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STUDY ON THE REASONABLE RSR OF ARCH AND ITS INFLUENCING FACTORS IN METRO USING THE PBA METHOD

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ABSTRACT

In this paper, based on the numerical calculation, the reasonable rise-span ratio (RSR) and its influencing factors of the arch in the pile-beam-arch (PBA) method are compared and analyzed, and the mechanical properties of the arch under different influencing factors (RSR, lateral pressure coefficient (LPC), and structure thickness) is further obtained. The results show that the deformation and bending moment of the arch structure decreases first and then increases with the increase of the RSR, that is, optimal RSR exists. Different LPCs have a great influence on the stress of arch structure, and the deformation and bending moment of arch structure decrease with the increase of LPC. The increase in arch structure thickness can effectively reduce structural deformation but may also lead to an increase in structural stress due to the increase in self-weight. At the same time, the comprehensive factors show that the optimal RSR increases with the increase of LPC and structure thickness, and it is suggested that the reasonable RSR should be 0.2-0.3. The rationality of the calculation is also verified by the application status of the station RSR with the PBA method in China.

KEYWORDS

Subway, PBA method, RSR, LPC, Structure thickness, Deformation law

INTRODUCTION

The PBA method is widely used in subway construction all over the country [1-3]. The main construction steps include small pilot tunnel excavation, pile-beam-column construction, initial lining, buckle arch of secondary lining, and main project excavation [4]. Among them, the arch structure is the key part of the main force system of the station. The force conversion mechanism of the structure at this position is complex, and the force conversion mainly occurs at the arch. The arch's structural form will also have a great influence on the structural force. The arch's structural form is mainly reflected in the RSR [5-7], and its safety and stability are of great significance to the entire station. Fang [8] analyzed the structural section of a subway station and concluded that for the underground excavation structure, the principle is that the arch should be arched as much as possible, and the RSR of the arch should not be greater than 1/3. Fu [9] analyzed the influence of the RSR of the inverted arch in the expansive rock stratum on the mechanical properties of the secondary lining and pointed out that the RSR of the inverted arch had the greatest influence on the inverted arch and side wall of the secondary lining. The larger the RSR, the bending moment of the secondary lining at the inverted arch and the side wall, and the axial force of the wall foot all showed a decreasing trend. Zheng et al [10] took the arch structure of the station with the PBA method as the research object and obtained the stress characteristics and surface deformation law of steel pipe columns with different RSR. Liu [11] studied the difference in the mechanical performance of bridge arch structures under different RSR. Fang *et al* [12] studied the mechanical characteristics of the tunnel and proposed some vital suggestions for practical engineering. Ma et al [13] suggested that the RSR of tunnel invert should be 1/6-1/8 in the heavy-haul railway tunnel. Based on the case of a metro collapse project in Beijing, Li et al [14] found that the failure form of a shallow buried tunnel was related to the overburden span ratio and RSR of the tunnel, and analyzed the distribution of the plastic zone and the failure process of the tunnel. Xu et al [15] found that geological strength index has the greatest influence on the minimum RSR of long-span cavern, and the better the rock mass quality, the smaller the minimum RSR. The relationship between minimum RSR and LPC and buried depth is not linear. Huang et al [16] pointed out that the floor heave of an invert decreases with the increase of the RSR, and the larger the RSR is, the smaller the reduction is. The reasonable RSR is suggested to be 0.125 ~ 0.25. Song [17] analyzed the relationship between the stress on the invert structure and the RSR of the weakly expansion-contraction high-speed railway tunnel, and found that the maximum axial force on the invert structure was inversely proportional to the RSR, and the greater the RSR, the more significant the influence on the stress on the arch foot.

The above research mainly reflects the importance of arch structure, or mainly focus on the RSR of the tunnel invert, but there are few systematic studies on reasonable RSR and its influencing factors of arch in underground engineering. It can be seen from the engineering practice that the selection of the RSR has a great influence on the stress, construction convenience, and economy of the structure. Therefore, further exploration of the reasonable RSR can provide some guiding suggestions for the project. Therefore, based on the Tianhedong subway station project of Guangzhou Metro Line 11, the mechanical performance difference and deformation law of the arch structure of the station under different influencing factors (RSR, LPC, and structure thickness) is analyzed, and a reasonable RSR is obtained, which provides some vital reference for subsequent related research.

THEORETICAL ANALYSIS

Investigation of the station RSR with the PBA method in China

This paper collects the side span RSR ρ of the station using the PBA method in China, as shown in Table 1 and Figure 1. In Table 1 and Figure 1, the range of the side span RSR of the station with the PBA method is between 0.21 ~ 0.33, and the station with the RSR of 0.27 is the majority, which also shows that the selection of RSR in the actual project has a certain regularity.

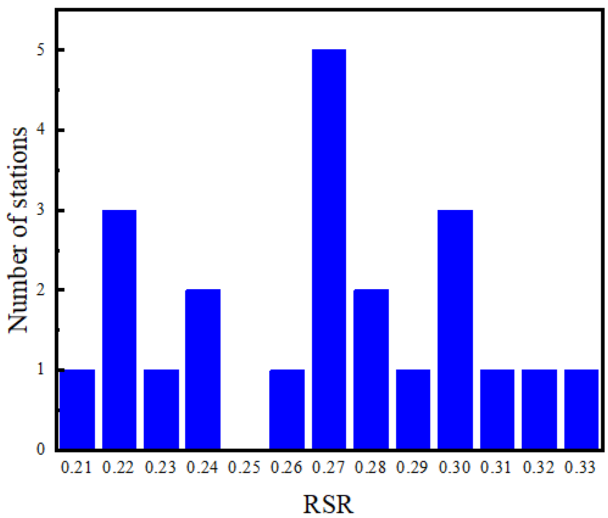

Fig. 1 - The distribution of stations number under different RSR

Theoretical analysis

The force of arch structure is simplified as shown in Figure 2. It is assumed that the arch structure is subjected to horizontal load and vertical uniform load on both sides. Since the weak point of the arch is generally at the vault, the bending moment as well as axial force at vault C is calculated to obtain its variation with RSR (ρ= f/l). It can be seen from Figure 2 that the influencing factors of the force of vault C mainly include RSR, LPC, and structure thickness.

Tab. 1 - Application of station RSR with PBA method

Station name	ρ	Station name	ρ
Guangzhou Shahe Station	0.24	Beijing Xiangheyuan Station	0.27
Beijing Dongdaqiao Station	0.30	Guangzhou Tianhe East Railway Station	0.27
Beijing Puhuangyu Station	0.30	Guangzhou Huajing Road Station	0.22
Beijing Yonganli Station	0.29	Beijing Tiananmen West Railway Station	0.22
Beijing Financial Street Station	0.28	Beijing Chaoyang Park Station	0.28
Beijing Tuanjiehu Station	0.30	Dalian Labour Park Station	0.24
Beijing Liaogongzhuang Station	0.31	Urumqi Wangjialiang Station	0.21
Beijing Wangfujing Station	0.23	Shenyang Youth Street Station	0.22
Beijing Niujie Station	0.32	Harbin Provincial Government Station	0.27
Guangzhou Liuhua Road Station	0.33	Shenyang Chongshan Road Station	0.26
Beijing Mudanyuan Station	0.27	Shenyang Youth Park Station	0.27

The bending moment and axial force about the vault change with RSR, and the change range is determined by the coefficient *K* [18]. Assuming that the LPC is *a*, that is, q_2 = aq_1, the bending moment and axial force about the vault can be obtained, as shown in *Eqs*. (1) ~ (2).

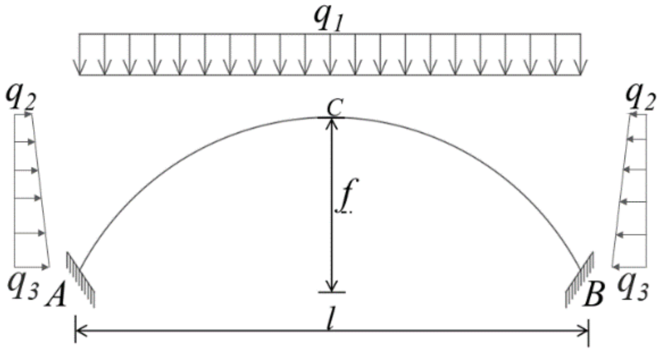

Fig. 2 – Stress diagram of the Arch

$$M_c = l^2 q_1 \left(K_1 + a\rho K_2\right) = K_M l^2 q_1 \quad (1)$$

$$N_c = l q_1 \left(K_3 + \left(K_4 + 1\right) a\rho\right) = K_N l q_1 \quad (2)$$

Among them, K_1, K_2, K_3, and K_4 are the coefficients that change with RSR. In addition, K_M and K_N are the coefficients of bending moment and axial force of the vault respectively. The relationship between them and RSR can be obtained by checking the table [18], as shown in Figures 3 ~ 4 (assuming that the LPC is 0.4). Note: from Table 1, it can be seen that the range of the side span RSR of the domestic PBA station is between 0.21~0.33, so the range of the RSR discussed in this paper is 0.1 ~ 0.5.

From Figures.3~4, the bending moment about the vault increases with RSR, and the axial force of the vault decreases with the increment of RSR. It also shows that for the arch structure, the selection of RSR can effectively improve the structural force and the safety of the structure.

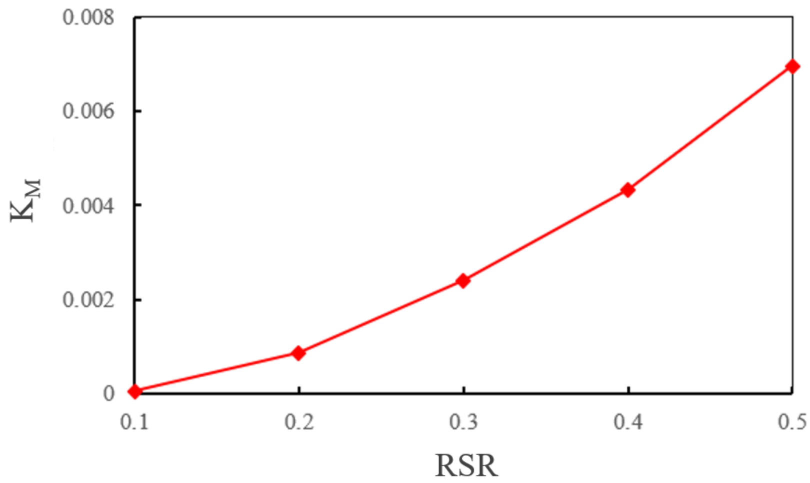

Fig. 3 - Curve of bending moment coefficient of the vault with RSR

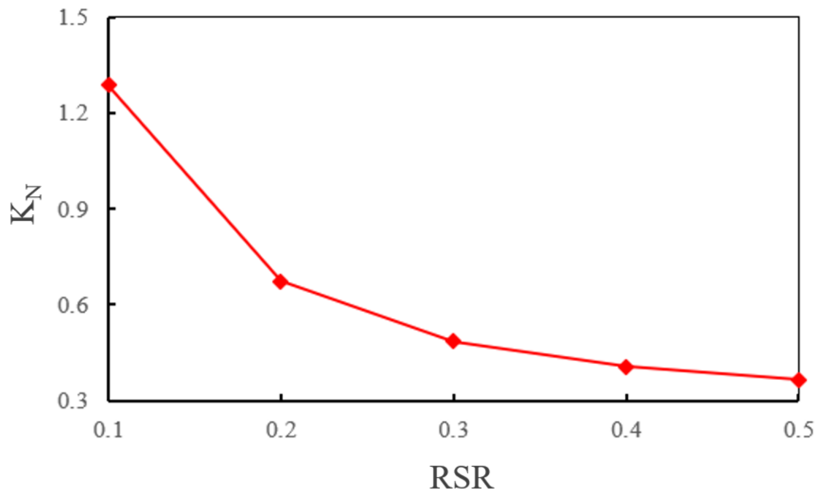

Fig. 4 - Curve of axial force coefficient of the vault with RSR

NUMERICAL CALCULATION ANALYSIS

Calculation instruction

For the arch structure, there are many factors affecting the force of the arch. Based on the theoretical analysis, this paper mainly discusses the influence of RSR, LPC, and structure thickness on the stress and deformation of arch structures. Load-structure model is adopted for this paper. ANSYS software is used for numerical calculation and analysis, the calculation model is presented in Figure 5. For the numerical simulation, the arch structure is modeled adopting the beam structure element, and the interaction between the arch structure and surrounding rock is realized by spring element. Note that the interaction springs around the arch structure can only bear compressive load, and the force of spring will set to zero when tensions appear, the outer end of the spring is fixed. The vertical load q = 400 kPa and the single arch span l= 10 m are fixed, and the horizontal load changes with the change of the LPC, and the arch height f is determined by the corresponding RSR.

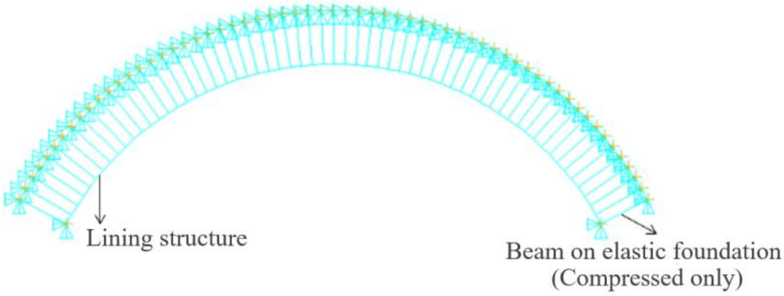

Fig. 5 - Calculation model

Calculation results and analysis

The influence of RSRs

To further explore the influence of the RSR on the arch deformation and stress, the fixed LPC and arch thickness are 0.4 and 0.35 m respectively, and the arch height *f* is 1m, 2m, 3m, 4m, 5m (i.e., the corresponding RSR is 0.1, 0.2, 0.3, 0.4, 0.5, respectively),

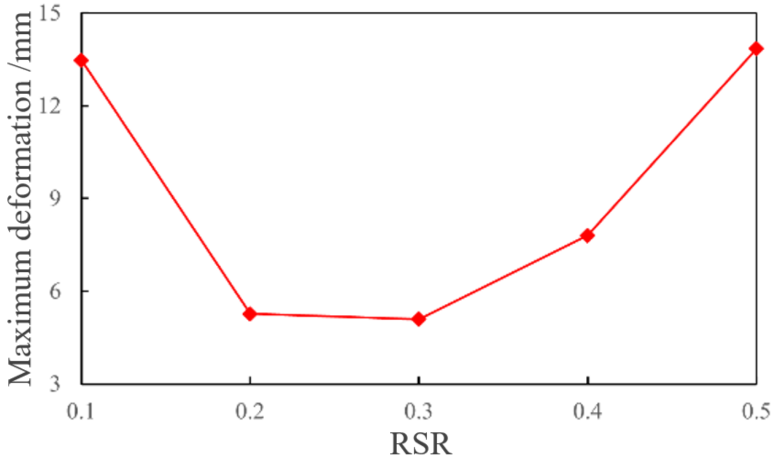

Fig. 6 - Curve of the maximum deformation of arch structure with RSR

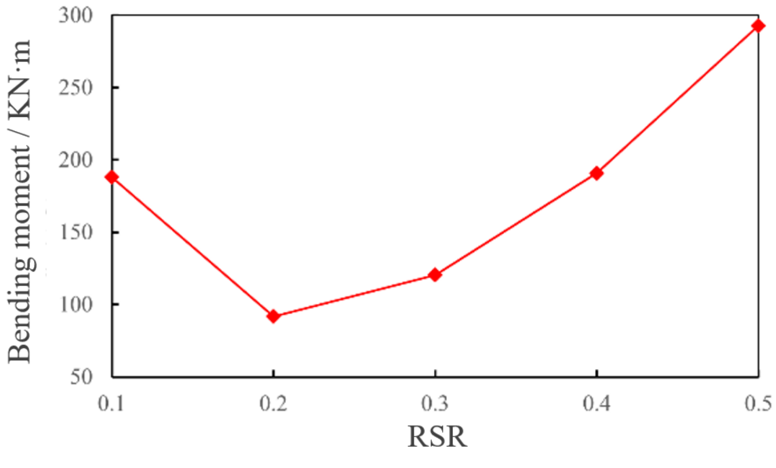

Fig. 7 - Curve of the bending moment of the vault with RSR

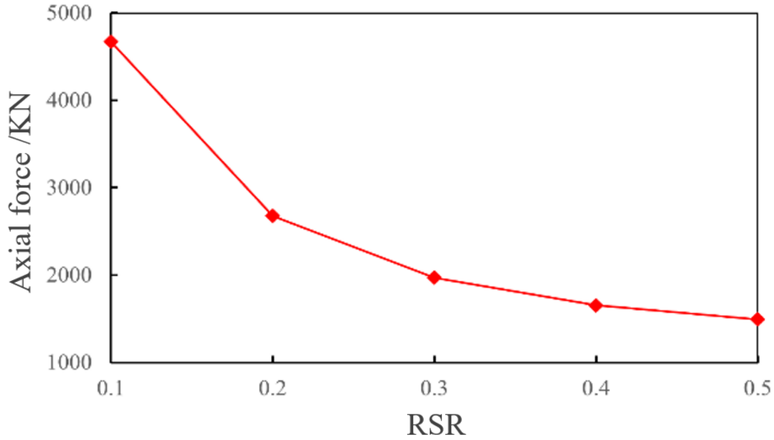

Fig. 8 - Curve of the axial force of vault with RSR

The variation law of the maximum deformation of the arch structure with RSR is presented in Figure 6, and the distribution of internal force about the vault is shown in Figures 7 ~ 8. From Figures 7~ 8, the maximum deformation and bending moment of the arch structure decrease first and then increase with RSR (i.e., from flat arch to sharp arch). When RSR is 0.5, the maximum arch deformation is 13.85 mm. When the RSR is 0.3, the maximum arch deformation is only 5.10 mm, and the reduction rate is 63.17 %. At the same time, the maximum and minimum values of the bending moment of the vault at different RSRs are 292.78 kN·m and 91.79 kN·m, respectively, and the difference reaches 68.65 %, indicating that the RSR greatly influences the deformation and stress of the arch structure. There exists optimal RSR making the stress as well as deformation about arch structure relatively minimum. Under this condition, the reasonable RSR is between 0.2 and 0.3, which is consistent with the investigated 0.21-0.33 in the previous section.

Besides, the axial force of the vault gradually decreases with the increase of RSR, and there is a sharp downward trend at RSR = 0.2, indicating that the increase of the RSR can also effectively improve the axial force of the arch structure.

The influence of LPCs

Fix the RSR and structure thickness at 0.3 and 0.35m respectively, and the LPCs are taken 0, 0.2, 0.4, 0.6, and 1.0 respectively, the influence of LPC on the deformation and stress of the arch is studied. The distribution of maximum deformation and internal force of arch structure under different LPCs are calculated, as shown in Figures. 9 ~ 11.

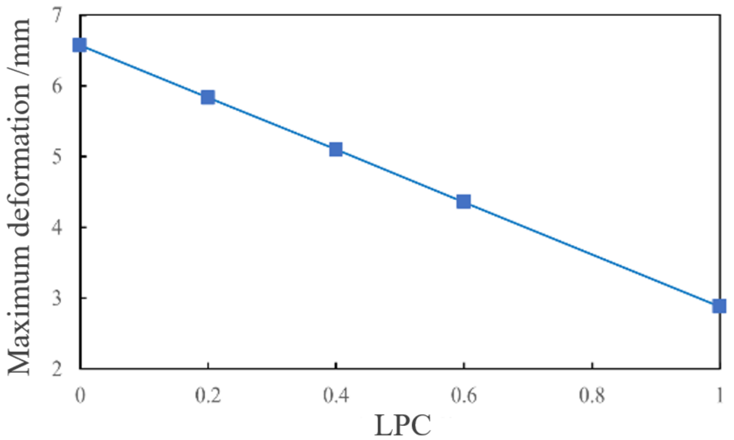

Fig. 9 - Curve of maximum deformation of arch structure with LPC

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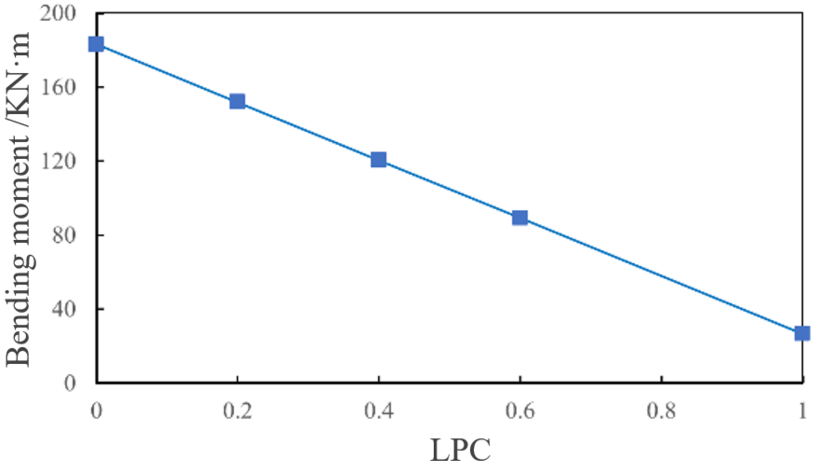

Fig. 10 - Curve of the bending moment of the vault with LPC

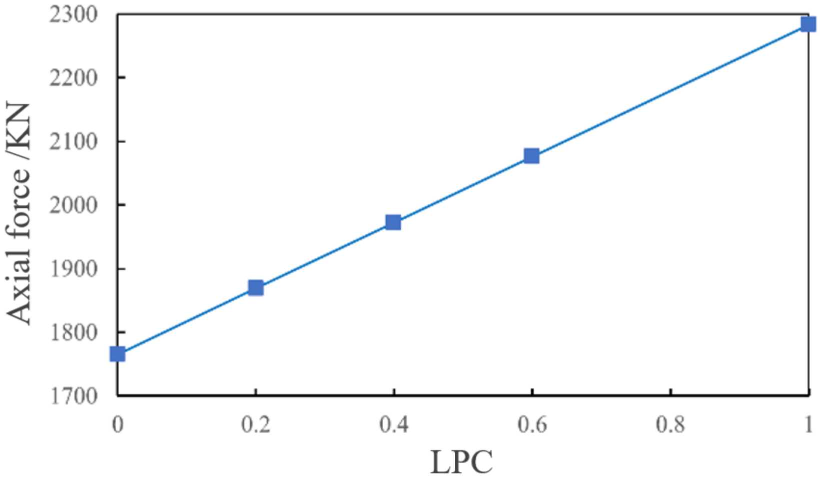

Fig. 11 - Curve of the axial force of vault with LPC

From Figures 9~11, the deformation and bending moment of the arch decrease with the increase of the LPC, while the axial force of the vault increases gradually and is linearly related. When the LPC is 0~1, the maximum deformation values of the vault are 6.57 mm and 2.88 mm, the bending moment values are 183.14 kN·m and 26.66 kN·m, and the axial force is 1765.44 kN and 2283.51 kN. It shows that LPC greatly influences the arch structure, and LPC is closely related to the surrounding rock conditions. Therefore, more attention should be paid to the surrounding rock conditions in the design of the station structure to improve the force as well as the deformation of the structure.

The influence of structure thicknesses

Fix RSR and LPC at 0.3 and 0.4 respectively, and the structure thickness is taken as 0.35m, 0.5m, 0.65m, 0.8m, 1m, and 1.2m respectively to study the impact of structure thickness on the deformation and stress of arch. The calculation results are shown in Figures 12~14.

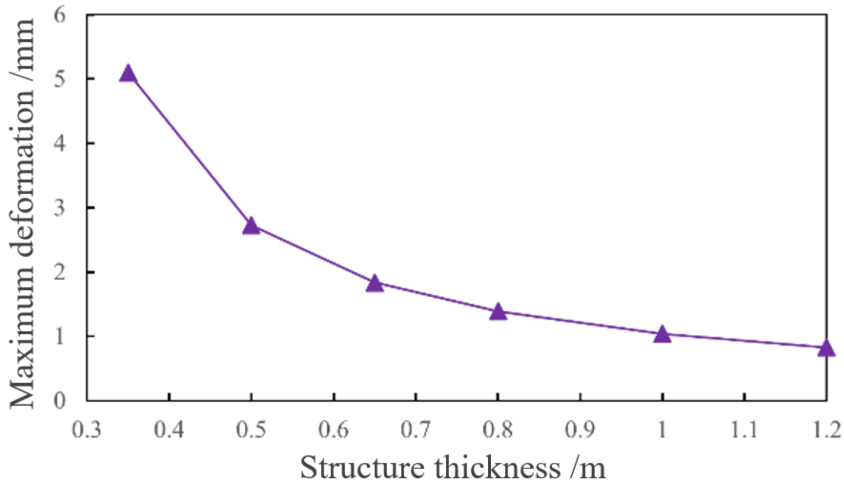

Fig. 12 - Curve of the maximum deformation of arch structure with structure thickness

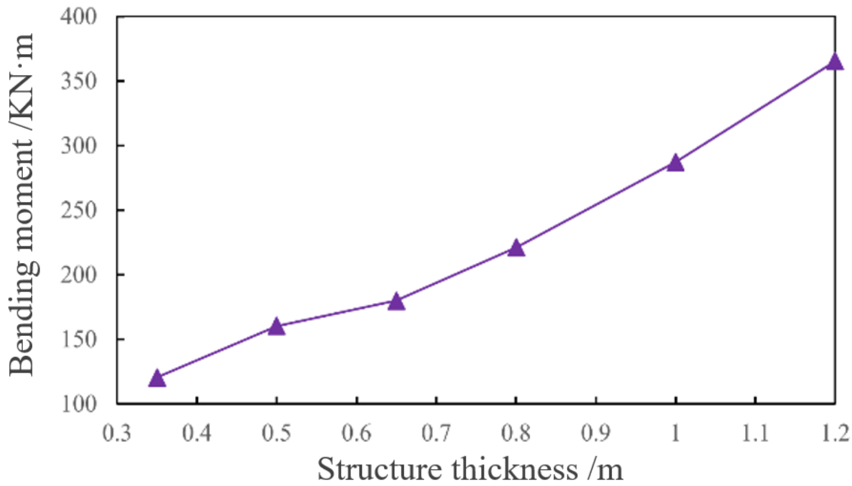

Fig. 13 - Curve of bending moment of the vault with structure thickness

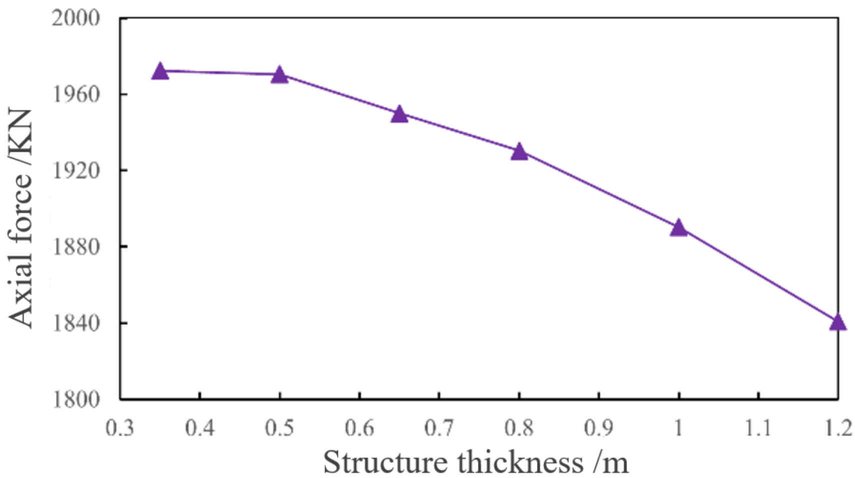

Fig. 14 - Curve of the axial force of vault with structure thickness

From Figures 12~14, as the thickness of the arch structure increases, the deformation of the arch structure gradually decreases, and the bending moment about the vault gradually increases. Since the structural stiffness increases with structure thickness, which can effectively reduce the deformation of the structure. However, the increase in structure thickness also leads to the increase of structure self-weight and increases its vault bending moment, and has no significant effect on the axial force of the vault.

Comprehensive analysis

To further study the influence of RSR, LPC, and structure thickness on the safety of the arch, the influence of LPC-RSR and RSR-structure thickness on the safety factor of the vault are discussed respectively. The following is the variation law of the safety factor of the vault of the LPC =0 ~ 1.0 and the structure thickness = 0.35m ~ 1.2m when RSR is 0.1 ~ 0.5.

When the fixed structure thickness is 0.35 m, the safety factor of a vault under different RSRs and LPC conditions is calculated, as shown in Figure 15.

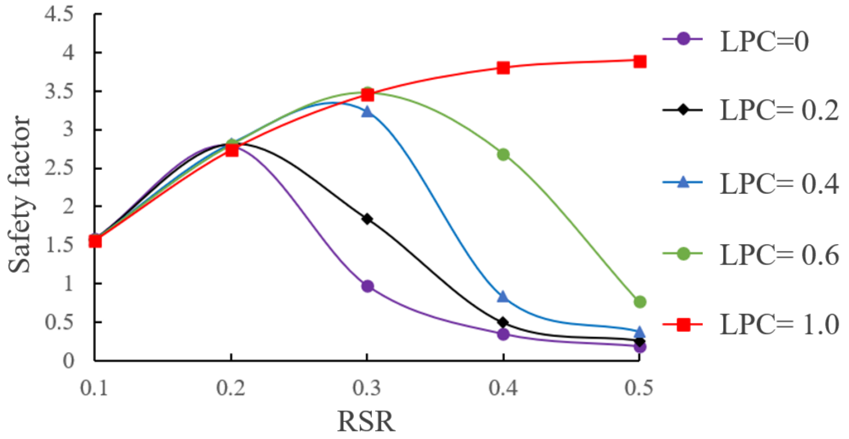

Fig. 15 - Curve of the safety factor of the vault with RSR (different LPC)

From Figure 15, within the range LPC=0-0.6, the safety factor about the vault increases first and then decreases with RSR. When LPC=1.0, the safety factor about the vault increases with RSR. It can be also found that with the increase of LPC, the largest safety factor about the vault needs larger RSR, and even no largest safety factor appears when LPC=1.0. The safety factor varies greatly with different LPCs. The larger the LPC, the greater the safety factor of the vault. It can also be seen that the larger the RSR, the greater the influence of LPC on the safety factor of the vault. In general, when RSR is between 0.2~0.4, the vault safety is high.

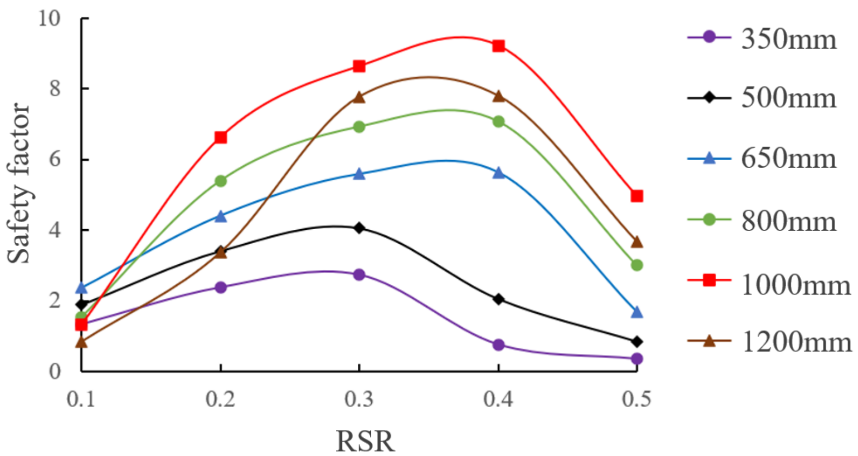

Fig. 16 - Curve of the safety factor of vault with RSR (different structure thickness)

When the LPC is fixed at 0.4, the safety factor of the vault under different RSRs and structure thickness is calculated, as presented in Figure 16. The vault safety factor increases first and then decreases with RSR, and when the structure thickness is no more than 1 m, vault safety factor increases with structure thickness. The safety factor at the structure thickness = 1.2 m is less than that of the structure thickness = 1 m, indicating that increasing the structure thickness after the structure thickness reaches 1 m does not continuously increase the safety of vault. At the same time, it can be seen that the greater the structure thickness, the greater the RSR corresponding to the maximum safety factor, indicating that when the structure thickness increases, the better RSR can be also increased.

CONCLUSIONS

(1) When the structure thickness and LPC are fixed, the deformation and bending moment of the arch structure decrease first and then increase with RSR. The difference in deformation and bending moment under different RSRs is 63.17 % and 68.65 % respectively, which shows that RSR greatly influences the deformation and stress of arch structure, and there exists optimal RSR making the bending moment and deformation of arch structure relatively minimum. It is suggested that the reasonable RSR is 0.2 ~ 0.3.

(2) When the structure thickness and RSR are fixed, the deformation and bending moment of the arch decrease with the increase of the LPC, and the axial force of the vault increases gradually and linearly. When LPC is 0~1, the deformation of the arch structure and the bending moment of the vault are reduced by 56.16 % and 85.45 % respectively, indicating that LPC has a great influence on the arch structure. LPC is closely related to the surrounding rock conditions, so attention should be paid to the surrounding rock conditions when designing the station structure.

(3) When RSR and LPC are fixed, the deformation about arch structure decreases with the increase of structure thickness, and the bending moment of the vault gradually increases. This is mainly because the structure stiffness increases with structure thickness, which can effectively reduce the structural deformation. However, the increase in the structure thickness increases the structure ‘s self-weight, thus increasing the bending moment of the structure itself, while the influence on the axial force is not significant.

In addition, LPC can improve the optimal range of RSR to a certain extent, and the influence law of structure thickness is similar to that of the LPC.

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

DATA AVAILABILITY

All data, models, and code generated or used during the study appear in the submitted article.

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