EFFECTS OF RESERVOIRS IN KARST AREAS ON EARTHQUAKES

by

Petar Stojić

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ABSTRACT

The study of effects of reservoirs in karst areas on the regime of local earthquakes uses the earthquake data from the observational seismic station at the Grančarevo Dam Site, on the River Trebišnjica, Yugoslavia. The data, though only obtained at a station, were analyzed for the purpose of finding the relationship between the large Bileća Reservoir, created by this dam in a highly karstified region with a large karst aquifer, and the regime of local earthquakes. It was hypothesized that the increase of karst aquifer levels by 70 meters and the increased load by the reservoir and additional aquifer water storage has affected the earthquakes. Various simple statistical techniques are used in this analysis.

Regardless of some deficiencies in the collection and processing of data, it was found that the number of local earthquakes per year has been significantly increased in the first four years of filling and emptying of the reservoir or the years after the first phase of four years has passed. The reservoir has been filled with water in stages for several years, in order to avoid that the sudden loading of the reservoir triggers a large earthquake. This case study is instructive for planning observations and for advancing explanations of potential relationship between the reservoirs (especially in highly pervious formations and close to large fault zones) and the regime of earthquakes.

FOREWARD

The potential (or expected) relationship between the reservoirs, especially those in highly pervious geological formations, and the regime of earthquakes in their vicinity, has been of interest to specialists from the moment some new water storage reservoirs were inferred or hypothesized to have triggered large earthquakes. The construction of reservoirs in highly karstified (pervious) limestone and dolomite areas and their potential effects on the regime of local earthquakes have been of interest to researchers within the bilateral United States--Yugoslavian cooperative research project and endeavors related to karst hydrogeology, hydrology and water resources that lasted from 1972 through 1978. This bilateral U.S.--Yugoslavian cooperation through this research project was sponsored by the Joint U.S.--Yugoslavian Board for Scientific and Technical Cooperation, with the U.S. National Science Foundation acting as the U.S. cooperating agency and both sides financially supporting these activities. The University of Sarajevo, Yugoslavia, and Colorado State University, Fort Collins, Colorado (and George Washington University, Washington, D.C., recently) U.S.A., were the cooperating institutions. Amongst many subjects investigated, attention was paid to reliable information and developments that may have helped to understand the potential relationship between the new reservoirs in karst areas and the regime of the local earthquakes.

Basically, when a large reservoir in karst areas is built, in many cases it submerges karst springs for dozens of meters. This then significantly increases the levels of water tables of karst aquifers. Physical changes that are hypothesized herein to be mainly of these two types are:

(1) Reservoirs create an increase in the load over a rock formation, with a change in the distribution of pressures in deep underground layers, where the earthquake processes occur; and

(2) By increasing the water pressures in the underground, the vapor phase (water in the pores or fissures being in the vapor phase) of deep layers of a karst formation is also changed, with this phase occurring beneath the liquid phase (water in the pores and fissures being in the liquid phase) of karst aquifers, with this change of surface water levels meaning a decrease of levels at which the vapor phase replaces the liquid phase.

For this hypothesized second physical change, induced by reservoirs in karst areas, the assumption may be valid that the increased depth of liquid phase would serve as a lubricant in still deeper underground layers in comparison with the pre-reservoir conditions. If this hypothesis comes out to be correct, the stresses in rock formations that are induced by stress buildup forces would be released earlier than the case would be under the pre-reservoir conditions. The shocks would be triggered either more often or immediately after the reservoir was filled, as one of the consequences of creating reservoirs. The combination of the load and the potential change in levels of liquid-gaseous interfaces in deep layers of karst aquifers, are likely the physical phenomena that produce the interaction between the reservoirs and the regime of the local earthquakes. For impervious formations under the reservoirs, one would then expect only the reservoir load to affect the distribution of pressure in that portion of the earth's crust in which the earthquake processes occur.

The case presented in this paper, namely the Reservoir Bileća on the Trebišnjica River, as the largest reservoir in Yugoslavia, is so situated that the reservoir backwater curve reaches a very large karst aquifer. The aquifer levels are increased by about 70 meters at the full reservoir. The study of this case was not intended to, was not expected to, and cannot answer the question of a definite relationship between the reservoirs in karst areas and the earthquake regime in the surroundings of these reservoirs. However, and regardless of some difficulties in obtaining the most reliable research data because of various subjective factors, the analysis of data of this case is considered as a contribution to understanding of the potential relationship. Furthermore, this case study should instigate new approaches for data collection, observations and interpretations in the future, and for a better understanding of the potential relationship between the reservoirs and the earthquakes.

The basic results of this paper show that after the reservoir was filled in stages, and had undergone several cycles of filling and emptying, an increase in the number of earthquake events occurred in the first years of reservoir operation in comparison either with the years prior to the first filling of the reservoir or in the years after the reservoir has been in operation for about 3-4 years.

One can venture then a hypothesis, namely that the accumulated stress in the underground, prior to filling of the reservoir, or during its cycles of filling and emptying, has been released much more often during the first years of reservoir operation than in the pre-reservoir years, because of the above factors that may affect the earthquake regime in the vicinity of the reservoir. Both factors, the load by the reservoir and the eventual change in the position of liquid-gaseous interface in the underground, may be the factors affecting an early release of stresses accumulated in the underground after the reservoir was put into operation. The potential change in the level of the liquid-gaseous water interface in the underground may be a cause for a larger number of small energy earthquakes in the first years of reservoir operation, with some long-range, permanent effects on the earthquake regime, than the case was without the reservoir. These hypotheses are speculative, and are expected to be eventually resolved by further research, but particularly by better observations on many reservoirs in karst areas in the future.

The reservoirs in karst areas of the Mediterranean countries, especially those of Southern Europe and the Middle East, are very important for the viewpoint that this area is earthquake-prone, being on the contact of two large earthcrust plates. The combination of high permeability of karstified limestone and dolomite formations in these areas, and high risks of earthquakes, require special attention to this topic.

This paper results from the work on a doctoral dissertation by Mr. Petar Stojić, carried out at the University of Sarajevo, Yugoslavia. He is at present Acting Director of the newly-established Research Institute for Investigation of Karst Water Resources, an outfit of the Hydroelectrical Power Company of the Trebišnjica River.

The dissertation mainly resulted from the author's work in Yugoslavia, both within his activities in this Company and under the bilateral U.S.--Yugoslavian Research Project on Karst Hydrology and Water Resources of the last eight years. During a six-month visit and study at Colorado State University in 1977-78, Dr. Petar Stojić, and the staff of the Karst Research Project at Colorado State University, reviewed several aspects of this problem of reservoir-earthquake interaction in karst areas, and helped the author to further advance his research results. It should be underlined that the author's position that earthquakes should not be studied only by their isolated extreme events, but also as stochastic time processes, is especially valid in studying the effects of reservoirs on earthquakes in general, and on earthquakes of karst areas in particular. During Dr. Stojić's six-month stay at Colorado State University, his activities were partially supported by the NSF-sponsored Karst Research Project at Colorado State University.

This work is presented as a Colorado State University Hydrology Paper with the expectation that the question of interactions between reservoirs and earthquakes, especially in highly permeable formations, like karstified areas, will receive full attention by professionals and owners of reservoirs in the future.

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Chapter 1
INTRODUCTION

Systematic observations and investigations of eventual effects of storage reservoirs on earthquakes was initiated in Yugoslavia with the construction of the system of hydroelectric power plants on the Trebišnjica River, Fig. 1-1. In order to better follow the results of investigation on the effects of storage reservoirs on earthquakes in karst regions, the most general information on this system and on the Grančarevo Dam, where the major earthquake observations were made, is given in this introduction.

The Trebišnjica River is the largest subterranean karst river in Yugoslavia; it sinks underground in Popovo Polje after a course of about 100 km, with waters outflowing either close to the Adriatic Sea or at the Neretva River. The length of its course depends on the flow. The surface flow is shortest during the summer, about 35 km, when the river channel dries several kilometers downstream of the town of Trebinje. The construction of the system of hydroelectric power plants in the area has substantially changed the flow regime of the river.

Hydroelectric power plant Trebinje I (Fig. 1-2) is the oldest hydroelectric plant, built in 1967 on the Trebišnjica River, located 18.2 km downstream of the river spring (17 km upstream of Trebinje). Its

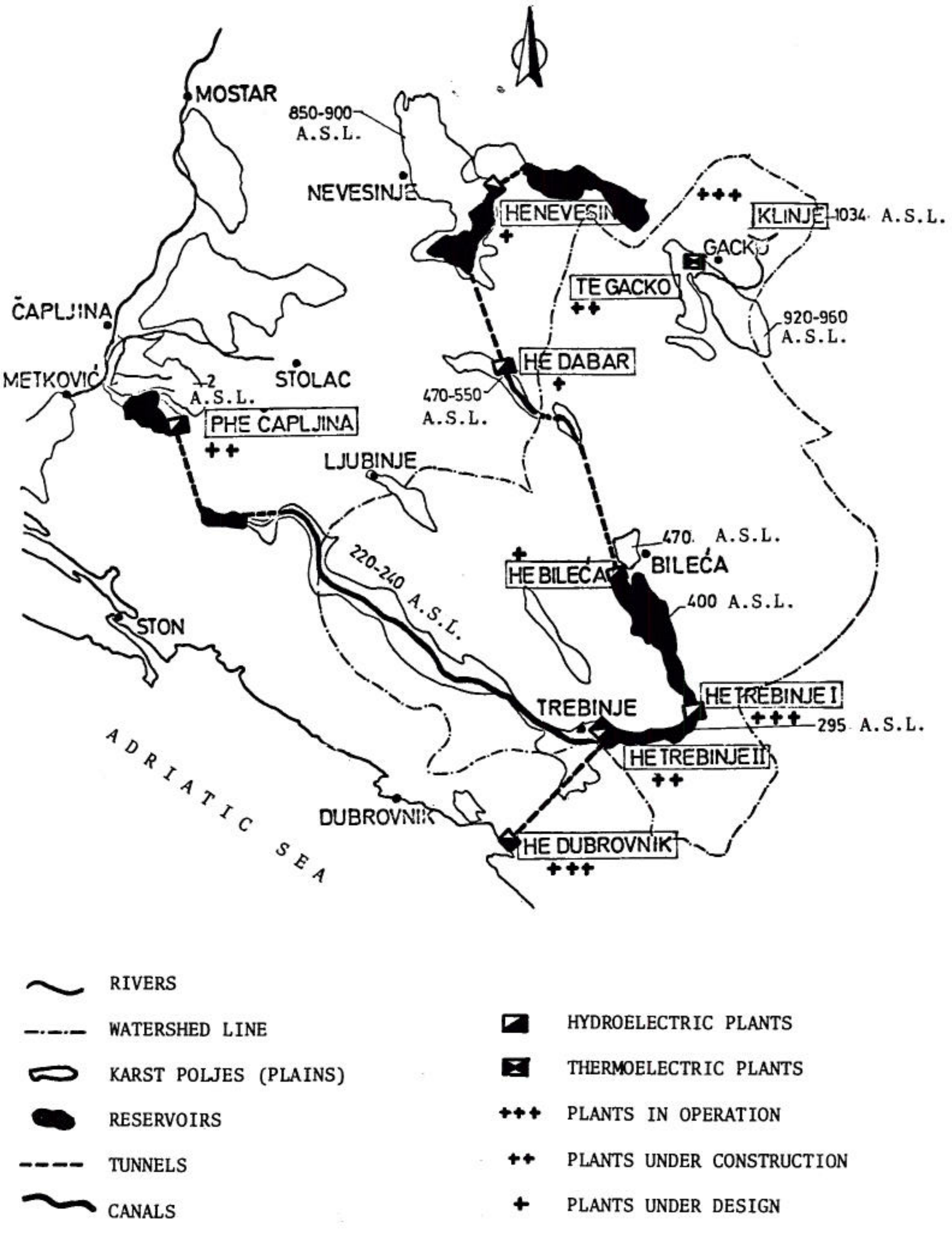


Fig. 1-1 System of hydroelectric power plants on the Trebišnjica River, Yugoslavia

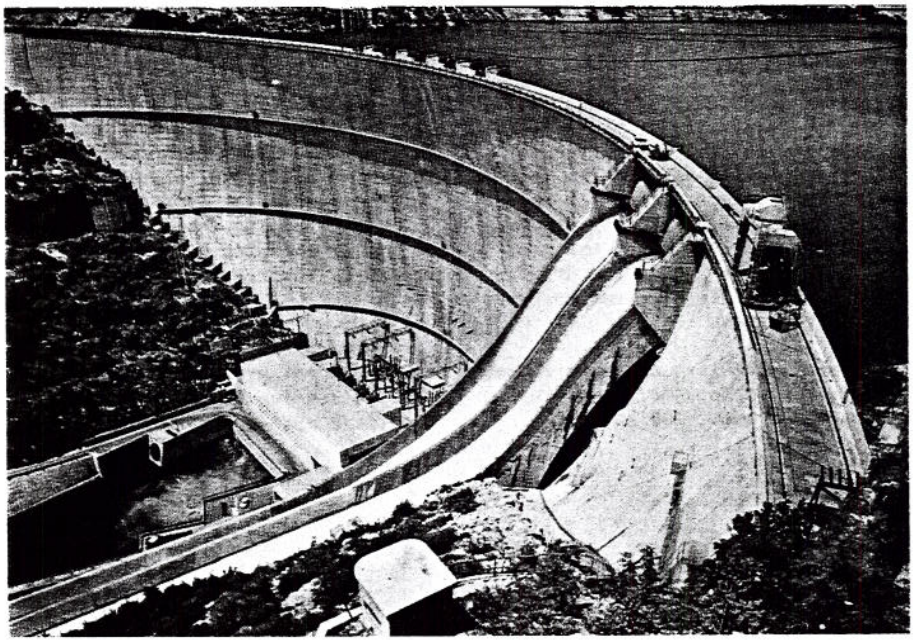
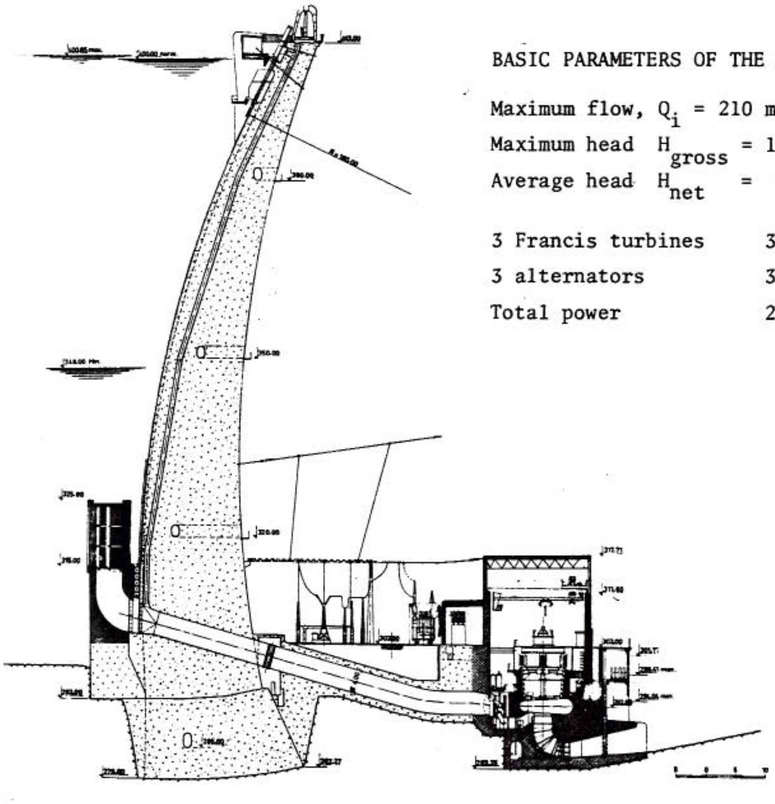


Fig. 1-2 Hydroelectric plant Trebinje I



BASIC PARAMETERS OF THE PLANT

Maximum flow, Q_i = 210 m^3/sec

Maximum head H_{gross} = 105.05 m

Average head H_{net} = 83.00 m

3 Francis turbines	3 x 74.000 Ks
3 alternators	3 x 60 MVA
Total power	2 x 54 MW = 162 MW

Fig. 1-3 The cross section of the Grančarevo Dam and power plant

large reservoir ($1.28 \times 10^9 m^3$) seems to have somewhat changed the seismic activities of the region. By construction of an arch dam, 123 m high, with the dam crown about 450 m long, the Bileća Reservoir was created. For a level difference of 52 m, the beneficial storage capacity is 1.1×10^9 m^3 (Fig. 1-3). This reservoir belongs to the largest reservoirs built in karst areas; it is the largest in Yugoslavia. By creating the reservoir, the Trebišnjica River Springs were flooded by 77 m. The reservoir also created a relatively large underground storage of inundated primary and secondary karst porosity. The dam site is in limestone, deeply karstified at the left bank.

The Bileća Reservoir is located in a complex karst environment. Large permanent and intermittent springs of the Trebišnjica River occur at the contact of limestone and dolomite at the town of Bileća. Downstream of these springs the river flowed along a wide karst valley, with numerous springs of sizable yields along its banks. Dolomites appear on both river banks. Impervious dolomites made the reservoir feasible in these highly pervious karst.

Very complex hydrogeological conditions did not permit an exact determination of the watershed area of the Trebišnjica River. The subterranean watershed does not fit even approximately the surface watershed, because many karst poljes (plains) and terranes drain through the underground into the river.

The whole region is intersected by a system of faults and important fissures of various kinds, orientations and slopes. The geological and engineering explorations have shown that the storage reservoir and the dam are situated in a large geological block, surrounded on all sides by faults, however relatively distant from the reservoir and the dam.

The geological conditions of the dam and reservoir area are important from one particular viewpoint, namely that the potential exists for the reservoir to be connected with the deep, pervious karst formations and karst aquifers. The changes induced in the underground by fluctuations of reservoir levels and loads, in the form of water and water vapor pressures and stresses in the underlying rocks, deep in the karst aquifers, fissures and faults, are hypothesized to have some effects on earthquakes in karst regions. The changes in water pressures inside the karst formations around the reservoir are observed at 90 deep pieozmetric boreholes.

Chapter 2
HISTORICAL INFORMATION ON EARTHQUAKES, DAM AND RESERVOIR

According to historic seizmologic data, one of the most active seismic *lines* of the Dinaric Mountains is found at about 8 km downstream of the Grančarevo Dam. This region belongs to VII-VIII degree of seismic intensity according to Mercalli-Cancani-Sieberg (MCS) scale.

The strongest earthquake in this region, for the period 1901-1976, had an intensity of VIII MCS. It occurred in 1927 in the surroundings of Stolac (about 60 km northwest of the dam site, Fig. 1-1). During that 75-year period 47 earthquakes of magnitude $M \geq 4.1$, with the average hypocenter depth of about 15 km, were recorded. Regional seismic explorations of the earth's crust characteristics have shown (a) that it has a thickness of about 43 km in the reservoir region, and (b) that its thickness increases in the direction of the Adriatic Sea and decreases in the direction of the hinterland.

The city of Dubrovnik on the Adriatic Coast, about 30 km from the reservoir, was destroyed in 1667 by a catastrophic earthquake. Until then, it had been a very influential Mediterranean city state.

Extensive geological, hydrogeological, speleological, geophysical, geotechnical and hydrological investigations were undertaken in order to acquire the necessary data for the project and for the control of changes to be eventually induced by water storage. By using the complex, but advanced investigation methods on factual, reliable data, a significant experience in planning, design and construction of systems of hydroelectric power plants, particularly of large dams and reservoirs under the complex karst conditions, were acquired. (Some results were presented in the two-volume proceedings book, "Karst Hydrology and Water Resources," US-Yugoslavian Symposium, Dubrovnik, June 2-7, 1975; published by Water Resources Publications, Fort Collins, Colorado, USA, 1976.)

The state of the advanced technique of physical modeling in the period of about 1960 enabled the proper simulation of rock characteristics in general, and the in-situ rock mass characteristics in particular. An appropriate choice of physical model materials enabled the construction of dynamic and geotechnical arch-dam models. Because of sensitivity of arch dam to characteristics of limestone at the dam site, physical and mathematical models were used to assess the future stability of the dam and of the rock-dam interaction.

The behavoir of the dam under the conditions of strong seismic activity was investigated on three dynamic, three-dimensional dam models at the scale 1:180. Two models (Figs. 2-1 and 2-2) were exposed to horizontal seismic vibrations parallel and perpendicular to the arch base on the top of the dam, while the third model (Fig. 2-3) was exposed to vertical seismic vibrations. The above investigations, shown in Figs. 2-1 through 2-3 and Tables 2-1 through 2-3, indicated a high degree of the dam's seismic resistance.

The physical models enabled determination of earthquake effects on dam stability and stability of its abatements. If the general character of earthquakes (say their number and the released energy) shows in the further studies to be changed by the reservoir, because of potential changes in the water conditions of deep karst formations, the investigations of effects of changed earthquakes on the dam can be analogously carried for the eventual altered seismic activity.

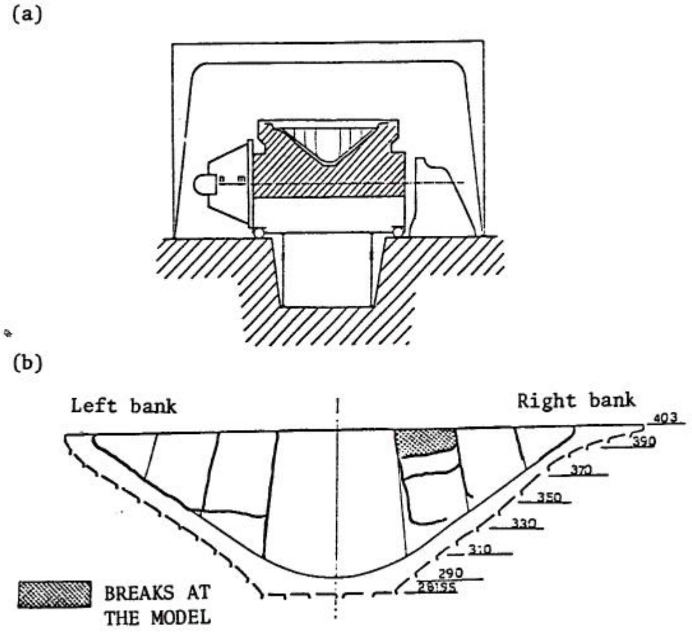


Fig. 2-1 Experiment with the Grančarevo Dam earthquake model under the condition of horizontal seismic vibrations parallel to the arch base on the top: (a) Model scheme; (b) Results of the break

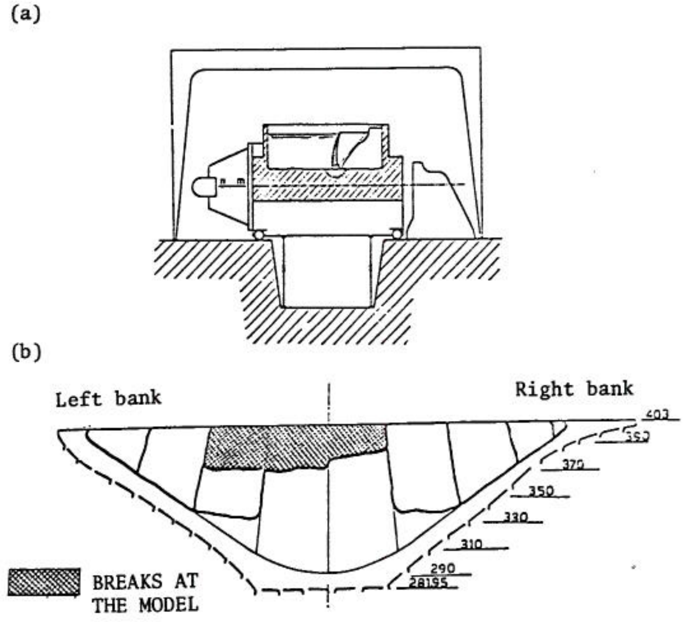


Fig. 2-2 Experiment with the Grančarevo Dam earthquake model under the condition of horizontal seismic vibrations perpendicular to the dam (parallel with the valley): (a) Model scheme; (b) Results of the break

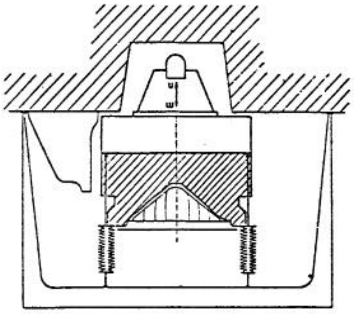


Fig. 2-3 Experiment with the Grančarevo Dam earthquake model under the condition of vertical seismic vibrations

Table 2-1 Results of Test of Model of Fig. 2-1

Duration of earthquake, t in minutes	Amplitude, A in mm	Frequency, F in Hz	Acceleration α.g in cm/s^2
3.9	125	1.16	0.34 g

Break of the model close to the right bank

Table 2-2 Results of Test of Model of Fig. 2-2

Duration of earthquake, t in minutes	Amplitude, A in mm	Frequency, F in Hz	Acceleration α.g in cm/s^2
4.0	195	1.20	0.50 g

Break in the model in the center of the dam and closer to the left bank

Table 2-3 Results of Test of Model of Fig. 2-3

Duration of earthquake, t in minutes	Amplitude, A in mm	Frequency, F in Hz	Acceleration α.g in cm/s^2
4.1	250	1.00	0.485 g

It was not possible to break the model

Because of geological engineering, geotechnical and hydrological characteristics of the dam site and the reservoir area, a gradual and controlled loading of the dam and the reservoir was carried out in three successive phases:

(i) Filling up to the storage level 368.81 m A.S.L. (planned 370.0) in 1967/68;

(ii) Filling up to the storage level 391.29 m A.S.L. (planned 390.0) in 1968/69; and

(iii) Filling up to the storage level 400.00 m A.S.L. (planned 400.0) in 1969/70.

Observations indicated that during the loading and unloading of underground by filling and emptying of the reservoir, the special attention was not given only to the behavior of the dam and the rock in its foundations, but also to various effects in the area around the reservoir. Both the behavior of the dam and the effects in the surrounding reservoir area may be the results of very complex geophysical processes. These effects may be independent or dependent. The dependent effects make it difficult to determine as the relations between the individual causes and their partial effects. Various cause-effect relationships contribute to the complexity of deformations in the dam's surroundings. Deformations may be results of seismic activity either of a general or of a local character, namely in disturbing the rock-mass equilibrium by reservoir loadings and unloadings. They produce a consolidation and an adaptation of the surrounding terrain to the new load conditions, with deformations being of miscellaneous origins. Deformations can greatly modify the conditions of the dam foundations, endanger its safety, as well as the safety of downstream area. Gradual and controlled loading was aimed at avoiding any surprise. Sudden over-straining was avoided, mainly not to cause sudden block movements in the earth's crust, especially due to the eventual already accumulated stresses in the earth's crust as the precursors of future earthquakes.

The historic data on natural seismic activity of both the general and the local character were taken into consideration in the Grančarevo Dam design. They were described by mathematical models and tested on physical models. In relation to seismic activity, the dam and the reservoir were considered as reacting systems. However, the question was posed on whether and how the dam and the reservoir may act as the active systems, exerting influence on the natural seismic characteristics. In this latter regard, the experience in the world is relatively limited with many references not published at the time of loading the dam and area by filling the Grančarevo reservoir.

Considering the complex karst conditions under which the Grančarevo storage reservoir was built, as well as some experience from various countries, three highly sensitive seismographs of "Hagiwara" type (Japan) were installed: two for recording of the horizontal and one for recording of the vertical seismic rock movements. Photoclinographs of Caloi type (Italy) were also installed for the control of rotation and inclination at the observational points.

The following instruments were installed to follow the deformations at the dam site: (a) high-precision bimetal dilatometer; (b) twelve high-precision invar tapes, installed in boreholes of 101 mm diameter; (c) four extension meters at five observational points for the rock fissure control, each about 60 m long; and (d) two high-sensitivity water tube tiltmeters.

This set of instruments was supplemented by various instruments for the control of the dam behavior.

From the very beginning of observations, it was noted that it would be difficult to always distinguish between the natural seismic activity, the tremors provoked by various blastings during construction in the dam's site surrounding, and the influence of various phenomena around the dam and the reservoir.

It was planned originally to undertake the seismic observations sufficiently in advance of any construction at the dam site. It was logical due to the character of natural seismic activities, to observe the seismicity a few years before filling the reservoir, to establish the natural seismic patterns. Various factors delayed the procurement of seismic instruments until the end of 1962. The catastrophic earthquake of Skopje (July 21, 1963) required the instruments to be installed there near the earthquake epicenter. Seismographs were installed at the dam site of the Bileća Reservoir, and observations started, in February 1965 as the construction of the dam was already under way.

Chapter 3
PROCESSING OF OBSERVATIONAL DATA AND ESTIMATES OF THEIR RELIABILITY

The observed earthquakes in the Bileća Reservoir area depend also on various constructions (mainly blasting and rock stress releases) and phenomena connected with the project. Construction at the dam site started in 1960, with foundation excavations initiated in 1964. Seismographs were installed on February 6, 1965, during the start of dam body construction. In this period rock blastings in foundations were limited and sporadic, such as the correction of the foundation lines, in rock quarries, and deepening of the river channel immediately downstream of the dam site.

Seismographs were installed on the right river bank at the dam site at the elevation 423 m A.S.L. just above the top of the dam. Seismographs recording horizontal movements were set in such a way that one would record movements parallel to the arch base on the top of the dam (approximately in the east-west direction), and the other for the movements in the direction of the axis of centers of arches (approximately in the north-south direction). The axis of the centers of arches forms an angle of $11^{\circ}\ 29'\ 59''$ counterclockwise in the north-south direction. The third seismograph would record the vertical movements. After several changes and investigations for magnification of certain components, the magnification of 5600 was adopted for all three components. Seismographs themselves oscillate at the period of 1 sec.

Apart from the miscellaneous effects, the seismograph records and data interpretation were affected by the parasitic waves that are not related to earthquakes. These parasitic waves came from:

(1) Explosion shock waves due to blastings in dam foundation, river bed excavation, and blastings in the rock quarry;

(2) Microseismic shocks produced by the turbine operation, water passing through the bottom outlets, and water evacuation over spillways;

(3) Seismic shocks linked to some geophysical phenomena in wider regions; and

(4) Air water shocks produced in the underground karst channels.

Proper interpretation of the basic data on earthquakes, particularly of the parasitic seismic waves, is essential for any reliable conclusions to be derived from the entire fund of seismic observations, as related to the effect of large reservoirs in karst areas on earthquake patterns. Therefore, full attention is given to the reliability of data.

3-1 Explosion Shock Waves Due to Rock Blasting

Immediately upon the installation of the seismological stations, a very strict record of blastings was imposed. The time of blastings, as well as the quantity of dynamite used were recorded. However, these records were lost during a flood. The strict record, however, meant an additional commitment to contractors, who tried to avoid it. That increased difficulties in data interpretation. The blasting shocks created the elastic waves often recording on the graph as vibrations similar to nearby earthquakes. It posed difficulties in properly distinguishing between the shocks caused by blastings and those by earthquakes.

According to measurements, the amplitudes of waves caused by blasts ranged within the following limits: (i) horizontal E-W component of 0.020-0.460 μ; (ii) horizontal N-S component of 0.020-0.264 μ; and (iii) vertical component of 0.020-0.506 μ. The parasitic effects of blasting decreased as the termination of works at various structures of the dam approached, but some blasting was registered even as late as 1968.

According to the records available, the total number of recorded earthquakes was:

Period before filling of the reservoir (2/6/1965 - 10/31/1967):	2,629
Period after filling of the reservoir (11/1/1967 - 10/31/1976):	9,636
Total:	12,265

The basic geophysical interpretation for the period before the filling of the reservoir, assumed that only 82 natural earthquakes have occurred, with the rest of the recorded earthquakes assumed mainly to be produced by blasting. In other words, all the recorded shock phenomena for which the energy could not be estimated were assumed to be a consequence of rock blasting. This interpretation is questionable because it is evident that as many as 2,547 rock blastings have not occurred in such a short period. Rechecking and reanalyzing the interpretation of the available data by the writer showed that doubts in the basic interpretation were justified. Only 1,591 earthquakes can be counted as resulting from rock blastings. Even this interpretation may be in question, because a certain number of recorded earthquakes may have been caused not only by blastings, but also by sudden dislocation of natural rock equilibrium and by a stress release due to rock excavation. Rock blastings may have initiated the rock stress releases, recorded as seismic shocks.

The final estimate of the origin of earthquakes is: 1,038 natural earthquakes (2,629 minus 1,591), with the distance of epicenters determined for 813 earthquakes, and the released energy for 111 earthquakes. It should be noted that the distance (D), and the energy (E), and in some instances both of these two characteristics (D,E), could not be estimated for all the earthquakes. The reasons were usually trivial; sloppy handling of the recording film, bad quality of recordings, one of the components ceasing to function during recordings, negligence on the part of staff and visitors, and similar reasons. This has lead to a decision in 1977, namely to change the way in which the earthquakes are recorded.

The earthquakes caused by rock blasts were recorded also during the period following the filling of the reservoir, but only in 1968, with 333 earthquakes recorded and interpreted by the geophysicists as rock blasts. This interpretation was also in question, because after the reservoir entered into operation, no work was performed in excavation pits. To decrease doubts of interpretation, the writer used the degree of correlation between the monthly values of the number of earthquakes and the mean monthly water level in the reservoir for seven years of observation, with the results for the two cases:

(1) The total number of recorded phenomena, with $r = 0.59$; and

Table 3-1 Number of Recorded Earthquakes in the Period 1967/68 - 1973/74 (Seven Years)

Case 1: All Registered Tremors

y	92	61	110	107	140	129	165	131	92	31	65	138	68	85	167	256	335	223	262	271	160	114	89
x	18.16	40.21	58.90	59.96	63.47	66.81	63.61	66.56	62.87	51.94	31.29	30.30	46.07	63.72	74.09	83.67	90.14	90.74	90.82	90.20	83.56	72.06	65.91
y	33	32	21	95	110	281	229	310	312	199	287	178	57	58	66	88	81	135	168	169	84	100	92
x	54.76	35.84	59.86	79.58	88.10	94.52	99.67	99.99	99.11	92.56	83.82	73.86	62.57	55.96	55.24	74.16	83.44	83.74	92.41	94.04	87.68	79.85	73.75
y	80	57	59	58	42	30	55	35	34	30	34	37	48	33	55	63	62	79	55	49	80	58	55
x	62.60	55.21	51.41	65.87	63.68	66.56	77.08	77.69	81.98	77.34	70.83	63.00	58.45	55.19	54.41	57.77	51.47	58.11	62.35	68.73	74.94	71.92	66.71
y	60	36	29	45	39	45	36	32	20	29	36	41	57	31	46								
x	60.40	54.60	46.25	32.46	30.76	58.11	63.98	71.85	71.25	77.38	76.60	73.21	69.41	62.81	76.37								

Case 2: Without Tremors Estimated as Resulting from Blastings

y	11	27	110	107	140	129	130	109	82	.31	46	6		as above
x	18.16	40.21	58.90	59.96	63.47	66.81	63.61	66.56	62.87	51.94	31.29	30.30		as above

y = monthly number of tremors (with or without the blastings), as dependent regression variable (n);

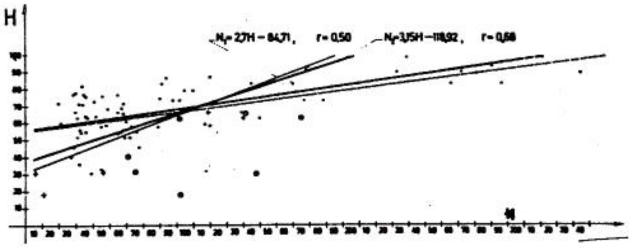
x = mean monthly reservoir levels, as independent regression variable (H).

Table 3-2 Linear Correlation between the Monthly Number of Tremors and the Mean Monthly Level of the Reservoir, for n = 7 x 12 = 84 months

	Case 1	Case 2
$x-\bar{x}=\frac{S_{xy}}{S^2_y}(y-\bar{y})$	$N=2{,}7H-84{,}71$	$N=3{,}15H-118{,}92$
$y-\bar{y}=\frac{S_{xy}}{S^2_y}(x-\bar{x})$	$H=\cancel{0{,}13N}+55{,}12$	$H=\cancel{0{,}15N}+54{,}02$
$\bar{y}=\frac{\sum_{i=1}^{n} y_i}{n}$	$\frac{8246}{84}=98{,}17$	$\frac{7913}{84}=94{,}20$
$\bar{x}=\frac{\sum_{i=1}^{n} x_i}{n}$	$\frac{5689{,}31}{84}=67{,}73$	$67{,}73$
$S_{xy}=\frac{\Sigma(x_i-\bar{x})(\bar{y}_i-y)}{n}$	$\frac{66014{,}15}{84}=785{,}88$	$\frac{76931{,}11}{84}=915{,}85$
$S^2_y=\frac{\Sigma(y_i-\bar{y})^2}{n}$	$\frac{514234{,}36}{84}=6121{,}84$	$\frac{528496{,}16}{84}=6291{,}62$
$S^2_x=\frac{\Sigma(x_i-\bar{x})^2}{n}$	$\frac{24448{,}91}{84}=291{,}06$	$291{,}06$
$r=\frac{S_{xy}}{S_x S_y}$	$\frac{785{,}88}{78{,}24\cdot 17{,}06}=0{,}59$	$\frac{915{,}85}{79{,}32\cdot 17{,}06}=0{,}68$
	$\boxed{r=0{,}59}$	$\boxed{r=0{,}68}$

(2) The recordings labeled only as natural earthquakes, with r = 0.68.

Table 3-1 gives the basic data and Table 3-2 the estimated correlation coefficients.



Note:
- . Recordings that are not controversial
- \+ Number of earthquakes without records designated as blastings
- o Number of earthquakes with records estimated as blastings

Fig. 3-1 Correlation between the monthly number (n) of recorded earthquakes, and the mean monthly levels (H) of the Bileća Reservoir

For the linear correlation, a larger correlation of the number of earthquakes with the monthly mean water level of reservoir leads to the interpretation that the recorded seismic waves should be labeled as natural earthquakes (Fig. 3-1). This graphical presentation indicates also the existence of a positive correlation between the number of earthquakes (n) and the water level (H) of the reservoir. However, it is not realistic to interpret all the numerous shock waves, recorded in November 1967 and in October 1968, to have been caused by low water levels in the reservoir. This analysis led to the conclusion that some recorded tremors were caused neither by natural earthquakes nor by changes in reservoir levels and, therefore, have not been used in the further analysis.

3-2 Microtremor Activity Caused by Turbine Operation, Water Passing Through Bottom Outlets and Over Spillways

A comparison of records of operation of turbines and generators of the hydroelectric power plant at the dam with the recorded seismic waves, showed that they have been responsible for some microtremor activity, namely of two kinds of vibrations, of a period of about 0.1 sec, and of a period of about 0.2 sec. Their amplitudes varied in the wide range, of the order of the magnitude of $n \times 10^{-3}$, with $1 \leq n \leq 10$. For the period 0.1 sec the wave amplitudes were largest for the E-W component, average for the N-S component, and smallest for the vertical Z component, with amplitude ratios

$$A_Z : A_{N-S} : A_{E-W} = 1.0 : 1.4 : 1.53 . \qquad (3\text{-}1)$$

The ratios of average amplitudes of vibrations for the period of 0.2 sec were:

$$A_Z : A_{N-S} : A_{E-W} = 1.0 : 0.64 : 0.84 . \qquad (3\text{-}2)$$

Whenever the spillway was in operation during the Spring of 1970 the microtremor activities were recorded due to water vorticity in the stilling basin. They were very intensive during the hydraulic investigations, which were conducted for the comparison between the spillway performance and the result of hydraulic small-scale models and the corresponding mathematical expressions. The amplitudes of this induced seismicity were so high that the neighboring seismogram tracings intersected, converged and mixed. Therefore, it was unfeasible to either analyze their characteristics, or to interpret the tremors caused by spillway operation. During this operational time, the natural seismic activity and the seismic activity induced by the changes in water storage in the reservoir could not be followed either, especially those originated at distances under 5 km.

It should be pointed out that the parasitic influences by various waves generated at the power plant, bottom outlets and spillway of significant amplitudes of microseismic activity made the indentification of waves produced by the natural earthquakes either impossible or practically unfeasible. The two lines on the top of the graph on photograph (Fig. 3-2) of the recorded microseismic waves represent recordings by seismographs during the period for which the operation of the spillway was intentionally stopped in order to enable comparison between the conditions of the spillway being active and inactive. It was clear that at the maximum water level in the reservoir and during the operation of the spillway, the total seismic activity could not be properly recorded and investigated. This fact was taken into consideration in data analysis. However, the inference was that the natural seismic activity within the 5 km radius should not have been very different in comparison with the previous loading cycles of the reservoir during which the spillway was not in operation.

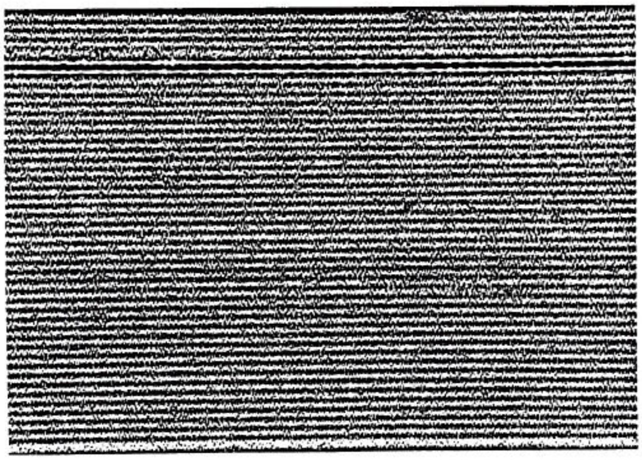


Fig. 3-2 Microtremor activities due to spillway operation (East-west component of recorded seismic waves)

3-3 Earthquakes Resulting from Geophysical Phenomena of a Wider Region Surrounding the Reservoir

Earthquakes of region-wide and continent-wide origins, according to interpretation by the geophysicists, were recorded nearly constantly but with a variable intensity. They are assumed to be linked to processes occurring in reservoir surrounding areas and not caused by the locally induced seismicity of various kinds. The intensity of waves naturally induced varies within a wide range, with amplitudes highest during the period November to Mid-April, when also the intensity was highest. These intense seismic activities occurred mostly in the late fall, winter, and spring. Their periods range within wide limits, most often between 1.7 and 2.7 sec, but exceptionally between 10 and 16 sec. Their amplitudes are the highest for the vertical Z component, up to $n \times 10^{-2}\mu$ with $1 \leq n < 10$. The ratios of the average amplitudes of individual components were

$$A_Z : A_{N-S} : A_{E-W} = 1 : 0.55 : 0.48 . \qquad (3\text{-}3)$$

These earthquakes did not affect interpretation of seismograph recordings, regardless whether they have been natural earthquake events or the earthquake events induced by the fluctuation of the reservoir level.

3-4 Air and Water Shocks

The increases in water level of the reservoir change the natural hydrological conditions of water pressures and flows in fissures and underground channels in karst formations in the immediate or even distant surroundings of the reservoir. They especially change the conditions of the Trebišnjica River Springs, covered by the reservoir for about 70 m. The groundwater levels in boreholes around the reservoir boundaries, as well as in the catchment area of the storage reservoir show that the above changes have occurred. The increase in the reservoir levels, but also the rate of change of this level, depend on the precipitation conditions (intensity, duration, total rainfall, snowfall, snowmelt) in the catchment area and on the drainage conditions of the reservoir underground catchment area.

The changes in the condition of subterranean water states and flows in karst areas often produce the air and water shocks which propagate through the karst formations as the elastic waves. They present themselves as local earthquakes, often followed by the sound effects of the escaping air on the ground surface. Several phenomena such as the sound of escaping air, changes in water color in some parts of the reservoir, observed in the vicinity of occurrence of these shock waves, have been identified. Some occurred immediately upstream of the dam, especially at the right river bank, in the region of a swallow hole. It was not feasible to distinguish these shock waves from the natural earthquake waves, except when they have been caused by rock blastings. The times of their occurrences and recording of these air and water shock waves excluded the possibility that they have been caused by rock blastings.

The above analysis indicates that a long and tedious effort was necessary to differentiate, with a plausible certainty, between the natural earthquakes and those caused by the reservoir water storage, with relative numbers of recorded waves of 1,038 and 9,303, or of the total of 10,341, respectively. It should be noted that the total number of earthquakes was also affected by the fact that only the earthquakes of relatively small energy, which occurred at short distances from the seismologic station at the dam site, could be recorded.

3-5 Determination of Distance of Hypocenter from the Recording Site

The distance of the hypocenter was determined as the time difference between the arrival of longitudial (primary) P-waves and transversal (secondary) S-waves (see Subchapter 3-9). Engineering seismology states that in the homogenious and isotropic media the following relations are valid:

$$D = \frac{V_S\, V_P\, (T_S - T_P)}{V_P - V_S} = \beta(T_S - T_P) \qquad (3\text{-}4)$$

with D = the distance of hypocenter in km, V_P = the dispersion velocity of longitudinal waves (km/sec), V_S = the dispersion velocity of transversal waves (km/sec), T_P = the time of the passage at the recording site of longitudinal waves (sec), and T_S = the time of the passage at the recording site of the primary transversal waves (sec).

A large number of measured values of dynamic rock module E, as well as the other geophysical investigations, lead to the estimate of the average celerity of elastic waves in the reservoir surrounding rocks as $V_P = 5.1$ km/sec and $V_S = 2.95$ km/sec. Taking the parameter β in Eq. (3-4) as a constant, then

$$\beta = \frac{5.1 \times 2.95}{5.1 - 2.95} = \frac{15.045}{2.15} = 6.998 \simeq 7.0 \text{ km/sec} .$$

The minimum value of the time difference between the passage of the primary earthquake waves, $(T_S - T_P)$, which was determined, was 0.1 sec. Accordingly, the minimum distance to the hypocenter is determined as $D_{min} = 0.7$ km.

The distance of the epicenter cannot be computed exactly from the recording of one seismologic station only; to locate the epicenter, the recordings of three seismic stations are needed (Fig. 3-3). It means that the location of the depth of the hypocenter (focus) can be determined by

$$D^2 = \Delta^2 + d^2 , \qquad (3\text{-}5)$$

with Δ = the distance of the epicenter (km), and d = the depth of the hypocenter (km).

The report on investigation of effects of storage reservoirs in karst areas on seismic activity foresaw the installation of two more seismologic stations of high sensitivity in the vicinity of the reservoir. However, this program was not implemented because of difficulties of economic and technical nature, and the lack of awareness on the significance of outlined investigations.

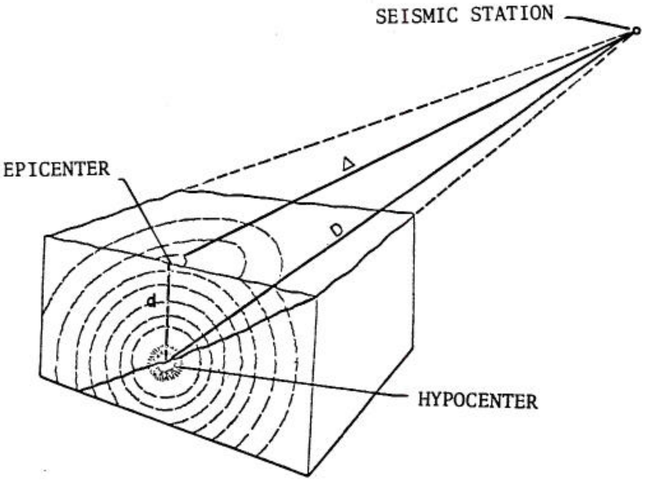


Fig. 3-3 The use of three seismic stations to determine the earthquake's hypocenter

Because of the impossibility to determine distances of epicenters precisely, it was estimated in all the geophysical interpretations that the epicenter distance equals the hypocenter distance. This approximation would be correct only if the hypocenter and the seismologic station were at the same elevation (namely in this particular case of 423 m A.S.L.). In all other cases the error depends on the location of the hypocenter. The following examples show the errors in determining the epicenters (Δ) for the two depths, 1.0 and 5.0 km:

(a) Hypocenter depth, d = 1.0 km

D = 75.0 km	Δ = 74.99 km	Error = 0.01 km (0.013%)
D = 30.0 km	Δ = 29.98 km	Error = 0.02 km (0.066%)
D = 10.0 km	Δ = 9.95 km	Error = 0.03 km (0.15%)
D = 5.0 km	Δ = 4.89 km	Error = 0.05 km (2.2%)
D = 1.0 km	earthquake in vicinity of station	Error = 1.00 km (100%)

(b) Hypocenter depth, d = 5.0 km

D = 75.0 km	Δ = 74.83 km	Error = 0.17 km (0.022%)
D = 30.0 km	Δ = 29.58 km	Error = 0.42 km (0.14%)
D = 20.0 km	Δ = 19.36 km	Error = 0.64 km (0.32%)
D = 10.0 km	Δ = 8.66 km	Error = 1.34 km (1.34%)
D = 5.0 km	earthquake in vicinity of station	Error = 5.00 km (100%)

As the above simple computations show, the equating of hypocenter distance with epicenter distance, the errors increase as the epicenter distance decreases and the hypocenter depth increases. According to the literature, the hypocenters of most natural earthquakes are at depths of 3-30 km, while the most destructive ones have hypocenter depths at 60-100 km. In some cases (Kuril Islands) the hypocenter depths of 300-700 km were recorded.

The earthquakes assumed to be induced by storage reservoirs had hypocenter 1-11 km deep (Koyna Dam, India, 5 km; Hsinfengkian Dam, China, 1-11 km). The earthquakes caused by injecting water into the underground (Denver and Rangley, Colorado, USA) had hypocenters at the depth of 2-3.5 km.

The feasibility report on the project on seismic activities related to the Bileća Reservoir has intended to classify the registered earthquakes according to their epicenter distance from the seismologic station, as follows: less than 1 km, 1-5 km, 10-20 km, 20-30 km, and 30-75 km.

The study of the geographical location of epicenters contains the error due to the above approximation. It was not feasible to determine the hypocenter depth for most earthquakes. However, the hypocenter depth of earthquakes that released the energy greater than 10^{15} ergs can be determined by using the seismologic stations Sarajevo, Titograd, and Mostar, which are about 100 km distant from the dam-site station. The hypocenter depth can also be estimated by the difference between the times of passage of P and S waves at the recording station, because that difference increases with an increase of the hypocenter depth. This latter approach permitted an approximate determination whether the hypocenter was deep or shallow. Great care was given to this method because of potential of large errors to be made, by estimating the focus depth.

3-6 Determination of the Azimuth of Epicenter

Since recordings at only one seismic station are available, the azimuth of epicenter as the second polar coordinate can be estimated by relating the amplitudes of the primary longitudinal waves recorded at the horizontal seismogram, namely as

$$\text{tg}\ \alpha = \frac{A_{E-W}}{A_{N-S}} \qquad (3-6)$$

where α = the epicenter azimuth, A_{E-W} = the amplitude of the primary longitudinal waves on the E-W horizontal component, and A_{N-S} = the amplitude of the primary longitudinal waves on the N-S horizontal component.

In estimating the location of the azimuth large errors are due to the difficulty of exactly determining the amplitudes of primary waves, which are usually very small. Often it is not feasible to read them, so that the phases are not correctly identified; sometimes the first one that appeared at the recording graph was adopted. It is especially difficult to estimate the location of the azimuth when it coincides or nearly coincides with the orientation of one of the seismographs.

The concentration of epicenters at about 0.7 km comes from the fact that the shorter epicenter distances could not be accurately determined. Accordingly, the seeming regularities in the geographical location of epicenters (under 5 km) should be treated as results of rough estimates only.

3-7 Released Energy

The released earthquake energy is estimated on the basis of the following assumptions:

(1) All of the released energy is transferred into the elastic waves;

(2) The elastic wave energy is not transformed into other kinds of energy; and

(3) The formations through which the elastic waves travel are homogeneous and isotropic.

The following expression is used for the calculation of released energy:

$$E = 2\pi^3 \rho D^2 \sum_{i=1}^{k} t_i V_i \left(\frac{A_i}{T_i}\right)^2 \qquad (3-7)$$

where ρ = the rock density of 2.67 gr/cm^3 (based on geophysical measurements), D = the hypocenter distance, V_i = the celerity of the observed wave, T_i = the period of the observed wave, A_i = the amplitude, t_i = the impulse duration, and k = the number of impulses that can be read on a recording and that resulted from the same earthquake.

The greater the distance from the seismologic station, the smaller the number of low energy earthquakes was recorded. It was hard, actually impossible, to determine their parameters because of seismograph sensitivity and various other interferences. In other words, beyond a certain distance from the station, these earthquakes could not be registered.

The reliability of recorded data is based on the literature results and on various tests performed by the geophysicists and the writer. The conclusions on this reliability are:

Earthquake frequency. This is reliable information because it is derived from the registered graphs. Earthquakes resulting from the rock blastings were eliminated, although there was a doubt for the existence of a large number of rock blasts as assessed. It was evident from the analysis that those quakes were not caused either by the reservoir or by natural processes.

Epicenter distance. The hypocenter distance is an estimated information, based on characteristics of each earthquake. This estimate is subject mainly to the error contained in the expression for D of Eq. 3-4. The hypocenter distance was taken as the epicenter distance, with a large error committed for hypocenter distances shorter than 5.0 km.

Azimuth. It is an estimated information based on the recorded graphs. Errors in data interpretation are likely.

Geographical location of the epicenter. This information is based on the estimated values for the hypocenter distance, assumed equal to the epicenter distance. This information is subject to the errors contained in values on which it is based. A detailed geological and geotectonical analysis would determine the reliability of this information. For this study, it is characterized as a rough approximation.

Released energy. Information on released energy was obtained for each earthquake from the instrument recordings. The errors contained in processing the recorded graphs are such that they do not introduce large unreliability. Together with the information on earthquake frequency, this is the most accurate and valuable information on data on earthquakes around the Bileća Reservoir, taken herein as an example of investigating the effects of storage reservoirs on earthquakes in karst areas.

3-8 General Information on Seismic Waves

To enable readers to follow this text, whose specialty is outside the field of engineering seismology, the general information on waves caused by earthquakes and on seismology is summarized here.

Energy released at the hypocenter travels through the earth's crust in the form of elastic, seismic waves. Vibrations caused by earthquakes are complex. The seismic movements at a point on the surface are irregular, non-periodic, although some general regularity exists. The intensity and irregularity of vibrations of a terrain depend on such factors as: (i) the release of focal energy, with its spectral composition and dominating direction of propagation; (ii)epicenter distance and hypocenter depth; (iii) the composition and structure of the earth's crust; (iv) the degree of loss of the emitted energy to the non-elastic processes; (v) the composition and structure of the terrain at the given point; and similar factors. Accordingly, no simple regularities govern the transformations of seismic waves which affect the earth's surface at a point and cause vibrations recorded on seismographs.

Types of waves are: body and surface waves. Body waves are: (i) longitudinal seismic waves of higher celerity registered at the seismologic stations as P, or primary waves; and (ii) transversal seismic waves with celerities smaller than those of longitudinal waves, and which do not travel through liquids, registered as S, or the secondary waves.

The characteristics of the P and S waves are best illustrated by Fig. 3-4, taken from J. Gilluly et. al (1975). The P and S waves are of great importance in seismology because as body waves they served for Mohorovičić to discover the discontinuity (Moho-layer) between the earth's crust and the upper section of the mantle. According to J. Gilluly et. al (1975, p. 104), "The Mohorovičić discontinuity is a fundamental feature of the earth structure."

The investigation by scientists in USSR (1962) raised the hopes for predicting the catastrophic earthquakes on the basis of relations of celerities of the P and S waves of artificial or natural earthquakes. It was inferred, on the basis of their properties, the outer part of the core should be in the molten state since only the P-waves and not the S-waves travel through it. The properties and the composition of the earth's crust, for example the Gutenberg-Wiechert discontinuity or the boundary of the core, are also inferred from the changes in seismic wave characteristics as they change with the depth. The study of celerities and of the other wave characteristics, such as the surface wave characteristics as the Love or the Rayleigh waves and the above discussed body waves, produced the basic information on the earth's crust. They also contributed to the advancement of the tectonic plate theory. The recent investigations showed that earthquakes most frequently occur along the boundaries of tectonic plates. The earthquakes are conceived as the consequences of various activities along these boundaries, and relate to the history of tectonic plates. Study of the properties of seismic waves provides an insight into the direction of relative movement between the tectonic plates. The scientists are not unanimous on the question of movements of continents, as certain doubts have been raised.

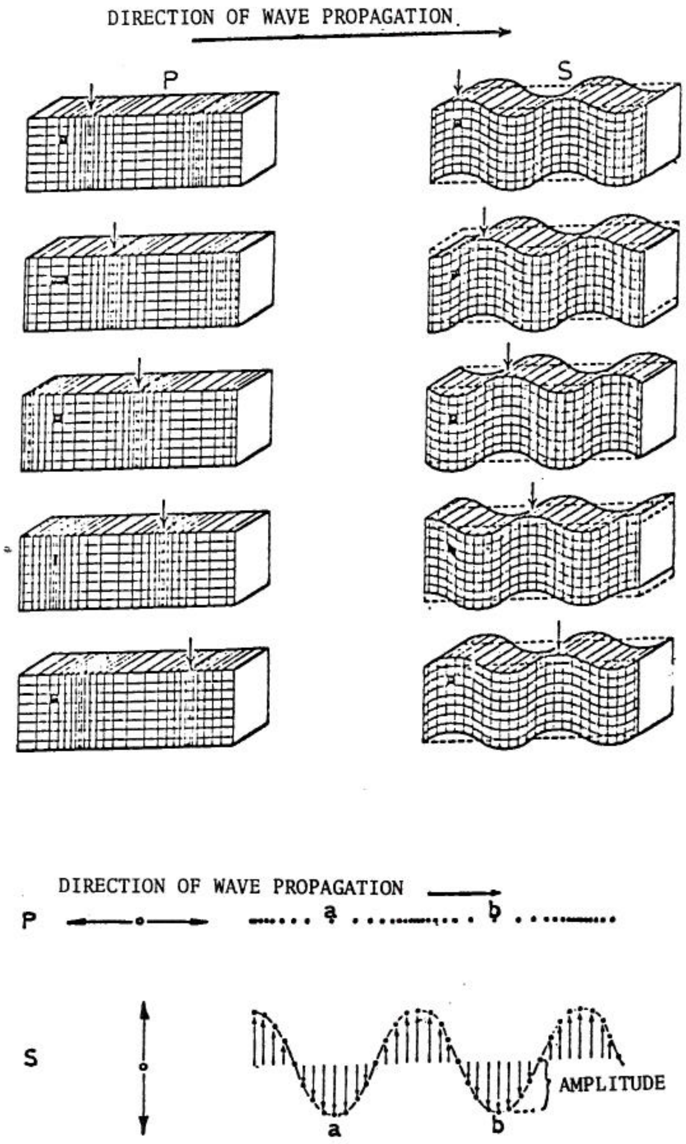


Fig. 3-4 Propagation of seismic waves, according to the books "The Way the Earth Works (page 9)," and "Principles of Geology (page 95)."

During each earthquake a seismic field is formed on the earth's surface with a very complex system of vibrations. The greater the number of observed points, the better the earthquake properties can be determined. To register vibrations of the terrain, the pendulum seismographs of large mass are used. The pendulum has a large period of its motion, much larger than the period of earth's surface vibrations. The earth's vibrations do not exert influence on the mass of the pendulum, or their influence is negligible, so that the pendulum does not respond to terrain vibrations. The pendulum is connected (mechanically, optically by light rays, electro-dynamically, electro-magnetically, electronically) to instruments for recording the relative motions of the terrain in relation to the pendulum. Three seismographs are usually employed: two to register the horizontal movements along X and Y coordinates (E-W and N-S directions), and the third to register the vertical movements on the Z coordinate.

The earliest records of an instrument for detecting earthquakes are found in the ancient past. Figure 3-5 presents an instrument from the period 78-139 B.C., constructed by Chang Hen, a Chinese geographer, astronomer and mathematician. It is kept in Peking Geological Museum. The oldest recorded and registered earthquakes in China date as early as 780 B.C.

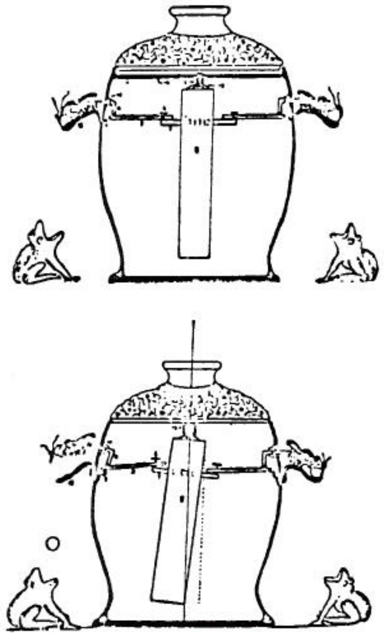


Fig. 3-5 An ancient type instrument (China, period 78-139 B.C.), taken from the Journal Le Courier (UNESCO, May 1976)

The historic data on earthquakes on Yugoslavian territory date to 360 A.D., encompassing an interval of 17 centuries. Within the frame of studies on tectonic plates, very interesting data are published for Yugoslavian territory, belonging to the "Mediterranean Valley" which is located on the boundaries between the Eurasian and African tectonic plates. Yugoslavia is situated in a geologically and seismologically very active region, belonging to the earthquake belts of the earth.

Nowadays a wide range of instruments are used to collect information on earthquakes, as the seismologic tools, such as: accelerometers, clinographs, vibration graphs, seismographs, magnetometers, extensiometers, sound sensors, water tube tiltmeters of high sensitivity, tiltmeters, lasers, geodynamic satellite (NASA-1976), various geodetic instruments, and similar. An important role is played by the piezometers, i.e. the deep boreholes for observing the subterranean water levels.

Methods applied in seismology vary, but depend on the period studied. The following data (according to S. V. Medvedev) should be used, but with great care:

	Time Periods in Years	
Tectonical Methods	1,000,000--	100,000,000
Geomorphological Methods	1,000--	1,000,000
Non-Instrumental Seismo-Statistics	50--	1,000
Geodetical Measurements	5--	50
Observations at a Network of Seismologic Stations	5--	50
Expeditional Instrumental Methods	1--	5

The greatest difficulty in studying and generalizing the regularities in seismology is to find specific regularities of particular regions of the earth. Besides, investigations by various authors differ, making difficult the use and generalization of information.

Likely the future developments in seismology will not be limited only to establishing the relationships between the seismic activity and the geological conditions and the properties of the surface. The mathematical and physical models, as well as the investigations both in situ and in laboratories will give opportunities for a more complex analysis in determining the cause-effect relationships.

Chapter 4
SCREENING THE POOL OF SEISMIC DATA FOR ANALYSIS

4-1 Geographical Location of Earthquakes

The fact that the available data had been obtained from only one seismologic station conditioned that the estimated geographical locations of epicenters be treated only as approximations, especially for those which occurred within the 5.0 km radius. Figure 4-1 points out that earthquakes are located at the same positions prior and after the filling of the reservoir.

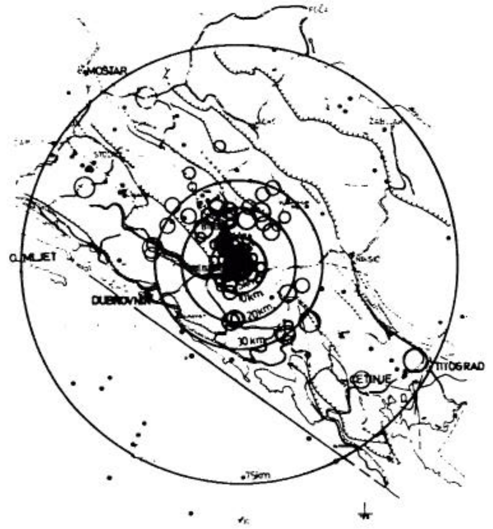


Fig. 4-1 Determined earthquake locations within a large region (up to 75 km) around the Bileća Reservoir, with the earthquake released energy represented by the circle area

Earthquakes outside the region of the reservoir occur mainly along or within the vicinity of important faults. Therefore, the approximations may be relatively good, regardless that the hypocenter distance was taken equal to the epicenter distance. The earthquake epicenters are shown in the larger region for research purposes only for those earthquakes which released the energy of $E \geq n \times 10^9$ ergs, with $1 \leq n \leq 10$, only for the first three cycles of reservoir loading and unloading in the years 1967/68, 1968/69, and 1969/70. At that time, the effects of the reservoir on earthquakes, judging by graphical displays and the initial mathematical analysis, seemed to exist.

It is interesting to note that the distribution of epicenters are concentrated in the northwest-southwest direction, especially along the following lines:

(i) Čapljina-Stolac-Jasen-Titograd;

(ii) Nevesinje-Sniježnica-Dabarsko Polje-Nikšić; and

(iii) Dubrovnik-Petrovac.

Attention should be paid to the analysis of earthquakes that occurred in the Adriatic Sea at a certain distance from the coast, with this occurrence several times numerous prior to filling of the reservoir. They did not occur practically at all during the first three loading and unloading cycles of the reservoir. This may be explained by the fact that natural seismic activities are not uniform either over the years or over a year, with clusters of time periods of increased and time periods of decreased seismic activity. The seismic activity is not only nonuniform in time but also in space. The noted distribution of epicenters in the adjacent region of the Adriatic Sea to the reservoir deserves study, which is outside the scope of this text.

The earthquake concentration in the reservoir region is to be noted in Fig. 4-2, giving the epicenters of earthquakes within 5.0 km radius, only for those earthquakes for which the coordinates of epicenters, namely the azimuth and distance, have been determined. Assuming the hypocenter distance to be equal to the epicenter distance gives large errors for this region. Though the number of registered earthquakes and the regularity in their distribution in the period after filling of the reservoir somewhat decreased, that does not eliminate doubts in the reliability of estimates. The fact is that earthquakes are concentrated in the three regions, two upstream and one downstream of the reservoir. The two upstream regions are approximately in the directions ENE-WSW and ESE-WNW, and they remained almost unchanged during the first three cycles of

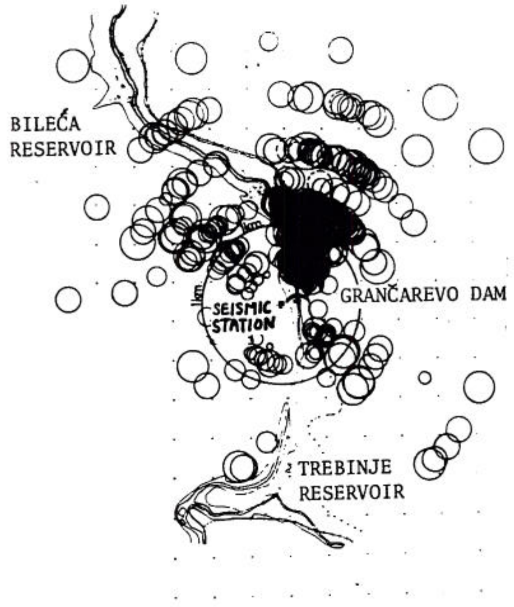


Fig. 4-2 Determined earthquake locations within 5 km distance from the seismic station after the second cycle of filling and emptying of the Bileća Reservoir (areas of circles proportional to energy releases, mostly in the range of 10^9 - 10^{11} ergs).

loadings by the reservoir, while the third in downstream direction did almost disappear during the third cycle when the maximum level of the reservoir, at 400.09 m A.S.L. was reached. Accordingly, a regularity may exist in the grouping of observed earthquakes.

The earthquake occurrence along these directions is also noted in the period preceding the filling of the reservoir. The earthquake concentration in the vicinity of the dam could have been caused by the works on the dam site.

The distribution of epicenters along the three directions is also confirmed by experience of the people living in the area. The owner of the reservoir had to pay damages to inhabitants of a village situated in the ESE-WNW direction upstream from the dam, where the concentration of earthquakes of energy $n \times 10^{6} < E < n \times 10^{10}$ ergs, with $1 \leq n < 10$, were observed. However, the distribution of earthquakes in concentric circles around the dam, as seen in Fig. 4-2, does not seem realistic. The explanations by geophysical engineers were that simplifications in decoding recordings and in data interpretation were responsible for this phenomenon. Determining the very accurate epicenter distances would be time consuming but may not be of practical importance. Attention was given to properly determining the azimuth of earthquake epicenters while the analytical estimates of distances were rounded, which caused their distributions to be in concentric circles.

4-2 Number of Earthquakes and Their Released Energy

In Chapter 3 the reliability of instrumental data was discussed. The observation period is basically divided into two subperiods, one preceding and the other following the filling of the reservoir.

Period preceding water storage. In the period preceding the water storage, from February 6, 1965 to October 31, 1967, 1,038 earthquakes were observed, inferred not to have occurred from rock blastings. Figure 4-2, however, indicates a concentration of earthquakes to have occurred in the vicinity of the dam, with relatively short distances. This phenomena deserves attention, because some of these earthquakes might have been caused by unloading and releasing of natural stresses due to the excavation of about 300,000 m^{3} of rock (about 750,000 tons) for the foundation of the dam and powerhouse. The foundation area is of about 11,000 m^{2}, with the average unloading up to 6.8 kg/cm^{2}. Apart from the rock excavation, during the same time extensive grouting works took place with high grouting pressures, ranging between 5.0 and 40.0 atm for the deepest portions of the grouting curtain, in the same area.

According to information in the literature, grouting can also induce earthquakes. This is confirmed in the Rocky Mountain Region (1962-65) 26 km northwest of Denver for the case of grouting the waste liquids and by grouting the Rangely oil region in northwest Colorado. Earthquakes in the vicinity of the Grančarevo Dam, particularly those that have occurred within the radius of 1.0 km (about 35% of earthquakes), could have been caused by the construction work phenomena.

The number of earthquakes that occurred prior to filling of the reservoir is presented in Tables 4-1 through 4-3. Out of the total of 1,038 recorded earthquakes, the epicenter distance was estimated for 813 earthquakes, and the energy for 110 earthquakes. It can be seen that 50.2% of earthquakes, for which the distance was estimated, occurred within the radius of 5.0 km. All except 22 earthquakes were recorded in

Table 4-1 Number of Earthquakes in the Period Preceding the Loading of the Reservoir, February 6, 1965 to October 31, 1967

	1965			1966			1967			TOTAL		
	EARTH-QUAKES	UNKNOWN D	UNKNOWN E	EARTH-QUAKES	UNKNOWN D	UNKNOWN E	EARTH-QUAKES	UNKNOWN D	UNKNOWN E	EARTH-QUAKES	UNKNOWN D	UNKNOWN E
JANUARY				25	12	25	27	10	23	52	22	48
FEBRUARY	14	1	11	26	15	25	14	1	8	54	17	43
MARCH	14	6	11	19	5	19	30	5	21	63	26	51
APRIL	31	8	29	10	5	8	20	8	15	61	21	52
MAY	21	1	19	20	10	19	22	10	18	63	21	56
JUNE	41	2	36	4	3	4	18	6	13	63	11	53
JULY	61	6	59	42	12	41	25	13	19	128	31	119
AUGUST	83	1	77	80	1	79	38	22	33	201	24	189
SEPTEMBER	72	6	68	22	2	21	16			110	8	89
OCTOBER	74	4	72	10		39	7			91	7	81
NOVEMBER	53	5	51	9	1	9				62	6	60
DECEMBER	80	24	77	10	7	10				90	31	87
$\sum$	544	64	510	277	86	268	217	75	150	1038	225	928

Table 4-2 Number of Earthquakes with Known Distances from the Recording Station for the Period February 6, 1965 to October 31, 1967

	1965	1966	1967	TOTAL	%
< 1km	273	–		273	33.6
1- 5	113	16	16	135	16.6
5-10	11	4	17	32	3.9
10-20	14	5	29	48	5.9
20-30	20	9	25	54	6.7
30-75	49	157	65	271	33.3
Σ	480	91	142	813	100.0

Table 4-3 Number of Earthquakes with Known Energy in the Period February 6, 1965 to October 31, 1967

	1965	1966	1967	TOTAL
<1km				
1- 5	2	–	5	7
5-10	8	1	13	22
10-20	13	3	27	43
20-30	11	5	11	27
30-75	–	–	11	11
Σ	34	9	67	110

1965 immediately after excavation and during the grouting in the deepest parts of the grouting curtain. The distribution of earthquakes (59.5%) which occurred within the 5.0 km radius was very similar to the distribution in the period following the filling of the reservoir. The number of earthquakes (33%) within the radius of 30-75 km, which were not influenced by constructions on the dam site should be paid a special attention.

The earthquake distribution by energy released is given in Tables 4-3 through 4-6, showing the 110 earthquakes in the period between February 1965 and October 1967 released a total energy of 4.65×10^{15} ergs.

Table 4-4 Distribution of Earthquakes According to Energy Classes (in Ergs) and Classes of Distances from Recording Station, in the Period February 6, 1965 to October 31, 1967

	10^6	10^7	10^8	10^9	10^{10}	10^{11}	10^{12}	10^{13}	10^{14}	10^{15}	10^{16}	TOTAL
<1km												
1- 5			1	3	3							7
5-10				3	9	7	1	2				22
10-20					10	13	17	3				43
20-30					1	7	7	7	5			27
30-75						2	2	2	4	1		11
			1	6	23	29	27	14	9	1		110

Table 4-5 Distribution of Earthquakes According to Energy Classes (in Ergs) and Years of Observation in the Period February 6, 1965 to October 31, 1967

	10^6	10^7	10^8	10^9	10^{10}	10^{11}	10^{12}	10^{13}	10^{14}	10^{15}	10^{16}	TOTAL
1965			1	1	5	9	11	5	2			34
1966						2	44	2	1			9
1967				5	18	18	12	7	6	1		67
Σ			1	6	23	29	27	14	9	1		110

Table 4-6 Distribution of the Released Energy (in Ergs) in the Period February 6, 1965 to October 31, 1967

km	1965	1966	1967	TOTAL
< 1				
1- 5	$1.80x10^{10}$		$8.00x10^{10}$	$9.80x10^{10}$
5-10	$1.56x10^{13}$	$4.09x10^{13}$	$0.18x10^{13}$	$5.83x10^{13}$
10-20	$4.92x10^{13}$	$0.20x10^{13}$	$22,63x10^{13}$	$2.78x10^{14}$
20-30	$7.99x10^{14}$	$2.42x10^{14}$	$3.14x10^{14}$	$1.36x10^{15}$
30-75			$2.96x10^{15}$	$2.96x10^{15}$
∑	$8.64x10^{14}$	$2.85x10^{14}$	$3.50x10^{15}$	$4.65x10^{15}$

In using the statistical analysis, and assuming that the distributions of earthquakes with distance (813) and of energy released represent (110) samples selected at random, the assumption is logical that similar properties of earthquakes can be attributed to all earthquakes of the samples for the same class of distances. Misinterpretations arise from choosing the subsample size and whether it is representative of the entire sample size. Then the frequency distribution of the subsample is used as the frequency distribution for the sample, namely the total number of earthquakes as for those for which the distances are estimated. That required the division of the total number of earthquakes into the classes of distances:

< 1 km	33.6%	349
1 - 5 km	16.6%	172
5 - 10 km	3.9%	40
10 - 20 km	5.9%	61
20 - 30 km	6.7%	70
30 - 75 km	33.3%	346
		∑ n = 1,038

The above frequency distribution is by classes of distance. The frequency distribution by classes of distance and by individual years are:

	1965	1966	1967	Total
1 km	309	-	-	309
1 - 5 km	128	23	10	161
5 - 10 km	13	6	26	45
10 - 20 km	16	7	44	67
20 - 30 km	23	14	38	75
30 - 75 km	55	227	99	381
	544	227	217	1,038

It should be pointed out that in the statistics the sample taking and calculations based on percentages are objected to. To ensure the objectivity in this kind of data analysis, the simple, prevailing statistical computations are used, being aware of the fact that the methods of statistical analysis in itself do not change the reliability of basic data. In other words, the statistical analysis cannot be better than the validity and accuracy of the data. Without the application of this simple statistics, the observed earthquakes would be a set of unrelated values.

Starting from the fact that it was not feasible to determine all the characteristics for the statistical sample of 1,038 earthquakes that were recorded prior to filling of the reservoir, the question arises of what conclusions can be derived from this sample. The two main properties of sampling are singled out:

(1) The sample should be representative and of sufficient size, because the conclusions derived from small samples can differ greatly from the population properties; and

(2) The sampling should be at random (though sometimes it is systematically taken), or that each observed sample should have similar probability of being a realization of the process.

For the study of the number of earthquakes, the 813 earthquakes are used by division into classes of the sample of 1,038 earthquakes. The new subsample of size 813 was considered to be representative and a random selection of earthquakes. The picture does not essentially change when a somewhat smaller or larger subsample was selected.

The situation is different in the analysis of energy released. Here, the sample is taken at random because the seismologists could not affect the selection of sample data. The basic question is the representativeness and sample size. In this case, the energy released was determined for only 110 earthquakes. Their distribution by classes of earthquake hypocenter distances from the dam site is:

	Frequency for Known Energy	Total Number of Earthquakes	% of Total Earthquakes
1 km	0	349	-
1- 5 km	7	172	4%
5-10 km	22	40	55%
10-20 km	43	61	70%
20-30 km	27	70	39%
30-75 km	11	346	3%
	110	1,038	

For the energy characteristics of the subsample, classified by distances, the released energy distribution of the total sample was inferred to be:

Distance	Number of Earthquakes	Energy Released
1 km	349	0
1 - 5 km	172	2.4×10^{12} ergs
5 - 10 km	40	10.6×10^{13} ergs
10 - 20 km	61	3.94×10^{14} ergs
20 - 30 km	70	9.53×10^{15} ergs
30 - 75 km	346	93.10×10^{15} ergs
	1,018	97.132×10^{15} ergs

The influence of earthquakes that occur within the 1-5 km radius from the dam on the total energy is not important, totaling 0.0024×10^{15} ergs only. This fact affected the decision to assume that earthquakes that occurred within the 1-5 km radius, or a total of 521 earthquakes, were caused by construction work at the dam site, however, excluding the rock blastings.

In comparing the number of earthquakes in selected subsamples, doubt persisted on how representative they are of earthquakes with the known released energy for the classes of distances within the radius of 30-75 km. The question posed was whether the above distribution of released energy only for some earthquakes in 1967, is acceptable also as the released energy for all earthquakes that occurred within the radii of 30-75 km, immediately prior to filling of the reservoir.

The following observations seem to be statistically correct:

(1) From the total number of recorded 1,038 earthquakes, a large number of 521 events within the radius of 5 km were excluded from the analysis, under the assumption that they have been caused by human activities. The remaining 517 earthquakes released the total energy of 23.4×10^{15} ergs. The order of the magnitude of released energy does not significantly change when the energy released by the earthquakes that occurred within the 1-5 km radius is included, which would total to 29.17×10^{15} ergs.

(2) The estimates of released energy for the individual years are:

1965	$\frac{107}{32} \times 8.64 \times 10^{14} =$	28.9×10^{14} ergs
1966	$\frac{250}{9} \times 2.85 \times 10^{14} =$	79.2×10^{14} ergs
1967	$\frac{208}{62} \times 3.50 \times 10^{15} =$	11.74×10^{15} ergs
		22.55×10^{15} ergs

Also in this case, if the analysis includes earthquakes with the epicenter distance within 1-5 km radius, the order of the magnitude of released energy would not substantially change, totaling 26.35×10^{15} ergs.

The basic conclusion from the above discussion is that earthquakes with the hypocenter distance from 1 to 5 km do not significantly affect the total energy released by earthquakes that have been recorded prior to filling of the reservoir. Another conclusion is that the relative occurrence of estimates of released energy, for the estimate of the released energy for the total number of earthquakes, may seem as a play with numbers. The released energy based on the subsamples properly selected carries some weight from the statistical point of view. However, doubt always exists whether the subsample of earthquakes for the distance 30-75 km is or is not representative, because the number of earthquakes for which the released energy (3%) was estimated may be very small. Tables 4-4 and 4-5 give the values of large energy earthquakes:

$E = n \cdot 10^{11}$ ergs - 2 earthquakes

$E = n \cdot 10^{12}$ ergs - 2 earthquakes

$E = n \cdot 10^{13}$ ergs - 2 earthquakes

$E = n \cdot 10^{14}$ ergs - 4 earthquakes

$E = n \cdot 10^{15}$ ergs - 1 earthquake

The energy released by an earthquake, with $E = 1.64 \times 10^{15}$ ergs, has a large effect on the distribution of energy released in the subsample.

The further conclusion is that a reliable estimation of the released energy is the basic premise for any realistic inference to be drawn of the effect of storage reservoirs in karst areas on seismic activity. This may be viewed as an introduction to more advanced analysis of the problem. The basic interpretation depends on recorded earthquakes after the reservoir is filled. The opportunities lost to gather proper data prior to filling of the reservoir and for the adequate interpretation of earthquakes recorded, cannot be alleviated by the methods of data processing. The validity of conclusions decreases when logical thinking replaces the lack of reliable data. The more the studied phenomenon fluctuates (measured by the variance), the less frequent its occurrence and the higher the demand for reliability in the derived conclusion, the larger should be the representative sample. The subsample of earthquakes that occurred at distances 30-75 km has not been sufficiently large for the period of earthquake recording prior to filling of the reservoir.

The omissions in data gathering or earthquakes for the period prior to filling of the reservoir, may be explained by the fact that the experience in this type of investigation was limited, even though it had been known for some time that earthquakes may be affected by water storage reservoirs (Marathon Dam, Greece, 1930; Hoover Dam, USA, 1935). The effects of water storage reservoirs on earthquakes did not draw attention and advanced research approaches for some time. Observational data from some sites were not available to a wider circle of experts. Besides, data made available in most cases were either incomplete or unreliable or both. Conclusions on reservoir effects on earthquakes derived from the available data for some storage reservoirs, that can be found in the current literature, are not unanimously accepted, because of the lack of definite proofs, either from the viewpoints of instrumental data used or from the viewpoints of methods applied.

Data and conclusions published often fit the particular hypothesis of the project leader in order to ensure the priority of ideas or findings, often on the expense of hard facts supporting those hypotheses. With a few exceptions, the published papers present a general discussion of data with hypothetical conclusions based on the relatively uncertain information. This approach is often defined by citing the complex nature of the potential relationship between the reservoirs and earthquakes. As the consequences of conclusions on this relationship may be a decisive factor for the future planning of large dams and storage reservoirs, they need the very critical evaluations. Examples exist for which the public opinion and a justified fear of earthquakes have stopped the construction of large dams and reservoirs. The unsupported, and especially the hasty conclusions, based on the insufficient documentation have long-range technical implications on water resources developments. The observational omissions and careful screening of recordings in the period prior to filling the Bileća Reservoir are instructive, not to be repeated in the similar future cases.

Period after filling of the reservoir. The period following the filling of the Bileća Reservoir (November 1, 1967 to October 31, 1976) is characterized by more complete and more reliable data than the period prior to filling. After the water storage has been initiated, a total of 9,303 earthquakes were registered (Table 4-7) in this period. The epicenter distances were determined for 8,607 earthquakes (Table 4-8) while the energy released was estimated for 8,548 earthquakes (Table 4-9).

The distances could not be determined for 7.5%, or 696 out of 9303 recorded earthquakes. The frequency distribution of the total number of recorded earthquakes by distance of epicenters is:

Table 4-7 Period of Filling of the Reservoir and of the Reservoir Use, November 1, 1967 to October 31, 1976

	1967/68			1968/69			1969/70			1970/71			1971/72			1972/73			1973/74			1974/75			1975/76			TOTAL			
	n	no D	no E	n	no D	no E	n	no D	no E	n	no D	no E	n	no D	no E	n	no D	no E	n	no D	no E	n	no D	no E	n	no D	no E	n	no D	no E	H
November	11			68	3	3	32	4	4	58	6	6	59	11	13	55	5	5	45			100	1	1	51			479	30	32	50,22
December	27			85	2	2	21	1	1	66	5	5	58	11	11	63	5	7	39	15	15	94	1	1	67			520	40	42	59,84
January	110	5	5	167	4	5	95	2	2	88	6	6	42	5	5	62	3	5	45	5	5	78	3	3	65	1	2	752	34	38	68,56
February	107	11	13	256	9	15	110	1	1	81	5	5	30	2	2	79	26	26	36	4	5	55	1	1	46			800	59	68	71,76
March	140	15	15	335	13	18	281	9	11	135	21	21	55	3	4	55	8	8	32	1	1	41		1	31	2	2	1105	72	81	75,54
April	129	18	19	223	10	11	229	25	31	168	19	19	35	4	4	49	4	5	20			39	1	1	51	2	2	943	83	92	79,92
May	130	3	5	262	2	4	310	20	20	169	17	17	34	1	1	80	13	15	29	1	1	51	1	1	81		3	1146	58	67	82,49
June	109	12	14	271	5	5	312	28	28	84	7	7	30			58	3	5	36			72			68			1040	55	59	80,43
July	82	6	7	160	9	9	199	22	22	100	9	9	34	1	1	55	5	7	41	2	2	36	2	2	70			777	56	59	75,74
August	31	9	10	114	5	5	287	53	53	92	8	8	37	2	3	60	7	8	57	2	3	57			51			786	86	90	68,92
September	46	13	13	89	5	5	178	46	46	80	6	6	48	10	11	36	1	1	31	3	3	89	3	3	33			630	87	88	60,77
October	6			33	12	12	57	7	7	57	8	8	33	5	7	29	3	4	46	1	1	24			40			325	36	39	56,53
Σ	928	92	101	2063	79	94	2111	218	226	1178	117	117	495	55	62	681	83	96	457	34	36	736	13	14	654	5	9	9303	696	755	
H_a	51,18			175,46			80,85			74,77			67,44			60,64			63,80			79,04			69,87						69,63

Energy is known for 8,548 earthquakes, and distance is known for 8,607 earthquakes

No D = data unavailable for epicenter distance from the recording station; No E = data unavailable for released energy; n = monthly number of earthquakes; H = monthly mean water level (in meters above sea level); and H_a = yearly mean water level (in meters above sea level)

Table 4-8 Number of Earthquakes with Known Epicenter Distances from the Recording Station in the Period November 1, 1967 to October 31, 1976

	1967 1968	1968 1969	1969 1970	1970 1971	1971 1972	1972 1973	1973 1974	1974 1975	1975 1976	Σ	%
< 1km	369	946	549	167	30	61	50	127	115	2414	28,1
1 - 5	248	719	898	543	77	71	27	132	4	2719	31,6
5 - 10	25	83	82	37	81	197	123	179	184	991	11,5
10 - 20	43	76	66	50	46	92	53	101	60	587	6,8
20 - 30	48	48	54	73	92	61	46	76	90	588	6,8
30 - 75	103	112	244	191	114	116	124	108	196	1308	15,2
Σ	836	1984	1893	1061	440	598	423	723	649	8607	
%	9,7	23,1	22,0	12,4	5,1	6,9	4,9	8,4	7,5		100,0

Table 4-9 Distribution of Earthquakes with Known Energy in the Period November 1, 1967 to October 31, 1976

	1967 1968	1968 1969	1969 1970	1970 1971	1971 1972	1972 1973	1973 1974	1974 1975	1975 1976	Σ	%
< 1km	363	931	549	167	28	60	48	126	114	2386	27,9
1 - 5	248	719	892	543	76	67	27	132	4	2708	31,7
5 - 10	25	83	80	37	77	192	123	179	184	980	11,5
10 - 20	41	76	66	50	46	89	53	101	60	582	6,8
20 - 30	47	48	54	73	92	61	46	75	90	586	6,8
30 - 75	103	112	244	191	114	116	124	109	193	1306	15,3
Σ	827	1969	1885	1061	433	585	421	722	645	8548	
%	9,7	23,9	22,9	12,4	5,1	6,8	5,0	8,4	7,6		100,0

0 - 1 km	27.9%	(2414 + 196)	2610
1 - 5 km	31.7%	(2719 + 220)	2939
5 - 10 km	11.5%	(991 + 80)	1071
10 - 20 km	6.8%	(587 + 47)	634
20 - 30 km	6.8%	(588 + 47)	635
30 - 75 km	15.3%	(1308 + 106)	1414
		(8607 + 696)	9303

The number of earthquakes for which the epicenter distance could not be estimated represent a small percentage of the total number, such that they would not impair the drawing of inferences, without correcting for this deficiency. For the sake of presentation and analysis of how the earthquakes, for which the epicenter distance and the released energy could not be estimated, affect the energy picture as a whole, some corrections are made to account for that number of earthquakes for which distance and energy could not be estimated.

As stated in Chapter 3, the energy could not be calculated for the earthquakes for which distances could not be estimated. Interferences in recording were responsible for not being able to estimate the released energy, and in some cases for a larger number of earthquakes than those for which the distances could not be determined. The released energy was not estimated for 8.1%, or 755 out of 9303 recorded earthquakes. Their distribution by distances is:

0 - 1 km	224	(28)
1 - 5 km	231	(11)
5 - 10 km	91	(11)
10 - 20 km	52	(5)
20 - 30 km	49	(2)
30 - 75 km	108	(2)
	755	(59)

The difference in the number of earthquakes for which distances were determined and in the number of earthquakes for which the released energy is estimated is given in parentheses. The classification of earthquakes according to energy released is presented in Table 4-10 and 4-11. The total energy released by all those earthquakes is 1.142×10^{17} ergs (Table 4-12). To enable a comparison, the earthquake responsible for the destruction of the city of Skopje in Yugoslavia (July 21, 1963, with about 1,500 casualities) released the energy of that order.

Table 4-10 Distribution of Number of Earthquakes According to Classes of Epicenter Distances from the Recording Station and Energy Classes in the Period November 1, 1967 to October 31, 1976

	10^{6}	10^{7}	10^{8}	10^{9}	10^{10}	10^{11}	10^{12}	10^{13}	10^{14}	10^{15}	10^{16}	Σ	%
< 1km	306	1094	715	211	56	3	1					2386	27,9
1 - 5	3	398	1030	925	302	46	4					2708	31,7
5 - 10	1	3	32	344	500	87	13					980	11,5
10 - 20		2	5	74	234	192	58	15	2			582	6,8
20 - 30			1	24	142	254	129	27	7	2		586	6,8
30 - 75	1		1	8	126	398	435	242	81	13	1	1306	15,3
Σ	311	1497	1784	1586	1360	980	640	284	90	15	1	8548	100,0

Table 4-11 Distribution of Earthquakes According to Energy Classes and Periods of Observations in the Period November 1, 1967 to October 31, 1976

	10^{6}	10^{7}	10^{8}	10^{9}	10^{10}	10^{11}	10^{12}	10^{13}	10^{14}	10^{15}	10^{16}	Σ	%
1967-1968	18	172	217	161	75	68	54	44	13	5		827	9,7
1968-1969	86	491	542	436	196	93	71	37	14	3		1969	23,0
1969-1970	67	395	542	357	210	162	102	24	20	5	1	1885	22,0
1970-1971	76	263	239	148	124	139	50	13	8	1		1061	12,4
1971-1972	9	33	40	63	100	95	56	33	4			433	5,1
1972-1973	3	35	54	134	157	108	51	29	13	1		585	6,8
1973-1974	5	22	24	50	115	88	64	46	7			421	4,9
1974-1975	8	40	83	115	205	118	96	33	6			722	8,5
1975-1976	39	46	43	104	178	109	96	25	5			645	7,6
Σ	311	1497	1784	1586	1360	980	640	284	90	15	1	8548	100,0

Table 4-12 Distribution of Released Energy (in Ergs) in the Period November 1, 1967 to October 31, 1976

	1967 1968	1968 1969	1969 1970	1970 1971	1971 1972	1972 1973	1973 1974	1974 1975	1975 1976	Σ
< 1km	7,90 x10 [illegible]	15,10 x10 [illegible]	13,80 x10 [illegible]	0,686 x10 [illegible]	0,755 x10 [illegible]	2,15 x10 [illegible]	0,624 x10 [illegible]	1,21 x10 [illegible]	1,01 x10 [illegible]	5,332 x10 [illegible]
1 - 5	4,034 x10 [illegible]	6,96 x10 [illegible]	6,14 x10 [illegible]	1,11 x10 [illegible]	0,10 x10 [illegible]	0,121 x10 [illegible]	0,311 x10 [illegible]	8,88 x10 [illegible]	0,062 x10 [illegible]	2,765 x10 [illegible]
5 - 10	0,331 x10 [illegible]	2,59 x10 [illegible]	1,07 x10 [illegible]	0,257 x10 [illegible]	0,274 x10 [illegible]	1,07 x10 [illegible]	0,374 x10 [illegible]	0,352 x10 [illegible]	1,00 x10 [illegible]	7,318 x10 [illegible]
10 - 20	0,87 x10 [illegible]	1,91 x10 [illegible]	6,39 x10 [illegible]	0,324 x10 [illegible]	0,275 x10 [illegible]	0,433 x10 [illegible]	0,172 x10 [illegible]	0,521 x10 [illegible]	0,621 x10 [illegible]	1,132 x10 [illegible]
20 - 30	2,566 x10 [illegible]	0,50 x10 [illegible]	0,281 x10 [illegible]	0,306 x10 [illegible]	0,321 x10 [illegible]	0,111 x10 [illegible]	0,514 x10 [illegible]	0,090 x10 [illegible]	0,126 x10 [illegible]	4,821 x10 [illegible]
30 - 75	1,565 x10 [illegible]	1,09 x10 [illegible]	6,00 x10 [illegible]	0,55 x10 [illegible]	0,198 x10 [illegible]	0,684 x10 [illegible]	0,302 x10 [illegible]	0,252 x10 [illegible]	0,178 x10 [illegible]	0,815 x10 [illegible]
Σ	1,831 x10 [illegible]	1,16 x10 [illegible]	6,09 x10 [illegible]	0,584 x10 [illegible]	0,233 x10 [illegible]	0,70 x10 [illegible]	0,355 x10 [illegible]	0,268 x10 [illegible]	0,198 x10 [illegible]	1,142 x10 [illegible]

The earthquakes for which the released energy could not be estimated, because of various interferences, by analogy could have released the following energies for given distances:

Distance	Number of Earthquakes	Released Energy
0 - 1 km	224	5.00×10^{11} ergs
1 - 5 km	231	2.36×10^{12} ergs
5 - 10 km	91	6.79×10^{12} ergs
10 - 20 km	52	1.01×10^{14} ergs
20 - 30 km	49	4.03×10^{14} ergs
30 - 75 km	108	8.94×10^{15} ergs
	755	$E_1 = 9.454 \times 10^{15}$ ergs

As for the period prior to filling of the reservoir, the estimates of released energy for all those earthquakes for which the energy could not be estimated in the post-filling period are given below for both the total post-filling period observed and for each water year of observations.

In the post-filling period, (November 1, 1967 to October 31, 1976), as stated, the energy could not be estimated for 755 earthquakes. By analogy with those earthquakes for which the energy could be estimated, their released energy approximately would be

$$E_2 = 755 \times \frac{1.142 \times 10^{17}}{8548} = 1.008 \times 10^{16} \text{ ergs.}$$

According to each year observations, the released energy of the 755 earthquakes would be, by inference, approximately:

1967/1968	101 earthquakes	2.236×10^{15} ergs
1968/1969	94 earthquakes	0.554×10^{15} ergs
1969/1970	226 earthquakes	7.301×10^{15} ergs
1970/1971	117 earthquakes	0.644×10^{15} ergs
1971/1972	62 earthquakes	0.334×10^{15} ergs
1972/1973	96 earthquakes	1.149×10^{15} ergs
1973/1974	36 earthquakes	0.304×10^{15} ergs
1974/1975	14 earthquakes	0.052×10^{15} ergs
1975/1976	9 earthquakes	0.028×10^{15} ergs
	755 earthquakes	$E_3 = 1.260 \times 10^{16}$ ergs

The ratios of the three values of E (E_1, E_2, E_3) then become $0.945 \times 10^{16} : 1.008 \times 10^{16} : 1.260 \times 10^{16}$ ergs, or 1 : 1.06 : 1.34. The differences of ratios are not significant. The question to be posed is whether a correction for the total energy is necessary to take care of those earthquakes for which the released energy could not be estimated. The writer found that this correction was not necessary, because it would influence the total released energy only by 8.2% - 11.0%. If correction is made, it would look like the following:

	Estimated Total Released Energy	Corrected Total Released Energy
0 - 1 km	5.332×10^{12}	5.832×10^{12} ergs
1 - 5 km	2.765×10^{13}	3.001×10^{13} ergs
5 - 10 km	7.318×10^{13}	7.997×10^{13} ergs
10 - 20 km	1.132×10^{15}	1.233×10^{15} ergs
20 - 30 km	4.821×10^{15}	5.224×10^{15} ergs
30 - 75 km	10.815×10^{16}	11.709×10^{16} ergs

with the total estimated released energy of 1.142×10^{17} ergs before the corrections, and the total released energy of 1.243×10^{17} ergs after the corrections are made.

According to the individual years of observations, the distribution of the released energy is:

	Estimated Released Energy	Corrected Released Energy
1967/1968	1.831×10^{16}	2.055×10^{16} ergs
1968/1969	1.16×10^{16}	1.215×10^{16} ergs
1969/1970	6.09×10^{16}	6.820×10^{16} ergs
1970/1971	0.584×10^{16}	0.648×10^{16} ergs
1971/1972	0.233×10^{16}	0.266×10^{16} ergs
1972/1973	0.700×10^{16}	0.712×10^{16} ergs
1973/1974	0.355×10^{16}	0.385×10^{16} ergs
1974/1975	0.268×10^{16}	0.273×10^{16} ergs
1975/1976	0.198×10^{16}	0.201×10^{16} ergs

The data given above confirm that the total estimated release energy, based on the instrumental recordings, substantially does not change in the case a correction is made for the values of released energy of the earthquakes by the statistical method. The writer is not of the opinion that the estimated released energy is within the errors of this potential correction. The order of the magnitude, the distribution of released energy over its classes and by the years do not change substantially.

The estimates of released energy, without corrections for those earthquakes for which the energy could not be estimated, will be used in the analysis of effects of reservoirs in karst regions on earthquakes.

Chapter 5
EFFECTS OF WATER STORAGE RESERVOIRS IN KARST REGIONS ON EARTHQUAKES

5-1 Sequence of Earthquake Events as a Sample of Time Dependent Random Variables

A time series of recorded earthquakes can be treated as an empirical multidimensional realization of a process, studied by its two characteristics:

(1) Number of earthquakes per unit time; and

(2) Energy released by earthquakes.

The number of continuously observed earthquakes is a time series of 12 years, of 10,341 recorded earthquakes for 4,286 days (998 days prior and 3,288 days in post-filling period). The number of earthquake series is obtained by counting the number of events per unit time, as a discrete variable and a discrete time series.

The released earthquake energy is calculated from the recorded data. The 12 years time series has 8,658 such values out of a total of 9,065 events. The energy released by earthquakes is then a discrete time series with unit time intervals of a continuous random variable.

The errors contained in earthquake events are random and systematic. Considering the character of the phenomenon, it is estimated that errors likely are not excessive, and that they will not mask the basic properties of series to be detected. Some short interruptions of recordings have occurred, mainly during the days without seismic activity.

The earthquakes may be considered as stochastic processes. Very strong earthquakes are relatively rare. The effects of storage reservoirs on earthquakes then represent a problem of statistical detection of any significant changes in the natural earthquake processes. The investigations of this Chapter are then limited to only studying the relationship between the effects (in this case the earthquakes) and the causes (in this case the water storage reservoirs), with the following relationships sought:

(1) Number of earthquakes as related to the state variables of storage reservoirs;

(2) Released energy by earthquakes as related to the state variables of storage reservoirs; and

(3) The eventual relationship of the number of earthquakes and of the released energy to the random variables which are affected by the water storage, such as the total water stored, water level, or their rates of change, as the causal factors and the random variables.

The relationships of all these random variables are statistical, with the number of earthquakes and the released energy as the dependent variables, and the water stored and other variables as the independent variables. The water level, as a random variable, is limited between the full and the empty reservoir. This level may be expressed either by the height of the water column or by the total water volume of the reservoir.

In this Chapter a description is made of deduced hypotheses and inferred regularities by using the statistics for the available sample data, given in the form of tables or graphs. The hypotheses drawn are then tested by using the statistical approach, as presented in the next Chapter.

The question of the unit time to use was posed, namely whether to use the daily time series with a lot of pieces of data, or a larger unit time with a smaller number of series values. After several attempts, the study showed the number of earthquakes and the released energy either as the monthly or as the annual series would suffice for the purposes of detecting the eventual effects of reservoirs on earthquakes. In that way, it is easier to treat the series without short intervals with zero seismic activity. The reservoir changes are represented by the monthly and annual average water levels. The mean water levels characterize in a certain way the duration of reservoir storage state. In most cases the maximum water level is also given, although it was found in the recordings immediately after filling of the reservoir that the highest daily seismic activity does not respond to the maximum levels within the unit time intervals used.

5-2 Frequency Analysis of Earthquake Characteristics

In the period February 6, 1965 through October 31, 1976 a total of 10,341 earthquakes was recorded (Table 4-1 and 4-7), namely (i) in the period (February 6, 1965 through October 31, 1967) prior to filling of the reservoir of 1,038 earthquake events (Fig. 5-1); and (ii) in the period (November 1, 1967 through October 31, 1976) after filling the reservoir of 9,303 earthquake events (Fig. 5-2).

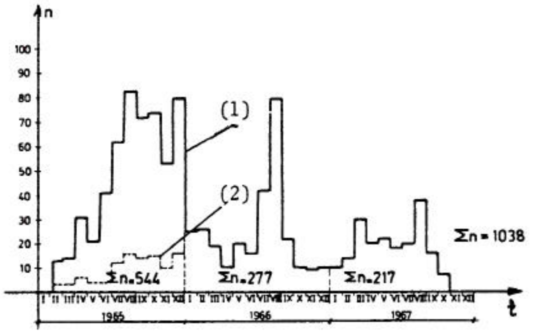
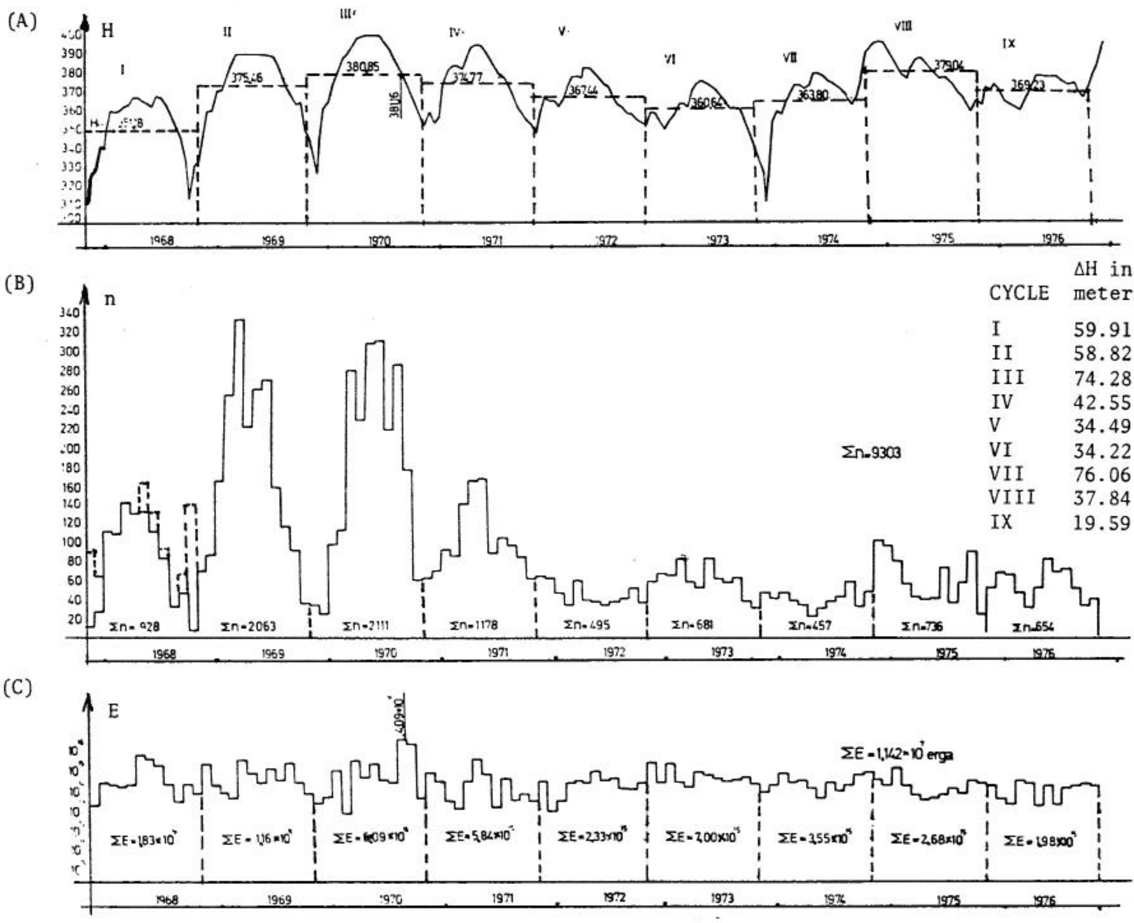


Fig. 5-1 Distribution of the number of earthquakes, n, over the months, prior to filling of the reservoir, period February 2, 1965 - October 31, 1967: (1) All earthquakes; and (2) Excluding earthquakes with epicenter distances less than 5 km from the recording station

For the period after filling of the reservoir, the water years instead of calendar years were used, with the water years corresponding to the periodic cycle of loading and unloading of storage reservoir. The water year begins November 1 of each year and ends on October 31 of the following year (Fig. 5-2). It coincides with the hydrologic water year.

The comparison of the annual series of the number of earthquake events and the annual series of their released energy (Fig. 5-3) with the corresponding mean annual water levels of the Bileća Reservoir shows



CYCLE	ΔH in meters	H_{max}	H_{min}
I	59.91	368.81	311.90
II	58.82	391.29	332.37
III	74.28	400.09	325.81
IV	42.55	395.09	352.44
V	34.49	382.83	348.34
VI	34.22	375.70	341.48
VII	76.06	387.78	311.72
VIII	37.84	394.44	356.60
IX	19.59	377.57	357.98

Fig. 5-2 Properties of reservoir levels and earthquakes during period of filling and use of the reservoir, February 1, 1967 through October 31, 1976: (A) Reservoir level, H versus time, with I-IX cycles (water years) of filling and emptying, with levels in meters a.s.l.; (B) Monthly number, n, of recorded earthquakes versus time; and (C) Released energy, E, in ergs, of earthquakes versus time; with $\Delta H = H_{max} - H_{min}$, and H = mean monthly reservoir water level

the seismic activity in the reservoir region to have been suddenly increased after filling of the reservoir. It is obvious that the first four cycles (years) of loading and unloading of the reservoir, and the corresponding water levels in the reservoir have affected the maximum number of earthquakes and the maximum energy released. These maxima correspond to the highest mean water level and the maximum water level (Figs. 5-3 and 5-4).

The cumulative graph of monthly values of the number of earthquakes pretty closely follows the cumulative graph of mean monthly water levels in the reservoir (Fig. 5-5). The inspection of this graph shows that the seismic activity has increased with the first cycle of loading and unloading, when the reservoir elevation of 368.81 m A.S.L. was reached. This activity increased and remained almost unchanged during the second and third cycles of loading, when the elevations 391.29 and 400.00 m were reached, respectively. The fourth period of loading and unloading, with the elevation of 395.09 m reached, may be inferred as a transition period, after which the period of a decrease in the seismic activity started. The cumulative curve of the mean monthly reservoir water levels does not show the above trend found in earthquake activities.

The relative mean monthly values of the number of earthquakes for the period prior and following water storage (Fig. 5-6), compared with the mean monthly and the maximum monthly water levels in the reservoir, also indicate that changes have been caused by water storage. The mean monthly values of the number of earthquakes follow the increase and decrease in the mean monthly water levels in the reservoir except for the month of April. The highest relative monthly value of the number of earthquakes corresponds to the maximum mean monthly reservoir level. Prior to filling of the reservoir, the maximum relative value of the number of earthquakes was registered in August (1965, 1966, 1967). In the period after filling of the reservoir the highest number of earthquakes occurred in May (1968-1976), which corresponds to the highest mean monthly water levels in the reservoir.

The presentation in Fig. 5-6 illustrates the relationship between the relative number of earthquakes, the mean monthly water level, the mean maximum water level and the absolute highest water level in the reservoir. The monthly absolute maximum water level does not show itself as a significant factor, while the highest mean monthly water level parallels less the relationship as it exists between the relative monthly number of earthquakes and the mean monthly water level (Fig. 5-6, vertical arrow).

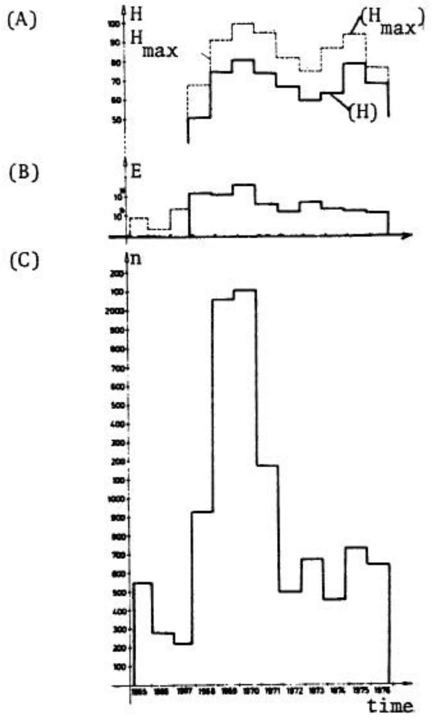


Fig. 5-3 Annual properties of reservoir levels and of earthquakes for the period February 2, 1965 through October 31, 1976: (A) Maximum Level, H_{max}, within a year and annual average reservoir level, H; (B) Total annual released energy, e, in ergs; and (C) Number, n, of recorded earthquakes per year

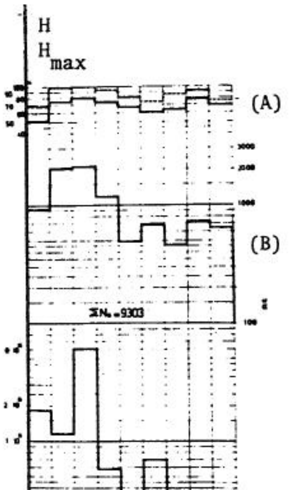


Fig. 5-4 Annual properties of reservoir levels and of earthquakes for cycles of filling and emptying of reservoir in the period February 1, 1967 through October 31, 1976: (A) Maximum level, H_{max}, within a year and annual average reservoir level, H; (B) Recorded number, n, of earthquakes per year; and (C) Total annual released energy, E in ergs.

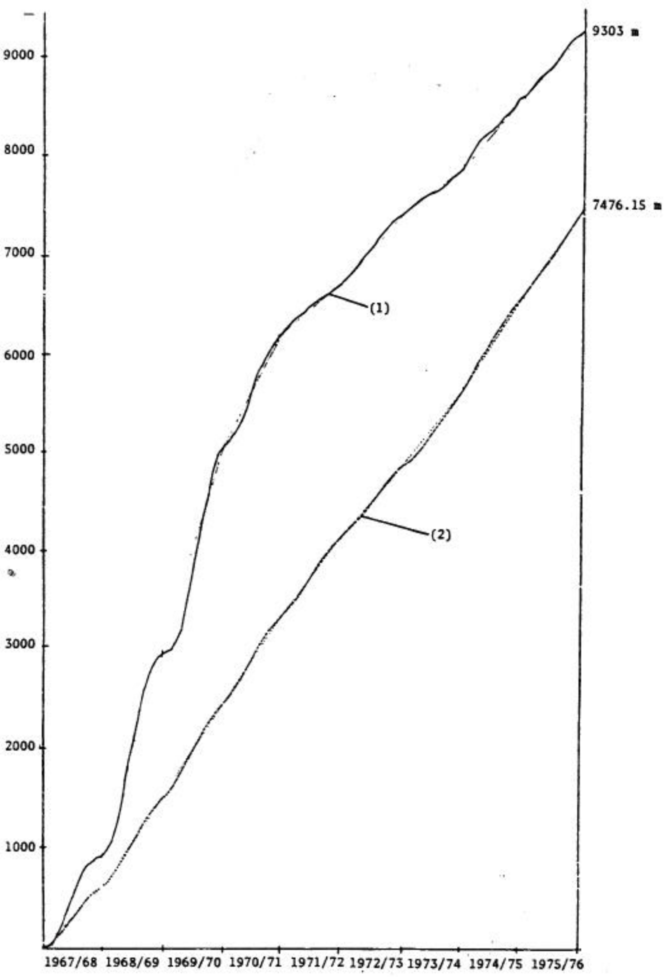


Fig. 5-5 Cumulative curves of: (A) Monthly number of earthquakes; and (B) Mean monthly water level

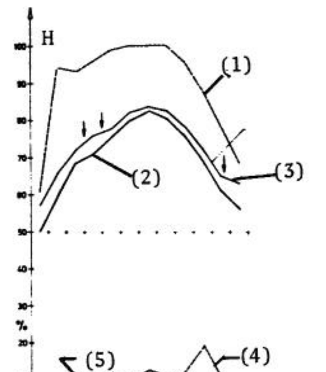


Fig. 5-6 Levels of reservoir (H in meters) and percentage (frequency) of monthly number of earthquakes: (1) maximum observed level; (2) Average level; (3) Average maximum level; (4) Distribution of percentage on the number of earthquakes over 12 months prior to filling of the reservoir; and (5) Distribution percentage over 12 months after filling of the reservoir

The relative frequency of the number of earthquakes for the classes of epicenter distances of earthquakes from the seismic station for the periods prior and after filling the reservoir is

	Prior to Filling	After Filling
0 < 1 km	33.6%	28.1%
1 - 5 km	16.6%	31.6%
5 - 10 km	3.9%, 7.9 %	11.5%
10 - 20 km	5.9%, 11.85%	6.8%
20 - 30 km	6.7%, 13.33%	6.8%
30 - 75 km	33.3%, 66.91%	15.2%

For the period prior to filling of the reservoir, the above second values of relative frequencies in percent for distances over 5.0 km represents the relative monthly values of the number of earthquakes, after the 521 earthquakes that occur within the 5 km radius were subtracted. It is assumed that those 521 earthquakes were produced by various activities around the dam site.

The comparison of data before and after filling of the reservoir leads to the hypothesis that the reservoir has caused some changes in the seismic activity both at short and great distances from the reservoir. The hypothesis is that a significant increase has occurred in the number of earthquakes within the 10.0 km radius and a significant decrease at larger distances. The noticeable decrease in the relative monthly number of earthquakes seems to have occurred within the 30-75 km radius.

The data for the period after filling the reservoir are presented in Table 5-1. It shows the minimum and maximum number of earthquakes that occurred for each day and the corresponding daily minimum and maximum water level. It shows that earthquakes do not occur during the days of minimum or close to minimum water level for a cycle of loading and unloading. The maximum number of earthquakes does not follow the maximum water level, although it is related to high water levels in the reservoir. The water level for which either the minimum or the maximum number of earthquakes was recorded is given in parentheses in Table 5-1. The asterisk sign singles out the class of the number of earthquakes at which the strongest earthquake has occured for that region. It was at the epicenter distance of 63 km northwest from the seismologic station on August 25, 1970. It released the energy of 4.09 x 10^{16} ergs. This particular earthquake is analyzed in more detail in Chapter 6.

Table 5-1 Minimum and Maximum Numbers of Earthquakes per Day

Period (Water Year)	Minimum	Maximum
1967-1968	n = 0 (319.9) H = 311.9	n = 13 (356.5) H = 368.81
1968-1969	n = 0 (332.8) H = 332.37	n = 24 (390.1) H = 391.29
1969-1970	n = 0 (326.4) H = 325.81	n = 51 (381.16)* H = 400.09
1970-1971	n = 0 (353.3) H = 352.44	n = 14 (392.5) H = 395.09
1971-1972	n = 0 (348.7) H = 348.34	n = 6 (358.4-382.5) H = 382.83
1972-1973	n = 0 (342.8) H = 341.48	n = 12 (351.1) H = 375.70
1973-1974	n = 0 (311.8) H = 311.72	n = 6 (340.4-359.3) H = 387.78
1974-1975	n = 0 (357.0) H = 356.60	n = 24 (365.5) H = 394.44
1975-1976	n = 0 (357.98) H = 357.98	n = 13 (376.8) H = 377.57

n = number of earthquakes; H = daily minimum and maximum water levels in meters A.S.L. in the reservoir; and (...) = water level at the time of recording the minimum and the maximum number of earthquakes per day

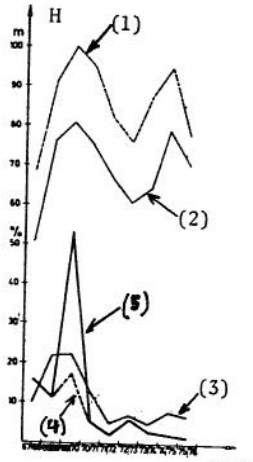


Fig. 5-7 Levels of reservoir and percentage (frequency) of the annual number and the annual released energy of earthquakes during the period of filling and operation of reservoir: (1) Maximum level; (2) Average level; (3) Distribution (frequency) of percentage of annual number of earthquakes over 9 years; (4) Distribution (frequency) of percentage of annual released energy over 9 years; and (5) Earthquake of August 25, 1970 with 36.78% of released energy

The series of the relative annual number of earthquakes and the series of mean annual and maximum annual water level in the reservoir (Fig. 5-7) show that a great change has occurred in the seismic activity during the second reservoir loading cycle. The increase in the mean water level was 24.28 m, while the maximum water level was 22.48 m higher (Fig. 5-2). However, though the maximum level of 400.09 m was reached during the third cycle, the earthquake frequency did not change substantially, with only about 48 earthquakes more than in the second cycle. The mean annual water level in the third cycle was 5.39 m higher than in the second cycle, while the maximum water level was 8.00 m higher. In the fourth cycle the mean annual level was only 0.99 m lower than in the second cycle, while the maximum water level was 3.80 m higher, with a significant decrease of the seismic activity in the fourth cycle, somewhat of the same acitivity as in the first cycle. The relative numbers of earthquakes in the period after 1970/71 or in the years 1971/72, 1972/73, 1973/74 do not seem to follow the water level fluctuations.

The loading and unloading cycle of 1974/75 had high water levels but a relatively low seismic activity. These observations lead to another hypothesis, namely that the initial cycles of loading the reservoir increased the seismic activity, while in the following cycles the effects of the reservoir so decreased as to approach the earthquake patterns of the period prior to filling of the reservoir.

Table 5-2 shows the monthly number of earthquakes, the mean monthly and the maximum monthly water level for the first four cycles of reservoir loading and unloading. This table gives only those months that have shown the following characteristics:

Table 5-2 Data on Earthquake Number During the First Four Cycles of Loading and Unloading of the Bileća Reservoir

Period	Number of Earthquakes	Mean Reservoir Water Level	Maximum Reservoir Water Level
1967-1968			
November	11	318.16	329.44
December	27	340.21	350.48
January	110	358.90	360.08
February	107	359.96	362.34
March	140	363.47	366.65
April	129	366.81	367.61
May	130	363.61	365.31
June	109	366.56	368.81
July	82	362.87	367.04
August	31	351.91	357.37
1968-1969			
December	85	363.72	371.50
January	167	374.09	377.35
February	256	383.67	389.63
March	335	390.14	390.14
April	223	390.17	391.00
May	262	390.82	391.18
June	271	390.20	391.29
July	160	383.56	388.51
1969-1970			
January	95	379.58	385.63
February	110	388.10	390.63
March	281	394.52	398.90
April	229	399.67	400.09
May	310	399.99	400.08
June	312	399.91	400.03
July	199	392.56	396.42
1970-1971			
January	88	374.16	381.37
February	81	383.74	383.78
March	135	383.74	387.04
April	168	392.41	394.40
May	169	394.04	395.09
June	84	387.68	391.13
July	100	397.85	383.37

(i) A substantial increase of seismic activity, recorded during the first loading cycle of January 1968, with 110 earthquakes observed, when the mean monthly reservoir depth at the dam was 59 m (level 358.90 m);

(ii) A sudden increase in the number of earthquakes during the second loading cycle, recorded as late as February 1969, with the 256 earthquakes recorded during the mean monthly reservoir depth at the dam of 80.0 m (level 383.67 m);

(iii) The absolute maximum number of earthquakes of 335, recorded in March 1969 was during the mean monthly reservoir depth of 90.0 (level 390.14 m);

(iv) During the maximum reservoir depth of 100.0 m (the mean monthly level 399.9 m) of the third cycle the number of earthquakes was of the same order of magnitude as in the second cycle; and finally

(v) A noticed decrease in seismic activity occurred in the fourth cycle.

By comparing data in Tables 5-1 and 5-2, and keeping in mind the above inferences, the following observations are made:

(a) A fast increase in water level is followed by an increase in seismic activity during the reservoir loading period;

(b) Unloading of the reservoir is followed by a decreased seismic activity for the same or similar water level regime during the loading, with an expected random fluctuation in the number of earthquakes; and

(c) If a certain water level is maintained for a prolonged time, the seismic activity seems not to change substantially.

The conclusions to be derived from these observations are:

(1) A substantial increase in seismic activity, measured by the number of earthquakes, is recorded in the loading of the reservoir when its water depth at the dam reached 60 m. This is in contradiction with findings and positions of organizations such as the U.S. Bureau of Reclamation, expressed in "Consideration of Reservoir Induced Seismicity in Establishing Seismic Loadings for Dams," that the reservoir effect on earthquakes starts with the reservoir depths of more than 90.0 m.

(2) A controlled loading of reservoirs by a gradual attaining of the maximum reservoir level, in the successive cycles of loading and unloading, somewhat alternates the seismic activity at maximum water levels above 60 m in comparison with the rapid loading. The seismic activity is related to the water depth of the reservoir and not to the height of a dam.

The histogram of the number of earthquakes (Fig. 5-2) shows a general trend for the increased seismic activity to be tied to the increased reservoir levels. The number of recorded earthquakes was mainly higher for higher reservoir levels, except for the years 1971/72 and 1973/74, when for the high levels a decrease in the number of earthquakes was experienced.

The distribution of the number of earthquakes according to classes of epicenter distance are given in Fig. 5-8. The seismic activity, expressed by the number of earthquakes, is the lowest for distances 10-30 km, highest for distances under 5 km, and quite high for distances 30-70 km.

The number of earthquakes within 5.0 km radius is not representative for earthquakes as 36 percent of earthquakes for this distance released energy of $E \leq n \times 10^7$ ergs ($1 \leq n \leq 10$), and these types of small tremors could not be recorded for greater distances from the seismologic station. Another station or a group of seismic stations would likely show an increase in the number of recorded nearby earthquakes.

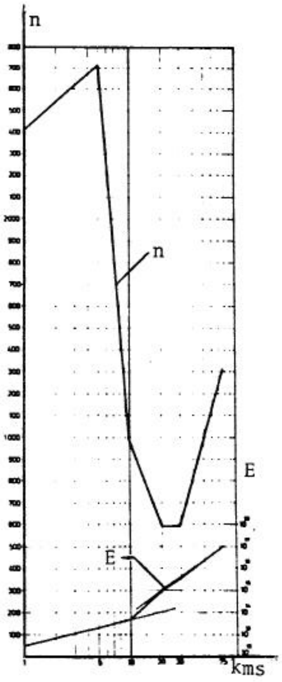


Fig. 5-8 Distribution of the number, n, of earthquakes, and the energy released, E in ergs (in logarithmic scale) versus class intervals of epicenter distances from the recording station (also in logarithmic scale)

5-3 Released Earthquake Energy

The earthquake energy released in the period February 6, 1965 to October 31, 1967 for three successful statistical interpretations was:

(i) First interpretation	9.7×10^{16} ergs
(ii) Second interpretation	2.3×10^{16} ergs
(iii) Third interpretation	2.3×10^{16} ergs

The energy released was 11.42×10^{16} ergs in the period November 1, 1967 through October 31, 1976 (see Chapter 4). For this energy, compared with the released energy prior to filling of the reservoir (first interpretation), with times of observations prior to and after filling taken into consideration, it may be concluded that a decrease in seismic activity took place after filling of the reservoir. However, as it will be shown later, a strong earthquake occurred during the third cycle of loading and unloading of the reservoir, which released the energy of 4.0×10^{16} ergs, i.e. 36 percent of the total computed released energy. Because such a strong earthquake was not recorded during the observations prior to filling of the reservoir, the hypothesis that the seismic activity expressed by earthquakes released energy by the first interpretation cannot be accepted. The above statistical data of released energy, as given by the second and third interpretations, are used for further studies and comparisons, with the assumption that seismic activity measured by the released energy has increased in the period after filling of the reservoir.

The frequencies of the released energy (Figs. 5-1 and 5-3) indicate that the energy released was highest in the first and third cycles of loading and unloading of the reservoir. For the released energy of the strong earthquake in the third cycle (August 25, 1970) excluded, the third cycle still shows the largest released energy, slightly greater than that of the first cycle (Fig. 5-7). The second cycle is characterized by a lower seismic activity in comparison with the first and third cycles. A substantial decrease in energy activity has occurred in the fourth cycle. Only in the sixth cycle (year 1972/73) less energy was released than in the fourth cycle. A decreasing trend is noticeable in the released energy in the period November 1, 1973 through October 31, 1976 (Fig. 5-4).

The policy proposed and followed, namely to load the reservoir in three-year cycles, with a stepwise increase of maximum reservoir level, has been shown to be a wise step. The accumulated earthquake-producing energy seems to have been released slowly rather than suddenly during loading by the reservoir.

In making decisions concerning the future high dams and large reservoirs, it is useful to consider all the opposing views, with both the economic and technical factors taken into account. The interests of the user of the reservoir are often determining factors in final decisions related to the controversial problems such as the effects of storage reservoirs on earthquakes, particularly of those in karst regions.

Frequencies of released energy (Figs. 5-3 and 5-4) show the released energy to be of the same order of magnitude, namely 1.98×10^{15} - 3.35×10^{15} ergs, during the loading and unloading cycles in water years 1971/72-1975/76. The loading and unloading cycle of the year 1974/75 is characterized by the third highest water level and the second highest mean annual water level reached in filling of the reservoir, with the released energy of 2.68×10^{15} ergs, or the seventh in rank. Another hypothesis is that reaching a higher reservoir level in loading cycles following some main release of energy does not release the same energy, because a new underground equilibrium may have been already established after the main energy release. This hypothesis is illustrated by the series of the relative annual released energy of Fig. 5-7 which in a certain way relates to the probability of the earthquake to occur in filling of the storage reservoir.

In the analysis of seismic activity expressed by the number of earthquakes, the regions of increased and decreased seismic activity may be distinguished. The graphical representation of released energy according to the epicenter distances of Fig. 5-8 seems to contradict this hypothesis. The graphs indicate an increase in the total released energy with an increase in the distance, however, with two regularities, the region within the 10 km radius, and the region within the 20-75 km radii, with the region of 10-20 km radii as an intermediate region. The region within 20-30 km radii had the lowest number of earthquakes, however, with a total released energy relatively high.

The number of earthquakes according to the released energy is given in Tables 4-9, 4-10, and 4-11, and their absolute frequencies in Fig. 5-9. The summarized data are:

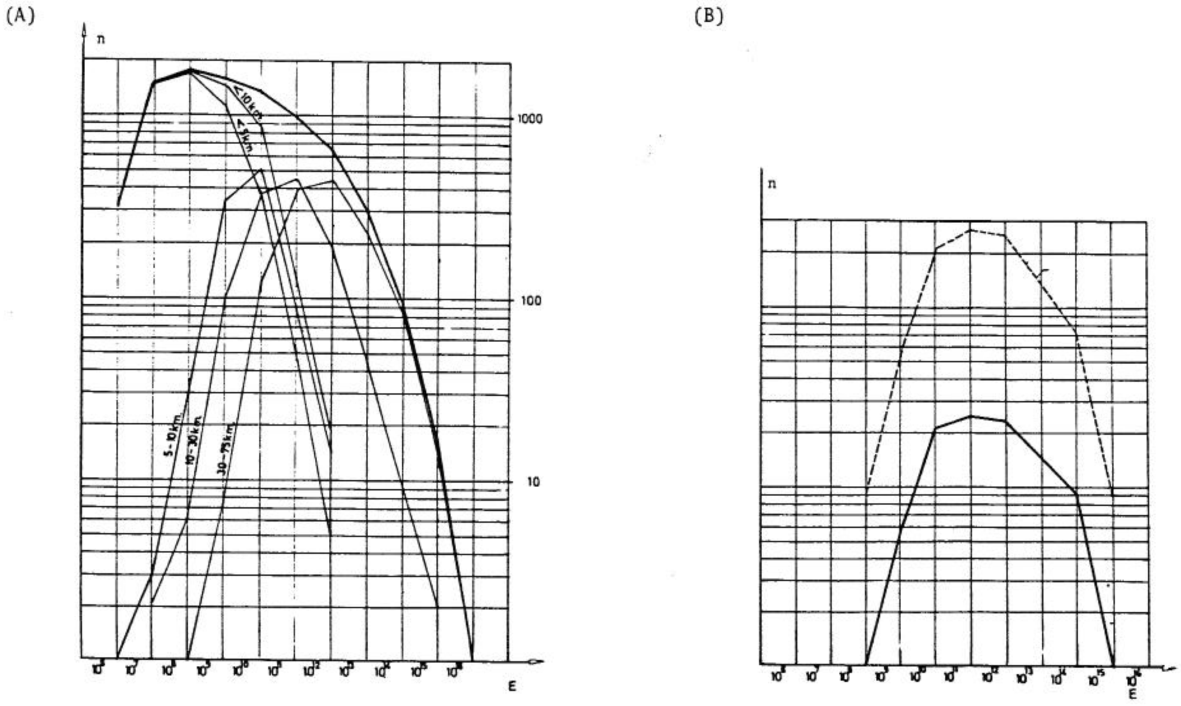


Fig. 5-9 Relationships in logarithmic scales of the number of earthquakes, n, to released energy, E in ergs, for given class intervals of epicenter distance of two cases: (A) After filling of the reservoir (November 1, 1967 through October 31, 1976); and (B) Prior to filling of the reservoir (February 6, 1965 through October 31, 1967), but for all distances

Class Interval of Energy	Number of Earthquakes	Energy Released
10^8 ergs -	3592	1.45×10^{16} ergs
10^9 ergs -	1586	
10^{10} ergs -	1360	
10^{11} ergs -	980	
10^{12} ergs -	640	
10^{13} ergs -	284	
10^{14} ergs -	90	2.47×10^{16} ergs
10^{15} ergs -	15	3.41×10^{16} ergs
10^{16} ergs -	1	4.09×10^{16} ergs

This means that 106 earthquakes of energy class interval of 10^{14} ergs released the energy of 9.97×10^{16} ergs, i.e. 87 percent of the total released energy, while the 8,442 remaining earthquakes released only the energy of 1.45×10^{16} ergs. The released energy seems to be inversely proportional to the number of earthquakes.

The highest energy frequency prior to filling of the reservoir was for the energy class interval of 10^{11} ergs, Fig. 5-9. After filling of the reservoir the highest frequency was for energy class interval 10^8 ergs, as Chapter 4, and Fig. 9 demonstrate. According to the class intervals of distance, the distribution of highest frequencies are

Distance	Order of Energy Released
< 1 km	10^7 ergs
1 - 5 km	10^8 ergs
5 - 10 km	10^{10} ergs
10 - 20 km	10^{10} ergs
20 - 30 km	10^{11} ergs
30 - 75 km	10^{12} ergs

or in the distance ranges

Distance	Order of Energy Released
less than 5 km	10^8 ergs
5 - 10 km	10^{10} ergs
10 - 30 km	10^{11} ergs
30 - 75	10^{12} ergs

As the distance increases, the class interval values of the frequent energy released also increases. Characteristic frequencies for given class intervals of epicenter distances (shown in logarithmic scales in Fig. 5-9), in the order of magnitude, are

Distance	Minimum E	Most Frequent E	Maximum E
less than 1 km	10^6	10^7	10^{12} ergs
1 - 5 km	10^6	10^8	10^{12} ergs
5 - 10 km	10^6	10^{10}	10^{12} ergs
10 - 20 km	10^7	10^{10}	10^{14} ergs
20 - 30 km	10^8	10^{11}	10^{15} ergs
30 - 75 km	10^{10}	10^{12}	10^{16} ergs

and in distance ranges

less than 1 km	10^6	10^7	10^{12} ergs
10 - 30 km	10^7	10^{11}	10^{15} ergs
30 - 75 km	10^8	10^{12}	10^{16} ergs

The conclusion to be derived from the above analysis is that as the distance of epicenter from the dam increases, so do the minimum, maximum and most frequent energy class interval values.

Table 5-3 presents the absolute minimum and the absolute maximum energy released by the individual earthquakes and in parentheses the corresponding water level in the reservoir. Also, the minimum and the maximum water levels of each cycle are given as values H.

Table 5-3 Maximum and Minimum Released Energy by Earthquakes

Period Prior to Filling Reservoir	Minimum Released Energy Minimum Water Level	Maximum Released Energy Maximum Water Level
Period February 2, 1965 to October 31, 1967	E = 6.74×10^8 ergs	1.64×10^{15} ergs
Water Years after Filling Reservoir		
1967-1968	E = 4.33×10^6 (364.5) H = 311.90 m.A.S.L.	E = 6.81×10^{15} (366.4) H = 368.81 m.A.S.L.
1968-1969	E = 1.65×10^6 (375.8) H = 332.37	E = 3.50×10^{15} (389.9) H = 391.29
1969-1970	E = 2.44×10^6 (373.8) H = 325.81	E = 4.09×10^{16} (381.2) H = 400.09
1970-1971	E = 2.12×10^6 (363.2) H = 352.44	E = 2.94×10^{15} (388.0) H = 395.09
1971-1972	E = 1.93×10^6 (364.4) H = 348.34	E = 5.31×10^{14} (381.3) H = 382.83
1972-1973	E = 5.96×10^6 (351.5) H = 341.48	E = 1.16×10^{15} (358.6) H = 375.70
1973-1974	E = 3.94×10^6 (371.6) H = 311.72	E = 4.78×10^{14} (358.8) H = 387.78
1974-1975	E = 3.36×10^6 (378.6) H = 356.60	E = 3.51×10^{14} (390.2) H = 394.44
1975-1976	E = 1.16×10^6 (364.4) H = 357.98	E = 2.09×10^{14} (373.5) H = 377.57

E = energy released; H = the reservoir minimum and maximum water level during a water year cycle; (in parantheses) the reservoir levels when the earthquakes of minimum and maximum release of energy occurred for a water year

The earthquakes of the minimum and maximum released energy in cycles of loading and unloading of the reservoir, do not correspond to the minimum and the maximum water level in the reservoir. In all cycles the minimum released energy was of the order of magnitude of 10^6 ergs. For the first four cycles the maximum released energy was of the order of magnitude 10^{15} - 10^{16} ergs, while in the remaining cycles it was 10^{14} ergs, except for the year 1972/1973.

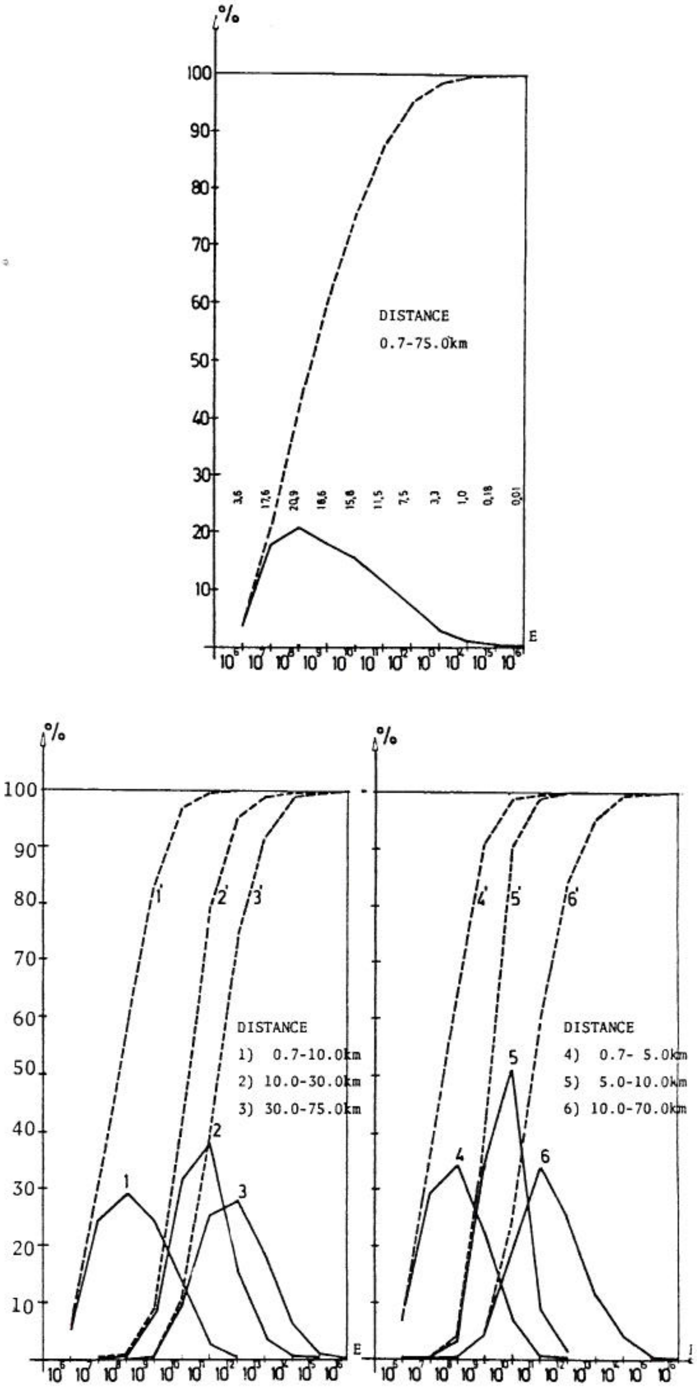


Fig. 5-10 Relative and cumulative frequencies of released energy, E in ergs, for various epicenter distances from the recording station

The total released energy of earthquakes, with the order of magnitude of released energy of 10^6 - 10^7 ergs, is relatively small. All earthquakes of this order of magnitude released the total energy of about 1.5×10^{11} ergs. In the total energy released of 1.142×10^{17} ergs the effect of these small-energy earthquakes affects the figure only on its third decimal point value.

Relative and cumulative frequencies of Fig. 5-10 indicate that the probability of an earthquake to release the energy greater than 10^{14} ergs is very small. For the frequency histogram of all earthquakes, the frequency is higher for small energy values, with clearly evident positive asymetry.

5-4 Number of Earthquakes and Their Released Energy

In subchapters 5-2 and 5-3 the number of earthquakes and their released energy, as random variables, were analyzed separately for the whole period of observation February 6, 1965 through October 31, 1976. This subchapter treats the number of earthquakes and their released energy only for the period November 1, 1967 through October 31, 1976 during the operation of the reservoir.

The number of earthquakes and their released energy per unit time are basic series showing the seismic activity. Previously, the variation of these variables were analyzed independently. The analysis has shown that these variables seemingly exhibit some opposite characteristics. A large number of earthquakes does not represent a high mean energy released, as the basic property used for measuring the effect on the ground surface. When studying the effects of reservoirs on earthquakes, this position may not be correct, as supported by the example of the Grančarevo Dam and the Bileća Reservoir. The inhabitants of the village Selina, on the right river bank upstream from the dam, continuously experience a large number of earthquakes of small energy. These earthquakes are relatively unpleasant as they also produce some damages to buildings due to the very frequent tremors. The cracks on buildings are observed by a special service, and found to be related to seismic activity. However, this activity as well as the strongest recorded earthquake did not yet show any effect on the large dam and its structures.

A joint analysis of both the number and energy released of earthquakes is necessary. The time series had missing recordings, however, only during days without earthquake activity. For 3,288 observed days, no seismic activity was recorded in 643 days, as shown in Table 5-4.

Table 5-4 The Number of Days per Month when Seismic Activity Was not Recorded

MONTH	WATER YEAR	1967-1968	1968-1969	1969-1970	1970-1971	1971-1972	1972-1973	1973-1974	1974-1975	1975-1976	Σ
November		20	6	11	5	6	8	9	1	4	70
December		17	5	17	5	2	4	10	6	2	68
January		3	-	4	1	8	6	7	5	4	38
February		-	-	2	1	10	2	10	4	7	39
March		1	-	-	1	5	3	12	4	15	44
April		-	1	2	-	10	4	15	9	7	48
May		1	-	-	-	10	5	14	6	2	38
June		2	-	-	2	12	7	9	3	6	41
July		3	2	-	1	14	5	8	8	6	47
August		10	1	-	3	12	7	6	7	6	52
September		7	3	1	3	8	8	9	8	12	59
October		26	12	4	6	12	13	4	15	7	99
	Σ	90	30	41	28	109	72	113	82	78	643

The highest number of days free of seismic activity occurred in 1967/1968 during the first loading of the reservoir, for the months of low water levels in the reservoir. Generally, times of low water levels had the highest number of days without seismic activity. Exceptions are loading and unloading cycles of water years 1971/1972 and 1973/1974, when the results were opposite. These two cycles were discussed in the previous chapter. Data shown in Table 5-4 support the hypothesis advanced and conclusions derived.

This subchapter deals with the seismic activity expressed jointly by the number and released energy (in ergs) of earthquakes, but not in relation to epicenter distance, as function of unit areas determined by that distance. This information looks as a realistic indicator of average seismic activity, even though in particular there are subareas of lesser and greater seismic activity.

Table 5-5 and Figs. 5-11 and 5-12 present the general regularities in the changes of earthquake activity. The number of earthquakes per km^2 of an area is almost linearly related with the decrease of logarithm of distance, while the energy released is substantially lower at distances 5-10 km, as shown in Fig. 5-12.

Table 5-5 Distribution of the Number and of Energy of Earthquakes per Unit Area (km^2)

R km	A km^2	ΔA km^2	N_o	$\frac{N_o}{\Delta A}$ $\frac{N_o}{km^2}$	ΣE ERG	$\frac{\Sigma E}{\Delta A}$ $\frac{ERG}{km^2}$
1,00	3,14	3,14	2414	768,79	$5{,}33\times10^{12}$	$1{,}70\times10^{12}$
		75,36	2719	36,08	2765×10^{12}	$0{,}37\times10^{12}$
5,00	78,50					
		235,50	991	4,21	$73{,}18\times10^{12}$	$0{,}31\times10^{12}$
10,00	314,00					
		942,00	587	0,62	$1132{,}00\times10^{12}$	$1{,}20\times10^{12}$
20,00	1256,00					
		1570,00	588	0,37	$4821{,}00\times10^{12}$	$3{,}07\times10^{12}$
30,00	2826,00					
		14836,50	1308	0,09	$108150{,}00\times10^{12}$	$7{,}29\times10^{12}$
75,00	17622,50					
		17662,50 (Σ)	8548 (Σ)	0,48 ($\frac{\Sigma N_o}{A}$)	1142000×10^{12} (Σ)	$6{,}47\times10^{12}$ ($\frac{\Sigma E}{A}$)

To assess the differences in results when using the distance or the unit area values, a comparison is presented for the number and energy released of earthquakes, given as in Fig. 5-12. In using distances the seismic activity measured by the number of earthquakes decreased for distances of 10-30 km radii, while the released energy increases with the increase of the distance. In using the unit area, the number of earthquakes decreases for distances over 5 km, while the energy released in ergs/km^2 is relatively low in the region of 5-10 km radii from the seismic station at the dam. On the bases of the presented data the conclusion is that an increase in distance from the reservoir the specific number of recorded earthquakes decreases, while the released energy increases. The next hypothesis is drawn from these observations, that at distances of less than 20 km from the reservoir the influence of stored water dominates while at greater distances the influence of natural forces prevails.

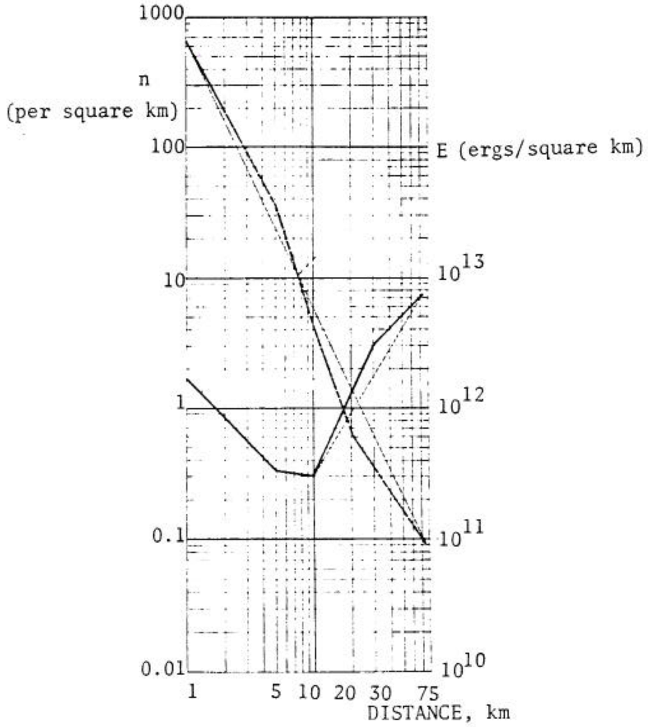


Fig. 5-11 Number, n, of earthquakes per unit area and released energy per unit area, E in ergs/square km, versus epicenter distance from recording station

The question remains open, and it should not be avoided, namely if the hypothesis that the reservoir causes the changes in earthquakes even at distances up to 75 km would be shown as realistic, what are the processes in nature that cause such changes over an area of about 17,660 km^2 of water stored in the area of 27.3 km^2? In this paper, investigations are limited to the cause-effect relationship and not to natural processes that cause earthquakes. Stored water may be eventually considered only an early trigger of the natural processes.

5-5 Resume of Postulated Hypotheses and Derived Conclusions

The postulated hypotheses are:

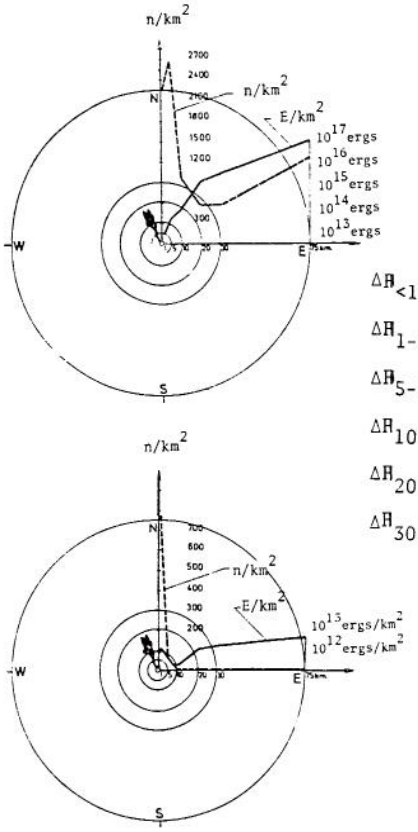
(1) Filling of the reservoir would cause changes in seismic activity even at great distances from the reservoir;

(2) During the initial cycles of loading and unloading of the reservoir, the seismic activity is evidently affected by reservoir levels, while in cycles that followed, the effects of the reservoir seem to decrease, as the surrounding terrain tends to revert to the natural earthquake process;

(3) After reaching in a stepwise approach the highest reservoir levels, after a couple of initial cycles of reservoir loading and unloading, the following cycles of loading do not release the same energy as the initial cycles, because a kind of new equilibrium is again attained for earthquakes; and

(4) The terrain at distances within 20 km radius from the reservoir is under influence of stored water, while for the terrain at greater distances the influence of natural forces seems to prevail.

The conclusions drawn are:



$\Delta A_{<1} = 3.14$ km^2
$\Delta A_{1-5} = 75.36$ km^2
$\Delta A_{5-10} = 235.50$ km^2
$\Delta A_{10-20} = 942.50$ km^2
$\Delta A_{20-30} = 1570.00$ km^2
$\Delta A_{30-75} = 14836.50$ km^2

TOTAL AREA $A_{75} = 17,662.5$ square km

RESERVOIR SURFACE $A_r = 27.3$ square km

Fig. 5-12 The number, n, of earthquakes per unit area (n/km^2) versus distance and the released energy per unit area, E in ergs/square km, versus distance for the reservoir area

(1) A noticeable increase in seismic activity has occurred for the reservoir depths at the dam site of over 60 m;

(2) A slow loading of the reservoir, with a gradual reaching of the maximum reservoir level by the successive cycles of loading and unloading, above the reservoir depth of 60.0 m has likely slowed the pace of seismic activity at the maximum elevations in comparison what would have occurred if loading to highest levels was rapid;

(3) The seismic activity measured by the number and the total released energy of earthquakes increased after the start of filling of the reservoir;

(4) The released energy is inversly proportional to the number of earthquakes, or the higher the number of earthquakes the less energy they release;

(5) With increase of the earthquake epicenter distance from the reservoir, the minimum, the maximum and the most frequent class interval of the energy released also increase; and

(6) With the increase of the epicenter distance from the reservoir the average number of earthquakes per unit area decreases, while the average energy released by these earthquakes increases.

Chapter 6
ANALYSIS OF THE MAIN EARTHQUAKE OBSERVED IN THE RESERVOIR REGION

The strongest earthquake within the region around the reservoir happened on August 25, 1970, with the released energy of 4.09×10^{16} ergs.*) It then belongs to V-VI of the MCS scale, with M = 4.5, if the following empirical relation

$$\log E = 5.8 + 2.4\, M \qquad (6\text{-}1)$$

is used as a connection between the magnitude (M) and the energy (E).

Strong earthquakes that occurred around certain dams and reservoirs, having been topics of scientific investigation, are:

Dam and storage reservoir	Magnitude of earthquake
Kremasta	M = 6.3
Koyna	M = 6.25
Hsinfengkiang	M = 6.1
Kariba	M = 5.8
Hoover	M = 5.0
Kurobe	M = 4.9
Nurek	M = 4.5
Contra	M = 4.25
Keban	M = 3.5

Some of the above earthquakes occurred in regions that have not been considered as seismic prior to construction of the dam. They induced discussions among experts, namely whether those strong earthquakes were caused by the reservoir storage of water or not. The investigations of most cases were made by an analysis of seismic activity immediately prior and after the occurrence of a strong earthquake. The control of seismic activity at some dam sites and the surrounding reservoir regions often began with that event. The strong earthquakes are classified in literature by their seismic activity which is measured by the number of earthquakes that occur prior (foreshocks) and after (aftershocks) the main earthquake (Fig. 6-1). Approximate patterns in occurrence of the number of earthquakes prior and after the main shock, for some of the dams, are given by Figs. 6-2 through 6-4, and Fig. 6-5 for the Grančarevo Dam.

In the case of the Bileća Reservoir, for the strong earthquake of August 25, 1970; 51 earthquakes were recorded, with 31 releasing the energy of 3.984×10^{14} ergs, and the strong earthquake the energy of 4.09×10^{16} ergs. Energy could not be estimated for the other 19 small earthquakes because of various interferences.

For observations over a month, as shown in Fig. 6-6, the time distribution of the number and released energy of earthquakes are as follows:

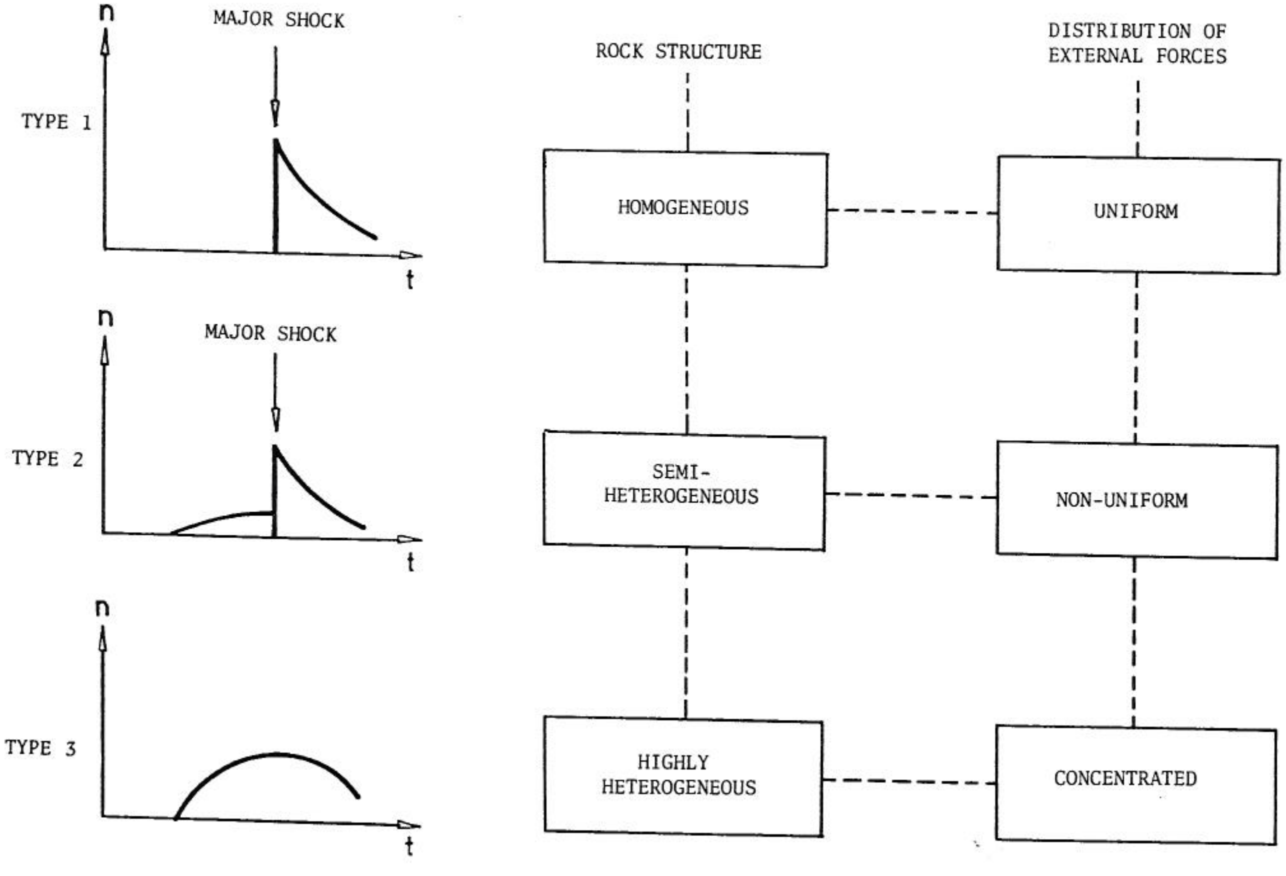


Fig. 6-1 Models of seismic activities prior and after the major shocks as related to the rock characteristics and distribution of external forces

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*) The very large earthquake, that occurred in 1979 in the region, with heavy destructions in the area of the Southern Adriatic Sea in Yugoslavia, and its effects in the Bileća Reservoir area, are not covered in this paper.

	Number of earthquakes	Released energy
1-24 August 1970	166	0.22×10^{14} ergs
25 August 1970	51	4.13×10^{16} ergs
26-31 August 1970	70	5.13×10^{14} ergs
1-30 September 1970	178	1.34×10^{16} ergs

For the total period of observations of November 1, 1967 through October 31, 1976 the distribution of the number of earthquakes and the released energy would be as follows:

	Number of earthquakes	Released energy
November 1, 1967 - August 25, 1970	4,796	3.63×10^{16} ergs
MAIN SHOCK, August 25, 1970	1	4.09×10^{16} ergs
August 26, 1970 - October 31, 1976	4,506	3.70×10^{16} ergs
TOTAL	9,303	11.42×10^{16} ergs

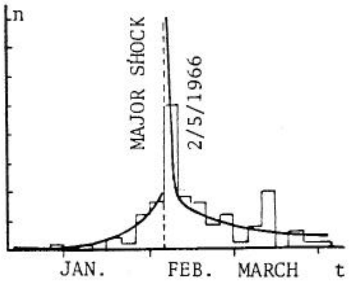


Fig. 6-2 Number of earthquakes, n, versus time, t, for the Kemasta Dam

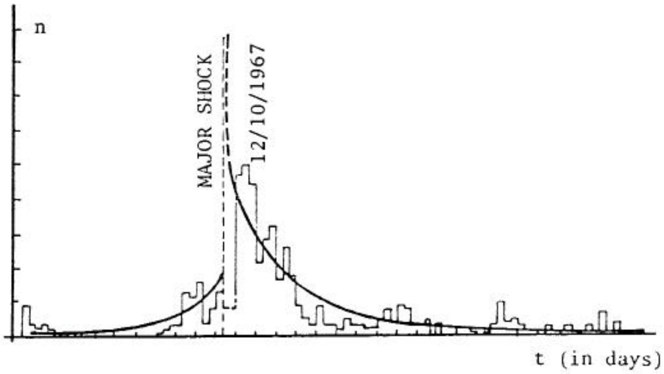


Fig. 6-3 Number of earthquakes, n, versus time, t, for the Koyna Dam

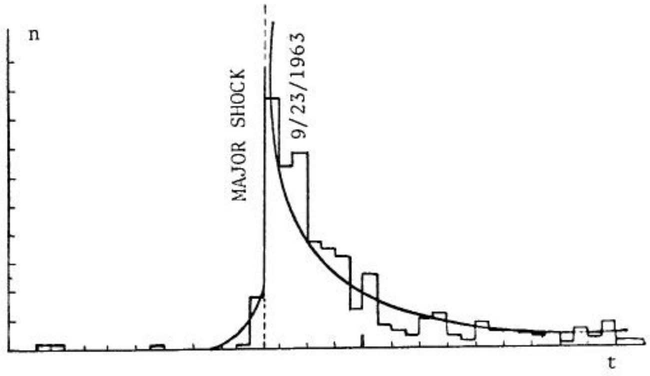


Fig. 6-4 Number of earthquakes, n, versus time, t, for the Kariba Dam

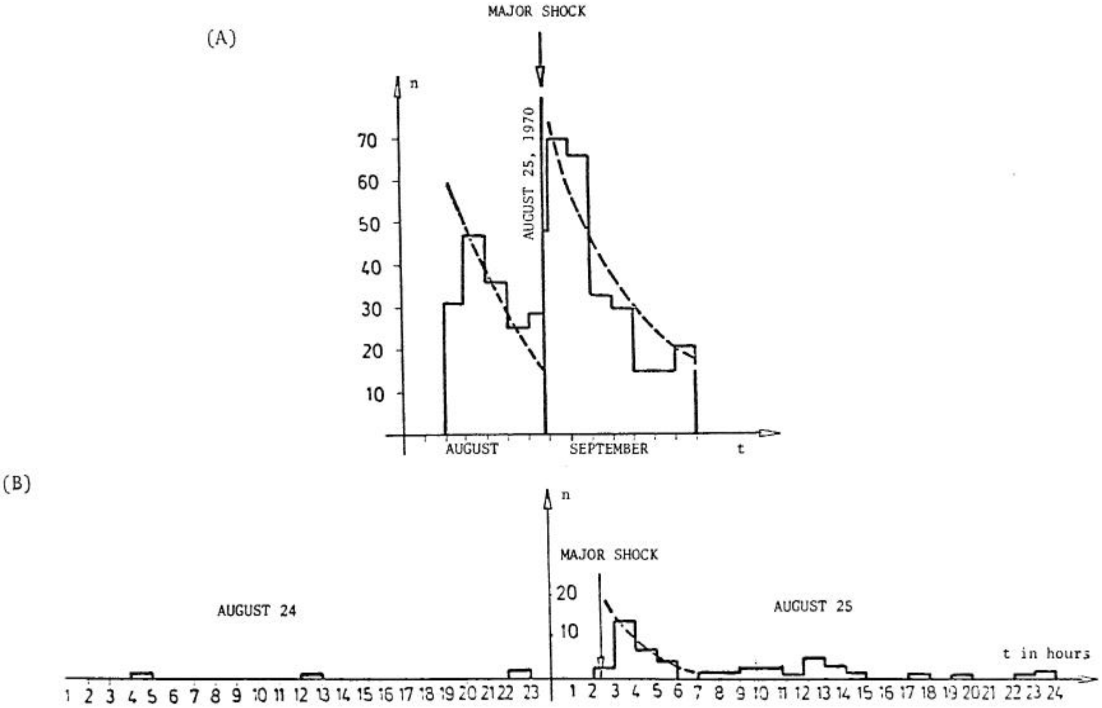


Fig. 6-5 Time distribution of the number of earthquakes prior and after the major shock of the major earthquake for Grančarevo Dam and Bileća Reservoir (Yugoslavia): (A) Large time interval; and (B) Hour interval, for two days, prior and after the major shock of the earthquake

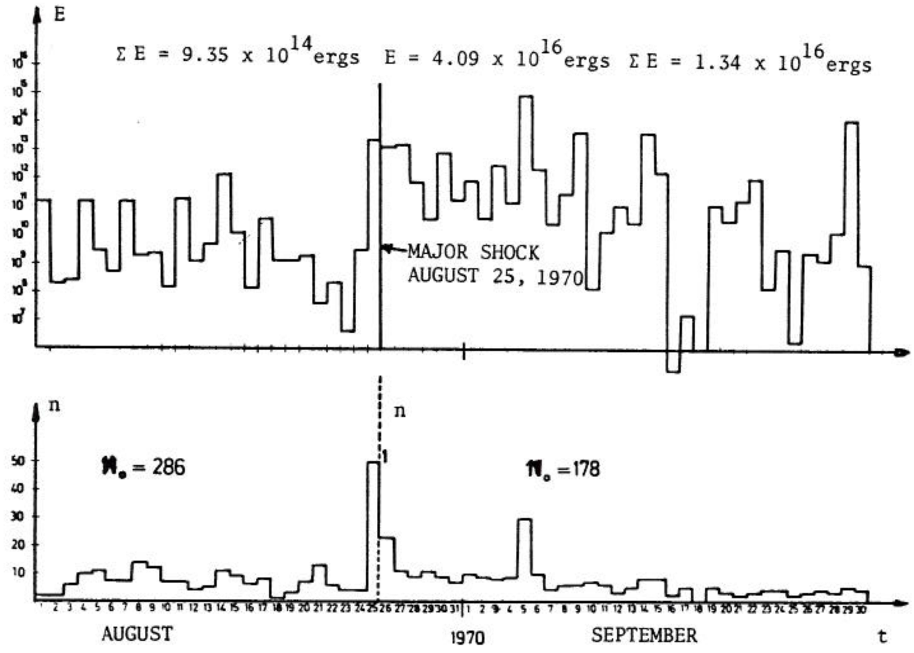


Fig. 6-6 Daily distribution of released energy, E in ergs, and the number, n, of earthquakes per day, for two months, August and September 1970, with N_0 = total monthly number, for the Grančarevo Dam in Yugoslavia

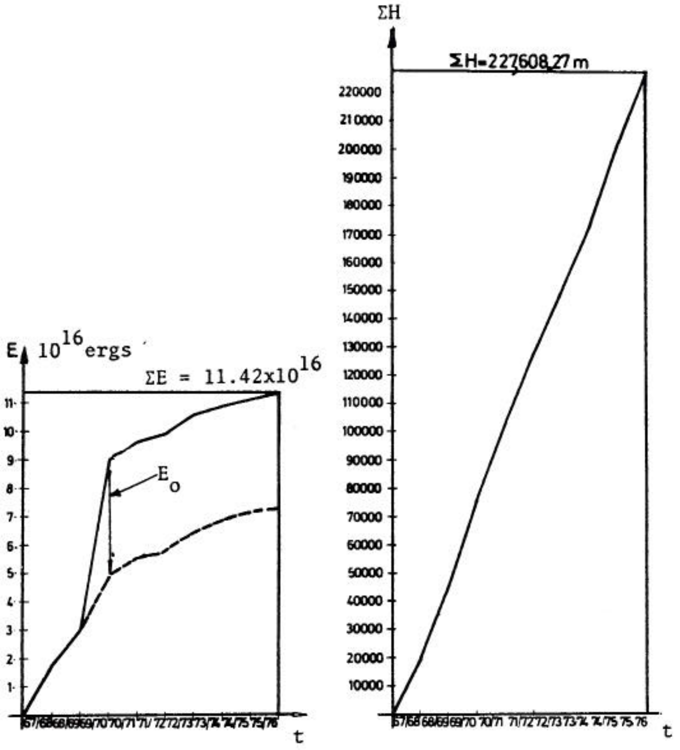


Fig. 6-7 Cumulative released energy (left graph) and cumulative daily levels (right graph) of the reservoir versus time (cycles of filling and emptying of the Bileća Reservoir) during period 1967-1976, with E_0 = the released energy of the major earthquake of August 25, 1970

The question to answer is whether the equilibrium that seems to be attained for the number and released energy of earthquakes before and after the main shock of the earthquake of August 25, 1970 is a normal event or not. The cumulative released energy of Fig. 6-7 illustrates the process of energy release and the effect of the main shock on the total released energy.

Discussions in literature about the origin of strong earthquakes, namely whether they are caused by the water storage or not, likely results from the lack of reliable data for all the cases discussed. Observation of an isolated event cannot lead to correct conclusions because the realization of the stochastic process of earthquakes cannot be investigated only from an isolated random event.

One of the main misconceptions in doing the seismic research may be the isolated analysis of some strong seismic shocks as the rare, catastrophic natural event, instead of analyzing the entire earthquake process. Microseismic activity in the isolated events approach is usually neglected, as a sequence of random events in time. The continuous observations of discrete time events of earthquakes for some reservoirs are a recent phenomenon.

An analogy to flood may seem appropriate. The study of isolated flood events of a river may not be as valuable as studying all the flood events as a process. When long realizations of this process are available, the use of proper extraction of information on flood flows, even the largest ones, becomes more reliable.

Progress in seismologic studies of effects of reservoirs on earthquakes will likely result from the analysis of all the information available, as the realizations of the random time processes in time, rather than from the studies of isolated, individual large earthquakes. Earthquakes that release small energy, say of the magnitude $M \leq 2$, which are not even felt by humans, belong to the category of information which may be very beneficial in the frame of the entire process. The low level seismic activities are usually either neglected or considered not worthy of observations.

Chapter 7
MATHEMATICAL STATISTICAL MODELS OF RESERVOIR EFFECTS ON EARTHQUAKES

7-1 Use of Water Level as an Independent Random Variable in Regression Analysis

It had been pointed out in Chapter 5 that the effects of changing water levels in the reservoir can be presented in two ways: (i) By the water level itself as the pressure (kg/cm^2) and (ii) By the volume or weight of water (in tons) for given level, with the pressure p (level) and the weight of water depending on the water level. Their variations would not be complete without the variation in the total pressure $P = \gamma H^2/2$, with γ = the specific water weight, as it depends on the square of depth of water in the reservoir. The total pressure is then an integral over the area of this unit pressure for a given water depth.

The influence of the Bileća Reservoir on earthquakes occurred in the first 3-4 cycles of loading and unloading of the reservoir. A question arose whether it can be proved mathematically. By attempts described later, it was determined that not much difference exists in correlation coefficients between the earthquakes and the reservoir water depth (pressure) or the water volume (weight) of the reservoir, even though the correlation coefficient is slightly higher in case of the water volume. Since no essential difference is found in correlation, and to make studies simpler, water depth is used as the independent variables for the relationships sought by statistical analysis. This is shown in Fig. 7-1, which presents: the frequency distribution of the mean monthly water depth in the reservoir and the frequency distribution of the number of earthquakes and the corresponding released energy at these water depths. Parallelism of the graphs is striking, because the variations of the frequency of water depth is closely followed by the variation of frequency of the number and released energy of earthquakes except for reservoir water depth at the dam site of 80-85 m (and 65-70 m only for the released energy).

The daily reservoir water inflows are determined by daily water levels and by the production of energy in downstream plants, with the depth fluctuating around the basic patterns of monthly levels.

How the mean monthly water depth represents the level variations is illustrated by this example:

Loading cycle	Maximum water level	Mean water level
1968/1969	391.29 m	375.46 m
1970/1971	395.09 m	374.77 m

In the 1968/69 high water levels above 385 m were maintained about 2.5 months, while in 1970/71 about 1.5 months. The mean water levels seem to integrate the influence of the state of the reservoir on earthquakes, while the maximum water levels characterize only the states of the reservoir attained only for short periods of time.

Recorded earthquake data are viewed as the multidimensional time processes, represented in this study only by the number of earthquakes and their released energy. These two random variables are treated as dependent variables, and each separately is related to reservoir water depth at the dam site, as the independent random variable in statistical analysis.

For the purpose of studying the correlation between the number of earthquakes (y) and reservoir water depth (x), the simple linear correlation $y = a + bx$ is used. In some cases the nonlinear correlation of the type $y = ax^b$ was investigated, but in the linearized form $\log y = \log a + \log x$, with a better correlation. Linear correlation gave a high value of correlation coefficients.

7-2 Individual and Successive Correlation of Monthly Variables

Data presented in tables and figures of Chapter 5 are used also for the individual and successive correlations in two ways:

(1) Correlation for each individual cycle of loading and unloading of the reservoir, conceived as subsamples of the entire sample of time series; and

(2) Correlation for the total number of previous cycles of loading and unloading for each of the following cycles.

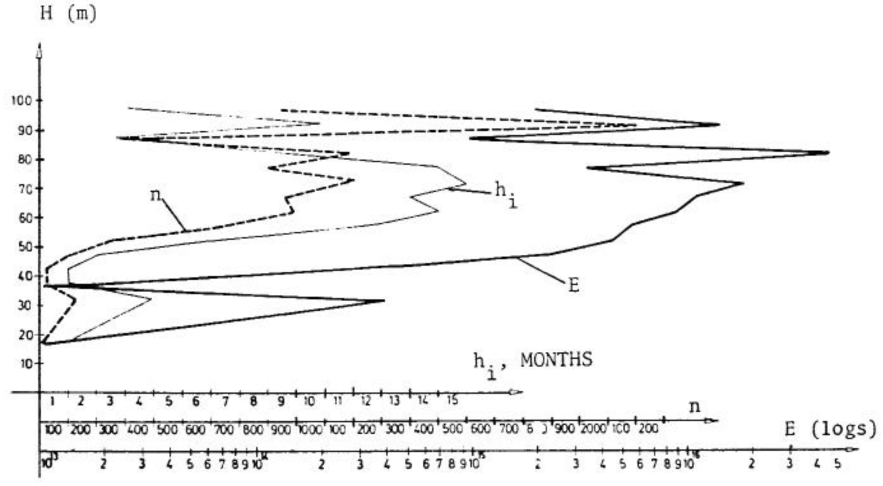


Fig. 7-1 Absolute frequencies, h_i in months, of the mean monthly water level with the corresponding number of earthquakes, n, and released energy, E, for class intervals of reservoir water levels

Correlation for individual cycles. The results of correlation of each individual loading and unloading cycle (for each water year), as subsamples from the sample, are:

Water year	Correlation coefficient
1967 - 1968	0.88
1968 - 1969	0.90
1969 - 1970	0.86
1970 - 1971	0.82
1971 - 1972	-0.36
1972 - 1973	0.49
1973 - 1974	-0.22
1974 - 1975	0.47
1975 - 1976	0.61

The correlation coefficients indicate a strong association between the monthly number of earthquakes in subsamples and the mean monthly water depth in the reservoir during the first four cycles of reservoir loading and unloading. The correlation is especially high during the second cycle of loading and unloading, with $r = 0.90$. The third cycle, characterized by the largest energy released, shows a weeker correlation of $r = 0.86$, approximately of the same order as the correlation coefficient of the first cycle of $r = 0.88$.

Even though one can question the above approach, because each subsample has only 12 pairs of values x_i and y_i (12 months), the results show two groups of subsamples, one of the first four cycles (water years 1967-1971), with $\bar{r} = 0.865$, and the other group of the last five cycles (water years 1971-1976) with $\bar{r} = 0.20$. The substantial difference between these two mean values of r supports the general hypotheses advanced and the conclusions derived in Chapter 5.

Earthquakes that occurred during the later five cycles, and especially 1971/1972 and 1973/1974, have either a negative, or a relatively small correlation coefficient. It can be said that earthquakes were mostly caused by natural forces, with no or a limited effect from the stored water. Asymmetrical frequency distribution of estimates of correlation coefficients is presented in Fig. 7-2.

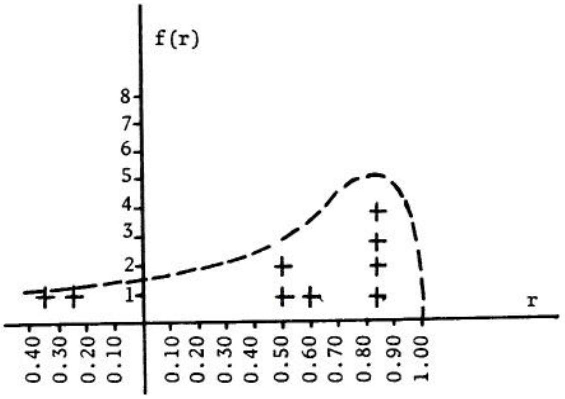


Fig. 7-2 Asymmetrical frequency distribution of estimates of correlation coefficients between the monthly number of earthquakes of each year and the corresponding mean monthly water depth in the reservoir for the period 1967/68 through 1975/1976.

The loading and unloading cycles of 1971/1972 and 1973/1974 were discussed in detail in Chapter 2. It was also shown by the above correlation that the lower values of the number of earthquakes correspond to the higher water depths in those cycles. Those cycles had the smallest number of earthquakes within the radius of less than 5 km and less than 10 km. It was hypothesized that these earthquakes have been affected by the reservoir. The highest number of earthquakes at these distances correspond to the highest correlation coefficient, namely in the second loading cycle. The number of earthquakes for these distances for all cycles, and the computed correlation coefficients are:

Cycle	Number of earthquakes distance up to 5 km, and up to 10 km (in parentheses)	Correlation Coefficient
1967-1968	617 (642)	r = 0.88
1968-1969	1665 (1748)	r = 0.90
1969-1970	1447 (1529)	r = 0.86
1970-1971	710 (740)	r = 0.82
1971-1972	107 (188)	r = -0.36
1972-1973	132 (329)	r = 0.49
1973-1974	77 (190)	r = -0.22
1974-1975	259 (438)	r = 0.47
1975-1976	119 (303)	r = 0.61

The linear regression equations of monthly number of earthquakes (n) versus the mean monthly water depth in the reservoir (H), with the corresponding correlation coefficients (r), are

1967-1968	$\frac{n = 2.61\,H - 56.22;}{H = 66.0\text{ m},\ n = 116}$	r = 0.88 (109 - 129)
1968-1969	$\frac{n = 5.69\,H - 257.56;}{H = 90.0\text{ m},\ n = 254}$	r = 0.90 (223 - 335)
1969-1970	$\frac{n = 5.01\,H - 229.24;}{H = 99.0\text{ m},\ n = 272}$	r = 0.86 (229 - 312)
1970-1971	$\frac{n = 2.19\,H - 65.73;}{H = 83.0\text{ m},\ n = 116}$	r = 0.82 (81 - 135)
1971-1972	$\frac{n = 0.40\,H + 68.82;}{H = 77.0\text{ m},\ n = 37}$	r = -0.36 (30 - 55)
1972-1973	$\frac{n = 0.82\,H + 7.03;}{H = 60.0\text{ m},\ n = 56}$	r = 0.49 (60 - 79)
1973-1974	$\frac{n = -0.13\,H + 46.36;}{H = 70.0\text{ m},\ n = 37}$	r = -0.22 (20 - 57)
1974-1975	$\frac{n = 1.17\,H + 31.15;}{H = 75.0\text{ m},\ n = 57}$	r = 0.47 (36 - 72)
1975-1976	$\frac{n = 1.67\,H - 62.15;}{H = 76.0\text{ m},\ n = 65}$	r = 0.61 (51 - 81)

The linear regression equation for the cycle 1969/1970 is presented in Fig. 7-3.

The total observed time series has nine cycles, investigated separately with different statistical parameters, seems to be nonstationary.

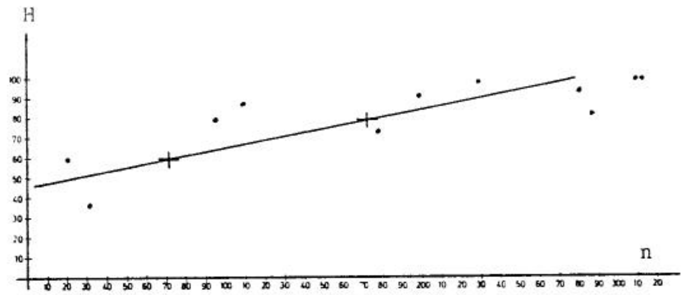


Fig. 7-3 Regression straight line of the monthly number of earthquakes, n, versus the mean monthly level of the reservoir, H, for 12 months of the cycle 1969/70, with r = 0.86 and the equation n = 5.01 H - 229.24

Correlation of successive lengths of all previous cycles. The study of correlation for the time series of n previous cycles, with n = 1,2,3,4,5,6,7,8, and 9, gives the following results (regression equations, correlation coefficients), assuming the samples are from a stationary process:

1967-1968 (series of 1 yr)	n = 2.61 H - 56.22	r = 0.88
1967-1969 (series of 2 yrs)	n = 3.95 H - 125.52	r = 0.89
1967-1970 (series of 3 yrs)	n = 3.97 H - 133.01	r = 0.86
1967-1971 (series of 4 yrs)	n = 3.57 H - 121.10	r = 0.80
1967-1972 (series of 5 yrs)	n = 3.48 H - 130.82	r = 0.73
1967-1973 (series of 6 yrs)	n = 3.41 H - 129.92	r = 0.72
1967-1974 (series of 7 yrs)	n = 3.15 H - 118.95	r = 0.68
1967-1975 (series of 8 yrs)	n = 2.77 H - 101.44	r = 0.62
1967-1976 (series of 9 yrs)	n = 2.41 H - 79.40	r = 0.59

The successive increases of the sample show a gradual decrease in the correlation coefficient, supporting the conclusion from the correlation of individual cycles.

The correlation coefficients of successively increased samples of n preceding years indicate a weakening of the correlation. The changes are presented in Fig. 7-4. A decrease in the correlation coefficient after 1971 is affected by small correlation coefficients for the later cycles, with the findings that after the cycle 1970/71 the earthquakes did not depend on reservoir water depth.

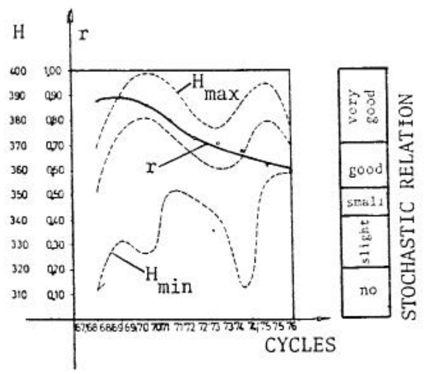


Fig. 7-4 Correlation coefficients, r, and reservoir water levels (H_{max}, H = average level, H_{min}) for the annual cycles of filling and emptying of the reservoir, and the sequentionally increased number of cycles used in correlation

In order to sum up the investigations, time periods 1967/1968-1970/1971 and 1971/1972-1975/1976 (Figs. 7-5 and 7-6) are separated. The results support assumptions made.

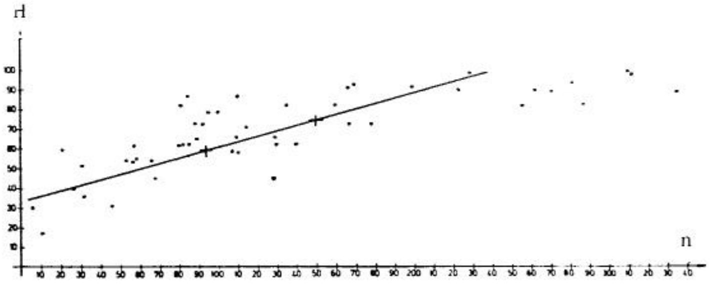


Fig. 7-5 Linear regression of monthly number, n, of earthquakes versus the corresponding mean monthly reservoir level, H, for the first four cycles (1967/68 - 1970/71), with r = 0.80 and n = 3.57 H - 121.10

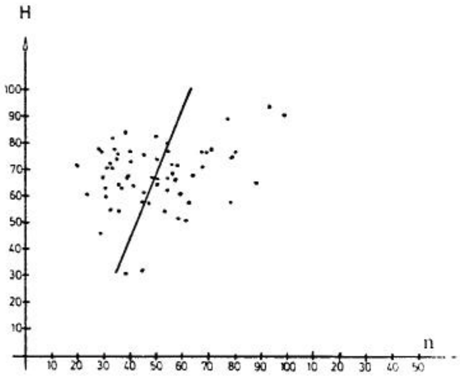


Fig. 7-6 Linear regression of monthly number, n, of earthquakes versus the corresponding mean monthly reservoir level, H, for the last five cycles of filling and emptying of the reservoir (1971/72 - 1975/76), with r = 0.29 and n = 0.43 H + 21.07

7-3 Correlation of Annual Series

A further step in the linear correlation between the number of earthquakes and the reservoir water depth is made for the annual values of eight cycles (1967/68-1974/45):

(1) The total annual number of earthquakes correlated with the maximum annual water depth gave r = 0.51;

(2) The total annual number of earthquakes correlated with the mean annual water depth gave r = 0.55;

(3) The total annual number of earthquakes correlated with the water weight, that corresponds to the maximum annual water depth, gave r = 0.54; and

(4) The total annual number of earthquakes correlated with the water weight, that corresponds to the mean annual depth, gave r = 0.58.

These correlations were estimated by ignoring the nonstationarity of the process. The annual number of earthquakes shows a better correlation with the mean annual water depth. A somewhat better correlation is obtained between the annual number of earthquakes and the water weight than with the water depth, with water depth considered as the independent variable in these correlations.

The correlation for the total reservoir observational period for nine cycles gives the regressions n = 34.90 H - 1382.46, with r = 0.53, where n_a and H_a are annual values, respectively for the number of earthquakes and the mean reservoir water depth. The correlation coefficient is smaller than for the period of eight cycles of r = 0.55, which is in accordance with the previous conclusions. The mean annual water depth, the annual number of earthquakes and regression equation for this case are given in Fig. 7-7.

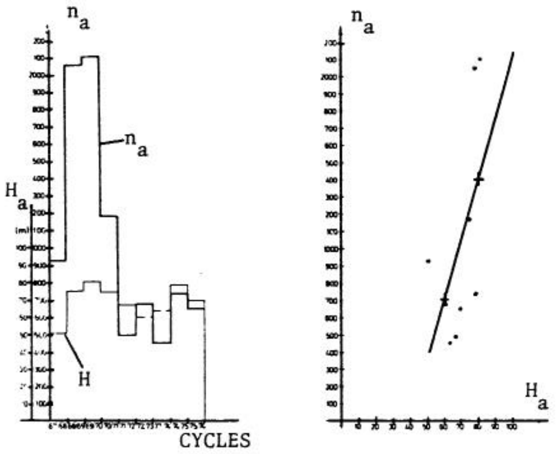


Fig. 7-7 Annual number of earthquakes, n_a, and the mean annual water depth, H_a, of the reservoir versus cycles (left graph), and the regression line of the annual number, n_a, of earthquakes versus mean annual water depth, H_a, for nine cycles (right graph), with r = 0.53 and n_a = 34.0 H_a - 1,380.46

7-4 Correlation for Total Values of Each Twelve Months

The study of tables and figures in Chapter 5 indicated that the seismic process is more or less active in certain months. Because of that, the correlation of the total number of earthquakes for each month and for all the observed years with the corresponding water depth for each of 12 months, are examined for following periods:

(1) November (1967/1968, ..., 1975/1976)

(2) December (1967/1968, ..., 1975/1976)

(3) January (1967/1968, ..., 1975/1976)

. . . .

(12) October (1967/1968, ..., 1975/1976)

A high degree of correlation, with r = 0.915, was obtained in this type of study. It was defined by the regression equation $n_m = 22.40\ H_m - 773.10$ (see Fig. 7-8).

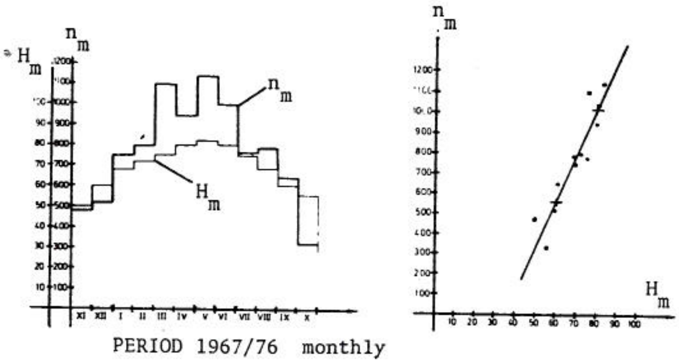


Fig. 7-8 Distributions of monthly number, n_m, of earthquakes and mean monthly reservoir water level, H_m, for the nine cycles (1967-1976) over the 12 months, (left graph), and regression line of n_m versus H_m for the nine cycles (right graph), with r = 0.915 and $n_m = 22.40\ H_m - 773.10$

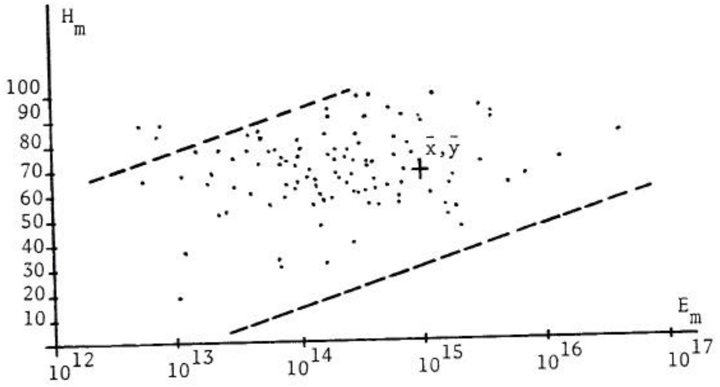
In order to check the results obtained in Subchapter 7-3, an estimate of the correlation coefficient for the same period of eight years is made. The water depth and the water weight in the reservoir were used as independent variables alternately. The results were: (i) The total of monthly number of earthquakes correlated to the mean water depth for each of twelve months had r = 0.91; and (ii) The total monthly water depth correlated to the water weight that corresponds to the mean water depth of each of twelve months, gave r = 0.92. The correlation with the water weight as an independent variable gives a little higher correlation coefficient than for the water depth.

7-5 Earthquake Energy as a Dependent Variable

The correlation of the energy released by earthquakes is made for the following two cases: (1) The released energy versus the water depth as the independent variable; and (2) The number of earthquakes versus the released energy, as two variables affected by the same causal factor, the water depth in the reservoir.

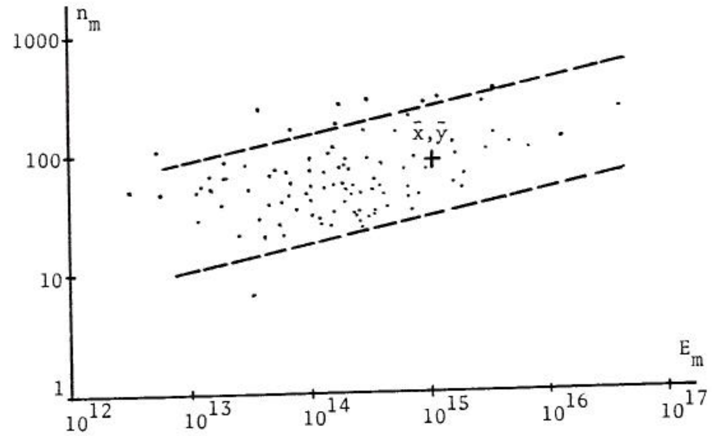
The relationship of the released energy to the mean monthly water depth is given Fig. 7-9. The deviations of points from any fitted straight regression line are quite large. Values are presented in logarithmic scales.

Figure 7-10 presents the relationship of monthly number of earthquakes to the energy released in logarithms, representing the nonlinear relationship in Cartesian coordinates. A relatively small correlation coefficient is obtained.



$$\bar{x} = \frac{114.2}{108} = 1.06 \times 10^{15} \text{ergs}; \quad \bar{y} = \frac{7,476.15}{108} = 69.23 \text{ m}$$

Fig. 7-9 The scattered graph of points of H_m (monthly average water depth in meters in the reservoir at the dam site) and E_m (monthly released earthquake energy, in ergs), in logarithmic scales



$$\bar{x} = \frac{1,142 \text{x} 10^{15}}{108} = 1.06^{15} \text{ ergs}$$

$$\bar{y} = \frac{9,303}{108} = 86.14$$

Fig. 7-10 The scattered graph of points of n_m (monthly number of earthquakes) and E_m (monthly released earthquake energy, in ergs) in logarithmic scales

Chapter 8
FITTING DISTRIBUTION FUNCTIONS TO RELEASED EARTHQUAKE ENERGY

8-1 Fitted Probability Distributions for Released Energy of Earthquakes

The histogram of absolute frequency of logarithms of released energy allows theoretical probability distribution functions to be fitted. The class marks of released energy are given by their logarithms (Figs. 8-1 and 8-2).

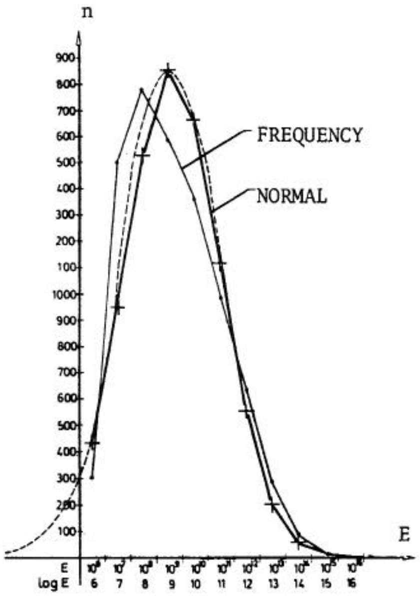


Fig. 8-1 Frequency distribution of the number, n, of earthquakes for class intervals of the released energy, E, of earthquakes, and the fitted normal distribution (in logarithmic scale for energy)

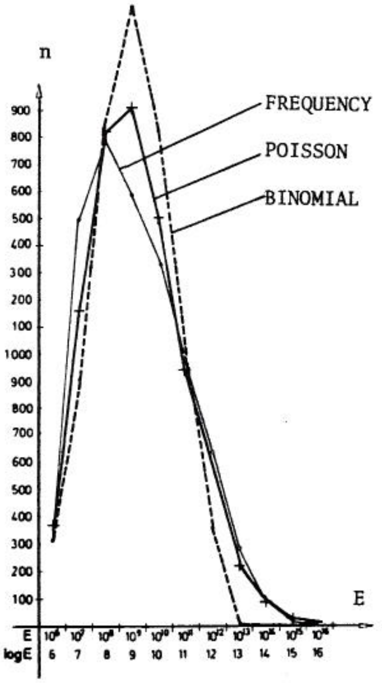


Fig. 8-2 Frequency distribution of the number, n, of earthquakes for class intervals of the released energy, E, and the fitted binomial and Poisson distribution functions (in logarithmic scale for energy)

Some authors assume that the number of earthquakes, as rare natural phenomenon, are Poisson distributed (A. E. Scheidegger, 1975), namely

$$p(x) = \frac{m^x e^{-m}}{x} \quad , \tag{8-1}$$

where m = np, with x = number of earthquakes in a unit time, p = the small probability of earthquake occurrence in a large number of intervals n, and p(x) is the probability for the number of rare earthquakes (x = 0, 1, 2, ...) to occur in a given interval. The Poisson distribution is the asymptotic distribution of the binomial distribution for small p and large n, namely of

$$p(x) = \binom{n}{x} p^x q^{n-x} , \tag{8-2}$$

or when $p \to 0$ and $n \to \infty$, with np a constant $m > 0$, and $q = 1 - p$. For $n \to \infty$, the binomial distribution tends to normal, so that it is feasible to approximate the binomial distribution by the normal distribution under the following conditions: (i) the occurrence of earthquakes is not a time dependent process, and (ii) the number of intervals in which the rare earthquakes are observed is large (large n). Then the normal distribution used is

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \tag{8-3}$$

with μ = the expected value (mean), and σ^2 = the variance of x. They are estimated by the sample parameters $\bar{x}$ and s^2. The standardized normal distribution for

$$t = \frac{x - \bar{x}}{s} \tag{8-4}$$

becomes

$$f(t) = \frac{1}{\sqrt{2\pi}} e^{-t^2/2}, \tag{8-5}$$

which is tabulated in many textbooks on statistics and applied statistics in various disciplines.

By using the transformed variables, the theoretical distributions, and the statistical tables (Yevjevich, V., 1972; Pavlić, I., 1970), the estimates of probabilities for classes of released energy are made for various probability functions, and shown in Table 8-1.

Regardless that the Poisson distribution is used only for the discrete variables, here the released energy is considered only for discrete class intervals, so that this distribution is fitted to the logarithms of these class intervals. The comparison of empirical and theoretical distributions (Table 8-1, Figs. 8-1 and 8-2) indicates that the Poisson distribution applied to logarithms of classes of released energy best fits the empirical distribution, because it shows the lowest value of χ^2 = 254.88 in the χ^2-test, with χ^2 given by

$$\chi^2 = \sum_{j=1}^{n} \frac{(f_i - f_{t_i})^2}{f_{t_i}} \tag{8-6}$$

Table 8-1 Fitting Three Probability Distribution Functions to Frequencies of Logarithms of Class Interval Values for the Released Energy of all Earthquakes Observed during the Filling of the Bileća Reservoir in the Period 1967-1976.

ENERGY E (ergs)		10^6	10^7	10^8	10^9	10^{10}	10^{11}	10^{12}	10^{13}	10^{14}	10^{15}	10^{16}	$\sum$	χ^2-test
LOG E		6	7	8	9	10	11	12	13	14	15	16		
FREQUENCY		311	1497	1784	1586	1360	980	640	2840	90	15	1	8548	
THEORETICAL DISTRIBUTION	NORMAL	437	946	1529	1847	1659	1113	552	204	57	17	2	8356	549.92
	POISSON	370	1162	1824	1909	1499	941	493	221	87	30	9	8545	254.88
	BINOMIAL	197	904	1862	2275	1823	1002	381	10	2	0.2	0.008	8456	12463.65

Table 8-2 Fitting Three Probability Distribution Functions to Frequencies of Logarithms of Class Interval Values **for** the Released Energy for Earthquakes that are at Distances 10-75 km from the Earthquake Observation Station during the Filling of the Bileća Reservoir in the Period 1967-1976.

ENERGY E (ergs)		10^7	10^8	10^9	10^{10}	10^{11}	10^{12}	10^{13}	10^{14}	10^{15}	10^{16}	$\sum$	χ^2-test
LOG E		7	8	9	10	11	12	13	14	15	16		
FREQUENCY		2	7	106	507	851	626	288	94	16	1	2498	
THEORETICAL DISTRIBUTION	NORMAL	2	19	135	469	798	696	312	69	8	1	2504	45.69
	POISSON	32	139	304	441	481	419	304	190	103	50	2463	850.02
	BINOMIAL	7	58	213	457	613	581	360	141	33	3	2466	243.69

where f_i = the empirical frequency and t_i = the theoretical probability.

The above value of χ^2 is relatively high, which means that differences between the frequency f_i and the probability f_{t_i} are large, so that the logarithms of released energy classes may not follow the theoretical probability distribution functions fitted (Table 8-1).

It was pointed out in Chapter 5 that the frequency distribution is symmetrical for released energy at distances 10-75 km (Table 8-2 and Fig. 8-3). The fit of theoretical distribution functions to empirical frequency distribution (Table 8-2 and Fig. 8-3) indicates that the normal distribution is best, even though its χ^2-test shows that a substantial differences exist between the theoretical probabilities and the empirical frequencies with $P(\chi^2 = 45.69) < 0.001$ (Pavlić, I., 1970). Therefore, the logarithms of class marks of released energy do not follow the normal distribution but are close to it. In other words, the lognormal distribution function is very close to fit the frequency distribution of the released energy at distances 10-75 km.

The purpose of this chapter was to investigate to what degree the theoretical distribution functions fit the frequency distributions in order to be able to estimate the probabilities of occurrence of strong earthquakes, such as those with energy released

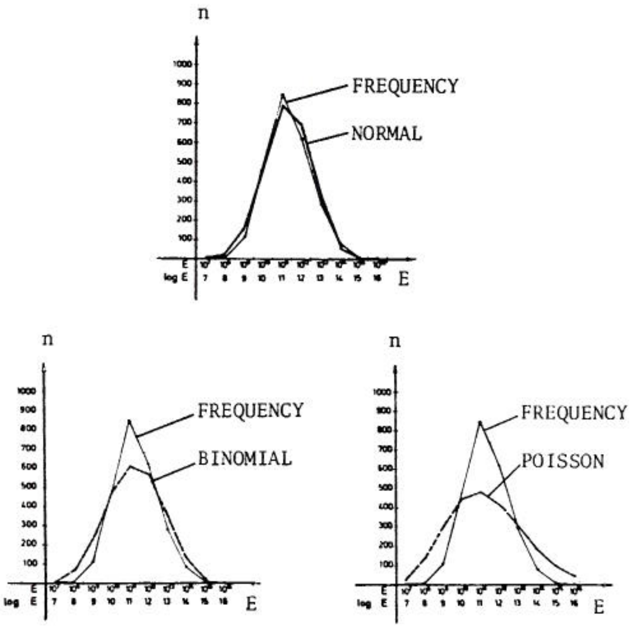


Fig. 8-3 Frequency distribution of the number, n, of earthquakes for class intervals of the released energy, E, for epicenter distances 10-75 km from recording station, and fitted normal (top graph), binomial (left graph), and Poisson (right graph) distribution functions (in logarithmic scale for energy)

$E \geq 10^{16}$ ergs, when this extrapolation becomes justified for released energies higher than the energy released by the strongest, already observed earthquake. If one accepts that the lognormal distribution best fits the frequency distribution of released earthquake energy at distances of 10-75 km, then the probability is $P(E \geq 10^{16}$ ergs$) \leq 0.00003$, because it is outside the boundaries of $\bar{x} + 4s = 16.14$. In other words for the average seismic activity after the cycle 1970/71, one can expect an earthquake like that to reoccur about every 66 years. This conditionally confirms that the assumption that these strong earthquakes are rare phenomena is acceptable. It means that a relatively long time period is needed until the next strong release of the accumulated energy occurs. There is no energy release unless it is accumulated. The question is what will be the cause, i.e. what will trigger the future energy releases. In the case analyzed in this study, namely the Bileća Reservoir, it is concluded that the stored water may have been this trigger.

It may come out that the hypergeometric or better the gamma distributions may come out to be the better fits to frequency distributions than all of the above investigated distributions. The earthquakes of discrete classes of a high released energy are located on the right tail of the frequency distributions, meaning that probabilities of their occurrence are small. Because of a large uncertainty in extrapolation of the tail for the high values of released energy, for whatever type of distributions is used, research on the best fit of theoretical distribution functions to frequency distributions of released earthquake energy was not pursued further in this paper.

It should be stated at the end of this Chapter that the above presentation and the fact that there is no energy released unless it is accumulated, bring about a basic question, namely whether the stored water does induce and moderate natural earthquake processes. An affirmative answer to that question may mean that the natural seismic conditions were near the limit stresses of earthquake release, and that the stored water only triggered the release of energy somewhat earlier than the natural stress of energy accumulated in the rock would have done it anyway.

It is obvious that the increase in the accumulated water could not cause the energy release if that energy had not already been accumulated. Therefore, if a natural large earthquake had preceded the filling of the storage reservoir further large energy releases and induced shocks should not be expected, because there is no significant stored energy remaining in the same underground.

8-2 Earthquakes at Distances 30-75 km from Recording Seismic Station

It was stated in Chapter 6 that the strong earthquake of August 25, 1970, which released the energy of $E = 4.09 \times 10^{16}$ ergs, should be analyzed as a part of the set of earthquake random variables for distances 30-75 km. Any regularity that would apply to that entire set should also be valid for this observed strongest earthquake.

The degree of correlation between the annual number of earthquakes and the mean annual water levels in the reservoir (Table 8-3) is given by the equation $N_{pod} = 2.79 H_{pod} - 47.77$ with $r = 0.52$.

Studies in subchapter 7-3 indicated that the correlation coefficient for all earthquakes is $r = 0.53$. The earthquakes for the class distances of 30-75 km had about the same correlation coefficient with the mean water depth of the reservoir. The correlation coefficient of $r = 0.52$ is a relatively low correlation (only about 25% of the variance explained). However, it is more important in this case to show that the correlation exists rather than what is its degree of association. This correlation gives the answer to the question posed in Chapter 5, namely that the earthquakes at distances of 30-75 km are also affected by the stored water.

Chapter 9
THE ANALYSIS OF MEANS AND VARIANCES

9-1 The Analysis of Means

Following the central limit theorem in the theory of sampling, the arithmetic means of subsamples approximately follow the normal distribution, independently from the type of distribution of the variable x of the main sample. Even though the mean relates herein to the subsamples of one year, the investigation of their means should present some important characteristics for this 9-year long sample. The arithmetic means of these subsamples are a new series, that should be compared with the general arithmetic mean $\bar{x}$ of the 9-year sample.

The standard deviation of the distribution of subsamples arithmetic means $\bar{x}_i$ is

$$s_{\bar{x}} = \frac{s}{\sqrt{n}} \sqrt{\frac{N - n}{N - 1}} \tag{9-1}$$

where N = the sample size and n = the number of subsamples, with the standardized variable of subsample means being

$$t = \frac{|\bar{x}_i - \bar{x}|}{s_{\bar{x}}} \quad . \tag{9-2}$$

This new variable t is t-distributed, with their probability values P(t) tested for not to be very small. If any one of nine values is less than 0.05 (or a stronger test of less than 0.01) the proposition that the arithmetic means of subsamples are from the same population, and statistically equal to $\bar{x}$ of the sample to which the subsamples belong, should be rejected. The means of subsamples are given in Table 9-1.

The mean value of the total sample of nine years is $\bar{x} = 86.14$, and their standard deviation is

$$s = \sqrt{\frac{\sum_i \sum_j (\bar{x}_{ij} - \bar{x})^2}{N}} = 72.18, \text{ so that Eq. (9-1)}$$

gives $s_{\bar{x}} = 19.8$.

Values for P(t) of the t-distribution are given in Table 9-2.

Table 9-1 Means of Subsamples

CYCLE	1967 1968	1968 1969	1969 1970	1970 1971	1971 1972	1972 1973	1973 1974	1974 1975	1975 1976
MEAN MONTHLY VALUES	77.33	171.92	175.92	98.17	41.25	56.75	38.08	61.33	54.50

Table 9-2 Probabilities of Standardized Values of Subsample Means

1967/1968	$t_1 = 0.45$	0.6	$< P(t) < 0.7$
1968/1969	$t_2 = 4.33$	0.001	$< P(t) < 0.1$
1969/1970	$t_3 = 4.53$		$P(t) < 0.001$
1970/1971	$t_4 = 0.61$	0.5	$< P(t) < 0.6$
1971/1972	$t_5 = 2.27$	0.05	$< P(t) < 0.1$
1972/1973	$t_6 = 1.48$	0.1	$< P(t) < 0.2$
1973/1974	$t_7 = 2.43$	0.02	$< P(t) < 0.05$
1974/1975	$t_8 = 1.25$	0.2	$< P(t) < 0.03$
1975/1976	$t_9 = 1.60$	0.1	$< P(t) < 0.02$

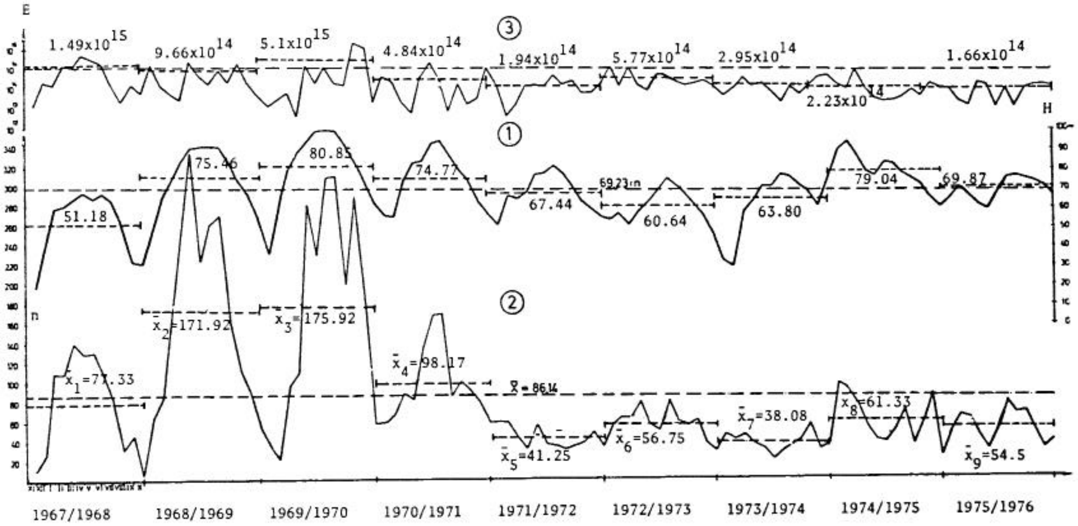


Fig. 9-1 Comparison of three basic time series for study of earthquake characteristics for the Grančarevo Dam: (1) Mean monthly levels, H, of the reservoir; (2) Monthly number, n, of earthquakes; and (3) Monthly released energy, E, by all earthquakes in each month

It can be seen from Table 9-2 that the probabilities of subsample means for years 1968/69 and 1969/70 are very small (under 0.01). It leads to the conclusion that these subsample means do not belong to the same population as the other subsample means. The subsample means for years 1967/68 and 1970/71 have sampling probabilities of about 0.40-0.60, and the subsample means for years 1971/72 - 1975/76 are characterized by probabilities that are greater than 0.02 and smaller than 0.03. The differences in these probability values point out to several phases of seismic activity:

(1) The phase prior to filling of the reservoir, as a natural, stationary state of seismic activity;

(2) The phase of intensive seismic activity as the transient state, influenced by the storage of water, with the changes in seismic activity over time not permitting to estimate precisely the effect of water storage in this phase; and

(3) The equilibrium phase, namely the new trend in the underground for a new stationary state (new dynamic equilibrium), with the natural variations in seismic activity under the existence of the water storage.

The changes in earthquake activity of phases (2) and (3) are presented in Fig. 9-1. Since the phase (1) had been under the influence of construction of the dam prior to loading of the reservoir, its data are not feasible for the comparison with the earthquake activity in phases (2) and (3) without the danger of producing erroneous conclusions. This shows that it is essential to start the investigations on the effect of stored water on seismic activity long before any construction around the reservoir and the reservoir loading, to allow the period prior to construction to be sufficiently long for the properties of natural seismic activity to be established.

9-2 The Analysis of Variances

The assumption that all nine annual subsamples, each with the 12 monthly values belong to the same population, from which the main sample is taken, is tested by using the F-test. According to this test the parameter

$$F = \frac{\sum\limits_i \sum\limits_j \left(\frac{\bar{x}_i - \bar{x}}{s}\right)^2 / (n - 1)}{\sum\limits_i \sum\limits_j \frac{(x_{ij} - \bar{x})^2}{s} / (N - n)} = \frac{s_t^2}{s_u^2} \qquad (9\text{-}3)$$

where x_{ij} = the values of the sample, $\bar{x}_i$ = the means of subsamples, $\bar{x}$ = the mean of the sample and s = the standard deviation of the sample, F follows the F-distribution, with the degrees of freedom of $n - 1$ in the numerator and $N - n$ in the denominator. The condition to be satisfied is that x_{ij} are random variables of normal distribution with the mean $\bar{x}$ and variance s^2. This condition somewhat decreased the validity of this test, since it was found in Chapter 8 that the variables describing the earthquakes do not follow the normal distribution.

The estimates of F by Eq. (9-3) are simplified by the fact that

$$\sum_i \sum_j (x_{ij}-\bar{x})^2 = \sum_i \sum_j (x_{ij}-\bar{x}_i)^2 + \sum_i \sum_j (\bar{x}_i-\bar{x})^2. \qquad (9\text{-}4)$$

The values in Eq. (9-4) are:

$$\sum_i \sum_j (x_{ij} - \bar{x})^2 = 562{,}712.77$$

$$\sum_i \sum_j (x_{ij} - \bar{x}_i)^2 = 293{,}507.51$$

$$\sum_i \sum_j (\bar{x}_i - \bar{x})^2 = 269{,}205.26$$

$$s_t^2 = \frac{1}{n - 1} \sum_i \sum_j (\bar{x}_i - \bar{x})^2 = 33{,}650.66$$

$$s_u^2 = \frac{1}{N - n} \sum_i \sum_j (x_{ij} - \bar{x}_i)^2 = 2{,}964.72$$

so that

$$F = \frac{33{,}650.66}{2{,}964.72} = 11.35 > 2.03/2.69 = F_0 \quad ,$$

with $P(F) < P(F_0 = 0.05/0.01)$, with the degree of freedom of 8 in the nominator and 99 in the denominator.

Since the values s_t^2 and s_u^2 are substantially different, it means that the subsamples do not belong to the same basic population, of the sample of nine years of observations, as far as the variance is concerned.

The empirical data is grouped in nine subsamples (n), each having the mean

$$\bar{x}_i = \frac{1}{n_i} \sum_{j=1}^{n_i} x_{ij} \quad , \quad \begin{array}{l} i = 1,2,\ldots,9 \\ j = 1,2,\ldots,9 \end{array} \qquad (9\text{-}5)$$

The data for the variable x_{ij} and the mean values $\bar{x}_i$ are given in Table 9-3.

For the similar estimates made for the subsamples of cycles 1967/68 - 1970/71, the results become:

$$s_t^2 = \frac{91{,}823.61}{4 - 1} = 30{,}607.87$$

and

$$s_u^2 = \frac{279{,}263.11}{44} = 6{,}346.89 \quad ,$$

with $F = 4.82 > 2.82$ or $F = 4.82 > 4.26$, with

$F > F_{t_{0.05}} = 2.82$ for the 0.05 probability level,

and $F = F_{t_{0.01}} = 4.26$ for the 0.01 probability level.

This result tells of a small probability that these subsamples belong to the same population, represented by this four-year sample.

Table 9-3 Computation of Means of Nine Subsamples of Observed Earthquakes

	1967 1968	1968 1969	1969 1970	1970 1971	1971 1972	1972 1973	1973 1974	1974 1975	1975 1976
X_{ij}	1	2	3	4	5	6	7	8	9
1	11	68	32	58	59	55	45	100	51
2	27	85	21	66	58	63	39	94	67
3	110	167	95	88	42	62	45	78	65
4	107	256	110	81	30	79	36	55	46
5	140	335	281	135	55	55	32	41	31
6	129	223	229	168	35	49	20	39	51
7	130	262	310	169	34	80	29	51	81
8	109	271	312	84	30	58	36	72	68
9	82	160	199	100	34	55	41	36	70
10	31	114	287	92	37	60	57	57	51
11	46	89	178	80	48	36	31	89	33
12	6	33	57	57	33	29	46	24	40
Σ	928	2063	2111	1178	495	681	457	736	654

$\bar{X} = 86{,}14$

$\bar{x}_i$	$\bar{x}_1$	$\bar{x}_2$	$\bar{x}_3$	$\bar{x}_4$	$\bar{x}_5$	$\bar{x}_6$	$\bar{x}_7$	$\bar{x}_8$	$\bar{x}_9$
	77.33	171.92	175.92	98.17	41.25	56.75	38.08	61.33	54.50

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Regardless of some deficiencies in the collection and processing of data, it was found that the number of local earthquakes per year has been significantly increased in the first four years of filling and emptying of the reservoir or the years after the first phase of four years has passed. The reservoir has been filled with water in stages for several years, in order to avoid that the sudden loading of the reservoir triggers a large earthquake. This case study is instructive for planning observations and for advancing explanations of potential relationship between the reservoirs (especially in highly pervious formations and close to large fault zones) and the regime of earthquakes.

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