Underground solution for Su-Pan 1 hydropower project in Vietnam

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Abstract

Su-Pan 1 is a small hydropower project with installation capacity of 30 MW, maximum water head of 250 m, and maximum discharge of almost 17 m3/s. The project is located in Sapa district, Lao-Cai province, Vietnam, and in outskirt of a national protected forest (Hoang Lien forest).

After due considerations, it was found that underground solution is an optimum solution for the project from both environmental and economical point of view. The project was built with 2740 m headrace tunnel, underground powerhouse, and 415 m tailrace tunnel. The project was successfully put in operation in December 2018 and in good production since then.

This paper presents practical experiences during the design and construction of the project, particularly focuses on the rock engineering issues including rock mass evaluations and rock stress measurements. Experiences learned from this project can be used for similar hydropower projects in future.

Keywords: Hydropower, Underground powerhouse, Tunnel, Stress measurement

1. Introduction

Su-Pan 1 is a small hydropower located in four communes Su-Pan, Hau Thao, Ta Van, Ban Ho, belonging to Sapa district, Lao Cai province, Vietnam. Main features of the project are installation capacity of 30 MW (two units), maximum water head of 250 m, and maximum discharge of almost 17 m3/s. The project consists of a concrete arch dam with maximum height of 52.5 m, a headrace tunnel of 2.7 km (tunnel width D=4 m), underground powerhouse, and tailrace tunnel of approximately 0.4 km. The project was competed and commissioned in December 2018 (first unit), and January 2019 (second unit).

During planning and construction of this project, two main challenges were encountered:

- The project is located at the border of a natural protected area. Thus, minimum disturbance from the project to the nature is strictly required.
- The project is located at the slope of a high mountain range. The top of the mountain is approximately 2000 m above sea level, whilst the project is at elevation of 700 to 900 m above sea level. This gives an overburden of more than 1000 m to underground parts of the project and cause some rock stress issues.

Some innovative solutions have been applied including the following: underground powerhouse, unlined tunnel, no surge chamber, stress measurement, and arch dam. These solutions made this project both technical feasible and cost effective and kept the unit investment cost of the project to approximately 35 billion VND per MW of installation capacity (estimated cost as per 2016). This was 12% less than the general investment cost for a hydropower project in Vietnam at that time.

With the successful implementation of Su-Pan1 HPP, this paper presents some lessons learnt during planning and construction of the tunnel and cavern of the project, so that it can be used for similar HPPs in future. It is noted that concrete arch dam is not included in this paper as it would require a separate paper.

2. Project layout with underground solution

Geological map indicates that rock mass on the right side of the river is granite, granite-biotite, while the rock on the left side of the river is sedimentary and metamorphic rock (quat-schist, mica-schist, sericite). Geological conditions on the right side of the river (looking with flow direction) are considered to be much more favourable than on the left side. Thus, the waterway of the project was selected to be on the right side.

Several options were considered during the planning phase of the project for the waterway system:

- Option 1: The waterway consists of a sub-horizontal upper tunnel, a vertical shaft, a lower sub-horizontal tunnel with a pipe connection to convey over the river to an open powerhouse on the left side of the river. Layout of this option is shown in Figure 1 (a).
- Option 2: The waterway consists of a sub-horizontal upper tunnel, two vertical shafts, two lower sub-horizontal tunnels, and an open powerhouse on the right side of the river. Layout of this option is shown in Figure 1 (b).

Advantages and disadvantages of the options are that:

- With Option 1: The powerhouse is located on the left side with lower topography, so the excavation work is reasonable. This option has a long vertical shaft, which may be difficult for obtaining a suitable local contractor to construct.
- With Option 2: The long vertical shaft in Option 1 is divided into two shafts making it shorter and more suitable for local contractors. Open house and entrances to the two shafts are designed to be in a steep slope, increasing the excavation volume and causing more negative impact to the environment.
- In all options, careful hydraulic calculations have made so that surge chamber can be removed.

Evaluations and analyses were carried out and concluded that the proposed options do not meet environmental requirements and are not competitive. After due considerations and site visit, another option was proposed. In this option, the powerhouse was placed underground. The headrace tunnel was designed to be inclined with 8.5% inclination along the entire length, without any vertical shaft, as shown in Figures 2 and 3. Detailed analyses showed that this option has minimum surface excavation, and therefore has minimum disturbance to the environment. This option was also found to be very competitive from economic point of view. Thus, this option was selected for implementation of the project. The solution is considered to be innovative as this is the first time an underground powerhouse is used for such small hydropower, following experience from Norwegian hydropower industry.

Underground solution for powerhouse also required much more detailed information about geological conditions, including rock mass quality and in-situ rock stress. Additional geological investigation was made including dedicated core drilling at the tentative location of the underground powerhouse, and rock stress measurement was made in the access tunnel toward the underground powerhouse.

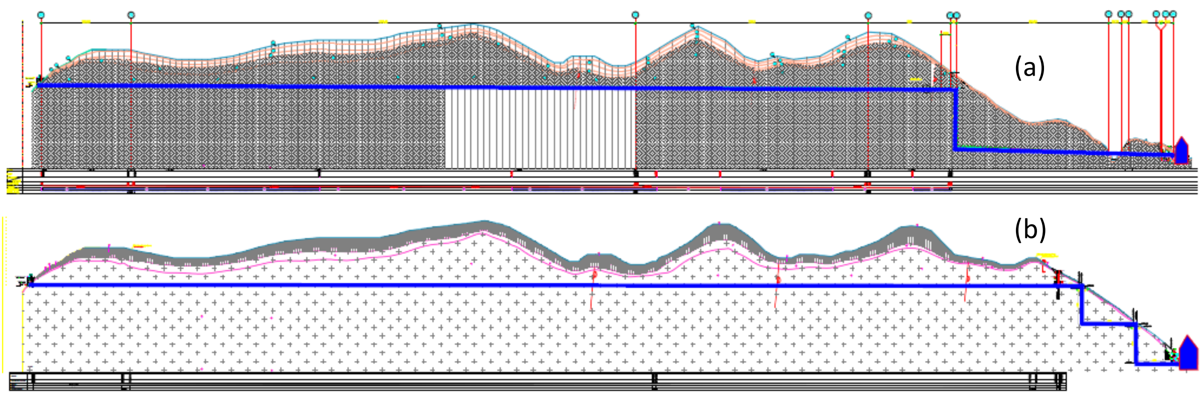

Fig. 1. Some proposed options during early planning stage of the project: (a) tunnel in the right side of the river and open powerhouse on the left side of the river, one vertical shaft, (b) both tunnel system and open powerhouse in the right side of the rive with two vertical shafts.

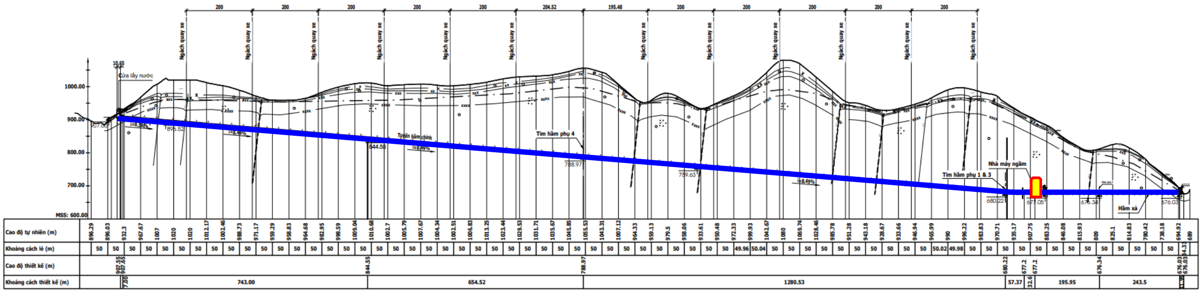

Fig. 2. Selected option of the project: inclined headrace tunnel of 8.5% inclination and underground powerhouse.

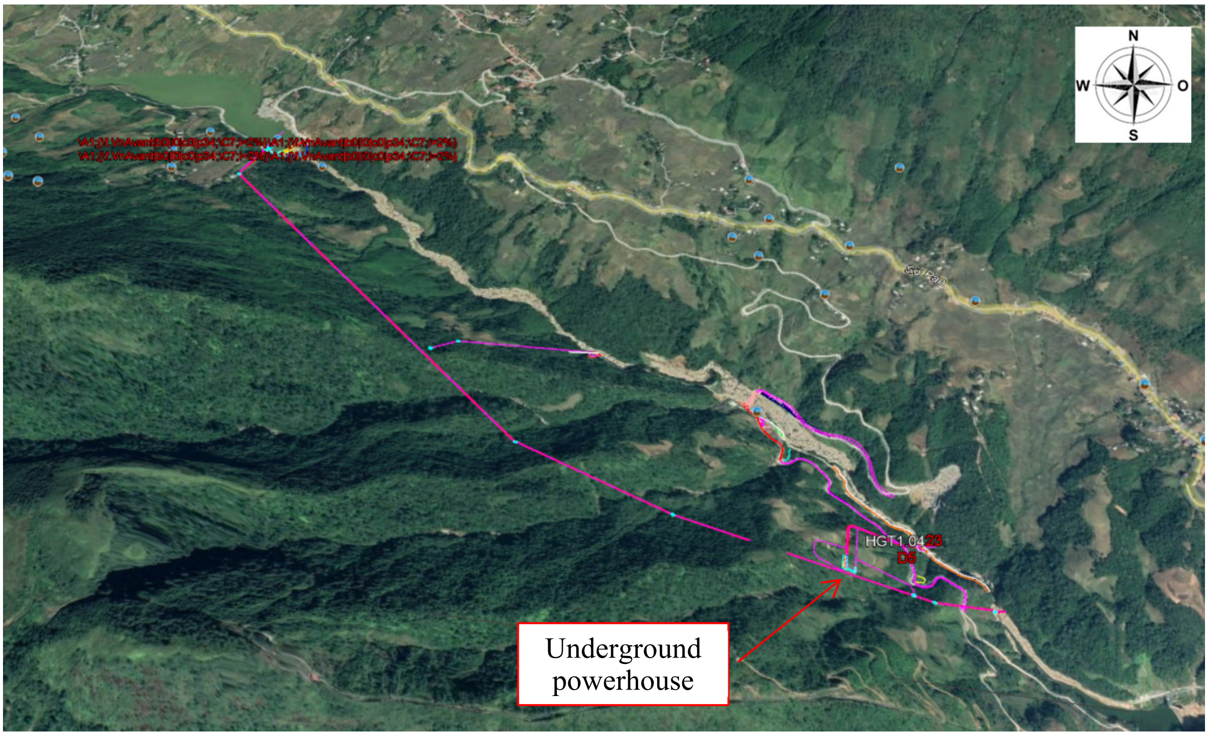

Fig. 3. General layout of Su-Pan 1 HPP – selected option, plotted in Google map.

3. Rock stress measurement

SINTEF conducted in-situ 3-dimensional stress measurements by overcoring at the Su-Pan 1 HPP (SINTEF, 2017). The measurements were carried out in the access tunnel at the tunnel face at approximately KO +270. The rock overburden at the test location is 213 meters. The measurements were conducted during the period of 05th to 10th December 2016.

The 3D overcoring for in-situ stress measurements starts with diamond drilling of a core hole of 76 mm in outer diameter to the desired depth. The hole bottom is then flattened with a special drill bit, and a concentric hole with smaller diameter (36 mm outer diameter) is subsequently drilled 30 cm further. The measuring cell is then inserted with a special installing tool, which can apply compressed air in order to expand the cell inside the hole, and get adhesion between the strain gauges and the rock hole contour. The measuring cell will start to log data as soon as adhesion is achieved. The small hole containing the measuring cell will then be overcored by the larger drill bit, thus stress relieving the core. The resulting strains will continuously be recorded during the overcoring. The core will finally be extracted from the drill hole by a special core catcher equipment, and the whole measuring process can restart at the desired next depth inside the borehole.

For calculation of the in-situ rock stress obtained from the strain recordings, the in-house developed computer program DISO (Determination of In situ Stress by Overcoring) is used. DISO computes the in-situ stress from 3D overcoring, by randomly selecting strain readings from different measurements in the hole, which results in statistical calculations and presentation of mean stress values with their respective deviations.

The input data from the measurements are checked carefully in order to remove obvious erroneous readings. This includes a thorough visual investigation of the cores after the overcoring.

All cores from the measuring points are tested in either uniaxial compression test, or biaxial cell with the 3D cell connected after overcoring. All cores are tested in biaxial cell with the 3D cell where strains are recorded, and Young’s modulus are obtained. For the calculation of stresses, the representative values of Young’s modulus from biaxial tests have been used.

The cores obtained from the 3D measuring holes have also been tested at SINTEF rock mechanic laboratory for determination of mechanical properties of the rock, providing further information for checking the stress calculation. Average values of the tests are presented in Table 1.

Result of the stress calculation is presented in Table 2 and Figures 4 and 5. The result of in-situ stress was used extensively for designing the powerhouse cavern as well as calculation for the length of steel lining part of the pressure tunnel.

Table 1 Average mechanical properties of the rock.

Measuring location	Young's modulus (GPa)	Poisson ratio	UCS (MPa)	Density (kg/m3)	Point load test (MPa)
K0+275	51.9	0.17	217	2637	18.8

Table 2 Result of stress measurement.

Measuring location	Stress component	Value (MPa)	Trend (degree)	Plunge (degree)
K0+275	Major principal stress	12.5±1.4	89	14
	Intermediate principal stress	5.3±0.7	315	70
	Minor principal stress	3.6±1.3	14	14

The calculated stress ellipsoid can be converted to the following horizontal and vertical components:

- Vertical stress: σV = 5.6 MPa
- Maximum horizontal stress σh max = 12.1 MPa trending N90°E
- Minimum horizontal stress σh min = 3.7 MPa trending N180°S

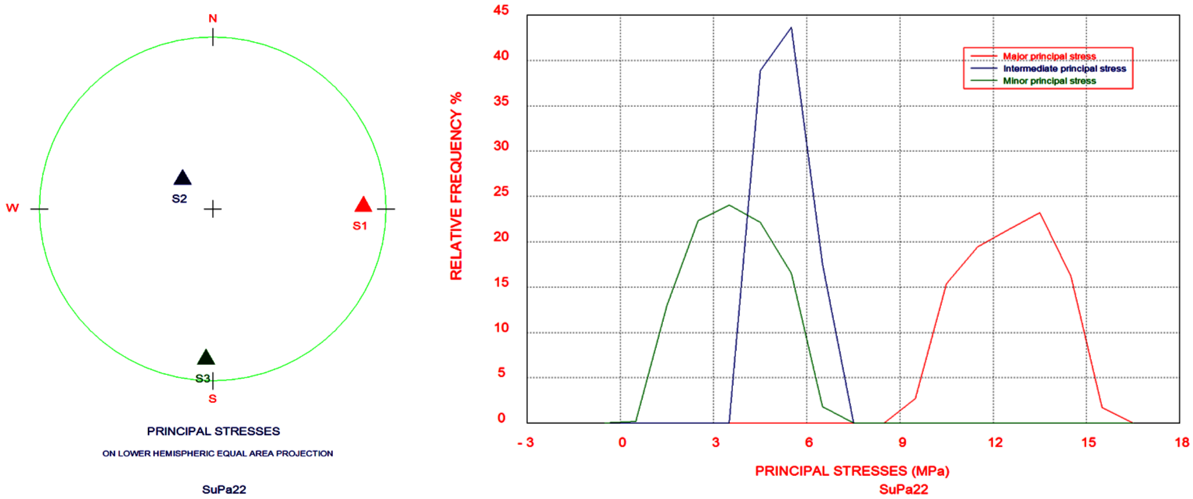

Fig. 4. Result of stress measurement.

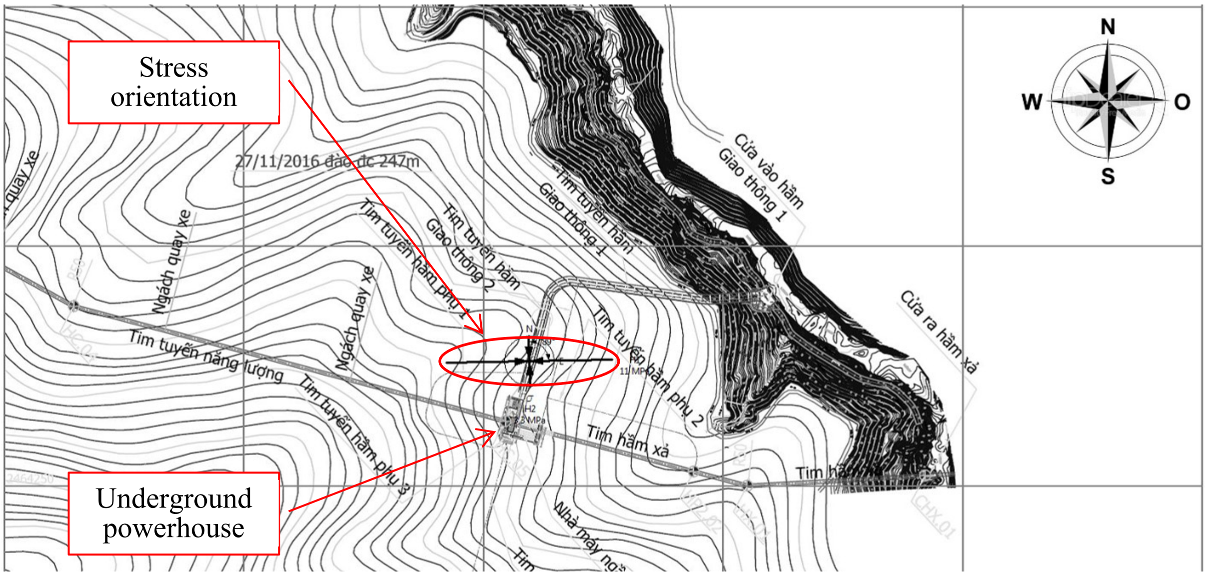

Fig. 5. Orientation of measured stresses.

To understand the need of this rock stress investigation and the important role of the rock stress for the design process for Su-Pan1 HPP, it is necessary to review some achievements as well as "expensive lessons" learnt during HPP development in Norway.

Norway is the 6th largest Hydro Electric Power (HEP) producer in the world and is well known for its clean energy system comprising over 1 500 power plants, an installed capacity around 31 000 MW and a mean annual production around 130-140 TWh in the last 10-20 years (Statista, 2022). The Norwegian HEP production is based on high head, limited water flow and more or less continuous production (Grøv et al, 2011). The hydropower sector is the backbone of the Norwegian power system (Energimeldingen 012/16), accounting for more than 90% of the total annual production in Norway as per 2021 (Energifaktanorge, 2021). The Norwegian HEP industry has developed several innovative solutions, such as: underground air-cushion surge chambers, lake taps, unlined high-pressure tunnels and shafts (Broch, 2013), and underground powerhouses. Around 5.000km of tunnels have been excavated for Hydro Electric Power (HEP) and almost one third of the underground powerhouses in the world are in Norway. The Norwegian HEP production is truly an underground industry.

Experience through the development of HEP projects in Norway has shown that an in-situ rock stress that is not large enough to balance to the water pressure in a pressurised unlined water tunnel and/or shaft, a hydraulic jacking/fracturing situation is likely to happen. Hydraulic jacking/fracturing will lead to an opening of existing joints (in the worst case create new fractures), leading to an excessive water leakage situation. To prevent this from happening, steel lining is an option for a safe design, though a very expensive solution. The Norwegian design, however, takes advantage of the in-situ rock stress knowledge to properly locate underground infrastructure and minimise steel lining in headrace system of a HEP, hence providing a much more cost-effective solution. Several authors have pointed out that a proper knowledge of in-situ rock stress is a key factor for a successful development of unlined high-pressure tunnels and shafts, which then strongly contributes to reduce construction costs and time (Nilsen and Thidemann, 1993; Nilsen and Palmstrøm, 2000; Ødegaard and Nilsen, 2018).

Experience from Norway also shows that if the rock stress is not sufficient, then it is likely that "expensive failures" can be encountered. As described in Basnet and Panthi (2018), Herlandsfoss, Skar, Byrte, Askara, Bjerka, and Fossmark are examples, as shown in Figure 6. Those failures have caused different levels of damage to the tunnels system, from major leakage to serious jacking cracks, lifting, and noises. In addition to the mentioned cases, the most recent incident at Bjørnstokk HEP lead to a major leakage that caused a 180 000 m^3 landslide, destroying the county road 76 and closing it for 3,5 months (Nordal et al., 2018).

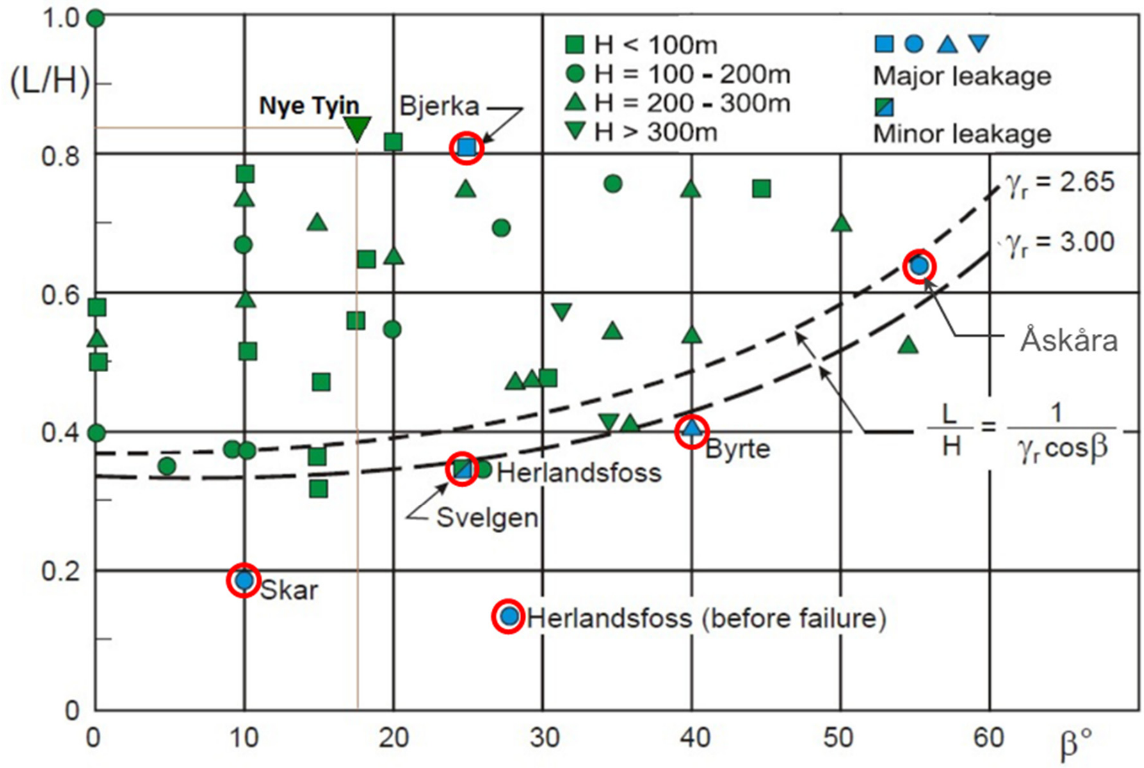

Fig. 6. Overview of hydropower plants where leaks have occurred due to hydraulic fracturing in the rock mass (Broch, 1982) – L is shortest distance of an unlined tunnel to the valley side, H is overburden, β is slope angle of the valley side, γ_r is the unit weight of the rock.

Understanding the important role of rock stress for hydropower development, lot of stress measurements have been carried out for many hydropower projects in Norway. With over 1 500 hydropower power projects built, number of rock stress measurement would be large. For better used of the rock stress information at the national level, a research project has been created and named as NoRSTRESS – Norwegian in-situ Rock Stress for Sustainable Development of Hydroelectric Power (NoRSTRESS, 2021). One of the tasks in NoRSTRESS project is that it will gather data of all relevant stress measurements in a systematic way to create a database. The database together with proper analyses to gain deeper understanding of in-situ rock stress and using it for further development of hydropower.

4. Rock stress issue and rock support

As mentioned above, the project is located in a foothill of a high mountain range with a steep slope – up to 35 degrees. The height of the slope is more than a thousand meters. This caused a stress induced situation along the headrace tunnel. It was observed in the headrace tunnel that stress concentration appears on the left corner of the tunnel (looking with flow direction), as shown in Figure 7. This corner is facing the rock slope, and this stress issue appear on major part of the tunnel length. In some particular tunnel sections, where stress concentration is too high, rock burst was encountered with strong rock break sound and released of rock fragments as shown in Figure 8.

Permanent rock support of the tunnel was design based on experience from Norwegian hydropower tunnel. According to the experience, the tunnel can be designed basically as "unlined tunnel". The philosophy behind the "unlined tunnel" design is that the rock has certain capacity of self-support depending on rock mass quality. Additional rock support measures such as rock bolt, shotcrete, or concrete lining will only be added locally where needed.

To evaluate the need for rock support, the Q-system (a rock mass classification system) was used. The Q-system is an empirical method, developed by NGI (Norwegian Geological Institute) in 1974 (Barton, Lien, and Lunde, 1974). Since then it has been updated several times to include the most modern types of tunnel support, and this empirical method is now based on data from more than 1250 examples from existing tunnels around the world (NGI, 2015). The Q-method is a system for quantitative and qualitative rock mass quality determination. It is further used as a method that provides a guideline for recommendations on the permanent rock support in tunnels and caverns.

Using the Q-system, the rock support for Su-Pan 1 tunnel system was 83% without support, 13% with systematic bolting and shotcrete, and 4% with concrete lining. Figure 8 shows the powerhouse cavern during construction. The cavern was completed without any concrete lining, as shown in Figure 9.

Fig. 7. High stress causing rock burst in some section of the headrace tunnel.

Fig. 8. Rock burst with rock fragment released.

Fig. 9. Underground powerhouse cavern of the Su-Pan 1 HPP – During construction.

5. Conclusions

Su-Pan 1 HPP is a small hydropower project, located in a challenging topographical location and at the border of a natural reserved area. The natural conditions at the project site location caused challenges for planning and construction. The innovative solutions have been applied for the successfully implementation of the project as listed below:

- Underground powerhouse.
- Inclined headrace tunnel without vertical shaft and no surge chamber.
- Unlined tunnel with minimum steel lining.
- Rock stress measurement to provide concrete information for the design of underground powerhouse and steel lining.
- Concrete arch dam (not included in this paper).

These solutions are also available and applicable for planning and construction of similar HPPs in Vietnam in future.

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References

Barton, N., Lien, R. and Lunde, J. (1974) Engineering Classification of Rock Masses for the Design of Tunnel Support. Rock Mechanics, 6, 189-236. https://doi.org/10.1007/BF01239496

Basnet C. B. and Panthi K. K., 2018: Analysis of unlined pressure shafts and tunnels of selected Norwegian hydropower projects. Journal of Rock Mechanics and Geotechnical Engineering. Vol. 10, pp 486-512.

Broch E., 1982: "The development of unlined pressure shafts and tunnels in Norway". Proceedings of the ISRM international symposium. ISRM; 1982. p. 545-54.

Broch E., 2013: Underground hydropower projects - lessons learned in home country and from projects abroad. Norwegian Tunneling Society. p. 11-19.

Energifaktanorge, 2021: Hydropower in Norway. https://energifaktanorge.no/en/norsk-energiforsyning/kraftproduksjon/ (accessed on 31/10/2022).
Energimeldingen 012/16 Vannkraften er ryggraden i norsk energiforsyning. Accessed on https://www.regjeringen.no/no/aktuelt/energimeldingen-vannkraften-er-ryggraden-i-norsk-energiforsyning/id2484259/.
Grøv Eivind, Bruland Amund, Nilsen Bjørn, Panthi Krishna, Lu Ming, 2011: CEDREN report: "Developing future 20 000 MW hydro electric power in Norway", SINTEF report.
NGI, 2015, "Rock mass classification system: Q-system". Available at https://www.ngi.no/eng/Services/Technical-expertise/Engineering-geology-and-rock-mechanics/Q-system (access on 29th October 2022).
Nilsen B & Palmstrøm A., 2000: Engineering Geology and Rock Engineering. Norwegian Group of Rock Mechanics, Handbook No. 2, 249 p.
Nilsen B & Thidemann A, 1993: Rock Engineering. Hydropower Development, Vol. No. 9, NTH Division of Hydraulic Engineering, 156 p.
Nordal, S., Grøv, E., Emdal, A., L'Heureux, J. (2018) " Skredene i Tosbotn, Nordland, 1. og 2. april 2016 ". Available at https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2611459 (Accessed on 31/10/2022).
NoRSTRESS, 2021: project website https://www.sintef.no/projectweb/norstress/ (accessed on 31/10/2022).
SINTEF, 2017, project report: "Rock stress measurement by 3D overcoring – Su-Pan 1 HPP, Vietnam".
Statista, 2022: " Hydropower production in Norway 2008-2020", published by Bruna Alves, Mar 16, 2022. Available at https://www.statista.com/statistics/1024893/electricity-production-from-hydro-power-in-norway/ (accessed on 31/10/2022).
Ødegaard H & Nilsen B (2018): Engineering Geological Investigation and Design of Transition Zones in Unlined Pressure Tunnels. 10th Asian Rock Mechanics Symposium, Singapore November 2018, 10 p.