Theoretical Research on the Pendulum-type Wave in Nonlinear Block-rock Mass Based on Hyperbolic Elastic Model

Co-author: Kuan Jiang & Cheng-zhi Qi

Presenter： Kuan Jiang

Beijing University of Technology, China

jiangkuan2017@126.com

北京工業大學
BEIJING UNIVERSITY OF TECHNOLOGY

List

01 Background

02 Theoretical model

03 Results

04 Conclusions

01

Background

➢ Block-rock mass

Rock mass is characterized by the block-hierarchical structures. The deformation of rock mass is mainly concentrated in interlayers between rock blocks, and the deformation of the rock block can be ignored.

➢ Pendulum-type Wave

Kurlenya and Oparin found the sign-alternating reaction of rocks to dynamic effects in the underground explosion, and they think that there is a nonlinear sign-alternating wave in rock masses, called the pendulum-type wave.

1. Background

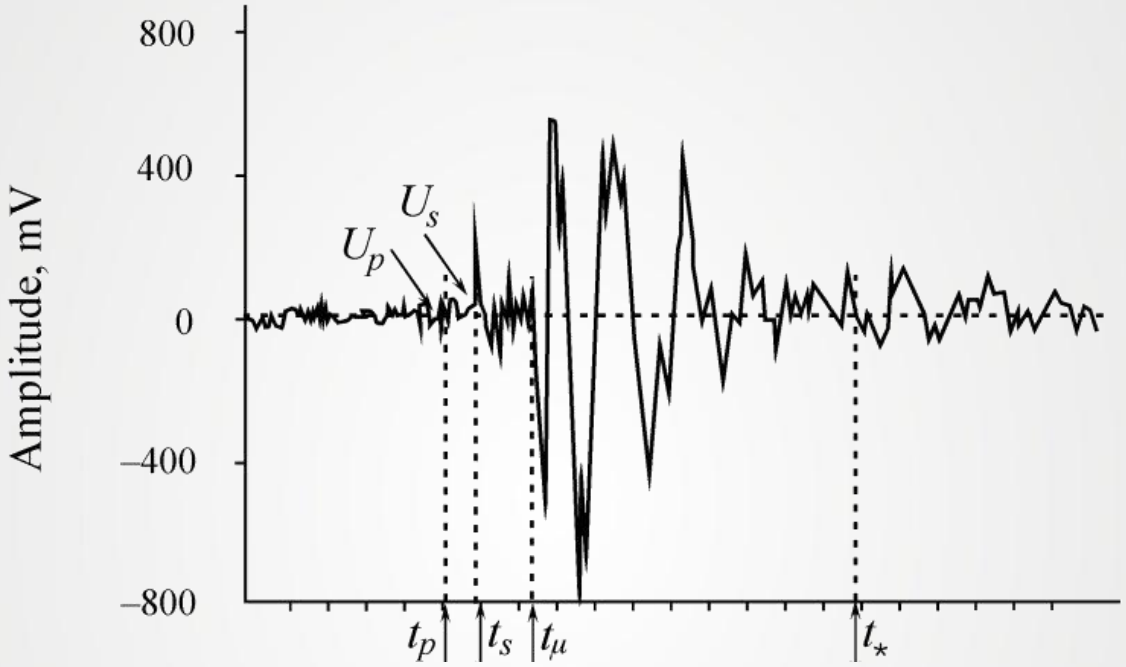


Fig.1 Pendulum-type wave isolated from rock mass

The phenomenon of pendulum-type wave can easily cause engineering disasters in deep rock mass such as rockbursts.

02 Theoretical model

2.1 Dynamic model of pendulum-type wave

2.2 Hyperbolic elastic model

2.3 Dynamic equation

The block-rock mass is simplified as an incompressible block and an interlayer with viscoelastic properties. The spring is linear, and there are two drawbacks:

- Nonlinear deformation cannot be represented.
- The interlayers can deform indefinitely.

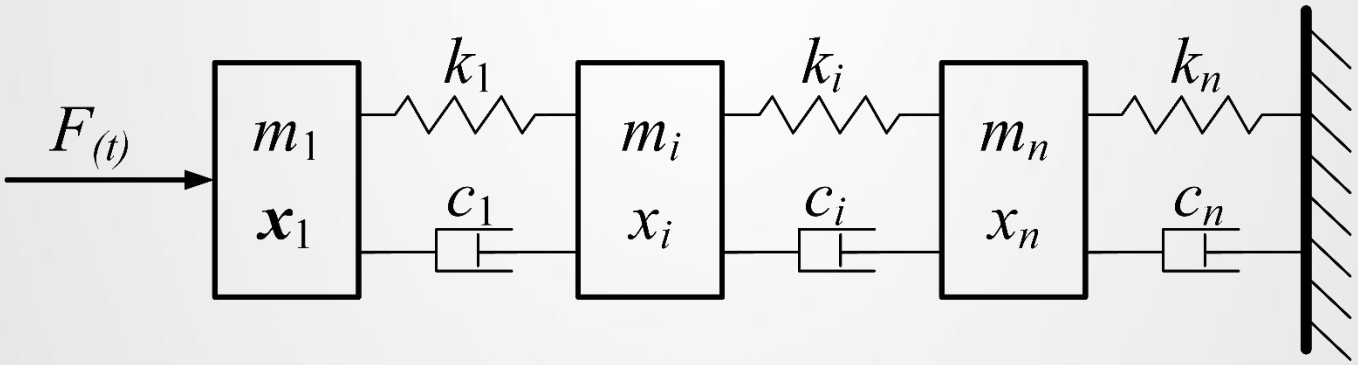


Fig.2 Dynamic model of pendulum-type wave in block-rock mass

2.2 Hyperbolic elastic model

The expression of the hyperbolic elastic model is as follows:

$$\Delta V_{\mathrm{j}} = \frac{\sigma_{\mathrm{n}} V_{\mathrm{m}}}{K_{\mathrm{ni}} V_{\mathrm{m}} + \sigma_{\mathrm{n}}}$$

ΔV_{j} — joint closure;
σ_{n} — normal stress;
V_{m} — maximum possible closure;
K_{ni} — initial normal stiffness

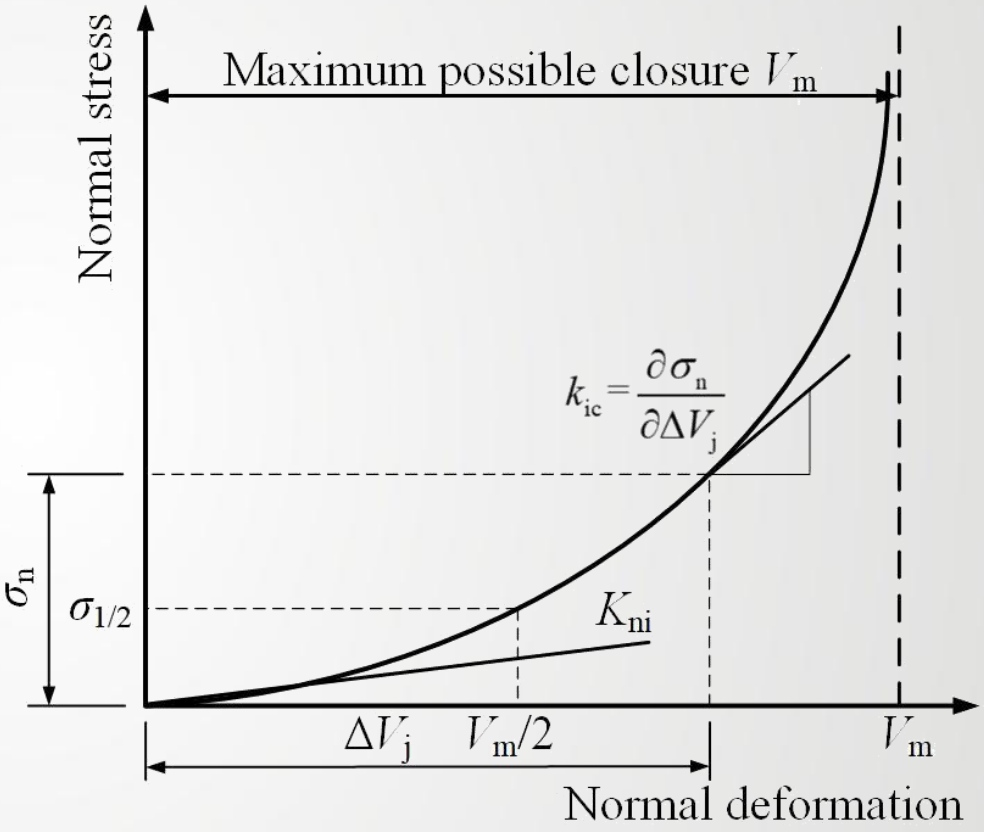


Fig. 3 Curve of hyperbolic elastic model

The dynamic equation of block-rock mass in the matrix form:

$$M\ddot{X}(t)+C\dot{X}(t)+F_s=F(t)$$

Where, $\boldsymbol{M}$ is the mass matrix; $\boldsymbol{C}$ is the damping matrix; $F_s=[-F_{k1}, F_{k1}-F_{k2}, \cdots, F_{k(i-1)}-F_{ki}, \cdots, F_{k(n-1)}-F_{kn}]^T$ is the resistance vector generated by nonlinear springs.

When $1 \le i < n$,

$$F_{ki}=\begin{cases} -\dfrac{AK_{ni}V_m\Delta V_j}{V_m-\Delta V_j}=-\dfrac{AK_{ni}V_m(x_i-x_{i+1})}{V_m-(x_i-x_{i+1})}, & x_{i+1}-x_i \le 0 \\ K_{ni}(x_{i+1}-x_i), & x_{i+1}-x_i > 0 \end{cases}$$

When $i=n$,

$$F_{kn}=\begin{cases} -\dfrac{AK_{ni}V_m\Delta V_j}{V_m-\Delta V_j}=-\dfrac{AK_{ni}V_m x_n}{V_m-x_n}, & x_n \ge 0 \\ -K_{ni}x_n, & x_n < 0 \end{cases}$$

03 Results

3. Results

Defining the maximum compression deformation of interlayers

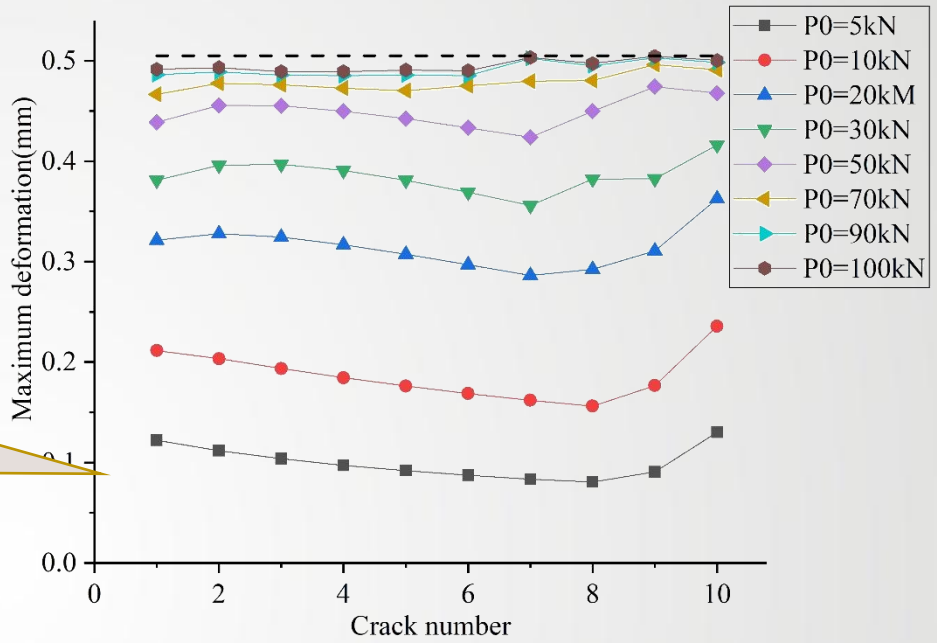
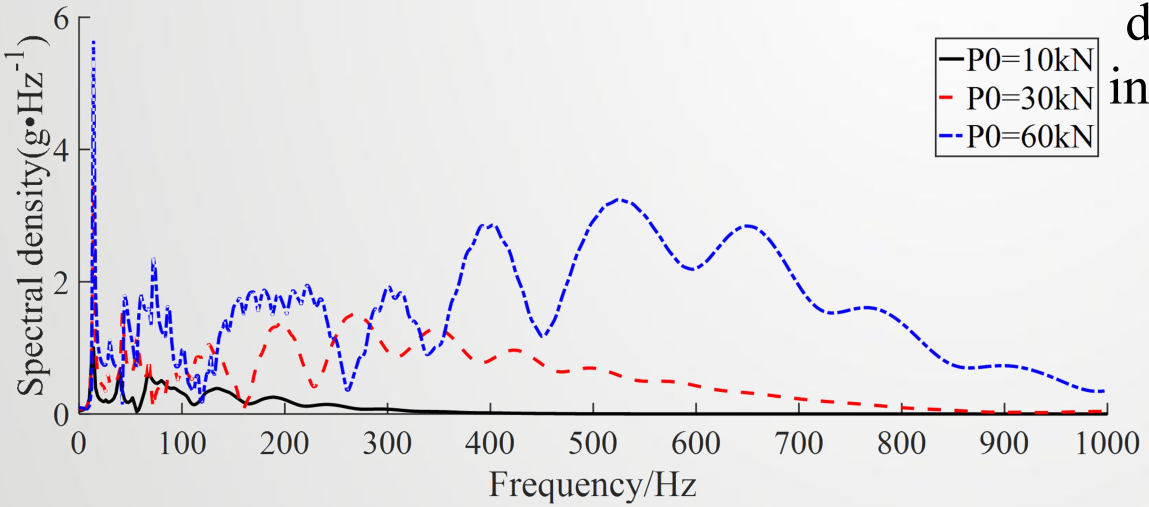


Fig.4 Maximum compression deformation of cracks with the increase of propagation distance



Moving to high frequencies

Fig.5 Frequency response of the rock block

3. Results

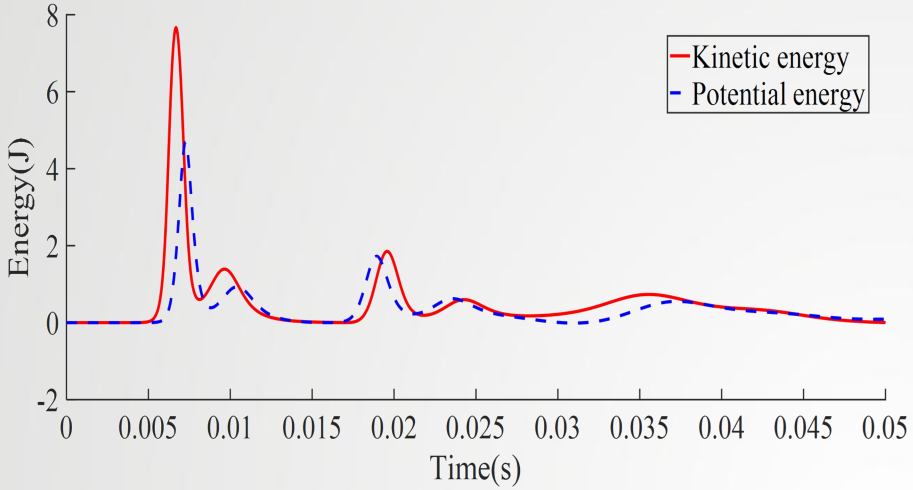


Fig.6 Kinetic energy and potential energy in a block-spring element

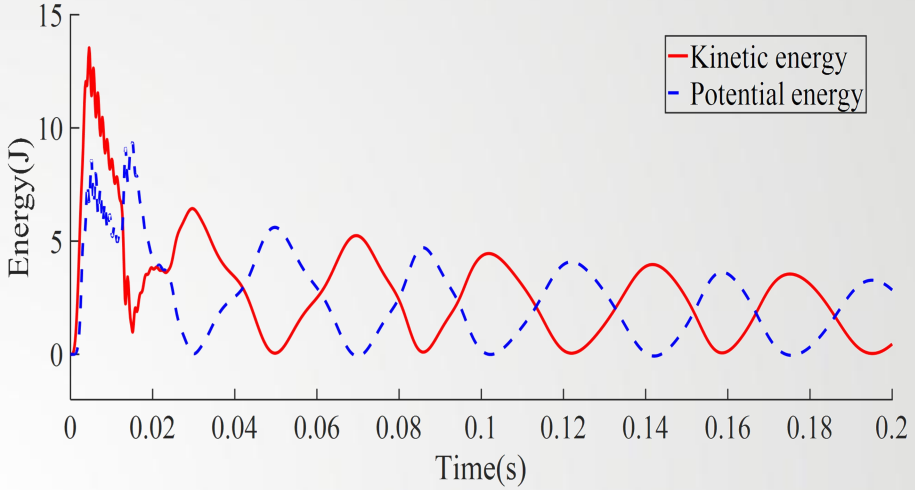


Fig.7 Kinetic energy and potential energy in block-rock mass

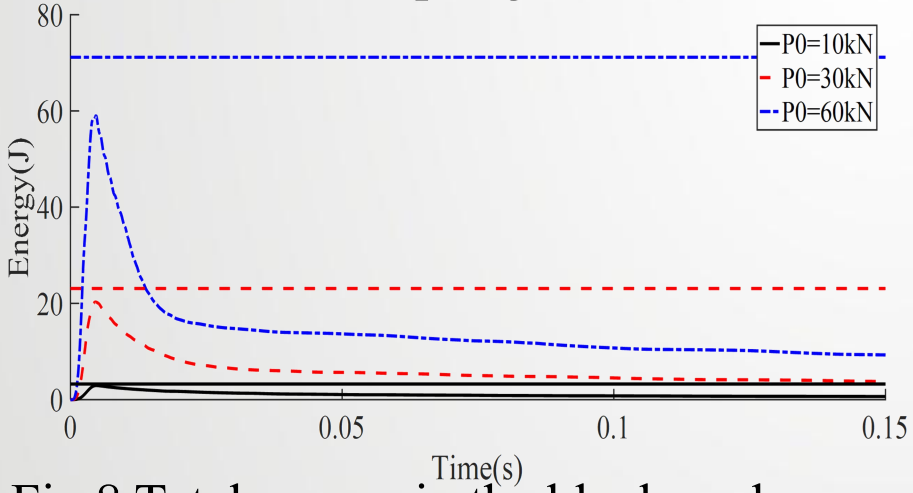


Fig.8 Total energy in the block-rock mass (The dashed line parallel to X-axis represents the total input energy)

The law of transfer and transformation of kinetic energy and potential energy in block-rock mass is obtained.

Consideration of initial geostress

The hyperbolic elastic model can be grouped into three categories: low stress state, high stress state and ultra-high stress state.

$\sigma_{1/2}$ — normal stress when the deformation is half of the maximum possible closure V_m

σ_u — normal stress when the deformation reaches 95% of the maximum possible closure V_m

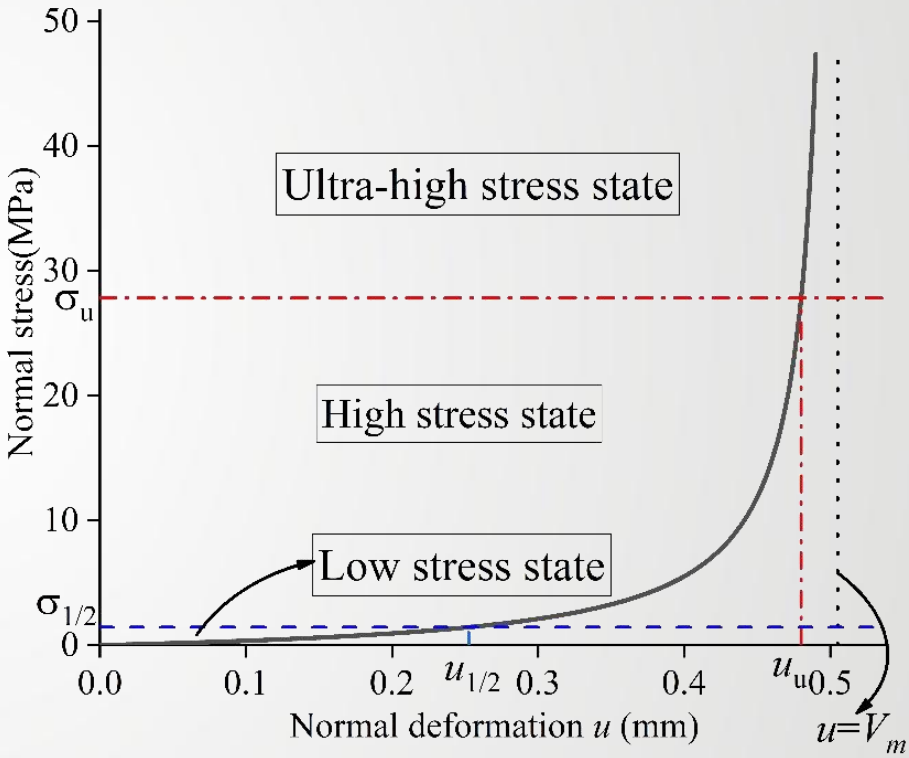


Fig.9 Division of stress states

3. Results

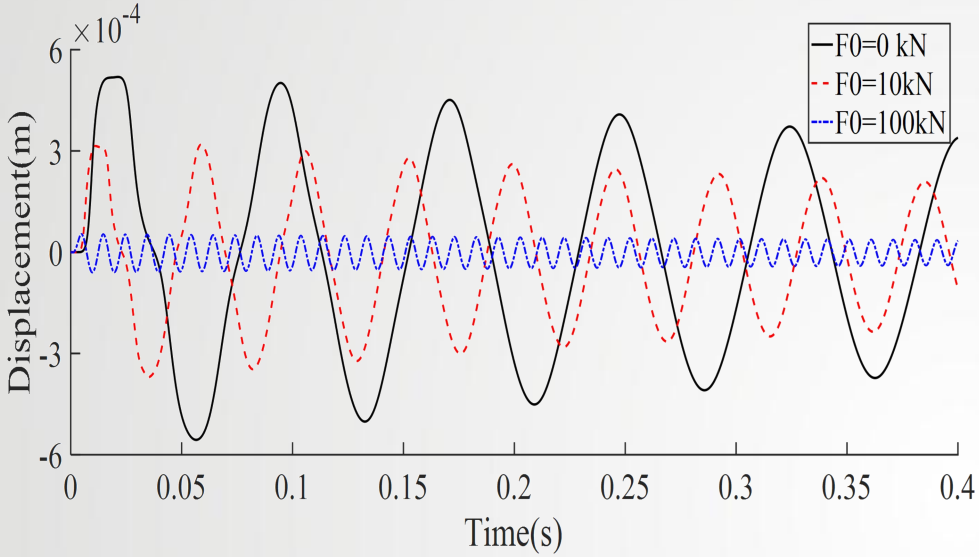


Fig.10 Displacement curves of the rock block in three initial stress states

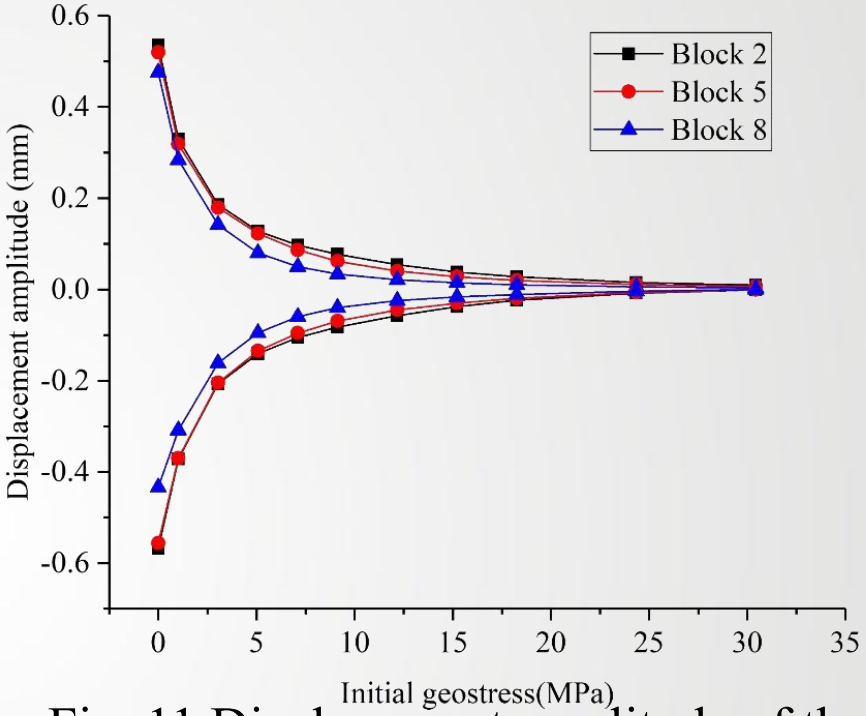


Fig. 11 Displacement amplitude of three blocks with the increase of initial geostress

With the increase of initial geostress, the displacement amplitude decrease approximately exponentially.

Based on the above analysis, we make a prediction that in the ultra-high stress state, the phenomenon of the pendulum-type wave does not occur in block-rock mass, and the wave propagation is close to the longitudinal wave. There are two main reasons:

- The cracks (interlayers) are basically closed under the ultra-high stress state, and the vibration displacement of rock blocks relative to the initial position is extremely weak. At this time, the deformation of rock blocks cannot be ignored or even become the main part of deformation, and the deformation of block-rock mass is no longer dominated by that of interlayers.
- When cracks of the block-rock mass are almost completely compressed, kinetic energy is no longer the main way of carrying energy.

04 Conclusions

4. Conclusions

- The improved nonlinear model can not only shows the nonlinear deformation of block-rock mass, but also limits the maximum compression deformation of cracks between rock blocks.
- Kinetic energy and potential energy are constantly transformed to each other in block-rock mass, and in the free vibration stage, they are in inverse phase.
- In the ultra-high stress state, the phenomenon of the pendulum-type wave will not occur in block-rock mass, and the wave propagation is close to the longitudinal wave.

北京工業大學
BEIJING UNIVERSITY OF TECHNOLOGY

EGU General Assembly 2022

THANKS!

If you have any questions, please don't hesitate to contact me.

Presenter： Kuan Jiang
Beijing University of Technology, China
jiangkuan2017@126.com
DOI: 10.1007/s12517-021-09299-y