Multi-factors influence of anchorage force on surrounding rock under coupling effect of creep rock mass and bolt/cable

Yuting Liu\textsuperscript{a,b}, Pengqiang Zheng\textsuperscript{a,b} and Pu Wang\textsuperscript{b}

\textsuperscript{a}College of Civil Engineering and Architecture, Shandong University of Science and Technology, Qingdao, China; \textsuperscript{b}College of Resources, Shandong University of Science and Technology, Tai'an, China

\section*{ABSTRACT}
Assuming that relative sliding does not occur to the coordinated deformation of bolt/cable and surrounding rock, a constitutive model of coupling effect between bolt/cable and creep surrounding rock is established to study the variation law of anchorage force on surrounding rock with time increasing, the parameters of physical-mechanics of bolt/cable and the mechanical parameters of surrounding rocks analyzed, and the sensitivity of the above parameters to anchorage force compared using sensitivity analysis method. Results show that the validity and effectiveness of the proposed constitutive model is verified by numerical simulation. And the main factors affecting the anchorage force for creep rock are diameter ($D$), elastic modulus ($E$), and initial pre-stress force ($F$) of bolt/cable, viscoelastic modulus ($E^R$), viscoelastic coefficient ($\eta^R$) and initial \textit{in situ} stress ($\sigma_0$) of surrounding rocks, respectively. For bolt or cable, increasing the parameter values of $D$, $E$, and $F$ can strengthen the anchorage force; while for surrounding rocks, large value of $\sigma_0$ and small value of $\eta^R$ are beneficial to the exertion of anchorage force. The sensitivities of these factors from high to low are $D$, $E$, $\sigma_0$, $E^R$, $F$, $\eta^R$, respectively. The result can provide some guidance for the formulation of on-site support scheme and parameters selection.

\section*{1. Introduction}
As an important and effective support material, bolts and cables are widely used in many engineering projects, such as coalmines, tunnels, hydropower stations and slopes (Xu et al. 2018; Zhang et al. 2019; Wang et al. 2020). With the gradual development of coalmines and tunnels to deeper area, the mechanical environment is increasing complex, and the geological and mining environment of surrounding rocks tend to be worse (Wang et al. 2018; Jiang et al. 2019; Han et al. 2020; Wang et al. 2020).
Moreover, the surrounding rock of roadway with high in situ stress often undergoes obvious rheology, which seriously affects the roadway stability (Zhao et al. 2017; Wang et al. 2019). For instance, only based on the rheological viewpoint of rock mass, the engineering problems such as the instability of tunnel caving, the deformation of surrounding rock, and the time-dependent interaction between lining support and surrounding rock can be reasonably explained (Sun 2007; Wang et al. 2018).

The deformation-failure of surrounding rock is closely related to its creep characteristic. The accelerated creep stage of surrounding rock will cause rapid changes of deformation for surrounding rock, increase the stress of bolt, and may lead to tension failure or interface debonding failure of bolt. In order to give full play to the support role of bolts, the coupling and coordination between bolts and creep surrounding rocks should be considered to allow stable creep of surrounding rocks and limit accelerated creep (Dong et al. 2018).

The law of interfacial load transfer in anchorage system is the basis of studying the interaction between creep rock and bolt. For this reason, numerical studies have been conducted by many domestic and foreign scholars. The mechanical analysis models of discrete, friction-coupled and continuous friction-coupled bolts for supporting tunnel, respectively, were proposed, and compared them with the numerical results (Bobet and Einstein 2011). The bolt support system was studied using the improved Shear-Lag theory (Cai et al. 2004). The pre-stressing loss of bolt with creep surrounding rock was studied by building component models or carrying out laboratory tests, and then the factors affecting the pre-stressing loss were analyzed further (Xia 2010; Wang et al. 2014; Dong et al. 2018). Based on the deformation characteristics of surrounding rock, the constitutive models which can reflect the accelerated creep of surrounding rock and the working characteristics of bolt were constructed (Chen et al. 2002). A mechanical model of interaction between bolt and surrounding rock was proposed, and the support mechanical effect of bolt analyzed (Indraratna and Kaiser 1990; Hyett et al. 1996; Guan et al. 2007). Assuming that the deformation-failure of surrounding rock conform to Hoek-Brown strength criterion, the elastic-plastic distribution of surrounding rock with bolt support was studied considering the non-linear failure characteristics after stress peak, and then the relationship between bolt support and fracture range of surrounding rock was analyzed (Osgoui and Oreste 2010). Aiming at the rock mass with brittle failure and plastic softening failure, a calculation model of surrounding rock characteristic curve of roadway under active bolt support was put forward, and then it is pointed out that reducing the distance between bolts is an effective measure to improve the stability of surrounding rock (Fahimifar and Ranjbarnia 2009). The surrounding rock of soft rock roadway is divided into anchorage support area and non-anchorage support area and a viscoplastic mechanical model of surrounding rock with anchorage support is proposed (Dai et al. 2004).

Numerous literatures mainly focused on the creep characteristics of rock mass (Cristescu et al. 1987; Xu et al. 2012; 2013; Fu et al. 2020; Xu et al. 2020), while the creep characteristics of surrounding rock were rarely considered when studying the interaction between bolt and surrounding rock. Moreover, previous studies mostly
focused on the stress analysis of bolts or the effect of bolt support, or studied the state of bolt support in creep rock mass, and only considered individual influencing factor, such as loss of pre-stress of bolts, row spacing between bolts, etc.; and did not carry out multi-factors influence study and sensitivity analysis based on the coupling effect of creep rock mass and bolt which lacks guidance for design of field support scheme and selection of parameters.

Hence, assuming that relative sliding does not occur to the coordinated deformation of bolt/cable and surrounding rock, a constitutive model of coupling effect between bolt/cable and creep surrounding rock is constructed to study the variation law of anchorage force on surrounding rock with time increasing, analyze the parameters of physical-mechanics of bolt/cable and the mechanical parameters of surrounding rocks, and then compare the sensitivity of the above parameters to anchorage force by using sensitivity analysis method. Study results can provide design guidance for supporting scheme and parameter selection of deep underground engineering.

2. Constitutive model of coupling effect between bolt/cable and surrounding rock

2.1. Constitutive model to characterize creep of surrounding rock and bolt/cable

In field engineering, the deformation of surrounding rock with large in situ stress often shows elastoplasticitical characteristics and rheological behaviour. Moreover, the main rheological forms of rock mass include creep and stress relaxation. However, the creep characteristic of surrounding rock has the most intimate relationship with rock engineering and its construction, which has important study value and engineering practical value (Sun 2007).
Figure 1 depicts a typical creep curve of rocks. According to the different strain rates, the creep process can be divided into three stages: initial creep (stage ab), constant velocity creep (stage bc) and accelerated creep (stage cd) (Qian et al. 2011). When the rocks are in the stage of accelerated creep, the deformation speed is fast and deformation amount large; it is difficult to coordinate deformation for the surrounding rocks and the bolt/cable, which will cause the failure of the bolt/cable. Through a large number of field investigations, the bolt/cable often breaks or the interface debonds with the surrounding rock in the stage of accelerated creep; while in the stage of stable creep, no slip deformation occurs which can be well coupled into a whole. Hence, the stage of stable creep of surrounding rock is chosen to study the cooperative mechanism for coupling between the bolt/cable and the surrounding rock.

Figure 2 shows Kelvin model and its creep curve (Qian et al. 2011). It can be seen that Kelvin model can simulate the stable creep characteristics of rock mass, and its constitutive equation and creep equation are as shown in Eqs. (1) and (2). Figure 3 depicts the stress–strain curve of elastomer under tension and presents the stress increases rapidly in elastic stage with the oblique straight line while that of basically unchanged in plastic stage with the horizontal straight line; then, this feature reflected by the lastic stage can guide the selection of an elastic element and then characterize the mechanical response characteristics of the bolt/cable; moreover, the constitutive equation of this elastic stage is as Eq. (3).

Constitutive equation of Kelvin model: $\sigma = E\varepsilon + \eta \dot{\varepsilon}$  \hspace{1cm} (1)

Creep equation of Kelvin model: $\varepsilon = \frac{\sigma_0}{E} \left(1 - e^{-\frac{\varepsilon t}{\eta}}\right)$ \hspace{1cm} (2)

Equation of elastomer: $\varepsilon = \frac{\sigma}{E}$ \hspace{1cm} (3)

Figure 2. Kelvin model and its creep curve.
2.2. Establishment of constitutive model of coupling effect between bolt/cable and creep rocks

Figure 4 shows diagram of coupling effect between bolt/cable and surrounding rock. In actual bolt/cable construction of field engineering, the rock mass at the anchor end is relatively stable and the compression is small; while the stability of the free end is relatively low and affects the effectiveness of bolt/cable support. Hence, anchor end of the bolt/cable is regarded as the fixed section, and only the variation of its free section is considered; and then the coupling effect between the bolt/cable and its surrounding rock is studied.

For continuous, homogeneous and isotropic surrounding rock, it is assumed that the anchorage force is evenly distributed, and the bolt/cable and the surrounding rock deform together without any sliding. Figure 5 depicts a constitutive model of coupling effect between bolt/cable and surrounding rock. The model is composed of...
two elastomer and a Kelvin model, and is divided into two branches, marked as branches I and II. Branch I (elastomer element $E^c$) can simulate the equivalent elastic modulus of bolt/cable, and branch II can characterize the creep characteristics of surrounding rocks. Herein, the elastomer $E_1$ is used to simulate the pre-stress force of bolt/cable, and $E^R$ of Kelvin model can represent the viscoelastic modulus and $\eta^R$ is viscoelastic coefficient of surrounding rock.

For the Kelvin model in branch II, the strain equation of surrounding rock along the axis of bolt/cable at $t$ time is as follows:

$$\varepsilon_2 = \varepsilon^R = \frac{\sigma_0}{E^R} \left[ 1 - \exp \left( - \frac{E^R}{\eta^R} t \right) \right]$$

where $\sigma_0$ is the initial in situ stress, MPa

For the elastomer $E_1$ in branch II, the stress is equal to that in Kelvin model, that is, $\sigma_1 = \sigma_2 = \sigma_0$. The strain equation of the elastomer is

$$\varepsilon_1 = \frac{\sigma_0}{E_1}$$

Considering the pre-stress force of bolt/cable, the initial strain is

$$\varepsilon_1 = \frac{\sigma^C}{E^C} = \frac{F}{SE^C} = \frac{4F}{\pi D^2 E^C}$$

where $S$ is the cross-sectional area of the bolt/cable; $D$ is the diameter of the bolt/cable; and $\sigma^C$ is the stress of the bolt/cable.

Combining usage Eqs. (5) and (6), we can get

$$E_1 = \frac{\pi D^2 E^C \sigma_0}{4F}$$

It can be seen that $E_1$ is related to the in situ stress of surrounding rock $\sigma_0$, diameter of bolt/cable $D$, elastic modulus of bolt/cable $E^C$ and pre-stress force $F$. 
Hence, the total stain of branch II is as Eq. (8).

\[
\varepsilon = \varepsilon_1 + \varepsilon_2 = \frac{4F}{\pi D^2 EC} + \frac{\sigma_0}{E^R} \left[1 - \exp \left(-\frac{E^R}{\eta^R} t \right) \right] \tag{8}
\]

When the coordinated deformation occurs caused by coupling effect between the bolt/cable and surrounding rock, the total deformation of branches 1 and 2 should be same, as shown in Eq. (9).

\[
\int \varepsilon^C(l) dl = \int (\varepsilon_1 + \varepsilon_2)(l) dl \tag{9}
\]

If the deformation along the bolt/able axis is simplified to uniform strain, we can get the Eq. (10) as follows:

\[
\varepsilon^C = \varepsilon_1 + \varepsilon_2 \tag{10}
\]

By substituting Eqs. (6) and (8) into Eq. (10), the following results can be obtained:

\[
\sigma^C = E^C \left\{ \frac{4F}{\pi D^2 EC} + \frac{\sigma_0}{E^R} \left[1 - \exp \left(-\frac{E^R}{\eta^R} t \right) \right] \right\} \tag{11}
\]

Because the axial force of bolt/cable is \( P = \sigma^C \cdot S \) and the cross-sectional area of bolt/cable is \( S = \pi \left(\frac{D}{2}\right)^2 \), the anchorage force of bolt/cable to surrounding rock is obtained as follows:
\[ P = F + \frac{E^c}{4} \left[ \frac{\sigma_0}{E_R} \left[ 1 - \exp \left( -\frac{E_R}{\eta^R} t \right) \right] \right] \pi D^2 \]  

(12)

where \( P \) is the anchorage force of bolt/cable to the surrounding rock. It can be seen that the anchorage force increases slowly with time after applying a certain pre-stress force \( F \), and finally reaches equilibrium.

### 2.3. Verification of proposed model

In order to explain the rationality of the fore-mentioned proposed model, a cylinder model of surrounding rock-bolt/cable is established by Fast Lagrangian Analysis of Continua (FLAC 3D), as shown in the Figures 6 and 7. The model size is 2 m in diameter and 4 m in height. Kelvin creep model is selected for surrounding rock. The length of free segment of bolt/cable is 2 m. The other parameters are \( E^c = 210 \text{ GPa} \), \( E^R = 12 \text{ GPa} \), \( \eta^R = 20 \text{ GPa}\cdot\text{d} \), \( \sigma_0 = 10 \text{ MPa} \), \( D = 0.02 \text{ m} \) and \( F = 40 \text{ kN} \). The end of the model is fixed with plate. During the simulation, the surrounding rock is applied with confining pressure and the bolt/cable is applied with preload. The friction contact between the free segment of bolt/cable and surrounding rock is in contact. Finally, observe the change of the anchorage force of bolt/cable to the surrounding rock with time.

Then, in order to explain the rationality of the fore-mentioned proposed model, the supporting force of bolt/cable to surrounding rock can be calculated based on Eq. (12), and the calculated result is carried out to compare the numerical simulation result. Figure 8 depicts the results of numerical simulation and theoretical calculation with the supporting force of anchor/bolt to surrounding rock of 40 kN.
It can be seen that the variation anchorage force of this proposed model is similar with that of numerical simulation. The value of supporting force increases rapidly with time rising in the initial stage, and then gradually eases down until it is stable. This indicates that the proposed model is valid and effective.

3. Influence factors for anchorage force of bolt/cable

In the field engineering, the parameters of physical-mechanics of bolt/cable, and the mechanical parameters of surrounding rocks play an important role in the bolt/cable support. As can be seen from Eq. (12), the main factors affecting the anchorage force for creep rock are elastic modulus, diameter and initial pre-stress force of bolt/cable, and viscoelastic modulus, viscoelastic coefficient and initial in situ stress of surrounding rock. In order to intuitively analyze the effect of the parameters of physical-mechanics of bolt/cable and the mechanical parameters of surrounding rocks on the anchorage force, the parameters in Eq. (12) are numerically computed, and then the numerical examples are carried out. The initial values of each parameter are respectively as follows: \( E^c = 210 \) GPa, \( E^R = 12 \) GPa, \( \eta^R = 20 \) GPa-d, \( \sigma_0 = 10 \) MPa, \( D = 0.02 \) m, \( F = 40 \) kN.

3.1. Parameters of physical-mechanics of bolt/cable

From Eq. (12), it can be seen that the factors influencing the anchorage force are elastic modulus, diameter and pre-stress force of bolt/cable. In this paper, the single variable method is used to select one variable and control other parameters unchanged.
3.1.1 Effect of bolt and cable diameter

The diameters of bolts/cables are chosen as \( D = 0.01, 0.02 \) and \( 0.03 \) m, and then the influence of bolt/cables diameters on anchorage force is studied. By substituting the above initial parameters into Eq. (12), the relationship curves among anchorage force, diameters and time are obtained, as shown in Figure 9.

In Figure 9, it can be seen that the variation of anchorage force is similar with different diameters of bolt/cable, but the effect of the diameters on the maximum anchorage force is significant. When \( D = 0.01 \) m, the maximum anchorage force of bolt/cable is the smallest with only \( 43.37 \) kN, and it has little change with the initial force \( 40 \) kN, which indicates that the anchorage force of bolt/cable for supporting is not effective. With the diameter of bolt/cable increasing, the maximum anchorage force rises significantly with \( 313.24 \) kN when \( D = 0.03 \) m, which indicates that the anchorage efficiency of bolt/cable increases sharply and the support effect is relatively well. In addition, with the increase of the bolt/cable diameter, the anchorage force of bolt/cable reaches stability for almost the same time (about 16 days) with the different diameters; it further shows that under certain conditions, increasing the diameter of bolt/cable can significantly improve the maximum anchorage force efficiency, and does not affect the time when the anchorage efficiency reaches the optimal capacity.

3.1.2 Effect of elastic modulus for bolt/cable

The elastic modulus of bolts/cables are chosen as \( E^c = 100, 210 \) and \( 300 \) GPa, and then the influence of elastic modulus on anchorage force is studied. By substituting the above initial parameters into Eq. (12), the relationship curves among anchorage force, elastic modulus and time are obtained, as shown in Figure 10.

From Figure 10, it can be seen that the variation of anchorage force is similar with different elastic modulus of bolt/cable, and the maximum anchorage force of bolt/cable rises linearly with elastic modulus increasing. When \( E^c = 100 \) GPa, the maximum anchorage force of bolt/cable is smallest with only \( 65.70 \) kN; which indicates that the bolt/cable exerts certain anchorage efficiency, but the anchorage effect is
general. With the increase of elastic modulus, the maximum anchorage force increases linearly; herein, it rises to 117.11 kN with \( E^c = 300 \) GPa, which indicates that the anchorage efficiency is improved and the supporting effect is relatively good. Moreover, with the increase of elastic modulus of bolt/cable, the time when the anchorage force reaches stability is also basically about 16 days. It also shows that under certain conditions, increasing the elastic modulus of bolt/cable can improve the maximum anchorage force efficiency, and does not affect the time when the anchoring efficiency reaches the optimal capacity.

3.1.3 Effect of pre-stress force of bolt/cable
The pre-stress force of bolt/cable are chosen as \( F = 40, 50 \) and \( 60 \) kN, and then the influence of pre-stress force on anchorage force is studied. By substituting the above initial parameters into Eq. (12), the relationship curves among anchorage force, pre-stress force and time are obtained, as shown in Figure 11.

As can be seen from Figure 11, the variation of anchorage force is similar with different pre-stress forces of bolt/cable, and the maximum anchorage force of bolt/cable rises linearly with the pre-stress force increasing. When \( F = 40 \) kN, the maximum anchoring force of bolt/cable is smallest, but it can still reach 93.93 kN; it indicates the anchorage force of bolt/cable exerts remarkable anchoring effect. Moreover, the maximum anchorage force rises linearly with the pre-stress force increasing and it rises to 113.93 kN when \( F = 60 \) kN, which indicates that the anchoring efficiency is further improved and the supporting effect is correspondingly enhanced. Generally, it is required that the initial pre-stress force of bolt/cable should reach a certain value in order to achieve effective support in the field engineering.

3.2. Influence of surrounding rocks parameters on anchorage force
As can be seen from Eq. (12), the factors of surrounding rocks affecting the anchorage force are the viscoelastic modulus, the viscoelastic coefficient and the initial \textit{in situ} stress of surrounding rocks.
3.2.1 Effect of viscoelastic modulus of surrounding rocks

The viscoelastic modulus of surrounding rocks are chosen as $E^R = 8, 10$ and $12$ GPa, and then the influence of viscoelastic modulus on anchorage force is studied. The single variable control method is still used, and other parameters are consistent with those in the previous section. By substituting the above initial parameters into Eq. (12), the relationship curves among anchorage force, viscoelastic modulus and time are obtained, as shown in Figure 12.

As can be seen from Figure 12, the variation of anchorage force is similar with different viscoelastic modulus of surrounding rocks, but the maximum anchorage force of bolt/cable decreases linearly with the viscoelastic modulus increasing. When $E^R = 8$ GPa, the maximum anchoring force of bolt/cable is largest with the value of $122.47$ kN; it shows that the anchorage force of bolt/cable has the highest anchoring efficiency and the best supporting effect. With the increase of viscoelastic modulus, the maximum anchorage force decreases linearly which sharply drops to $94.98$ kN when $E^R = 12$ GPa; it indicates the anchorage efficiency of bolt/cable decreases, and the support effect is relatively poor.

3.2.2 Effect of viscoelastic coefficient of surrounding rocks

The viscoelastic coefficient of surrounding rocks are chosen as $\eta^R = 10, 20$ and $40$ GPa·d, and then the influence of viscoelastic coefficient on anchorage force is studied. By substituting the above initial parameters into Eq. (12), the relationship curves among anchorage force, viscoelastic coefficient and time are obtained, as shown in Figure 13.

From Figure 13, we can see that the viscoelastic coefficients of surrounding rocks have little effect on the maximum anchorage force with different viscoelastic coefficients, but have a great influence on the time required to reach the maximum anchorage force stability. When $\eta^R = 10, 20, 40$ GPa·d, all the maximum anchorage force are $93.97$ kN. However, the anchorage force tends to be stable at 10 days with $\eta^R = 10$ GPa·d, at 16 days with $\eta^R = 20$ GPa·d and at 20 days with $\eta^R = 40$ GPa·d. It
indicates that with the rise of viscoelastic coefficient of surrounding rocks, the stability time of anchorage force for bolt/cable increases.

### 3.2.3 Effect of initial in situ stress of surrounding rocks

The initial in situ stress of surrounding rocks are chosen as $\sigma_0 = 10$, 15 and 20 MPa, and then the influence of initial in situ stress on anchorage force is studied. By substituting the above initial parameters into Eq. (12), the relationship curves among anchorage force, initial in situ stress and time are obtained, as shown in Figure 14.

As can be seen from Figure 14, the variation of anchorage force is similar with different in situ stress of surrounding rocks, and the maximum anchorage force rises linearly with the in situ stress increasing. When $\sigma_0 = 10$ MPa, the maximum anchorage force is the smallest, but it can still reach 93.97 kN, which shows the anchorage
efficiency of bolt/cable is higher; then, it rises linearly with the increase of in situ stress of surrounding rocks and significantly reaches to 149.95 kN with $\sigma_0 = 20$ MPa, indicating that the creep of surrounding rocks is more obvious and the anchorage force is more advantageous with the high initial in situ stress.

Hence, it can be concluded that increasing the diameter, elastic modulus and initial pre-stress force can increase the anchorage force for creep surrounding rock. For surrounding rocks, high stress and small viscoelastic modulus are beneficial to the exertion of anchorage force; however, the smaller the viscoelastic coefficient of surrounding rocks, the shorter the time it takes for anchoring force to reach its maximum.

4. Factors sensitivity of affecting anchorage force of bolt/cable

4.1. Sensitivity analysis method

Sensitivity analysis is a common method to analyze the dependence of parameters on system characteristics. Given $T = f(x_1, x_2, \ldots, x_n)$ and a normal state $T^* = f(x^*_1, x^*_2, \ldots, x^*_n)$ (herein, $x_i$ is the determine parameter of system characteristic), and then the system characteristic $T$ deviates from the normal conditions $T^*$ caused by the parameters variation is analyzed. In order to facilitate the analysis of factors sensitivity, the dimensionless sensitivity function is defined as:

$$a_i = \frac{dT}{dx_i} \frac{x^*_i}{T^*} \text{ or } a_i = \frac{\Delta T}{\Delta x_i} \frac{x^*_i}{T^*}$$

where $a_i$ represents the sensitivity with $x = x_i$; and $T^*$ is a function of parameter $x$ and $T^* = f(x)$.

Hence, through the analysis of parameter sensitivity function, the sensitivity of system characteristics to each parameter can be obtained. Moreover, the greater the
sensitivity value, the more sensitive to the parameter, and then the comparative evaluation of each factor can be carried out.

According to the fore-mention analysis, the sensitivity of the characteristic parameters to the anchorage force is the variation influence of the parameter on the

Table 1. Datum value and its variation of parameters of bolt/cable and surrounding rocks.

| Parameters         | $D$ (m) | $E_c$ (GPa) | $F$ (kN) | $\eta^b$ (GPa·d) | $E_R$ (GPa) | $\sigma_0$ (MPa) |
|--------------------|---------|-------------|----------|------------------|-------------|-----------------|
| Datum value        | 0.02    | 200         | 50       | 20               | 10          | 15              |
| Variation range    | 0.01–0.03 | 100–300    | 40–60    | 10–40            | 8–12        | 10–20           |

Figure 15. Calculation results of sensitivity analysis: (a) Diameter of bolt/cable. (b) Elastic modulus of bolt/cable. (c) Pre-stress force of bolt/cable. (d) Viscoelastic modulus of surrounding rocks. (e) Viscoelastic coefficient of surrounding rocks. (f) Initial in situ stress of surrounding rocks.
anchorage force of the bolt/cable. In this section, the system characteristics are as follows:

\[
T = P \\
x = (D, E^c, F, E^R, \eta^R, \sigma_0)
\]  
(14)

\[
P = F + \frac{E^c}{4} \left\{ \frac{\sigma_0}{E^R} \left[ 1 - \exp \left( -\frac{E^R}{\eta^R} t \right) \right] \right\} \pi D^2
\]  
(15)

Hence, the sensitivity function of factors affecting anchorage force of bolt/cable can be expressed as Eq. (16) and Table 1 lists the datum value and its variation of parameters of bolt/cable and surrounding rocks.

\[
a_i = \frac{\Delta P}{\Delta x_i} \frac{x_i^*}{P^*} \quad (i = 1, 2, ..., n)
\]  
(16)

### 4.2. Analysis of calculation results

According to Eq. (16) and its fore-mention analysis, the sensitivity analysis is carried out for anchorage force of bolt/cable and the support effect through the influence factors of diameter, elastic modulus and pre-stress force of bolt/cable, and viscoelastic modulus, viscoelastic coefficient and initial in situ stress of surrounding rock, as shown in Figure 15.

As can be seen from Figure 15, the anchorage force of bolt/cable rises with the increasing of diameter, elastic modulus, pre-stress force of bolt/cable and the initial *in situ* stress of surrounding rocks, with the decreasing of viscoelastic modulus of surrounding rocks; moreover, it remains unchanged with the variation of the viscoelastic coefficient for surrounding rock. However, the effect of these factors on the anchorage force of bolt/cable is notably different. Hence, by substituting the values of Table 1 into Eq. (16), the sensitivity value of factor parameters is calculated and depicted as shown in Figure 16.

In Figure 16, it can be seen that the sensitivity values of influence factors from the bolt/cable and surrounding rocks to the anchorage force is different and the values of \(D, E^c, F, E^R, \eta^R\) and \(\sigma_0\) correspond to 1.26, 0.56, 0.43, 0.88, 0 and 0.73 in turn. Hence, the sensitivities of these factors from high to low are diameter of bolt/cable, viscoelastic modulus of surrounding rock, initial *in situ* stress of surrounding rock, elastic modulus of bolt/cable, pre-stress force of bolt/cable, viscoelastic coefficient of surrounding rock, respectively. The result can provide some guidance for the formulation of on-site support scheme and parameters selection.

### 5. Conclusions

In this paper, based on the hypothesis that relative sliding does not occur to the coordinated deformation of bolt/cable and surrounding rock, a constitutive model of
coupling effect between bolt/cable and creep surrounding rock is constructed. Then, the parameters of physical-mechanics of bolt and cable, and the mechanical parameters of surrounding rocks are studied and the sensitivity of the above parameters to anchorage force is analyzed. We can obtain several conclusions as follows.

- Main factors affecting the anchorage force of bolt/cables for creep rock are diameter, elastic modulus, and initial pre-stress force of bolt/cable, and viscoelastic modulus, viscoelastic coefficient and initial in situ stress of surrounding rocks.
- Increasing the diameter, elastic modulus, initial pre-stress force can increase the anchorage force of bolt/cable, while high stress and small viscoelastic modulus are beneficial to the exertion of anchorage force of bolt/cable; moreover, the smaller the viscoelastic coefficient of surrounding rocks can shorten the time it takes for anchoring force to reach its maximum.
- The sensitivities of fore-mentioned factors from high to low using sensitivity analysis method are diameter of bolt/cable, viscoelastic modulus of surrounding rock, initial in situ stress of surrounding rock, elastic modulus of bolt/cable, pre-stress force of bolt/cable, viscoelastic coefficient of surrounding rock, respectively.

Study results can serve as a reference for the formulation of on-site support scheme and parameters selection under similar conditions.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

**Funding**

The study was funded by the National Natural Science Foundation of China (no. 51804182), Shandong Provincial Natural Science Foundation Science and Technology (nos. ZR2020QE120 and ZR2020ME097), Support plan for Outstanding Youth Innovation Team in Shandong
colleges and Universities (no. 2019KJG007), The Second Batch of Cooperative Education Projects of Ministry of Education in 2019 (no. 201902153001), Key R & D plan of Shandong Province (no. 2019SDZY034-1).

References

Bobet A, Einstein HH. 2011. Tunnel reinforcement with rockbolts. Tunnell Undergr Space Technol Incorporat Trenchless Technol Res. 26(1):100–123.
Cai Y, Esaki T, Jiang YJ. 2004. A rock bolt and rock mass interaction model. Int J Rock Mech Min Sci. 41(7):1055–1067.
Chen AM, Gu JC, Shen J, Ming ZQ. 2002. Model testing research on the variation of tension force of anchor cable with time in reinforcement of soft rocks. Chin J Rock Mech Eng. 21(2):251–256.
Cristescu N, Fotă D, Medveş E. 1987. Tunnel support analysis incorporating rock creep. Int J Rock Mech Mining Sci Geomech Abst. 24(6):321–330.
Dai HL, Wang X, Xie GX, Wang XY. 2004. Theoretical model and solution for the rheological problem of anchor-grouting a soft rock tunnel. Int J Pressure Vessels Piping. 81(9):739–748.
Dong EY, Wang WJ, Ma NJ, Yuan C. 2018. Analysis of anchor space-time effect and research of control technology considering creep of surrounding rock. J China Coal Soc. 43(5):1238–1248.
Fahimifar A, Ranjbarnia M. 2009. Analytical approach for the design of active grouted rockbolts in tunnel stability based on convergence-confinement method. Tunnell Underground Space Technol. 24(4):363–375.
Fu TF, Xu T, Heap MJ, Meredith PG, Mitchell TM. 2020. Mesoscopic time-dependent behavior of rocks based on three-dimensional discrete element grain-based model. Comput Geotech. 121:103472.
Guan Z, Jiang Y, Tanabasi Y, Huang H. 2007. Reinforcement mechanics of passive bolts in conventional tunnelling. Int J Rock Mech Min Sci. 44(4):625–636.
Han W, Li GX, Sun ZH, Luan HJ, Liu CZ, Wu XL. 2020. Numerical investigation of a foundation pit supported by a composite soil nailing structure. Symmetry. 12(2):252.
Hyett AJ, Moosavi M, Bawden WF. 1996. Load distribution along fully grouted bolts, with emphasis on cable bolt reinforcement. Int J Numer Anal Methods Geomech. 20(7):517–544.
Indraratna B, Kaiser PK. 1990. Analytical model for the design of grouted rock bolts. Int J Numer Anal Meth Geomech. 14(4):227–251.
Jiang LS, Wang P, Zheng PQ, Luan HJ, Zhang C. 2019. Influence of different advancing directions on mining effect caused by a fault. Adv Civ Eng. 2019:1–10.
Osgouiri RR, Oreste P. 2010. Elasto-plastic analytical model for the design of grouted bolts in a Hoek-Brown medium. Int J Numer Anal Meth Geomech. 34(16):1651–1686.
Qian MG, Shi PW, Xu JL. 2011. Ground pressure and strata control. Xuzhou: China University of Mining and Technology Press.
Sun J. 2007. Rock rheological mechanics and its advance in engineering applications. Chin J Rock Mech Eng. 26(6):1081–1106.
Wang P, Jia HJ, Zheng PQ. 2020. Sensitivity analysis of bursting liability for different coal-rock combinations based on their inhomogeneous characteristics. Geomatics Nat Hazards Risk. 11(1):149–159.
Wang P, Jiang LS, Jiang JQ, Zheng PQ, Li W. 2018. Strata behaviors and rock-burst-inducing mechanism under the coupling effect of a hard thick stratum and a normal fault. Int J Geomech. 18(2):04017135.
Wang P, Jiang LS, Li XY, Qin GP, Wang EY. 2018. Physical simulation of mining effect caused by a fault tectonic. Arab J Geosci. 11(23):741.
Wang P, Jiang LS, Zheng PQ, Qin GP, Zhang C. 2019. Inducing mode analysis of rock burst in fault-affected zone with a hard-thick stratum occurrence. Environ Earth Sci. 78(15):467.
Wang QB, Zhang C, Wang H, Wen XK, Shi ZY, Lü RS, Wang TT. 2014. Study of coupling effect between anchorage force loss of prestressed anchor cable and rock and soil creep. Rock Soil Mech. 35(8):2150–2156.

Wang YJ, He MC, Yang J, Wang Q, Liu JN, Tian X, Gao Y. 2020. Case study on pressure-relief mining technology without advance tunneling and coal pillars in longwall mining. Tunnell Underground Space Technol. 97:103236.

Xia X. 2010. A generalized Burgers model of reinforced slope by anchorage. Rock Soil Mech. 31(1):69–73.

Xu M, Jin DH, Song EX, Shen DW. 2018. A rheological model to simulate the shear creep behavior of rockfills considering the influence of stress states. Acta Geotech. 13(6):1313–1327.

Xu T, Fu T-F, Heap MJ, Meredith PG, Mitchell TM, Baud P. 2020. Mesoscopic damage and fracturing of heterogeneous brittle rocks based on three-dimensional polycrystalline discrete element method. Rock Mech Rock Eng. 53(12):5389–5409.

Xu T, Tang CA, Zhao J, Li LC, Heap M. 2012. Modelling the time-dependent rheological behaviour of heterogeneous brittle rocks. Geophys J Int. 189(3):1781–1796.

Xu T, Xu Q, Tang CA, Ranjith PG. 2013. The evolution of rock failure with discontinuities due to shear creep. Acta Geotech. 8(6):567–581.

Zhang C, Zhu Z, Zhu S, He ZI, Zhu D, Liu JZ, Meng SS. 2019. Nonlinear creep damage constitutive model of concrete based on fractional calculus theory. Materials. 12(9):1505.

Zhao YL, Wang YX, Wang WJ, Wan W, Tang JZ. 2017. Modeling of non-linear rheological behavior of hard rock using triaxial rheological experiment. Int J Rock Mech Min Sci. 93:66–75.