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**Research paper**

# Practical tunnel classification: synthesizing geological and environmental factors

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**Abstract:** The majority of existing methodologies for tunnel assessment and classification are rooted in empirical construction practices. Traditionally, these approaches ascertain the magnitude of a tunnel's scale by relying on a solitary parameter, such as its length or cross-sectional dimensions, often neglecting the critical role of environmental factors. This oversight significantly restricts the methods' broader utility. Hence, there is a pressing need to innovate a comprehensive tunnel assessment and grading framework that seamlessly incorporates both geological and environmental parameters, thereby broadening its applicative horizons. To achieve a more nuanced understanding of tunnel scales, an encompassing classification paradigm has been conceived. This paradigm takes into account a spectrum of six critical determinants: tunnel length, cross-sectional dimensions, the geological influence coefficient, the structural importance of the tunnel, the gradient of the tunnel's slope, and the net distance between interconnected tunnels. A sophisticated formula has been devised to calculate the total volume of excavation, with geological considerations primarily hinged on the tunnel's length and cross-sectional dimensions. Additionally, the formula is calibrated to integrate other pivotal factors, notably environmental impacts. Upon this robust foundation, a novel tunnel assessment and classification protocol has been articulated. This protocol harmoniously blends geological and environmental attributes with pragmatic considerations. A case study, focusing on a quintessential tunnel, has been meticulously conducted, yielding results that substantiate the method's efficacy and reliability. The research's deliverables offer a substantive benchmark for tunnel assessments and classifications within contexts characterized by intricate environmental dynamics.

**Keywords:** tunneling assessment, environmental influences, tunneling classification, geological influences, practical applications, intricate environmental dynamics

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# 1. Introduction

The importance of tunnel classification is paramount as it provides a systematic framework for understanding the diverse characteristics and requirements of various tunnel types. This categorization is crucial for several reasons: it enables more accurate risk assessments, informs the selection of appropriate construction materials and methods, and guides the development of tailored maintenance and safety protocols. Furthermore, a clear classification system is instrumental in the planning and design phases, as it allows for the prediction of potential challenges and the implementation of cost-effective solutions. It also aids in regulatory compliance and the establishment of industry standards, thereby ensuring the longevity and reliability of tunnel infrastructure. In essence, the meticulous classification of tunnels is foundational to the advancement of tunnel engineering and the realization of safe, efficient, and sustainable subterranean networks. Many tunnel classification methods are defined according to various conditions, such as use purposes, geological conditions, construction methods, length, and sectional area of tunnels [1–6], etc. In accordance with their purposes, tunnels are categorized as road tunnels, rail tunnels, rapid transit tunnels, water tunnels, sewage tunnels, hydroelectric tunnels, and service and utility tunnels. Similarly, based on different topographical conditions, tunnels can be classified as those found in mountains, urban areas, rivers, seas, and so on. Additionally, considering different surrounding geological conditions, tunnels can also be divided into tunnels in rock, tunnels in soil, and tunnels in complex geological conditions. Moreover, there are various classifications due to different tunnel construction methods, such as tunnels constructed using conventional mining, tunnels using the New Austria Tunneling Method (NATM), rock tunnels bored by Tunnel Boring Machines (TBMs) for rock strata, shield tunnels for soil strata, cut-and-cover tunnels, immersed tube tunnels, pipe-jacked tunnels, and tunnels excavated using conventional excavators such as road headers and mobile mining equipment [7].

As shown in Table 1, the tunnel classifications are based on tunneling length, as per Chinese design specifications [8, 9].

Table 1. Different classifications of tunneling length from Chinese design specifications

| **Tunnel Type $L$ /m** | **Short Tunnel** | **Middle Long Tunnel** | **Long tunnel** | **Very Long Tunnel** |
|---|---|---|---|---|
| Highway Tunnels | $L < 500$ | $500 \le L < 1000$ | $1000 \le L < 3000$ | $L \ge 3000$ |
| Railway Tunnels | $L < 500$ | $500 \le L < 3000$ | $3000 \le L < 10\,000$ | $L \ge 10\,000$ |

Differently, the ITA classifies tunnels based on their cross-sectional area [1], as shown in Table 2.

Table 2. Different classifications based on the tunnel section area from ITA

| **Tunnel Type** | **Very small tunnel** | **Small Tunnel** | **Moderate Tunnel** | **Large Tunnel** | **Very Large Tunnel** |
|---|---|---|---|---|---|
| Sectional area /m$^2$ | 2–3 | 3–10 | 10–50 | 50–100 | ≥ 100 |

In addition, other scholars have also proposed different classification methods. Three indicators with a low correlation were utilized to categorize levels III, VI, and V into distinct sub-levels using hierarchical cluster analysis [10]. Furthermore, a rock mass classification method has been examined through geological investigation within the context of the New Austrian Tunneling Method (NATM) [11].

With the application of mechanical construction methods, new classification methods have also emerged for shield tunnels and TBMs. For example, the performance of TBMs is significantly predicted by a new Chinese rock mass classification system known as the Hydropower Classification (HC) method [12]. Consequently, tunnel stability [13–17] and classification are also influenced by the stabilization [18–20] and pre-reinforcement of the surrounding rock. Thus, some scholars have incorporated this factor into the tunnel classification process. Through theoretical analysis, a mechanical model for grading roadway hidden dangers has been established, along with a method for classifying tunnel collapse hazards [21–25]. Based on this classification, a cable support design method has been developed [26].

From the above, the tunneling scale is related to not only the length and the cross-sectional area but also other crucial factors. Therefore, a comprehensive classification method of tunneling scale should be proposed, based on more significant influencing factors.

## 2. Classification method of tunnelling scale based on sectional area

### 2.1. Principle for difference of area as an arithmetic progression

From Table 2, five classes are used to describe tunnel classification with the cross-sectional area: a very small tunnel, a small tunnel, a moderate tunnel, a large tunnel, and a very large tunnel. As tunnel functional requirements and construction methods are improving, tunnels with cross-sectional areas exceeding 200 $m^2$ have become increasingly common, such as the Dageshan highway tunnel [27] (with a length of 496 m, an excavated width of 22 m, and a height of 18 m) and the Wumengshan No. 2 railway tunnel [28] (with a length of 538 m, an excavated width of 28.4 m, and an area of 354 $m^2$ in China. Therefore, it is necessary to reclassify tunnels into different types according to their cross-sectional area.

Assuming the differences in area are an arithmetic progression, the ITA classification defines the area of moderate tunnels as 10 to 50 $m^2$ and those of large tunnels as 50 to 100 $m^2$ [1]. Therefore, the differences between these areas are 40 $m^2$ and 50 $m^2$, respectively. An additional area of 20 $m^2$ is considered between 10 $m^2$ and 50 $m^2$, as illustrated in Table 3. Consequently, the differences are 50 $m^2$, 30 $m^2$, and 10 $m^2$. The equal difference, since the area is more than 10 $m^2$, is 20 $m^2$. According to the ITA classification, the area of moderate tunnels is 10 to 50 $m^2$; however, an additional classification of 20 to 50 $m^2$ is also provided. Thus, tunnels with a cross-sectional area of 10 to 20 $m^2$ are classified as small tunnels. Furthermore, the cross-sectional characteristics of exceptionally small tunnels are less than 2 $m^2$. For example, very small tunnels have a cross-sectional area of 3 to 10 $m^2$, while those of extremely small tunnels are between 2 to 3 $m^2$. When the cross-sectional area exceeds 100 $m^2$, following the principle of an arithmetic progression, the differences are 70 $m^2$ and 90 $m^2$. Consequently, very large tunnels, extremely large tunnels, and exceptionally large tunnels can be classified in Table 3.

For tunnels constructed using the TBM method, the diameters of different types are presented in Table 3. For improved application, the diameter data for TBM tunnels are conveniently simplified.

Table 3. Different classifications of sectional area based on principle for difference of area as an arithmetic progression

| **Type** | **Exceptionally Small Tunnel** | **Extremely Small Tunnel** | **Very Small Tunnel** | **Small Tunnel** | **Moderate Tunnel** | **Large Tunnel** | **Very Large Tunnel** | **Extremely Large Tunnel** | **Exceptionally Large tunnel** |
|---|---|---|---|---|---|---|---|---|---|
| Sectional Area $A$ /$m^2$ | ≤ 2 | 2–3 | 3–10 | 10–20 | 20–50 | 50–100 | 100–170 | 170–260 | ≥ 260 |
| Difference /$m^2$ | – | – | – | 10 | 30 | 50 | 70 | 90 | – |
| TBM Tunnel $D$ /m | ≤ 1.596 | 1.596–1.954 | 1.954–3.568 | 3.568–5.05 | 5.05-7.98 | 7.98-11.284 | 11.284–14.712 | 14.712–18.2 | ≥ 18.2 |
| Simplification $D$ /m | ≤ 1.5 | 1.5–2.0 | 2.0–3.5 | 3.5–5.0 | 5.0–8.0 | 8.0–11.5 | 11.5–15.0 | 15.0–18.0 | ≥ 18.0 |

It should be noted that an underground space with a cross-sectional area greater than 2 $m^2$ could be defined as a tunnel. Therefore, those with a cross-sectional area of less than 2 $m^2$ are referred to as exceptionally small tunnels.

## 2.2. Principle for difference of area as a geometric progression

Assuming the differences in areas form a geometric progression, the ITA classification defines the area of moderate tunnels as ranging from 10 to 50 $m^2$, and those of large tunnels as ranging from 50 to 100 $m^2$. An area of $A$ ($m^2$) is added between 10 $m^2$ and 50 $m^2$, as shown in Table 4. Then, assuming the common ratio in the geometric progression is 2.0, the following two equations are proposed.

$$10 + 2x = A \tag{2.1}$$

$$A + 4x = 50 \tag{2.2}$$

where, the $x$ is the basic difference of area.

After equations (2.1) and (2.2) are solved, $x$ is 6.77 m$^2$, and $A$ is 23.33 m$^2$. All the limits of the tunnel classification are shown in Table 4 under different cross-sectional areas. Similarly, the tunnel classification under the TBM construction method has also been calculated and added to Table 4.

Table 4. Different classifications of sectional area based on principle for difference of area as a geometric progression

| **Type** | **Exceptio-nally Small Tunnel** | **Extremely Small Tunnel** | **Very Small Tun-nel** | **Small Tun-nel** | **Mode rate Tunnel** | **Large Tun-nel** | **Very Large Tun-nel** | **Extremely Large Tunnel** | **Exceptio-nally Large tunnel** |
|---|---|---|---|---|---|---|---|---|---|
| Sectional area $A$ /m$^2$ | ≤ 2 | 2–3.33 | 3.33–10 | 10–23.33 | 23.33–50 | 50–103.33 | 103.33–210 | 210–423.33 | ≥ 423.33 |
| Difference /m$^2$ | – | – | 6.67 | 13.33 | 26.67 | 53.33 | 106.67 | 213.33 | – |
| Simplification of $A$ /m$^2$ | ≤ 2 | 2–3 | 3–10 | 10–20 | 20–50 | 50–100 | 100–200 | 200–400 | ≥ 400 |
| TBM tunnel $D$ /m | ≤ 1.596 | 1.596–1.954 | 1.954 – 3.568 | 3.568–5.05 | 5.05–7.98 | 7.98–11.284 | 11.284–15.958 | 15.958–22.568 | ≥ 22.568 |
| Simplification of $D$ /m | ≤ 1.5 | 1.5–2.0 | 2.0–3.5 | 3.5–5.0 | 5.0–8.0 | 8.0-11.5 | 11.5–16.0 | 16.0–22.5 | ≥ 22.5 |

## 2.3. Comparative analysis of two classification methods

The sectional areas of tunnels are almost the same for the two different classification methods when the cross-sectional area is less than 100 m$^2$. However, when the cross-sectional area is more than 100 m$^2$, the classification interval value of the method under the geometric progression is larger than that under the arithmetic progression. The area increases by a factor of two under the geometric progression for areas of 210 m$^2$ and 423.33 m$^2$. The area is doubled for the range from 50 m$^2$ to 100 m$^2$ in both classification methods. Consequently, the classification method under the geometric progression is more rational than the one under the arithmetic progression.

As the areas in row 2 of Table 4 have decimals, and the areas are simplified from decimals to integers starting from row 6 of Table 4, this makes it more convenient for applications. On this basis, with the modified area values, the parameters associated with the TBM tunnel are also listed in Table 4. For example, the M-30 tunnel in Madrid [29] has a TBM (EPB) diameter of 15.2 m and belongs to an extremely large tunnel according to the classification method based on arithmetic progression. However, by the classification method based on geometric progression, the M-30 tunnel is considered a very large tunnel.

# 3. Classification method of tunnelling scale based on the length

In Chinese design specifications for highway tunnels and railway tunnels [8, 9], the classification limits for long tunnels and very long tunnels differ. The primary reason is that the cross-sectional area of highway tunnels is generally larger than those of railway tunnels in China. As long tunnels are developing rapidly worldwide, they should be defined as having a length ranging from 3 km to 10 km, similar to the classification method for railway tunnels outlined in Table 1. Consequently, the limits of tunnel lengths are presented in row 2 of Table 5, categorized from very short to very long tunnels.

The difference in tunnel length does not represent an arithmetic progression across different tunnel types, as indicated in row 3 of Table 5; it should represent a geometric progression. The common ratio of this progression ranges between 3 and 4.

Table 5. Different classifications of length based on principle for difference of length as a geometric progression

| **Tunnel type** | **Extremely Short tunnel** | **Very Short tunnel** | **Short tunnel** | **Middle long tunnel** | **Long tunnel** | **Very long tunnel** | **Extremely long tunnel** |
|---|---|---|---|---|---|---|---|
| Tunnel-length $L$ /km | – | $L < 0.5$ | $0.5 \leq L < 1.0$ | $1.0 \leq L < 3.0$ | $3.0 \leq L < 10.0$ | $L \geq 10.0$ | – |
| Difference Dif /km | – | – | 0.5 | 2.0 | 7.0 | – | – |
| Dif ($n = 3$) /km | – | $x/3 = 0.24$ | $x = 0.73$ | $3x = 2.19$ | $9x = 6.57$ | $27x = 19.71$ | – |
| $L$ ($n = 3$) /km | $L < 0.26$ | $0.26 \leq L < 0.5$ | $0.5 \leq L < 1.23$ | $1.23 \leq L < 3.42$ | $3.42 \leq L < 10.0$ | $10.0 \leq L < 29.71$ | $L \geq 29.71$ |
| $Ls$ ($n = 3$) /km | $L < 0.25$ | $0.25 \leq L < 0.5$ | $0.5 \leq L < 1.25$ | $1.25 \leq L < 3.5$ | $3.5 \leq L < 10.0$ | $10.0 \leq \mathrm{L} < 30$ | $\mathrm{L} \geq 30$ |
| Dif ($n = 4$) /km | – | $x/4 = 0.1131$ | $x = 0.4524$ | $4x = 1.81$ | $16x = 7.24$ | $64x = 28.96$ | – |
| $L$ ($n = 4$) /km | $L < 0.387$ | $0.387 \leq L < 0.5$ | $0.5 \leq L < 0.95$ | $0.952 \leq L < 2.76$ | $2.76 \leq L < 10.0$ | $10.0 \leq L < 38.96$ | $L \geq 38.96$ |
| $Ls$ ($n = 4$) /km | $L < 0.35$ | $0.35 \leq L < 0.5$ | $0.5 \leq L < 1.0$ | $1.0 \leq L < 2.75$ | $2.75 \leq L < 10.0$ | $10.0 \leq L < 40$ | $L \geq 40$ |
| Dif ($n = 3.772$) /km | – | $x/n = 0.133$ | $x = 0.5$ | $nx = 1.886$ | $n2x = 7.114$ | $n3x = 26.834$ | – |
| $L$ ($n = 3.772$) /km | $L < 0.367$ | $0.367 \leq L < 0.5$ | $0.5 \leq L < 1.0$ | $1.0 \leq L < 2.886$ | $2.886 \leq L < 10.0$ | $10.0 \leq L < 36.834$ | $L \geq 36.834$ |
| $Ls$ ($n = 3.772$) /km | $L < 0.35$ | $0.35 \leq L < 0.5$ | $0.5 \leq L < 1.0$ | $1.0 \leq L < 3.0$ | $3.0 \leq L < 10.0$ | $10.0 \leq L < 36$ | $L \geq 36$ |

Firstly, it should be assumed that the equal ratio ($n$) is 3, the following equation is established.

$$0.5 + x + 3x + 9x = 10 \tag{3.1}$$

where $x$ is the basic difference in tunnel length. So, the value of $x$ is 0.73. The limits of tunnel length are shown in rows 5 and 6 of Table 5. And Ls is the simplified value of the tunnel length.

Then, as the $n$ is 4, the following equation is established.

$$0.5 + x + 4x + 16x = 10 \tag{3.2}$$

The value of $x$ is 0.4524 after running equation (3.2). The limits of tunnel length are shown in rows 8 and 9 of Table 5.

Finally, assuming that the variable $x$ ranges from 0.5 to 1.0 and is then decreased by 0.5, the following equation is established:

$$1.0 + 0.5n + 0.5n^2 = 10 \tag{3.3}$$

The result of $n$ is 3.772 ($n > 0$). Analogously, the limits of tunnel length are listed in row 11 and row 12 of the Table 5.

When the basic difference in tunnel length is 0.5 km and the common ratio is 3.772, the length limits are between 3 km and 4 km. As shown in row 12 of Table 5, the length limits of 0.5 km, 3.0 km, and 10.0 km correspond to those in the Chinese design specifications for highway and railway tunnels [8, 9]. Therefore, this classification method is recommended for application. For example, the New Guanjiao Railway Tunnel [30] in China, which is 32.6 km long, and the Lötschberg Base Tunnel [31] in Switzerland, at 34.6 km, both are classified as very long tunnels according to this method for 10.0 km $\leq L <$ 36 km. However, the Gotthard Base Tunnel, with a length of 57 km, is classified as an extremely long tunnel due to $L \geq$ 36 km.

# 4. Influencing coefficients of geology and structural importance and gradient

## 4.1. Influencing coefficient of gradient

During long tunnel construction, shafts or inclined shafts are used to create more working surfaces, thereby shortening construction times. The shaft tunnels and main tunnels are built using different construction methods, and the costs vary under different gradients. In order to describe the tunneling scale precisely, the influence coefficient of the gradient ($k_\alpha$) is shown in Table 6 under different gradients ($\alpha$).

Table 6. Influencing coefficient of gradient under different gradients

| $\alpha$ /° | $\alpha \leq 5$ | $5 < \alpha \leq 30$ | $30 < \alpha \leq 60$ | $60 < \alpha \leq 90$ |
|---|---|---|---|---|
| $k_\alpha$ | 1.0 | 1.1 | 1.3 | 1.5 |

## 4.2. Influencing coefficient of geology

In addition, the safety and stability of a tunnel are directly related to the geological conditions of the surrounding rock. Tunnels are constructed using various methods, and costs also vary with different geological conditions. When the tunneling scale needs to be accurately described, the geological condition factor should be taken into account. There are two main classification methods for the rock mass in tunnels: the Rock Mass Rating (RMR) method [32] and the Q-System method [33].

If *Rm* represents the maximum in each RMR rating limit, then the calculation equation for the geological influence coefficient ($k_g - r$) is established using the RMR system.

$$k_g - r = 1.0 + (100/Rm - Rm/100)/10 \tag{4.1}$$

For example, in Class A, when *Rm* equals 100, according to equation (4.1), the result for the geological influence coefficient ($k_g - r$) is 1.0, as shown in Table 7. To conveniently use the $k_g - r$ data, the value of $k_g - r$ is simplified to $k_g - r_s$.

In the rock mass classification method based on the Q-System, the value of the geological influence coefficient ($k_g - q$) is also provided in Table 7, taking into account the principle of consistent tunnel lining parameters. The $k_g - q$ values are the same as $k_g - r_s$ from Class A to Class D. For Classes E, F, and G, $k_g - q$ can be calculated using equation (4.2), as follows.

$$k_g - r = 1.0 - (2m_1 - m_2)/10 \tag{4.2}$$

In equation (4.2), $m_1$ and $m_2$ are powers of 10 related to the $Q$-value. If, for Class F, $m_1$ is –2 and $m_2$ is –1, then $k_g - q$ equals 1.5 after calculation, as shown in row 9 of Table 7.

Table 7. Influencing coefficient of geology ($k_g$) based on RMR and $Q$-System

| RMR rating | 81–100 | 61–80 | 41–60 | 21–40 | | < 20 | |
|---|---|---|---|---|---|---|---|
| Class | A | B | C | D | | E | |
| *Rm* | 100 | 80 | 60 | 40 | | 20 | |
| $k_g - r$ | 1.0 | 1.045 | 1.107 | 1.21 | | 1.48 | |
| $k_g - r_s$ | 1.0 | 1.05 | 1.1 | 1.2 | | 1.5 | |
| $Q$-value | 40–1000 | 10–40 | 4–10 | 1–4 | 0.1–1 | 0.01–0.1 | 0.001–0.01 |
| $m_1 - m_2$ | – | – | – | – | –1–0 | –2– –1 | –3– –2 |
| Class | A | B | C | D | E | F | G |
| $k_g - q$ | 1.0 | 1.05 | 1.1 | 1.2 | 1.2 | 1.5 | 1.8 |

## 4.3. Influencing coefficient of structural importance

Different linings are required for tunnels to meet their varying functional requirements, which are quantified using the influencing coefficient of structural importance ($k_i$). The functional requirements of tunnels are categorized into five classes based on the excavation support ratio (ESR) in the $Q$-System, as depicted in Table 8. In the Chinese design code for concrete structures [34], $k_i$ is defined according to the service life ($T$) of concrete structures. $k_i$ is 1.1 when $T$ is more than 100 years. It is 1.0 when $T$ is at least 50 years, and $k_i$ equals 0.9 when $T$ is at least 5 years. Consequently, the influencing coefficients of structural importance range from 1.2 to 0.8, corresponding to classes A through E.

Table 8. Influencing coefficient of structural importance for different using purposes of tunnels

| **Important class** | **The types of using purposes of tunnels** | $k_i$ |
|---|---|---|
| A | Underground nuclear power stations, railway stations, sports and public facilities, underground factories. | 1.2 |
| B | Underground power station caverns, major road and railway tunnels, civil defense chamber, tunnel portals and intersections. | 1.1 |
| C | Storage rooms, water treatment plants, minor road and railway tunnels, surge chambers and access tunnels in hydro-electric project. | 1.0 |
| D | Permanent mine openings, water tunnels for hydro-electric projects, pilot tunnels, drifts and headings for large excavations. | 0.9 |
| E | Temporary mine openings. | 0.8 |

## 4.4. Influencing coefficient of net distance between tunnels

The new tunnel is influenced by the existing tunnel, and the level of influence is determined by the net distance between them. The minimum net distance varies under complex geological conditions; if there is no influence on the existing tunnel during the construction of the new tunnel. For the two geological classification methods of rock mass – both the RMR method and the $Q$-System method – the minimum net distances ($d_n1$) for each class are shown in Table 9. Here, B represents the maximum excavating span of tunnels. The influencing coefficient of net distance ($k_{nd}1$) is defined as 1.0 when the net distance between tunnels exceeds the minimum value.

The minimum net distance between tunnels ($d_n4$) allowable in engineering design is one quarter of the minimum net distance ($d_n1$) that does not influence the existing tunnel under each class of rock mass. The influencing coefficients for net distances ($k_{nd}2$, $k_{nd}3$, and $k_{nd}4$) and the net distances ($d_n2$, $d_n3$, and $d_n4$) are shown in Table 9. If no existing tunnel is present when the first new tunnel is constructed with the maximum excavating span B1, it is not necessary to consider the influencing coefficients of net distance. When the second tunnel is built with maximum excavating span B2, the influencing coefficient of net distance should be calculated based on B1. Thus, the best approach is to initially construct a smaller tunnel, which can serve as a service tunnel or one for geological surveys.

Table 9. Influencing coefficients of net distance between tunnels

| RMR rating | 81–100 | 61–80 | 41–60 | 21–40 | | < 20 | |
|---|---|---|---|---|---|---|---|
| Class | A | B | C | D | | E | |
| $d_n1$ | ≥ 1B | ≥ 1.5B | ≥ 2B | ≥ 2.75B | | ≥ 3.5B | |
| $k_{nd}1$ | 1.0 | 1.0 | 1.0 | 1.0 | | 1.0 | |
| $d_n2$ | 0.75–1B | 1.15–1.5B | 1.5–2B | 2–2.75B | | 2.65–3.5B | |
| $k_{nd}2$ | 1.05 | 1.05 | 1.05 | 1.05 | | 1.05 | |
| $d_n3$ | 0.5–0.75B | 0.75–1.15B | 1–1.5B | 1.35–2B | | 1.75–2.65B | |
| $k_{nd}3$ | 1.15 | 1.15 | 1.15 | 1.15 | | 1.15 | |
| $d_n4$ | 0.25–0.5B | 0.35–0.75B | 0.5–1B | 0.65–1.35B | | 0.85–1.75B | |
| $k_{nd}4$ | 1.3 | 1.3 | 1.3 | 1.3 | | 1.3 | |
| $Q$-value | 40–1000 | 10–40 | 4–10 | 1–4 | 0.1–1 | 0.01–0.1 | 0.001–0.01 |
| Class | A | B | C | D | E | F | G |
| $d_n1$ | ≥ 1B | ≥ 1.5B | ≥ 2B | ≥ 2.5B | ≥ 3.0 B | ≥ 3.5B | ≥ 4B |
| $k_{nd}1$ | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| $d_n2$ | 0.75–1B | 1.15–1.5B | 1.5–2B | 1.85–2.5B | 2.25–3B | 2.65–3.5B | 3–4B |
| $k_{nd}2$ | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 |
| $d_n3$ | 0.5–0.75B | 0.75–1.15B | 1–1.5B | 1.25–1.85B | 1.5–2.25B | 1.75–2.65B | 2–3B |
| $k_{nd}3$ | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 |
| $d_n4$ | 0.25–0.5B | 0.35–0.75B | 0.5–1B | 0.65–1.25B | 0.75–1.5B | 0.85–1.75B | 1–2B |
| $k_{nd}4$ | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 |

# 5. A comprehensive classification method of tunneling scale

## 5.1. The principle of comprehensive classification method

To describe the tunnel scale more reasonably, a comprehensive classification method is proposed, incorporating six influencing factors: tunnel length, cross-sectional area, geological influence coefficients, structural importance, gradient, and net distance between tunnels. The total excavated volume of the rock mass is primarily determined by the tunnel's length and cross-sectional area, with modifications made according to the various influencing factors present. The calculation equation for the total excavated volume (V) is as follows.

$$V = k_0 \sum_{j=1}^{m} \sum_{i=1}^{n} \left( k_{nd(i)}^{j} \cdot k_{i(i)}^{j} \, k_{s(i)}^{j} \, k_{g(i)}^{j} \cdot L_{(i)}^{j} \, A_{(i)}^{j} \right) \tag{5.1}$$

Where, the $m$ is the number of tunnels in one project. The $n$ is the number into which one tunnel is divided according to different geological conditions, which including shafts built with this tunnel. If $j$ is 1, the $k_{nd(i)}^{j}$ is 1. It means that this is the first tunnel. The $k_0$ is the influencing factor of the number of tunnels in a tunnel project. If the $m$ is 1, the $k_0$ is 1; thus if $m$ is 2, the $k_0$ is 1/2. So, $k_0$ equal to $1/(2 + As/Am)$ in case of two mains tunnel and one service tunnel, As is the sectional area of the service tunnel and Am is the sectional area of the main tunnel.

For a tunnel project, the standard sectional area should be defined before classifying the tunnel scale, after calculating the total excavated volume using equation (5.1). Different service requirements for tunnels necessitate different standard sectional areas. Statistics on the net area of high-speed railway tunnels worldwide are presented, as shown in Table 10.

Table 10. Statistics of net area about high-speed railway tunnel in the world [35]

| **Regions** | **Design velocity /km/h** | **Net area of Two-track /$m^2$** | **Net area of single-track /$m^2$** |
|---|---|---|---|
| Japan | 250–300 | 60–65 | – |
| France | 300–350 | 71–100 | 46–70 |
| Germany | 250–300 | 82–92 | – |
| Spain | 250–350 | 75–100 | 40–55 |
| Korea | 350 | 107 | – |
| Taiwan | 350 | 90 | – |
| China | 200–350 | 80–100 | 50–70 |

The standard sectional area for the excavation of a single-track railway tunnel is 50 $m^2$ when the design velocity is less than 200 km/h, and it is 70 $m^2$ when the design velocity exceeds 200 km/h. For two-track railway tunnels, the standard sectional area is 100 $m^2$ when the design velocity is less than 250 km/h, and it increases to 140 $m^2$ when the design velocity is more than 250 km/h, based on statistical results. The diameter of water diversion tunnels, such as the Yellow River Water Diversion Project [36] in China with designed diameters of 4.9 m and 4.8 m, is approximately 5 m, resulting in a standard sectional area of 20 $m^2$. The diameter of single-track metro tunnels, like the Chongqing Metro [37] in China with an excavated diameter of 6.36 m, is about 6.3 m, yielding a standard sectional area of 30 $m^2$. In two-lane highway tunnels in China, with an inner diameter of 10 m and an excavated diameter of approximately 11.5 m, the standard sectional area is 100 $m^2$.

Classes for tunnel scale are proposed based on different service requirements of tunnels, with classifications of length following the principle that the difference in length is a geometric progression, as per the last row of Table 5. The calculation method involves multiplying the standard sectional areas of excavation for tunnels under various service requirements by the lengths of different tunnel classes. The results are shown in Table 11.

Table 11. The classes of tunneling scale under different service requirements of tunnels

| **Extremely Small Tunnel** | **Very Small Tunnel** | **Small Tunnel** | **Moderate Tunnel** | **Large Tunnel** | **Very Large Tunnel** | **Extremely Large Tunnel** |
|---|---|---|---|---|---|---|
| Standard sectional area equals 20 $m^2$ for water diversion tunnel /1000 $m^3$ | | | | | | |
| $< 7$ | $7 \le V < 10$ | $10 \le V < 20$ | $20 \le V < 60$ | $60 \le V < 200$ | $200 \le V < 720$ | $V \ge 720$ |
| Standard sectional area equals 30 $m^2$ for single-track metro tunnel /1000 $m^3$ | | | | | | |
| $< 0.5$ | $10.5 \le V < 15$ | $15 \le V < 30$ | $30 \le V < 90$ | $90 \le V < 300$ | $300 \le V < 1080$ | $V \ge 1080$ |
| Standard sectional area equals 50 $m^2$ for single-track railway tunnel (velocity < 200 km/h)/1000 $m^3$ | | | | | | |
| $< 17.5$ | $17.5 \le V < 25$ | $25 \le V < 50$ | $50 \le V < 150$ | $150 \le V < 500$ | $500 \le V < 1800$ | $V \ge 1800$ |
| Standard sectional area equals 70 $m^2$ for single-track railway tunnel (velocity $\ge$ 200 km/h)/1000 $m^3$ | | | | | | |
| $< 24.5$ | $24.5 \le V < 35$ | $35 \le V < 70$ | $70 \le V < 210$ | $210 \le V < 700$ | $700 \le V < 2520$ | $V \ge 2520$ |
| Standard sectional area equals 100 $m^2$ for two-track railway tunnel (velocity $\le$ 250 km/h) and two-lane highway tunnel /1000 $m^3$ | | | | | | |
| $< 35$ | $35 \le V < 50$ | $50 \le V < 100$ | $100 \le V < 300$ | $300 \le V < 1000$ | $1000 \le V < 3600$ | $V \ge 3600$ |
| Standard sectional area equals 140 $m^2$ for two-track railway tunnel (velocity >250 km/h)/1000 $m^3$ | | | | | | |
| $< 45$ | $45 \le V < 70$ | $70 \le V < 140$ | $140 \le V < 420$ | $420 \le V < 1400$ | $1400 \le V < 5040$ | $V \ge 5040$ |

In general, highway and railway tunnels typically have a sectional area of 100 $m^2$. Therefore, a classification for tunnel scale can be proposed based on standard classes. These classes are determined by the different uses of tunnels and are categorized according to the tunnel length classifications.

## 5.2. A Case study

The China–Laos railway starts from Yuxi city in Yunnan Province, passing through Pu'er City, Xishuangbanna, Mohan (Mohan), and Luang Prabang to Vientiane, the capital of Laos. In the future, it will also connect to the railway networks of Thailand and even Malaysia. The Yumo (Yuxi-Mohan) railway spans a total length of 508.53 km in China, while the Mowan ( Mohan–Vientiane) railway extends 414 km in Laos. The Mowan railway includes nearly 62 kilometers of bridges and 198 kilometers of tunnels, comprising 62.7% of the total length of the railway line. Designed as a standard-speed railway with Chinese technical standards, the China–Laos railway has a passenger functional speed of 160 km/h and a freight functional speed of 120 km/h, respectively. Construction of the China–Laos railway began in December 2016 and is expected to span a total period of five years, with completion and opening for traffic scheduled for December 2021.

The Sencun No. 2 tunnel is the longest tunnel on the Mowan Railway, with a total length of 9384 meters from DK 221+358 to DK 230+742. The tunnel has a longitudinal slope of less than 0.3%, which corresponds to an angle of 0.172°. An auxiliary tunnel excavation mode featuring one transverse tunnel and one inclined shaft has been adopted.

The cross hole measures 905 meters in length with a slope of 0.5%, corresponding to an angle of 0.286°. The inclined shaft, meanwhile, is 1642 meters long with a slope of 9.2% and an angle of 5.256°. The maximum buried depth of the Sencun No. 2 tunnel reaches 684 meters. Table 12 presents the length, excavated cross-sectional area, and varying surrounding rock levels for the main tunnel, cross hole, and inclined shaft. The tunnel scale is classified using the following criteria with the comprehensive classification method.

1. Influencing Coefficient of Gradient ($k_\alpha$)
   According to Table 6, the slope impact coefficients for the main tunnel, transverse tunnel, and inclined shaft are 1.0, 1.0, and 1.1, respectively.
2. Influencing coefficient of geology ($k_g$)
   It can be seen from Table 7 that the geological influence coefficients of the surrounding rock, denoted as kg-rs, are as follows: 1.1 for the main tunnel, 1.2 for the transverse tunnel, and 1.5 for the inclined shaft, respectively.
3. Influencing coefficient of structural importance ($k_i$)
   According to Table 8, the importance grade of the main tunnel is B, with a corresponding coefficient $k_i$ of 1.1. Similarly, both the transverse tunnel and the inclined shaft have an importance grade of D, each with a coefficient ki of 0.9.
4. Influencing coefficient of net distance between tunnels ($k_{nd}$)
   Since the Sencun No. 2 tunnel is a single-track tunnel, the corresponding parameters are set as $m = 1$ and $n = 9$. Consequently, the derived coefficient $k_{nd}$, which may represent a specific calculation involving m and n, equals 1.
5. The influencing factor of the number of tunnels ($k_0$)
   Similarly the influencing factor of the number of tunnels $k_0$ is 1.
6. The calculation of the total excavated volume ($V$)
   The $V$ can be calculated from the formula (5.1) and the parameters in Table 12.

$$
\begin{aligned}
V &= k_0 \sum_{j=1}^{m} \sum_{i=1}^{n} \left( k_{nd(i)}^{j} \cdot k_{i(i)}^{j}\, k_{s(i)}^{j}\, k_{g(i)}^{j} \cdot L_{(i)}^{j}\, A_{(i)}^{j} \right) \\
&= 319010.5 + 307982.4 + 301529.3 + 17820 + 14256 + 15059.25 + \\
&\quad + 32343.3 + 43110.14 + 16277.09 \\
&= 1067387.98\,\mathrm{m}^3 = 1067.388 \times 10^3\mathrm{m}^3
\end{aligned}
\tag{5.2}
$$

Since the Sencun No. 2 tunnel is a single-hole, single-track tunnel, the excavated cross-sectional area of the main tunnel ranges from 67 to 77.5 $m^2$. Additionally, the tunnel is designed for a speed of 160 km/h. According to Table 11, the calculated value for the Sencun No. 2 tunnel, which is 1067.388, falls within the range of 500 to 1800. Consequently, the Sencun No. 2 tunnel on the China–Laos railway is classified as a Very Large Tunnel. This classification can more accurately guide the construction process.

Table 12. The calculation of the total excavated volume ($V$)

| **Tunnel** | **Main Tunnel** | | | **Transverse tunnel** | | | **Inclined shaft** | | |
|---|---|---|---|---|---|---|---|---|---|
| Class on RMR | C | D | E | C | D | E | C | D | E |
| Length $L$/ m | 3935 | 3070 | 2358 | 400 | 275 | 230 | 660 | 756 | 226 |
| Area $A$/ $m^2$ | 67 | 76 | 77.5 | 45 | 48 | 48.5 | 45 | 48 | 48.5 |
| $k_\alpha$ | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.1 | 1.1 | 1.1 |
| $k_g - r_s$ | 1.1 | 1.2 | 1.5 | 1.1 | 1.2 | 1.5 | 1.1 | 1.2 | 1.5 |
| $k_i$ | 1.1 | 1.1 | 1.1 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 |
| $k_{nd}$ | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| $k_0$ | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| $V_i$/ $m^3$ | 319010.5 | 307982.4 | 301529.3 | 17820 | 14256 | 15059.25 | 32343.3 | 43110.14 | 16277.09 |
| $V$/ $m^3$ | 1067387.98 | | | | | | | | |

# 6. Conclusions

Properly discriminating tunnel scales and types is a prerequisite for selecting appropriate construction methods. Consequently, both the World Tunnel Association and individual countries have established their own classification systems. However, these existing methods possess several shortcomings, particularly when it comes to practical application. To address these limitations, a new, comprehensive tunnel scale classification method that incorporates multiple factors has been proposed.

- To provide a more rational description of tunnel scales, a comprehensive classification method for tunnel scales has been proposed, predicated on six influential factors. The method utilizes the length and cross-sectional area of tunnels as fundamental parameters, while also incorporating correction factors such as the geological influence coefficient, structural significance, gradient, and the net distance between tunnels.
- A calculation formula, $V = k_0 \sum_{j=1}^{m} \sum_{i=1}^{n} \left( k_{nd(i)}^{j} \cdot k_{i(i)}^{j}\, k_{s(i)}^{j}\, k_{g(i)}^{j} \cdot L_{(i)}^{j}\, A_{(i)}^{j} \right)$, based on the excavation quantity of earthwork has been derived. This parameter, which is crucial for both the stability of tunnel construction and tunnel classification, is determined by the product of the tunnel's cross-sectional area and its length. Subsequently, the basic value for tunnels with varying surrounding rock classes is adjusted to account for the geological class, structural significance, gradient, and clearance distance between tunnels. Ultimately, the total excavation quantity is calculated. Additionally, a formula for the total excavated volume has been developed, where the factors of the rock mass are predominantly determined by the tunnel's length and cross-sectional area.

– Regarding the standard maintenance procedures for tunnels serving different functions, including water route tunnels, single-track metro tunnels, single-track railway tunnels, two-track railway tunnels, and highway tunnels with two lanes, a tunneling scale index system has been proposed with 7 levels.
– A case study has been conducted using the comprehensive classification method for tunnel scales. The subject of this analysis is the Sencun No. 2 tunnel on the China–Laos railway, which measures 9,384 meters in length. The calculation results is 1067.388, falls within the range of 500 to 1800, which indicates that the tunnel is classified as a Very Large Tunnel. This method accounts for the influence of various complex factors on tunnel scales, including the grade of surrounding rock, structural importance, slope, and net distance between tunnels. As a result, it offers a more rational approach that is deserving of wider promotion and application.

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