.1 ≤ M ≤ 4.0	152
4.1 ≤ M ≤ 5.0	114
5.1 ≤ M ≤ 6.0	26
6.1 ≤ M ≤ 6.8	9
Total	**330**

Prepare by Prof. Milutinovic

Table 4. Review of recording / processing record (IZIIS – database)

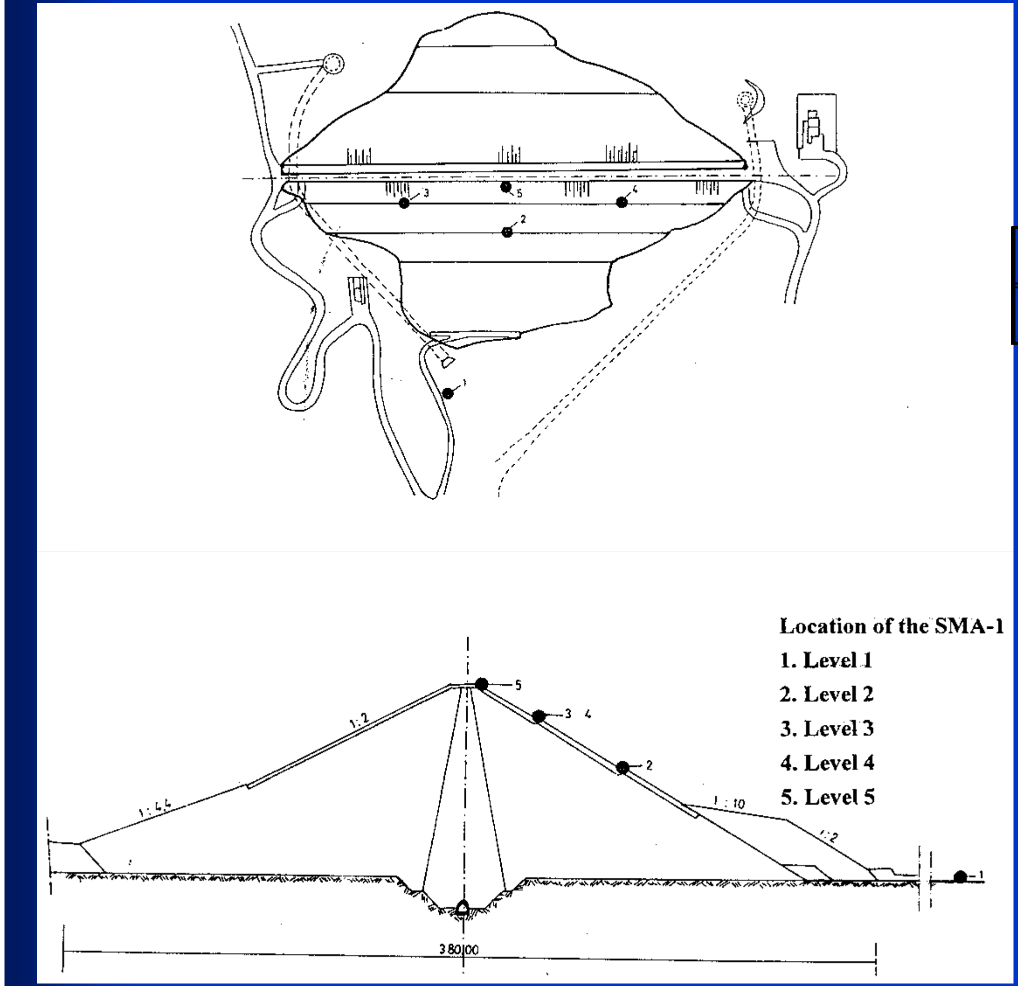
Year	No. record accelerograms	Cum. No	No. Processing	No. Processing (USC)	Cum. No: IZIIS/USC
1973	5	5	4	/	4/0
1974	16	21	5	6	9/6
1975	32	53	18	15	18/15
1976	39	92	19	22	46/37
1977	57	149	11	8	57/45
1978	62	211	6	11	63/57
1979	350	561	52	262	115/318
1980	125	686	2	64	117/382
1981	149	835	10	64	127/422
1982	58	893	4	17	131/439
1983	57	950	6	10	137/449
1984	50	1000	2	/	139/449
1985	27	1027	6	/	145/449
1986	39	1066	6	/	151/449
1987	3	1069	/	/	151/449
1988	31	1100	/	/	151/449
1989	14	1114	5	/	156/449
1990	39	1153	12	/	168/449
1991	15	1168	/	/	168/449
1992	38	1206	/	/	168/449
1993	/	1206	/	/	168/449
1994	78	1284	7	/	175/449
1995	25	1309	/	/	175/449
1996	11	1320	/	/	175/449
1997	17	1337	4	/	179/449
1998	21	1358	10	/	189/449
1999-2012	67	1425	6	/	195/449

USC - University of Southern California- Department of Civil Engineering

Table 5. Review of recording / processing record (IZIIS – database)

Period	1973 to 2012
Magnitude	2.5 to 7.2
Earthquake Occur	Albania, Greece, Bulgaria, Romania, Italy
No. of record acclerograms	1425
Processing	~200/~450
Location of instruments	61-locations (Geophysics investigation)
Investigation:	• Empirical relation ships for attenuation • Pick acceleration, velocity, displacement • Fourier amplitude spectrum • Time duration of strong motion part of accelerogram • Relation between Intensity scale and pick accel., vel. Disp.
Response spectra and Fourier amplitude spectrum have a multi-purpose use:	- design of structures and equipment of nuclear power plants; - verification of design seismic pararneters; - ground amplification; - soil-structure interaction; - dynamic response of the structure - structure-equipment interaction; - modifications, supstitutions and gualification of eguipment.

Data Base Usage



Location	Date	Time (GMT)	Coordinate		Io MSK-64	M Richter	Depth (km)
			N	E			
Bitola-Resen	01-09-1994	18h12'	41.13 o	21.24 o	VII	5.2	23

LOCATION	Comp. N40W Acc. (cm/s/s)	Comp. N50W Acc. (cm/s/s)	Comp. UP. Acc. (cm/s/s)
Dam Crest	-246.7	166.3	179.9
Loc-2 Berma - I Central Part	-244.3	-149.4	107.9
Loc-3 Berma -II Left Side	199.9	103.2	216.8
Loc-4 Berma -II Right Side	313.1	-161.9	128.6

Fig. 1 Seismic monitoring on Strezevo Dam. Location of instruments

CONCLUSION

The installation of networks for recording of strong earthquakes and the results which are obtained from them, has become an common point, in the earthquake engineering practice and has considerable contribution to the overall activities for seismic risk reduction of existing urban media and for the minimizing of the damage to these structures under the effect of disastrous earthquakes.