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Correlation between Micro-Activity and Variation of Water Level at the Schlegeis-Reservoir*

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Abstract. The Schlegeis-reservoir in the Austrian Alps is a recently built man-made lake at the western margin of the granitic window "Tauernfenster". During the last five years the reservoir has been under continuous seismic surveillance by a one-component station. Only low magnitude events with $M_L \leqq 0$ could be observed in the seismic quiet region. However, these events correlated clearly with the variations of the water level in the reservoir. The main activity coincides always with the minimum of the water level and also with the most rapid lowering of this level. Thus the time of maximum activity was predictable. During the 1973 and 1974 minima of the water level a small array of stations with magnetic tape recording was installed. The time and space distribution of the recorded events is presented. Possible mechanisms for the causal connection between the observed phenomena include a postulated thrust-type faulting, compatible with regional tectonics and the increase in activity during unloading.

Key words: Induced seismicity – Micro-earthquakes – Failure mechanism

Introduction

More than 20 cases are known where changes in seismic activity have been related to the filling of large reservoirs. A number of reviews have already been made of previous work on induced seismicity associated with dams (e.g. Bozović, 1974; Simpson, 1975; Gupta and Rastogi, 1976). Simpson (1975) has grouped the reported cases of induced seismic activity into four categories: a) major induced earthquakes, b) minor induced earthquakes, c) changes in micro-earthquake activity, and d) transient changes in seismicity. The seismic activity at Schlegeis, which is the subject of this paper, belongs to group c) of this classification.

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The Schlegeis-reservoir in the Austrian Alps has been under continuous seismic surveillance since May, 1971 by a one-component vertical seismic station. Its detection level is $M_L \geqq -2$ up to 2 km and $M_L \geqq 0$ up to 30 km. The pre-impounding, natural seismicity of the region is very weak. Blum and Fuchs (1974) report first results of the observation till 1973, showing the occurrence of local tremors with magnitudes $M_L \leqq 0$. Now data on four complete filling cycles are available. The characteristic time and spatial distribution of the events are presented together with possible causes. For a detailed discussion see Blum (1975) of which this paper is an extended summary.

Time Distribution

During 4 years a total number of 550 events has been observed. Their time distribution (Fig. 1) shows a conspicuous correlation with the variations of water level. The seasonal variation of water level amounts to 100 m. The first complete filling was accomplished in September 1971. At this time the first events started to appear, just after the first maximum of water level. With the lowering of the water level the number of events increased. The period of raising water level is characterized by the absence of tremors. During the next filling cycles this distribution of tremors becomes more pronounced: "silence" during raising water level, increasing activity with growing velocity of the subsiding water

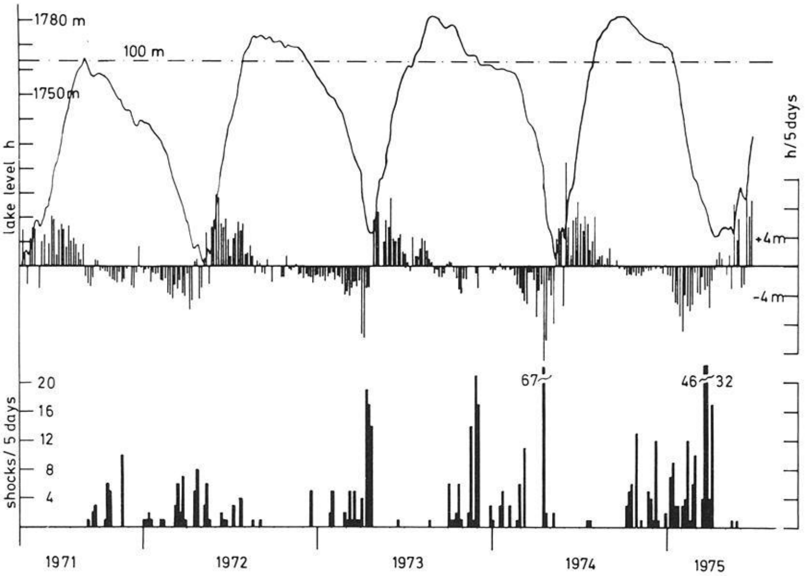

Fig. 1. Water level and seismic events at Schlegeis-reservoir from 1971–1975. Upper part: Lake level elevation h above sea level, the level of 100 m depth is marked and change of water level $\Delta h/5$ days. Lower part: Number of observed shocks/5 days, recorded at the permanent station. S-P times are less than 0.2 s

level. The maximum number of events occurs at the lowest water level, where the velocity of subsidence has also a maximum.

Correlation coefficients have been computed between the number of shocks per five days, $n(t)$, and the height of lake level $h(t)$, as well as the rate of subsidence of the lake level $\dot{h}(t)$. The correlation coefficient between $n(t)$ and $h(t)$ reaches its largest value of 0.2 with a time lag of three months. However, the correlation between $n(t)$ and $h(t)$ reaches with its largest value of 0.2 the 99% significance level with a time lag of three months. However, the correlation is more likely and instantaneously linked to the subsidence velocity of the water level. This is a rather surprising observation: usually the maximum of activity coincides with the period of rapid filling or of maximum load (see for example: Božović, 1974).

Spatial Distribution

As soon as this correlation between the time distribution of the events and of the water level had been recognized, it was possible to predict the maximum of activity for the coming cycle. So a temporary local network could be installed in time for the observation of the expected tremors during the minimum of the water level. The configuration of the small array (Fig. 2) was constrained by technical problems, such as data transmission and power supply. The signals of stations 1–4 are amplified at the seismometer. All signals are transmitted to the dam by cable, and from there, using frequency-multiplexing to the power station down-hill which was always accessible. There signals of the six stations have been recorded on magnetic tape together with a radio time signal. The array was kept in operation in the period from March 25 till the end of April 1974 and removed thereafter while the one-component station (no. 1) continued recording.

The localization capacity of the array has been tested by a small shot in the lake. The horizontal coordinates of the shotpoint could be calculated with an error of ±20 m from four *P*-wave arrivals, read as accurate as 5 ms. To derive a reasonably accurate estimate of the depth, at least one *S*-wave reading of a station close to the shotpoint was required additionally. Since the activity started at the expected time, its main part was recorded. An example of a play-back is given in Figure 3 for a well-recorded event. From the records it may be seen, that it is rather difficult to identify the phases of these weak tremors. So localization was successful only for 30 events, while more than 60 have been recorded altogether in April 1974.

Figure 4 contains the results of the localization work. A calculation of epicenter errors, corresponding to a reading accuracy of ±5 ms showed that localizations inside the network are rather stable. All events are shallow and not deeper than 300 m. They are concentrated on the waterside of the dam extending beyond the lake proper. Only a few events appeared in the region of greatest water depth.

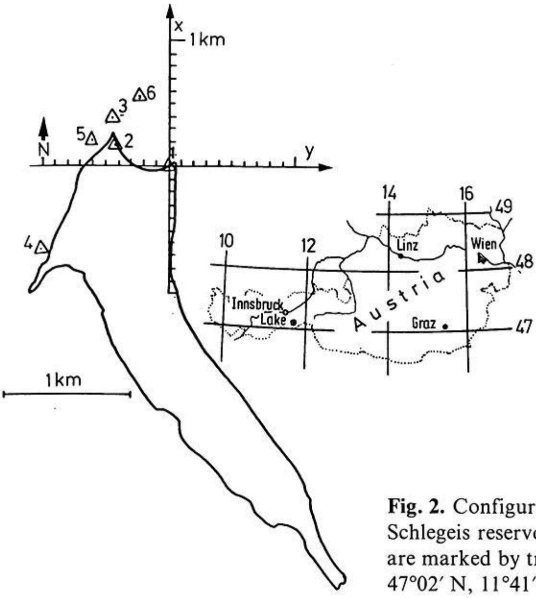

Fig. 2. Configuration of seismic array at Schlegeis reservoir in 1974. Seismometer sites are marked by triangles. Origin of x, y-system at 47°02′ N, 11°41′ E

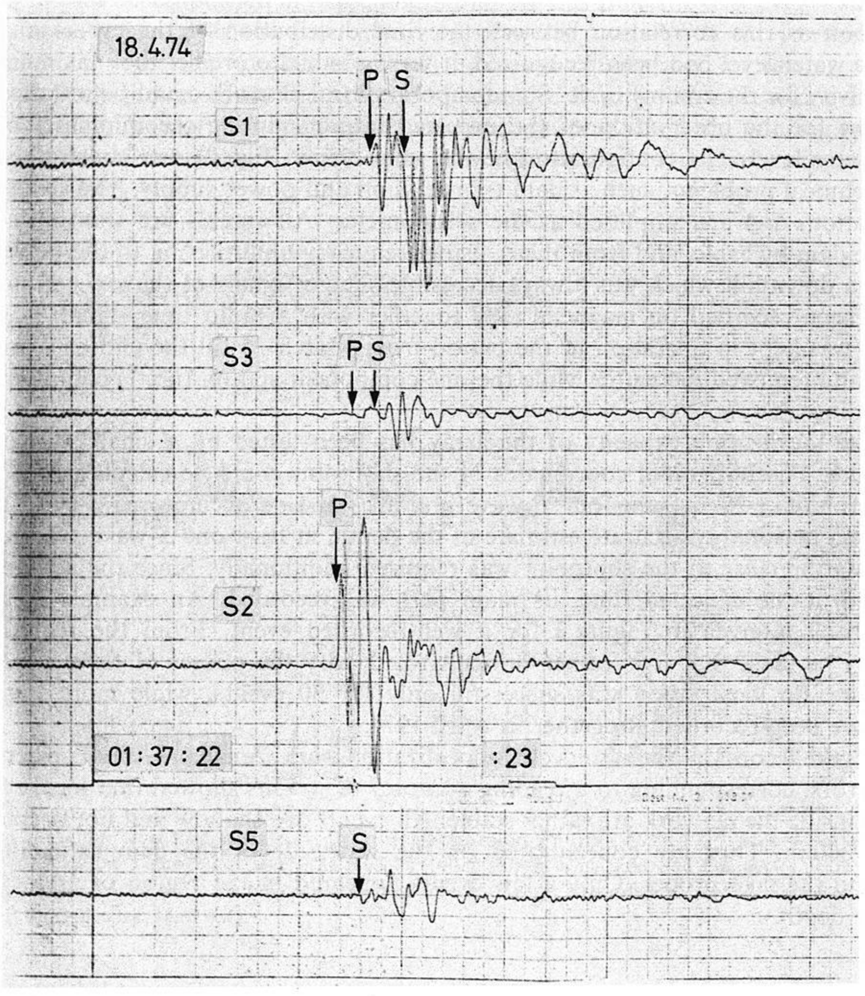

Fig. 3. Play-back of a local event, recorded as vertical components at four stations on April 18th, 1974. *P* and *S* readings indicated

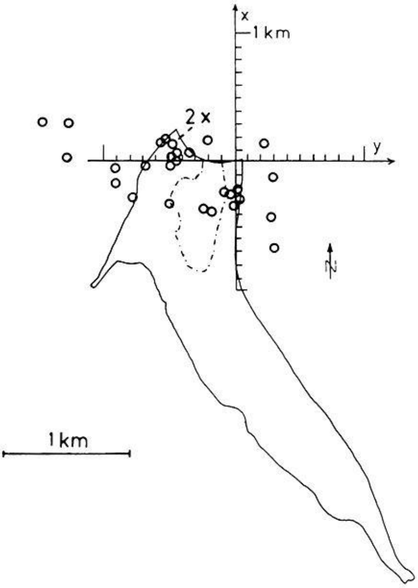

Fig. 4. Localizations of events, recorded in April 1974. Within the dashed line the water depth of the completely filled lake exceeds 100 m

Possible Mechanisms

The observed characteristic temporal and spatial distribution of the micro-activity and its correlation with the lake level variation require an explanation and suggest possible mechanisms for the presence of induced shocks. Especially the occurrence of seismic activity near the dam and during the lowering of the water level must be explained.

One plausible idea is that the dam itself might cause indirectly the seismic activity. It generates stresses in the underground which are dependent on the water load. Loading the dam will result in tensile stresses in the rock at the water side. That means, the pore volume in the rock and thus the content of pore-fluid increases. Taking off the load results in a reduction of the pore volume. At a fast subsidence of the water level the additional pore-fluid cannot escape fast enough. The porepressure will increase and facilitate fracture.

The increasing pore pressure will reduce the effective normal stresses whereas the shear stresses remain constant (Hubbert and Rubey, 1959). Thus, the frictional resistance is reduced and fracture is facilitated. This mechanism has been proposed to explain earthquakes triggered by fluid injections into deep wells (e.g. Healy et al., 1968).

This mechanism requires, however, that the epicenters of the observed shocks should be concentrated more in the immediate neighbourhood of the dam itself. There the tensile stresses are reaching their maximum, as Widmann (1973) derived from extensometer measurements.

For this reason a mechanism has been proposed by Fuchs et al. (1975)

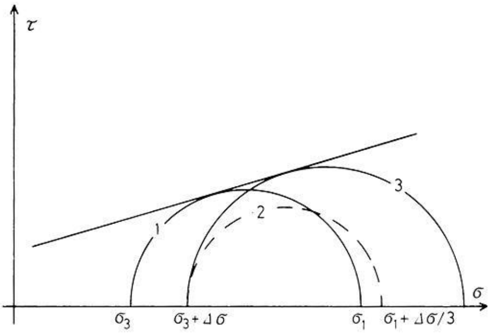

Fig. 5. Mohr's diagram for the model of storing tectonic stress during loading. Greatest principal stress σ_1 is horizontal, least principal stress σ_3 is vertical. Circle 1 marks the initial conditions, circle 2 the strengthening caused by the increased load $\Delta\sigma$ and circle 3 the new equilibrium after storing of additional horizontal tectonic stress

by which the lake induces tremors directly and which considers local geological characteristics as well as the regional stress field which is required to have a horizontal axis of maximum compression. In such a field an active thrust fault is stabilized during increasing vertical compression caused by the load of a reservoir (Snow, 1972), even if the effective principal stresses are diminished by increasing pore pressure, there remains a stabilizing effect on the thrust fault from the filling of a reservoir. It is not sure, however, whether pore pressure plays an important part in the failure mechanism of the Schlegeis-reservoir as only a few events are located in the region of greatest water depth. After removing the load it could be expected that stress conditions return to the starting point. However, failures could occur if meanwhile additional stresses have been stored in the rock. This is feasible if there is a sort of dynamic equilibrium, i.e. that the stress condition is always close to the Mohr envelope and a surplus of stress is always removed immediately by creep and microfractures below the seismic detection threshold. This initial condition before loading is marked by circle 1 in Figure 5. Here, the greatest principal stress σ_1 is horizontal the smallest one, σ_3, is vertical. σ_1 might be connected with the folding of the Alps corresponding to a NNW-SSE-direction. The increasing load produces a smaller increase in horizontal than in vertical main stress. The result is marked by circle 2 in Figure 5. After this consolidation additional horizontal stress from the regional stress field, caused by the present folding of the Alps, may now be stored in the rock without fracture till a new equilibrium is reached (circle 3 in Fig. 5). The hypothesis of predominant horizontal stresses is supported by post-crystalline developed shear-cracks (Mignon, 1972) and great deformations in newly built tunnels (Mignon, personal communication). Although a composite fault-plane solution proved to be insufficient to determine the fault plane and the dip direction the observed first motions do not contradict the assumption that the greatest principal stress is horizontal.

The rapid reduction of the water load drives the shear stress beyond the Mohr envelope causing failure. The most favourable orientation for a failure surface is striking in WSW-ENE-direction with a small dipping angle. A system of joints near the surface, which proved to be rather mobile during in-situ deformation tests (internal report of Tauernkraftwerke AG, 1969) fulfills these requirements. Therefore, the described model could explain the observed weak and shallow tremors and their triggering during lowering of the water level. Additional, morphologically caused instabilities may be connected with the concentration of epicenters below the slopes.

Conclusions

The micro-activity at the Schlegeis-reservoir correlates significantly with the negative or subsiding velocity of the water level. This seems to be especially clear due to the low natural seismicity in this region. The tremors could be localized in the neighbourhood of the arch-dam on the water side. For these reasons the triggering of the event is attributed to the influence of the reservoir. The most favourable model for their occurrence is the assumption of a predominant horizontal stress field. The small shocks may also indicate, that the rock reacts promptly to small changes in the stress conditions.

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