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Effects of Seasonal Precipitation on the Amount of Seepage-A Case Study of Tunnel 3 of Bazai Irrigation Project Khyber Pakhtunkhwa

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Abstract: Infiltration of water into tunnel within a harsh geological formation is a vital issue in tunnelling. The consequence impacts due to seepage include tunnel rock instability, pore-water pressure imposition and diminution of operational capacity. The spatial variation in rainfall due to climate change intensifies the threat to tunnel stability. Likewise, to understand the impacts of climate change scenarios on the seepage of tunnel 3 of the Bazai irrigation project was numerically simulated in SEEP/W software by manipulating the rainfall data. The net annual precipitation is followed by two sets of rainfall data i.e., dry and wet season precipitation depending upon the magnitude of rainfall. The analysis revealed that most of the seepage occurred in the unlined portion. In order to determine the future impacts of precipitation on seepage quantity, the wet season precipitation was further increased by 10% and 50% for A_1B and B_2 conditions respectively. The seepage quantity into the tunnel increases with variation in precipitation patterns. To reduce the risk to tunnel stability, the model was also treated with cement-bentonite grout and bentonite slurry containing 6% solids. The performance of both grouting techniques leads to noticeable seepage deduction. The study further suggests that cement-bentonite is more effective in seepage remediation.

Keywords: Seepage, tunnel, climate change, SEEP/W software, effective

1. Introduction

The quantity of water passing through a permeable material is known as seepage. The seepage forces mostly depend on the permeability of materials [1]. The seepage study during designing is necessary for engineers while constructing hydraulic structures like dams, tunnels, weirs and retaining walls. The stability of a structure is affected by the seepage of water, which alter the effective stress and create upward forces in the structure [2], [3].

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Tunnels are widely used to convey water for domestic, industrial and agricultural uses. Most of the tunnels have been subjected to some amount of seepage, which increases the risks of tunnel instability due to excess pore water pressure and maintenance costs [4]. The seepage forces created due to the hydraulic gradient act in the direction of the tunnel face, which endangers the tunnel stability [5]. The pore-water pressure around the tunnel increased due to the inrush of water [6]. It reduces the speed of excavation during construction and may also reduce the stability of the tunnel in the long term [7, 8]. The drainage system deterioration is one of the leading factors influencing the long-term operation by weakening the bond between tunnel lining and ground [9].

The main sources of seepage of water are the worst geological arrangement like a fracture in rocks, folds and faults. Before the construction of the tunnel, these geological structures should be well determined in order to avoid the seepage flow across the tunnel direction [10, 11]. The collapse of rocks across the tunnel occurred, when the distortion value due to creep exceeds the maximum limit. It insinuates that the rock around the tunnel is firm when the tunnel deformation is lower than the maximum deformation limit [12]. Analytical and numerical approaches are used for the determination of pore-water pressure and seepage forces through rock mass [13]. However, numerical methods have been conventionally used for the determination of characteristics of large-scale cracks and seepage in the rock mass, which depend on geometric characteristics of crack and continuous non-spatial methods obtained from plotting of perceptible rocks investigation and rock fractures [14]. The infiltration of groundwater into the tunnel had been represented with numerical methods. However, the analytical method is still applicable for indirect evaluation or to check the precision of numerical methods [15].

Shin, Potts & Zdravkovic [16] examined the dormant damages of pore-water pressure on tunnel lining using finite element analysis. The lower and upper boundary approach based on the finite element method was used for tunnel stability in undrained soil [16], [17]. Numerical methods using the finite element method are applied to the seepage problem[18]. The Plaxis software was used for the numerical simulations of an urban train tunnel in Ahvaz to calculate the seepage water magnitude [19]. The recharge and inflow magnitude and water flux for saturated or unsaturated conditions are mostly estimated and predicted with the SEEP/W module [20].

This study focused on the numerical simulations of Tunnel 3 of Bazai irrigation project (BIP) Khyber Pakhtunkhwa (KP) using finite element package SEEP/W for various climate change scenarios. The cross-sections of Tunnel 3 at different rocks were modelled in SEEP/W for seepage determination and each model was analyzed for various climate conditions. Furthermore, the tunnel models were also treated with cement-bentonite and bentonite slurry containing 6% solids.

1.1 Study Area

The Bazai irrigation project has resulted from the Malakand III hydropower project and a mega project of the Irrigation Department Khyber Pakhtunkhwa. The water resulting from the silt extruder of the powerhouse complex has been used for the Bazai irrigation project. The Bazai irrigation project is composed of various hydraulic structures such as syphons, aqueducts, tunnels, distributies and other allied structures. Tunnel 3 is located at Baizo-Kharkai near the main Palai road, which is shown in Fig. 1. The annual temperature of the project areas ranges from 0 °C to 39.4 °C. The mean yearly rainfall over the project area is identical to that of the surrounding region which is approximately 736 mm/year. The length of the tunnel is 720m and its cross-section is a modified horse toe shape, which is rectangular at the bottom and semi-circular from the top. The bottom section in which water flows is lined with concrete, while the top section is composed of precast concrete arches, which are connected by cement mortar. The seepage occurred into the tunnel at various locations where the arches are missing and also within the joints between two arches.

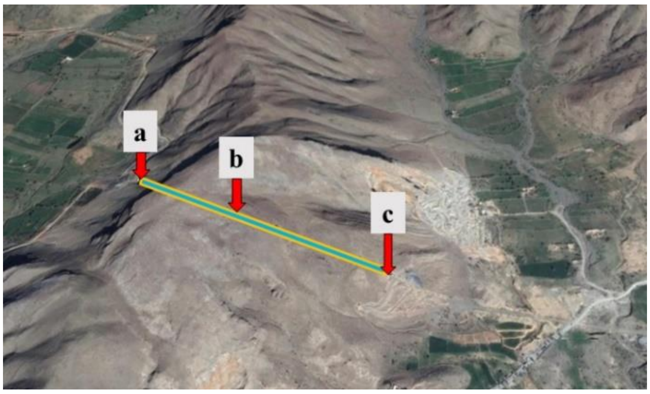

Fig. 1 - Satellite map of Tunnel 3 showing the physical features of the study area (a) tunnel inlet; (b) mid; (c) tunnel outlet

1.2 Geotechnical Properties of Tunnel 3

The study area has been located in the Indo-Pak plate which emerged from the formation of exceptional mountain tectonic history [21]. Tunnel 3 of Bazai irrigation project is comprised of three distinct types of rocks as shown in Fig. 2. The upstream side of the tunnel consist of rich strata of chlorite graphite pyrite. The central portion consists of massive limestone while graphite quartz-mica schist and inter-bedded carbonate rocks are located on the downstream side. The massive limestone has a faulted contact with the overlying and underlying rock formation. The hydraulic conductivity of chlorite graphite pyrite, limestone and graphite quartz-mica schist are 5.07E-3, 5.00E-7 and 5.47E-3 m/sec respectively.

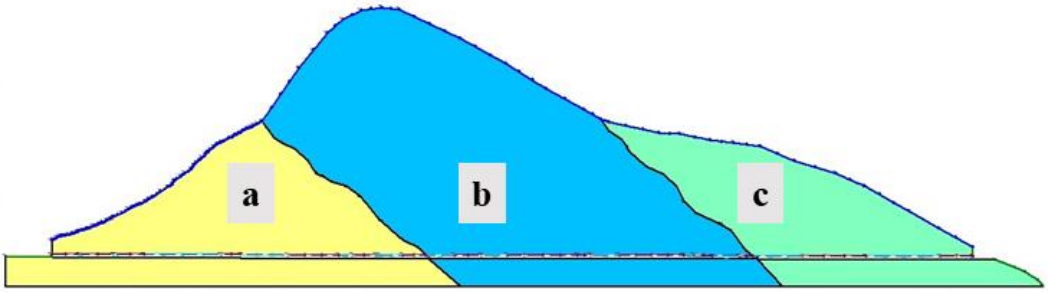

Fig. 2 - Profile view of Tunnel 3 describing three types of rock (a) chlorite graphite pyrite; (b) limestone; (c) graphite quartz-mica schist

2. Seepage Analysis

Manual approaches were used for the estimation of seepage before the invention of software. Those methods were time-consuming and had a greater probability of errors. After the invention of computer software, it became possible to solve these complex problems. The engineers developed different software for seepage determination i.e. SEEP2D, SEEP/W, FLAC 2D/3D, SVFlux 2D/3D and FIDES [3]. The SEEP/W software is used by engineers for the determination of seepage, and draw-down of the water table due to pumping and pore water pressure in a civil engineering project. The SEEP/W software was used for seepage analysis through the foundation of the Ilham earthen dam and Gotvand dam [22, 23]. Hasani et al. (2013) presented that seepage calculation in SEEP/W employs partial differential equations. The Laplace equation governs the two-dimensional water flow within a porous medium observes the basic laws of heat transfer in steady-state and current flow through conductors [24]. The two-dimensional flow in the “x” and “z” planes through a porous medium is represented in Eq. (1).

$$\frac{\partial^2 h}{dx^2} = \frac{\partial^2 h}{dz^2} = 0 \tag{1}$$

Eq. (1) represents the Laplace equation for flow in two directions, which is illustrated by two sets of perpendicular lines known as flow net. The vertical lines connecting the points of the same equal head are called equipotential lines, while the horizontal flow path is known as the flow line.

This study was performed to determine the amount of seepage into Tunnel 3 using GEO STUDIO: SEEP/W (2007) software. The actual amount of seepage was also determined from the difference in discharges at the outlet and inlet of the tunnel using the Area-Velocity method. The seepage estimated from both methods was compared with each other.

The climatic changes have emerged in the last two decades on a global scale. A huge variation in climate has taken place in Pakistan such as in northwest India had been emerged in the past. The major source of climatic change was the spatial shift of rainfall. Several disasters variation like monsoon rainfall patterns, drought and storms have affected approximately 40% of the people of Pakistan [25]. A sequence of monsoon rainfall for Pakistan was produced by taking the average of 38 stations data, which approximately covered 88% area of the country. In Pakistan, about 58.8% of the annual precipitation is monsoon rainfall based on the 1901-1990 rainfall data [26].

Due to variation in climate, Tunnel 3 of BIP was analyzed for the following five conditions considering the nearest station rainfall data from 1909 to 1990 (Dargai station). The annual rainfall data is shown in Fig. 3 for each month. The whole annual precipitation follows two types of patterns depending upon the magnitude of rainfall according to the precipitation data of Dargai station i.e. dry season precipitation and wet season precipitation. The wet season precipitation includes the month of January, February, March, July, August and September. Meanwhile, the dry season precipitation has been followed by April, May, June, October, November and December.

a) Total annual precipitation
b) Wet season precipitation
c) Dry season precipitation

d) A_1B condition
e) B_2 condition

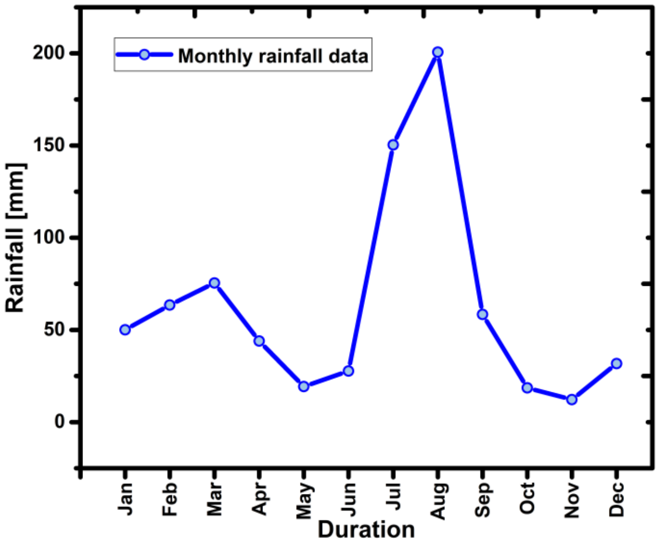

Fig. 3 - Average monthly rainfall data recorded at Dargai rain gauge station (1909 - 1990)

The total annual precipitation in the area is 751.83 mm. The total depth of dry season precipitation is 153.41 mm and that for the wet season is 598.41 mm. Due to variation in climate, the wet season precipitation has been increased for the two conditions such as A_1B condition and B_2 condition. In A_1B condition the wet season rainfall data is increased by 10%, for which the precipitation becomes 657.8 mm. While for the B_2 condition the wet season precipitation is increased by 50%, so the magnitude of the rainfall becomes 897 mm.

3. Results and Discussions

The effect of various climatic conditions on the seepage magnitude is discussed by simulating the cross-section of Tunnel 3 in SEEP/W software. Additionally, the models were also treated by considering cement-bentonite and bentonite slurry containing 6% solids.

3.1 SEEP/W Model Results for Different Climatic Conditions without Treatment

The cross-sections of Tunnel 3 in each type of rock were analysed for the seepage quantities using their corresponding hydraulic conductivity. The cross-sections were further taken for a lined and unlined portion of the tunnel. The precipitation was applied as a unit flux in the SEEP/W software. The amount of rainfall is too low in the dry season and their average depth is less than 50 millimetres. The amount of seepage for each cross-section at different types of rock shows various results due to variation in their corresponding permeability. The seepage was determined for both lined and unlined portions of the tunnel. To find the total seepage magnitude across the total length of the tunnel, the seepage value was multiplied by the unlined and lined length of the tunnel. Fig. 4 show the SEEP/W model results for the unlined cross-section in chlorite-graphite-pyrite rock for the dry season. The precipitation was applied on the top of the tunnel cross-section as shown by vertical downward directed arrows.

In the wet season period, most of the annual precipitation occurs. It is also known as the rainy season or monsoon season. All the rainfall values exceed 60 millimetres each month. The amount of seepage into the tunnel increases due to heavy precipitation in the area during this duration. The wet season precipitation is increased by 10% for the A_1B condition due to uncertainties in climate. The rainy season precipitation is extended to 657.8 mm depth and adopted to all cross-sections at each rock type. The magnitude of seepage across the tunnel section is increased in the B_2 climate change scenario, which assumes a 50% increase in the wet season precipitation due to climate uncertainties in the future. The annual rainfall data of the Dargai rain gauge station was employed for the purpose of yearly seepage determination.

The seepage values of each cross-section for various climatic scenarios are enlisted in Table 1. The corresponding seepage values of each cross-section are multiplied by the lined and unlined length of the tunnel for each rock portion. The seepage results indicate that most of the seepage occurs in the unlined portion of the tunnel and their values rise with increasing the magnitude of rainfall. The SEEP/W software results for each climatic condition are summarized in Fig. 5. The line graph reveals that seepage infiltration to the tunnel is maximum for annual precipitation and B_2

condition and slightly lower for A_1B condition and wet season precipitation. The graph plunges down to a minimum value for dry season precipitation due to less amount of precipitation.

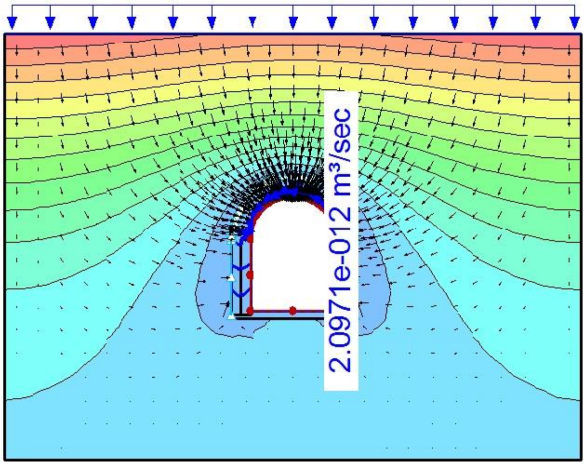

Fig. 4 - SEEP/W model results for the unlined cross-section in chlorite-graphite-pyrite rock for the dry season

Table 1 - SEEP/W seepage results for various climatic conditions at different rock cross-sections (m^3/sec)

Description	Lined section			Unlined sections		
	Inlet	Mid	Outlet	Inlet	Mid	Outlet
Dry season Seepage quantity	4.131E-10	6.145E-09	2.285E-10	0.52046	3.307E-05	0.5363
Wet season seepage quantity	4.141E-10	2.540E-08	2.280E-10	0.83355	8.634E-05	0.5721
A_1B condition seepage	4.140E-10	2.777E-08	2.279E-10	0.88572	8.550E-05	0.6437
B_2 condition seepage	4.137E-10	3.638E-08	2.278E-10	1.14646	6.346E-05	0.7869
Yearly seepage	4.138E-10	3.092E-08	2.279E-10	1.04215	6.882E-05	0.7154

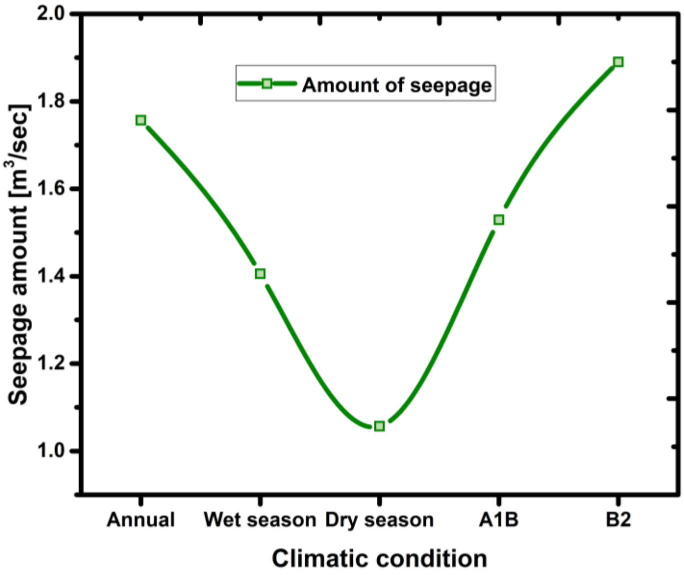

Fig. 5 - Amount of seepage for the various climatic condition

3.2 SEEP/W Model Results for Different Climatic Conditions with Remedial Measures

Grouting techniques are commonly used for minimizing the permeability of rocks. Grouting involves the filling of pores, cavities and fissures formed in soil and rocks, by creating it watertight. The permeability of rocks may be affected due to blasting in the exaction stage. Various grouting methods are adopted for reducing the rocks permeability such as cover grouting from the tunnel face, back wall grouting and pre-grouting from the surface boreholes [27]. The grouting mainly depends on the permeability of the grout material. The permeability of rocks can be reduced with different materials [28]. Table 2 describes the permeability of three different grouting materials. The permeability of cement-bentonite is too much low than neat cement and bentonite slurry containing 6% solids.

Table 2 - Permeability values of different grouting materials Mikkelsen [28]

S/No.	Grout Type	Permeability (cm/sec)
1	Neat cement	10^{-5} to 10^{-7}
2	Bentonite slurry (6% solids)	10^{-5}
3	Cement-bentonite	5×10^{-8}

The proposed tunnel was analysed for two types of grouts such as bentonite with 6% solids and cement-bentonite. The unlined cross-sections of the tunnel were analysed in SEEP/W software to check the effectiveness of each grout in seepage remediation.

3.2.1 Cement Bentonite Grouting

The tunnel was treated with cement-bentonite grout containing a mixture of cement, bentonite, and water in 1:1:4 proportions. The permeability of cement-bentonite grout is 5×10^{-8} cm/sec. The unlined cross-section is grouted with cement-bentonite for each climatic condition. The seepage magnitude of all treated cross-sections and lined cross-sections multiplied by their corresponding length. Fig. 6 indicates the seepage amount after being treated with cement-bentonite for different climatic conditions. Seepage quantities are reduced to nearly zero with cement-bentonite grout for each condition.

3.2.2 Bentonite Slurry Grout

In many engineering projects, bentonite is adopted as a seepage barrier. The unlined portion of the tunnel grouted with bentonite slurry containing 6% solids content. The hydraulic conductivity of the bentonite slurry with 6% solids is 10^{-5} cm/sec. All the unlined cross-section was analysed in SEEP/W for various climatic scenarios. The seepage amount after treating with bentonite slurry for various climatic conditions is displayed in Fig. 6. The results show that the amount of seepage decreased for all conditions. It is evident from the analysis that cement-bentonite grout is more efficient in seepage remediation than bentonite slurry with 6% solids.

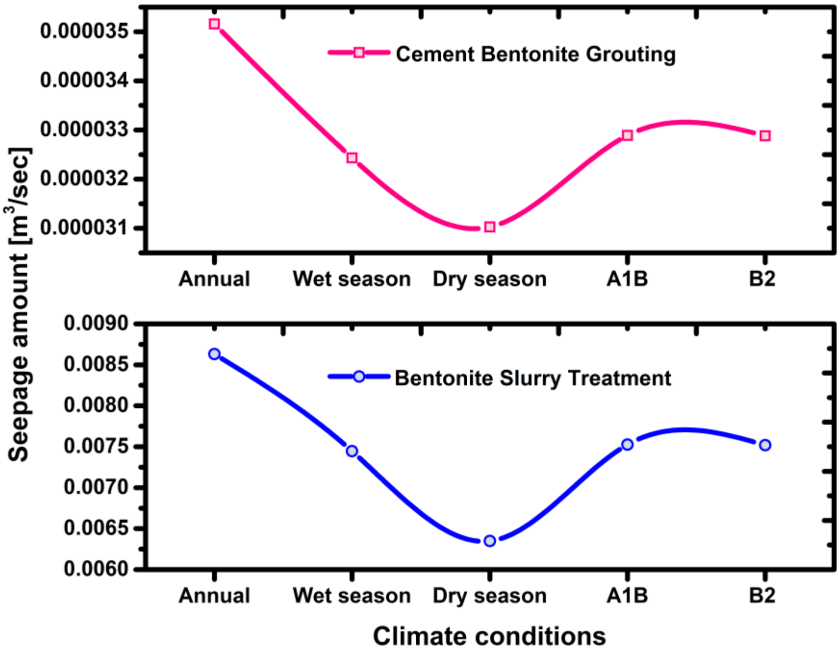

Fig. 6 - Seepage quantity for Tunnel 3 treated with cement bentonite grouting and bentonite slurry

4. Conclusion

The effect of various climatic conditions on the seepage magnitudes for the cross-sections of Tunnel 3 was analyzed in this study. The numerical simulation results revealed that maximum seepage occurred in the unlined portion of the tunnel. The seepage amounts rise with an increase in precipitation for different conditions i.e. the infiltration of water into the tunnel is maximum for the B_2 condition than dry and wet season precipitation. The cross-sections of the tunnel were treated with cement-bentonite grout and bentonite slurry containing 6% solids to mitigate the inrush of water into the tunnel. The study suggests that cement-bentonite grout is more effective in controlling seepage.

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