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Review

Rock falls in selected Norwegian hydropower tunnels subjected to hydropeaking

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ABSTRACT

Unlined rock-blasted hydro tunnels are key components of the Norwegian hydropower system (NHS), used both as water collectors and conveyors. Long-term stability of these constructions is essential to ensure continuous and cost-effective operation. Recent trends in the energy market have led to so-called hydropeaking production patterns, which increase the frequency of unsteady flow situations in the hydro tunnels. Such production patterns can trigger structural instability in the tunnel systems in form of rock falls, which reduces the cross-sectional area and cause head loss. This work examines the quantity of rock falls in hydropower tunnels subjected to hydropeaking through a series of inspections. The results indicate that the frequency and total volume of rock falls increases if a tunnel is subjected to hydropeaking.

Contents

1. Introduction

In the past century, over 3500 km of drill and blast tunnels have been excavated and applied as water conveyors in Norway (Fig. 1). The design philosophy has been to utilise the rock mass as a structural element, and limit the amount of reinforcement and concrete lining. Underground developments provide a wide flexibility regarding location and shape of waterways, surge chambers and power stations, and are therefore recognised as both efficient and environmental friendly (Kristiansen and Stokkebø, 1992). The design has benefited from developments of tunnelling methods and improved geological knowledge. Early solutions for high-head plants often included steel penstocks placed above ground. Improved knowledge of rock mechanics enabled use of unlined underground pressure shaft solutions, which in the 1960s became generally adopted. A decade later, a new layout was introduced, using an unlined pressure tunnel together with an air cushion surge chamber. This layout enables use of an inclined tunnel instead of a pressure shaft, which simplifies the tunnel construction and reduces the total length (Rathe, 1975; Broch, 1985; Nilsen and Thidemann, 1993; Palmstrøm, 1988). Fig. 2 shows the

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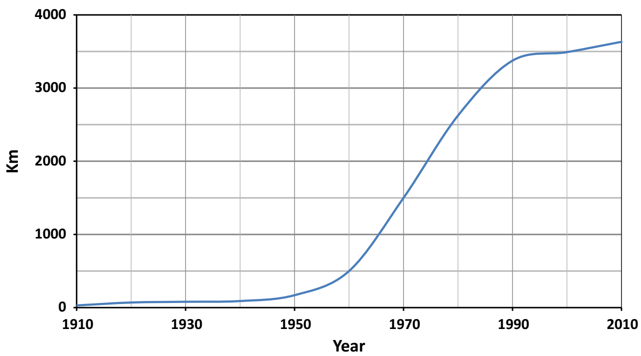

Fig. 1. Accumulated length of hydropower tunnels excavated in Norway.

main historical shifts in the design of the hydropower plants in Norway.

In general, the Norwegian rock mass is not regarded as a material that needs additional support (Palmstrøm, 2003). The hydropower tunnels are primarily designed by taking advantage of the self-supporting capabilities of the rock mass, even in highly jointed areas (Thidemann and Bruland, 1992). A central part of the design philosophy of unlined hydropower tunnels has been to accept minor instabilities in the form of small rock falls. The cost of installing rock support to completely avoid rock falls has been considered to be significantly higher than the subsequent cost of the additional head loss these rock masses cause. To avoid sand and rock transportation down into the turbine, a sand trap is constructed in the end of the unlined tunnel. Before 1960, on average, approximately 5% of the length in Norwegian hydro tunnels was reinforced by concrete lining. Shotcrete was introduced as a support method around 1970, which led to double use of support. Although both support techniques are common, shotcrete is the prominent technique in modern tunnelling (Thidemann, 1981). Rock support can be separated in two main categories; preliminary support required due to safety during construction, and permanent support for long term stability. There is not necessarily a practical difference between the two groups, as support methods such as rock bolts or pre-grouting function as both (Thidemann and Bruland, 1992).

The degree of stability problems in hydropower tunnels vary widely, as does the need for rock support, from 1.5% up to 60% of the total tunnel length (Thidemann, 1981). Between 1986 and 1991, a study was conducted to investigate if the long term stability of the hydro tunnels were in accordance with safety and economic requirements (Bruland and Thidemann, 1991). The study quantified the frequency, volume, and causes of rock falls and other stability problems for 35 tunnels, corresponding to a total length of 330 km. The record from this study offers unique reference data.

In 1991, a new energy law implemented in Norway stipulated that the hydro electrical production would be gradually altered

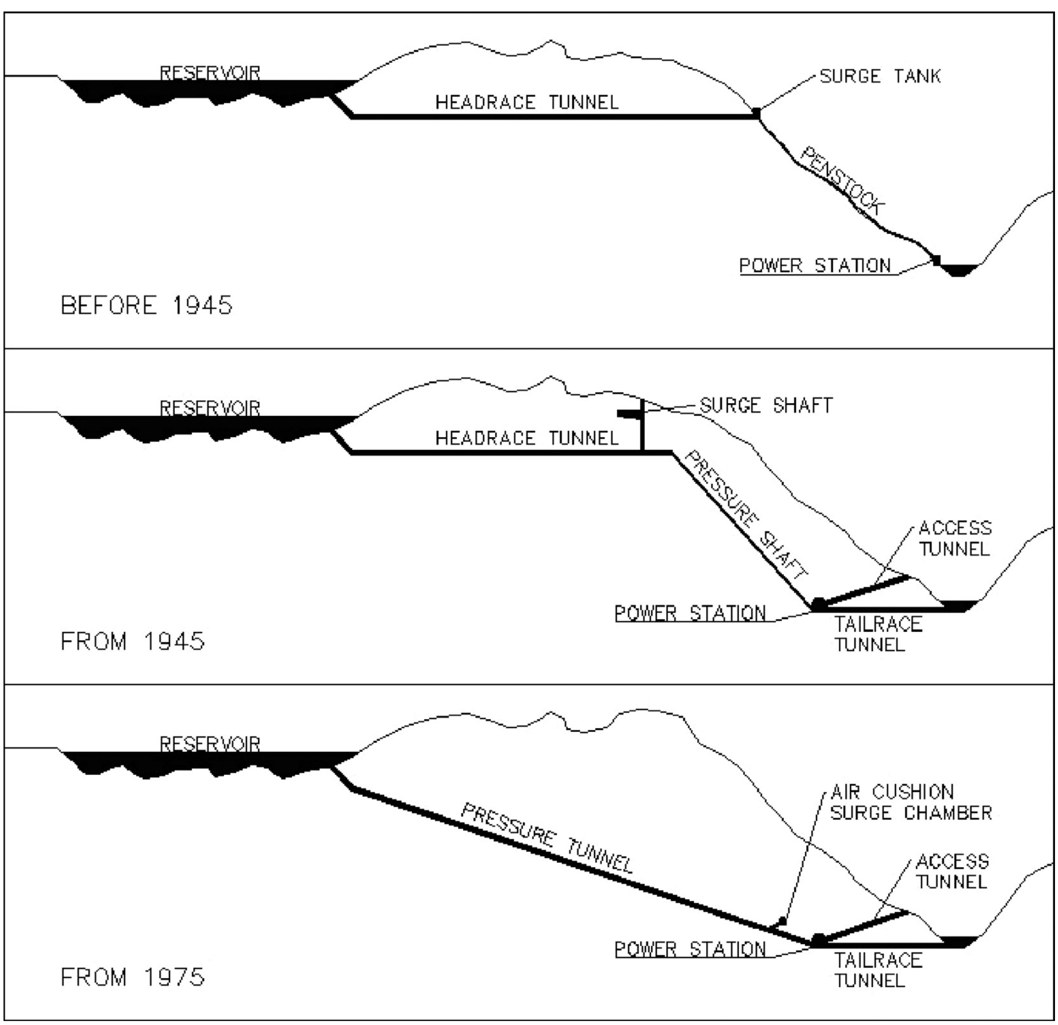

Fig. 2. Historical development of hydropower tunnel system in Norway.