Skewed Pressure Characteristics of Equivalent Load in Double-Arch Tunnel

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Abstract. It is of great importance to reasonably estimate the surrounding rock load of a double-arch tunnel for the design, construction and stability evaluation of the tunnel. Currently, the basic theory on surrounding rock pressure of double-arch tunnels is insufficient for properly making the design and calculations. Generally, simplified calculations based on experience are used, such as the calculation method of Protodyakonov's theory, the building code method and others. Considering the fact that the surrounding rock pressure of double-arch tunnels has skewed distribution characteristics, a computational model of a double-arch tunnel was built using data from an actual excavation of a highway tunnel. Taking some factors into consideration, such as different stress states, different construction methods and different sizes of double-arch tunnels, the pressure evolution of the surrounding rock was analyzed during step-by-step excavation of the double-arch tunnel. The results showed that in each condition the surrounding rock pressure of the double-arch tunnel displayed skewed distribution characteristics. The skewed distribution of the surrounding rock pressure varied with changes in stress state, construction sequence and excavation size. The skewed pressure of the double-arch tunnel was converted to equivalent load. The conversion method and distribution characteristics of the equivalent load are specified. They have important theoretical significance and practical value for similar engineering practices.

Keywords: *double-arch tunnel; numerical calculation; pressure-arch; skewed distribution; surrounding rock.*

1 Introduction

In 1974, the first double-arch tunnel was constructed in Japan, after which this structural form was also successively adopted in some European countries. The design and construction of the double-arch tunnel have been developed for nearly 40 years. Due to higher space utilization rate, less occupation area, smoother linear route, more convenient management and other outstanding

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advantages, the double-arch tunnel developed rapidly. However, the whole span of the double-arch tunnel is large, its construction process is complex, the variation pressure of the surrounding rock is complicated and accidents frequently occur during construction, such as collapse and roof caving [1]. Currently there is no surrounding rock pressure theory that can meet the demands of double-arch tunnel design and construction [2] and in the current building code of China a load calculation method for double-arch tunnels is not given explicitly. The design of double-arch tunnels is done on an empirical basis, mainly referring to the mechanical analysis results of single-arch tunnel lining loads. Therefore, the load design of the surrounding rock of double-arch tunnels is often rough and casual.

2 State of the Art

Singh, *et al.* put forward a support pressure assessment method for arched underground tunnels that go through poor rock mass [3]. Specifically for semi-circular tunnels, Exadaktylos, *et al.* studied the distribution of stresses and displacements around the tunnel periphery with an analytical model [4]. Jaehong, *et al.* conducted a dynamic analysis to investigate the spacing influence and the seismic affection on the mechanical behavior of a double-arch culver [5]. Karakus, *et al.* analyzed the convergence of twin tunnels in Turkey by using the finite element method [6]. Chen, *et al.* have gained an understanding of the stress redistribution and pressure-arch development during tunnel excavation by using a three-dimensional numerical model [7].

In China, Shen proposed that the net size adopted in the load calculation of a double-arch tunnel comes from the entire span of the double-arch tunnel minus the middle wall thickness [8]. Yu, *et al.* put forward that the load of a double-arch tunnel can be calculated according to a single-arch tunnel under a certain construction sequence [9]. Based on the assumptions of Protodyakonov's theory, Ding, *et al.* put forward a calculated value of the loose pressure of a double-arch tunnel between the half-width corresponding values and the entire excavation width corresponding values, combined with the empirical formula given in the building code of China, and proposed a load calculation method for double-arch tunnels [10]. Li, *et al.* derived the pressure formula for the surrounding rock based on the mechanical characteristics of a double-arch tunnel [11]. Wang, *et al.* proposed a practical load calculation method for the surrounding rock pressure of double-arch tunnels through a pressure-arch excavation affection analysis [12]. Zheng, *et al.* got the loose circle range of a double-arch tunnel and the loose rock pressure distribution patterns, and gave the corresponding formulas through numerical simulation methods [13]. Wang, *et al.* have conducted a study on the pressure-arch of a deep circular tunnel [14].

Liang, *et al.* conducted an experimental and numerical analysis of the self-adjusting arching characteristics under surrounding rock stress [15].

It can be seen that previous studies were all conducted with the assumption that the surrounding rock pressure profile of a double-arch tunnel is symmetrical but due to some factors – such as construction method and terrain – the surrounding rock pressure profile of a double-arch tunnel is asymmetric and displays a skewed distribution. Therefore, if the skewness effect is not considered in the load calculation of a double-tunnel, the result will not match the actual force distribution, which will inevitably affect the construction safety and economic costs of the project. In this paper, a numerical simulation analysis of a double-tunnel excavation was carried out with ANSYS and FLAC3D software using the positive bench method. Then, a calculation method of the equivalent load of the surrounding rock pressure of the double-arch tunnel was developed based on the skewed characteristics of the surrounding rock pressure. Finally, the skewed characteristics were determined under different stress states, different construction methods and different excavation sizes.

The rest this paper is organized as follows: Section 3 establishes the load calculation method, Section 4 discusses and analyzes the results, Section 5 summarizes our conclusions.

3 Methodology

3.1 Load Calculation Based on Protodyakonov's Theory

Protodyakonov's theory suggests that there exists a self-supporting pressure-arch in the surrounding rock of a tunnel after excavation. The rock mass outside the pressure-arch is not disturbed while the rock mass within the pressure-arch is likely to be damaged. Therefore, the weight of the rock mass within the pressure-arch is the load supported by the support system. In order to conveniently calculate in practical engineering, generally, the largest surrounding rock pressure at the top of the tunnel is treated as the uniform load, regardless of the arch's axis variation causing surrounding rock pressure variation. A schematic diagram is shown in Figure 1.

The formulas of Protodyakonov's theory for the load calculation of the surrounding rock are as in Eqs. (1) to (3).

$$q = \gamma \cdot h_{eq} \tag{1}$$

$$h_{eq} = \frac{B/2 + h\tan(45^{\circ} - \varphi/2)}{f} \tag{2}$$

$$e = (q + \frac{1}{2}\gamma h)\tan^2(45^{\circ} - \varphi_g / 2) \tag{3}$$

where q and e are the vertical load and the lateral load, respectively, where q is regarded as uniform load, kN/m^2; γ is the rock unit weight, kN/m^3; h_{eq} is the equivalent load; kN/m^2; f is the apparent coefficient of friction; B and h are the width and height of the tunnel, respectively, m; φ is the internal friction angle; φ_g is the equivalent mean friction angle of the surrounding rock.

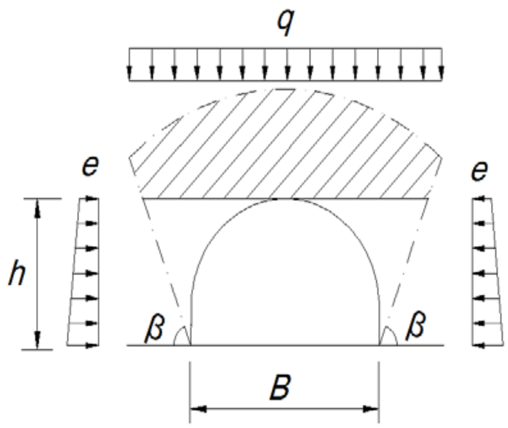


Figure 1 Schematic load of Protodyakonov's theory.

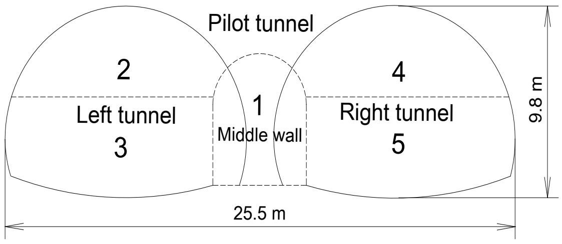
Previous studies have suggested that the calculation span should be between half-width and full width, no matter what kind of empirical formula will be used to calculate the load, the building code method or Protodyakonov's theory [10-13]. In order to analyze the load, three extreme cases are generally assumed: the first is the most favorable situation, in which case the middle wall is very stable and the backfill is close-grained, taking the half-width span to calculate the load; the second is the most unfavorable situation, in which case the supporting role of the middle wall is not considered, taking the whole excavation width to calculate the load; the third case is in between the other two cases.

This study adopted a numerical simulation method, assuming that the middle wall is very stable and the backfill is compacted, taking the half-width of structure to calculate the surrounding rock loads of the double-arch tunnel in accordance with Eqs. (1) to (3). To define the inner and outer boundaries of the pressure-arch for the surrounding rock of a double-arch tunnel, the stress analysis method was used according to [16-18].

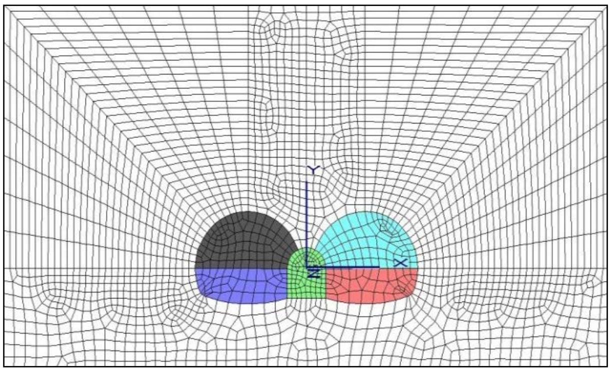
3.2 The Numerical Model and Simplified Equivalent Load

3.2.1 The Computational Model

The numerical model represents a highway double-arch tunnel, whose cross-section is two-way four-lane with an integral casting lining and curved wall structure, located in III grade rock. The shape and dimensions of the double-arch tunnel are shown in Figure 2(a). Its whole span is 25.5 m and its height is 9.8 m. The inner contour line of the tunnel is formed by a three-centered arch. The tunnel is constructed at a depth of 80 m and its hydro-geological conditions are simple, while the terrain is plain without biasing. The tunnel was excavated with the positive bench method. The excavation step sequence was 1-2-3-4-5, as shown in Figure 2(a).



(a) Excavation sequence of the tunnel.



(b) Numerical model and its meshing.

Figure 2 Excavation sequence of the tunnel and the numerical model.

The calculation parameters of the double-arch tunnel were selected as listed in Table 1.

Table 1 Calculation parameters of the surrounding rock of the tunnel.

Unit weight (kN/m^3)	Elasticity modulus (GPa)	Poisson ratio	Cohesion (MPa)	Friction angle (°)	Tension (MPa)
25.0	20	0.3	1.5	48	0.5

The three-dimensional numerical model was built using FLAC3D and ANSYS. The numerical model, divided into 9536 elements, was 70 m long, 40 m high and 4 m wide in the *x*-, *y*-, and *z*-axis separately, as shown in Figure 2(b). Because the infinite long tunnel can be simplified as a plane problem, the *z*-axial length of the model is thin. The four lateral boundaries of the model were restricted and its bottom was fixed. The vertical load was applied to the upper surface of the model, which was converted from the weight of the overlying rock mass. The Mohr-Coulomb strength criterion was chosen in the model and moreover the model was assumed to be in hydrostatic stress state.

3.2.2 Subdivision of Pressure-arch and Simplified Equivalent Load

When the step-by-step excavations of the double-arch tunnel were conducted with the positive bench method, the pressure-arch boundary shape was obtained through the numerical simulation, as shown in Figure 3.

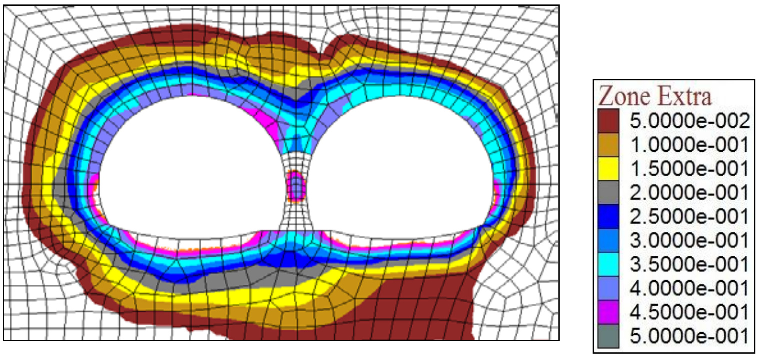


Figure 3 Pressure-arch shape of the double-arch tunnel.

Through the 1-2-3-4-5 sequence of the excavation, the pressure-arch in the double-arch tunnel gradually formed and developed until at last the boundary shape became as shown in Figure 3 (the contours indicate the element stress variable *e* that is defined the same as in [17]). The loads of the double-arch tunnel can be divided into three regions, namely the left tunnel region, the pilot tunnel region and the right tunnel region, which are denoted as L-tunnel, P-tunnel and R-tunnel. When we regard the rock weight within the outer boundary of the pressure-arch as loose load and simplify it as the uniform distributed load, we get the load calculation diagram of the double-arch tunnel as shown in Figure 4.

In Figure 4, the rock weights of the above three regions are respectively represented as S_1, S_2 and S_3. These were converted to uniform distributed loads q_1, q_2 and q_3. The weight of the rock located between the left tunnel and the right tunnel and under the horizontal line of the dome was simplified as the triangular distributed load q_4. Therefore, the loads of the pilot tunnel region consisted of two parts, namely the uniformly distributed load q_2 and the triangular load q_4. The lateral loads, which act on the two lateral linings of the left and the right tunnel, can be calculated according to the Rankine active earth pressure theory.

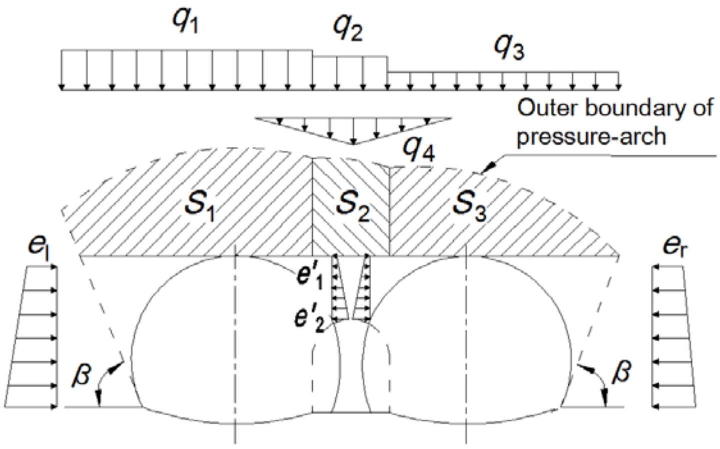


Figure 4 Schematic of the pressure-arch and the simplified loads.

4 Result Analysis and Discussion

4.1 Stress State Effect

When other conditions are the same and only the stress state is different, λ is used to represent the lateral pressure coefficient. Three conditions were selected for the numerical simulation, $\lambda < 1$, $\lambda = 1$ and $\lambda > 1$. The load distribution of the double-arch tunnel when λ was equal to 1.0 is shown in Figure 5. Figure 6 shows the difference between the heights of different regional equivalent loads in the different stress states.

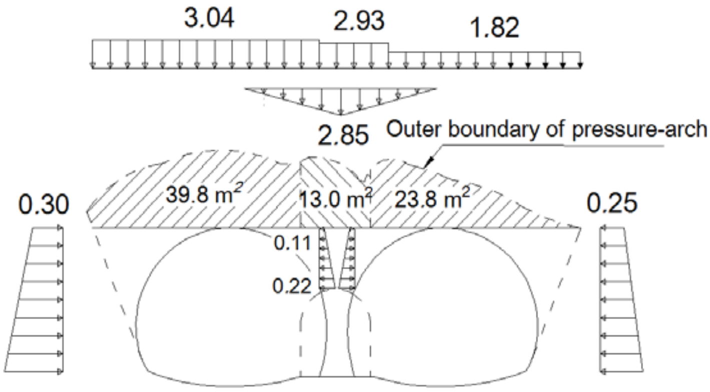


Figure 5 Pressure-arch and equivalent load height when $\lambda = 1$ (m).

In theory, the equivalent load values of the left and the right tunnel should be symmetrical to the pilot tunnel, but it can be seen from Figure 6 that the equivalent load values of the left tunnel were greater than that of the right tunnel under different stress states, indicating that the load distribution of the double-arch tunnel was skewed. For the lateral horizontal loads, the load distribution was skewed and the lateral horizontal load was between 0.1 times and 0.15 times of the vertical load, which is consistent with the range given in the building code of China.

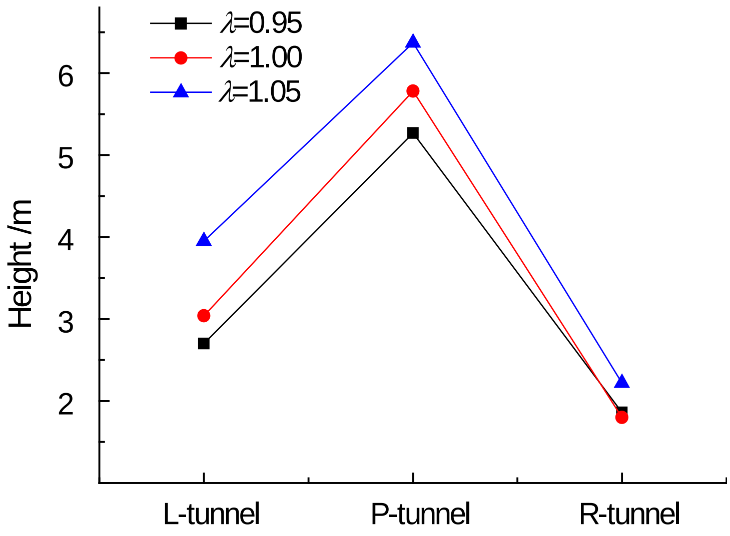


Figure 6 Equivalent load height under different stress states.

The surrounding rock loads of the left tunnel and the pilot tunnel both increased with the increase of λ, indicating that the greater the lateral pressure, the greater the height of the equivalent load of the surrounding rock.

For the equivalent load of the right tunnel, the equivalent load is smallest when $\lambda = 1$ and it is largest when $\lambda > 1$. When it is between the above two cases it is $\lambda < 1$. From Figure 6 it can also be seen that the range of the equivalent load of the left tunnel is larger than that of the right tunnel, indicating that the impact of the construction disturbance to the left tunnel pressure is more obvious.

If the middle wall is very stable and has no deformation and the backfill is compacted, the left tunnel and the right tunnel can form an independent pressure-arch. In this case, the surrounding rock loads acting on the pilot tunnel should be the sum of the loads of three parts, namely coming from the left tunnel pressure-arch, the right tunnel pressure-arch and the pilot tunnel itself. The simulation results showed that the equivalent load of the pilot tunnel was greater than the load sum of the left and the right tunnel and less than the sum of the three parts under ideal conditions, which is a result of the interaction and mutual coordination of the three regional pressure-arches (Figure 7).

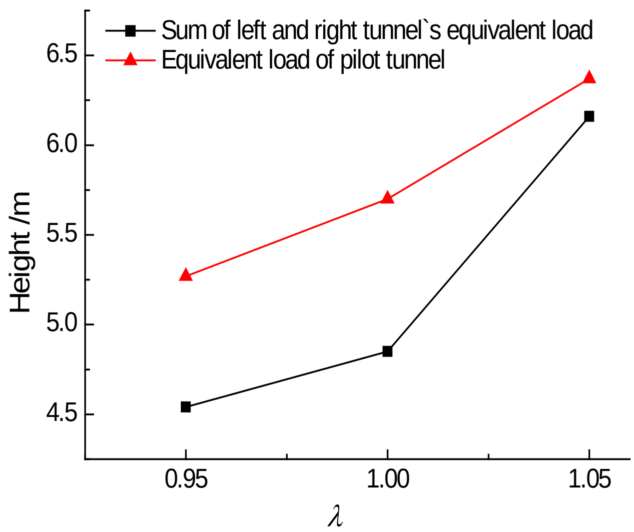


Figure 7 Comparisons of the equivalent loads.

To analyze the skewed characteristics of the equivalent loads, the gap between the equivalent loads of the left and the right tunnel was calculated. Figure 8 shows the gap variation with the change of λ.

It can be seen from Figure 8 that the load gaps of the left and the right tunnel increased with the increase of λ. The gap was 0.86 m when λ was equal to 0.95 and it even reached 1.73 m when λ was equal to 1.05, exceeding 40 % equivalent load of the left tunnel. The results suggest that in the support design of a double-arch tunnel the support parameters designed for the left and the right tunnel should be different, which is of important theoretical significance and engineering value.

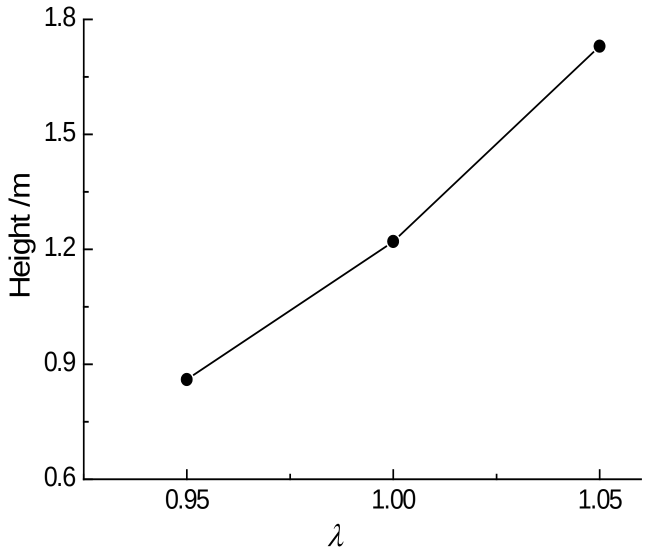


Figure 8 The load gap height with different lateral pressure coefficients.

4.2 Construction Sequence Effect

The bench method and the expanding method were adopted respectively. The construction sequences of the two construction methods were 1-2-3-4-5 and 1-2-4-3-5 respectively. The contrasts of the equivalent load of the double-arch tunnel under different construction sequences are shown in Figure 9.

The equivalent load under the expanding method was greater than that of the bench method, which shows that the disturbance range of the expanding method for the surrounding rock in the double-arch tunnel was greater than that of the bench method.

Under excavation of the expanding method, the equivalent load of the left and the right tunnel tended to be more symmetrical, while the gap between the equivalent loads of the left and the right tunnel was relatively small, accounting for 13% equivalent load of the left tunnel. However, under the excavation of the bench method, the skewness of the equivalent load was more obvious and the load gap between the left tunnel and the right tunnel was bigger than that of the expanding method, which accounted for 40% equivalent load of the left tunnel. Therefore, by comparing the two methods it can be seen that the skewed effect of the equivalent load induced by the expanding method was smaller.

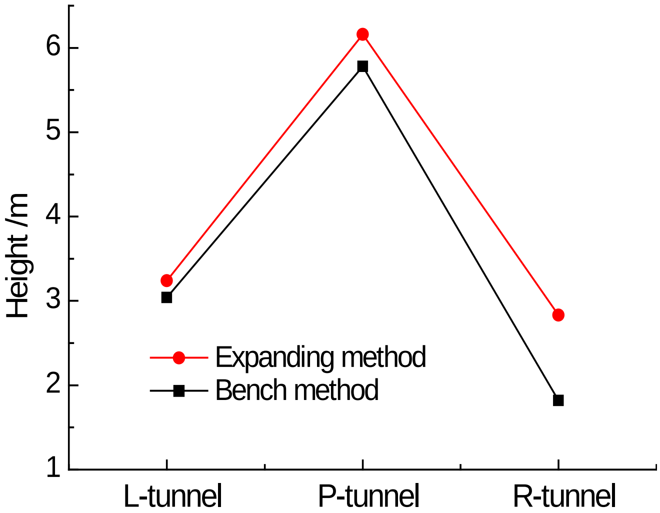


Figure 9 Equivalent load contrasts under two construction methods.

4.3 Excavation Size Effect

A two-lane tunnel and a three-lane tunnel were chosen as research objects. The other conditions were the same and only the excavation sizes were different. The contrasts of the equivalent loads between the two-lane tunnel and the three-lane tunnel under step-by-step excavation of the bench method are shown in Figure 10.

Figure 10 shows that the equivalent load of the three-lane tunnel was larger than that of the two-lane tunnel, indicating that in the double-arch tunnel the equivalent load obviously increased with the increase of the span. In addition, the gap between the equivalent loads of the left and the right tunnel in the three-lane tunnel was larger than that of the two-lane tunnel, indicating that the pressure skewness of the double-arch tunnel was more significant in the large span tunnel. Therefore, by comparison, the construction of a three-lane double-arch tunnel is more difficult and its support costs are significantly higher.

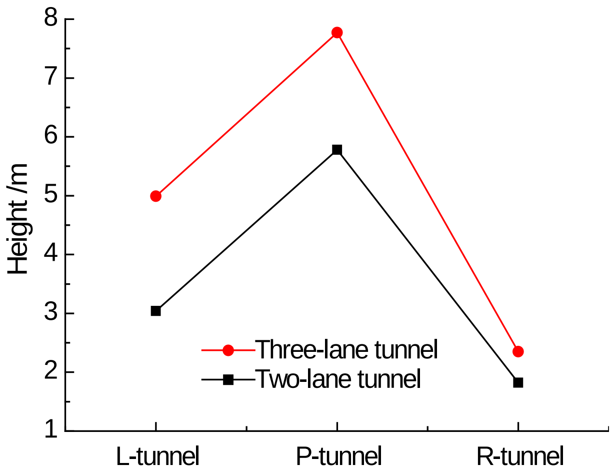


Figure 10 Equivalent loads under two sizes of tunnels.

5 Conclusions

When a double-arch tunnel is excavated using the bench method, the equivalent load distribution in the left and the right tunnel shows the obvious skewed characteristics. The construction method has great influence on the rock pressure distribution in a double-arch tunnel.

Under different working conditions, the pressure distribution of the surrounding rock of a double-arch tunnel has an obvious skewed effect. Under different stress states, the greater the lateral pressure coefficient, the larger the load gap between the left tunnel and the right tunnel. The construction sequence has a great effect on the skewness characteristics of the equivalent load: the larger the excavation span of the double-arch tunnel, the larger the load gap between the left tunnel and the right tunnel.

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