The collapse in the New, Lower Vinstra II hydropower tunnel

The Lower Vinstra (I) hydropower plant was constructed in 1947-52. The plant was extended in the late 1980ies, with installation of an additional 110 MW turbine (Figure 1). For this, a new 23 km long headrace tunnel was excavated, of which 17 km was excavated by TBM and the 5.9 km unlined pressure tunnel by drill & blast. The latter tunnel is sloping towards the powerhouse with a gradient of 1:12.

The rocks in the tunnel are of Cambrian – Silurian age (410-590 mill. years old), originally sedimentary rocks metamorphosed into alternation between meta-sandstones and schists. At the collapse, the rocks consist of phyllite with interbedded meta-sandstone (quartzite) benches.

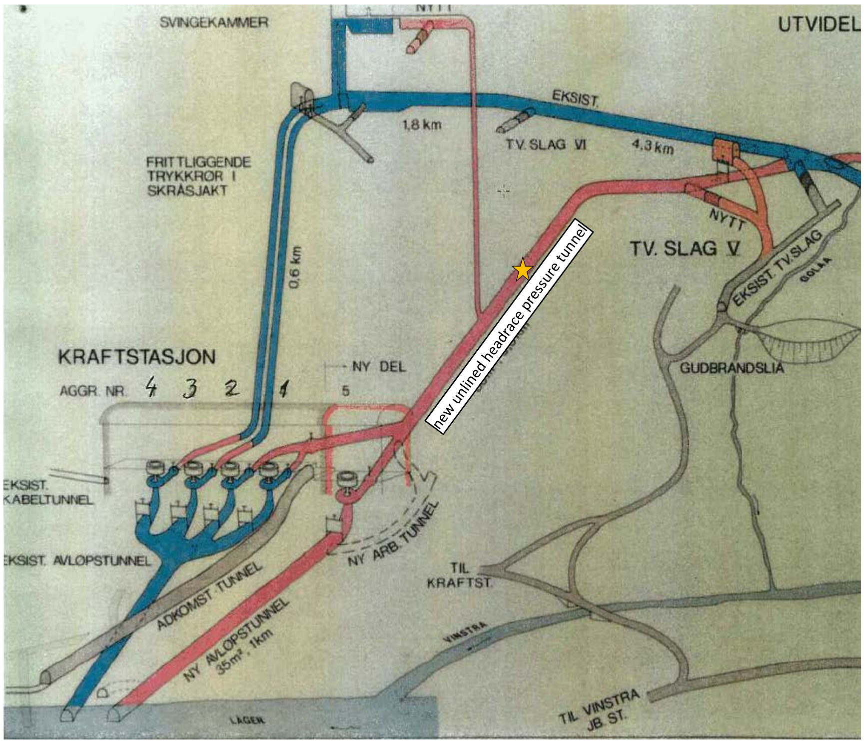

Figure 1: The old (in blue) and new (in red) Vinstra hydropower plant (collapse area indicated with yellow star)

Water filling of the headrace tunnel took place in autumn 1989. After about 2 years of power production, a serious collapse took place in the drill & blast tunnel 2.5 km upstream of the underground power house. More than 20,000m^3 of loose materials had been spread out along this 2.5 km long part of the headrace tunnel.

The cause of the collapse was explained by "initial erosion[1] of weak, clayey material in a rather minor fault zone, which had not been sufficiently protected, or sealed, by sprayed concrete". Before the collapse the tunnel had been emptied and watered up twice.

The main works performed and the time used are shown in Table 1.

[1] A water flow of 1 to 3 m/ in the tunnel during power production does not cause significant erosion (wear) of the tunnel wall. However, water flow combined with fall out or slide of unstable rockmass (loss of strength from water inundation) is more likely to have occurred

Table 1: Works and time used to repair the collapse. By selecting the earlier tunnel contractor for the repairing works, he could start up the works quickly.

Work	Date and time
The collapse was discovered.	Late November 1991.
The tunnel was emptied and the first inspection of the collapse made.	1 December 1991.
Construction of a lower bypass, tunnel[2] as access to the headrace tunnel.	Excavation started a few days after the first inspection.
Excavation from upper end of a 155m long, upper bypass tunnel around the collapse. The tunnel is approx. 155 m long with 40 m distance from the old tunnel.	January - February 1992.
Rock support works completed in the upper bypass tunnel.	18 February 1992.
1.1 m thick concrete plug in the main tunnel upstream and downstream of the collapse.	Completed 18 February 1992.
Removal of the debris in the tunnel downstream of the collapse section.	Start in January 1992
A new 10 m long concrete plug in the lower bypass tunnel designed for a water head of 458m. Grouting around the plug was done in 4 stages. Total leakage after watering up was very low (less than 1 l/min).	Placing of concrete was completed in the first week in April 1992.[3]
Watering up of the tunnel. Full water head against the plug reached.	Started 4 days after concreting of the plug Only 4 days after the formwork had been demolished.
The time elapsed before power production could start again was 17-18 weeks.[4]	

Some details

Watering up and emptying

The first watering up of the headrace tunnel took place in autumn 1989. The tunnel was then emptied and watered up twice, in summer 1990 and in August 1991. In November 1991 a pronounced increase in head loss was recorded. Therefore the tunnel was emptied and inspected in December 1991. It was found that a major failure had occurred at chainage 3,230, about 2.5 km upstream of the sand trap.

Collapse debris in the tunnel

Major quantities of loose materials with grading from sand and gravel to large boulders were found distributed from the sand trap towards the failure. 1700 m from the collapse, boulders of size 2.0 - 2.5 m^3 were found. 13 m downstream of the collapse the debris reached the tunnel roof, preventing access further upstream, see Figure 2. Many of the pieces in the debris were thin slabs with a very smooth, polished (slickenside) fragments, as are shown in Figure 3.

The conditions at the collapse

The width of the failure zone at chainage 3,229, was 15 - 20 m, measured along the tunnel, see Figure 4, in which two faults are shown, both with strike almost perpendicular to the tunnel axis. The most pronounced one at chainage 3,230 had about 0.75m thick central core with clayey, weak material. Also the surrounding rocks were weak. Slickensides and graphite coatings were commonly found on weakness planes.

[2] This access tunnel required that a concrete plug had to be constructed after completion of the repair works before watering up of tunnel system. The construction of this had a great impact on the construction time.

[3] Normally 4 - 5 weeks are considered necessary after construction of such a plug, before start of water filling. In this case special efforts were done both in regard to design and to construction in order to minimize this time.

[4] Due to the special efforts of design and construction of the concrete plug, the down-time for the power plant was reduced with about 4 weeks, with considerable cost savings.

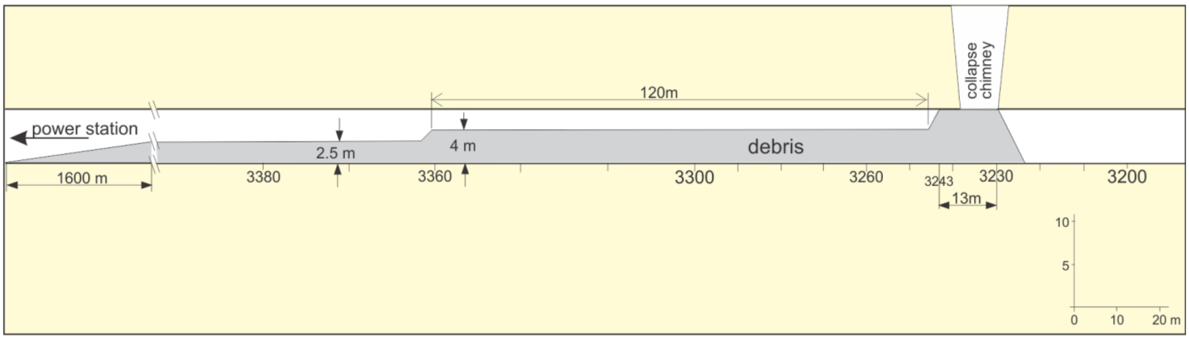

Figure 2: The debris in the tunnel, reaching 2.5 km almost to the underground power station

Figure 3: Photos of slabs from the Vinstra collapse in 1991. The thin slabs are polished with a coating of talc and graphite. The friction along such surfaces is very low when inundated.

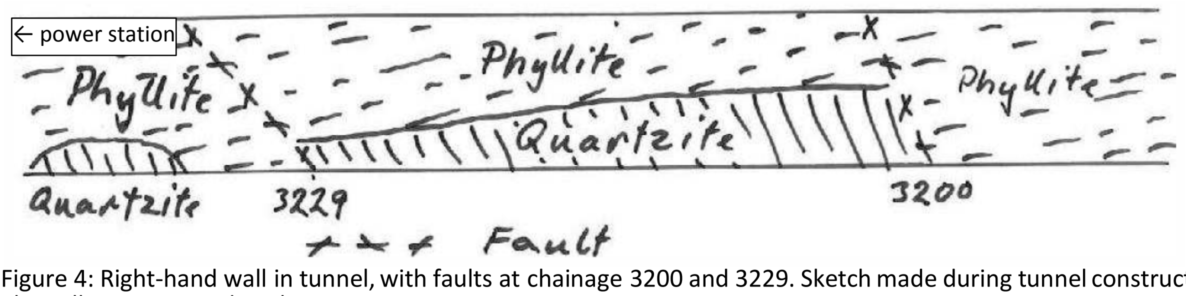

Figure 4: Right-hand wall in tunnel, with faults at chainage 3200 and 3229. Sketch made during tunnel construction. The collapse occurred at chainage 3230.

The rock support installed was rock bolts and shotcrete in roof and walls to 2.5m above the invert. During cleaning of the invert, before first watering up, it was found that the rock was weak and in the central, clayey part of the zone excavated to a depth of about 1.5 m below the shotcreted part in the walls. No support was installed in the invert and in the lower part of the walls.

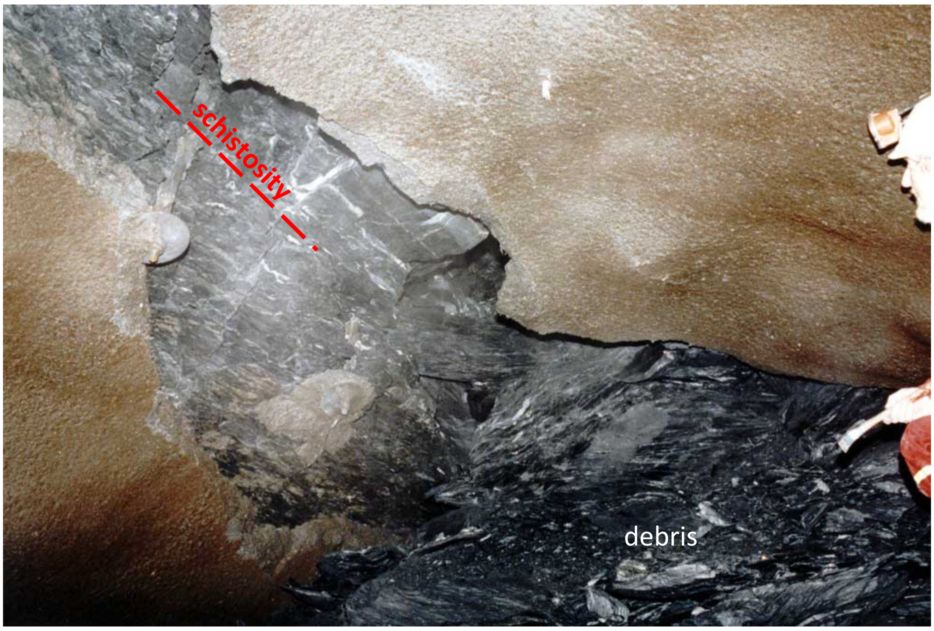

Figure 5: The conditions just upstream of the collapse. The schistosity planes with slickensides and graphite

Probable cause of the collapse

Observations in the headrace tunnel upstream of the collapse found that clay fillings in many faults/weakness zones had been washed or slid out sometimes to a depth of 2 - 3 m. Other location with similar conditions that had been supported by shotcrete showed no signs of cracking or damage. This indicates that the collapse had started in the unsealed parts of the zones of weak, clayey[5] rock which had been left without any protective support. Softening of the clayish material and reduced friction properties after inundation were probably the main causes.

Due to the softening of the clayey material and erosion by the water flow, the size of the tunnel here was increased resulting in sliding and collapses until the debris filled most of the tunnel profile downstream of the collapse area and almost blocked the water flow. It was concluded that if the shotcrete had been installed in the whole wall and in the invert, sealing of the loose materials, the collapse could have been avoided.

Figure 6 shows a possible explanation for the development of the collapse.

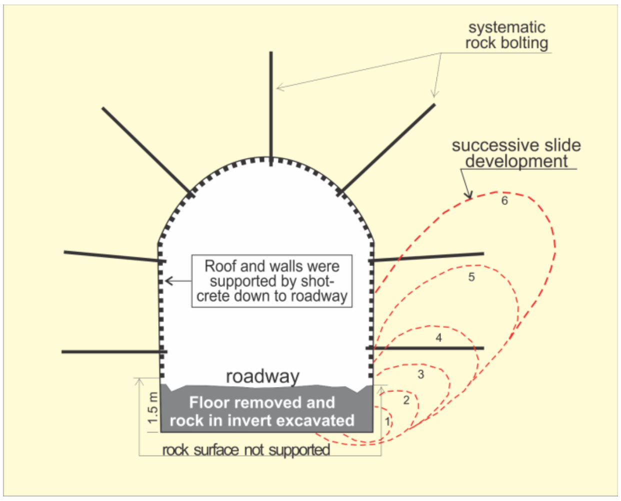

Figure 6: Possible development of the failure, mainly in the right side (looking downstream)

[5] Laboratory testing showed that the clay did not have swelling properties, i.e. swelling was not the cause of the collapse.

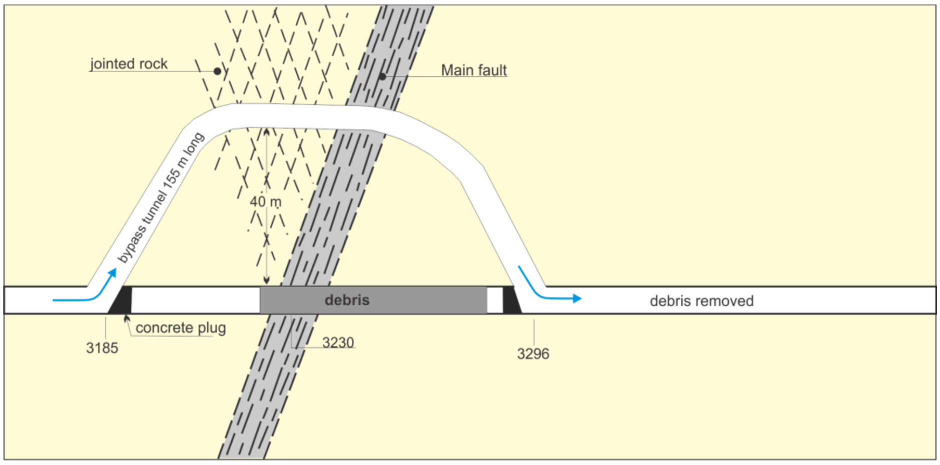

Figure 7:
The 155 m long bypass tunnel around the collapsed section

The chosen support design of the upper by-pass tunnel (Figure 7) was a combination of sprayed concrete with thickness 0.15-0.25m, sprayed concrete ribs and rock bolts (dowels). The tunnel invert was concreted.

References

Palmström A. (1991): Note made during site visit December 1991.

Buen B. (1991, 1992): Personal communication.

Halvorsen A. (2014): Personal communication.