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Analysis of unlined pressure shafts and tunnels of selected Norwegian hydropower projects

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ABSTRACT

Norwegian hydropower industry has more than 100 years of experiences in constructing more than 4000 km-long unlined pressure shafts and tunnels with maximum static head of 1047 m (equivalent to almost 10.5 MPa) reached at unlined pressure tunnel of Nye Tyin project. Experiences gained from construction and operation of these unlined pressure shafts and tunnels were the foundation to develop design criteria and principles applied in Norway and some other countries. In addition to the confinement criteria, Norwegian state-of-the-art design principle for unlined pressure shaft and tunnel is that the minor principal stress at the location of unlined pressure shaft or tunnel should be more than the water pressure in the shaft or tunnel. This condition of the minor principal stress is prerequisite for the hydraulic jacking/splitting not to occur through joints and fractures in rock mass. Another common problem in unlined pressure shafts and tunnels is water leakage through hydraulically splitted joints or pre-existing open joints. This article reviews some of the first attempts of the use of unlined pressure shaft and tunnel concepts in Norway, highlights major failure cases and two successful cases of significance, applies Norwegian criteria to the cases and reviews and evaluates triggering factors for failure. This article further evaluates detailed engineering geology of failure cases and also assesses common geological features that could have aggravated the failure. The minor principal stress is investigated and quantified along unlined shaft and tunnel alignment of six selected project cases by using three-dimensional numerical model. Furthermore, conditions of failure through pre-existing open joints by hydraulic jacking and leakage are assessed by using two-dimensional fluid flow analysis. Finally, both favorable and unfavorable ground conditions required for the applicability of Norwegian confinement criteria in locating the unlined pressure shafts and tunnels for geotectonic environment different from that of Norway are highlighted.

1. Introduction

Norway has built more than 200 underground powerhouses and 4200 km-long hydropower tunnels in the past 100 years (Broch, 2013). Experiences gained in design, construction and operation of waterway system have led to the development of innovative ideas. One of these ideas is the application of unlined high-pressure tunnels and shafts in hydropower schemes. It is estimated that over 95% of the waterway length of Norwegian hydropower schemes is left unlined (Johansen, 1984; Panthi, 2014). The earliest attempt to apply such concept in Norway was in Herlandsfoss project in 1919 (Vogt, 1922), and up to now, more than 4000 km-long unlined pressure shafts and tunnels with maximum static head of 1047 m have been in successful operation. Panthi and Basnet (2016) collected the information about most of the unlined tunnel projects and explained a brief history of development of unlined shaft and tunnel concept in Norway. They generalized the layout of such unlined shafts and tunnels in different hydropower schemes in four different arrangements, which are being practiced in Norway since the start of unlined pressure tunnel concept (Fig. 1). The arrangements shown in Fig. 1 are prepared based on the layout of a number of successful unlined shafts and tunnels in different hydropower schemes of Norway.

Apart from Norway, the unlined pressure tunnels are constructed worldwide where the layout planning, design and construction experiences from Norway are extensively used in

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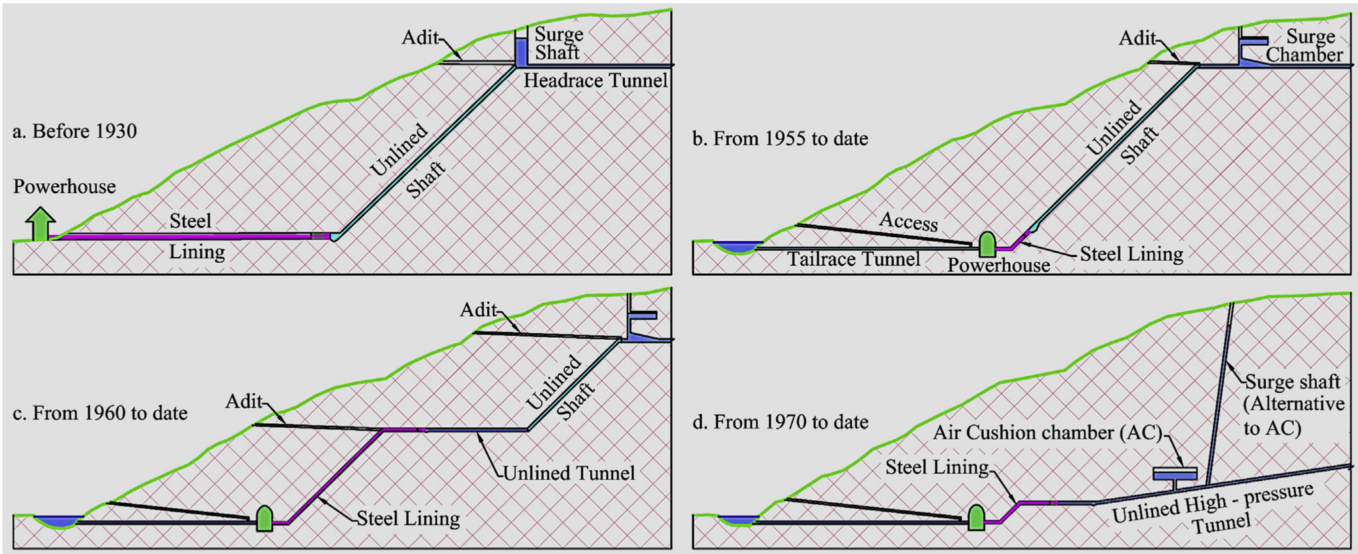

Fig. 1. Locations of unlined high-pressure shafts and tunnels in different hydropower schemes of Norway.

different geological and tectonic environments. Some examples of unlined pressure tunnels around the world are mentioned here. In Colombia, Chivor and Gauvio projects were planned with unlined pressure tunnels where Norwegian design principles were used in the design process (Broch, 1984; Broch et al., 1987). In Tanzania, unlined high-pressure tunnel of Lower Kihansi hydropower project was designed by using Norwegian criteria (Marwa, 2004). Palmstrom and Broch (2017) highlighted that two of the hydropower projects with unlined tunnels are in operation in Chile after the repair work of the collapses occurred after the waterway system is filled and power plants come in operation. Similarly, according to Norconsult (2017), the Las Lajas project in Chile is planned to use 9.5 km-long unlined pressure tunnel. In Portugal, Venda Nova II (Lamas et al., 2014) and Venda Nova III (Esteves et al., 2017) have successfully employed unlined pressure tunnels and both projects are in operation without any significant problem. In China, there is growing rate of use of unlined tunnels in the hydropower projects (Liu, 2013). In Nepal, Upper Tamakoshi Hydroelectric with unlined pressure tunnel is under construction (Panthi and Basnet, 2017) and is expected to be water-filled within two years of time.

The principle behind the idea of unlined pressure tunnel concept is that the rock mass itself works as a natural concrete against the pressure exerted by water column in the tunnel (Broch and Christensen, 1961; Selmer-Olsen, 1969; Broch, 1982). It is well known that Norway is geologically considered as a hard rock province, since two thirds of the country is situated in the Precambrian rocks consisting of gneisses (the most dominant rock type), granites, gabbros and quartzites. This hard rock province offers stiff rocks, which could work against the high water pressure without failure. However, about one third of the landscape is made up of rocks of Cambro-Silurian age (mainly Caledonian mountain range) consisting of different mixes of rock types such as gneisses, schists, phyllites, greenstones and marbles of varying degree of metamorphism as well as granites, gabbros, sandstones, shales, dolomites and limestones (Johansen, 1984). It is worthy to note here that waterway systems of many Norwegian hydropower schemes are aligned along the rock mass of the Caledonian mountain range, which do not represent as stiff rock mass as that of the Precambrian formations. The typical feature of Norwegian landscape is that the last deglaciation left the rock surface without any appreciable weathered material on the top of the surface, but there is a tendency of a frequent jointing in the rock mass near the surfaces. Selmer-Olsen (1969) explained that this condition may lead higher permeability of rock mass to a depth ranging from 5 m to 40 m, which could cause water leakage. On the other hand, more stabilized tectonic setting (relatively few tectonic activities in comparison to other mountainous regions) helped to increase confinement in the rock mass even near surface. In general, favorable engineering geological and geotectonic environment of the Scandinavian landscape has favored the use of unlined pressure tunnel concept in Norway.

The successful history of the operation of unlined pressure shafts and tunnels in Norway is almost 99% with very few stability problems along the waterway system excluding some exceptions where problems were registered during the initial phase of the development of unlined concepts. The detailed studies of the failure were carried out and the lessons learned from the failure were helpful in developing certain design principles and criteria for unlined high-pressure tunnels and shafts (Broch and Christensen, 1961; Selmer-Olsen, 1969, 1974; Broch, 1982; Selmer-Olsen, 1985). In addition to the design criteria for confinement, a concept came in practice after the 1970s that nowhere along the unlined shafts and tunnels, the minor principal stress should be less than the pressure due to static water head. In order to use this concept in practice, a set of standard two-dimensional (2D) finite element charts were prepared in 1971–1972 for valley side slope from 14° to 75° (Nilsen and Thidemann, 1993). Bergh-Christensen (1982), Bergh-Christensen and Kjolberg (1982), Buen and Palmstrom (1982) and Benson (1989) emphasized the necessity of more detailed study on the engineering geological and stress state conditions. The in situ stress measurement program became popular means to verify the assumptions made during the design of unlined concept in Norway as well as in other parts of the world (Bergh-Christensen, 1982, 1986; Myrset and Lien, 1982; Vik and Tunbridge, 1986; Palmstrom, 1987; Hartmaier et al., 1998; Panthi and Basnet, 2017). The risk of hydraulic jacking along the pre-existing joints and fractures and possibility of leakage were always the major issues in the design of unlined tunnels and shafts (Barton et al., 1987; Brekke and Ripley, 1987). Hydraulic jacking test and fluid flow analysis through the joints could also be used to assess the risk of

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