19th WORLD CONFERENCE OF THE ASSOCIATED RESEARCH CENTRES FOR THE URBAN UNDERGROUND SPACE
Belgrade, Serbia, November 4-7, 2025.

ACUUS BELGRADE 2025

Paper No: 2.14.68
DOI: 10.46793/ACUUS2025.2.14.68

ENGINEERING GEOLOGICAL ASSESSMENT AND GROUND BEHAVIOR OF TECTONICALLY DISTURBED ROCKS IN NORTHERN THAILAND. A CASE STUDY OF THE PHAYAO RAILWAY TUNNELS

Prarom S[*1,6], Jongpradist P[2], Thongdetsri T[3], Phienwej N[4], Dias D[5], Janrungautai S[6], Amorndechaphon D[7], Hasap A[8]

Abstract: This paper presents a geotechnical analysis of the southern Phayao Tunnels (T3), which are part of the Denchai-Chiang Rai-Chiang Khong Railway Construction Project (Contract 2, Ngao-Chiang Rai section) in the Lampang-Phrae Basin, Thailand. The geological and geotechnical challenges during tunnel construction are highlighted, focusing on analyzing rock mass behavior and events during tunnel excavation. The research has integrated data from three sources, including borehole investigation data, seismic refraction survey data, and actual field observations, to provide a comprehensive overview of the project area's geological conditions for assessing the rock mass's geotechnical properties. In evaluating rock mass properties, the study applied the Rock Mass Rating (RMR) system and Geological Strength Index (GSI), which helped efficiently classify and predict rock mass behavior in the tunnel area. Additionally, the study monitored and analyzed tunnel movements (convergence monitoring) to assess structural stability. Incidents that occurred during construction were analyzed in detail to identify the main causes and contributing factors and present effective and appropriate problem-solving approaches during tunnel excavation operations. The results of this study not only enhance understanding of tunnel construction in complex geological structures but also present recommendations for developing practical guidelines for future tunnel construction projects, especially in the context of challenging geological conditions in Thailand. The knowledge gained from this study can be applied to planning and risk management for large infrastructure projects facing similar geotechnical challenges.

Keywords: Tectonically Disturbed Rocks, Complex Geological Structures, Engineering Geological Assessment, Ground Behavior

1. INTRODUCTION

Thailand's accelerating infrastructure development has intensified tunnel construction activities to support economic expansion. Excavation through geologically complex and tectonically disturbed formations poses considerable engineering challenges, including complex predicted rock mass characteristics, structural discontinuities, and ground instability concerns. Mae Tang-Mae Ngad water diversion tunnel project, one of the projects that tunneled through a complex geological setting [1], demonstrates the consequences of unpredictable geological complexity, resulting in ground failure, support structure collapse, and project delays with associated cost escalations and safety risks during excavation and support installation phases. The construction project of the Denchai-Chiang Rai-Chiang Khong railway line, the State Railway of Thailand (SRT), covers four twin tunnels. The 2,700-meter-long Phayao Tunnel (T3) is a challenging project due to its complex geological conditions, which require excavation through the contact of unconsolidated sediment and rock geology, as well as through active fault lines as shown in Fig 1.

[1]*Railway Engineering and Technology, School of Engineering, University of Phayao, E-mail address: suphawit.pra@gmail.com
[2] Department of Civil Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi
[3] Department of Civil Engineering, School of Engineering, University of Phayao
[4] Department of Civil & Infrastructure Engineering (CIE), Geotechnical and Earth Resources Engineering (GTE), Asian Institute of Technology
[5] Laboratory 3SR, Grenoble Alpes University, Grenoble, France
[6] MAA Consultants, Co.Ltd
[7] Automotive and Transportation Technology Center (ATTC), School of Engineering, University of Phayao
[8] Railway Transportation System Testing Centre (RTTC) of TISTR, Thailand Institute of Scientific and Technological Research (TISTR)

The construction of the 500-meter-long southern part of Phayao Tunnel presented complex geotechnical challenges during the excavation that required careful geological data analysis, in-depth understanding of rock mass behavior, and effective management throughout the construction process. These challenges necessitated specialized geotechnical approaches to ensure tunnel access, structural stability, and construction safety while maintaining the project timeline.

The research aims to analyze the geological and geotechnical conditions encountered in the Phayao tunnel, focusing on the direction and impact of rock mass discontinuities, rock mass classification and behavior prediction, tunnel wall convergence analysis and significant incidents during excavation and the impact of geotechnical challenges on construction timelines. The findings from this study provide valuable insights into tunnel engineering in similar geological conditions and contribute to the development of geotechnical knowledge in complex geological environments.

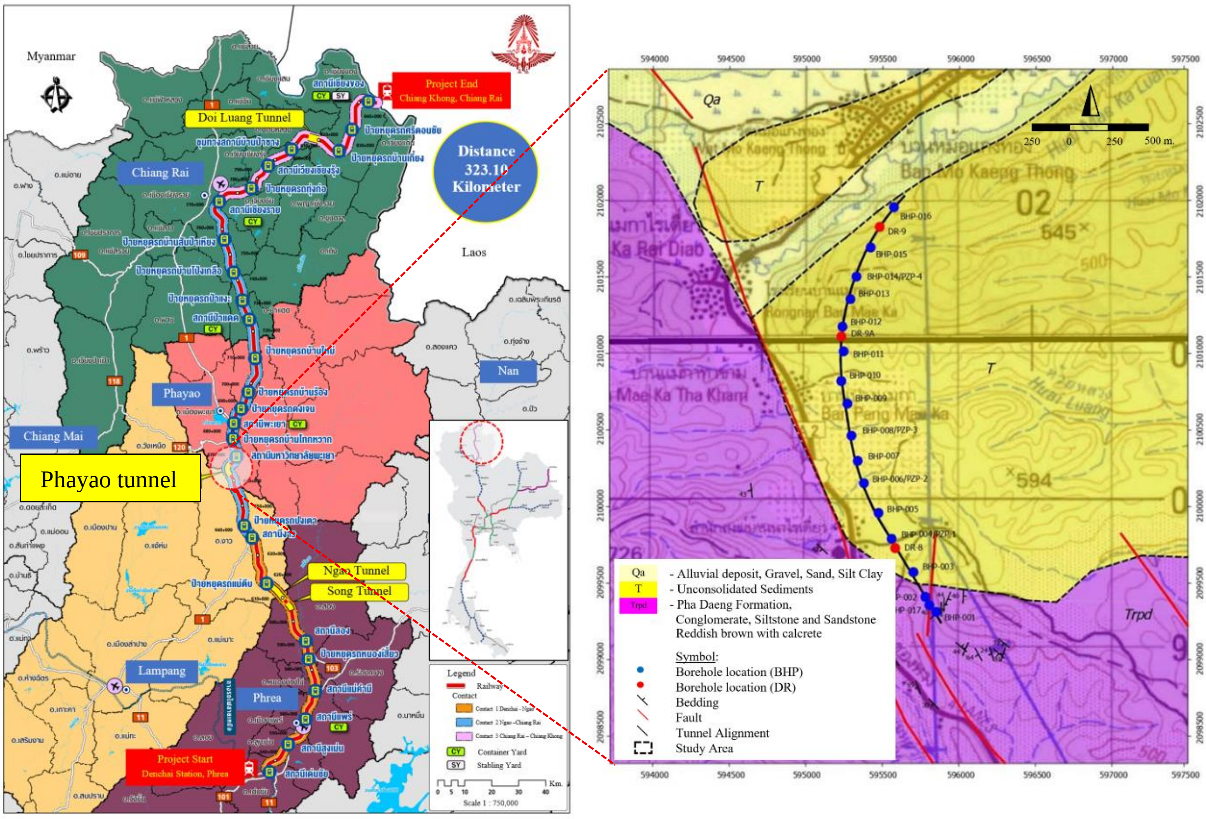


Figure 1. *Figure 1 Railway route of the Denchai-Chiang Rai-Chiang Khong double railway project (Modified SRT, 2024) and the geological plan of Phayao Tunnel (T3) length is 2,700 meters.*

2. GEOLOGICAL SETTING

2.1. Regional Geology and Local Geology of the Tunnel Alignment

The Lampang Phrae basin is part of a larger structural system in Northern Thailand, characterized by a complex formation of Triassic sedimentary rocks. This basin developed during the Mesozoic era and comprised various siliciclastic sedimentary rocks, including sandstones, mudstones, claystones, and some limestone units. The rock layers are deposited in two interconnected sub-basins: the Lampang sub-basin (located westward) and the Phrae sub-basin. (located eastward) [2] The geological formations in the study area are characterized by Triassic age sedimentary rocks, primarily composed of the Pha Daeng formation within the Lampang group. [3] These sedimentary rocks exhibit a complex lithological composition, featuring interbedded siltstone, sandstone, and conglomerate layers with distinctive brown to reddish-brown coloration. From thin to thick bedding, the rock mass strength is classified as medium to strong rocks according to the International Society for Rock Mechanics [4] standards, representing fresh to slightly weathered [3] geological conditions that present unique challenges for engineering and tunneling projects.

The tunnels are situated within the Pha Daeng Formation and Permo-Triassic volcanic rocks of the Lampang Phrae Basin, part of the Sukhothai Arc. The current geological structure results from tectonic disturbances related to plate movements, including subduction, collision, and fracturing during the Mid-Paleozoic to Late Mesozoic periods.[5] The geological map, as shown in Fig. 1, reveals a complex terrain with the purple-shaded area representing the Pha Daeng formation (Trpd) of the Lampang Group. This section is characterized by significant geological heterogeneity. The blue dots show multiple boreholes strategically positioned along the tunnel alignment. The longitudinal section (Fig. 2) indicates the presence of notable structural features, including faults (red lines) that intersect the tunnel route, suggesting potential geotechnical challenges. The purple geological zone, representing the Pha Daeng formation, appears to dominate the southern portal of the study area. The presence of multiple geological boundaries and the apparent structural complexity underscore the need for detailed geotechnical investigation and adaptive engineering strategies when tunneling through this geologically dynamic zone. The excavation distance of the tunnels on the south portal is approximately 500 meters of rock for each track (totaling nearly 1 kilometer of cumulative excavation).

As shown in Fig. 2, the actual geology during the tunneling, as measured by the tunnel face mapping, seismic refraction survey and borehole investigation data, revealed a complex subsurface structure with different geological units (sedimentary rocks, siltstone interbedded with sandstone) intersected by numerous faults (red lines), that were not observed prior to construction. This inconsistency highlights a significant geotechnical risk in tunnelling projects, where preliminary investigations cannot critical structural features like fault zones and discontinuity that can substantially impact construction methods, assessments, groundwater management, and ultimately project cost and schedule, emphasizing the importance of adaptive design approaches and comprehensive site investigation methods in underground construction.

As shown in Table 1, the geological documentation reveals a progressive transformation of sedimentary rock formations encountered during excavating the two double-track tunnels, characterized by siltstone and interbedded sandstone with brown to reddish-brown coloration. In contrast to the regional geology previously prescribed, rock mass along the tunnelling route exhibits complex geological characteristics, with intact rock strength ranging from 0 to 25 MPa, (weak rock) with moderate to low structural integrity. Progressive sections demonstrate increasing tectonic disturbance, transitioning from slightly weathered, medium-thickness beds to highly sheared rock masses with significant structural deformation. The geological profiles show progressively more complex structural conditions, including laminated sandstone, clay-filled joint planes, and nearly chaotic rock layers with broken and deformed sedimentary structures. These observations underscore the critical importance of detailed geotechnical investigation and adaptive engineering strategies when navigating through tectonically complex geological environments, where rock mass characteristics can change dramatically over relatively short distances.

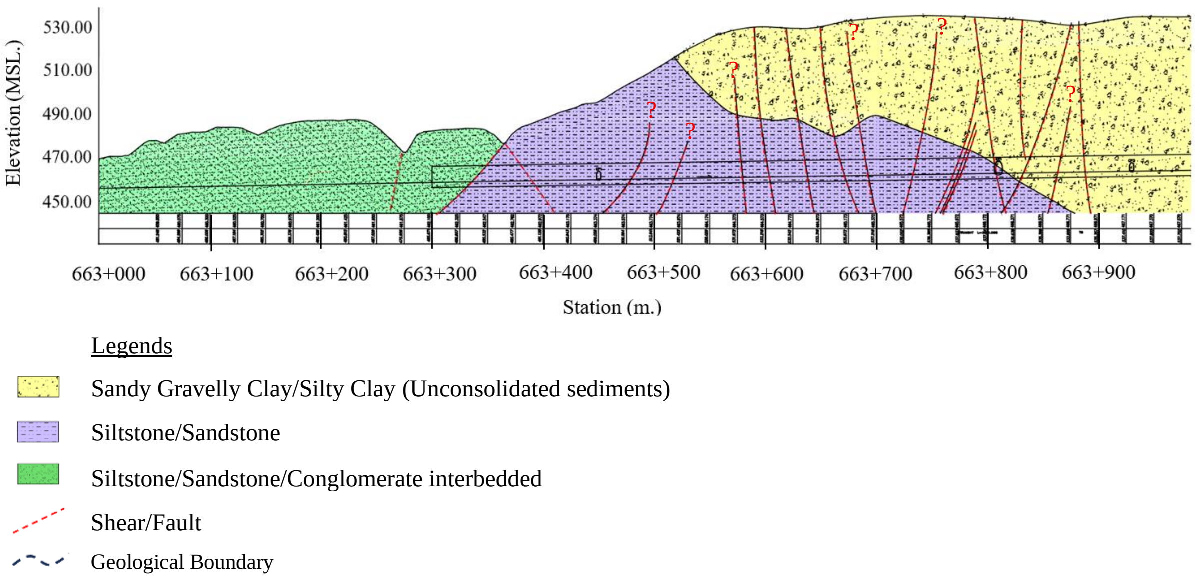
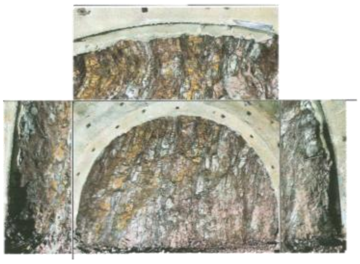


***Figure 2.** The picture shows the rock accumulation along the tunnel excavation of Phayao tunnel (T3) (The actual geology after the tunneling is completed)*

Table 1 Shows geological information that appear on the face along the Phayao tunnel excavation route.

STA 663+329.916	STA 663+600.116	STA 663+725.116
		
Siltstone brown to reddish brown, slightly to moderately weathered, medium to thick bed. The strength form field estimation is 25-50 MPa.	Siltstone interacted with laminated sandstone, brown to reddish brown, moderately to highly weathered, medium to thick bed. Highly sheared rock mass of low strength, the strength form field estimation is 5-25 MPa.	Siltstone interacted with laminated sandstone, brown to reddish brown, highly weathered, thin bed. Highly sheared rock mass of low strength is present filled with clay along the joint and bedding planes. Tectonically disturbed sheared siltstone with broken deformed sandstone layers. almost a chaotic structure
STA 663+775.278	STA 663+818.278	STA 663+826.116
		
Slightly disturbed of siltstone, with occasional thin sandstone and breccia bed, slightly weathering and soft to medium hard. The strength form field estimation is 1-5 MPa.	Silty clay, pale brown, silt and clay size particles, low cohesion. Sandy gravelly clay, pale brow to yellow, angular to subrounded gravel, pebble to boulder size sandstone, silt, and clay matrix with high cohesion.	Gravelly clayey sand, yellowish brown, medium to fine sand, gravel sized grain, angular to rounded particles, silt and clay matrix with moderate to low cohesion.

3. TUNNEL CONSTRUCTION

3.1. Cycle Time

The south tunnel excavation, which started in mid-May 2023, there were many problems caused by challenging geological conditions during the tunnel excavation, such as poor to very poor rock materials, roof collapses (occurred 7 times), mostly occurring when drilling through the fault zone and accumulating groundwater, resulting in deviations from the plan. Each roof collapse repair initially took about 1-2 weeks, then as experience increased. The total excavation time of the south portal of both tracks (Up and Down track) in the rock unit was 24 months, and the average daily progress rate was approximately 0.82 meters per day. Tunneling methods refer to the conventional tunnelling method standards by drilling and blasting at the beginning part around 50 meters, which is divided into two levels as Top Heading and Benching, before changing to a mechanical excavator (excavator with hydraulic breaker) when the geological conditions are not suitable. Tunneling with a mechanical excavator is divided into 3 levels: Top Heading, Benching, and Invert.

4. GEOTECNICAL ANALYSIS

4.1. Rock mass Classification and Ground Behavior type

The Rock Mass Rating (RMR) system is adopted to classify the rock masses in this project. The main rock is siltstone interbedded with sandstone, a sedimentary rock prone to cracking and mechanical changes when exposed to water. The data show that most rocks have uniaxial compressive strength (UCS) values in the range of 0 to 25 MPa, which is considered very weak to medium strength rock, which may affect stability during tunneling.

Rock Quality Designation (RQD) and joint frequency data showed that early in the tunnel, 10-25 joints per meter indicated relatively good rock quality. However, as the excavation progressed (see Fig. 3), the number of joints increased continuously until reaching a peak of more than 47 joints per meter on the down track tunnel, indicating that the rock was fragmented and had a low RQD. This is consistent with the joint frequency curve showing that the joint set increased from the middle to the end of the excavation.

Analysis of discontinuity spacing and groundwater conditions in the tunnel area revealed two main rock units: siltstone interbedded with sandstone, and disturbed siltstone and sandstone. The spacing between discontinuities ranges from 3-10 meters, depending on the type of discontinuity and rock layer characteristics. The aperture (crack

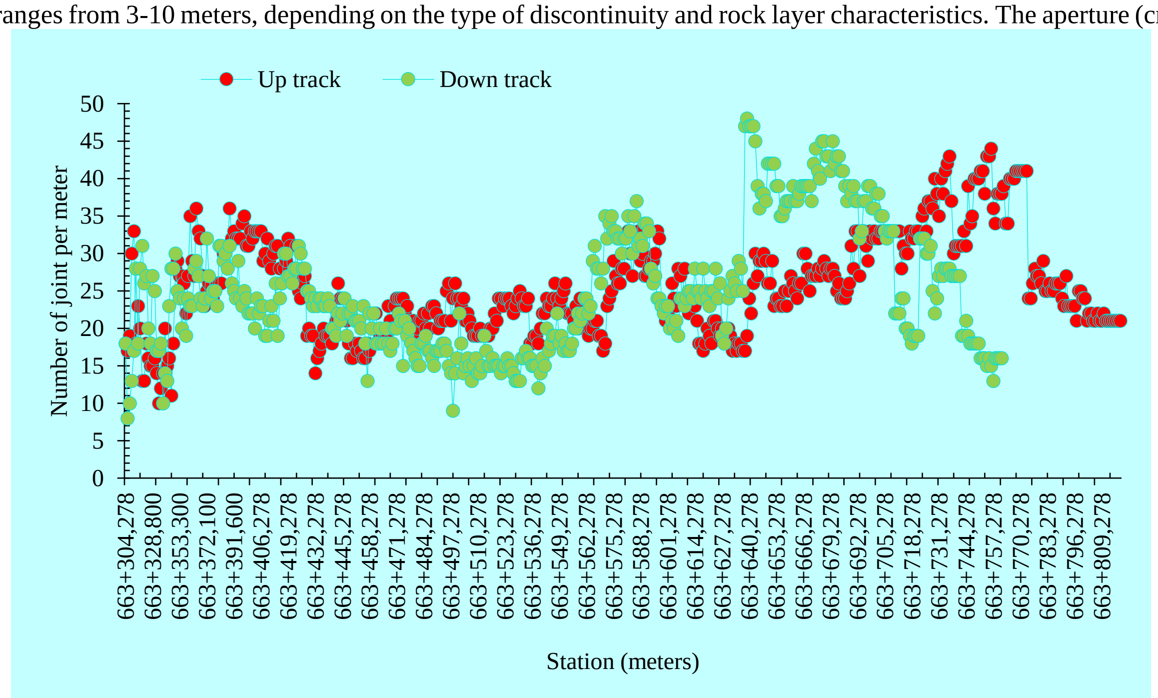


Figure 3. *The number of joints per meter along south tunnel*

width) typically exceeds 5 mm, particularly in faults with a high movement probability. Joint surface roughness is smooth to slickenside, indicating polishing from geological movement. Joint infilling consists of hard and soft materials, with faults specifically containing soft materials that may reduce rock mass strength. Regarding groundwater conditions, most areas exhibit levels ranging from dry to moist, which could affect tunnel stability. Therefore, tunnel structure stability plans should incorporate drainage and reinforcement, especially in areas with faults and highly porous rock masses.

Orientation analysis of discontinuity in Phayao Tunnel found that the discontinuities in the area have dip angle values of 20°-90° with various dip directions. The bedding plane has a dip direction of 60°-100° and 230°-260° depending on the rock type. The joints have a dip angle value of 20°-60° and the faults have a maximum dip angle value of 90°, indicating the geological movement in the past. The various orientations of the fractures may affect the stability of the tunnel, especially in areas where multiple faults and fractures intersect, which can easily cause the collapse of the rock mass.

As shown in Fig. 4, geotechnical data analysis along the entire 500-meter Phayao Tunnel excavated in rock (from south portal) reveals a clear relationship between RMR, GSI values, and geological conditions. The tunnel was excavated through two major rock units characterized by numerous joints, faults, high groundwater infiltration, and highly weathered rock. In these geologically complex areas, RMR and GSI values have significantly decreased. This decrease correlates with seven tunnel roof collapses, particularly at the interfaces between rock units. Rock mass quality fluctuates most dramatically in fault zones, while overburden layer thickness increases progressively along the drilling distance of both up-track and down-track tunnels. This study's results indicate that changes in geotechnical index values can serve as important indicators for predicting areas at risk of tunnel instability. Areas with extensive faulting and highly weathered rock require special pre-support measures to maintain stability.

The analysis of the evolution of the Rock Mass Rating (RMR) system in the Phayao Tunnel found that the estimated and actual values of the rock mass rating were significantly different, especially in the groups of rock classes III, IV and V. The estimated tunnelling length of class III was 10.31%, but it was not found in the actual excavation. The actual tunnelling length of class V was much higher than the estimation, from 5.15% to 18-21%, indicating that the rock in the area was in a worse condition than expected, resulting in the need for additional support measures. The average actual excavation rate was 0.82 m/day, with several roof collapses, resulting in delays and the need to adjust the stabilization method during tunnel excavation.

Fig. 5 illustrates geotechnical and geological data and a classification of ground behavior types along the tunnel alignment. This analysis demonstrates the relationship between five key parameters: Overburden (thickness of soil above the tunnel), Adjusted RMR (modified rock mass rating index), GSI (geological strength index), groundwater conditions, and fault line occurrences.[6] The area is divided into five distinct categories according to ground behavior, labeled GT1 through GT4, with each type exhibiting unique properties.

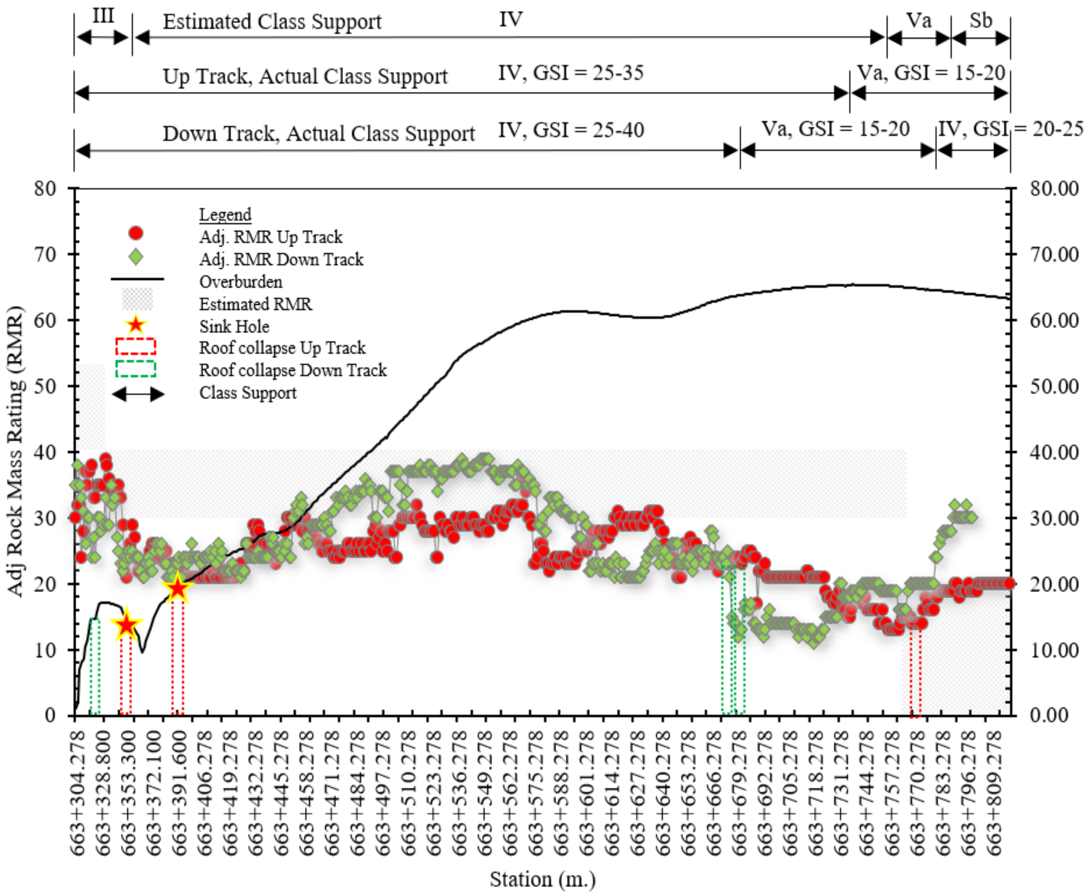


Figure 4. *Shows the analysis of the evolution of the Rock Mass Rating (RMR) system in the Phayao tunnel.*

The analysis reveals complex relationships between rock mass properties and tunnel behavior throughout the excavation distance. The area is classified into five ground types (GT1-GT4 and GT2.1) with distinct characteristics. Zone GT1 has adjusted RMR values of 30-40 and GSI of 35-45, indicating medium-low quality rock mass, yet still prone to Wedge/Chimney/Shearing behavior, especially in the section between stations 663+300 to 663+400 where multiple sink holes were detected. The most concerning zones are GT3 and GT4, with very low RMR values (15-25) and low GSI (20-30), indicating very poor rock quality (Class IV-V), combined with high overburden (60-65 meters) in the section between stations 663+700 to 663+780 where roof collapse incidents occurred. The moist groundwater conditions further increase the collapse risk. Special emphasis should be placed on additional reinforcement planning and support system installation in GT3 and GT4 zones, considering the combined factors of rock mass properties, moisture conditions, and overburden load to prevent future collapse incidents.

4.2. Reinforcement Design and Monitoring Analysis

The design of support systems and reinforcement in tunnels is critical for preventing collapse and enhancing structural stability.[7] Support systems help resist pressure from rock mass, groundwater forces, and seismic activities, ensuring tunnel strength and operational safety while reducing ground settlement that could impact the surrounding environment and structures. Based on geotechnical analysis data, excavation methods, support systems, and appropriate reinforcement, as well as predicted rock mass behavior during construction of the Phayao tunnel, excavation methods, support systems, and reinforcement can be modified according to geological conditions encountered during tunneling. Continuous on-site inspection and evaluation by tunnel engineers and geologists is necessary to assess rock mass changes and determine appropriate support measures, especially in cases of poor-quality rock (RMR Class support IV and V) and excavations through fault zones.

Additional measures beyond the specified design to ensure safety during the operation are as follows: From station 663+345.300 (Up track), the length from poral around 40 m. and station 663+323.700 (down track), the length from poral around 22 m, a spray flashcrete with a thickness of approximately 5 cm. is immediately used to cover the full face of the tunnel to ensure safety during the installation of steel ribs and rock bolt of the excavation stage, additional pre-support such as pipe forepoling or pipe roofs to reduce the possibility of tunnel roof collapse. This additional installation continued until the excavation of the southern tunnel was completed, when the excavation through the contact of unconsolidated sediment and rock geology.

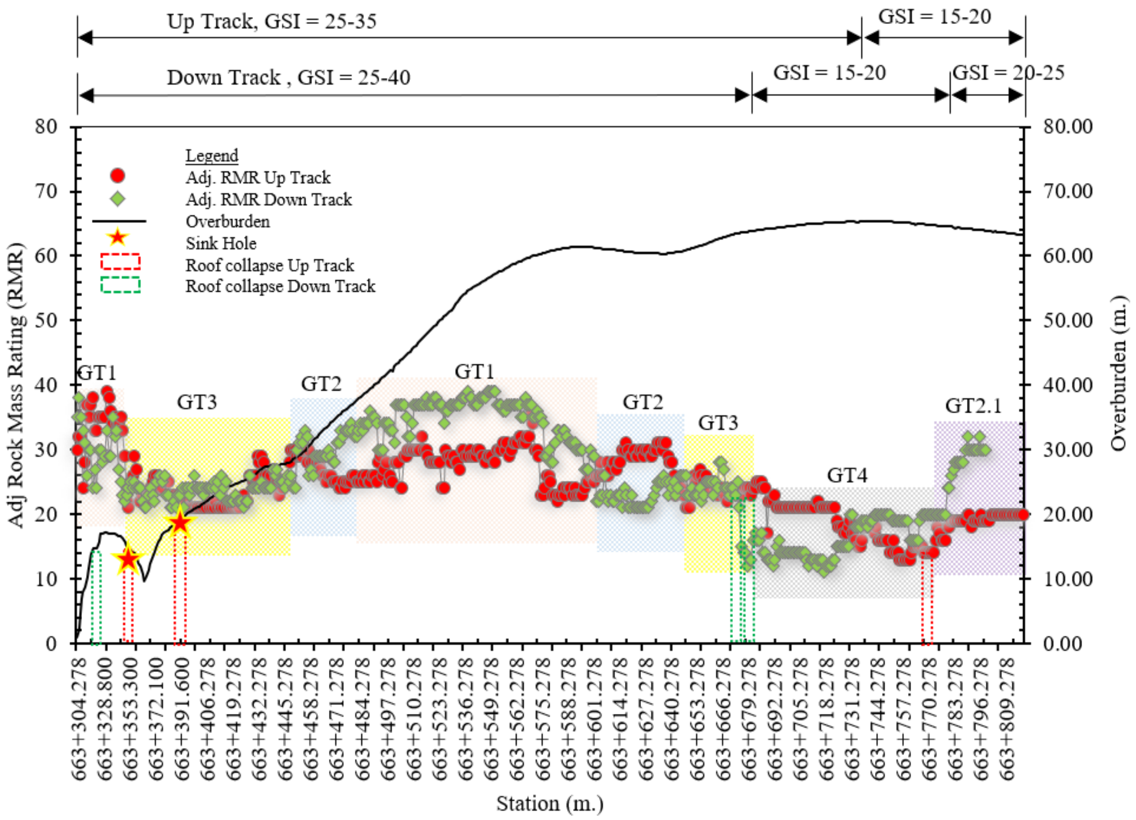


Figure 5. *The classification of ground behavior (Ground Behavior Type) along of Phayao Tunnel.*

Moreover, from station 663+353.300 (up track) and station 663+375.500 (down track), it was decided to change the excavation method from blasting to mechanized excavation in areas sensitive to vibration. Additionally, from station 663+398.278 (up track) and station 663+391.616 (down track), the excavation cycle length needed to be reduced from 1.5 m. to 1.0 m of class support IV due to the unfavorable geological conditions encountered to enable the installation of the support system quickly and efficiently. This reduction in excavation and change in excavation method continued until the end of the excavation of the south portal tunnel.

As shown in Fig. 6, analysis of tunnel wall deformation in rock from station 663+250 to 663+850 meters, under 15-65 meters of overburden, demonstrates the relationship between horizontal and crown convergence strain at 63 monitoring sections. Critical points with roof collapse and fault zones were identified at seven locations showing abnormally high deformation (1.0-1.5%), particularly at station 663+500, and in the 663+700 to 663+800 region displaying irregular movement near the excavation of equipment room which are directly affected by changes in the contact of unconsolidated sediments and rock geology. The differences between up-track and down-track tunnel values reflect asymmetric deformation due to rock mass heterogeneity. In contrast, the low deformation values at stations 663+500 to 663+625 indicate improved rock mass quality. The crown-to-horizontal convergence ratio provides insights into joint orientation within the rock mass. This data is very important for tunnel engineers to consider and decide on the appropriate excavation method, with high-convergence-strain areas requiring additional reinforcement to enhance tunnel construction safety.

Analysis of convergence monitoring at STA 663+500 (Monitoring section U8) reveals asymmetric deformation behavior, with maximum crown settlement reaching 110 mm, significantly exceeding the horizontal convergence. This reflects the influence of high vertical stress and the presence of horizontal joints in the rock mass. Time-displacement experienced the greatest settlement of 110 mm within 80 days, with high deformation rates during the first 40 days gradually decreasing until stabilization after 60-70 days. Meanwhile, horizontal displacement demonstrates inward movement toward the tunnel axis from both sides. This behavior corresponds to time-dependent deformation and ground reaction curve theories in low-quality rock mass near the fault zone. Additional reinforcement measures should be considered, such as increasing shotcrete thickness, installing longer rock bolts, or implementing steel ribs in this area to control deformation within acceptable limits and prevent long-term tunnel collapse.

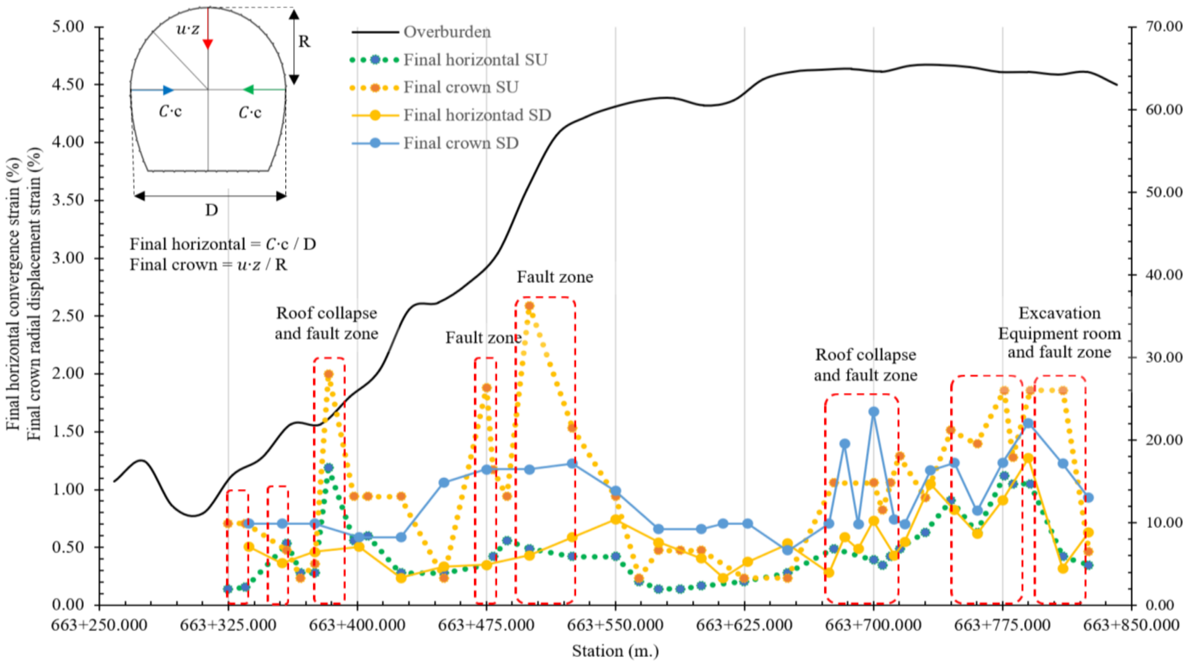


Figure 6. *Final convergence and crown radial displacement at 63 section monitoring cross-sections in the Phayao tunnel (including Up track and Down track tunnel)*

5. THE CASE STUDY OF TUNNELLING EXPERIENCE

During the excavation of the southern Phayao Tunnel, along the total distance of both tunnels (up and down tunnel), approximately 1,000 meters, there were seven incidents of tunnel roof collapses. Table 2 lists the collapse patterns and relevant geotechnical and geological parameters. Most tunnel collapse events showed rock mass behavior with a tendency to shear and raveling failure. For example, 1 in 7 incidents at STA 0+770.278 at the up-track tunnel was excavated using the mechanical method. This section encounters extremely challenging geotechnical conditions with severely damaged rock formations and strengths below 1 MPa, having been extensively damaged by tectonic disturbance. The geological profile featured collapse-prone structures with multiple shear zones, faults, and structurally deficient rock formations. The extremely low rock mass rating (RMR) of less than 20 classified the area as very poor rock with critical stability durations of only 24-54 minutes before collapse. The engineering assessment confirms that these severe instability factors, particularly the tectonically compromised structure and extremely brief standup time, were the direct causes of the roof failures experienced during tunneling operations. After the incident, as shown in Fig. 7, the correction was done by spraying flashcrete to cover the pile of rocks that fell in the tunnel. Install the pre-support of pipe roof in sufficient quantity according to the geological conditions. Then, inject cement water through the pipe roof according to the amount specified and wait for the cement to set according to the specified time. Then remove the fallen material and continue excavating according to the standard tunneling procedure. The work site has made corrections according to the operating procedures, which took 12 days to fix.

6. THE CONCLUSION

This research presents the geotechnical solutions for constructing the 1,000-meter-long south part tunnels of the main tunnels of a Railway Project, excavated through the complex geology of the Lampang-Phrae Basin. The study found that the tunnel faced three main challenges: (1) excavation through the siltstone interbedded with sandstone layer with low strength (UCS 0-25 MPa) and five to six main fracture systems, (2) the variable overburden of the tunnel roof and (3) the presence of faults and groundwater infiltration caused the RMR value to be less than 20, which is considered a very poor rock. The research method used the integration of geological data (Detailed Geological Mapping) together with the analysis of geotechnical indexes, including adjusted RMR and GSI along the tunnel. The analysis results revealed the most problematic of the four main rock mass behaviors (GT1-GT4 and GT2.1), especially in the GT3 and 4 zones. Despite experiencing seven roof collapses that caused construction delays, the systematic approach of thorough geological understanding, timely installation of additional reinforcement and pre-support systems, continuous monitoring of tunnel wall movements, and accurate prediction of rock mass behavior significantly improved construction safety and reduced the frequency of tunnel roof failures.

Finally, excavating the south portal tunnel into the rock took approximately 24 months, encountering much more challenging conditions than anticipated. The adaptive engineering approaches will be beneficial for future tunnel construction in similar tectonically complex geological environments.

Table 2 Summary of the tunnel roof collapse incident of the southern Phayao Tunnel.

Formation	STA.	Geological Unit	RMR	GSI	Overburden (m.)	Fault lines	Ground water	Ground Behavior
Pha Daeng	663+323.700	Siltstone /Sandstone	24	29	16.80	yes	Damp	Chimney
	663+345.300	Siltstone /Sandstone	33	38	16.30	yes	Damp	Chimney
	663+347.660	Siltstone /Sandstone	29	34	15.74	yes	Damp	Chimney
	663+395.700	Siltstone /Sandstone	15	20	20.30	yes	Damp	Shear/Ravelling
	663+674.116	Siltstone /Sandstone	14	19	25.84*	yes	Moist	Shear/Ravelling
	663+678.116	Siltstone /Sandstone	12	17	28.51*	yes	Moist	Shear/Ravelling
	663+770.278	Siltstone /Sandstone	14	19	12.37*	yes	Moist	Shear/Ravelling

** The overburden only considers the rock units and does not focus on the unconsolidation sediments cover.*

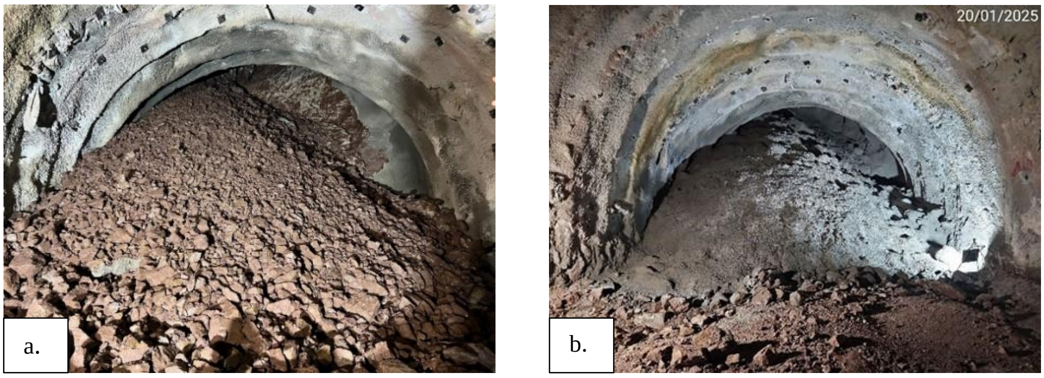


Figure 7. *Show the incident roof collapse at STA 0+770.278 (Up track)*
a.) Geological characteristics after the collapse of the tunnel.
b.) Starting to spray flashcrete to cover the pile of rocks.
c.) Install the pre-support of pipe roof.
d.) Inject cement water through the pipe roof.
e.) Remove the fallen material and continue excavating.
f.) Install the steel rib and proceed to the normal tunneling process.

7. ACKNOWLEDGMENTS

This research has received funding support from the NSRF via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation [grant number B13F670082-11]

The compilation of this research data would like to thank the officials and personnel of the State Railway of Thailand, the CSDCC Consulting Group, the CH. Karnchang-Sino-Thai Engineering & Construction Public Company Limited, CKST Joint Venture, the Den Chai-Chiang Rai-Chiang Khong Railway Construction Project, Contract 2, Ngao-Chiang Rai Section, and Right Tunneling Public Company Limited for supporting the data and facilitating the research to achieve the objectives.

8. BIBLIOGRAPHY

[1] Harnpattanapanich, T., Phienwej, N., Rodploy, J., Monthanopparat, N., Tanomtin, C., & Kongdang, K., 2023. Solving problem of encountering a huge cavern in a TBM drive for water diversion tunnel project in Northern Thailand. *Geomechanics and Tunnelling*, *16*(3), 304-311.

[2] Feng, Q., Chonglakmani, C., Helmcke, D., Ingavat-Helmcke, R., and Liu, B., 2005, Correlation of Triassic stratigraphy between Simao and Lampang–Phrae Basins: implications the tectonopaleogeography of Southeast Asia, Journal of Asian Earth Science, v. 24, pp. 777–785

[3] Chonglakmani, C., Grant-Mackie, J.A., 1993. Biostratigraphy and facies variation of the marine Triassic sequences in Thailand. In: Thanasuthipitak, T. (Ed.), Proceedings of the International Symposium on Biostratigraphy of Mainland Southeast Asia: Facies and Paleontology 1. Chiang Mai University, Chiang Mai, pp. 97–123

[4] ISRM (International Society for Rock Mechanics)., 2007. The complete ISRM suggested methods for rock characterization, testing and monitoring: 1974-2006. Commission on Testing Methods, ISRM, Lisbon.

[5] Hara, Y.,2017. Sandstone provenance and U–Pb ages of detrital zircons from Permian–Triassic forearc sediments within the Sukhothai Arc, northern Thailand: record of volcanic-arc evolution in response to Paleo-Tethys subduction Journal of Asian Earth Sciences Volume 146, 15 September 2017, Pages 30-55

[6] Marinos, V., Prountzopoulos, G., Fortsakis, P., Koumoutsakos, D. and Papouli, D., 2012. Tunnel Information and Analysis System: A geotechnical database for tunnels. Geotechnical and Geological Engineering. doi: 10.1007/s10706-012-9570.

[7] The International Tunnelling and Underground Space Association (ITA)., 2019. Guidelines for the Design and Construction of Tunnels.