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STRONG MOTION INSTRUMENTATION OF DAMS IN MACEDONIA

SOME EXPERIENCE AND RESALTS

Vladimir MIHAILOV [1] and Dragi DOJCINOVSKI [2]

SUMMARY

A high dam is a particularly important element in seismic risk evaluation of the wider dam site area, on which a dam is planned to be constructed. A large number of high dams in the world and in our country are located within high seismicity zones, which were affected by string earthquakes in the past.
Seismic monitoring of the dams and the results which are obtained from them, has become an increasing need in the earthquake engineering and has considerable contribution to the overall activities for seismic risk reduction. The main objective in seismic monitoring of dams are to facilitate response studies that lead to improved understanding of the dynamic behaviour and potential for damage to structures under seismic loading. The application of the results is equally important both for the theoretical and fundamental investigations in the field of earthquake engineering and for application and practical investigations in the earthquake engineering.
Presented in this paper shall be some ideas and results from the seismic monitoring of the dams in Macedonia.

INTRODUCTION

The earthquake phenomenon involves almost always numerous problems which cannot be solved exactly due to the lack of instruments for recording earthquake intensities and response of structures. Without such a record, damage and behaviour of structures during strong earthquakes cannot be compared to the seismic design criteria nor proper decisions concerning rational repair and reconstruction could be made.

Data on the ground motion during earthquakes to which structures are exposed and behaviour 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. The irregularity in earthquake occurrence makes difficult the possibility to obtain immediately the most useful data.

[1] Prof. d-r. Head of section, Institute of Earthquake Engineering and Engineering Seismology (IZIIS), University "Ss. Cyril and Methodius" - P.O.Box 101, 1000 Skopje, Republic of Macedonia. Email: mihailov@pluto.iziis.ukim.edu.mk
[2] Assistant, M.Sc., IZIIS, Email: dragi@pluto.iziis.ukim.edu.mk

One of the possible ways to solve these problems is to establish a network of a greater number of instruments for recording ground motion and response of structures during strong earthquakes. The main objective in seismic monitoring of structures (high-rise buildings, dams, power plants, bridges etc.) is to facilitate response studies that lead to improved understanding of the dynamic behavior and potential for damage to structures under seismic loading.

In this paper attention will be concentrated on code requirements for instrumentation of structures, particularly dams, and results obtained from some earthquake records.

GENERAL BACKGROUND INFORMATION

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 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. The application of the results is equally important both for the theoretical and fundamental investigations in the field of earthquake engineering and for application and practical investigations in the earthquake engineering.

The rapid development of networks for recording of strong earthquakes during the last twenty years has made a considerable contribution to the knowledge of the investigators that the theoretical investigations should have experimental proof - in the considered records - on the basis of which relevant decisions can be made.

Considering these reasons, in the beginning of the 70s, networks of strong earthquakes recording instruments were installed in several seismic regions in the world (USA, Japan, Italy, former Yugoslavia and others). This example was later followed by several other countries (Mexico, New Zealand, Iran, Turkey, Greece and others) thus, at present, there is a relatively high number of such networks, but still insufficient to cover all the seismically active regions in the world and to provide sufficient quantity of usable data. Therefore, a large number of countries in the engineering practice apply records obtained by other countries. However, having in mind that earthquakes are characterized by (1) the frequency and amplitude content, depending on the geological and the tectonic structure of the seismogene region; (2) the rate of the magnitude, i.e., the intensity of the earthquake; (3) the origin depth; and (4) the epicentral distance, it is obvious that they differ from those recorded in other areas, even in cases when earthquakes of the same intensity are considered. Therefore, it is necessary to use records from the actual seismogene region, or if used from another region, then one should be careful, and, if possible, use records from a region having similar seismo-tectonic characteristics.

A particular problem pose the records obtained by instruments placed at different types of structures. Apart from all the above state, in their case, care should be also taken about the type and the properties of the structure as well as the position of the instrument in it. Therefore, it is necessary, that the conclusions be brought very carefully and on the basis of more records.

Parallel to the development of the strong motion network, seismic monitoring of different types of structures was developed. Particular emphasis was put on seismic instrumentation of existing dams. Almost all the high dams in Macedonia as part of former Yugoslavia were instrumented. This paper contains some details related to the strong motion instrument network and seismic monitoring of dams in Macedonia.

MACEDONIAN STRONG MOTION NETWORK

The strong motion instrument network installed 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. The network was installed in the beginning of 1972 within the frames of the USA-Yugoslav scientific-research project entitled "Installation of Strong Motion Instrument Network on the territory of Yugoslavia". This project was realized by the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) in Skopje in cooperation with the Californian Institute of Technology (CALTECH) in Pasadena until 1975 and then it was continued in cooperation with the United States Geological Survey (USGS) from Menlo Park until 1979. After this, the realization of the project was continued by IZIIS as a national project.

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.

Until 1991, the Macedonian strong motion instrument network was part of the instrument network of former Yugoslavia. It consisted of 110 accelerographs and 60 seismoscopes, of which 34 accelerographs and 7 seismoscopes were installed on dams
To provide a more detail insight, presented briefly further is the main concept and some of the main characteristics of this network.

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.

In the design of major structures and facilities such as important buildings, dams, bridges and power plants, it is highly desirable to know the ground motion at a specific site that would result from a particular earthquake event. As the return period of major earthquakes associated with a given portion of a fault is generally quite long, it is impractical to wait for data from the particular event in question. Instead, it is necessary to extrapolate from data which have been obtained from other events which are thought to be in some sense similar to the particular event under consideration. This extrapolation process can only be reliable if there is an understanding of the individual factors which affect the character of strong ground motion such as: the nature of the source mechanism, the influence of the wave propagation path, and the effect of the local topographic and soil conditions. 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: earthquake source mechanism, wave propagation path, effect of local topography, free-field soil response at different soil conditions, site amplification factors, and structural response of different types of buildings and structures including soil-structure interaction. In areas of potentially unstable soils, strong motion records will help to determine the characteristics of the ground motions which might indicate landslides, subsidence, slumping and liquefaction.

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 deluvial sediments, 3) on structures (multistory buildings, dams, etc.). the instrument distribution, of both accelerographs and seismoscopes was made following this basic concept. Table 1 shows this distribution.

Table 1. Distribution of instruments

Location	Instruments	
	Accelerographs	Seismoscopes
On bed rock	9	9
On characteristic soil	19	34
On structure	78	11
Total	106	54

Besides, the network also includes instruments installed by IZIIS for the requirements of other projects and financed by other investors. These instruments are mainly installed on characteristic structures (high-rises building, dams and bridges) and locations foreseen for structures of capital importance.

The strong motion program consists of five subactivities: (1) network design,(2) network operation,(3) data processing,(4) network management and (5) research as well as application. All these activities are under the responsibility of IZIIS - Skopje.

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. To achieve this, instruments have been installed at previously defined points.

As can be seen from Table 1, included in the strong motion instrument network of Macedonia were also a total number of 78 SMA-1 accelerographs that were installed on different type of structures (high-rise building, dams, industrial facilities, etc.). Table 2 provides a review of structures on which these instruments were installed and the number of instruments.

Table 2. Instrumented structures

Type of Structures	Number of instrumented structures	No. of Instruments	
		SMA –1 Accelerographs	WM -1 Seismoscopes
High-rises building	10	32	4
Dams	11	34	7
Bridges	3	12	/
Total	24	78	11

Our past experience from 232 earthquake records taken on buildings in Banja Luka (Bosnia and Hercegovina), Skopje (Macedonia) and Zagreb (Croatia) and 229 records on dams supports the experience of other countries such as USA, that more studious approach is necessary for determination of the number of instruments and their location in the course of instrumentation of buildings.

Data Processing

Data processing in central to the entire strong-motion program; it serves as a focal point for the functions of archiving records, processing of data, and dissemination both the data and information about the program to the user community. In the archival phase, all records are stored by station and cataloged both by event and station. In data processing, all significant records are digitized after which the raw digitized data are used to generate the following: uncorrected and corrected acceleration time histories; velocity and displacement time-histories; and various forms of frequency domain spectra (response spectra and Fourier spectra.

The ground motion characteristics during an earthquake represent the basis for solving of earthquake engineering and engineering seismology problems. These characteristics can be obtained from strong motion instrument recordings.

The three components, as recorded by the accelerographs the response of the instrument to the earthquake ground motion. Due to the limited capability of the instruments, the response gives a proper ground acceleration only for a very small frequency range. On the other hand, for calculation of many earthquake engineering and engineering seismological problems, the exact functions of acceleration, velocity and ground displacement at a wider frequency range, response spectra, Fourier spectra and other ground motion information are required. The determination of all these ground motion characteristics necessitates detail processing of the recorded accelerograms.

The most serious problem for strong motion data processing is the determination of the exact ground acceleration function, the so called correct acceleration data at wider frequency range. In the past, these data used to be obtained by application of several methodologies. Recently, in order to obtain more correct information of the accelerograms many authors work on the development and unification of a standard strong motion processing procedure.

The application of the data processing method developed at IZIIS-Skopje, has been presented by the data processing results obtained from instruments located on dams in Macedonia.

SEISMIC MONITORING ON DAMS

General Needs

The main purpose of seismic monitoring of high dams is the following: (1) precise definition of the seismic activity of the site, i.e., precise location of earthquake epicentres and their depth: (2) definition of main earthquake parameters: magnitude, frequency characteristics and some indications of focal mechanisms; (3) prediction of the mode of occurrence of future earthquakes; (4) provision of data on the dynamic behaviour of the dam body for the purpose of objective evaluation of its functioning immediately after the occurred earthquake, and (5) verification of design parameters by the actual behaviour of the dam body under an earthquake.

To provide these information that are of different nature, it is necessary to investigate and monitor the dam site by means of:

- a local network of seismological stations - seismographs,
- Instruments for recording of strong earthquakes - accelerographs

The local seismological network distributed in a manner that it thoroughly covers the considered area provides an answer as to the spatial distribution of the earthquake epicentres and their energy characteristics, i.e., the local seismic activity. In these observations, importance is given to the period of filling of the reservoir due to the possibility of occurrence of "induced" local earthquakes as a result of the modification of the stress state of soil. This network should start being operational at least two 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 three years after putting the dam into effect. It is desirable, particularly in areas of high seismic activity that this network works on a permanent basis.

The seismological stations distributed around the reservoir have to record the seismic activity in the region of the dam and the reservoir. There are several basic reasons justifying this seismic instrumentation among which is the investigation of the normal seismic regime by these observations with the purpose of contributing to the seismotectonic investigations for definition of the seismicity of the seismogene zone. Apart from this, this phase of investigations confirms or negates the existence of induced seismicity as a result of filling of the reservoir. If such a seismicity do exists, its relation with the normal seismic regime is defined. The results from these observations provide the possibility for making corrections of the main seismic degree. This type of investigations are performed by means of a network of seismological instruments distributed around the reservoir and telemetrically connected with the central recording station.

The strong motion instruments installed on the dam 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 dam immediately after the occurred earthquake.

This phase of seismic osculation of dams mainly refers to engineering aspects of the structure. It contains installation of instruments (in the ground and at the base of the dam) for recording of strong motions. The instruments are located at characteristic points of the base and the dam and the possibly obtained records are an invaluable parameter for verification of the mathematical model of the structure and its behaviour under the effect of a real earthquake.

An important element of these instruments are their output information. It is desirable that these be in such a form that they could provide an information on the intensity of an earthquake immediately after its occurrence. Based on this, a decision could be made regarding further exploitation of the dam. For instance, if the dam is designed for a = 0.15 g as a design parameter, 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 dam with no particular repair or strengthening However, when the recorded acceleration is greater than 0.15, 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 dam caused by the forces from the recorded earthquake.

Technical Regulation

For the seismic monitoring of dams in former Yugoslavia, i.e., Macedonia, there is a Book of Regulations on Seismic Monitoring in which all the requirements related to instrumentation of dams are precizely defined. Some of them, along with the main parameters for preparation of a project on seismic monitoring of dams, are presented very briefly in the subsequent text because of the limited space.

According to technical regulations for seismic monitoring of dams of Macedonia, monitoring of dams was performed to provide data on (1) induced seismicity, and (2) dynamic behaviour of soil, the foundation and the dam body under the effect of earthquakes.
The induced seismicity is monitored by seismological stations (at least three) distributed around the dam reservoir. The dynamic behaviour of the dam discussed in this paper, was monitored by strong motion instruments distributed over the dam body.

The seismic instrumentation of the dam body 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 the most important of which are: the seismological and geological characteristics of the site, the foundation conditions, the type of the dam structure and the size of the reservoir.

The instrument locations are selected on the basis of dynamic analysis of the mathematical model of the dam and the experimentally defined dynamic characteristics of the structure by means of forced vibrations or measurement of ambient vibrations of the structure.

In principle, this method for definition of the instrument locations at the dam site is used for all dams in former Yugoslavia for which seismic monitoring is performed.

For each dam taken separately, projects on seismic monitoring were prepared in which particular attention is focused on the parameters stated below.

Project for Seismic Monitoring

Seismic monitoring of dams and water reservoirs is planned, designed, carried out and organized for each structure taken separately. 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 parameters pertaining to the first group have already been described in "Book of Technical Regulations for Seismic Monitoring of High Dams" (Chapter 6.3).

The parameters of the second group are defined for each structure taken separately. By certain systematization , the parameters 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.

All the above stated components have a partial and interactive effect upon the dynamic characteristics and the dynamic behaviour of the structures. However, in dynamic analyses of the mathematical model of the dam and experimental testing of full scale structures (full scale tests by forced vibrations and analysis by ambient vibrations), the structure and the local ambient are treated as an integrity so that the final concept of instrumentation for seismic monitoring is defined on the basis of results from dynamic analyses of the mathematical model of the dam and the experimentally defined values of dynamic characteristics of the dam, i.e.,

- natural frequencies
- damping capacity of the structure;
- vibration mode shapes of the structure.

Accordingly, it is necessary to elaborate a separate project for seismic monitoring of each structure in order to:

- establish an optimal system of seismic monitoring instruments;
- obtain practically usable and compatible data in case of an earthquake.

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

- verification of previous computations and analyses;
- analysis of the stress state and level of safety of the dam after the earthquake effect;
- analysis of the retroactive effect of the water reservoir on the seismic regime of the local territory;
- optimization of the process of design of future structures.

It is necessary to mention however that seismic monitoring of dams and reservoirs in many countries has been an obligatory part of osculation already for decades, particularly after the invention of seismic instruments with high quality electromechanical acceleration and velocity converters.

OBTAINED RESULTS

Since 1973, several strong earthquakes have occurred on the territory of Yugoslavia, (the Montenegro coastal area - 1979, M= 7.0; Kopaonik - 1980, =6.3; Banja Luka-1981, M=5.4) and the neighbouring countries (Friuli, Italy-1976, M=6.5; Vranchea, Romania-1977, M=7.2, Thessaloniki, Greece-1978, M=6.3, etc.). Many earthquakes of moderate intensity (M≥2.5) have occurred, too.

In this period, 1206 accelerograms have been obtained out of which 823 by instruments installed on free field and 383 by those installed on different structures.

Presented below are therefore only the results from the records obtained from instruments located on dams in Macedonia.

Significant set of data have been obtained from extensively instrumented structures during past earthquakes. Data sets obtained from well-instrumented structures, particularly dams, durin- the Negotino earthquake of Sep.28, 1985 (M=5.1). Bitola earthquake of Sep. 01, 1994 (M=5.2) and many other earthquakes of moderate intensity (M=3.5 - 5.5) will provide significant contribution to response studies.

The results from the records of these earthquakes shall be presented in the tables and the graphic presentations (records and response pectrum) that are given below. Apart from this, the locations of the instruments installed on the dam body shall be presented for the purpose of getting a thorough insight into the seismic monitoring of these dams and the results from such a monitoring.

More detailed data on these records and the obtained results can be obtained from the publications of the Institute of Earthquake Engineering and Engineering Seismology.

Table 3. Earthquake data obtained from instrumental data for Dam "Tikves" - Negotino

Earthquake Data								
Location	Date	Time (GMT)	Coordinate N	Coordinate E	Io MSK-64	M Richte	Depth (km)	Note
Demir Kapija - Negotino	28-09-1985	$14^{h}50'$	41.510^{o}	22.266^{o}	VII	5.1	4	Obtained from microseis

Table 4. Maximum acceleration, velocity and displacement for Dam "Tikves" - Negotino

Data on the SMA-1 Instrument		Date on Record								
		Component N 150 S			Component N 60 S			Component Up.		
Location	No.	Acc. cm/s/s	Velocity (cm/s)	Displ. (cm)	Acc. cm/s/s	Velocity (cm/s)	Displ. (cm)	Acc. cm/s/s	Velocity (cm/s)	Displ. (cm)
Dam Crest	1158	-46.7	-2.299	0.300	40.4	1.453	-0.093	-33.3	-0.828	-0.033
Loc-2 Central Part of Dam	1156	-20.0	-0.637	0.049	17.0	-0.434	-0.024	14.2	0.409	0.015
Loc.-3 Lover Part of Dam	1155	-12.8	-0.253	0.007	12.4	-0.235	-0.008	6.2	-0.151	0.006
Loc.-4 Soil	2809	5.3	-0.131	-0.005	-3.6	0.109	-0.003	-4.0	0.067	0.002

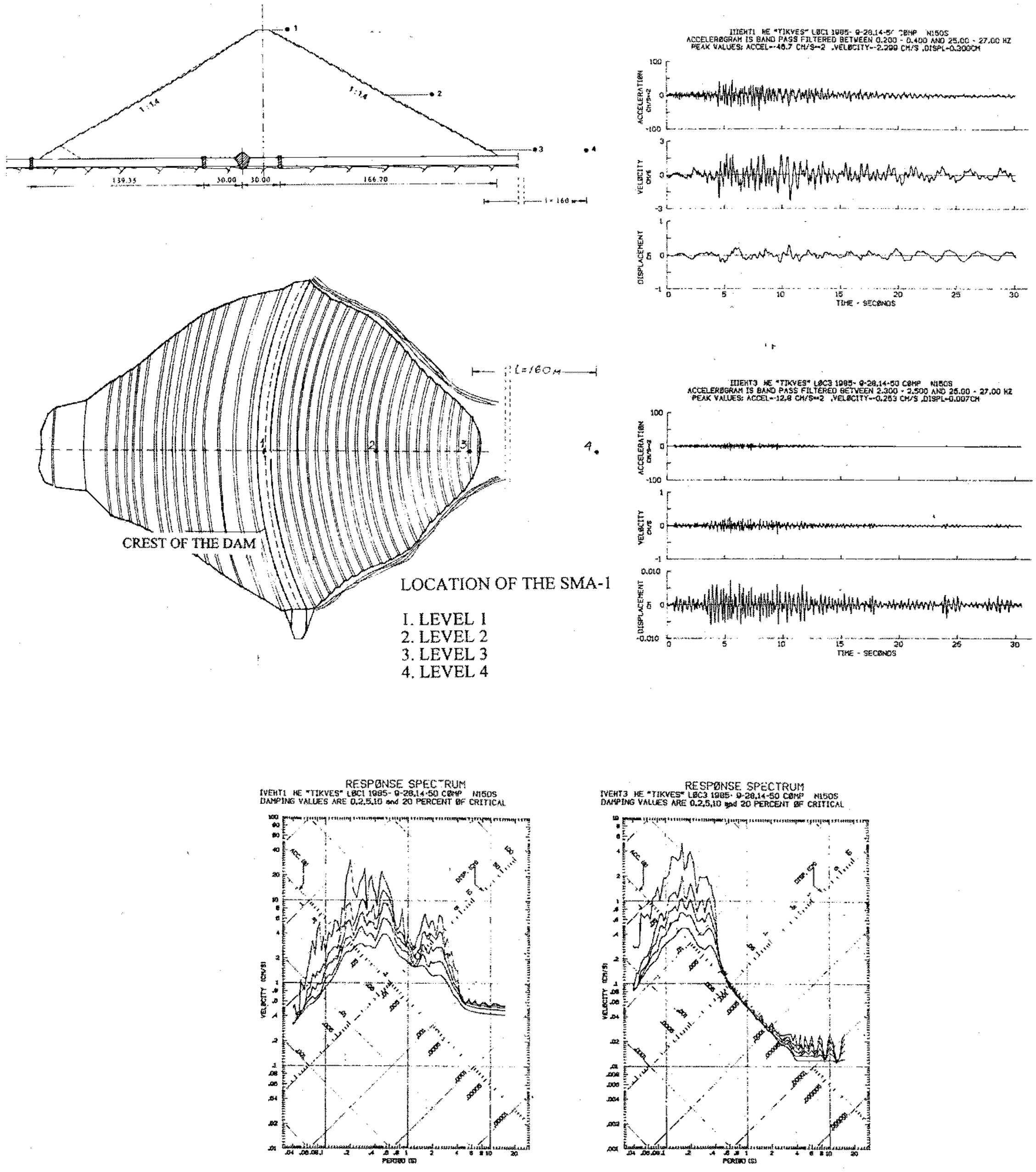

Fig.1. Seismic monitoring on the Tikves Dam. Location of Instruments, Accelerograms and Response Spectrum from Negotino Earthquake of Sept. 28, 1985.

Table 5. Earthquake data obtained from instrumental data for Dam "Strezevo" - Bitola

Earthquake Data								
Location	Date	Time (GMT)	Coordinate N	E	Io MSK-64	M Richter	Depth (km)	Note
Bitola-Resen	01-09-1994	$18^h12'$	41.13^o	21.24^o	VII	5.2	23	Obtained from microseismical data
Bitola-Resen	01-09-1994	$18^h12'$	41.10^o	21.18^o	VII^+	5.4	20	Obtained from microseismi-caldata

Table 6. Maximum acceleration, velocity and displacement for Dam "Strezevo" - Bitola

Data on the SMA-1 Instrument		Date on Record								
		Component N 40 E			Component N 50 E			Component Up.		
Location	No.	Acc. cm/s/s	Velocity (cm/s)	Displ.(cm)	Acc. cm/s/s	Velocity (cm/s)	Displ.(cm)	Acc. cm/s/s	Velocity (cm/s)	Displ. (cm)
Dam Crest	4777	-246.7	20.492	-1.992	166.3	-10.030	0.719	179.9	7.691	-0.449
Loc-2 Berma - I Central Part	5200	-244.3	-12.773	1.129	-149.4	-5.896	0.401	107.9	-2.407	0.091
Loc-3 Berma -II Left Side	4259	199.9	16.818	-1.478	103.2	-6.158	0.508	216.8	17.981	-1.576
Loc-4 Berma -II Right Side	5116	313.1	18.312	-1.865	-161.9	6.586	0.595	128.6	-3.740	-0.176

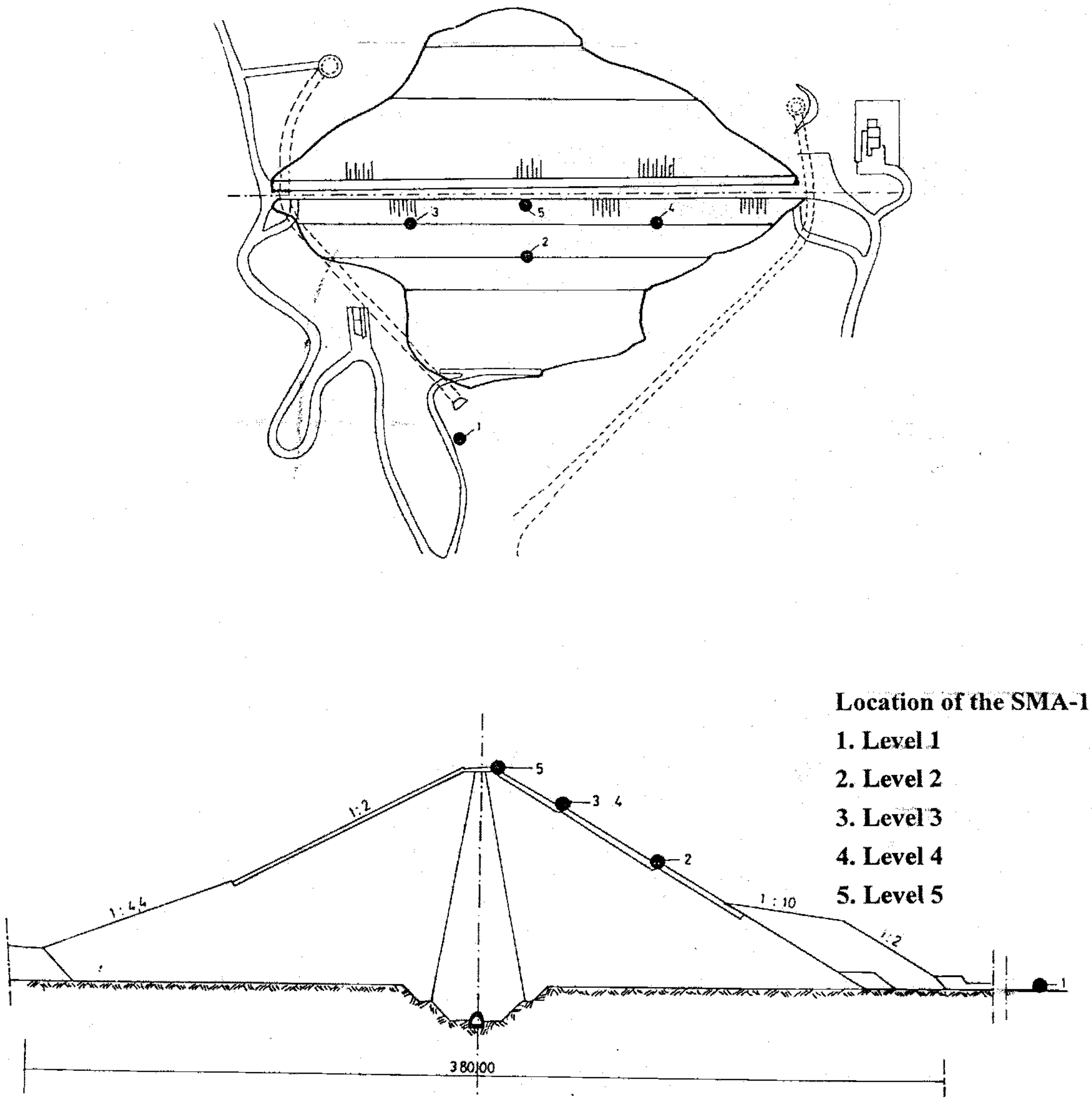

Fig. 2. Seismic monitoring on Strezevo Dam. Location of instruments

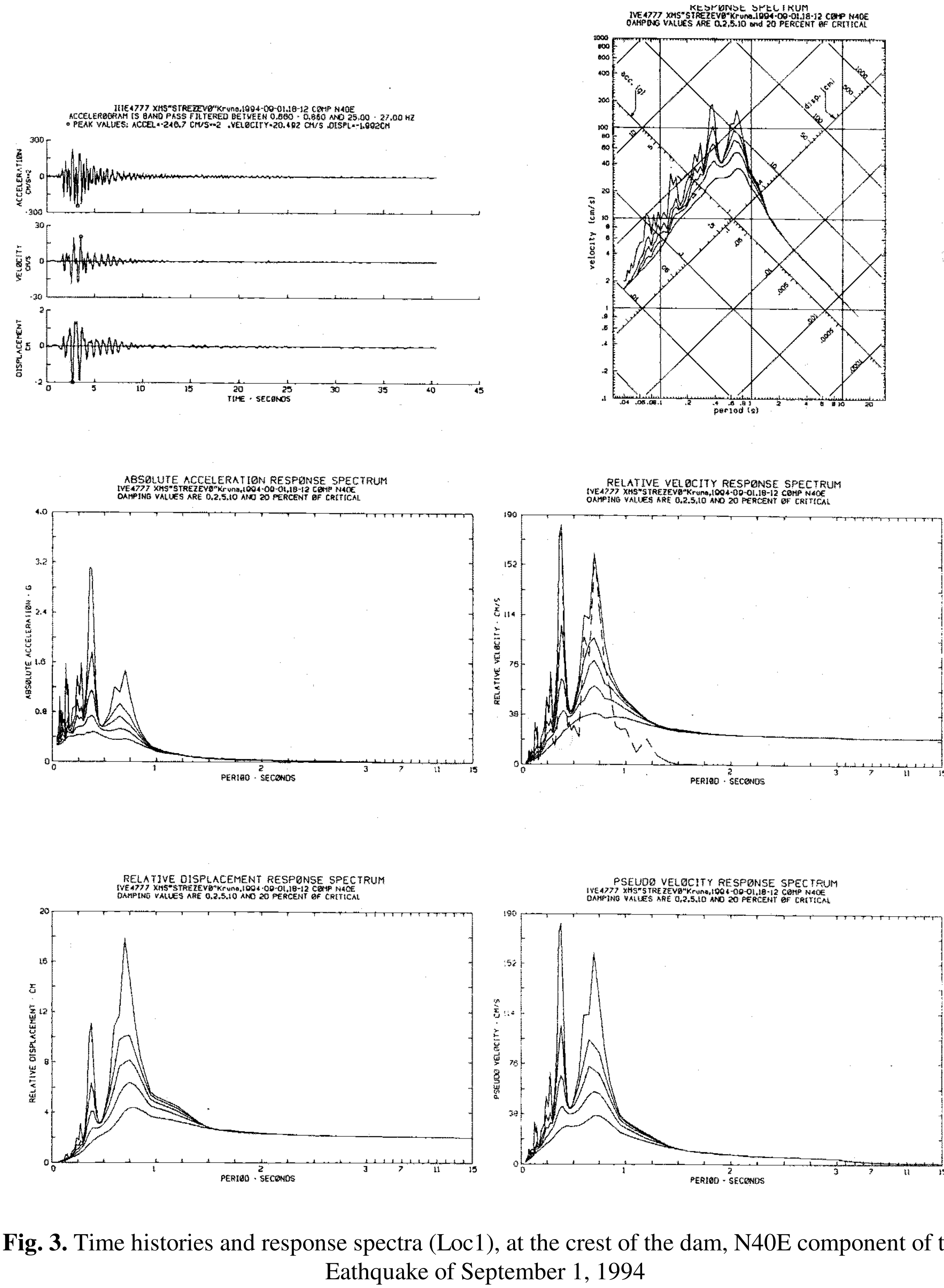

Fig. 3. Time histories and response spectra (Loc1), at the crest of the dam, N40E component of the Eathquake of September 1, 1994

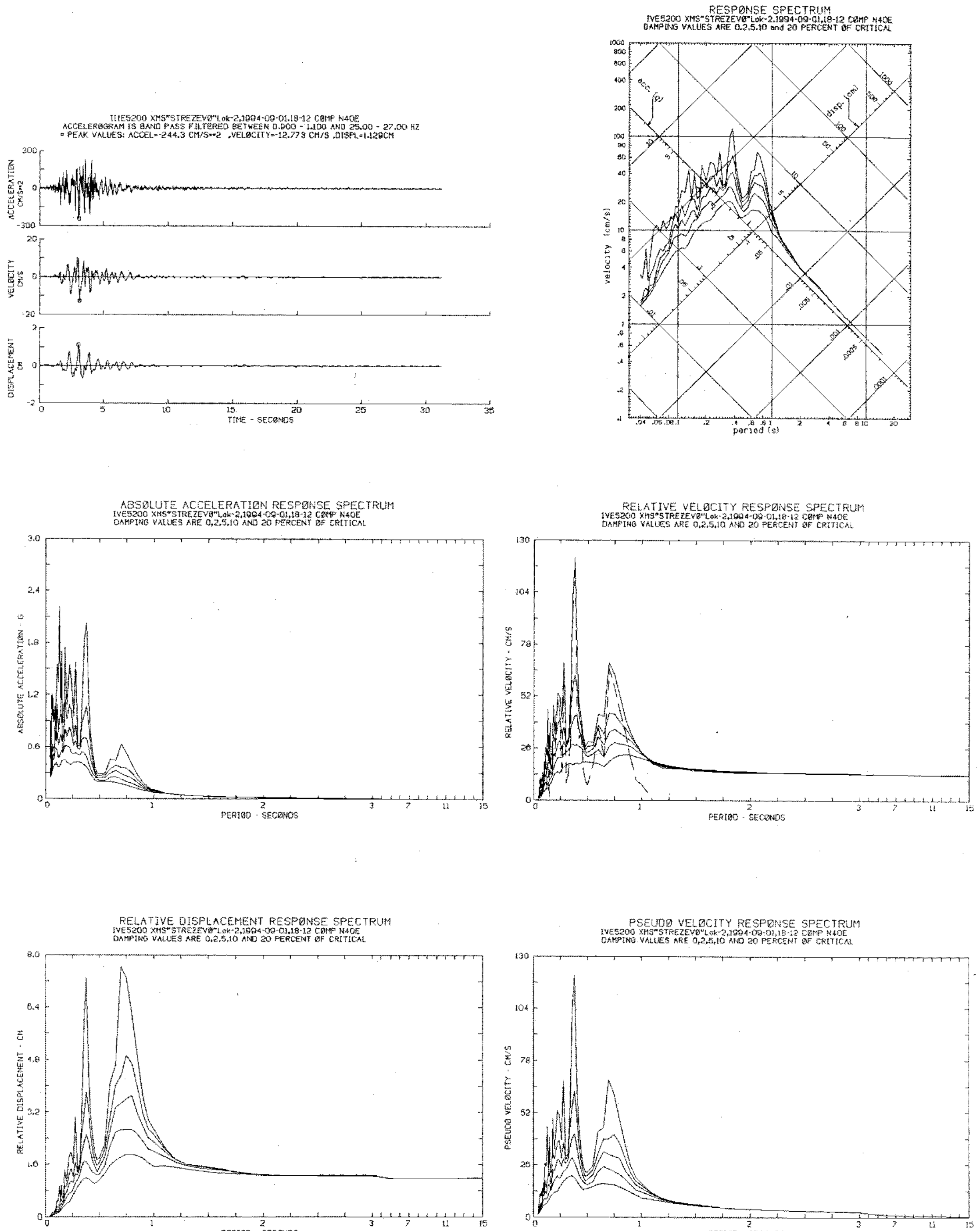

Fig. 4. Time histories and response spectra (Loc2), at the lover part of the dam, N40E component of the Eathquake of September 1, 1994

CONCLUSIONS

On the basis of the above presented results and the long term experience of seismic instrumentation of dams in former Yugoslavia and Macedonia, the following conclusions can be drawn:

- The seismic monitoring of dams is still an actual problem in earthquake engineering. The results from processed earthquake records make considerable contribution to experimental and analytical studies of the dynamic behaviour of dams. All these contribute, directly, towards optimization of the process of design and construction of aseismic dams.
- The existing number of instrumented dams is relatively small, even on world scale. Its increase is necessary by instrumentation of dams, particularly those constructed by the application of newer technologies and methods of design. It is technically and economically justified, since the cost of the instruments, compared to the total investment value of the dams is symbolic.
- The existing instruments, discussed in this paper, are technologically relatively out of date, which very much affects the process of maintenance of the instruments and the data processing. Their frequency bend and dynamic range are relatively small, compared to new generations instruments.
- According to the above mentioned examples, the seismic monitoring of dams in future should be conducted by instruments of the latest generations, since, despite other, the approach for processing of the data obtained by them is completely automatic.
- Significant efforts are required to provide rational protection of dams against seismic effects. Seismic instrumentation is one of the most rational ways of protection.

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