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Correlation Between Seismic Microactivity, Temperature and Subsidence of Water Level at Reservoirs

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Abstract. Large reservoirs in the Alps and Romanian Carpathians have been monitored by high gain seismic stations over a period of six years. Microearthquakes with local magnitudes less than zero showed a clear correlation with variations of the water level. A model is presented which explains the time-distribution of this weak seismic activity as caused by the freezing of water in near-surface cracks exposed to freezing temperatures when the water level falls. This model is supported by an analysis of the correlation between the seismic micro-activity, average daily temperature distribution and rate of water-level-decrease. Precise locations of the events and estimates of energy corroborate the proposed model for the generation of this type of seismic micro-activity at reservoirs in high mountain regions.

Key words: Ice induced seismicity – Daily variation of microtremors – Microtremors at reservoirs – Freezing water in near-surface cracks

Introduction

In 1971 a seismic monitoring program was started at two reservoirs in the Austrian and Swiss Alps. In addition, three reservoirs in the Romanian Carpathians have been monitored seismically since 1974. At the five reservoir sites compatible high gain short period seismic stations have been operated.

The longest duration of seismic recording was at the Schlegeis reservoir, Austria. Recording commenced in May 1971 and is still continuing. Results of the seismic observations at Schlegeis have been reported earlier (Blum and Fuchs 1974; Blum et al. 1977; Bock 1978b).

Numerous weak tremors with local magnitudes less than zero occurred here, predominantly during periods when the water level was being lowered and while it was at a minimum. This result was not expected because at other reservoirs with reported induced seismic activity, the activity usually starts during periods of rising water level. An example is the Vajont reservoir, Italy (Caloi 1966; Bozović 1974). Many other similar examples have been reported by Gupta and Rastogi (1976). But the characteristic feature of the temporal distribution of the seismic events at Schlegeis was not an isolated case. Similar seismic activity was also observed at other reservoirs such as Emosson (Switzerland), Bicaz, Lotru and Arges (Romania), where the seismic surveillance started later than at the Schlegeis. This paper summarizes the common features of the local seismic activity observed at the five reservoirs and presents a model which explains the observations.

Seismic Observations

At each reservoir at least one short-period vertical component seismic station was installed. The amplification of the total recording system was up to 10^6 at 10 Hz. Details of the reservoir and the seismic surveillance are given in Table 1, together with the dimensions of the reservoirs.

The seismometers are placed within the dam at Schlegeis, Emosson and Bicaz, and at the other reservoirs, within a distance of a few hundred metres from the dam. The seismic station in the Emosson dam is operated by the Schweizerischer Erdbebendienst, Zürich. Recordings are made on an ink recorder with continuous paper loop at a speed of 300 mm/min at Schlegeis (Blum and Fuchs 1974) and 240 mm/min at the seismic stations in the Romanian Carpathians (Merkler et al. 1975). The time-reading precision is 0.05 s. At Emosson a film recorder was installed providing a time-reading precision of 0.1 s.

Seismogram examples from local events are shown in Fig. 1. They are characterized by high frequency oscillations between 10–15 Hz with a duration of about 1 s. *S-P* travel times, as read in the case of some of the stronger tremors, are less than 0.2 s.

Local magnitudes of these local tremors have been estimated roughly from their signal duration (Tsumara 1967; Lee et al. 1972) to be $M_L < 0$. No local tremors with magnitudes greater than 0 have been observed. The radiated seismic energy ranges between 10^7–10^{12} erg, from application of the empirical relation between seismic energy and local magnitudes derived by Gutenberg and Richter (1956).

The time distribution of local events observed at the five reservoirs is depicted in Fig. 2. A striking feature in Fig. 2a–c is that the times when the water level was rising are characterized by decreasing seismic activity or even its absence. The maximum of local seismic activity is predominantly observed during periods of decreasing and minimum water level.

This is clearly seen for the time distribution of local events at the reservoirs Schlegeis, Emosson and Bicaz in Fig. 2a–c. At Lotru (Fig. 2d) a periodic occurrence of seismic events is also observed. But the variation of the lake level is too small to establish a coincidence of increasing activity and subsiding water level. However, there is a seasonal variation, the local events at Lotru also occurring predominantly in winter and spring. At Arges

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Table 1. Reservoirs under seismic surveillance

	Dam			Volume (10^6 m^3)	Year of completetion	Beginning of seismic observation	Amplification of ground displacement at 1 Hz
	Height (m)	Type	Basement rock				
Schlegeis, Austria	130	Arch. butress	Gneiss	129	1971	May 1971	16500 till April 1972; later 33000
Emosson, Switzerland	180	Arch	Granite	225	1974	Sept. 1973	10000 till Sept. 1974 later on 20000
Bicaz, Romania	127	Gravity	Flysch	1230	1961	Nov. 1974	30000 during the day 100000 during the night[a]
Lotru, Romania	118	Rockfill	Gneiss	340	1975	Nov. 1974	35000 during the day 70000 during the night[a]
Arges, Romania	166	Arch	Gneiss	465	1965	April 1965	30000 during the day 100000 during the night[a]

[a] Night amplification from 8 p.m. to 6 a.m. local time

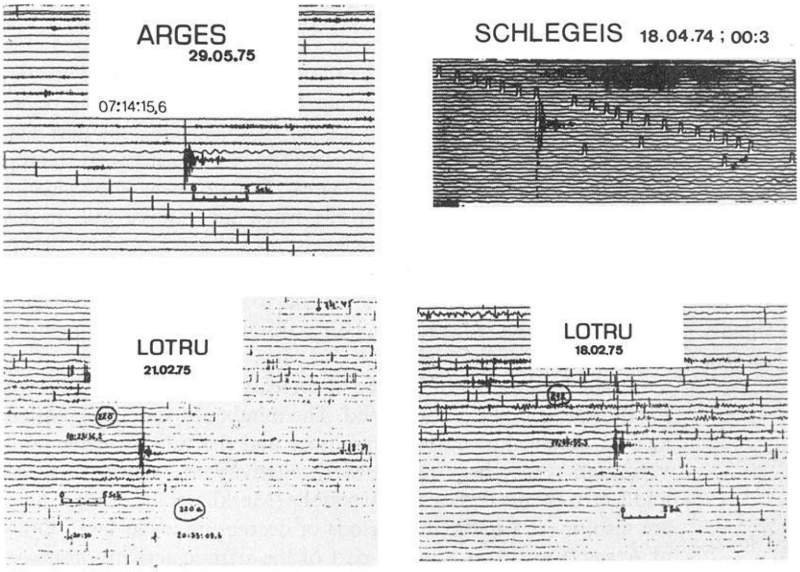


Fig. 1. Examples of seismograms

Table 2. Number of seismic events observed at the Romanian reservoirs Bicaz, Lotru, and Arges

Location	Total number	Number of events with *S-P* times between					Period of analysis
	(*S-P* ≦ 5 s)	(0–1 s)	(1–2 s)	(2–3 s)	(3–4 s)	(4–5 s)	
Bicaz	943	857	10	3	69	4	Nov. 4, 1974; June 1, 1978
Lotru	1777	1144	94	78	366	95	Nov. 7, 1974; June 1, 1978
Arges	651	75	314	155	79	28	April 4, 1975; June 1, 1978

(Fig. 2e) seismic activity increases during times of low water level. However, this area is characterized by a comparatively high level of seismicity, most likely of tectonic origin, throughout the year. For the Schlegeis reservoir (Fig. 2a), all local shocks have *S-P* times less than 0.2 s. For the Emosson reservoir (Fig. 2b) events with *S-P* times less than 0.2 s are plotted in the upper part of the temporal distribution. Most of the shocks with *S-P* times greater than 0.2 s are of natural tectonic origin (Bock 1978b).

The observed data from the seismic stations at the Romanian reservoirs are shown in Fig. 2c–e and all seismic events with *S-P* times up to 5 s are considered. However, at Bicaz and Lotru most of them have *S-P* times less than 1 s. At Arges, the maximum number of seismic events falls into the *S-P* time range between 1 and 2 s (i.e., 8–16 km). The proportion of local events with *S-P* times less than 1 s (i.e., < 8 km) at Arges is not as conspicuous as at the other two reservoirs in the Carpathians (see Table 2).

In the plot of the time distribution observed at the Romanian reservoir stations, earthquakes are also included which are part of the increased seismic activity in the Carpathians after the strong Vrancea-earthquake of 4 March 1977.

It has been pointed out by Fuchs et al. (1979) that seismic activity migrated after this date not only to the foredeep in the

Vrancea region but also into the Carpathian mountains up to distances of more than 100 km. At Bicaz (Fig. 2c) the peaks in seismic activity in March and April 1977 are part of this migration phenomenon. At Lotru the number of earthquakes also increased drastically in March and April 1977 (ISPH-IGK 1977) as can be seen in Fig. 2d. At Arges seismic activity doubled after the Vrancea-earthquake (Fuchs et al. 1979).

As reported by the Romanian-German seismological working group (Bock 1978a) epicenters of earthquakes from these series (March–April 1977) were located 20 km away from the Bicaz and Lotru stations. Therefore, seismic events connected with the migration phenomenon are eliminated from further analysis in this paper. They clearly fall outside the range of local events situated close to the reservoir stations which are characterized by *S-P* times of less than 0.2 s and 1 s, respectively.

Locations of some of the seismic events have been obtained for the Schlegeis reservoir (Blum et al. 1977). All located shocks are shallow and not deeper than 300 m. Due to lack of spatial resolution a more accurate determination of focal depths within the range $0 \leqq z \leqq 300$ m could not be given.

The epicenters are concentrated on the waterside of the dam. Only a few events appeared in the region of greatest water depth (Blum 1975; Blum et al. 1977). Bock (1978b) argues, on the basis of detailed numerical experiments, that in the case of Schlegeis reservoir the stress induced by loading and unloading and changes in effective water pressure at depth do not reach critical values for rock fracture.

In October 1977, two additional seismic stations were brought into operation at the Schlegeis reservoir, situated about 2 and 3 km south of the dam at the waterside (Fig. 3a). Local events were also recorded by these stations. An example is given in Fig. 3b. On the records of the dam stations no seismic signals were observed from these events. That means that their foci are located further away from the dam site.

Correlation Between Number of Events, Temperature, and Water Level Variations

The key to understanding the mechanism of the observed local shocks is in their seasonal variation **and** daily time distribution which is depicted in Fig. 4. With the exception of Arges, a clear maximum of seismic activity appears between 0 and 10 a.m. local time. The minimum activity occurs at noon.

At Bicaz and Lotru the stations had to be run during the day with $^1/_2$ or $^1/_3$ of the nightly gain, respectively, due to industrial noise (Table 1). The number of events likely to be unobserved by these stations during the day due to the reduced gain is negligible compared to the actually observed decrease in the number of detected events during the day (Bicaz about 250, Lotru about 230). Similar daily distributions of seismic events have been observed at the Kurobe dam (Hagiwara and Ohtake 1972), and the Kamafusa dam (Suzuki 1975), both in Japan, and also in Italy (Caloi 1972). They concluded that variations of physical parameters with a daily period should be part of the mechanism. From these parameters, the variations of atmospheric pressure and earth tides can be ruled out, because the seasonal variation of seismic activity could not be thus explained. Therefore, it seems to be more promising to consider seasonal and daily temperature variations as a possible mechanism. The correlations between the number of shocks on the one hand and the temperature and the change of lake level on the other hand are now discussed in detail.

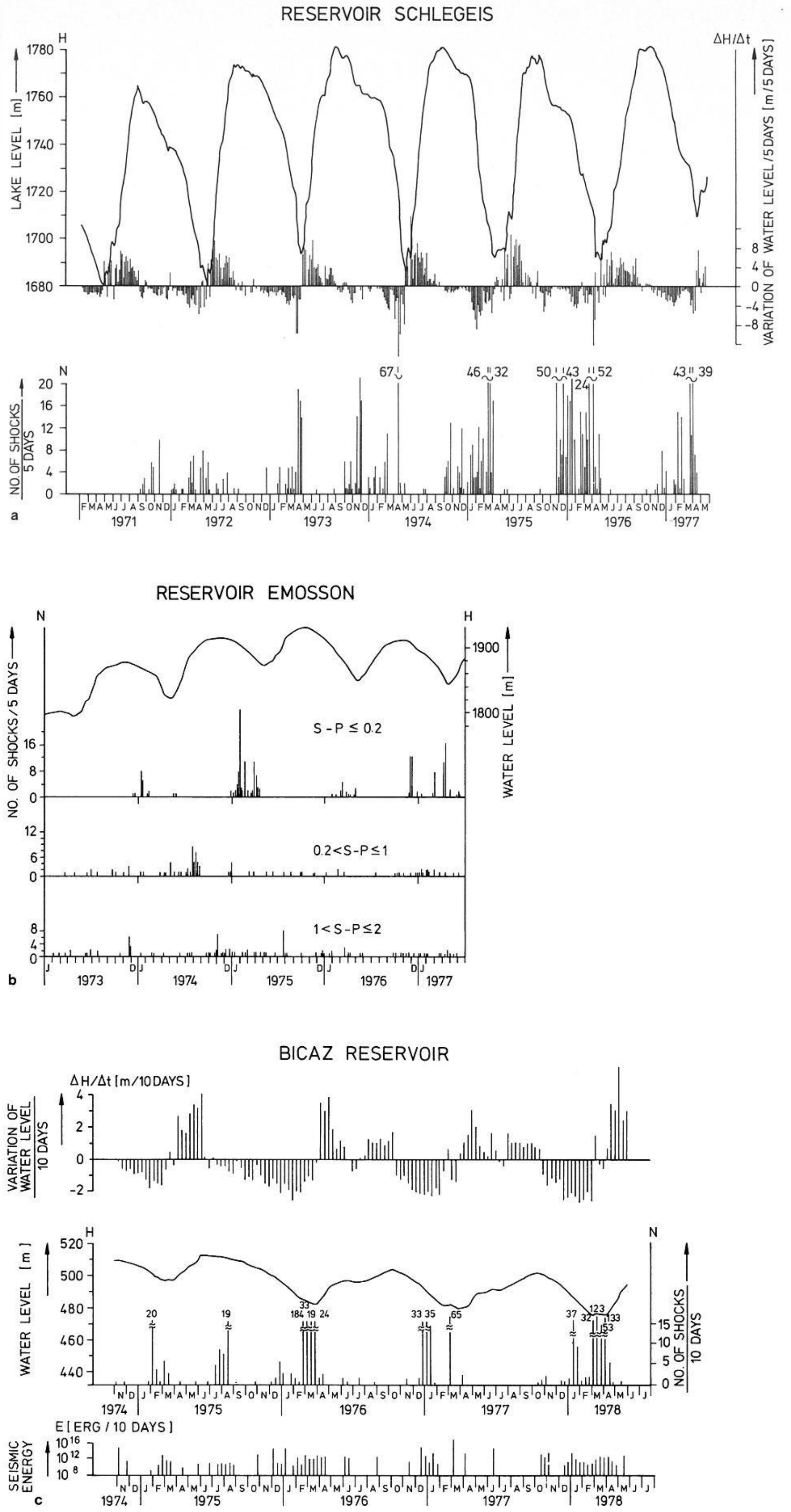
In the Fig. 5a–d the occurrence of local tremors is analysed with respect to the average daily temperature and with respect to changes of the water level. For one interval typical of the whole observation period the measured air temperature and the number of events are plotted in the upper parts of Fig. 5a–d. At Schlegeis as well as at Bicaz and Lotru, seismic acitivity increases as soon as the temperature falls below the freezing point of water. The relation between tremor frequency and the decrease of water level is less pronounced than the relation between tremor frequency and freezing temperatures. For instance local shocks were also observed during periods when the rate of fall of the water level was low (e.g., at Schlegeis in October–December 1974, see Fig. 5a). In spite of this the subsidence of the water level must also be taken into consideration to understand the mechanism of the observed tremors. This is discussed later in connection with the proposed model.

In the lower parts of Fig. 5a–d correlation diagrams are shown for the whole observation period. The number of shocks is plotted against the average daily temperature and the rate of water level variation, respectively. Most of the activity at Schlegeis, Bicaz and Lotru occurs during frosty periods (Merkler et al. 1980). These are also, more or less, the periods of decreasing water level. Only at Arges (Fig. 5d) is a major part of the seismic activity observed at periods when the average daily temperatures are positive. In Table 3 the corresponding values are given for the correlation diagrams. The observations are summarized as follows:

(a) the ratio between the number of frosty days with observed seismic activity and without activity is between 0.29 and 0.55.

Table 3

		Schlegeis 05.71–01.77	Lotru 06.74–03.77	Bicaz 11.74–02.77	Arges 04.75–06.78
Frosty days	With seismic activity (n^-B)	170	77	74	85
	Without seismic activity (n^-0)	583	222	212	154
	n^-B/n^-0	0.29	0.35	0.35	0.55
Frosty days with Subsidence of water level	With seismic activity ($n^{--}B$)	140	58	56	59
	Without seismic activity ($n^{--}0$)	449	120	208	114
	$n^{--}B/n^{--}0$	0.31	0.48	0.27	0.52
Frost-free days	With seismic activity (n^+B)	73	35	38	263
	Without seismic activity (n^+0)	1277	304	540	654
	n^+B/n^+0	0.06	0.12	0.07	0.40
	n^+B/n^-B	0.43	0.45	0.51	3.09
	$n^+B/n^{--}B$	0.52	0.60	0.68	4.46


RESERVOIR SCHLEGEIS
H
LAKE LEVEL [m]
1780
1760
1740
1720
1700
1680
ΔH/Δt
VARIATION OF WATER LEVEL/5 DAYS [m/5 DAYS]
8
4
0
-4
-8
N
NO. OF SHOCKS / 5 DAYS
20
16
12
8
4
0
67
46
32
50
43
24
52
43
39
F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M
1971
1972
1973
1974
1975
1976
1977
a
RESERVOIR EMOSSON
N
NO. OF SHOCKS / 5 DAYS
H
WATER LEVEL [m]
1900
1800
S - P ≤ 0.2
16
8
0
0.2<S-P≤1
12
6
0
1<S-P≤2
8
4
0
J
D J
D J
D J
D J
1973
1974
1975
1976
1977
b
BICAZ RESERVOIR
ΔH/Δt [m/10 DAYS]
VARIATION OF WATER LEVEL 10 DAYS
4
2
0
-2
H
WATER LEVEL [m]
520
500
480
460
440
N
NO. OF SHOCKS 10 DAYS
15
10
5
0
20
19
33
184
19
24
33
35
65
37
123
32
133
53
N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J
1974
1975
1976
1977
1978
E [ERG / 10 DAYS]
SEISMIC ENERGY
10^{16}
10^{12}
10^{8}
c

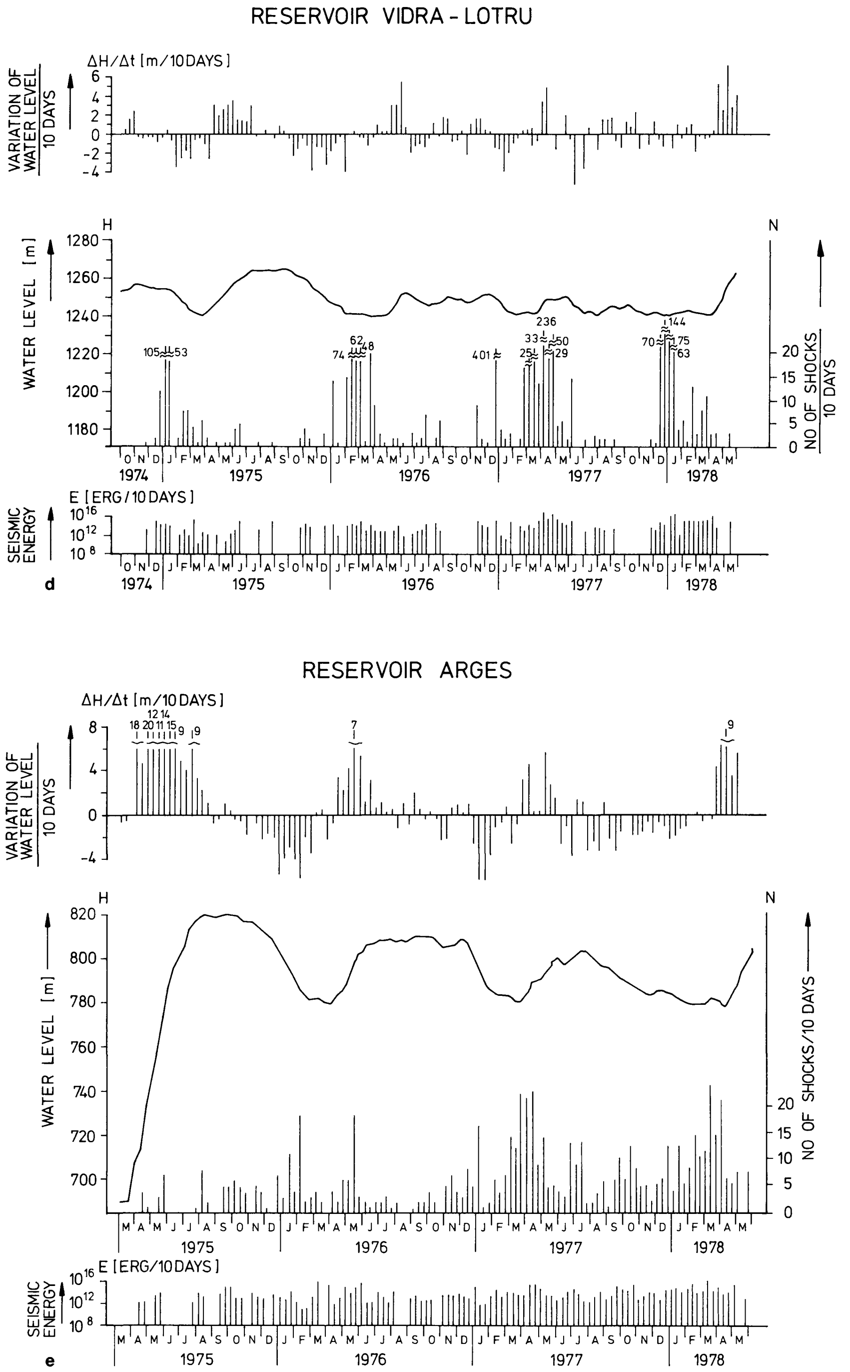


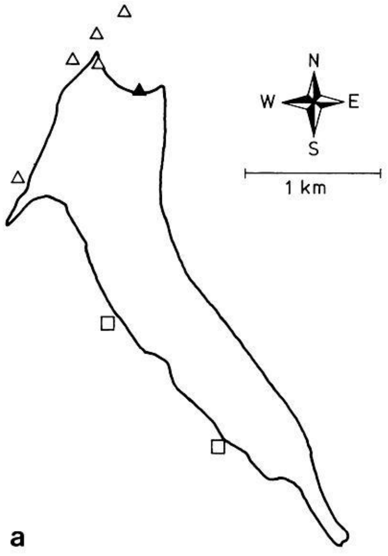
Fig. 2a–e. Lake level, rate of variation of lake level and number of shocks at **a** Schlegeis reservoir; **b** Emosson reservoir; **c** Bicaz Reservoir; **d** Lotru reservoir; **e** Arges reservoir

(b) a similar ratio is observed for the number of days on which frosty temperatures **and** decrease of the water level occurred at the same time and day. It is between 0.27 and 0.52. This indicates that most of the tremors on frosty days occur during subsidence of the water level.

(c) the ratio between the number of frost-free days with and without seismic activity observed at Schlegeis, Lotru and Bicaz is a factor between 3 and 5 smaller than the corresponding ratio for frosty days under (a). In contrast, the ratios under (a) and (b) observed at Arges are of the same order.

(d) the ratio between the number of frost-free days and frosty days with seismic activity is, at Schlegeis, Lotru and Bicaz, between 0.43 and 0.51. That means that about two thirds of the seismic activity shows up during frosty periods. On the other hand, at Arges this ratio is 3.09, that is more tremors occur on frost-free days. The ratio of the number of frost-free days with observed seismic activity to the number of frosty days with subsidence of water level at the same time is between 0.52 and 0.68 (lowest row of Table 3). At Arges, this ratio is also greater than 1 (Merkler et al. 1978).

Correlation coefficients have been computed between the number of shocks and the temperature or the rate of subsidence of the lake level, respectively. They have been calculated allowing for a time delay λ between the two corresponding time series



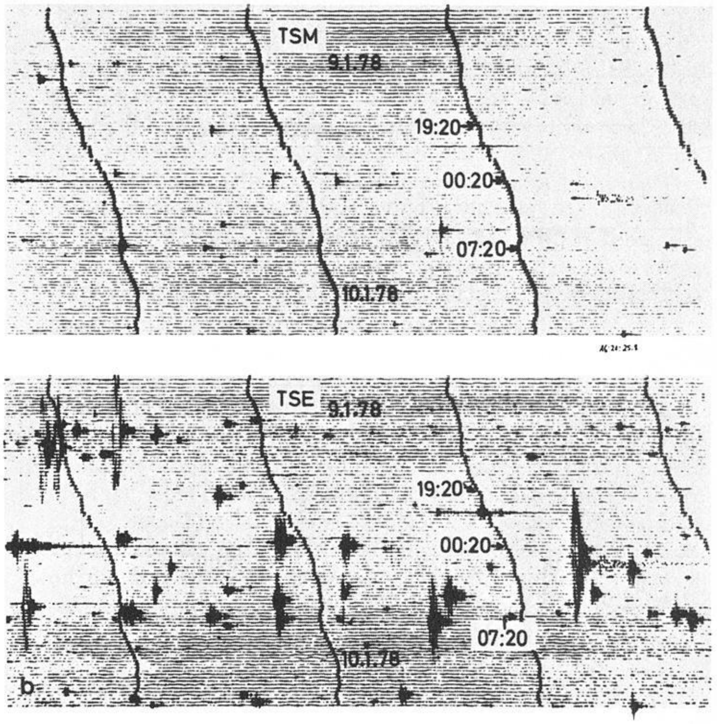


Fig. 3. a Location map of Schlegeis reservoir, Austria. Position of seismic stations marked as: ▲, Permanent seismic station (SCE); △, Temporary network 1974; □, Temporary telemetric stations 1977–1979. **b** Seismogram example from the seismic telemetric stations at Schlegeis reservoir

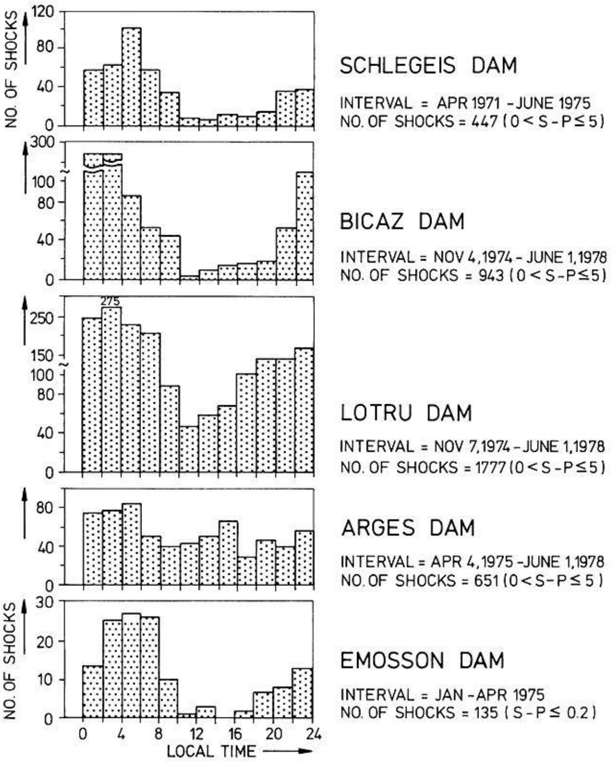


Fig. 4. Daily distribution of tremors

according to Taubenheim (1969):

$$\rho(\lambda)=\frac{\sum_{r=1}^{n}(X_{r+\lambda}-\bar{X})\cdot(Y_r-\bar{Y})}{\sqrt{\sum_{r=1}^{n}(X_{r+\lambda}-\bar{X})^2}\cdot\sqrt{\sum_{r=1}^{n}(Y_r-\bar{Y})^2}}$$

with $X_{r+\lambda}=0$ if $r+\lambda<0$ or $r+\lambda>n$. $(X_{r+\lambda}-\bar{X})$ and $(Y_r-\bar{Y})$ are the deviations of the values of two time series from their mean value. The expressions in the denominator are proportional to the standard deviations of the time series. The summation is carried out over n points. The X-series corresponds to the average daily temperatures and to the daily rate of subsidence of the lake level, respectively, the Y-series to the number of shocks per day. The 99.9 % significance level is given by $3.291/(N-\lambda-1)^{1/2}$ (Taubenheim 1969).

The absolute value of ρ (λ) for the Schlegeis reservoir reaches a maximum of 0.25 for the correlation of number of events and rate of level subsidence with a delay of 1 day compared to the rate of water subsidence (Blum 1975). There is a prompt seismic reaction following a temperature decrease (Fig. 6).

Discussion of Mechanism

The seismic observations at Schlegeis, Bicaz and Lotru indicate a certain correlation between the occurrence of local seismic events and negative temperatures. It is assumed that part of the local seismic activity observed at Lake Emosson is also caused by the same mechanism. This suggestion is mainly based on the characteristic daily time distributions of the local seismic events. Average daily temperatures which could confirm this suggestion were not available for the Emosson area at the time of this study. A model which does explain most of the observations is proposed in the following:

In the model proposed cracks are assumed which extend to the surface (Fig. 7). During periods of increasing and maximum water level the cracks are water-filled by the reservoir. In the period of subsiding water level, i.e., in winter and spring, the thermal insulation provided by the reservoir water is removed. The water level falls below the openings of the cracks. However, the cracks remain water-filled because the water cannot drain off quickly enough due to the low permeability of the surrounding rock. At temperatures below zero the water in the cracks freezes

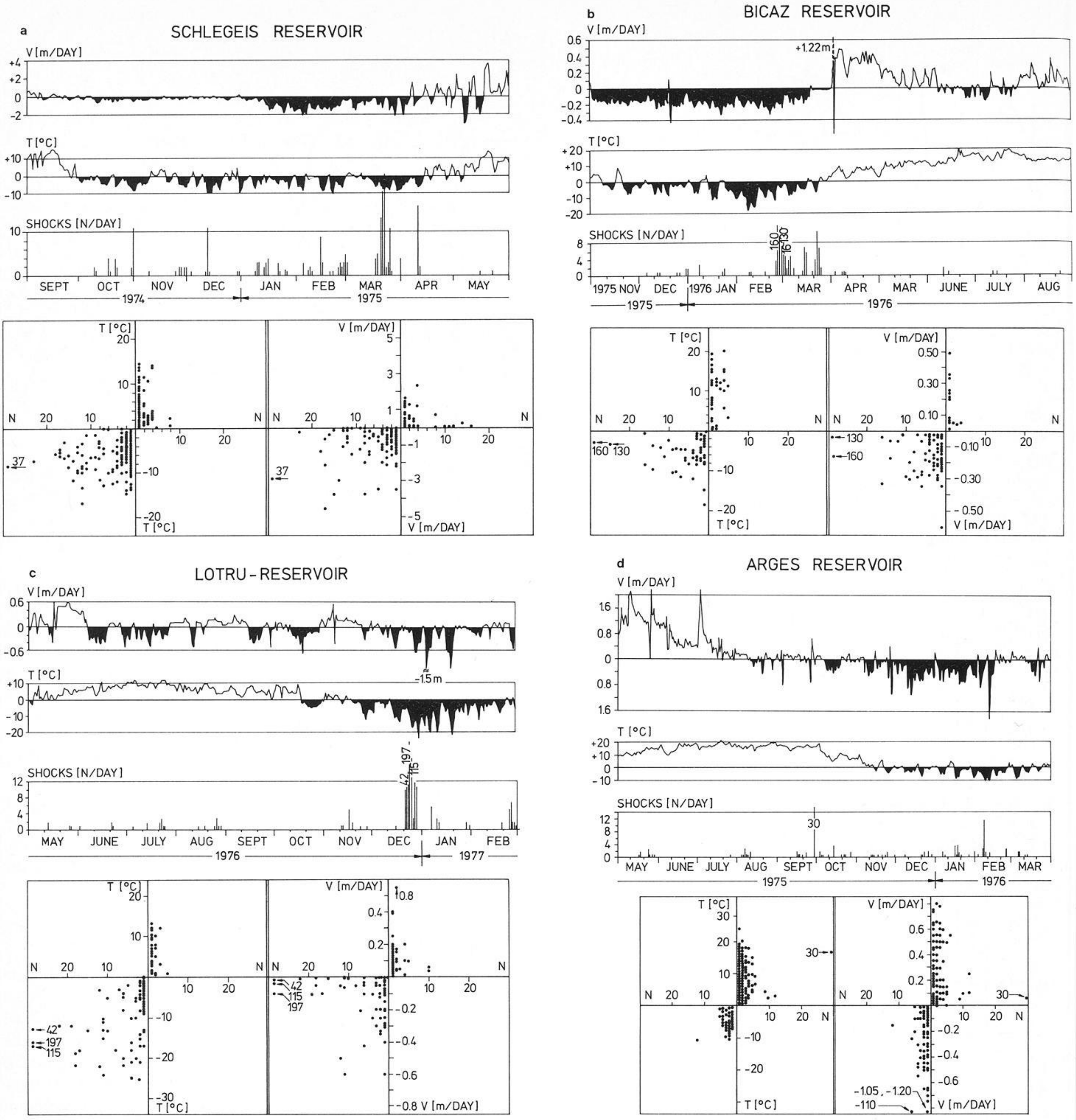


Fig. 5a–d. Correlation diagram between number of shocks and rate of lake level and temperature respectively **a** at Schlegeis reservoir; **b** at Bicaz reservoir; **c** at Lotru reservoir; **d** at Arges reservoir

leading to an increase in volume by 9% and to an extension of the crack width. The extension V of the crack with a length $2c$ can be estimated under plane stress conditions to (Jaeger and Cook 1971, p. 312):

$$V = 2\,pc/E \qquad (1)$$

with the inner pressure in the crack p, and the Young modulus E of the surrounding rock. An example illustrates the order of magnitude of p. A crack of width 0.1 cm is extended by 0.009 cm by the volume increase of the freezing water. If we put $c = 5$ cm and $E = 200\,000$ bar, an inner pressure of 180 bar is obtained. Assuming that all the water in the crack freezes, the induced stresses near the tip of the cracks can be estimated using the relations in Jaeger and Cook (1971, p. 262). The maximum tensional stress at a distance $r = c/2$ from the crack tip amounts to ${}^{1}/_{3}\,p$, the maximum shear stress at $r = c/2$ is $0.5\,p$. According to Müller

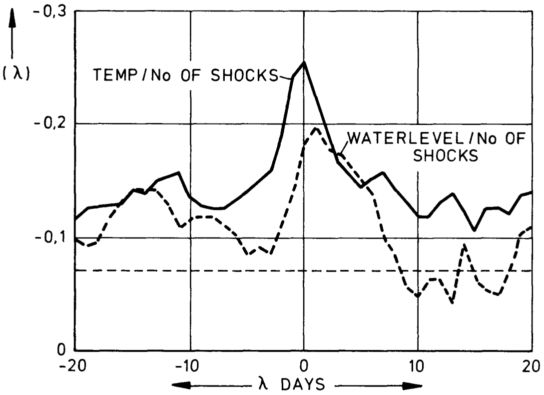


Fig. 6. Computed correlation coefficient between the number of shocks, temperature and rate of subsidence of lake level at Schlegeis reservoir (----- significance level)

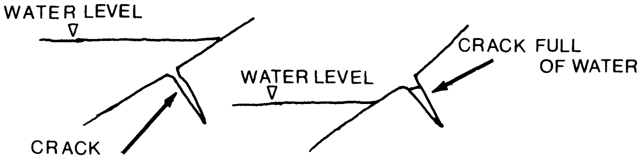


Fig. 7. Model of water-filled crack

(1963) it is difficult to give values for the tensional strength of a rock unit. They may be of the order of several bars to tenths of bars. The shear strength of Schlegeis basement rock is, according to Widmann (1973), in the range between 6 bar parallel and 350 bar perpendicular to the foliation plane. Therefore, it is reasonable to assume that the induced stresses near the end of cracks can be high enough to exceed the rock strength.

The model of triggering of local seismic events by freezing of water in cracks involves very shallow focal depths (10 m at most) since temperature variations can only affect the uppermost layer of the outcrop.

Focal depth determination for some of the shocks observed at the Schlegeis reservoir are not accurate enough to confirm or to reject the model. However, from the epicenter determination it is obvious that most of the epicenters are situated outside the area of the lake covered by water at the time of occurrence, which is compatible with the proposed model. For comparison the reader is referred to the paper by Blum et al. (1977).

A further observation which can be explained by the model is the low seismic energy radiated from foci, which is between 10^7 and 10^{12} ergs. Stronger local tremors have never been observed. In a plane of stress the potential strain energy W of a crack in disk of thickness t is given by (Jaeger and Cook 1971, p. 313):

$$W=\pi \cdot p^2 \cdot c^2 \cdot t/E.$$

Eliminating p by Eq. (1) leads to

$$W=0.25 \cdot \pi \cdot V^2 \cdot t \cdot E.$$

In this very rough approximation the strain energy W does not depend on the length $2c$ of the crack. For a numerial estimate we assume $V=0.009$ cm; $E=200000$ bar; $t=1$ cm and 100 cm. Then the strain erergy is 1.3×10^7 erg for $t=1$ cm and 1.3×10^9 erg for $t=100$ cm. These values are within the range of the estimated seismic energy.

Conclusions

Over the past 6 years microearthquake activity correlating with changes in reservoir level has occurred at the 5 reservoirs investigated. The activity is characterized by a concentration of near-reservoir microearthquakes when the water level is lowered and its minimum is reached during the months October to April. These microearthquakes were previously taken as being associated with a buildup of tectonic stresses during filling and their subsequent sudden release during rapid emptying of the reservoir. However, this hypothesis now appears less plausible, because most earthquakes tend to occur late at night, and there is a clear correlation between the onset of activity and sub-zero air temperatures during fast reservoir unloading. This correlation is now explained by a model in which cracks are exposed to freezing temperatures by the falling water table, causing the water remaining in the cracks to turn to ice. The estimated energy release of this process of in the same order of magnitude as that observed in the microearthquakes. The implication of these "ice-quakes" for the safety and stability of the dam walls warrants further investigation. Based on the experience of the present survey it would be relatively simple to monitor the weak zones of the slopes of reservoirs by locating the "ice-quakes" with a high resolution seismic network.

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