An Overview of Mined Tunnel Design in the Kingdom of Saudi Arabia: Constraints and Optimizations

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ABSTRACT

In recent years, Saudi Arabia has experienced a significant increase in civil engineering projects, driven by the government's Vision 2030 initiative to diversify the economy and improve national infrastructure. The paper highlights key considerations addressed the authors in the project practices that distinguish tunnel designs in the Kingdom of Saudi Arabia (KSA) from typical tunnel projects in Hong Kong. These include unique geological, geotechnical and seismic considerations. Additionally, it explores the use of different rock mass classification approaches in local tunnel design, and section geometry optimization strategies. The study also addresses environmental and aesthetic considerations in KSA tunnel design projects, emphasizing the importance of balancing technical requirements with broader social and environmental impacts. This paper underscores how international consultants contribute to advancing best practices in tunnel design and construction within KSA's dynamic engineering landscape.

1. INTRODUCTION

The Kingdom of Saudi Arabia (KSA) is currently experiencing a transformative phase of rapid infrastructure development, driven by its Vision 2030 initiative, which aims to diversify the economy and improve national infrastructure. As part of this ambitious plan, the construction of tunnels has become a critical component in supporting the nation's transportation networks and utility systems.

As Hong Kong consultants increasingly participate in infrastructure projects in the KSA region, this paper provides an overview of distinctive considerations in tunnel design within the KSA context relative to practices in Hong Kong. The study is based on our mined tunnel design practices in KSA's mountainous and low-lying coastal areas, predominantly utilizing the Drill and Blast technique for excavation purposes, with a primary function of accommodating transportation and utility transitions.

This paper first discusses geological characteristics, geotechnical constraints and rock mass classification methodologies pertinent to tunnel design in the KSA (Chapters 2-4). Chapter 5 investigates key elements of tunnel cross-sectional geometry and methodologies for optimizing design parameters to ensure a holistic approach that balances functionality, safety, and economic viability. Finally, Chapters 6 and 7 address environmental and aesthetic considerations of tunnel design in the KSA, emphasizing region-specific constraints and solutions.

2. GEOLOGICAL AND GEOTECHNICAL CONDITION

The geological condition in KSA is diverse and complex, significantly influencing the design and construction of infrastructure projects, including tunnels. The western region, dominated by the igneous rock of the Arabian Shield, is well-suited for mined tunnelling due to the high rock strength yet pose issues related to fracturing and jointing. The central and eastern regions predominantly consist of sedimentary rocks like limestone and sandstone, which pose issues related to aquifers and the presence of karst features. Coastal areas, particularly along the Red Sea, feature sabkha soils and high groundwater levels, posing challenges such as soil compressibility and seawater intrusion. In each case, treatment and support types will vary based on the prevailing site conditions.

2.1 Regional Geology

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The northwestern corner of the Arabian Peninsula called Midyan Peninsula is part of the crystalline shield of the Arabian plate. The structural style of this region appears to be controlled by the evolution of active faulting, with three recognized systems N-S, NW-SE, and E-W, respectively. These regional fault systems, actively control the sedimentary history of the basin. The Precambrian basement rocks consist mainly of granitic rocks intruded by basalt, rhyolite, and andesite dykes trending to the N and the NE. The Miocene and Pliocene rocks are mainly represented by a thick-sedimentary succession. Quaternary deposits are mainly represented by raised reefal limestones (Pleistocene), terraces of gravels and sands, gravel sheets, sabkha, eolian sand dunes, alluvial outwash (Holocene), and fringing reefs with saline sands (Recent).

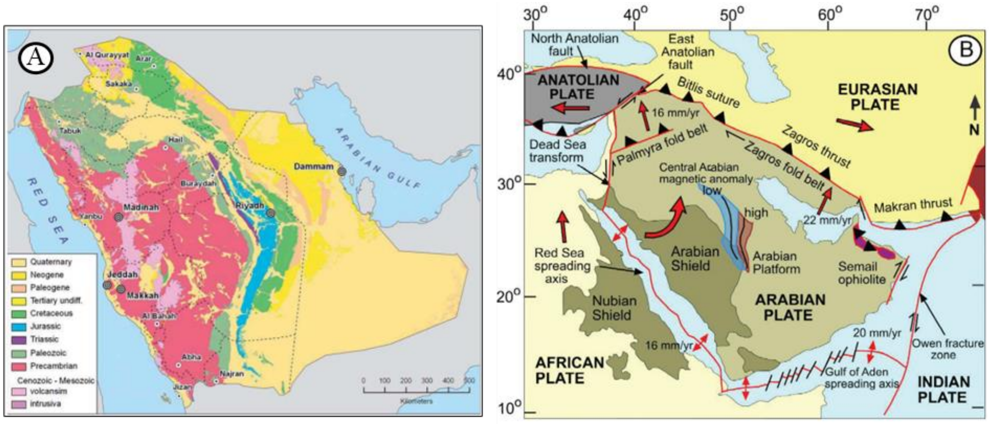

Figure 1 - (A) Simplified geological map of KSA (Al Saud & Rausch, 2012); (B) Tectonic map of the Arabian and East African plates (Stern and Johnson, 2010).

2.2 Topography

The study area is contrasted by topographic highs and flat lands. The elevated terrain, at around 600m above sea level, comprises of Precambrian (>400 Ma) basement rocks; whilst the lower-lying flat land, around 10m above sea level, is composed mainly of Quaternary deposits (<10 Ma). The existing rugged mountains altitude ranges from 50 to 600m above sea level. Broad and narrow dry desert wadis intersect mountainous areas. Along the coast, steep mountains are either separated from the shoreline by a narrow littoral fringe or plunge directly into the sea. Raised Quaternary limestones occur at the mouths of the wadis draining into the sea. They range in elevation from several meters to about 20 meters. The wadis themselves are filled with alluvial deposits characterized by large boulders derived from the Precambrian bedrock.

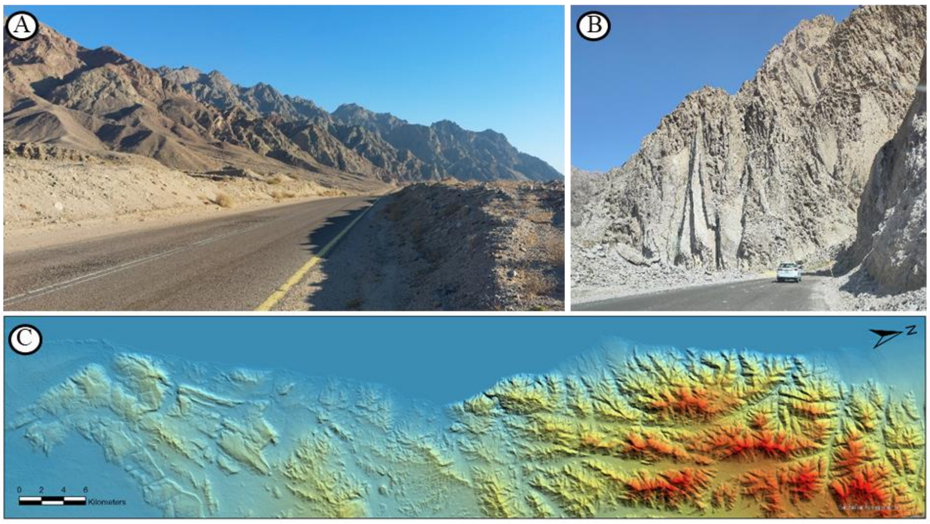

Figure 2 - (A) General topography of the study area; (B) Steep hillslope along the road; (C) Hillshade map of the study area

2.3 Geotechnical Constraints

Slope works for mined tunnel portals in this region required careful consideration of various geological hazards and their unique characteristics. Natural steep rock slopes are often characterized by fracturing and jointing of strong rock, exacerbated by erosion and seismic processes, where failure is controlled by discontinuities. Footslopes, formed of taluvium, present instability challenges due to the low shear strength of the of the unconsolidated rocky soil. Coastal areas are prone to Quaternary raised reefal limestones formed as shelves reef-building coral exposed during sea level regression or as a result of tectonic uplift. This irregular, porous and relatively weak structure is not controlled by jointing and will instead have issues related to bearing capacity or rotational / sliding failure in the mass. These varied conditions mean that both natural or cut slopes require different systems to assess and analyze as part of tunnel portal design works. The Q-system, GSI, RMR and Hoek-Brown failure criterion were used to assess the stability and mechanical behaviour of jointed, intact rock and heavily jointed rock masses.

The northeastern coastal region is prone to earthquakes, with magnitudes ranging from 5.5 to 6.0 on the Richter scale. The NNE-SSW trending Aqaba fault system and its branching faults represent one of the most tectonically active faults with the highest concentration of earthquakes in the Middle East.

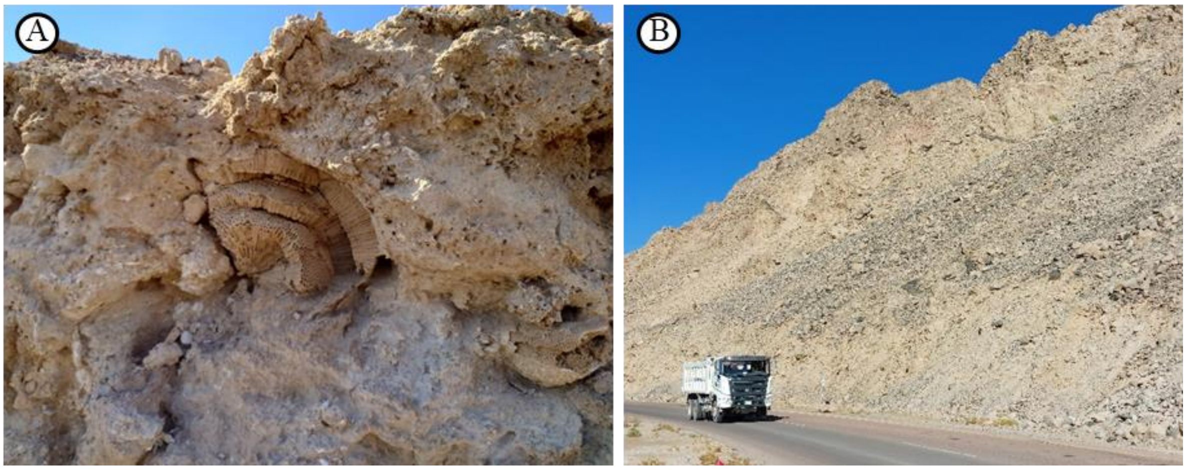

Figure 3 - (A) Reefal limestone; (B) Taluvium slope

Table 1 : Geotechnical Constraints

Identified Geohazard	Potential Impact

Quaternary reefal limestones	• Collapse associated with dissolution infill of cavities by weak material • Settlement and low bearing capacity due to the low shear resistance and high porosity
Taluvium / hillside accumulation / transported accumulation at slope toe (including lateral spread or flow slides)	• Increased foundation depths or robust stabilization measures • Difficulties in infrastructure construction on the strata • More challenging to reuse poorly sorted excavated material
Rock fall or debris flow	• High-cost remedial measures required due to highly fractured rock / taluvium on portal slopes
Liquefaction / dry sand settlement	• Increased foundation depths and/or footprint
Seismicity	• Liquefaction of soft / loose material • Affect previously stable rocks • Structural damage to infrastructure and services • Loss of life

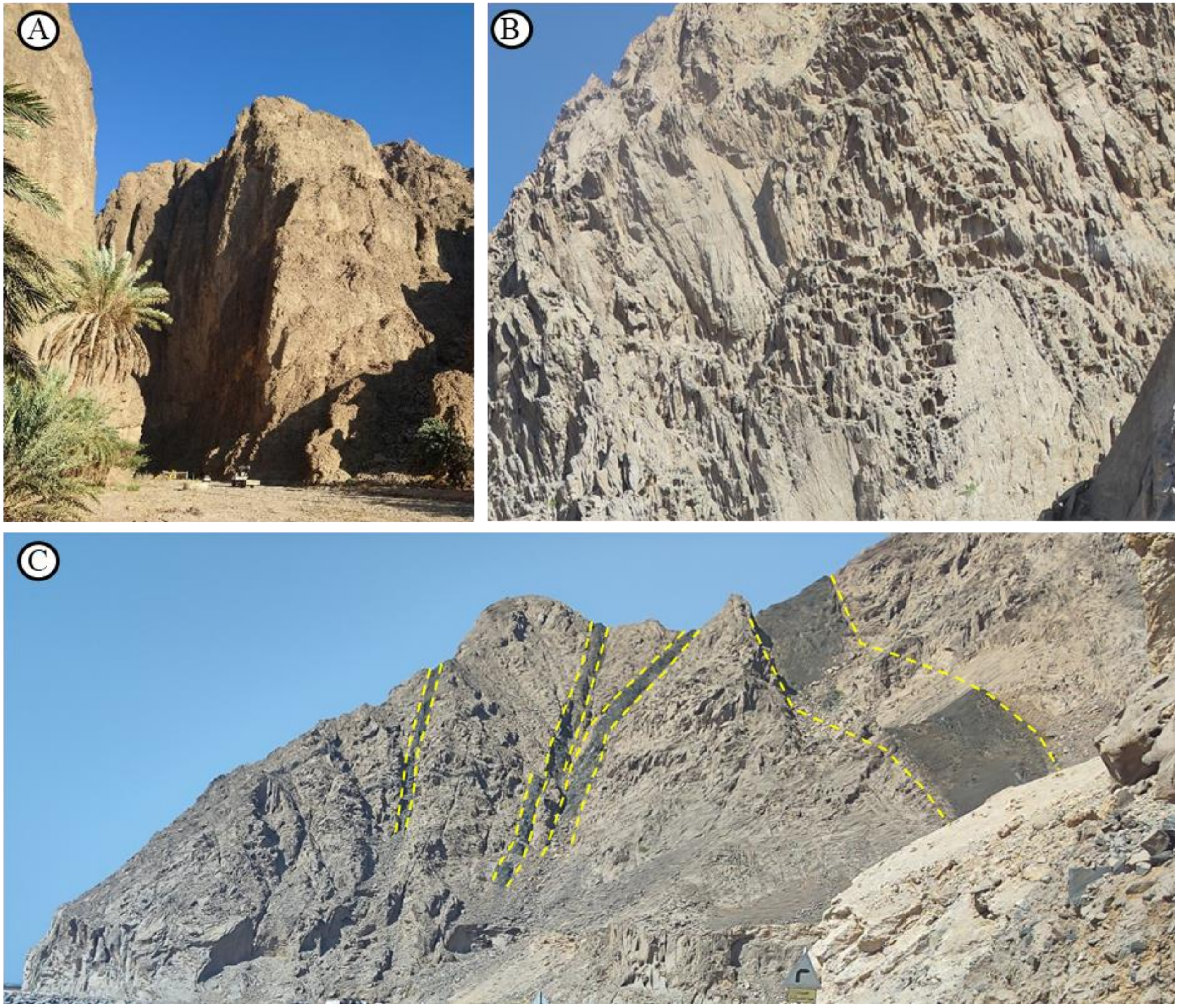

Figure 4 - (A) Wadi channel cutting through steep mountainous terrain; (B) Tafoni weathering pattern observed on a rocky cliff face showcasing intricate honeycomb-like structures; (C) Dykes cross cutting the granitic terrain

3. SEISMIC CONSIDERATION

Seismic design considerations for tunnels and infrastructure in KSA and Hong Kong (HK) differ significantly due to contrasting geological and tectonic settings. KSA, located on the stable Arabian Plate, experiences low to moderate seismic conditions, with risks concentrated near the Red Sea Rift Zone. As a result, seismic design in KSA is typically site-specific for most infrastructure, except in high-risk zones where localized fault activity and liquefaction risks may necessitate detailed analyses. KSA's codes (e.g., Saudi Building Code SBC-301-CR) apply seismic measures selectively based on localized tectonic risk.

Tunnel structures, in general, are subject to less impact from earthquake effects compared to above-ground structures. The procedure for seismic design and analysis for underground tunnel structures is recommended to be based on the ground deformation approach (FHWA, 2009). In contrast, the surface tunnel facilities such as the tunnel portal, earth retaining structures and portal slopes are designed based on the inertial force approach. For underground tunnel structure seismic analysis, at least three response-spectrum-compatible time histories were used for each component of motion (horizontal, longitudinal, and vertical) in representing the seismic design. The motion components in three directions are considered respectively. Dynamic time history analysis is performed in computer software MIDAS GTS NX to calculate the maximum response of the structure, which is adopted in LRFD load combination.

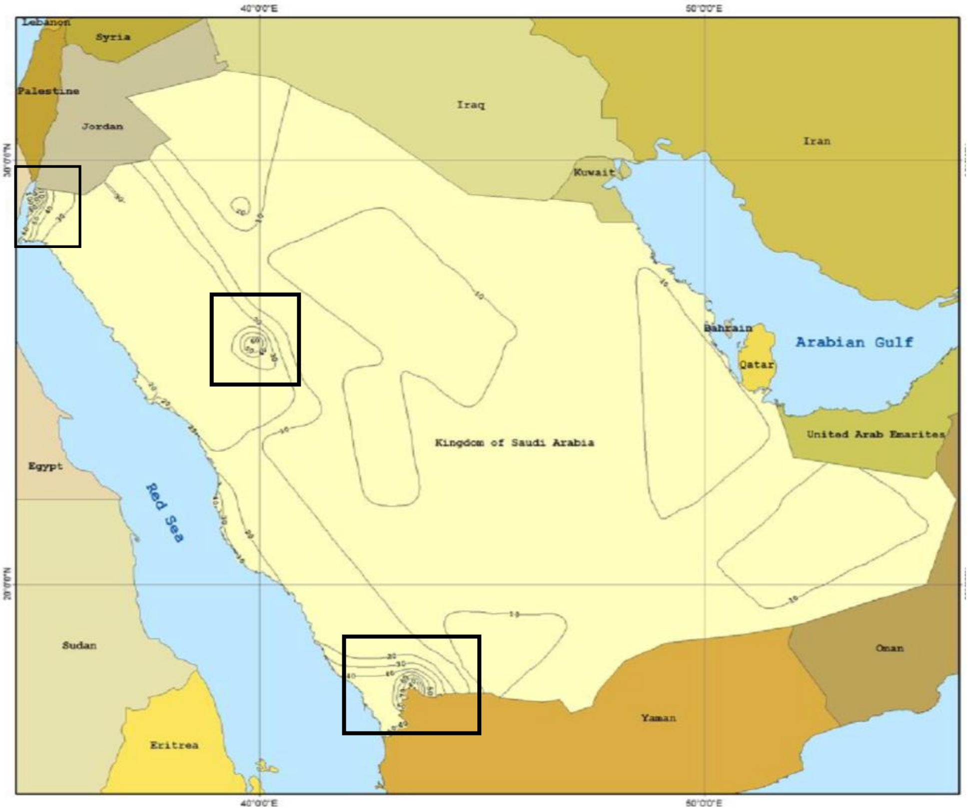

Figure 5 - Maximum Considered Earthquake Ground Motion for the Kingdom of 0.2 sec. Spectral Response Acceleration (Ss in %g) (5 percent of Critical Damping), Site Class B (MOMRA, 2013)

4. ROCK MASS CLASSIFICATION

The ground conditions of a tunnel case study were characterized by a strong rock mass intersected by a series of discontinuities, including faults, joints and dykes. These discontinuities meant the rock mass behaved as heterogeneous and discontinuous, in which the geotechnical properties and hydraulic conductivity were greatly impacted by spacing, continuity, orientation, aperture, and infilling of the discontinuities and must be defined for the rock mass as a whole based on zones apportioned along the tunnel alignment.

Field mapping records provided a foundational dataset for the area of this tunnel. RQD values were obtained from GI, whilst Q (NGI, 2022), GSI (Hoek & Brown, 1997) and RMR (Bieniawski, 1973) were recorded during geological mapping on site, see Table 2. Q-values for the tunnel alignment were derived from horizontal drillholes, nearby tunnel mapping, and field mapping integrated with satellite image interpretation. Additionally, high-resolution drone images were utilized to delineate faults and joints, enhancing the accuracy and extent of the analysis and the consistency with field mapping records. GSI values were obtained as an intermediate step in the design process for rock mass characterization through mapping or the well-established correlation with RMR.

Table 2 : Rock Mass Classification of a Case Study Tunnel

Area	Rock Type	RQD	Q-value	GSI	RMR
Mountainous	Granite	50-90	1.0-4.0	55	60
	Limestone	25-90	0.4-1.0	37	42
Coastal Low-lying	Sandstone	50-90	N/A	40	45
	Limestone	25-90	0.4-1.0	37	42
	Conglomerate	75-90	N/A	40	45

In Hong Kong, the Q-system (NGI, 2022) is the preferred classification method (Geoguide 4, 2018) and is extensively used in mined tunnel projects. In KSA, however, local codes (MOMRA, 2013) do not favor a specific empirical method, allowing for the use of Rock Loads (Terzaghi, 1946) & RQD (Deere, 1964), RSR (Wickham et al., 1972), RMR (Bieniawski, 1973) and the Q-system (NGI, 2022). Although historically more reliant on the RMR system, KSA's mined tunneling practices are now converging toward a hybrid approach that integrates both RMR and Q-system methods.

In our tunnel design practice for the KSA region, the Q-system was considered more applicable for tunnels with massive or variable spans compared to the RMR method. Therefore, the Q-system has been more applied during detailed and developed design stages, as well as for real-time support adjustments during construction. In a local mined tunnel project, the RMR method was employed in the conceptual design stage for the tunnel initial support design, particularly when the target tunnel span was around 10 meters. In this project, the RMR method was deemed applicable and intuitive for the earliest design phase. The adopted approach consisted of RMR values calculated directly from its principles rather than relying on Q-system correlations.

5. TUNNEL SECTION GEOMETRY OPTIMIZATION

5.1 Introduction

The geometric design of a mined tunnel section is an important aspect of tunnel design. This design decision not only affects the tunnel's structural stability, serviceability, inspectability, maintainability, and Fire-Life-Safety (FLS) performance but also impacts its economic viability and constructability (SHC 301 and 310, 2023). Furthermore, the tunnel span is often directly linked to support design parameters, with empirical methods like the Q-system and RMR method commonly used for this purpose. As a result, optimizing tunnel section geometry becomes a key consideration, offering significant advantages during the design phase.

The typical mined tunnel cross section elements are shown in the Figure 6. Tunnel span typically is affected by travel lane, shoulder, barrier, sidewalk and other elements. The summary of various codes' requirement regarding these elements and the optimization of tunnel geometry in KSA tunnel design practices is shown in Section 5.2.

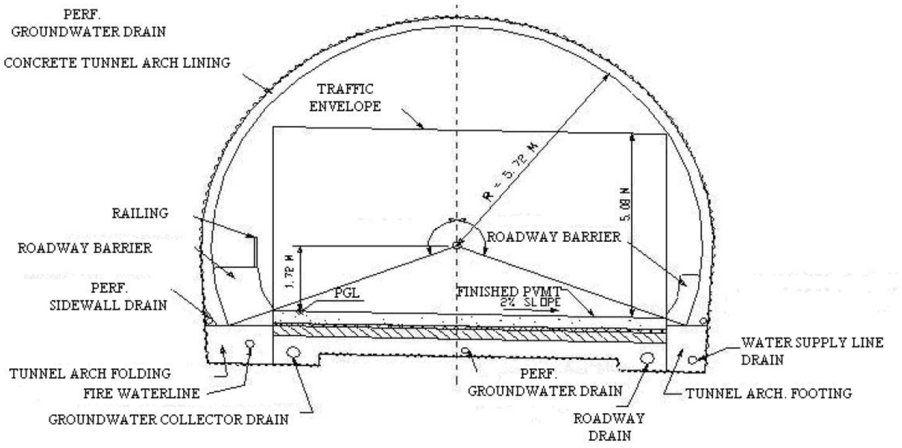

Figure 6 - Typical Two-Land Road Tunnel Cross Section and Elements (FHWA, 2009)

In KSA, the recent design of tunnels has focused on integration with new infrastructure assets, requiring meticulous planning for utility arrangements. Beyond the elements discussed above, the tunnel cross-section design also takes into account for the accommodation of utility systems, such as dry utilities (e.g., telecommunications and power cables), wet utilities (e.g., water and sewage systems), ICT infrastructure, and MEP & FLS (Mechanical, Electrical, Plumbing, and Fire Life Safety systems). Achieving a balance among these utilities is essential to ensure that tunnels fulfill both their primary transportation function and efficiently supports ancillary services. The design development of tunnel geometry through utility arrangement is presented in Section 5.3.

5.2 Tunnel Section Geometric Parameter

Comparing to Hong Kong infrastructure design which mostly take reference from European and British codes, KSA tends to reference American codes for infrastructure projects. However, European or British standards may be used in projects with European consultants or contractor involvement. Saudi Building Code (SBC) acts as an overarching framework for guiding the infrastructure design, mostly refers to American codes for tunnel-specific designs (e.g., AASHTO, ACI, NFPA 502, ASCE, and FHWA). In contrast, the Saudi Highway Code (SHC) integrates American codes, the European Union's Tunnel Directive 2004/54/EG, and German guidelines such as FGSV in tunnel geometric design requirements (SHC, 2023). It is therefore recommended to prioritize a hierarchy of applicable codes as an initial step in KSA tunnel design projects.

The standards and design manuals summarized in Table 3 are commonly referenced in KSA tunnel projects. They outline variations in recommendations for vertical clearance, shoulder width, sidewalk dimensions, and means of egress in a two-lane highway tunnel. It is important to acknowledge the cross-referencing and evolution of these design standards in tunnel design practices. For instance, FHWA (2009), the earliest design manual in Table 3, relies on outdated references such as the AASHTO Green Book (2004), necessitating alignment with its updated version in 2018. The latter has introduced stricter geometric recommendations (see Table 3, Column 3). Similarly, MOMRA (2013) draws heavily on the FHWA, AASHTO, and NFPA standards. Given the progressive revisions among these documents, the latest three: AASHTO (2018), SHC (2023) and NFPA 502 (2023) are considered more applicable for contemporary KSA tunnel design. Notably, NFPA 502 primarily provides guidelines for tunnel fire safety and ventilation design, while AASHTO and SHC are referenced for tunnel geometry requirements.

Table 3 : Geometric parameter requirements for a 2-lane tunnel in different codes

Reference Code	FHWA (2009)	MOMRA (2013)	AASHTO (2018)	NFPA (2023)	SHC (2023)
Vertical Clearance (m)	4.3-4.9	5.5	4.9	-	5.5

Horizontal Curb-Curb Clearance (m)	7.8	refers to FHWA and AASHTO	(26 ft) 7.9m	-	7.6
Shoulder Width (m)	0.6-3.0	refers to FHWA and AASHTO	0.6-3.0	-	-
Sidewalk Width (m)	0.5-0.7	0.9	1.1-1.5	1.12	1.0-2.2
Means of Egress (MOE)	Per NFPA502 (2023), Means of Egress (MOE) distance shall not be more than 300m (1000 ft), and most typical exit separations are between 30m and 200m, with minimum clear width of 1.12m..				Per SHC (2023), MOE distance is 300m.

Most codes typically do not impose strict or uniform regulations on geometric dimensions, but provide desirable guidelines (e.g., the AASHTO Green Book in 2018, for tunnels exceeding 60m in length), granting designers flexibility to optimize cost-effectiveness. For instance, some codes suggest that, considering additional construction cost, the inside shoulder can be eliminated, while the outside shoulder dimension is subject to a cost-benefit analysis and tunnel risk analysis (SHC, 2023). With appropriate design of road curbs and barriers aligned to the design speed, it is also acceptable to further reduce the shoulder width. This allows designers to optimize tunnel geometry based on project-specific factors like tunnel function (cable or road tunnel), design speed, location (urban or rural), traffic direction (unidirectional or bidirectional), lane count, and other parameters, ensuring functionality, safety, and economic efficiency.

Both the KSA standard (MOMRA, 2013) and American code (AASHTO, 2020) have indicated that the proper selection of road barriers can effectively absorb collision loads in tunnels (Table 4). As previously noted, the AASHTO (2020) is considered more applicable for KSA modern tunnel design. Given that tunnel sidewalk widths typically range from 1.0m to 1.5m, by implementing the AASHTO's requirement for a 1.07m high barrier, this can eliminate the need to incorporate a 2668kN collision load, thereby optimizing the tunnel cross-section. Conversely, omitting the barrier necessitates integrating collision loads into LRFD load combinations, significantly increasing structural demands (e.g., concrete volume and reinforcement). Additionally, the tunnel design life, serviceability and maintenance costs without the barrier should also be taken into considerations, and designers should compare these options and select the most applicable code and the proper design case to case.

Table 4 : Road barrier requirement for road tunnels within different codes

Reference Code	MOMRA Bridges, Tunnels, Culverts and Pedestrian Bridges Specifications in Urban Areas (2013)	AASHTO LRFD Bridge Design Specifications (2020)
Collision Load	1800kN	2668kN
Protection Measures	1.37m high crash tested TL-5 barrier when distance from barrier to component being protected is within 3.0m	1.07m high MASH crash tested rigid TL-5 barrier when distance from barrier to component being protected is greater than 1.0m

5.3. Utility Integration and Tunnel Section Design Development

The integration of utilities within tunnels depends on site-specific constraints and infrastructure priorities. In scenarios where no alternative diversion routes are available, utilities are fully integrated into the tunnel structure. While this centralizes maintenance access, it requires an enlarged cross-section to accommodate all utility systems. Conversely, external utility corridors can divert non-critical systems outside the tunnel, allowing the cross-section to prioritize essential operational utilities. This reduces the tunnel's geometry but demands coordination with external stakeholders and additional land allocation.

A hybrid approach—partial integration—aligns certain utilities with existing road infrastructure by partially embedding them within the tunnel and routing others externally. This balances spatial efficiency with flexibility for future upgrades. Table 5 provides a comparative analysis of the three utility arrangement strategies. However, the design of the appropriate utility integration approach should consider project requirements, client expectations, site conditions, and other relevant factors.

Table 5 : Pros and Cons by Utility Integration Considerations

Type	Pros	Cons
Type 1:Fully Integrated Utilities Inside Tunnel	• Centralized maintenance access. • Faster construction. • Enhanced utility security.	• Limited future adaptability. • Waterproofing challenges. • High risk of cascading failures.
Type 2: Fully External Utilities	• Isolates operational risks (e.g., leaks, fires). • Easy upgrades. • Long-term cost efficiency.	• High upfront costs. • Coordination complexity across stakeholders. • Requires external space.
Type 3: Partially Integrated Utilities	• Balances safety and flexibility. • Moderate costs. • Protects critical systems.	• Complex hybrid design. • Dual maintenance requirements. • Risk of utility misclassification.

Consolidating utilities within the tunnel footprint necessitates strategic planning to balance operational sustainability and maintenance efficiency. Firstly, maintenance accessibility is critical: utilities are required to be conveniently accessible through optimally located access points and corridors, enabling repairs without disrupting traffic. Secondly, seamless integration of external and internal networks demands precise alignment of pipelines and robust connections to prevent leakage. Thirdly, modular designs and phased maintenance minimize road closures by isolating tunnel sections for repairs. Finally, redundancy measures ensure tunnel operability during maintenance, avoiding full shutdowns. This holistic approach prioritizes functionality, maintenance efficiency, and minimal public disruption.

The arrangement of utility corridors significantly influences tunnel geometry, spatial efficiency, and operational functionality. Figure 7 below provides a design development by considering utility corridors at different locations. As shown in Figure 7(A), a complex utility corridor layout with densely clustered pipelines and equipment occupies a significant amount of tunnel space, reducing the effective cross-sectional area available for other purposes and increased construction costs. Such congestion also impedes maintenance workflows, as technicians encounter limited accessibility to critical systems. In contrast, Figure 7(b) illustrates a developed design where utilities are streamlined into consolidated, modular pathways. This approach minimizes redundant space and simplifies routing. The reduction of approximately 10% in the tunnel area in Figure 7(A) compared to Figure 7(B), achieved through the rearrangement of the utility corridor, offers significant advantages including reduced excavation volumes, less temporary work quantities, reduced construction cost, reduced construction time and associated risks.

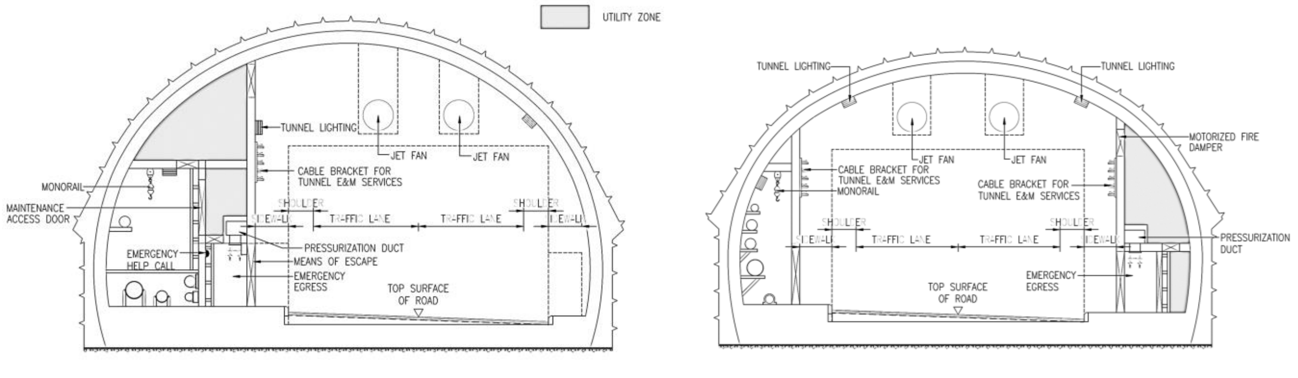

Figure 7 – (A) Utility Corridor Positioned on One Side (B) Utility Corridors Positioned on Both Sides

6. TUNNEL PORTAL SLOPE COSMETIC ENHANCEMENTS

Mined tunnel portals require site formation and cut slopes. In the KSA tunnel projects, the challenges are amplified by the need to balance geotechnical requirements with stringent contextual and aesthetic objectives. Therefore, the context-sensitive tunnel portal design becomes one of the key constraints the designer may face in KSA design projects.

Conventional cut slope designs often produce visually intrusive “engineered” landscapes that disrupt the natural surroundings. To better understand the scope of the aesthetic improvement works of the portal cut slopes, classification is conducted to determine the extent and type of typical tunnel portal slopes as shown in Table 6.

Table 6 : Tunnel Portal Slope Zone

Category	Definition	Requirement
A	Direct Exposure	For locations where individuals have direct access and proximity, such as near driveways, walkways, or parking spaces adjacent to tunnel portals, a high level of detailing is required to camouflage man-made structures. Solutions such as natural stone facades, vegetated retaining walls, or bespoke gabion systems filled with local materials is possible.
B	Vehicular Exposure	For slopes above the portal structures that are visible to road users at enter or exit tunnels, or on the driveways, the stabilization structures will require an intermediate level of detailing. Retaining elements would harmonize with the landscape and can afford to have a smaller degree of detail whilst blending into the natural surroundings, softening the visual impact.
C	Aerial or Elevated Exposure	For slopes where stabilization structures are visible from an elevated perspective, such as aerial viewpoints, from hillsides, or low-flying aircraft, camouflage solutions that integrate into the larger visual landscape are critical. Options such as vegetative covers, natural stone, and earth-coloured materials will be prioritized to create a seamless visual transition from above.

The following are recommended measures for enhancing the aesthetics of the tunnel portal slopes (Table 7, Figure 8, Figure 9 and Figure 10).

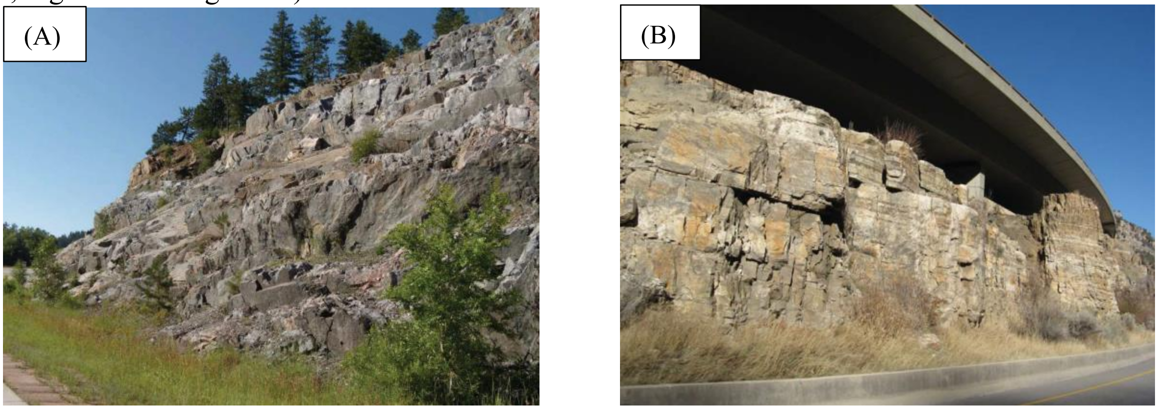

Figure 8 - (A) Rock slope excavated using slope variation and sculpting techniques (Andrew et al., 2011); (B) Staining on the completed slope to create a natural-looking rock face (Glenwood Canyon, Colorado).

Table 7 : Tunnel Portal Slope Aesthetics Improvement Measures

Slope Profile	Reinforcement	Mitigation

• Slope warping: Rounds the ends of the cut to smooth the transition between the rock cut and the natural terrain. • Slope rounding: Rounds the crest of the cut slope to smooth the transition to the natural terrain. • Slope angle variation: Varies the slope angle laterally along the slope to accentuate prominent geological features or differences in weathering rates.	• Spot or systematic bolting with hidden heads (recessed heads, headless dowels) • Fiberglass or carbon fibre reinforced polymers (GFRP, FRP, or CFRP): Strong, lightweight alternatives to steel; can be colored. • Textured or colored shotcrete: Adds both texture and color for environmental blending.	• Bio-engineering: Prevents erosion and maintains a natural appearance with suitable vegetation for site conditions, and is suitable for the local temperature and moisture. • Rock staining and artificial rock cladding: Alters the appearance of rocks to blend naturally. • Rockfall barrier offset at crest: Reduces visibility for road users. • Catch ditch at slope toe where space allows: Manages potential hazards like erosion or debris flow. • Steel element painting: Painting steel elements (e.g., rockfall barriers, dowels) to match surroundings.

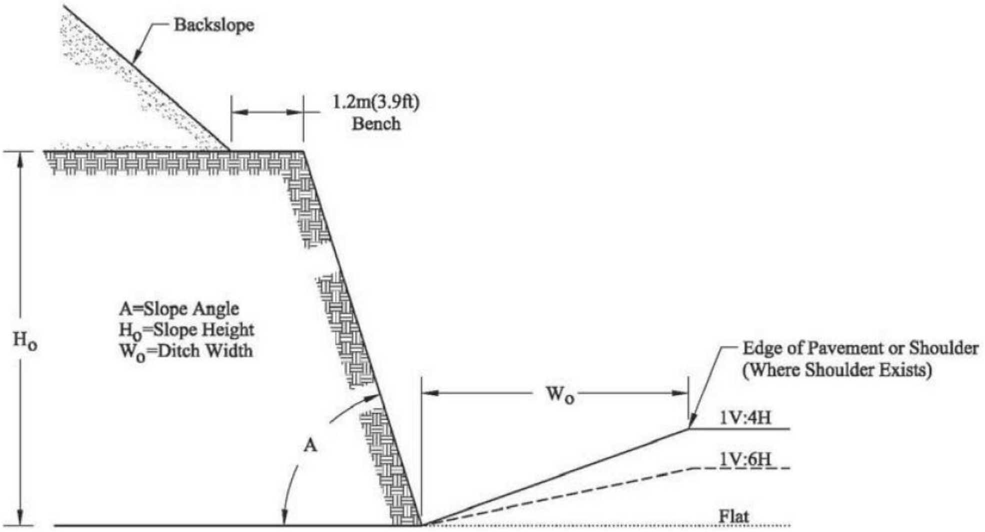

Figure 9 - A Typical Oregon ditch design, is aesthetically acceptable measures (modified from Pierson, Gullixson, and Chassie 2002).

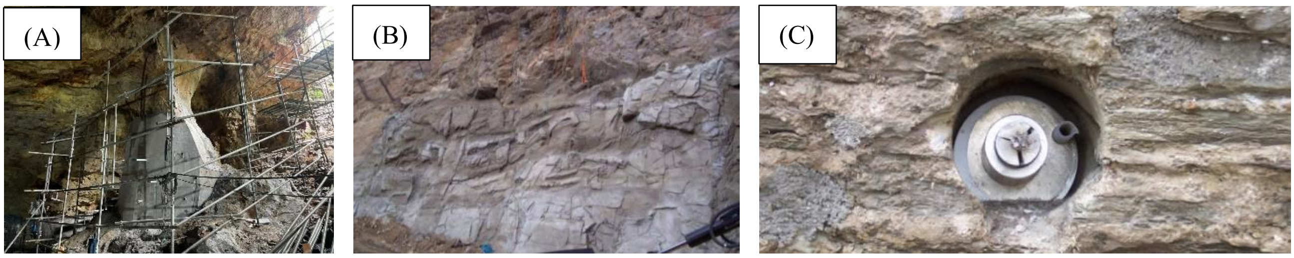

Figure 10 - (A) Rock cladding in glass fiber or aluminum with a textured and coloured finish (Lin Ma Hang, Hong Kong); (B) Completed structural shotcrete, ready for staining (Andrew et al., 2011); (C) Recessed head bolt which may be covered with facing brick or stone works.

7. ENVIRONMENTAL CONSIDERATIONS

Environmental considerations during mined tunnel construction in KSA are critical due to the region's unique ecological and climatic conditions. One of the primary concerns is groundwater management, as tunnelling activities can disrupt local aquifers, leading to water table depletion and affecting ecosystems and communities that rely on these resources. Grouting is often used to control groundwater ingress, but excessive extraction can harm vegetation and water supplies. To mitigate these impacts, careful monitoring of groundwater levels is essential. For instance, monitoring data can confirm that no significant drawdown occurs, ensuring that the design avoids disruption to local aquifers. Stabilizing the slope at the tunnel portal often required measures such as shotcrete, anchor bots, or gentler slope gradient. These measures can enhance slope stability although inherits potential environmental impacts. To address these concerns, mitigation strategies should be incorporated into the design, such as minimizing land disturbance and implementing erosion control measures.

Air and noise pollution from blasting and drilling operations and cut slope was minimized to protect nearby communities and wildlife. Dust suppression techniques and noise barriers were essential to mitigate these impacts. The disruption of natural habitats during construction, particularly in ecologically sensitive areas, required careful planning to avoid impact to biodiversity. Finally, sustainable practices, such as recycling excavated materials and using energy-efficient equipment, would reduce the environmental footprint of tunnelling projects. By addressing these considerations, tunnel construction in KSA, construction is carried out in an environmentally responsible manner, balancing infrastructure development with ecological preservation.

8. CONCLUSIONS

This study examines tunnel design practices in KSA, and highlights the region's unique geological and geotechnical characteristics. By evaluating local codes against international standards, and implementing utility integration strategies, engineers can ensure structural integrity, safety, serviceability, sustainability and cost-effectiveness in tunnel projects. The research also addresses the importance of context-sensitive design requirements for KSA projects, proposing solutions to achieve both functional and aesthetic objectives.

In conclusion, this study provides a valuable resource for professionals involved in KSA tunnel projects, offering practical insights into tunnel design in one of the world's most dynamic regions. Future research would focus on the application of innovative technologies and materials to further enhance and optimize tunnel design and performance in a safe and constructable method.

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