International Journal of Scientific & Engineering Research, Volume 9, Issue 11, November-2018
ISSN 2229-5518

Hydrogeological Issues Associate with Hydropower Tunnels through Hard Rock Terrain: An Experience from Sri Lanka

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Abstractð In the hard rock terrain of Sri Lanka, underground hydropower tunnels, constructed to convey water from reservoirs to power houses, have experienced a number of hydrogeological problems during and or after their construction. These problems often not only had delayed the work but also caused heavy economic losses. Hydrogeological issues encountered in tunnels can be related with the geological environment and therefore, the present study was conducted to evaluate encountered hydrogeological problems in four tunnels; Castlereagh, Polgolla, Kothmale and Victoria constructed in the central highland of the country and through crystalline rocks. Under the present study, the encountered problems; mainly high groundwater ingresseswere considered. The layout of the tunnels was plotted on orographic, topographic, geologic and structural maps. Also, for each tunnel, an effective catchment area which can contribute to groundwater ingresses was also demarcated. Situation of each tunnel was then compared with the encountered hydrogeological problem. The major problems encountered in these tunnels are large scale water ingress and debris flows into the tunnels. These problems in the tunnels could be attributed to the weak zones in the rock that were developed as a result of tectonically developed lineaments, fractures, faults, folds and, weathering prone lithology through which the tunnels have been excavated. It was also found that the effective catchment area that was present above the tunnel trace and the tunnel length have positive correlation with the severity of the encountered problem. Evaluation of the conditions revealed that those straight and shorter tunnels make less problems. Determination of an effective catchment area for each tunnel prior to excavation could help in managing ingress problems in the tunnels during the excavation.

Index Termsð Hydropower tunnels, water ingresses, Sri Lanka.

1 Introduction

The excavated tunnels in Sri Lanka can be classified as hydropower tunnels, railway tunnels, highway tunnels, mining tunnels and irrigation tunnels. In general, hydropower tunnels are used to transmit water from the reservoirs to powerhouses. In 1962, then Ceylon Electricity board, provided electricity in the country mainly based on hydropower for which the excavation of tunnels for several kilometers through the rock mass was inevitable.

The present study discusses hydrogeological issues encountered in four hydropower tunnels situated in the Central highlands of Sri Lanka. In Sri Lanka, three major hydroelectric powerhouse complexes can be identified, namely Lakshapana complex, Mahaweli complex and other hydropower complexes. Lakshapana complex is the first hydroelectric power complex which expands along the major tributaries of Kelani river such as Kehelgamu Oya and Maskeli Oya. There are five hydropower tunnels present in the Lakshapana complex. Of these, Castlereagh hydropower tunnel which is the oldest, is considered under the present study

Under the Mahaweli complex, water of Mahaweli river and adjacent river basins is used for irrigation and hydroelectric power generation purposes. There are six hydroelectric power projects under the Mahaweli complex.

Out of these, Polgolla, Kothmale and Victoria tunnels are considered under the present study. The locations of the studied tunnels are shown in figure 1.

The main hydrogeological issues encountered in hydropower tunnel constructions are excessive water leaks into the tunnels and collapsing of weak geological formations. Both these types of conditions create technical as well as environmental issues.

Lack of sufficient preliminary studies of geological, morphological, structural, and hydrogeological aspects in critical areas along hydropower tunnel traces leads to many dangerous problems during and after the construction. Unexpected problems that have occurred in underground hydropower tunnels have caused disadvantages such as long delays in hydropower projects, negative impacts on environment and disturbance to-day-to day life of local communities.

Castlereagh tunnel is the oldest hydropower tunnel in Sri Lanka, which was started in 1924. The tunnel conveys water from Castlereagh reservoir to a (Wimalasurendra) powerhouse in the Norton bridge. The Castlereagh tunnel is 6.1 km in length, horse shoe shaped and fully concrete lined tunnel. Diameter of the tunnel is 3.68 m and maximum discharge is 1050 cusecs. During construction of Castlereagh tunnel, huge water leakage occurred into the tunnel. However, their problem was solved and there was no any critical problem repeated after the tunnel completed.

During the four-year period from 1965-1968, preliminary studies were carried out for the development of Mahaweli river and surrounded river basins mainly for irrigation and hydroelectric power generation purposes. Polgolla tunnel is one of the hydropower tunnels under the Mahaweli complex. Polgolla hydropower tunnel is horse shoe shaped, 8 km long, underground tunnel, which conveys 2000 cusecs of water from Polgolla reservoir to Ukuwela hydropower station The tunnel has been excavated using drill and blast method.

Kothmale tunnel of the Mahaweli river development programme is the second most upstream tunnel which was constructed across the one of the tributaries namely, Kothmale oya of the Mahaweli river.

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Kothmale hydropower tunnel conveys water from Kothmale reservoir to Kothmale underground hydroelectric power station. This tunnel is 7 km long, horse shoe shaped pressure tunnel with 113.3 cusecs maximum capacity. Drill and blast method was used for excavation of the tunnel. The main purpose of Kothmale project is power generation. In addition to power generation, Kothmale reservoir is used to regulate river flow in the Mahaweli river in connection with irrigation management. After power generation, water is discharged back in into the Mahaweli river. During construction, water ingress and rock falls into the tunnel were encountered as problems.

Victoria tunnel is an underground hydropower tunnel also under the Mahaweli hydropower complex. Victoria tunnel is circular shaped, 5.7 km long tunnel, which convey water from Victoria reservoir to Victoria hydropower station. Major purpose of this tunnel is providing water for generation of hydroelectric power. In addition, water is used for irrigation purposes. The tunnel construction method was drill and blast method. Huge water leakage and rock falls into the tunnel had taken place while the construction of the Victoria hydropower tunnel.

Geologically all four hydropower tunnels are located in the central highlands of the country in the Precambrian metamorphic rock terrain (see figure 1).

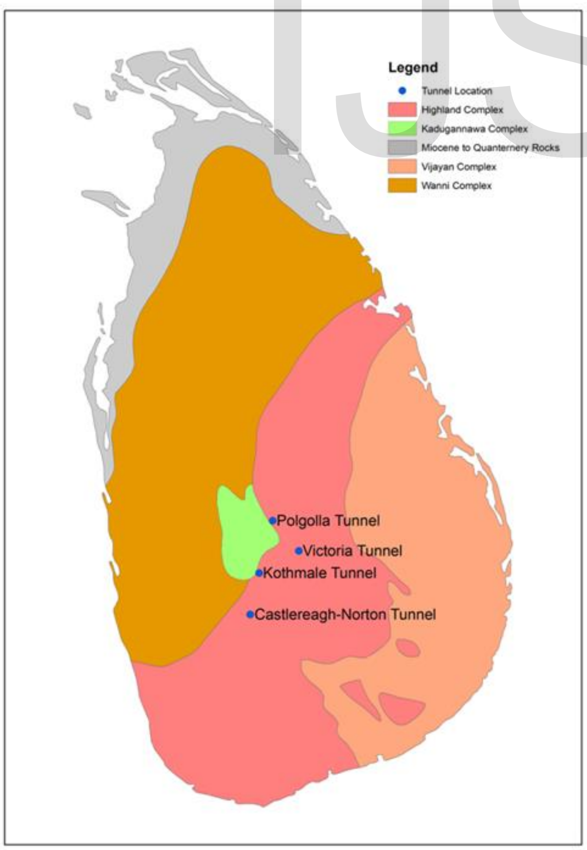

Fig 01: Locations of the investigated tunnels in relation to geology of Sri Lanka

2 Methodology

A preliminary review was done based on existing data, previous publications, and project reports of hydropower tunnels in Sri Lanka. Topographic, orographic, geologic and structural maps, aerial photographs and satellite images of the selected tunnel areas were studied for identifying tunnel locations, surface drainage pattern, geology, structures, elevation and geomorphology. For this purpose, 1:40 000 aerial photographs of the Survey Department of Sri Lanka, 1:50 000 and 1:63 360 topographic maps of the Survey Department, 1:100 000 geologic maps of the Geological Survey and Mines Bureau and satellite images which need for the study.

The tunnel traces were plotted on topographic, orographic, geologic and structural maps and by computer aided software (Arc GIS 10.4).

Effective catchment area was considered as the area above each tunnel outlet because they are the potential areas for transmitting ground water causing potential leakages in the tunnels. When plotting the effective catchment areas on the topographic maps it was found that there are very large areal extent and because the effect of the water seepage into the tunnel from distant areas gradually decreases away from the tunnel, only the area covered by the 5km distance from the tunnel trace was considered as the effective catchment area for leakages. Lineaments, (fracture traces) present in the areas were marked based on aerial photo interpretation. Finally, the amount, type and nature of the hydrogeological problems in each tunnel were compared with encountered problems.

3 Results and Discussion

The Castlereagh tunnel (Figure 02) runs through different crystalline rock types such as, Garnet sillimanite biotite gneiss, Charnockitic biotite gneiss and Quartzite. 30% of tunnel length passes through sound Charnockitic biotite gneiss and rest in other rock types. Highly weathered Kaolinize zone was observed in small part close to the tunnel inlet. The tunnel runs nearly parallel to the general strike trend of the rocks. There is a fault zone present in the area close to the tunnel inlet. Highly fractured quartzite beds are present in a small part of the tunnel near the inlet. Rock layers found in the tunnel area shows variable strike and dip directions. Mostly, shear zones and strike of the rocks are parallel or nearly parallel. During the excavation of the tunnel, unexpectedly a highly weathered and sheared kaolinized zone was observed which 160 m in length. The most problematic part was between 270 m to 400 m, along the hillside near the tunnel inlet. Enormous and unmeasurable amount of water leaked into the tunnel in this zone. New springs also encountered, and it was feared that collapsing of tunnel or even possibility of draining the Castlereagh reservoir could take place. Because of this problem, additional geological and geotechnical investigations had to be carried out to further investigate surface and subsurface conditions. This problem made one-year delay for the project and

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additional cost. As a solution, the tunnel was lined by concreate. Highly weathered part of the tunnel was stabilized by using reinforced concreate, steel ribs and rock bolts. The effective catchment area of the tunnel was estimated as 57.1 km2. The south-west side of the catchment area is small, but north-east side of the catchment area is large. Most of the catchment area is a hilly terrain.

Effective catchment area consists of rocks such as Garnet sillimanite biotite gneiss, Charnockitic biotite gneiss, Quartzite, Charnockitic gneiss and Garnetiferous quartzofeldspathic gneiss. Most of the tunnel length is passing through sound rocks. But small portion, close to the tunnel inlet, rock is highly weathered and kaolinized. Also, quartzite bed is highly fractured. These secondary porosities are interconnected, and the rock as a whole has a good permeability. These features of the area create a weak zone which can leak water into the tunnel. Considerable water leakage was found through weak zones connected to the Castlereagh lake with the tunnel.

The Polgolla tunnel (Figure 03) is passing through different rock layers, mainly Garnet sillimanite biotite gneiss, Charnockitic gneiss, Biotite hornblende gneiss and Granitic gneiss. Also, Biotite gneiss, Marble, Quartzite are present in lesser amounts. 60% of the tunnel passes through biotite hornblende gneiss. The tunnel runs parallel and nearly parallel to the general strike trends. There are three deep shears or fault zones present in longitudinal profile of the tunnel. The shear zone three runs along the axial plane of a synform and above the tunnel trace, small rift runs along a ridge. While excavation of the tunnel, water ingressed into the tunnel at 7800m length. This becomes a beginning of series of problems, which brought enormous volume of sand, silt, and rock debris into the tunnel. These disturbances delayed the construction of tunnel. The problem was solved by placing a reinforced concrete lining, grouting, rock support bolts and construction in drainage holes of this problematic section. 73% of the length of the tunnel was stable and is unlined while only 27% of the length has been lined with reinforced concrete. Although the tunnel was stabilized after the tunnel after its construction. But fallen rocks were found during after inspection within the tunnel. These rock falls mainly had taken place because of erosion in unlined section due to flowing water. But there is no any significant water leakage into the tunnel or from the tunnel, reported after the construction of the tunnel.

The effective catchment area of the tunnel is estimated as 127.8 km3. The area in general is geomorphologically flat. The effective catchment area is large. The tunnel is 8.0 km long and runs through different kind of rocks and structures. The effective catchment area contains Garnet sillimanite biotite gneiss, Charnockitic gneiss, Biotite hornblende gneiss, Granitic gneiss, Marble and Quartzite. About 70% of the tunnel passes through Biotite hornblende gneiss and the rock is sound and contains less weak zones. There are no any hydrogeological problems reported in this 70% but remaining part of the tunnel is problematic. The main reasons for the problems are related to the geological structures crossed by the tunnel. Problems occurred due to the weak segments which created by deep shear zones. Also, some of these zones are found to be situated along the axial plane of the synform and antiform which running through the tunnel forming weak zones. While the tunnel excavated across these weak zones, water ingressed into the tunnel.

The entire length of the Kothmale hydropower tunnel (Figure 04) passes through slightly weathered and very strong rocks. However, the intake area and small section of the tunnel has weak rock. The tunnel crosses a quartzite band in the chainage between 3800 and 4100m. The major rocks encountered h are Garnet sillimanite biotite gneiss, Charnockitic biotite gneiss and Quartzite. Tunnel runs nearly parallel to the direction of the strike. Folding, fracturing and foliation shear zones are the major geological structures encountered in the area of the tunnel. The tunnel crosses and surrounded by synforms and antiforms. Prominent fracture systems found in the catchment area are mainly, foliation joints and shear zones parallel to lineaments. The tunnel passes through two major lineaments, namely Ela fault and Ganga lineament which appear as narrow shear zones. Major foliation shears with slickensided surface are present at a considerable distance of the tunnel.

Only a few problems were encountered during the excavation of the tunnel. When the tunnel was passing through weathered rocks, especially in shear / fracture zones water ingressed into the tunnel at the chainages of 2750 and 5100. Attitudes of foliation changes occur around chainage 5100, only a limited amount of water ingressed into the tunnel in this region. In order to overcome this problem, steal arch supports were used in the area crossing the lineament. Other weak zones were treated by shotcrete to consolidate the rock, steal ribs, cavities filled with concreate, rock bolts and control blasting.

The effective catchment area of the Kothmale tunnel is 62.6 km2 which contains Garnet sillimanite biotite gneiss, Quartzite, Charnockitic biotite gneiss, Calc-gneiss, Charnockitic gneiss and Hornblende biotite gneiss. The tunnel is 7 km in length therefore the tunnel crosses many structures. At the central part of the tunnel crosses the Kothmale shear zone and "Ganga lineament". These structures are weak zones and responsible for the hydrogeological problems encountered during the construction period of the tunnel. There are some interconnected joints, fractures and "Ela fault" found in Garnet sillimanite biotite gneiss rock, which situated in the tunnel intake area, and these structures favors water inflow into the tunnel.

The Victoria tunnel (Figure 05) is passing through different rocks such as Hornblende biotite gneiss, Garnet sillimanite biotite gneiss and Quartzite. Downstream area of the tunnel close to the surge shaft is very close to a mega lineament. Also fractured rock layers present with over turned folds. The tunnel crosses through the Victoria shear zone. During the excavation of the tunnel, there was a heavy seepage and caving of

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ISSN 2229-5518

roof at the downstream part of the tunnel. Due to this problematic situation tunnel path and location of surge shaft were change into new locations. Field studies suggested that there is a possibility for adverse tunnel conditions in new tunnel path too. These problems were confirmed during excavation of tunnel although the new path of tunnel did not have critical conditions as before. Fissure grouting method was used to stabilize the zone of excavation and cement grout also injected. The whole tunnel was lined to solve the problems.

The effective catchment area of the tunnel is 105.1 km2 consisting mainly garnet sillimanite biotite gneiss, hornblende biotite gneiss and quartzite rocks. The first part of the tunnel excavation, the tunnel was crossing some major shear zones and lineaments. In addition, some highly fractured quartzite rock bands were also crossed. These geological structural features created some weaker zones in the tunnel which initiate huge water leakages into the tunnel.

After some re-examinations, the tunnel path was rearranged to evade identified weak zones created by geological structural features and to reduce the risk kind of water leakage in to the tunnel. As expected, the new tunnel path was excavated through sound rock which contained less weak zones and therefore, only limited number of hydrogeological problems throughout the new tunnel path was encountered.

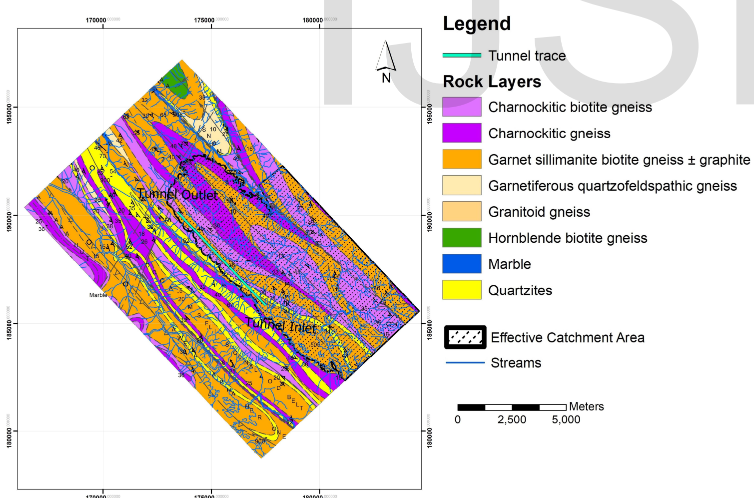

Fig 02: Effective catchment area of the Castlereagh tunnel

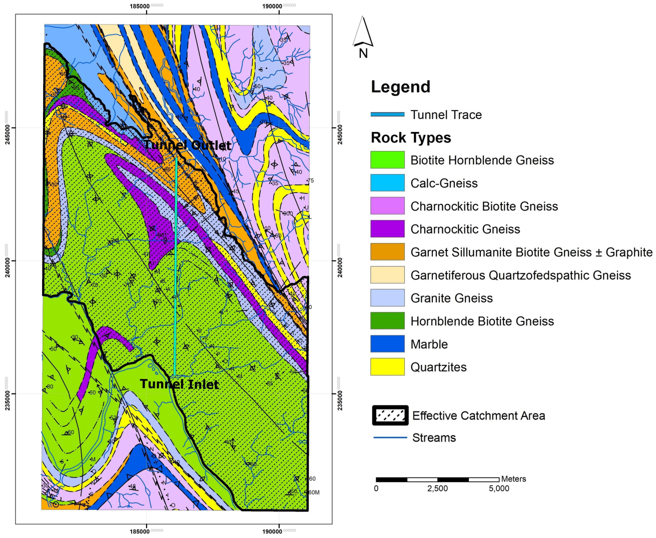

Fig 03: Effective catchment area of the Polgolla tunnel

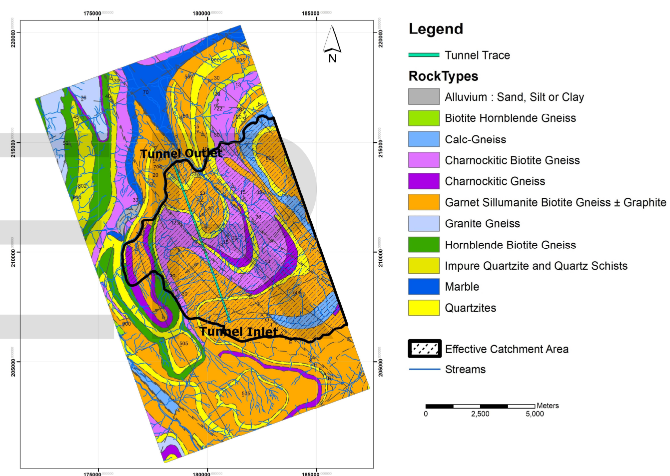

Fig 04: Effective catchment area of the Kothmale tunnel

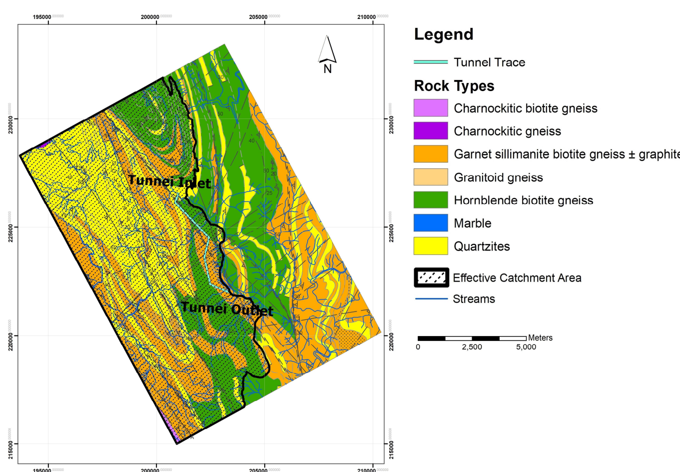

Fig 05: Effective catchment area of the Victoria tunnel

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6 Discussion

The main problems occurred in the investigated hydropower tunnels are water ingress and rock falls. These problems have occurred in different scales due to different causative factors such as geology, and geological structures. One or combination of these reasons makes a weak zone. Therefore, when tunnel crosses weak zones problematic situations have cropped up.

In the Castlereagh tunnel, highly fractured quartzite bands are the main reasons for creating critical situations in the tunnel. In Polgolla and Victoria tunnels, main reasons for the problematic situations are shear zones. In Kothmale tunnel shear zone, fractures and regional lineaments created the hydrogeological problems.

When tunnels pass through the hard rock with less fracture and weak zones there had been no serious problems encountered. Highly weathered rocks have often been problematic. When consider the geology, the tunnels through Charnockitic gneiss and Hornblende biotite gneiss has shown fewer problems than highly fractured quartzite. In the Victoria tunnel, the section through quartzite was problematic whereas the segment in Hornblende biotite gneiss was almost non-problematic.

Table 01: Compression of the studied tunnels

Description	Castlereagh	Polgolla	Kothmale	Victoria
Tunnel length (km) / Diameter(m)	6.1 km / 2.43 m	8 km / 6m	7 km / 6.4 m	5.7 km / 6 m
Tunnel shape	Horse shoe	Horse shoe	Horse shoe	Circular
Effective catchment area of the tunnel	57 km^2	91 km^2	63 km^2	98.8 km^2
Maximum depth from surface	270 m	340 m	410 m	440 m
Penetrated rocks	50% Gt-Si-Bt-gneiss 30% Char- Bt-Gneiss 20% Quartzite	60% Bt-Hb-gneiss 12% Granite gneiss 18% Gt-Si-Bt-gneiss 10% Char-Bt-gneiss	56% Gt-Si-Bt-gneiss 24% Char-Bt-gneiss 20% Quartzite	55% Gt-Si-Bt-gneiss 7% Hb-Bt-gneiss 5% Quartzite
Length of linig	100%	27.50%	100%	100%
Length of problametic section	Between 270 m - 400 m (130 m) 2%	Between 20000-26000 ft (1830 m) 23%	At the chainages of 2750 m and 5100 m, Between 3800 m and 4100 m (300m) 4% <	Initial part of the tunnel
Type of problems	Water ingress	Water ingress and sand, silt, and rock debris flow	Water ingress	Water ingress and caving of roof at the downstream part of the tunnel.
Problametic rocks / structures	Highly weathered and kaolinized zone, Highly fractured quartzite rock	Three shear zones	Shear zone, Linearment and faults, Highly fractured quartzite rock	East-West Mahaweli Minipe mega lineament, Highly fractured quartzite rock, Shear zone
Noted shapes and features	Staright tunnel	Straight tunnel	Straight tunnl	Zigzag tunnel
Overall problem encountered	Occurred during the construction. Mitigated successfully	Problem persisted for some time. Completely mitigated at present	Occurred during the construction. Mitigated successfully	Occurred during the construction. Mitigated successfully

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Most of the critical situations have occurred suddenly due to lack of preliminary studies. Polgolla tunnel was a good example, where problems occurred during construction because of this reason. In connection with Victoria and Castlereagh tunnels however, some detailed preliminary studies had been available.

Length of the tunnel also appeared to be influence the hydrogeological problems encountered in the tunnels. Naturally, when the tunnel is long, it can cross a large number of weak zones therefore, any problematic zones are possible to be encountered during the construction. Eight km long Polgolla tunnel crosses three shear zones. Kothmale tunnel is seven km long and that too crosses many weak zones.

Polgolla, Kothmale and Castlereagh tunnels are straight, and they cross many weak zones. However, Victoria tunnel path is not straight, and it avoids weak zones by changing the tunnel route.

When considering the tunnel diameter, Polgolla, Kothmale and Victoria tunnels are around 6 m in diameter while Castlereagh tunnel diameter is around 2 m. Tunnels with small diameter are better than tunnels with large diameters. Small diameter tunnels had made it easier to treat because the invaded open surface is smaller.

Another important factor is the effective catchment area of the tunnel. The effective catchment area is considered as the area from which water can be drained into the tunnel. When effective catchment area is large, and it contains many interconnected fractures and joints with tunnel, it increases the chance of water leak. Following table summarize the details of the studied tunnels and comparison of problem encountered. For all tunnels drill and blast method has been used as the tunnel excavation method.

As a mitigation method tunnels are lined, 2.2 km section was lined in Polgolla tunnel. Castlereagh, Kothmale and Victoria tunnels are completely lined.

7 Conclusion

The main hydrogeological problems encountered in the studied hydropower tunnels are large scale water ingress during the construction and collapsing, mud and debris flows in to the tunnels. All these problems in the tunnels can be related to presence of weak zones created by shear zones, lineaments, fractures, faults and folds. Lithology based problems were found only with quartzite bands. In all these tunnels the problems had been mitigated completely. Long term environmental issues have not been reported in connection with these tunnels. The detailed preliminary studies can provide information about potential critical conditions and therefore they can be avoided or mitigated effectively during or prior to tunnel excavation. Tunnels should not continue unless otherwise any problem encountered is solved at the point of its occurrence. The length of the tunnel is an important factor, the longer the tunnel the more problems are to be faced. Tunnels need not be straight always. Pre-identified weak or problematic zones can be avoided by changing the tunnel route. Victoria tunnel is a good example. However, the cost factor may need to be considered simultaneously. In the design stage of tunnel route, effective catchment area could be considered as an important factor so that an idea about the magnitude of possible water ingress can be obtained so that the safest route can be planned accordingly.

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