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Evaluation of Roadheader Performance Under Mixed-Face Conditions: A Case Study

*Pedram Zoughy[1)], Hamed Lamei Ramandi[2)], Jamal Rostami[3)], Joung Oh[4)]

[1), 2), 4)] *School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney, NSW 2052, Australia*
[3)] *Colorado School of Mines, 1500 Illinois St, Golden, CO 80401, USA*
[1)] *p.zoughy@unsw.edu.au*

ABSTRACT

Mixed-face conditions represent some of the more complex settings in tunnelling. They are often encountered in Sydney tunnelling projects, where Hawkesbury Sandstone is interbedded with shale and occasionally intersected by dolerite dykes. These heterogeneous face conditions significantly affect roadheader performance due to variations in cuttability, abrasivity, and structural integrity. This study presents a field-based evaluation of roadheader performance, focusing on selected sections of a Sydney tunnel project across three dominant geological settings: sandstone-dominated faces, mixed sandstone and shale faces, and sandstone with dolerite intrusions. Key performance indicators include daily advance rate (AR_d) and cutter consumption rate (CCR). These parameters were analysed in conjunction with support intensity and excavation processes.

Results indicate that sandstone-dominated faces provided the most favourable tunnelling conditions, achieving the highest average AR_d of 6.5 m/day and a CCR of 0.15 $picks/m^3$. In contrast, dolerite intrusions caused a threefold increase in pick consumption (0.46 $picks/m^3$) and resulted in the lowest average AR_d of 2.6 m/day, due to their high abrasivity and intense jointing. Although the presence of shale improved cuttability and resulted in the lowest CCR (0.11 $picks/m^3$), it required denser support systems, which ultimately reduced the average advance rate to 3.7 m/day.

These findings highlight the critical role of geological variability in tunnelling efficiency and underline the importance of accurate geological characterisation for performance prediction, planning, and cost control in mixed-ground tunnelling.

1. INTRODUCTION

Mixed-face conditions present a challenge in tunnelling, particularly within Sydney's

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[1)] PhD Candidate
[2)] Senior Lecturer
[3)] Professor
[4)] Associate Professor

Hawkesbury Sandstone formation. Tunnel faces in this region often comprise a combination of sandstone, interbedded shale lenses, and occasional intrusive dolerite dykes (Pells et al. 1980; Zhang et al. 2010). These geological variations result in substantial differences in rock mass cuttability, abrasivity, and structural integrity (Fowell and Johnson 1981; Vergara and Saroglou 2017), leading to fluctuations in roadheader performance and support requirements.

Understanding roadheader behaviour under such variable conditions is essential for accurate performance prediction, budgeting, planning and risk mitigation (Zhao et al. 2007). While numerous studies have investigated roadheader performance in coal seams (Dibvar et al. 2023; Kahraman et al. 2023a; Rostami et al. 2024), sedimentary rocks (Ocak and Bilgin 2010; Kahraman and Kahraman 2016), metamorphic formations (Thuro and Plinninger 1999; Jung et al. 2023), and igneous rocks (Comakli 2019), performance under mixed-face conditions remains underexplored.

This paper presents a field-based assessment of roadheader performance in a Sydney tunnelling project, focusing on the impact of mixed-face conditions containing sandstone, shale, and dolerite. By analysing key performance metrics across different excavation face types, the study aims to provide practical insights for improving excavation efficiency and optimising cutter usage for effective planning and decision-making in mixed-face geological settings.

2. GEOLOGICAL AND GEOTECHNICAL SETTING

The tunnel alignment passes through a geologically complex region of the Sydney Basin, predominantly comprising Triassic-aged Hawkesbury Sandstone. Three representative faces were selected for performance analysis, including (i) sandstone-dominated faces without major discontinuities (Fig. 1a), (ii) sandstone intersected by dolerite dykes (Fig. 1b), and (iii) mixed sandstone and shale faces (Fig. 1c).

Although the proportion of individual rock mass types varied from face to face, the classification was based on the persistent presence of those lithologies across the selected sections. To minimise the influence of structural discontinuities and focus on lithological effects, the analysed sections were selected from areas not affected by faulting or extensive jointing, with similar estimated intact rock properties for each rock type.

Fig. 1 Selected face types: (a) sandstone-dominated faces; (b) sandstone with dolerite dyke; (c) mixed sandstone and shale faces

Hawkesbury Sandstone mainly consists of medium- to coarse-grained quartzose sandstone, typically occurring in horizontal beds ranging from 1 to 3 m thick. These sandstones often contain small fragments of shale clasts. The uniaxial compressive strength (UCS) of fresh sandstone varies between 12 and 50 MPa. Abrasivity is moderate to relatively high, with a cerchar abrasivity index (CAI) ranging from approximately 2 to 3. The selected sandstone-dominated section often exhibits excellent rock quality, with a rock quality designation (RQD) greater than 90% and minimal jointing.

Shale lenses, interbedded within the sandstone, represent thin marine-deposited layers, usually 1–3 m thick. These materials are highly laminated (flaky) and exhibit lower strength, with UCS values generally between 7 and 38 MPa. Their texture contributes to higher cuttability and low abrasivity ($CAI \approx 1$). However, their poor structural integrity often necessitates denser roof support systems.

Doleritic dykes with steep angles (typically 70–80° dip) are present within Hawkesbury Sandstone. They vary in width from about 0.5 meters to more than 5 m and often intersect tunnel alignments in Sydney. These dykes are composed of a high-strength, highly abrasive core (UCS greater than 100 MPa, $CAI \approx 4$), encased by margins that exhibit moderate to intense weathering, with weathering progressing inward from the outer edges toward the core. They are generally heavily jointed throughout, with features such as calcite/chlorite veining and closely spaced fractures, which further complicate excavation and support.

3. METHODOLOGY AND PERFORMANCE METRICS

This study is based on the field data collected during the excavation of a twin road tunnel in Sydney. Excavation was carried out using 300 kW transverse-type roadheaders (Sandvik MT720) at varying geological conditions within Hawkesbury Sandstone, with different proportions of shale and dolerite present at the tunnel face. To evaluate the influence of mixed-face conditions on roadheader performance, two key metrics were analysed: cutter consumption rate (CCR) and daily advance rate (AR_d). CCR quantifies the number of picks consumed (N_P) per volume of excavated rock (V) (Copur et al. 1998; Comakli and Bayramov 2024):

$$CCR\ (picks/m^3) = \frac{N_P}{V} \tag{1}$$

AR_d represents the actual tunnelling progress, defined as the length of tunnel excavated per day, incorporating net cutting time, other operational activities, and delays (Hojjati et al. 2022; Kahraman et al. 2023b):

$$AR_d(m/day) = \frac{V_d}{A} \tag{2}$$

$$V_d\ (m^3/day) = ICR \times MU \times WT_d \tag{3}$$

Where V_d is the daily excavated volume (m^3/day), A is the tunnel cross-sectional area (m^2), ICR represents the instantaneous cutting rate (m^3/h), MU is the machine utilisation ($\%$), and WT_d indicates the daily working time (h/day). ICR reflects the production rate during active cutting periods (Zhang et al. 2017). It is calculated by dividing the excavated rock volume, V, by the net cutting time (NCT), which refers to the period when the cutterhead is in actual contact with the rock mass. This excludes delays due to other activities, such as support installation, mucking, loading, pick replacements, maintenance, equipment downtime, manoeuvring, and trimming (Copur et al. 2011; Restner and Plinninger 2015):

$$ICR\ (m^3/h) = \frac{V}{NCT} \tag{4}$$

MU denotes the proportion of net cutting time relative to the total available time in a given period (e.g., a shift). It typically decreases in complex geological settings, especially where frequent pick replacement, heavy support installation and/or shorter advance length are required (Copur et al. 1998):

$$MU\ (\%) = \frac{NCT}{Total\ Available\ Time} \times 100 \tag{5}$$

To account for excavation processes and support requirements, two supplementary parameters were also evaluated: advance length per cut (ALC) and bolt density (BD). ALC refers to the average excavation length per individual cut (m/cut), and BD indicates the average number of bolts installed (N_B) per unit area of the tunnel roof, reflecting support system intensity:

$$BD\ (bolts/m^2) = \frac{N_B}{A_{roof}} \tag{6}$$

Where A_{roof} is the area of the tunnel roof (m^2) requiring rock bolt installation, also known as ground support zone in the roof.

4. RESULTS AND DISCUSSION

Fig. 2 illustrates the variation in AR_d (blue diamonds) and CCR (red squares) over the 16-month excavation period. While the full dataset across all excavated sections is presented, the performance analysis in this study focuses on the three distinct geological conditions—sandstone with dolerite dyke (month 5), sandstone-dominated faces (months 7–9), and sandstone with shale (months 14–15)—highlighted by black-framed sections in the figure. The remaining sections were excluded from detailed analysis due to the influence of structural geological features (e.g., joint sets and faults), operational and managerial variability, or incomplete data. This exclusion ensures that the comparison remains consistent, controlled, and representative of performance under clearly defined lithological conditions.

Each segment is annotated with the corresponding ALC and BD, reflecting excavation patterns and support requirements under different lithologies. Both ALC and BD are strongly influenced by rock mass characteristics. In weak ground conditions, higher bolt densities are often necessary to meet the required safety levels, which significantly increase support installation time and directly reduce MU. Additionally, shorter advance lengths are typically adopted to control the risk of rock falls. These shorter cuts increase the frequency of excavation cycles (cutting, mucking, loading, support installation, machine repositioning, etc.), leading to longer delays and ultimately resulting in reductions in both MU and AR_d.

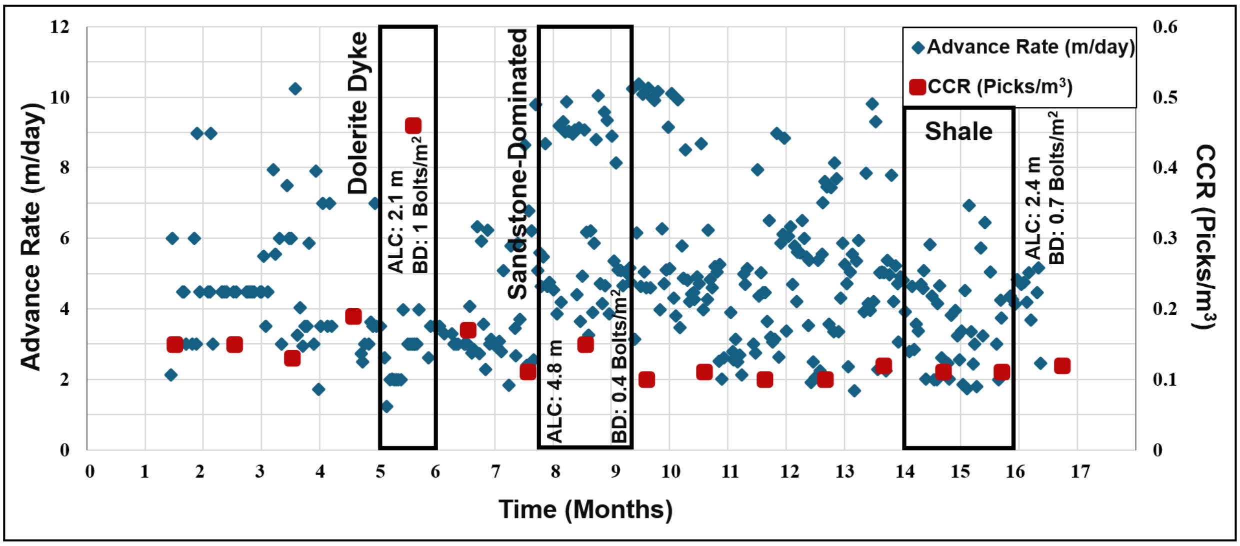

Fig. 2 Variation of AR_d and CCR over the 16-month tunnelling period, with study areas highlighted

A summary of roadheader performance, average cut lengths, and support requirements for the three selected face conditions is presented in Table 1.

Table 1 Summary of roadheader performance, cut lengths, and support intensity under different face conditions

Face Type	AR_d (m/day)			CCR $(picks/m^3)$	ALC (m/cut)	BD $(bolts/m^2)$
	Ave	Min	Max			
Full Sandstone	6.5	3.3	10.2	0.15	4.8	0.4
Sandstone + Dyke	2.6	1.2	4	0.46	2.1	1.0
Sandstone + Shale	3.7	1.8	6.9	0.11	2.4	0.7

The results reveal three distinct behavioural patterns corresponding to the dominant lithology at the tunnel face. Sandstone-dominated faces (Fig. 1a) offered the most favourable excavation conditions. The high rock quality and minimal jointing enabled longer advance lengths per cut ($ALC = 4.8\ m/cut$) and required minimal ground support requirements ($BD = 0.4\ bolts/m^2$). These conditions facilitated the highest average AR_d of 6.5 m/day, with a peak value of 10.2 m/day.

In contrast, dolerite dyke intrusions (Fig. 1b) significantly impaired excavation performance. CCR approximately tripled from 0.15 to 0.46 $picks/m^3$ due to dolerite's high strength and abrasivity, resulting in more frequent pick replacements and increased maintenance needs, which reduced MU. ALC decreased by 56% (from 4.8 to 2.1 m/cut), and the highest bolt density ($BD = 1\ bolts/m^2$) was required, further lowering MU. These combined factors led to the lowest recorded AR_d values, with an average of 2.6 m/day and a minimum of 1.2 m/day. Notably, the magnitude of changes in CCR and AR_d was closely related to the proportion of dolerite at the face: higher dolerite content corresponded to greater tool wear and lower excavation efficiency.

In the mixed sandstone-shale faces (Fig. 1c), the presence of shale resulted in a CCR reduction to 0.11 $picks/m^3$ (a 27% decrease from sandstone-dominated faces), reflecting shale's lower abrasivity and higher cuttability. However, despite improved cutting conditions and a higher ICR, the average AR_d still declined to 3.7 m/day (minimum: 1.8 m/day). This was primarily due to reduced MU, driven by increased roof support requirements ($BD = 0.7\ bolts/m^2$) and shorter advance lengths ($ALC = 2.4\ m/cut$). Thus, while greater shale content in the face improved cutting efficiency, its structural weakness necessitated operational adjustments that ultimately constrained daily advance.

These findings clearly demonstrate that mixed-face conditions—particularly the presence and proportion of dolerite and shale within the Sydney Sandstone formation—play a critical role in determining roadheader performance, support demands, and overall excavation efficiency.

5. CONCLUSIONS

This study investigated roadheader performance under mixed-face conditions commonly encountered in Sydney's Hawkesbury Sandstone formation. Field data from selected excavation sections revealed significant variations in performance associated with three dominant lithologies: sandstone-dominated faces, sandstone intersected by dolerite dykes, and sandstone with shale lenses.

Sandstone-dominated faces without significant discontinuities provided the most favourable conditions for tunnelling, enabling efficient excavation and the highest daily advance rates. In contrast, dolerite intrusions led to a sharp decline in excavation performance, marked by increased pick consumption, reduced advance lengths, and intensified ground support, resulting in the lowest observed AR_d. Shale lenses enhanced cuttability and reduced cutter wear, yet their poor structural integrity necessitated higher support densities and shorter advance lengths, ultimately limiting productivity despite favourable cutting conditions. The magnitude of performance variation was closely tied to the proportion of dolerite and shale at the tunnel face. An increase in dolerite content was associated with higher CCR and lower AR_d, while greater shale content resulted in lower CCR but also reduced AR_d.

These findings highlight the need for detailed geological characterisation—particularly the early detection of intrusive dykes and laminated shale zones—to enable accurate performance prediction and informed excavation planning. To enhance roadheader efficiency under variable ground conditions, future research should focus on integrating real-time geological mapping with adaptive excavation strategies. This integration aims to improve machine utilisation, optimise support design decisions, and enhance overall tunnelling productivity.

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