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# Tunnel Behavior Analysis and Support Optimization of the Road-Header Method Considering the Excavation Damaged Zone (EDZ)

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## ABSTRACT

As above-ground infrastructure in urban areas becomes increasingly saturated, the demand for underground space development has risen sharply to ensure efficient land use. In South Korea, large-scale tunnel construction projects such as the Great Train eXpress (GTX) and the Gimpo–Paju Han River Underwater Tunnel are actively underway. Consequently, the use of mechanical excavation methods—offering advantages in minimizing public complaints and improving construction safety—has grown significantly. In particular, the recent introduction of large-scale road-header machines at domestic tunnel sites has drawn increasing attention to enhancing excavation performance and optimizing support system efficiency. However, current support designs for mechanical excavation are still largely based on those developed for drill-and-blast methods, often resulting in excessive material use and reduced economic efficiency. Moreover, research efforts aimed at optimizing support patterns specifically for road-header excavation remain limited. This study performs numerical analyses that reflect the extent of the Excavation Damaged Zone (EDZ), which varies depending on the excavation method. Tunnel displacements and support member stresses under road-header excavation conditions are investigated to assess the potential for improving existing support patterns. Based on these findings, optimized support designs are proposed for rock mass classes II, III, and IV using the RMR14 classification system, allowing for rational reduction in support without compromising structural stability.

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## 1. INTRODUCTION

In the early stages of research on rock mass damage zones during the 1980s and 1990s, the terms "Excavation Disturbed Zone (EdZ)" and "Excavation Damaged Zone (EDZ)" were often used interchangeably (Kelsall et al., 1984; Pusch and Stanfors, 1992; Fairhurst and Damjanac, 1996; Stephansson, 1999). Later, Bäckblom (2008) proposed a distinction between the two in crystalline rock. The Damaged Zone (EDZ) was defined as the region closest to the underground opening where new fractures propagate and irreversible deformation occurs, whereas the Disturbed Zone (EdZ) was characterized as a zone affected by changes in stress and hydraulic head, but exhibiting minimal or reversible changes in material properties.

In general, the zones of disturbance and damage induced by excavation can be classified as shown in Fig. 1 (Perras and Diederichs, 2016). Harrison and Hudson (2000) defined the area immediately adjacent to the excavation surface, where severe structural damage occurs, as the Construction Damaged Zone (CDZ). The Highly Damaged Zone (HDZ) refers to a region characterized by extensive irreversible damage accompanied by a network of interconnected fractures. Beyond the HDZ lies the Excavation Damaged Zone (EDZ), which is defined as the zone where excavation-induced stress exceeds the elastic threshold of the rock mass, resulting in the initiation of new fractures. This EDZ corresponds to an irreversibly damaged zone where measurable changes in rock properties occur and structural stability is significantly compromised (Martino et al., 2007; Jonsson et al., 2009).

In cases where tunnel excavation is conducted using blasting, damage to the surrounding rock mass occurs due to the combined effects of blast-induced pressure and stress redistribution. This results in a zone where the initial rock properties are significantly altered, referred to as the Excavation Damaged Zone (Tsang et al., 2005). The extent of this damaged zone varies depending on the excavation method and rock type. In particular, for crystalline rocks, the EDZ is interpreted as a region of irreversible deformation, characterized by the initiation of new fractures and the propagation of existing ones caused by blasting.

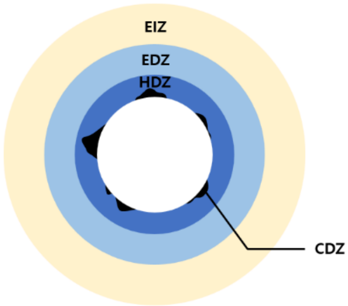



**Fig. 1** Excavation Damaged Zone (CDZ, HDZ, EDZ)


**Fig. 2** Excavation damage terminology in hard crystalline rock (Siren et al., 2015)

Siren et al. (2015) classified the Excavation Damaged Zone (EDZ) into two subcategories based on the cause of damage in the rock mass, as shown in Fig. 2 The $EDZ_{CI}$ (Construction-Induced EDZ) refers to the zone affected by excavation methods, with its extent varying between drill-and-blast techniques (NATM) and mechanical excavation methods (TBM, Road-header). In contrast, the $EDZ_{SI}$ (Stress-Induced EDZ) is the zone influenced by stress redistribution resulting from tunnel excavation, located farther from the excavation surface and relatively insensitive to the excavation method.

During drill-and-blast excavation, the $EDZ_{CI}$ typically ranges from 0.1 to 1.5 meters and is influenced by factors such as charge amount, intact rock strength, and the condition of discontinuities (Tsang et al., 2005). In TBM excavation, the $EDZ_{CI}$ is known to be minimal, typically ranging from 1 to 3 centimeters, and is affected by initial rock conditions and TBM thrust (Emsley et al., 1997; Davis and Bernier, 2003). At the Mont Terri Underground Research Laboratory (URL) and the Grimsel Test Site in Switzerland, where both blasting and mechanical excavation methods were employed, the EDZ produced by blasting reached up to 2.4 meters, while the EDZ resulting from mechanical excavation was approximately 0.3 meters indicating an eightfold difference in extent.

Previous studies on the Excavation Damaged Zone (EDZ) have mainly focused on drill-and-blast methods, with limited attention to mechanical excavation. Most EDZ-related numerical analyses have targeted special-purpose underground facilities, leaving a gap in research for typical road and railway tunnels. Mechanical excavation methods, such as TBMs and road-headers, cause less rock disturbance due to the absence of blasting, reducing the need for support elements like rock bolts and shotcrete. This can improve both stability and economic efficiency in tunnel construction.

Therefore, this study conducts two-dimensional numerical analyses that reflect the extent of the EDZ formed by different excavation methods, specifically comparing road-header excavation and the drill and blast. Tunnel displacements and support member stresses under road-header conditions are examined to assess the potential for improving existing support patterns. Based on the analysis results, this study proposes optimized support designs for rock mass classes II, III, and IV by applying the RMR14 classification system, enabling a rational reduction in support while maintaining structural stability.

## 2. Quantitative Evaluation of EDZ and Strength Reduction Behavior

Matsui et al. (2003) carried out a field test at the TONO mine to evaluate rock mass damage caused by blasting and mechanical excavation. Conducted at a depth of 135m in sedimentary rock (E = 2.8GPa, UCS = 6.6MPa), the test used P-wave velocity to identify damage extent. Results showed that blasting caused damage up to 0.3m at the wall and 0.8m at the floor, while mechanical excavation significantly reduced the extent of the damaged zone.

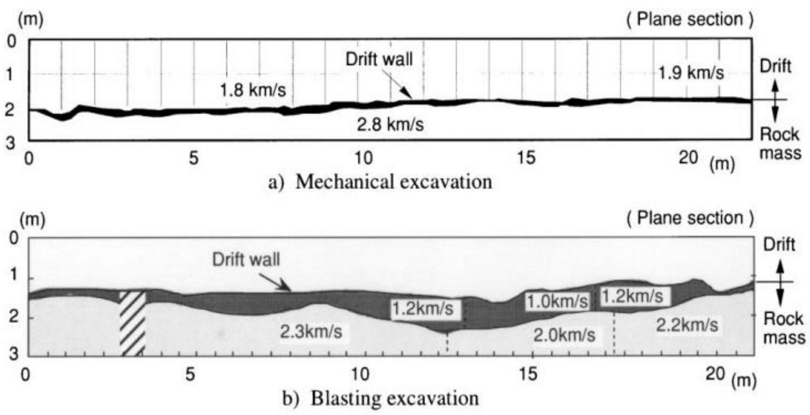



**Fig. 3** Comparative analysis of Excavation Damaged Zones induced by blasting and mechanical excavation (Matsui et al., 2003)

Hoek and Diederichs (2006) proposed empirical equations (Equations 1 and 2) to estimate the elastic modulus of damaged rock mass as a function of distance from the tunnel boundary in tunnels where an Excavation Damaged Zone (EDZ) has developed. These equations were derived based on the Geological Strength Index (GSI) and the disturbance factor (D) to estimate the elastic modulus within the blast-induced damaged zone. Even in cases where direct measurement of the intact rock modulus is difficult, Equation (2) provides a practical method for estimating the deformation modulus of the rock mass.

$$E_{rm} = E_i \left\{0.02 + \frac{1 - D/2}{1 + exp[(60 + 15D - GSI)/11]}\right\} \quad (1)$$

$$E_{rm} = 10^5 \frac{1 - D/2}{1 + exp[(75 + 25D - GSI)/11]} \quad (2)$$

B äckblom (2008) and Lee et al. (2011) quantitatively evaluated the extent of the Excavation Damaged Zone (EDZ) based on changes in rock mass properties before and after excavation, as summarized in Table 1 They also analyzed field data from major underground research facilities worldwide, comparing and organizing the extent of damage zones, tunnel diameters, and rock strength characteristics according to different excavation methods.

**Table 1.** The extent and properties of EDZ (modified from Lee et al., 2011, Bäckblom, 2008)

| Country | Project | Excavation Method | EDZ Extent (m) | Tunnel Diameter (m) | E (GPa) | $\sigma_{ci}$ (MPa) | Reference |
|---|---|---|---|---|---|---|---|
| Canada | Room 209 | Drill& Blast | 0~0.3 | 3.6 | 70 | 193 | Chandler et al., (2002) |
| | TSX | Drill& Blast | 0.3~1.0 | 3.9 | 65 | 238 | Chandler et al., (1996) |
| | BDAP | Drill& Blast | 0~0.6 | 4.0 | 66 | 220 | Read and Martin, (1996) Chandler et al., (2002) |
| | Mine-by Experiment | Mechanical | 0.2~0.3 | 3.5 | 66 | 220 | Chandler et al., (1996) |
| Sweden | Stripa | Drill& Blast | 0~0.8 | 3.6 | 69 | 207 | Gray, (1993) |
| | ZEDEX | Drill& | 0.3~0.8 | 5.0 | 69 | 195 | Emsley et al., |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Blast | | | | | (1997) |
| | | TBM | 0~0.03 | 5.0 | 69 | 195 | SKB, (1999) |
| | APSE | Drill& Blast | 0 | 1.75 | 76 | 211 | |
| | Prototype | TBM | 0.01 | 5.0 | 81 | 224 | Autio et al., (2005) |
| Switzerland | NFTP | Drill& Blast | 0~2.0 | 3.5 | 11.4 | 28 | Marschall et al., (1999) |
| | FEBEX | TBM | 0~0.003 | 3.5 | 56 | 152 | Bäckblom, (2008) |
| Japan | Kamaishi Mine | Drill& Blast | 1.4 | 3.5 | 64.3 | 151.9 | Matsui et al., (1998, 2003) |
| | | Mechanical | 0.8 | 3.5 | 64.3 | 151.9 | |
| | Tono Mine | Drill& Blast | 0.8~1.0 | 6.0 | 2.8 | 6.6 | Sugihara et al., (1993) |
| | | Mechanical | 0~0.3 | 6.0 | 2.8 | 6.6 | Sato et al., (2000) |
| | Horonobe | Mechanical | 0~0.2 | 4.0 | 1.82 | 15.4 | Matsui et al., (2007) |
| Korea | KURT | Drill& Blast | 1.1~2.4 | 6.0 | 56 | 100 | Lee et al., (2011) |
| Finland | ONKALO | TBM | 0~0.02 | 1.5 | 55 | 108 | Autio, (1996) Autio et al., (2006) |

## 3. Numerical Method

In this study, numerical analyses were conducted using the finite element method (FEM) software PLAXIS 2D, which allows for precise simulation of complex geometries while incorporating the Excavation Damaged Zone (EDZ). The cross-sectional model used in the analysis was configured as shown in Fig. 4. For computational efficiency and simplified interpretation of results, a homogeneous rock mass was assumed, and groundwater conditions were not considered.

In Section 3.1, the extent of the EDZ was defined based on previous studies summarized in Table 1, in order to simulate tunnel behavior under different excavation methods. Specifically, an EDZ of 2.0 meters was applied for drill and blast to reflect the extensive disturbance caused by blasting, while a 0.5-meter EDZ was assumed for the road-header method, considering its relatively lower impact on the surrounding ground.

In Section 3.2, a method for improving the support pattern in road-header excavation was examined by reducing the required support quantity. This was achieved by upgrading the rock mass properties using the RMR14 classification, reflecting the lower level of disturbance in mechanically excavated tunnels.

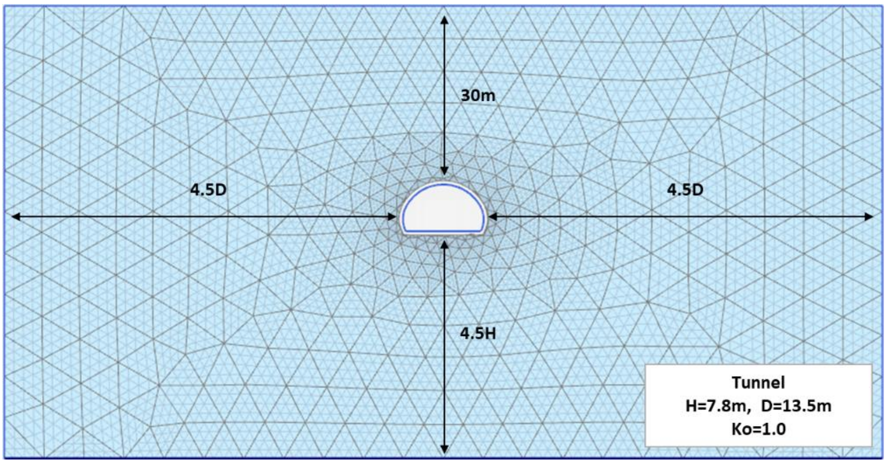



**Fig. 4** Modeling for numerical Analysis

*3.1 Support pattern Evaluation for Road-Header Excavation Considering EDZ*

The design parameters for the ground and the Excavation Damaged Zone (EDZ) used in the numerical analysis are summarized in Table 2 The Hoek–Brown failure criterion was adopted for the analysis model, and the mechanical properties of the EDZ were estimated using the disturbance factor (D) and Equation (1).

**Table 2.** Properties of rock mass and EDZ

| Category | EDZ thickness (m) | GSI | E (MPa) | γ ($kN/m^3$) | mi | D | Possion's ratio | $\sigma_{ci}$ (MPa) |
|---|---|---|---|---|---|---|---|---|
| Rock | - | 35 | 2400 | 23.4 | 18 | 0 | 0.27 | 40 |
| EDZ (D&B) | 2.0 | 35 | 100 | 23.4 | 18 | 0.8 | 0.27 | 40 |
| EDZ (R-H) | 0.5 | 35 | 100 | 23.4 | 18 | 0.8 | 0.27 | 40 |

To evaluate support pattern improvements for the road-header excavation method, various support cases were defined and are summarized in Table 3. A tunnel diameter (D) of 13.5 meters, corresponding to a typical road tunnel, was applied. Auxiliary construction methods, inner lining, and steel supports were excluded from the analysis. The material properties of the support elements used in the analysis are also presented in Table 4.

**Table 3.** Support patterns

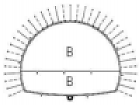
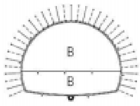
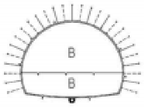
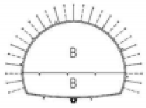
| Support Pattern | Case A | Case B | Case C | Case D |
|---|---|---|---|---|
| RMR | 40~21 | 40~21 | 40~21 | 40~21 |
| Overview of support cases |  |  |  |  |
| Excavation method | Half | Half | Half | Half |
| Thickness of S/C (mm) | 140 | 130 | 120 | 100 |
| Transverse interval of R/B (m) | 1.2 | 1.2 | 1.5 | 1.5 |
| Length of R/B (m) | 4.0 | 4.0 | 4.0 | 4.0 |

**Table 4.** Material properties and allowable stress of support

| Category | | Allowable stress | E (MPa) | γ (kN/m3) | v | Design strength (MPa) |
|---|---|---|---|---|---|---|
| Shotcrete | Soft | 8.4MPa | 5,000 | 24 | 0.3 | 10 |
| | Hard | | 15,000 | 24 | 0.3 | 21 |
| Rock bolt | | 88.7kN | 210,000 | 78.5 | 0.3 | SD350 D48 |

*3.2 Optimized Support Patterns for Road-Header Using RMR14*

B. Celada and I. Tardaguila et al. (2014) proposed the RMR14 classification system by introducing correction factors that account for excavation methods and the stress–strain behavior of the rock mass. Their proposal was based on previous studies indicating that mechanical excavation causes less rock mass disturbance compared to blasting, thereby resulting in higher RMR values. Additionally, when applying the correlation between RMR14 and RMR89, it was found that the RMR14 value can be up to 10 points higher than the RMR89 value when the RMR89 falls within the range of 40 to 75, as illustrated in Fig. 5.

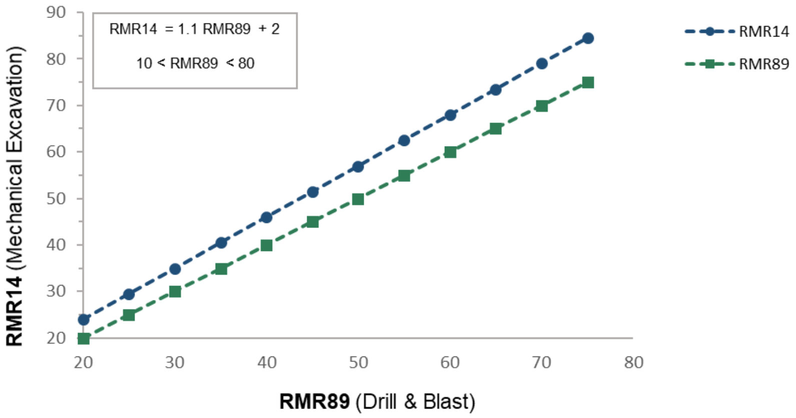



**Fig. 5** Correlation between RMR14 and RMR89

Based on the findings, the Geological Strength Index (GSI) was increased by 5 points to apply the Hoek–Brown model. The deformation modulus (E) was conservatively set to 30% of the intact rock modulus, following a review of previous studies (Bieniawski, 1978; Serafim and Pereira, 1983; Nicholson and Bieniawski, 1990; Aydan et al., 1993). The Hoek–Brown parameters by rock mass class based on RMR14 are summarized in Table 5.

**Table 5.** Hoek-Brown parameters by rock mass class based on RMR14

| Excavation Method | Rock class | GSI | E(MPa) | γ (kN/m3) | mi | D | v | σci (MPa) |
|---|---|---|---|---|---|---|---|---|
| D&B | Ⅱ | 65 | 13500 | 26.3 | 18 | 0 | 0.22 | 80 |
| Road-Header | Ⅱ | 70 | 17500 | 26.3 | 18 | 0 | 0.22 | 80 |
| D&B | Ⅲ | 55 | 6300 | 25.2 | 18 | 0 | 0.25 | 60 |
| Road-Header | Ⅲ | 60 | 8200 | 25.2 | 18 | 0 | 0.25 | 60 |
| D&B | Ⅳ | 35 | 2400 | 23.4 | 18 | 0 | 0.27 | 40 |
| Road-Header | Ⅳ | 40 | 3100 | 23.4 | 18 | 0 | 0.27 | 40 |

This study focused on rock mass classes II to IV, where support reduction is feasible. The reduction in support requirements for each class under road-header excavation was evaluated, and corresponding improvements in support patterns were proposed. Support cases reflecting the reduced quantities are summarized by rock class in Tables 6, 7, and 8. Auxiliary methods, inner lining, and steel supports were excluded from the analysis.

**Table 6** Hoek-Brown parameters for rock mass class Ⅱ based on RMR14

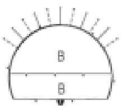
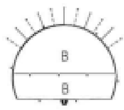
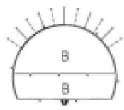
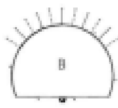
| Support Pattern | Case A | Case B | Case C | Case D |
|---|---|---|---|---|
| RMR | 80~61 | 80~61 | 80~61 | 80~61 |
| Overview of support cases |  |  |  |  |
| Excavation method | Bench cut | Bench cut | Bench cut | Full face |
| Thickness of S/C (mm) | 80 | 80 | 50 | 50 |
| Transverse interval of R/B (m) | 2.0 | 2.0 | 2.0 | 2.0 |
| Length of R/B (m) | 4.0 | 3.0 | 3.0 | 3.0 |

**Table 7** Hoek-Brown parameters for rock mass classⅢ based on RMR14

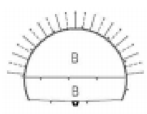
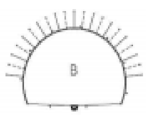
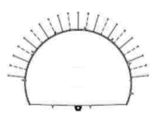
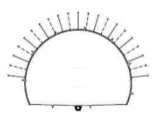
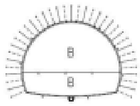
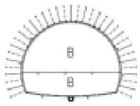
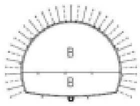
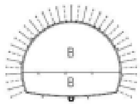
| Support Pattern | Case A | Case B | Case C | Case D |
|---|---|---|---|---|
| RMR | 60~41 | 60~41 | 60~41 | 60~41 |
| Overview of support cases |  |  |  |  |
| Excavation method | Bench cut | Full face | Full face | Full face |
| Thickness of S/C (mm) | 100 | 100 | 80 | 60 |
| Transverse interval of R/B (m) | 1.5 | 1.5 | 2.0 | 2.0 |
| Length of R/B (m) | 4.0 | 4.0 | 4.0 | 4.0 |

**Table 8** Hoek-Brown parameters for rock mass classⅣ based on RMR14

| Support Pattern | Case A | Case B | Case C | Case D |
|---|---|---|---|---|
| RMR | 40~21 | 40~21 | 40~21 | 40~21 |
| Overview of support cases |  |  |  |  |
| Excavation method | Bench cut | Bench cut | Bench cut | Bench cut |
| Thickness of S/C (mm) | 120 | 100 | 100 | 80 |
| Transverse interval of R/B (m) | 1.2 | 1.2 | 1.5 | 1.5 |
| Length of R/B (m) | 4.0 | 4.0 | 4.0 | 4.0 |

## 4. Results and Discussion

In this study, numerical analyses were conducted by incorporating the Excavation Damaged Zone (EDZ) associated with each excavation method. Displacement and support member stresses under road-header excavation were compared with those under the drill-and-blast method to evaluate the feasibility of support pattern improvement. Furthermore, for rock mass classes II to IV, where support reduction is considered practically applicable, the RMR14 classification system was applied to assess the appropriateness of support pattern optimization and to propose feasible improvement strategies.

### *4.1 Results of Support Evaluation for Road-Header Excavation Considering EDZ*

To investigate the displacement characteristics of different excavation methods, crown displacements were compared between the road-header and drill and blast methods under both unsupported and supported conditions, as illustrated in Figure 6. When an EDZ of 0.5m was applied, the road-header method exhibited only about 44% of the displacement observed in the drill and blast method (EDZ = 2.0m) under unsupported conditions.

This indicates that the smaller extent of the damaged zone significantly contributes to displacement reduction. Furthermore, as the support pattern was gradually reduced from Case A to Case D, the road-header method consistently maintained an average of approximately 51% of the crown displacement compared to drill and blast across all support cases. These findings suggest that current support patterns used in road-header excavation, which are typically based on drill and blast standards, may be overly conservative and demonstrate the potential for more economical support designs.

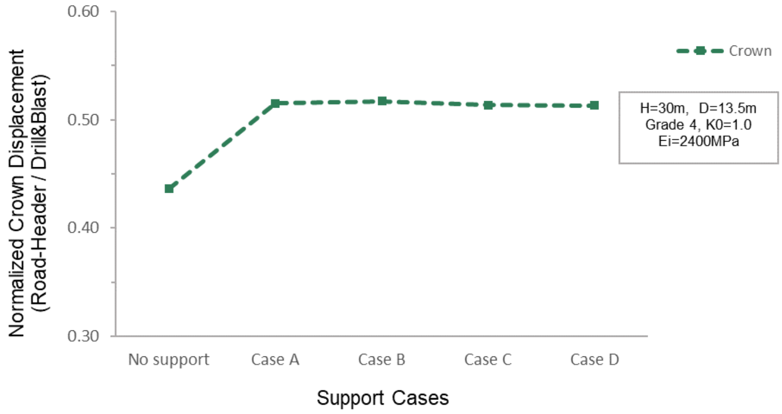



**Fig. 6** Crown displacements of the road-header compared to drill and blast under unsupported and supported conditions

The results of the support stress analysis comparing the road-header method with the drill-and-blast method for each support reduction case are presented in Fig. 7. In all support cases, the road-header method exhibited lower levels of rock bolt axial force and shotcrete bending-compressive stress compared to the drill-and-blast method. The normalized axial force of the rock bolts (RH/Drill and Blast) gradually increased from 0.73 in Case D to 0.84 in Case A, while the shotcrete bending-compressive stress maintained a stable average ratio of approximately 0.74 across all support cases. These trends indicate that the smaller Excavation Damaged Zone (EDZ) formed during road-header excavation helps preserve the initial stiffness of the rock mass, thereby reducing the loads transferred to the support elements. Notably, even in cases with reduced support, the stresses in the support members remained consistently lower than those in the drill-and-blast method, confirming that structural stability can still be maintained.

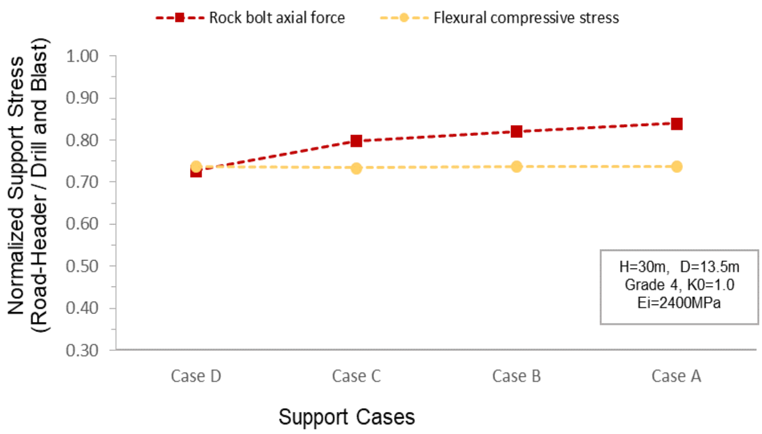



**Fig. 7** Normalized results of support stress for each support cases

Ultimately, the numerical analysis incorporating the Excavation Damaged Zone (EDZ) confirmed that the current standard support patterns, which are based on the Drill and Blast method, may be excessively applied when used for the road-header method.

Due to the relatively smaller extent of the damaged zone, the road-header method maintains higher initial rock stiffness, resulting in reduced loads on support members and improved structural stability. Even under gradually reduced support conditions, the road-header method maintained approximately 51% of the crown displacement observed in Drill and Blast, while normalized axial forces in rock bolts and compressive bending stresses in shotcrete remained at average levels of 0.84 and 0.74, respectively. These results indicate that more economical and rational support designs are achievable when applying the road-header method.

*4.2 Results of Optimized Support Patterns for Road-Header Using RMR14*

Section 4.1 analyzed the tunnel behavior and evaluated the potential for support reduction by reflecting the extent of the Excavation Damaged Zone (EDZ) according to excavation methods, specifically comparing drill and blast and the road-header method across different support cases. The results showed that the road-header method, due to its smaller displacements and reduced plastic zones, can maintain a stability level equivalent to drill and blast while allowing for effective support reduction. However, in practical tunnel design, it is uncommon to directly incorporate the EDZ into numerical analysis. When the EDZ is explicitly modeled, it may result in excessive displacement or induce unnecessarily high axial and bending stresses on the support elements. To address this issue, Section 4.2 explores an alternative approach by applying the RMR14 classification system, which allows for a realistic increase in rock mass properties under road-header conditions. This adjustment forms the basis for proposing optimized support patterns that enable rational support reduction while ensuring structural stability.

The maximum crown and sidewall displacements observed in Class II rock for both the Drill and Blast method and the road-header method under various support configurations are presented in Table 9. When applying the original support pattern (Case A), the Drill and Blast method showed maximum displacements of 0.63 mm at the crown and 0.29 mm at the sidewall. In contrast, under the most reduced support configuration (Case D), the road-header method recorded 0.49 mm and 0.23 mm, respectively. These values are approximately 80% of those observed in the Drill and Blast case, confirming that deformation remains effectively controlled even with reduced support.

**Table 9** Maximum Displacement by support case in Grade Ⅱ Rock

| Excavation Method | Rock Class | Crown Displacement (mm) | Side wall Displacement (mm) |
|---|---|---|---|
| Drill & Blast | Ⅱ | 0.63 (▲28.6%) | 0.29 (▲26.1%) |
| Road-Header | Ⅱ | 0.49 | 0.23 |

The axial force of rock bolts and the compressive bending stress of shotcrete for the Drill and Blast method with the original support pattern and for each support case of the road-header method in Grade II rock were illustrated in Fig. 8. Furthermore, to optimize the support system, safety factors were evaluated by calculating the ratio of actual stress to the allowable stress for each support member, and the results were presented in Fig. 9.

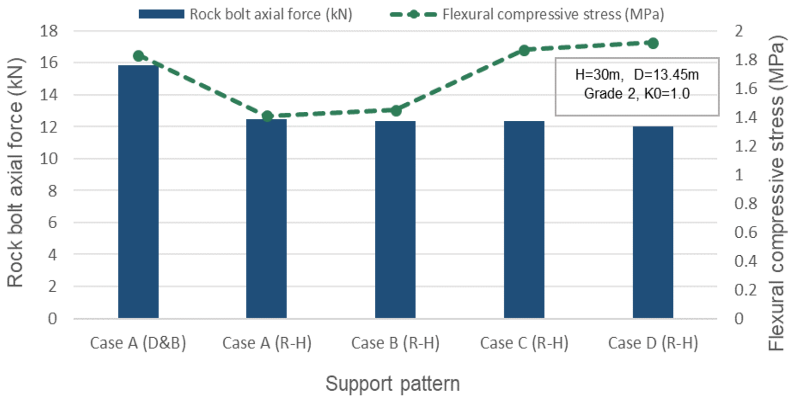



**Fig. 8** Rock bolt axial force and shotcrete flexural compressive stress by support cases for drill and blast and road-header methods in grade Ⅱ rock

In the Drill and Blast method with the standard support pattern (Case A), the axial force in rock bolts and the flexural compressive stress in shotcrete were 15.86kN and 1.83MPa, respectively. Under the same support conditions, the road-header method showed reduced values of 12.47kN and 1.41MPa, attributed to a smaller EDZ and improved rock mass properties based on the RMR14 classification, which help mitigate load transfer to support members.

In the road-header cases with reduced support (Cases B–D), the axial force in rock bolts gradually decreased from 12.36kN to 12.00kN, while shotcrete stress increased, reaching 1.92MPa in Case D. This trend reflects stress concentration due to reduced cross-sectional stiffness from decreased shotcrete thickness and the use of full-face excavation.

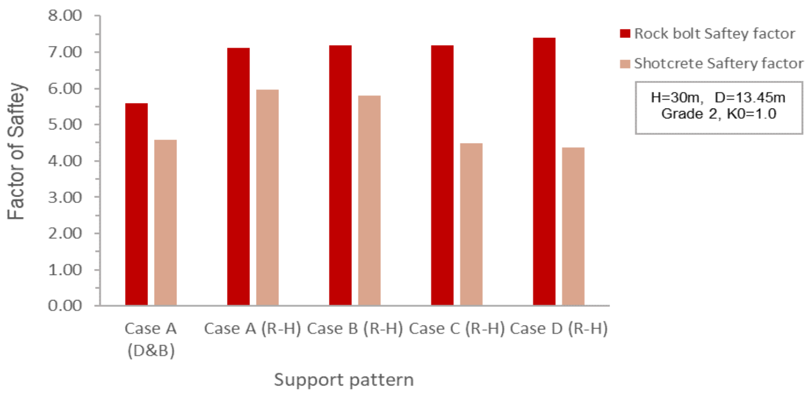



**Fig. 9** Safety factors of rock bolts and shotcrete for drill and blast and road-header methods by support cases in grade Ⅱ rock

Even when the support quantity was reduced to Case D during road-header excavation, both the rock bolts and shotcrete remained within allowable stress limits. The safety factor of the rock bolts was maintained at a high level of 7.39, and that of the shotcrete at 4.38. Accordingly, in Grade II rock, the application of the optimized support pattern corresponding to Case D was deemed feasible for road-header excavation, and the proposed support improvement plan is summarized in Table 10.

**Table 10** Support pattern improvement plan for road-header in grade Ⅱ rock

| Support Pattern | PD-2 (Drill and blast) | PD-2 (Road-Header) |
|---|---|---|
| RMR | 80~61 | 80~61 |
| Excavation method | Bench cut | **Full face** |
| Thickness of S/c (mm) | 80 | **50** |
| Transverse interval of R/B (m) | 2.0 | 2.0<br>**Random bolt if necessary** |
| Length of R/B (m) | 4.0 | **3.0** |

For Grade Ⅱ rock, a conservative design approach suggests that a shotcrete thickness of 50mm and a rock bolt length of 3.0m are applicable for road-header excavation. In particular, when discontinuities are favorably developed, applying random bolts with 50mm shotcrete results in safety factors of 7.1 for the rock bolts and 4.0 for the shotcrete, indicating that the use of random bolts is feasible. However, if the discontinuity conditions are unfavorable from a tunneling perspective, there is a risk of key block fallouts, and thus the application of random bolts should be carefully evaluated.

The normalized maximum displacements for the crown and sidewall using the primary support pattern (Case A) in Drill and Blast and various support cases in the Road-Header method for Grade Ⅲ rock are summarized in Table 11. In the Drill and Blast method, the maximum displacements were 1.3 mm at the crown and 0.61 mm at the sidewall. In contrast, the Road-Header maintained crown displacements of approximately 1.0mm and sidewall displacements of 0.48mm across all support cases. This corresponds to about 80% of the displacement observed in the Drill and Blast method, indicating that even with reduced support, as in Case D, structural stability can still be effectively maintained.

**Table 11** Maximum Displacement by support case in GradeⅢ Rock

| Excavation method | Rock Grade | Crown Displacement (mm) | Side wall Displacement (mm) |
|---|---|---|---|
| Drill and blast | Ⅲ | 1.3 (▲30.0%) | 0.61 (▲27.0%) |
| Road-header | Ⅲ | 1.0 | 0.48 |

In the Drill and Blast method with the primary support pattern (Case A), the axial force in rock bolts and the flexural compressive stress in shotcrete were 29.4kN and 1.77MPa, respectively, as shown in Fig.10. Under the same support condition, the road-header method (Case A) exhibited reduced values of 22.6kN and 1.32MPa, which is attributed to the enhanced rock mass properties reflected by the RMR14 classification. In the road-header cases with gradually reduced support (Cases B–D), the axial force in rock bolts increased from 23.2kN to 28.9kN, primarily due to the increased bolt spacing (from 1.5m to 2.0m), which led to stress concentration. The shotcrete stress also increased from 1.41MPa to 1.78MPa as support components were reduced. These results indicate that rock bolt quantity and spacing significantly influence axial force distribution, while shotcrete thickness and full-face excavation contribute to stress concentration in support members.

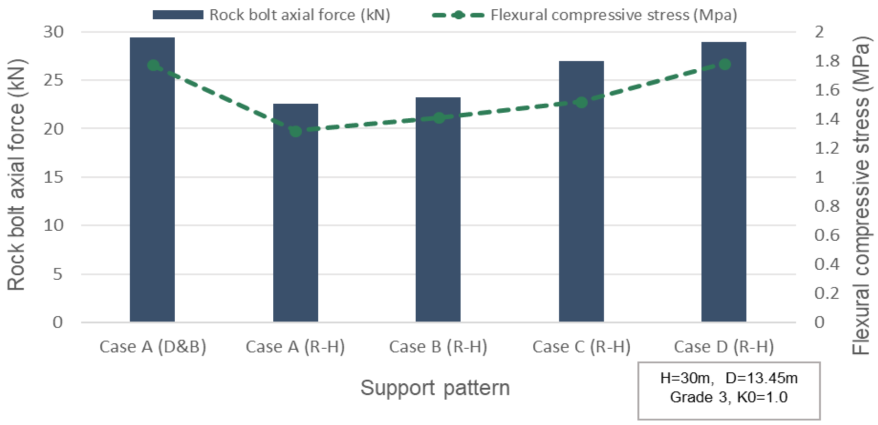



**Fig. 10** Rock bolt and shotcrete stresses by support cases in grade Ⅲ rock

In Case D, where the shotcrete thickness was reduced to 60mm and the rock bolt spacing was increased to 2.0m, the structural behavior remained comparable to that of the Drill and Blast method, as shown in Fig. 11. The safety factors also remained relatively high, with values of 3.07 for the rock bolts and 4.72 for the shotcrete. These results indicate that structural requirements can be satisfied even with a reduced support quantity compared to the standard Drill and Blast pattern, suggesting that practical support optimization is achievable with the road-header method.

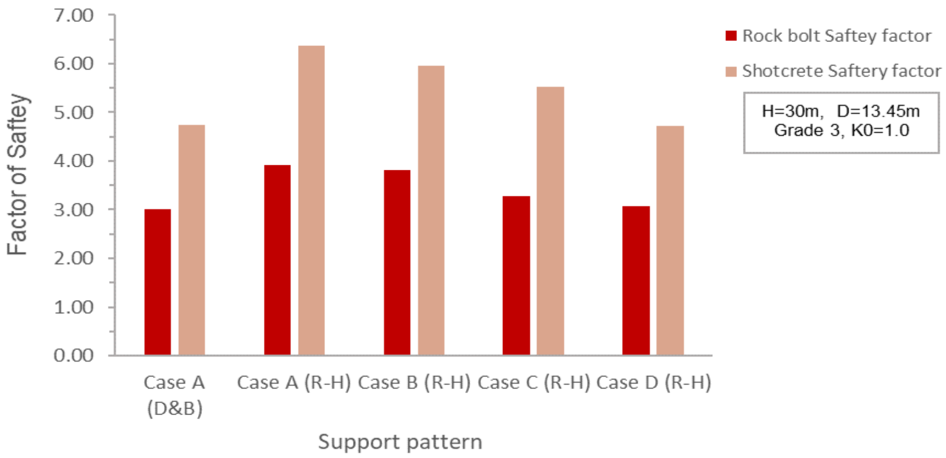



**Fig. 11** Safety factors of rock bolts and shotcrete for drill and blast and road-header methods by support cases in gradeⅢ rock

Under GradeⅢ rock conditions, when applying the road-header method, it is considered appropriate to adopt a conservative design approach that ensures both structural stability and construction efficiency. Accordingly, the shotcrete thickness is recommended to be applied within the range of 60 mm to 80 mm. Additionally, an optimized support configuration is proposed, as summarized in Table 12, in which the transverse spacing of rock bolts is increased from the conventional 1.5 m to 2.0 m.

**Table 12** Support pattern improvement plan for road-header in grade Ⅲ rock

| Support Pattern | PD-3 (NATM) | PD-3 (Road-Header) |
|---|---|---|
| RMR | 60~41 | 60~41 |
| Excavation method | Bench cut | **Full face** |
| Thickness of S/C (mm) | 100 | **60~80** |
| Transverse interval of R/B (m) | 1.5 | **2.0** |
| Length of R/B (m) | 4.0 | 4.0 |

The normalized maximum displacements at the crown and sidewall for the primary support pattern (Case A) of the Drill and Blast method and various support cases of the road-header method in Grade IV rock are summarized in Table 13. In the Drill and Blast method, Case A showed crown and sidewall displacements of 3.07 mm and 1.48 mm, respectively. In contrast, the road-header method across Cases A–D exhibited average displacements of 2.44 mm at the crown and 1.17 mm at the sidewall. These results indicate that even with reduced support, the road-header method maintains stable behavior compared to the Drill and Blast method.

**Table 13** Maximum Displacement by support case in GradeⅢ Rock

| Excavation method | Rock Grade | Crown Displacement (mm) | Side wall Displacement (mm) |
|---|---|---|---|
| NATM | Ⅳ | 3.07 (▲25.8%) | 1.48 (▲26.5%) |
| Road-header | Ⅳ | 2.44 | 1.17 |

As shown in Fig. 12, the Drill and Blast method with the primary support pattern (Case A) produced a rock bolt axial force of 64.7kN and a shotcrete flexural compressive stress of 6.96MPa. Under the same support condition, the road-header method resulted in lower values of 53.2kN and 6.20MPa, respectively, which can be attributed to the structural effect of enhanced rock mass properties based on the RMR14 classification.

In the road-header cases with gradually reduced support (Cases B–D), the axial force increased from 53.2kN to 60.9kN. Particularly in Cases C and D, increasing the bolt spacing from 1.2m to 1.5m led to localized stress concentrations. The shotcrete flexural compressive stress also increased with support reduction, reaching 7.13MPa in Case C and 8.45MPa in Case D, exceeding the allowable stress limit of 8.4MPa. Therefore, under the conditions of Case D, reducing the shotcrete thickness to 80mm or less is deemed structurally inadequate, indicating that this configuration approaches the design limit.

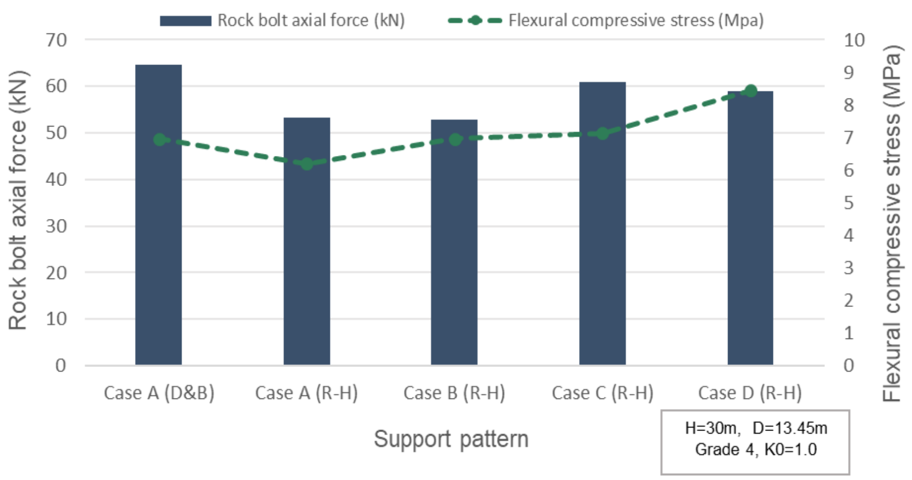



**Fig. 12** Rock bolt and shotcrete stresses by support cases in gradeⅣ rock

In Case C, where the shotcrete thickness was set to 100mm and the rock bolt spacing to 1.5m, the structural behavior remained similar to that of the primary support pattern used in the Drill and Blast method, as shown in Fig. 13. The safety factors for the rock bolts and shotcrete were 1.46 and 1.18, respectively, indicating a stable performance. In contrast, Case D—where the shotcrete thickness was reduced to 80mm—resulted in stress levels exceeding the allowable limit of 8.4MPa, indicating insufficient structural stability. These findings suggest that the road-header method can satisfy structural requirements even with reduced support quantities compared to the standard Drill and Blast pattern, highlighting the potential for practical support optimization.

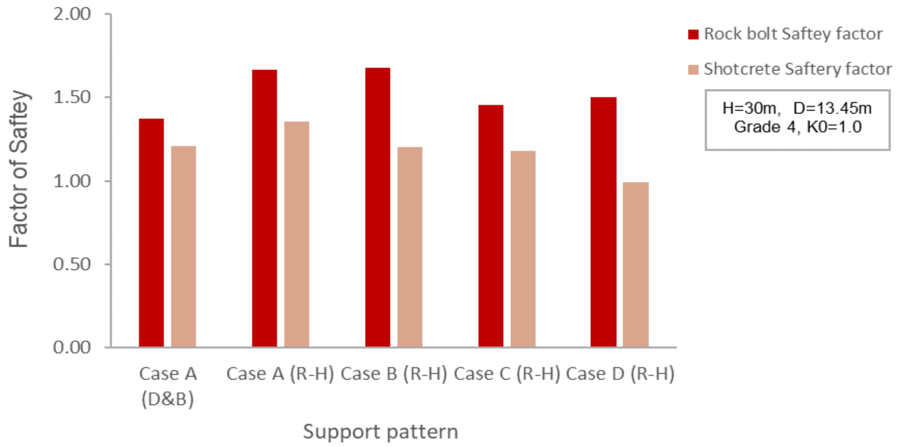



**Fig. 13** Safety factors of rock bolts and shotcrete for drill and blast and road-header methods by support cases in grade Ⅳ rock

For Grade IV rock, applying the road-header method requires the use of a sequential excavation approach to ensure face stability, as summarized in Table 14. Shotcrete thickness should be conservatively set at 100mm, considering both structural safety and construction efficiency. Given the high potential for flexural stress in this rock class, maintaining a minimum shotcrete thickness of 100 mm is essential. In addition, rock bolt spacing is optimized from 1.2m to 1.5m to enhance constructability and support interaction.

**Table 14** Support pattern improvement plan for road-header in grade Ⅳ rock

| Support Pattern | PD-4 (NATM) | PD-4 (Road-Header) |
|---|---|---|
| RMR | 40~21 | 40~21 |
| Excavation method | Bench cut | Bench cut |
| Thickness of S/C (mm) | 120 | **100** |
| Transverse interval of R/B (m) | 1.2 | **1.5** |
| Length of R/B (m) | 4.0 | 4.0 |

## 5. Conclusions

This study investigated the potential for optimizing support patterns for the road-header method by reflecting the extent of the Excavation Damaged Zone (EDZ) formed during tunnel excavation using both the Drill and Blast and road-header methods. Structural stability was comprehensively evaluated by analyzing displacements and support stresses under rationally reduced support cases. Based on these analyses, improved support patterns applicable to road-header excavation were proposed. The key findings of the study are summarized as follows:

1) The analysis considering the size of the Excavation Damaged Zone (EDZ) showed that the road-header method results in lower displacements and support stresses compared to the drill and blast method. Due to the smaller EDZ, the road-header maintained crown displacements at 51% and support stresses at 75% of those in drill and blast, even under reduced support conditions. This suggests that the road-header method allows for more economical support design while maintaining structural stability.

2) In practical tunnel design, it is uncommon to directly incorporate the Excavation Damaged Zone (EDZ), and overestimating its effects may lead to unrealistic predictions of tunnel displacements and support stresses. To address this, the present study applied the RMR14 classification system to evaluate the feasibility of optimizing support patterns for the road-header method. The results showed that even under reduced support conditions, the crown displacement remained at approximately 80% of that observed with the standard support pattern of the drill and blast method. Additionally, analysis of support stresses and safety factors confirmed that structural stability could still be sufficiently maintained.

3) The applicability of support pattern optimization for the road-header method was evaluated using RMR14 system under practical conditions in Grade II– IV rock. The analysis showed that shotcrete thickness can be reduced by up to 30%, and the lateral spacing of rock bolts can be increased by up to 30% without compromising structural stability. In Grade II rock, if discontinuities are favorably developed, the application of random bolts may be feasible, provided that a thorough preliminary assessment is conducted. Conversely, in Grade IV rock, maintaining a minimum shotcrete thickness of 100 mm is essential to ensure excavation stability during construction.

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