

Seismic surveillance of the Blåsjø reservoir

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ABSTRACT: The Blåsjø water reservoir in southwestern Norway was constructed in the early 1980s. Infilling started in 1985/86 and took 3-4 years to reach a maximum water volume of more than 3 km³. The seismic monitoring program started at a low level in 1980, and it was found that the reservoir area before impoundment was practically void of earthquakes. No increased seismic activity in the reservoir area was registered following the filling of the reservoir in 1986-1988, and the seismic surveillance was therefore reduced early in 1991. Although it is considered less likely now that induced earthquakes will occur, one can still not completely rule out the possibility for earthquakes related to pore pressure diffusion and/or flow of water away from the reservoir.

1 INTRODUCTION

The Blåsjø reservoir (Fig. 1) is located in southwestern Norway. It is regulated between the elevations of 930 and 1055 m, and the storage capacity is 3.1 km³ (Fig. 2). The reservoir covers an area of 81 km² at its highest level.

The impoundment of the reservoir started in late 1982, but it was not until mid 1986 that the main lakes

in the reservoir (see Fig. 2) reached the same water level (1025 m). Even though the reservoir was not filled up to 1055 m until the fall of 1989, it did reach a level 4 m lower already in the fall of 1987. The two years before that time (1986-87) was therefore the most active period of infilling at Blåsjø.

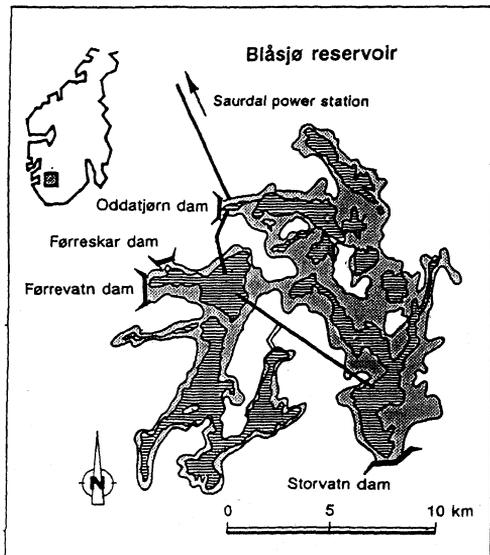


Figure 1. The reservoir area, with dam locations and outlines of the three main lakes: Storvatn, Førrevatn and Oddatjørn.

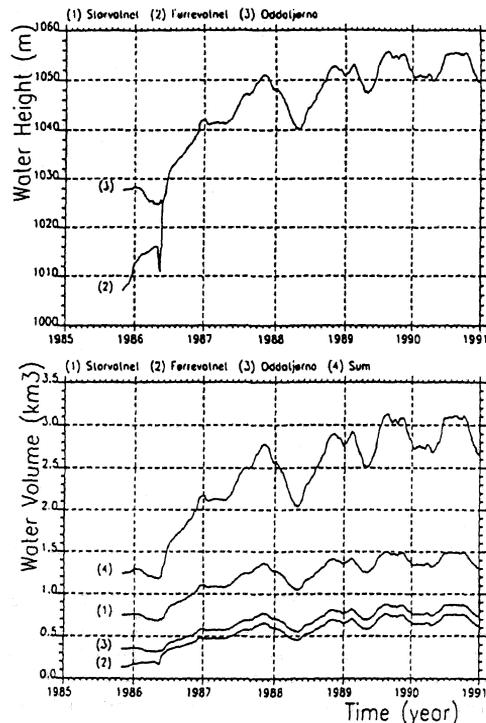


Figure 2. Infilling curves for the Blåsjø reservoir.

It has been known for a long time now that the filling of large amounts of water into a reservoir under certain (but not well known) conditions can induce earthquakes, as discussed in more details in the following section. On this background a seismic monitoring program for Blåsjø started in 1980.

2 DAMS AND INDUCED SEISMICITY

Ever since the construction of the huge Lake Mead (Hoover Dam) in the U.S.A. more than 50 years ago, the filling of large amounts of water into reservoirs has been known to have the potential for causing earthquakes (Gupta and Rastogi, 1976).

Several efforts have been made to review and assess the documented cases of possible reservoir-induced seismicity, with quite varying results depending critically upon the criteria used. It has been claimed, for example, that only 1% of the world's reservoirs have been associated with macroseismicity (magnitudes above 3), with the percentage increasing to 14 if only reservoirs deeper than 95 m were included (Stuart-Alexander and Mark, 1976). Using more relaxed criteria, Woodward-Clyde Consultants (Packer *et al.*, 1979) classified a substantially higher percentage of the reported cases as being reservoir induced.

Induced seismicity is commonly understood as being natural seismicity triggered to occur at an earlier time because of changes in pore pressure (Simpson and Negmatullaev, 1981), and it seems to be of two types (Simpson *et al.*, 1988):

1. Changes in seismicity that occur rapidly after the first filling of the reservoir, or which follow substantial later changes in water level. Both of these cases are related to rapid increase or decrease in elastic stress due to the load of the reservoir, or to changes in pore pressure coupled to elastic stress. This type of effects result from elastic deformation of the crust in response to increased or decreased surface loads.

2. Changes in seismicity that occur several (4–8) years after the first filling of the reservoir, at distances of the order of 10–30 km, related either to diffusion of pore pressure from the reservoir to hypocentral depths, or to flow of water from the reservoir into unsaturated pore space in cases when the water table prior to impoundment is low.

3 THE BLÅSJØ SEISMIC STATION

The first regional seismic network, the Southern Norway Seismic Network (SNSN), was installed in Norway in 1980 and was in operation for three years. A seismic station near the Blåsjø reservoir was originally proposed as part of SNSN. In the fall of 1984, the Western Norway Seismic Network (WNSN), operated by the Seismological Observatory in Bergen, was installed for the main purpose of studying offshore seismicity. This network was designed so that the Blåsjø station should contribute as much as possible.

In order to improve the quality of the recordings at the time of the main impoundment of the reservoir, a three-station network (with distances of 12 and 18 km between stations) became operational in September 1986, with all data transmitted over one telephone line to Bergen. Two years later, in September 1988, a fourth station was installed in Blåsjø, and this increased further the possibilities for accurate event locations, including focal depths, in the reservoir area.

4 REGIONAL SEISMICITY

The seismicity of western Norway and adjacent offshore areas has been studied extensively over the last few years, motivated first of all by the need within the petroleum industry for more reliable earthquake hazard analyses. This research has been covering both historical and more recent seismicity.

For the areas in and around southern Norway, a regional seismicity map is shown in Fig. 3, where it is seen that the seismicity is largely confined to the coastal areas and to the Viking Graben further offshore. The seismicity level is low to intermediate, with very few earthquakes above 5 in magnitude.

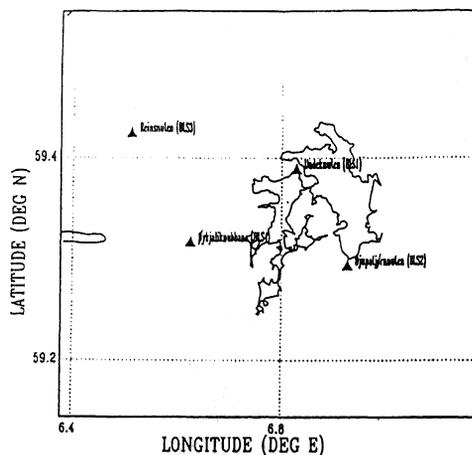


Figure 3. The Blåsjø reservoir (see also Fig. 1), with location of the seismic stations, 1987–1990.

Focal mechanism solutions in the area (Bungum *et al.*, 1991) reveal that the directions of the horizontal compressive stresses, in particular in the Blåsjø area, are somewhat more east-west oriented than what should be expected from the movements of the major tectonic plates (see Fig. 4). This indicates that the still ongoing post-glacial uplift and/or lateral variations in the structure of the Earth's crust, both expected to be more perpendicular to the coast line here, also contribute to the regional stress field.

It has also been found that there is a dominance of normal faulting in south-western Norway, while reverse faulting dominates offshore (with a more

anomalous strike-slip area in between). This indicates also that uplift still is a contributing factor to the regional crustal stress field (Bungum *et al.*, 1991).

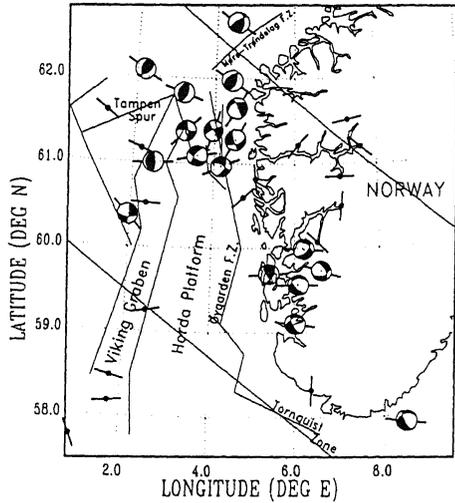


Figure 4. Focal mechanism solutions (circles) and *in situ* stress measurements (small black dots) in Western Norway and the northern North Sea, with the directions of compressional stress indicated in both cases by lines crossing the symbols. The two lines crossing the entire map in a NW-SE direction indicate the stress direction as expected from the movements of the major tectonic plates.

5 LOCAL SEISMICITY

Using the seismic networks and stations described above, the following results have been obtained on the local seismicity in the Blåsjø area and surrounding regions.

- The Blåsjø area is right at the edge of the seismically active areas in western Norway (Fig. 5). This seismicity includes some well-determined earthquakes quite close to the Blåsjø reservoir area, with magnitudes up to 3.6. It would therefore not be unreasonable to expect that earthquakes could occur, for natural reasons, also within or very close to the reservoir area.

For the time period 1980–1986 we found that a number of events remained, after removing all known explosions, within the reservoir area. Most of these occurred between 1984 and 1986, coinciding with the main construction activity in the area, and the events were also found to be very shallow. It was furthermore found that practically no events of any kind were found within the reservoir area for the three years after 1987, when the construction works had been completed. It was therefore concluded that the 1984–86 events within the reservoir area most likely were explo-

sions that had failed to be removed from the data base.

In Fig. 5 is shown an update of these seismicity maps, covering the time period from 1987 to the end of 1990. Three weak events now appear within the Blåsjø area, from October 4, 1989, M_L 1.7, November 18, 1989, M_L 2.0, and August 27, 1990, M_L 1.8. These events have been studied in more detail (including relocations), and the results do not indicate that the events are man-made (focal depths cannot, however, be determined with a quality which makes this an unequivocal conclusion). On the basis of what has been said above this does nevertheless not change our main conclusion that no induced seismicity so far has been found to occur in response to the water impoundment in the Blåsjø area.

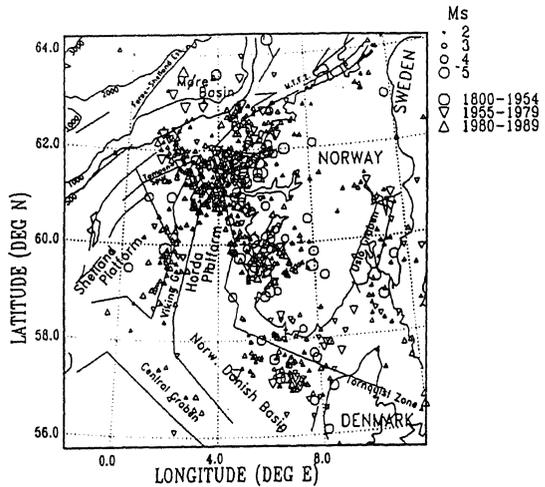


Figure 5. Seismicity in southern Norway and surrounding areas, based on three different time periods. Some structural information is included. From Bungum *et al.* (1991).

6 BLÅSJØ AND INDUCED SEISMICITY

Of the different types of induced seismicity discussed above, the first one is resulting from elastic deformation of the crust in response to increased surface (water) loads, which we know are significant in the case of Blåsjø (Fjeldskaar, 1990). Since corresponding effects on seismicity in this case should be immediate, and since the filling of the Blåsjø reservoir now has been through several almost full cycles (see Fig. 2), with no observed changes in seismicity, the probability is now very small that this type of effects will be present at Blåsjø.

The second type of induced seismicity, however, can still not be ruled out completely in the case of Blåsjø. The effects are here tied to diffusion of pore pressure and/or flow of water from the reservoir, which can result in seismicity changes that are delayed

by several years. By the end of 1990 it was more than 5 years since impoundment in Blåsjø started and more than 3 years since the 1050 m level was reached, and it should therefore now be less likely also to get any induced seismicity of the second type at Blåsjø.

Some of the uncertainties that we still have with regard to this question are tied to the following points:

- In the case of pore pressure diffusion, the presence of faults intersecting the reservoir is important since these faults may serve as conduits for flow away from the reservoir. The local fault pattern will therefore be instrumental for the way in which the reservoir will affect the local seismicity.
- In the Blåsjø area, we have established the existence of natural seismicity, with magnitudes up to 3.6 recently, at distances as close as 20--30 km from the reservoir. This is within the possible distance range for the pore pressure diffusion, dependent somewhat on the nature of the local fault system.
- These delayed effects on seismicity, tied to diffusion, are normally leading to larger magnitude earthquakes than those caused more immediately by the loading. This is tied to the way in which the diffusion mechanism can affect longer fault segments (Simpson *et al.*, 1988).

The seismicity map in Fig. 6 covers all recorded data from January 1987 and up to the end of 1990. The three small possible earthquakes within the Blåsjø area during this time period do not in this respect contradict our main conclusions that no induced seismicity has been found. On the basis of this complete assessment of the situation, including all of the arguments discussed above, an agreement was therefore reached between Statkraft and NORSAR to terminate the operation of the Blåsjø stations in the beginning of 1991.

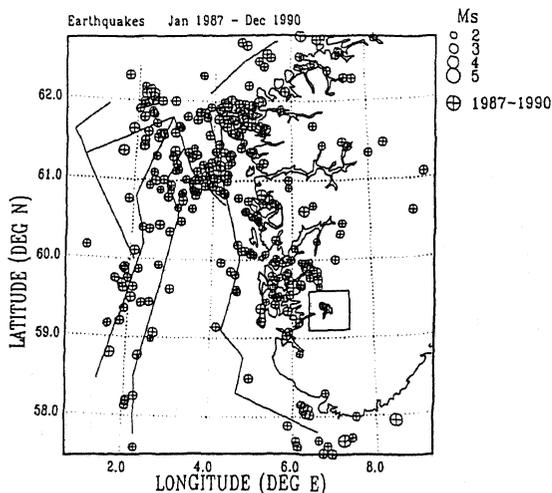


Figure 6. Earthquakes between 1 January 1987 and 31 December 1990, following removal of known and presumed explosions. The small square box encloses the Blåsjø reservoir.

It is important to note here, finally, that the Seismological Observatory (Institute for Solid Earth Physics) at the University of Bergen established a new 3-component station in the area in 1991. This new station, which will be a node in a new national network for Norway, will be sensitive enough to detect any significant changes in the local seismicity. If so, a rapid deployment of mobile seismometers will always be possible.

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