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Evaluation of The Effect of Rock Joints on the Stability of Underground Tunnels

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Abstract. To facilitate the water supply to the main cities in Malaysia such as Kuala Lumpur, Putrajaya and Cyberjaya, Pahang Selangor Raw Water Transfer Tunnel project is constructed in 2015. Facility tunnel of 44.6 km length with 5.2 m diameter are being constructed to transfer water from Karak to Hulu Langat. Granitic rock with dominant intrusive zones in various range of I until V were observed in the studied tunnel length. This tunnel has crossed sheared zone that categorized into fair, poor, and very poor rock classes with moderate to heavily jointed rock. At NATM-1, the discontinuities like joints that is close and far from the fault are one of the most important which caused to instability of the tunnel and reduced the performance of tunnel performance. In this paper, the joint orientation, overburden and distributions of discontinuities (joints and faults) into the tunnel were evaluated. These data were then simulated using discrete fracture networks with the direction of tunnelling excavation in the tunnel. Movement of blocks in the tunnel roof and wall is possible due to the creation of more intersection points in the critical zone. It also highlights how minor features, such as step-over joints in rock mass, can have a significant impact on instability.

1. Introduction

Main problems in infrastructure development are the geological and topographical conditions. The development and progress of a region in fact cannot be separated from the ability of the region to interact with other areas on a larger scale. The intended interactions are economic, social and resource activities. To support this, the means of supply of raw water in this case becomes very vital. During the constructing of the Pahang Selangor Raw Water Transfer Tunnel (PSRWT), the tunnel was built in metasedimentary and igneous rock, which upset the in-situ stress field and caused large ground movements, making the tunnel unstable.

Hayashi [7], Brown [8, 9], Ladanyi and Archambault [10], Einstein and Hirshfeld [11], and Reik and Zacas [12] have studied the strength and deformation response of linked rocks, joined masses of modelling materials, and laminated rocks. They looked into how joint sets and angles affected the strength of a rock mass. Chenevert and Gatline [13], Attewell and Sandford [14], and Brown et al. [15]

all looked at shale and slate. Deklotz et al. [16], Akai et al. [17], McCabe and Koerner [18], Nasseri et al. [19,20], and Singh [21] looked at how gneisses and schists reacted, while Ramamurth Rao et al. [23], Pomeroy et al. [24], and Allirote and Boehler [25] looked at how sandstone Tien and Tsao [26] did their research with things that didn't exist. When all of their work is looked at and analysed, the greatest strength at failure is either b1401 or 901, where b is the angle of the break with respect to s1, and the least strength is usually around b14301, or 45(j/2), where j is the friction angle along the plane of weakness.

Most of the time, the Karak, Pahang area is made up of many joints close to faults, which causes complex changes in stress and strain when tunnelling is done. During the construction of PSRWT, this project used both methods, the New Austrian Tunnelling Method (NATM) and Tunnel Boring Machine (TBM). While tunnelling through a variety of structures such as joints and faults, the rock mass condition and overburden will encourage tunnel instability and collapse. The primary goals of this research have been to investigate the influence of joint orientations, overburden, and modelling on tunnel face stability for varying dips. Then, for a complete range of 0–90 degrees, the influence of variation in dip direction difference on rock strength is explored.

1.1. Pahang Selangor Raw Water Transfer Tunnel Project.

The Malaysian government has designated Shimizu – Nishimatsu – UEMB – IJM Joint Venture (SNUI JV) as the project's contractor, through the Ministry of Energy, Green Technology and Water Malaysia (KeTTHA) since 90s and the tunnel is completely constructed in March 2015. This project is known as the Pahang – Selangor Water Transfer Project (PSRWT). The tunnel is crossing from Karak (inlet) to Selangor , Hulu Langat (Outlet). The tunnel is 5.2 meters in diameter and 44.6 kilometers long (Figure 1)(KETHA, 2000). To build a large and lengthy tunnel through variable meta-sedimentary and granite rock beneath the Titiangsa Mountains without incident, a good safety precaution is required. A site inspection should be carried out as a precautionary step. Proper site inspections are required before any additional development can begin in order to learn about the unseen subsurface state.

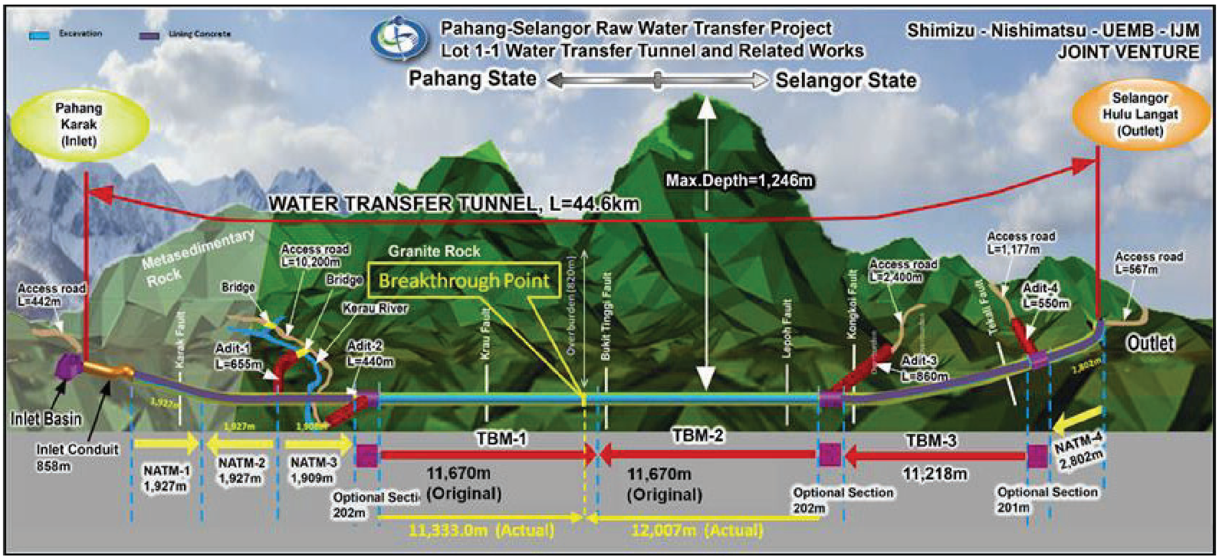

Figure 1. Study area NATM-1 (yellow box) allinged with the Pahang – Selangor Raw Water Transfer Tunnel (modifed after KETHA, 2000).

1.2. Meta-sedimentary rock formation.

The research area (NATM-1) is located within the Karak Formation, a meta-sedimentary rock that stretches beneath Sungai Karak (Figure 2). The Karak Formation contains metamorphic rock from the Devonian period. Metamorphic refers to the changes in mineral composition and texture that occur when a rock is exposed to pressures and temperatures that are different from those that created it. Magmatic rocks invade meta-sedimentary rocks often, which are enhanced by tectonic processes, indicating post-depositional events in the Sector's evolution. While little is known about the cellar where they gathered, they usually represent the first identifiable occurrence (Padget, 2004). The research area is located within the Karak Formation, a meta-sedimentary rock that stretches beneath Sungai Karak. The Karak Formation contains metamorphic rock from the Devonian period. Metamorphic refers to the changes in mineral composition and texture that occur when a rock is exposed to pressures and temperatures that are different from those that created it. Magmatic rocks invade meta-sedimentary rocks often, which are enhanced by tectonic processes, indicating post-depositional events in the Sector's evolution. While little is known about the cellar where they gathered, they usually represent the first identifiable occurrence (Padget, 2004). Meta-sedimentary rock is not as hard as igneous rock, such as granite. Even though it is hard, sedimentary rock breaks it up into many cracks and joints. The stability of a meta-sedimentary rock formation will change because of this crack and joint. Meta-sedimentary rocks often re-crystallize as they age and become more metamorphic, but their sedimentary nature is clear. Most rocks are made up of quartzite, micaceous quartzites, and pelitic (argillaceous) gneisses (Padget,2004).

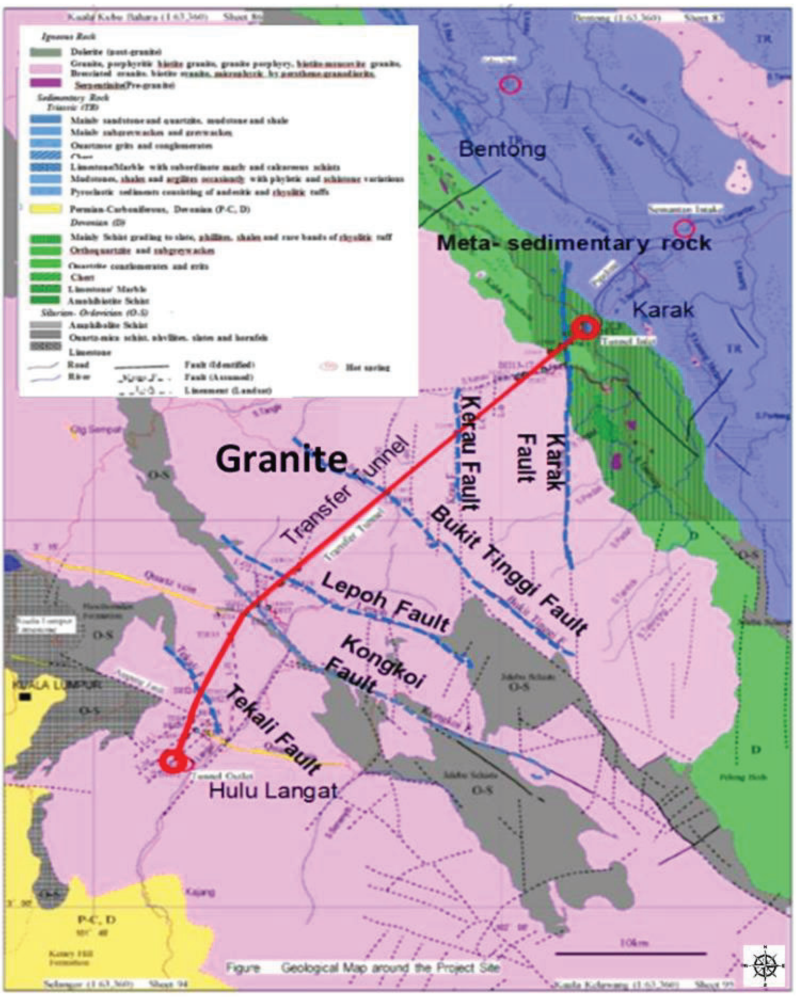

Figure 2. Geological Map of the study area (yellow box) and the 44km PSRWT (blue line) (modifed after KETHA, 2000).

1.3. Joint Pattern Development.

Geometric function of joint pattern in rock is crucial (Olson, 1993). The function of geologists in assessing common dangers and the stability of a site for engineering works has a long history that may be traced back to our ancestors' lore. In this study, researchers tried to do a thorough investigation to find out how rocks react to different confining pressures when the dip and dip direction differences of induced discontinuities change. In reality, there are a lot of times when discontinuities with different dip directions cross each other, especially when tunnelling in this shear zone. Interference of these breaks with the path of the load would change the way the rock broke, with a different amount of intact rock parts working together. In this study, artificial samples made of plaster and with clear breaks were used to show how the described combined effects work. Joint patterns at the study area (Figure 3) is most likely due to the influence of the surrounding environment. The surrounding environment, such as overburden and rivers, can result in a different joint pattern in meta-sedimentary rock than the Malaysian regional joint pattern (Figure 4). Uplift and volume expansion are the most common causes of intragranular joints in metamorphic rocks. But these seams happen in volcanic rocks because the rocks shrink in size in different ways as they cool. Most of the time, thermal stress is what causes joints to form in rocks that are cooling (Samanta, 2001). A shear or stress rupture can result in a rock fracture. Shear breakage causes faults, while rupture causes joint propagation. Joints are generally systematic and occur in sets over broad areas of more than 1500 km2, whereas faults are rarely systemic and are generally clustered in limited zones linked with a master fault or fold (Engelder and Lash, 2009). Fracture mechanics can be used to describe fracture start, propagation rate, and incremental propagation path (Olsen, 1993). Olsen (1993) says that cracks in rocks often start in a non-linear way because there is a lot of inelastic deformation on the grain scale before cracks form on the larger scale. The intragnular joints are not the result of tectonic processes because they don't have a preferred orientation in terms of an outside coordinate system. Instead, they might be caused by thermal tensions that form as a flow of lava cools. Textural features like the way crystals grow and the presence of phenocrysts in a fine-grained matrix also point to a sudden cooling of magma with early-formed crystals (Samanta, 2001).

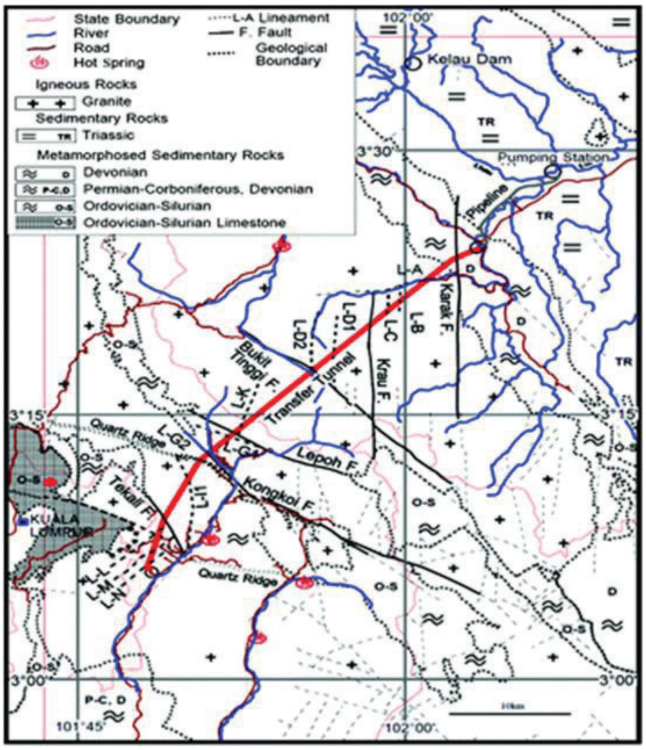

Figure 3. Cross section of tunnel with the Lineament (L-) and fault line (F.). Study area is marked by the yellow box.

2. Methodology

2.1. Tunnel Mapping.
The study site has been selected as NATM-1, Karak. Tunnel mapping / fieldwork provides a good opportunity to learn more about the geology of the research area as well as perform duties including tunnel mapping, digging and charging, and probing drilling. Apart from that, during this examination, the other tunnels in Karak, namely NATM-2, NATM-3, and TBM-1, were visited as a side search. This enables a comparison of tunneling properties between the NATM-1 and other tunnel components, such as geological composition, rock type, and tunnel development.

A tunnel mapping face (Figure 4 left). exercise is a critical operation carried out by geologists on site in order to record the tunnel face (Figure 4 right). It's finished after the mucking but before the support system is installed. The tunnel face was sketched after each blast to determine the stability, joint collection, and presence of groundwater. It must be evaluated and registered for future use as a guide.

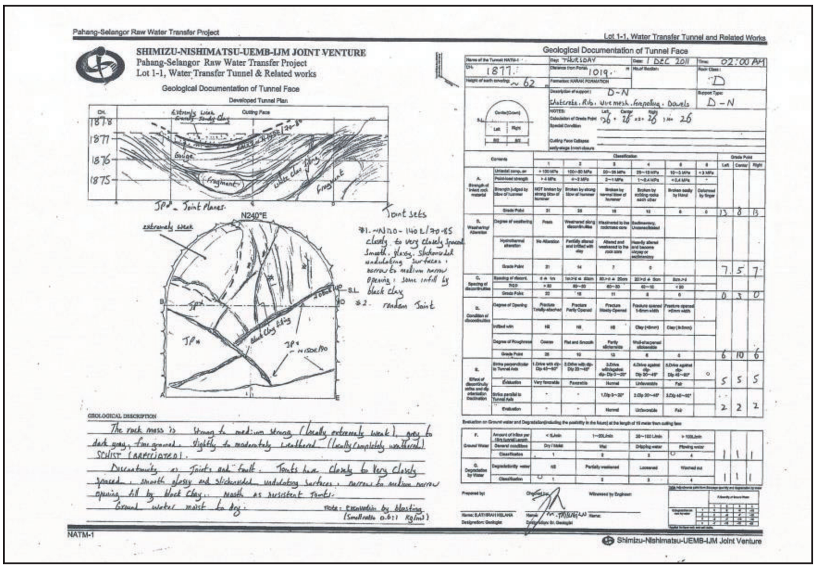

Figure 4. Tunnel Face Mapping (left), Tunnel Face (right).

3. Data Interpretation and Analysis

After the raw data has been extracted. The dip will be input into the program, along with its location, for study. The data will be analyzed using the Rocscience Dips tool. Based on plots from the dip and dip direction, this program generates a Fisher Concentration (Figure 5 a) and Rose Diagram (Figure 5 b) based on stereonet in rock mechanics, with the Rose Diagram illustrating the number of joints that go in each direction. By observing the shift in join pattern along the tunnel, these items can be studied. The joint pattern can change along the tunnel due to factors such as regional faults, overburden height, and climate. The findings of this study will be utilized to identify the source of specific joint pattern behavior and predict the possibility of the joint collapsing. To assess these data, it will take a lot of consultation with the supervisor who has enough knowledge and expertise in this subject. The interpretation process could go awry if there is no consultation, resulting in erroneous outcomes.

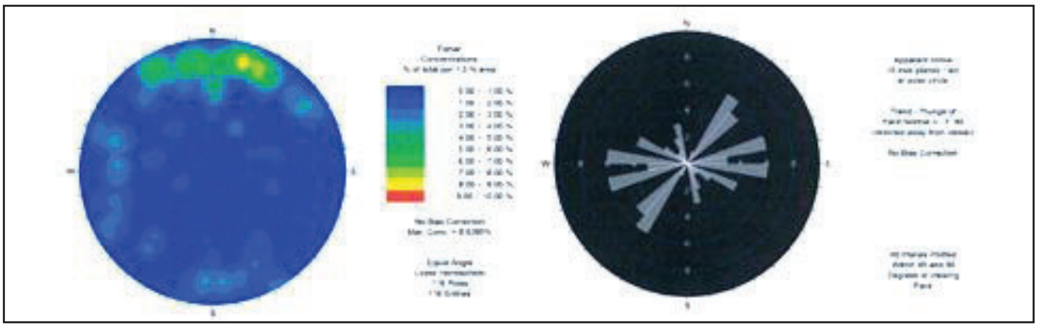

Figure 5. (a) Joints concentration (b) Direction of joint density (Rose Diagram).

4. Results and Discussion

4.1. Relationship between Joint Orientation and Overburden.
To develop the model, the extracted data was digitalized and entered into software. The pattern changes depending on the environment around the tunnel faces. The patterns begin with TD-0 and end with TD-909. The rock type existing at the tunnel face, the stability of the rock basis as determined by the Rock Mass Classification (Japan Highway Public Corporation; JH), the elevation of overburden, and the groundwater in the vicinity have all been considered. The joint pattern and the overburden can be seen in Figure 6.

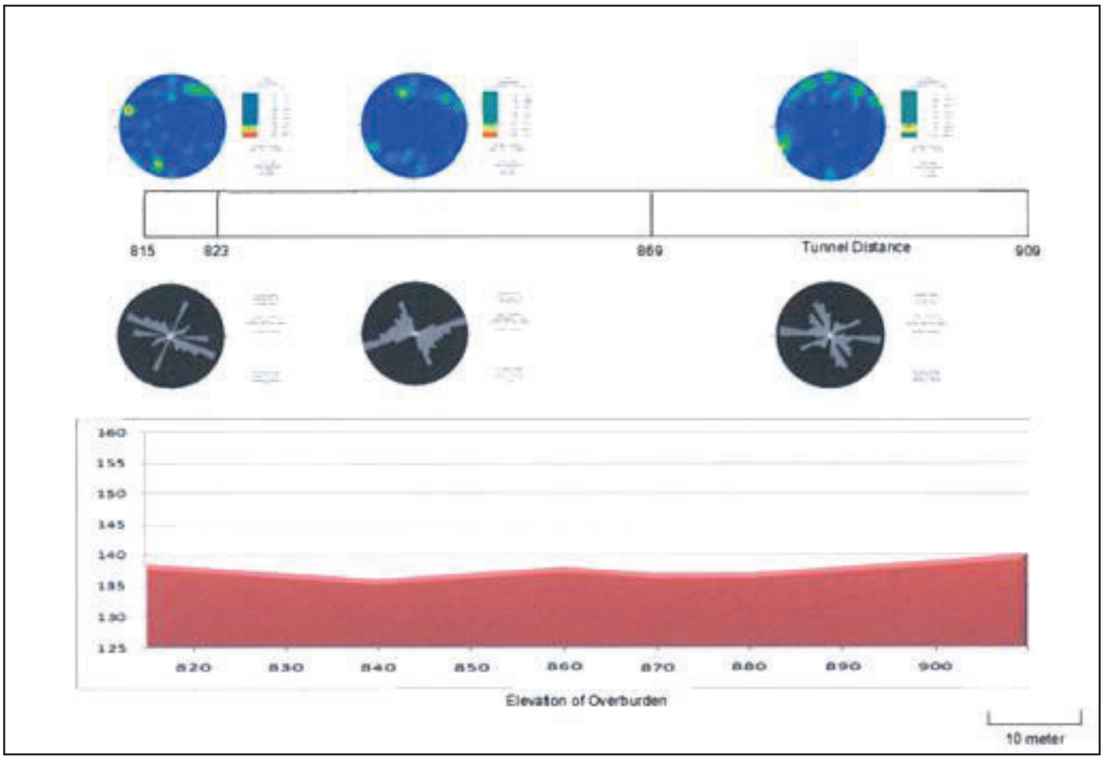

Figure 6. Joint Pattern of TD-815 to TD-909 with its elevation of overburden.

From Figure 6 , no significant relationship can be correlated. The rock stability in the NATM-1 area is threatened by numerous fractures and joints at the shear zone of Karak with the composition of the shale, homfels, phyllite, siltstone, sandstone, and slate as well as clay, breccla, quartzite, and chert were all found too. 1767 joints were recorded from the top of the tunnel face to the bottom. There are 430 faults, 278 smooth planar joints, 94 foliation joints, 9 bedding joints, and 956 random joints among the total joints. The majority of the joints were centered between N90° and 130°E / 60° and 80°. Except for TD-0 to TD-35, TD-81 to TD-96, TD-158 to TD-212, TD-229 to TD-268, TD-467 to TD-548, TD-759 to TD-813, and TD-823 to TD-909, the directional of joint pattem followed the regional fault pattem.

Throughout the tunnel, the elevation of overburden fluctuates. It reaches to a height of 205 meters above sea level from sea level. Then it dips to 150 meters above sea level and a river runs across a section of the overburden, affecting the joint pattem.

The seepage or groundwater can be dry, highly wet, or high inflow. It can occasionally produce flooding in the tunnel, posing a barrier to tunnel building. The largest groundwater flow rate is 300 L/min, which occurs when the river meets the overburden. From fair rock with weathered rock mass and some clay in joints to extremely poor rock with soil, crushing, and squeezing zones, rock stability ranges from class C-I to E.

4.1.1. Cause of Joint Development. As mentioned, the joint pattems have certain features in specific spots. These qualities are influenced by the climate in that place. After evaluating the features of joint pattem in each set of joints, there are some major environmental influences on joint pattems in an area. In comparison to the rest of the tunnel, the overburden at the inlet is very thin (thickness). As a result, the weathering of the rock formation in that location has begun. As a result of this process, the joint pattern was altered, and the rock structure became uneven. So, the regional fault pattern was somewhat distorted by the lateral dominant joint. It reveals that the weathering mechanism is one of the causes of joint development.

Between TD-550 and TD-654, the Karak River can be found at the top of the overburden. According to the Rose Diagram (Figure 5a and 5b) at the time, the joint's orientation is following the regional fault pattern. The orientation of the joints is unaffected by the river's position on top of the overburden. Regardless, this portion has much too many joints, with 192 joints compared to an average of 60-80 joints in other sections.

The joint pattern along the tunnel shows several improvements as the level of the overburden changes. There is no apparent link between these two traits and the modifications, however. As a result, no conclusive association can be inferred from this research. The relationship between these two objects will require more investigation. According to the paper, the Joint pattems have certain features in specific places. These qualities are influenced by the climate in that place. After evaluating the features of joint pattem in each set of joints, there are some major environmental influences on joint pattems in an area. In comparison to the rest of the tunnel, the overburden at the inlet is thin. As a result, the weathering of the rock formation in that location has begun. As a result of this process, the joint pattern was altered, and the rock structure became uneven. As a result, the regional fault pattern was somewhat distorted by the lateral dominant joint. It reveals that the weathering mechanism is one of the causes of joint development.

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4.1.2. Potential Failure in Tunnel Process with the Joint/ Fault Distance. Several incidences of tunnel falure during tunnel processing have occurred in NATM-1. This occurrence occurred at two locations in the research area: TD-220 and TD-816. Due to the joints and defects that emerge on the tunnel's façade, the tunnel has collapsed at these points. Fortunately, no SNUI -JV employees were wounded in the incident. It is critical to anticipate potential failures prior to the tunneling phase in order to avoid future accidents.

When TD-220 and TD-816 are compared, N320 E/45°-50° at TD-220 and N320 E/45°-50° at TD-816 are the sheared joints that can fail. While both TDs are in the same location, the sort of rock present in these sites is not. Based on this, there is a link between these two instances. Tunnel failure could theoretically be caused by the type of rock in a region, but based on this observation, no definite associations exist as to which type of rock causes tunnel failure. As a result, the directional of sheared at both TD has been chosen as the guideline for predicting the region in the tunnel phase that has possible failure for the evaluation of prospective failure in this tunnel.

Based on the shear zone of TD-220, certain groups have dominant joints that adopt the sheared joints direction. These classes have been marked as having a high chance of failing tunnel processing. The four classes are TD-229 to TD-256, TD-256 to TD-268, TD-815 to TD-823, and TD-823 to TD-869. In these groups' dominant and almost dominant joints, the shear zone at the failure location is close. These classes contain both TD and TD with failure incidents. As a result, these groups are at risk of failing, and they must proceed with prudence throughout the tunneling phase in these locations. If this type of joint is present in that site, a thorough examination of the tunnel face is required to avoid any failures.

4.1.3. Numerical Simulations: Model Establishment and Parameters. After collecting the joint data, three-dimensional discrete element software is used to look more closely at the numerical results (3DEC -discrete element method). Often, parts of the physical medium are different or don't fit together. Derived in terms can be seen as breaks in a material's properties or in its meso and macro structures. According to the concept of discrete composition, the medium has mechanical properties that vary from place to place. This means that when the medium is stressed, it changes in an unexpected way. In continuous media, things that aren't always the same interact with one another. This means that discrete media can be thought of as the sum of continuous media. The most basic parts of a rock mass, as an example of a general interpretation, are rock blocks with different lithological properties (Continuum) and geological discontinuities (discontinuous features). When pushed from the outside, rock blocks can function as a continuous medium, with "discontinuities" that allow them to interact with one another (discontinuous features). Rock blocks can behave like a continuous medium when the tension between the breaks is too great. The process of moving or separating rock blocks is known as shearing.

There is a clear asymmetric distribution phenomenon due to the clear geological features of the dominant joint angle of the surrounding rock in the main deformation area of the tunnel. This is evident from the tunnel's changing shape, the pressure on the rocks surrounding it, and the tension on the steel. The stress-causing failure features of a soft rock tunnel in a high geostress joint/fault fracture zone are identified, and the appropriate numerical model is developed to fully mimic the properties of the surrounding rock. The first stress field of a rock mass in the computer model is simply the stress field caused by gravity. The model is buried 500 metres underground, and geostress is applied to the top of it to simulate the stress caused by the weight of the strata above it. An elastic-plastic constitutive model is used for the rock surrounding it. A Coulomb slip constitutive model is used for the joints. The calculating model is 50 metres long and 50 metres wide. The tunnel is 50 metres long as well. The tunnel model is depicted in Figure 7. The joint is shown as a fault by default.

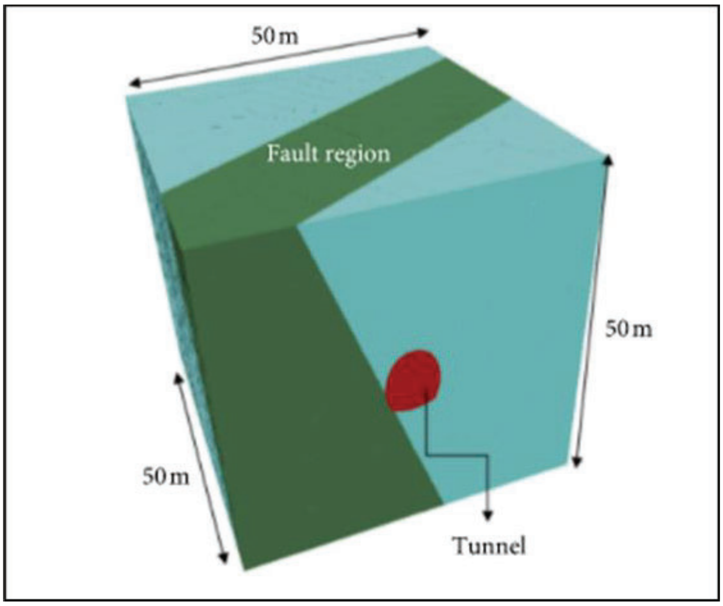

Figure 7. Numerical simulation of tunnel model.

4.2. Mechanism Analysis of Tunnel Collapse in Fault and Highly Jointed Zone

The joint/fault has an 18-20 metre range of effect on the tunnel ahead. During this procedure, the tunnel penetrates the fault zone for the first time. The surrounding rock has been disturbed as the tunnel has been plotted in both directions, left and right. The largest displacement, as seen, is 50 cm. The rock around the fault fracture zone is shattered, and its mechanical characteristics are not as good as those found elsewhere. During the excavation phase, the fault fracture zone exhibits more vault settlement, arch bottom uplift, and horizontal convergence of the tunnel body than the rest of the zone (Figure 8 a,b,c).

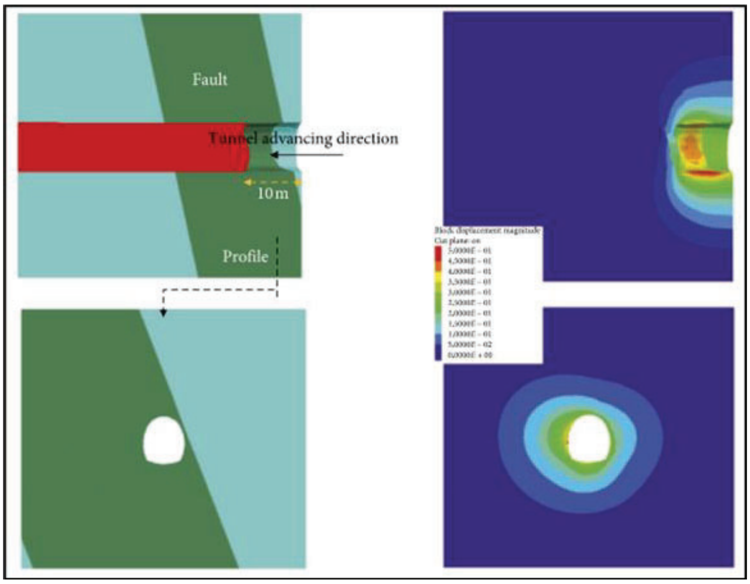

Figure 8 (a). The range of tunnel entering fault is 18-20 m.

The tunnel gradually penetrates the fault area during this process, and the fault regions surrounding the tunnel eventually converge. The surrounding rock of the tunnel has been displaced significantly in the fault area, and the deformed area on left or right sides gradually shifts from the considerable high stress zone deformation to their basic symmetrical deformation. There is the most movement between 21 and 30m at the point where the second and third phases of the left elliptical tunnel intersect (Figure 8b).

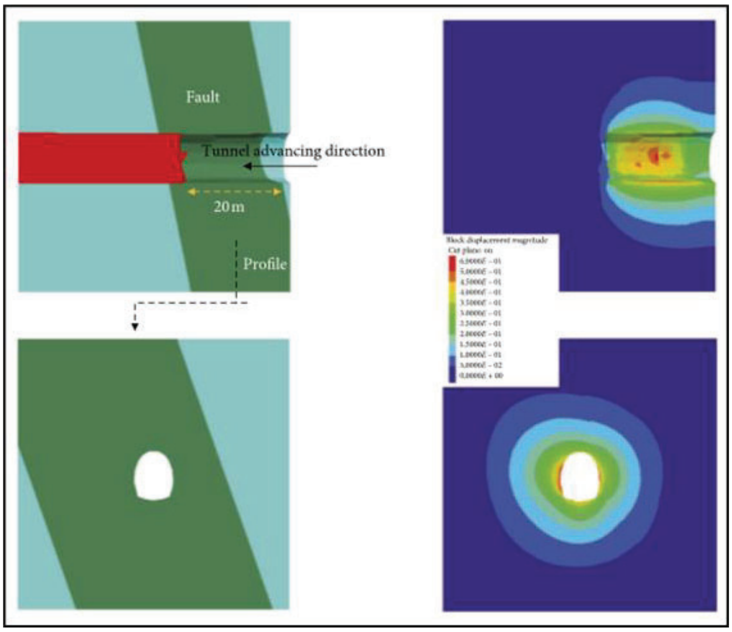

Figure 8 (b). The range of tunnel entering fault is 21-30 m in distance.

From where the fault is at the beginning of the tunnel, it moves more than 30 m forward. The tunnel gradually moves away from the fault line during this process, with the left side of the tunnel moving quicker than the right. The rock on both the left and right sides of the tunnel has shifted significantly in the fault area, and the deformation on both sides gradually shifts from the massive deformation on the left side to the basic symmetrical deformation on both sides. The most movement occurs at the junction of steps 2 and 3 of the left elliptical tunnel (Figure 8 c).

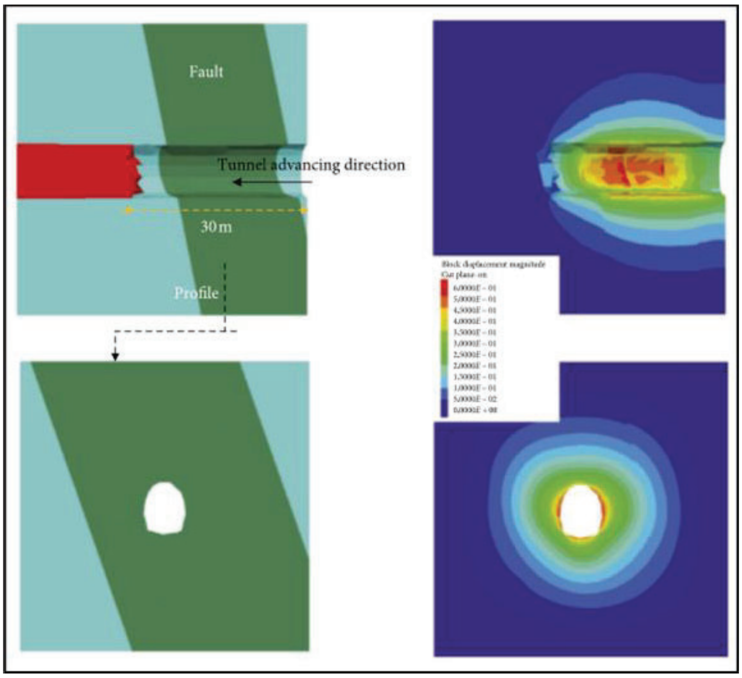

Figure 8 (c). The range of tunnel entering fault is at more than 30 m in distance.

5. Conclusion

Using field observation, theoretical analysis, numerical modelling, and other methodologies, this study investigates tunnel deformation during fault fracture zone crossing and the advance reinforcement effect under varied rock support conditions.

The following are the primary conclusions:

1. The joints present in meta-sedimentary rock influence the tunnel design in NATM-1. In the tunneling phase, it has caused considerable difficulties, which has slower the excavation pace in compared to the targeted performance about 20-30% recorded by KETTHA report in 2000. Several procedures and attempts have been made to deal with the current situation of excessive joints, especially by geologists and tunnel engineers, in order to complete the tunnel construction without incident or casualties. Weathering and the presence of a river in an area cause meta- sedimentary rock to create joints. According to the findings of this study, these two reasons have resulted in a shift in joint pattern. Overburden elevations appear to alter joint pattern as well, however there are no definitive relationship between joint pattern and overburden. As a result, more research is required to prove a solid relation between these two reasons. There are several points in the tunneling phase that have the potential for failure that all workers should be aware of in order to prevent incidents that can raise production costs, take longer, and result in personnel casualties.
2. The strength of surrounding rock in tunnel fault fracture zone is low, and the tunnel excavation leads to stress concentration, which aggravates the instability and collapse of the tunnel. Due to the change of rock dip angle and the position of soft and hard rock discontinuity, the deformation is obviously asymmetric.
3. Because advance support, advance bolt, and no grouting advance small pipe are unable to control rock deformation, advance grouting small pipe must be utilised to strengthen rock.
4. As the grouting reinforcement zone thickens, fault fracture zone rock deformation decreases considerably. A 2-meter grouting radius limits economic and construction distortion.

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