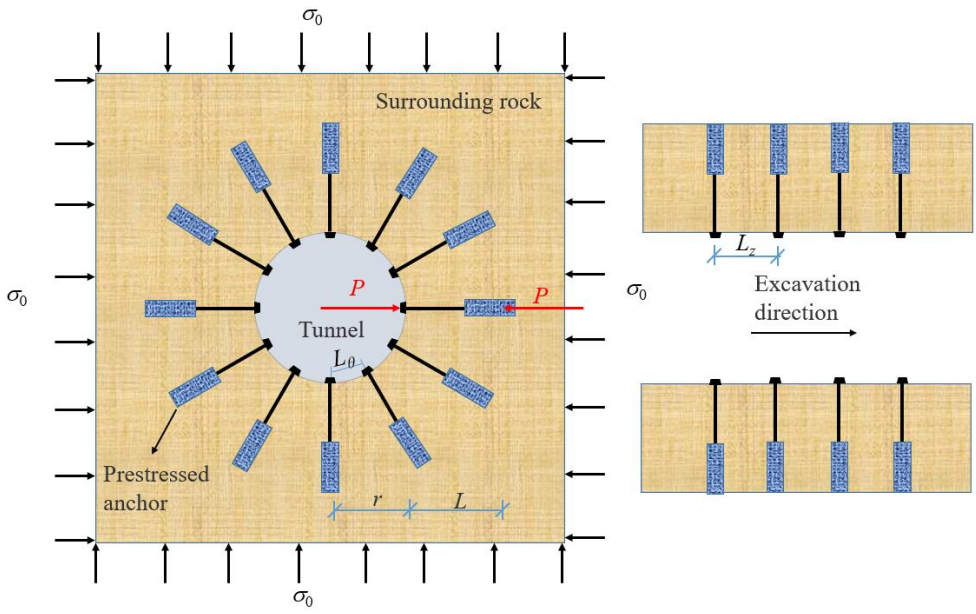
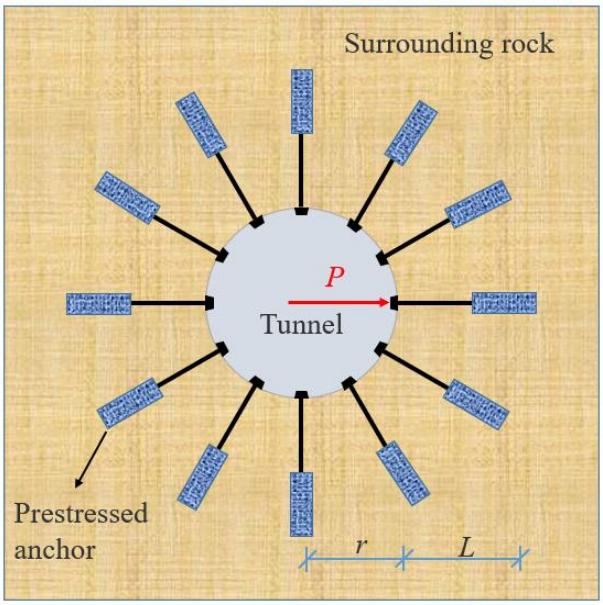
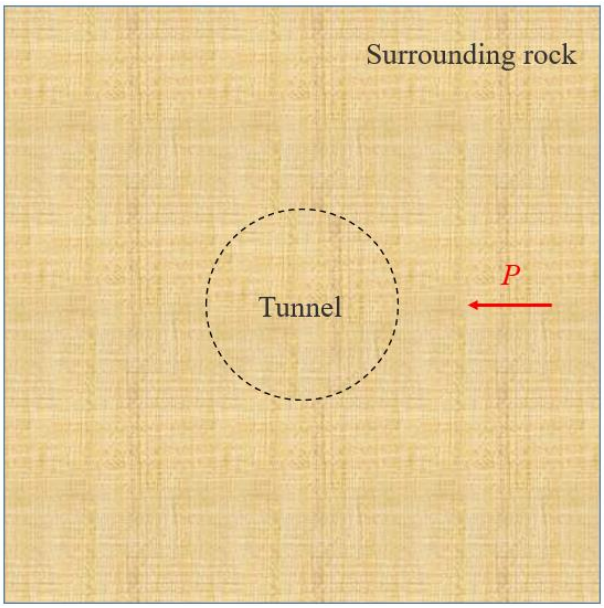


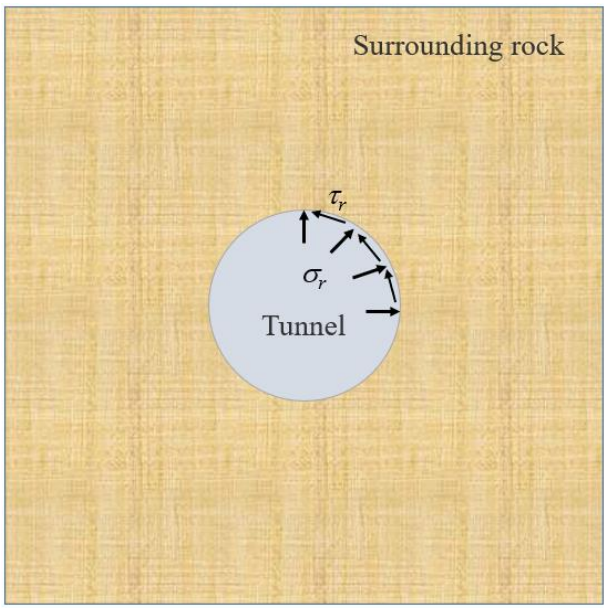
Figure 1. Simplified coupling mechanical model of bolts and tunnel rock mass



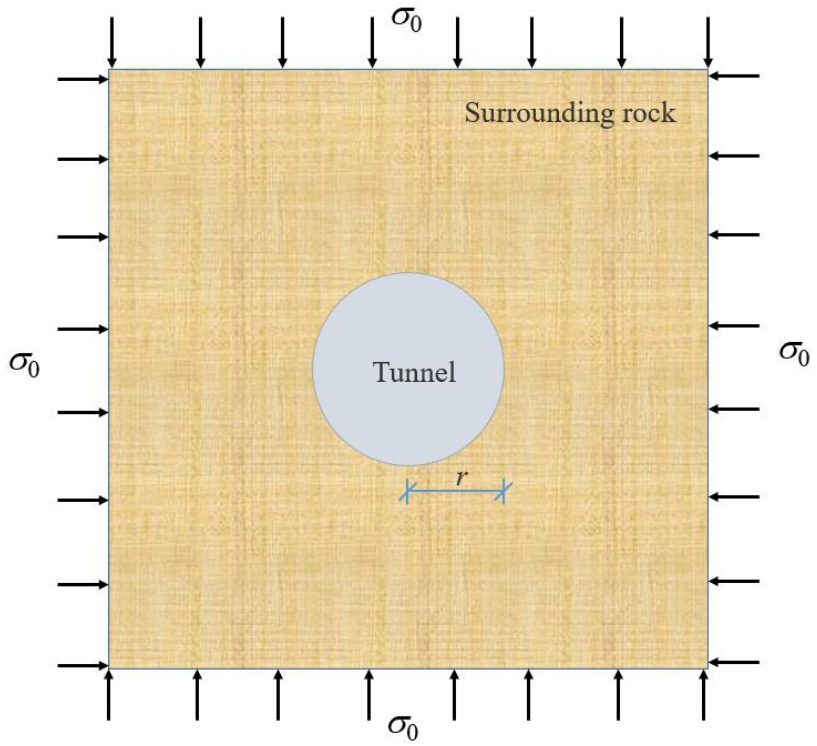
(a) Concentrated force P applied at the tunnel perimeter



(b) Concentrated force P in an infinite medium



(c) Stress field at the tunnel perimeter



(d) Tunnel with a far field stress

Figure 2. Decomposition diagram of coupling mechanical model of bolts and tunnel rock mass

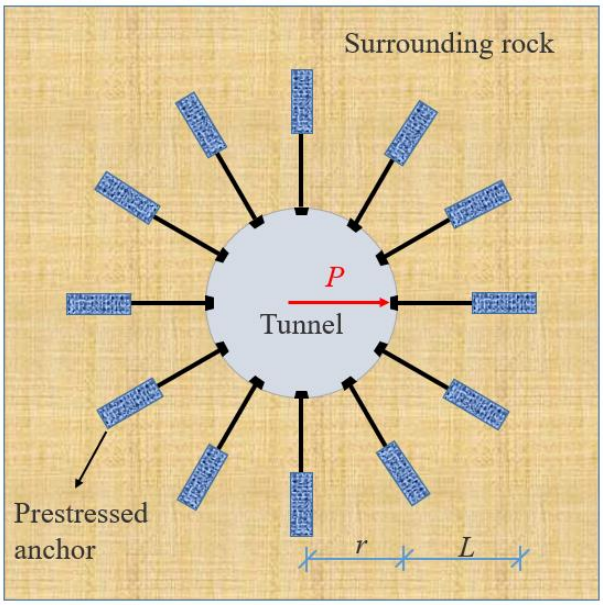
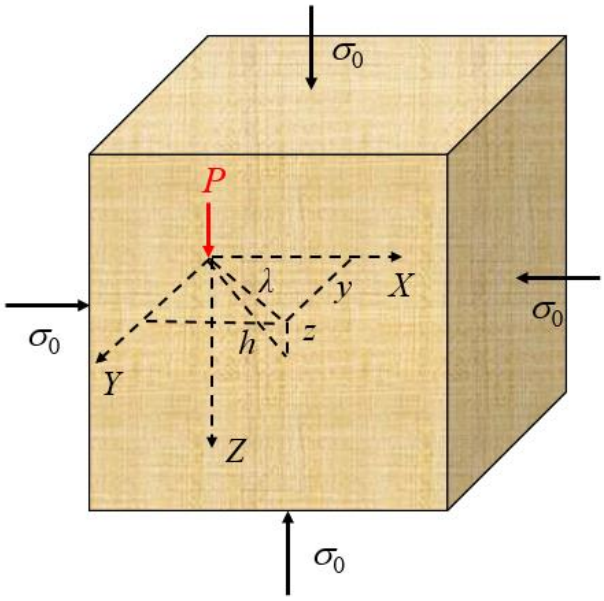
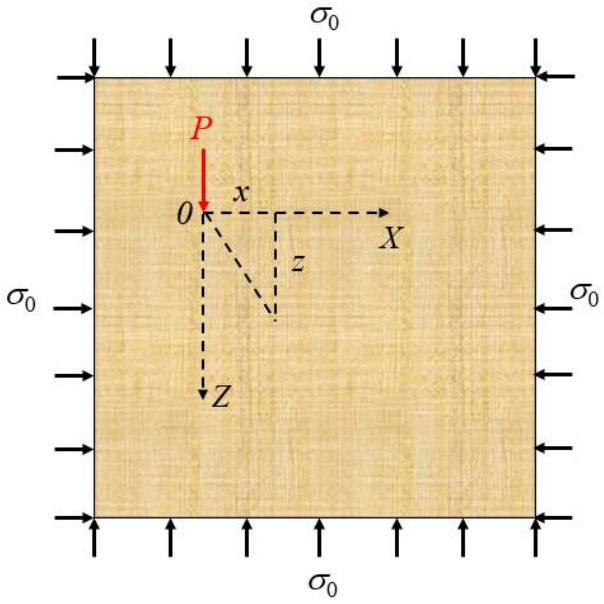


Figure 3. Mechanical model of the concentrated force *P* applied to the anchor head at the tunnel perimeter

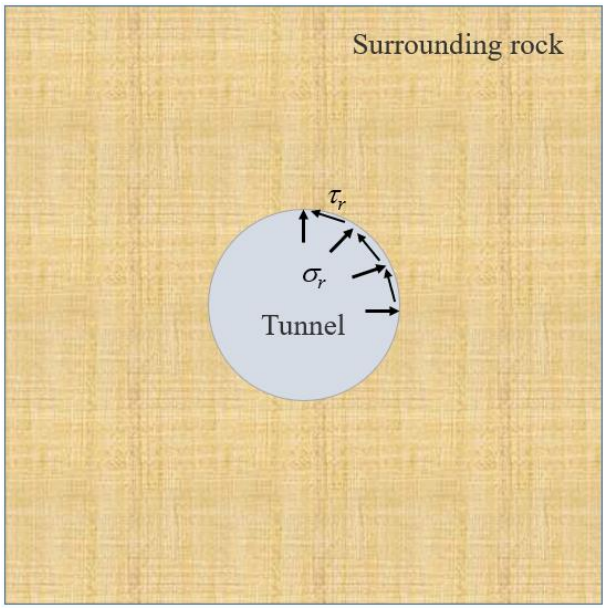


(a) 3D representation of the concentrated force *P* in an infinite medium

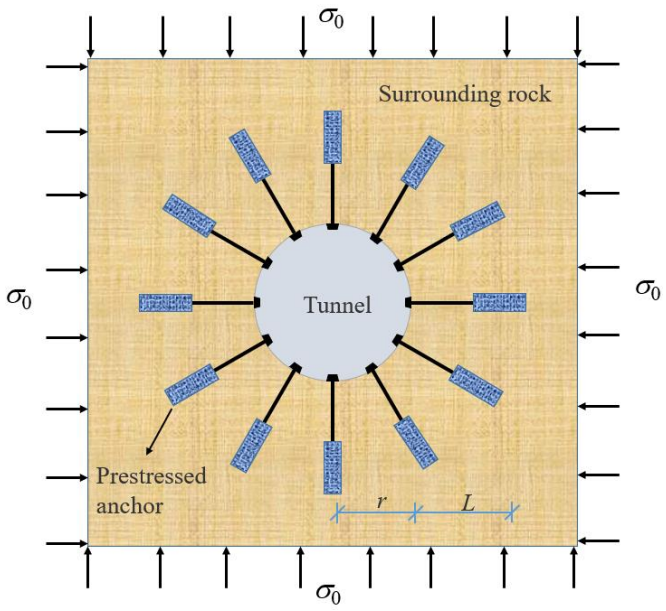


(b) 2D representation of the concentrated force *P* in an infinite medium

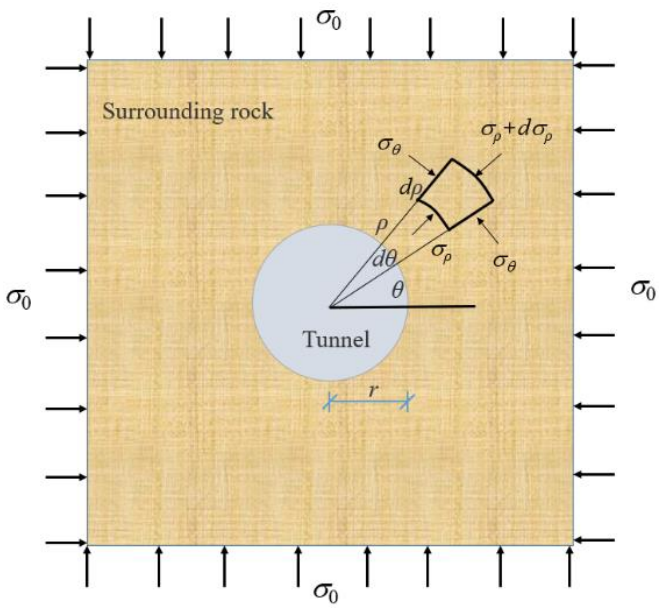
Figure 4. 3D to 2D representations of concentrated force *P* at the anchor end in an infinite medium



(a) Stress field at the tunnel perimeter

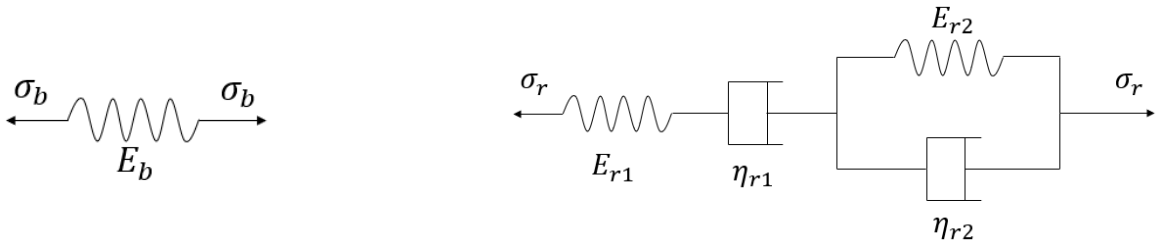


(b) Mechanical model of the tunnel under the action of the original rock stress



(c) Schematic diagram of the stress state in a representative elementary volume (REV)

Figure 5. Stress analysis of tunnel



(a) Elastic model for bolts (b) Burgers model for rocks

Figure 6. Creep models of the bolts and rocks

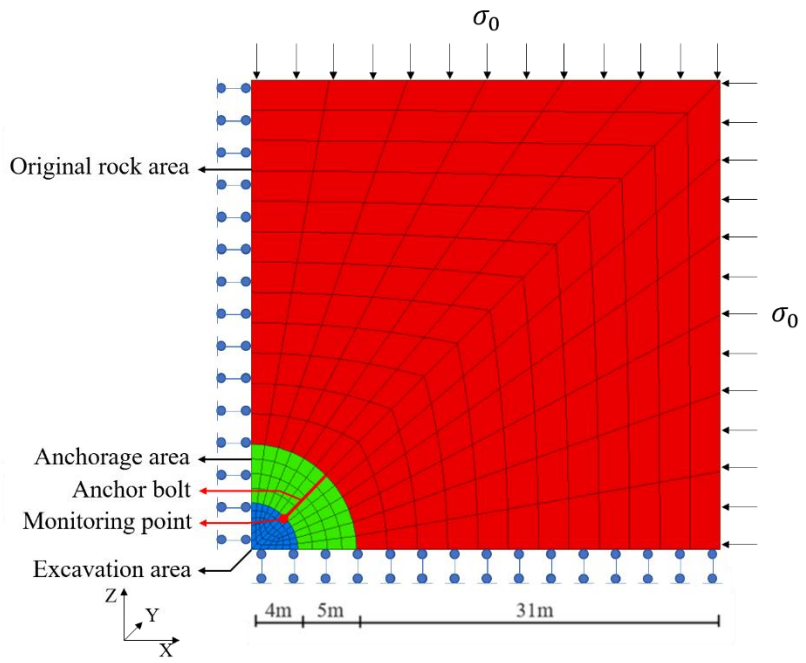


Figure 7. Dimension, grid and boundary conditions of the numerical model

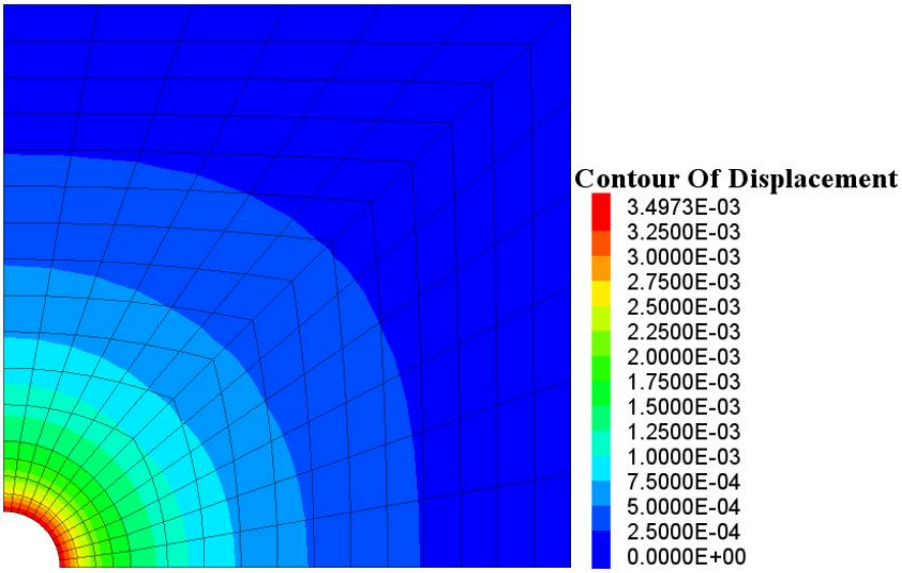
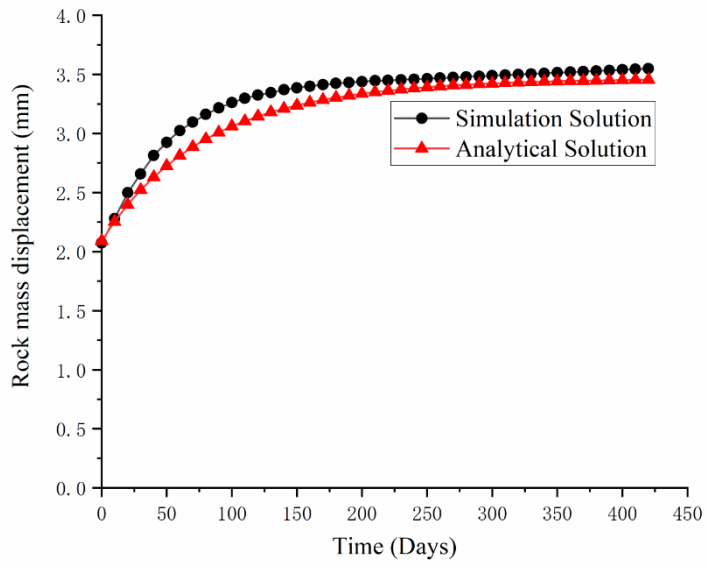
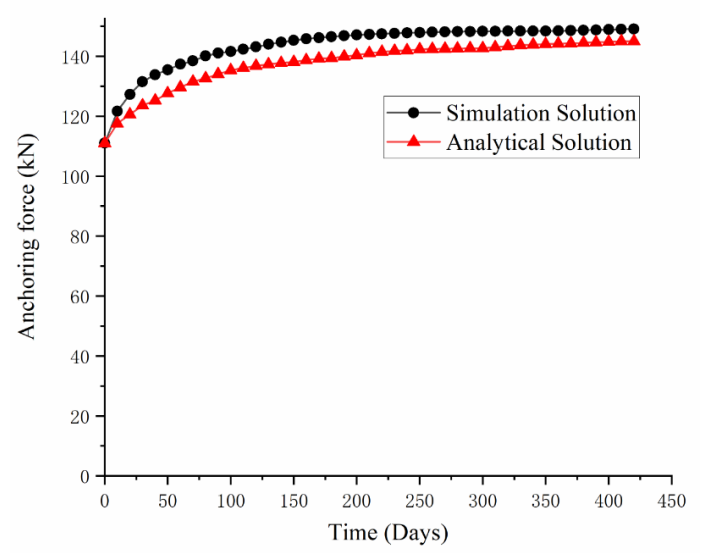


Figure 8. Tunnel total displacement nephogram (Unit: m)



(a) Comparison between analytical solutions and numerical simulation results of rock mass displacement



(b) Comparison between analytical solutions and numerical simulation results of the bolt anchoring force

Figure 9. Comparison between analytical solutions and numerical simulation results (The monitoring point is at the anchor head of the anchor bolt, as shown in Fig. 7)

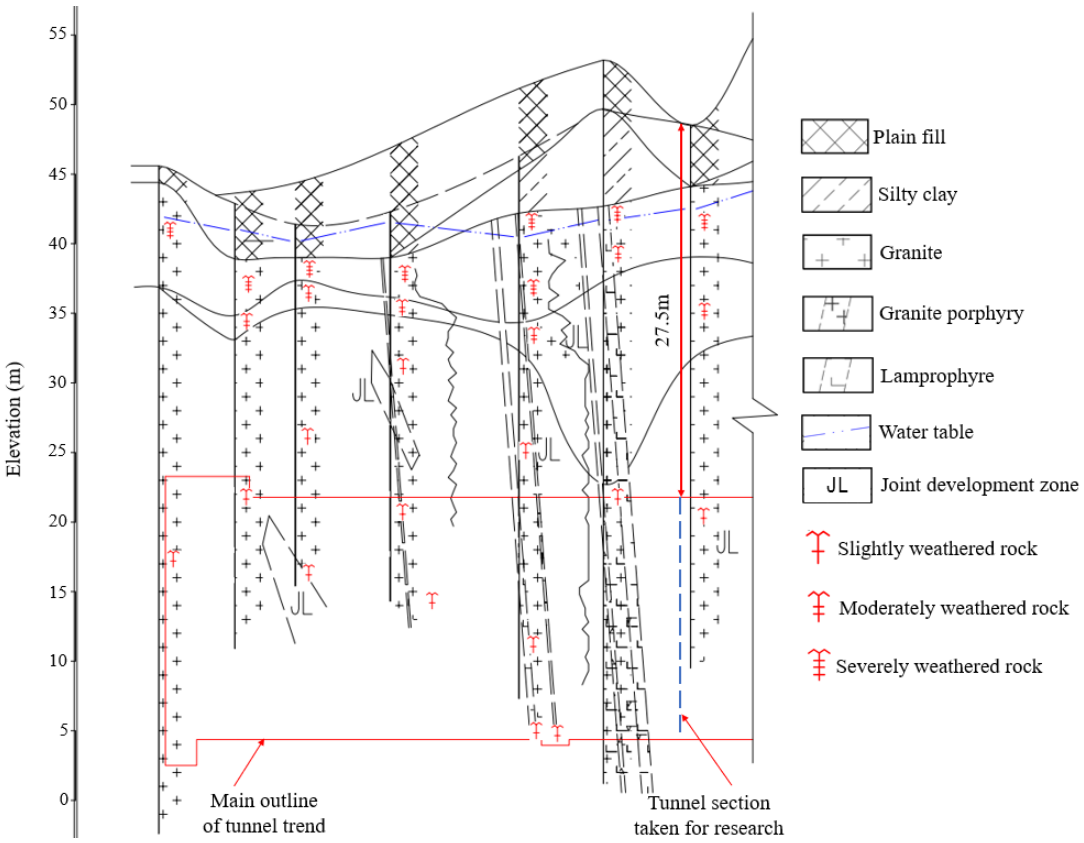


Figure 10. Geological cross-section of the tunnel project

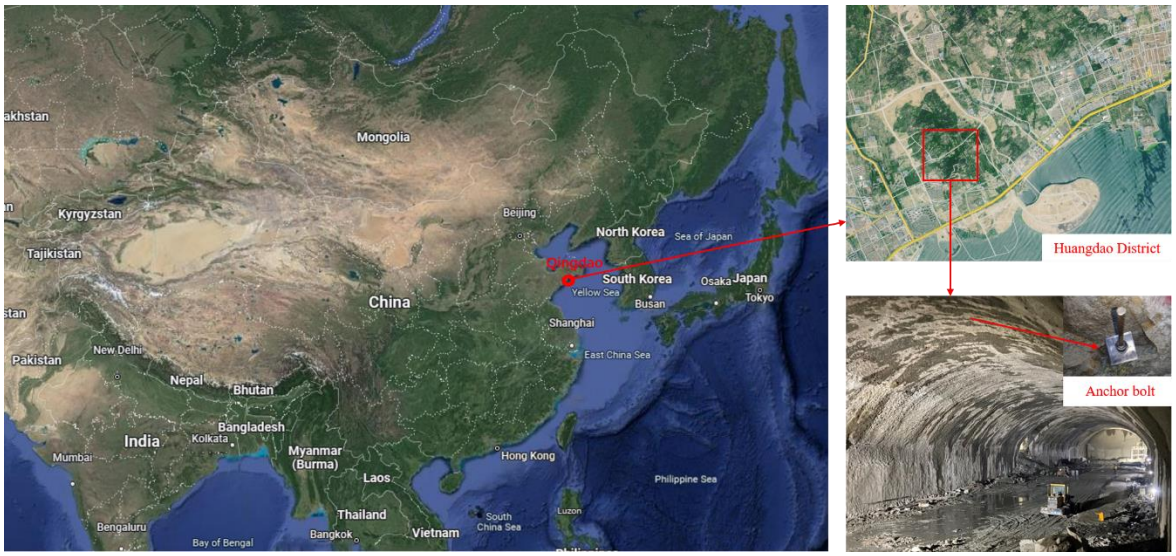


Figure 11. Location and anchoring details of tunnel construction

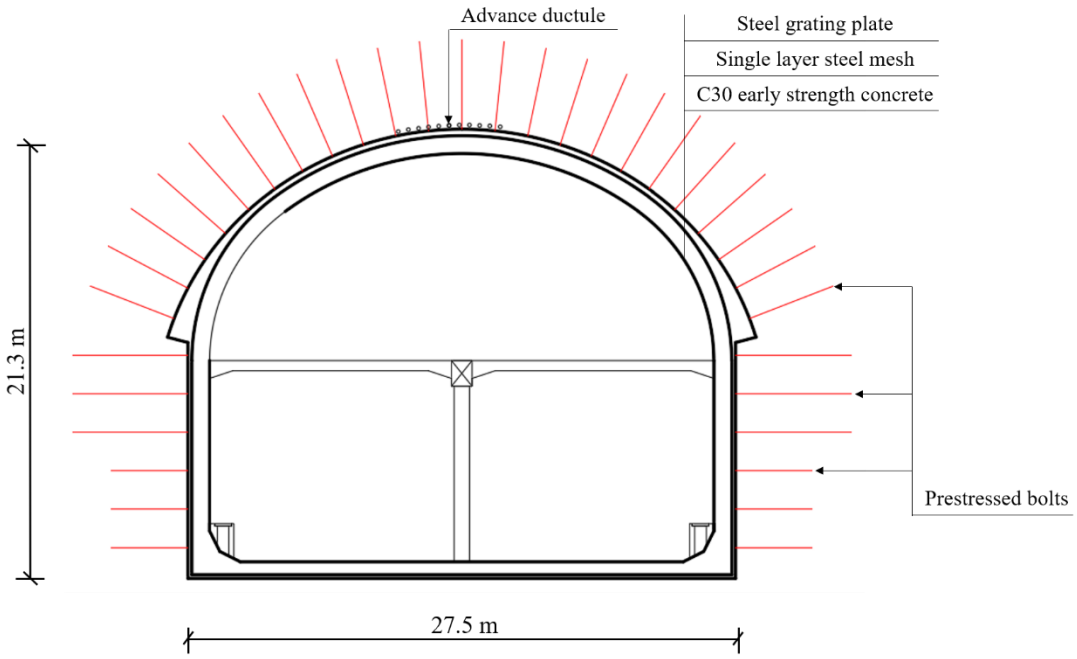
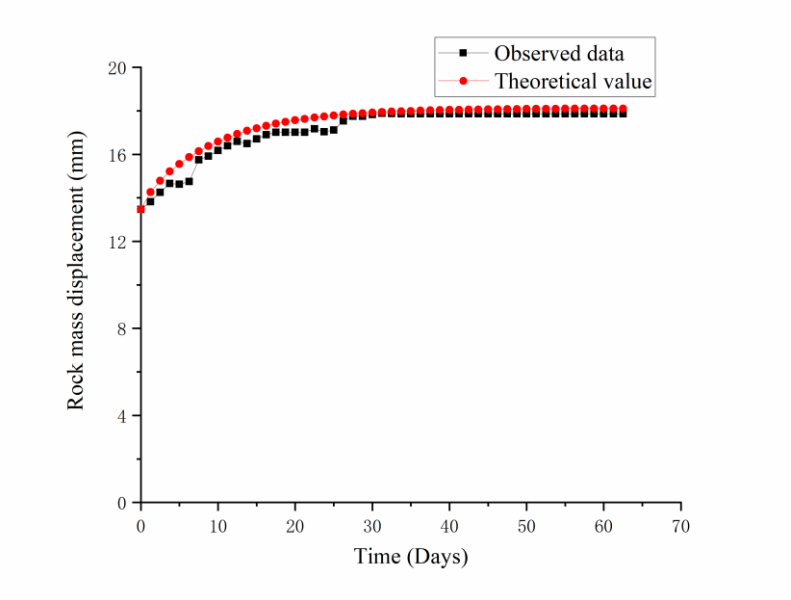
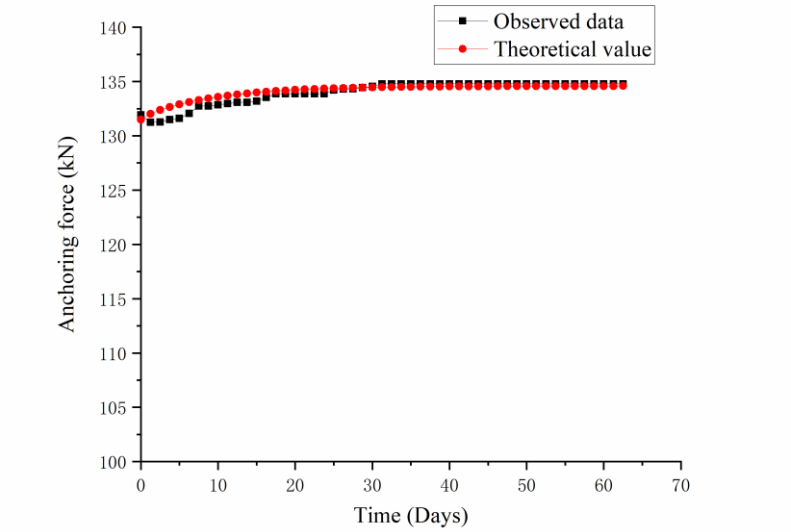


Figure 12. Field layout of the prestressed anchor bolts



(a) Comparison between the theoretical solutions and the monitored data of rock displacement



(b) Comparison between the theoretical solutions and the monitored data of the anchoring force

Figure 13. Comparisons between the theoretical solutions and the monitored data

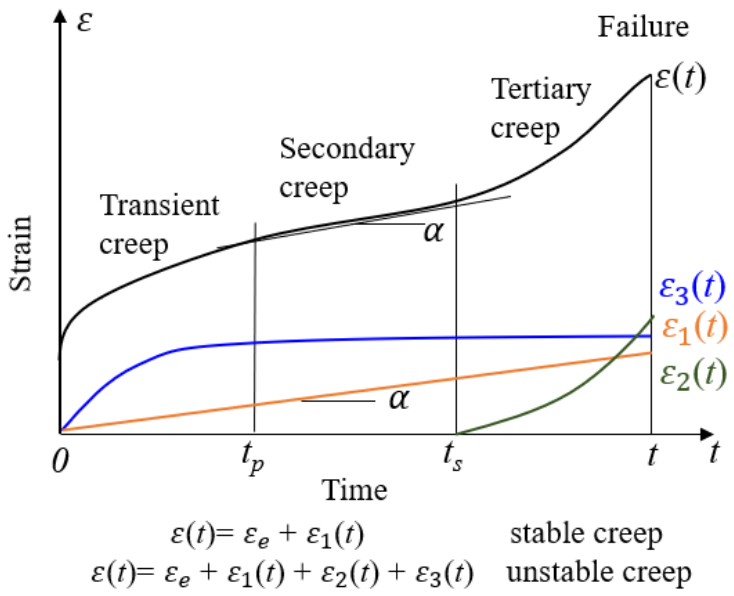


Figure 14. Creep decomposing into elementary strains in different stages

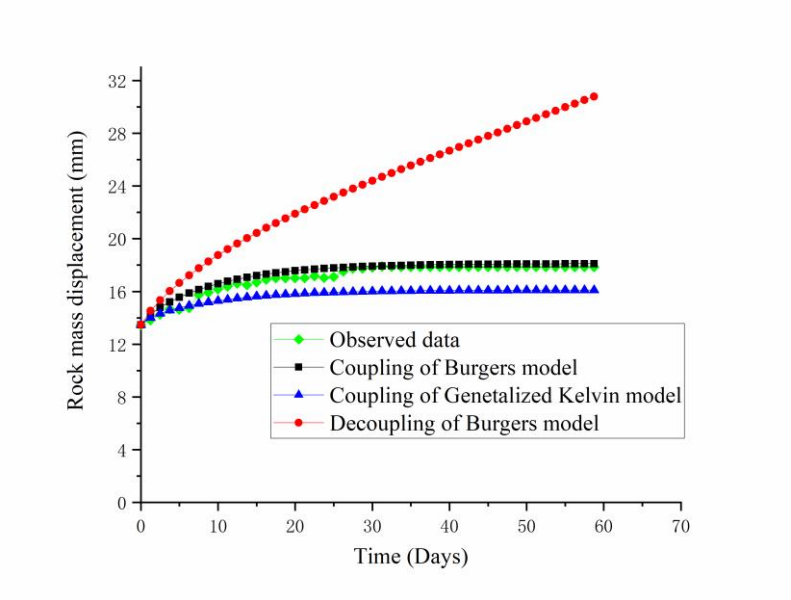


Figure 15. Comparison of rock radial displacement between coupled model and uncoupled model

Table 1. Rock mechanical parameters used in the numerical model

Parameter	σ_0 / MPa	K / GPa	r / m	ρ / (kg/m^3)	G_{1r} / GPa	G_{2r} / GPa	η_{1r} / GPa·h	η_{2r} / GPa·h
Value	-2	2	4	2650	0.15	1.5	200	3000

Table 2. Parameters of the prestressed bolt used in the numerical model

Parameter	L / m	T_0 / kN	E_b / GPa	r_b / m	d_g / m	θ
Value	5	100	200	0.022	0.045	30°

Table 3. Physical and mechanical parameters of the rock mass of the Qingdao Metro Line 6 project

Parameter	σ_0 / MPa	K / GPa	r / m	ρ / (kg/m^3)	G_{1r} / GPa	G_{2r} / GPa	η_{1r} / GPa·h	η_{2r} / GPa·h
Value	-2	2	13.75	2790	0.2	1	160	520