Integrated Research on Earthquake Disaster of High Dams, Underground Structures and Large-scale Cavern Groups

Prof. DU Xiuli

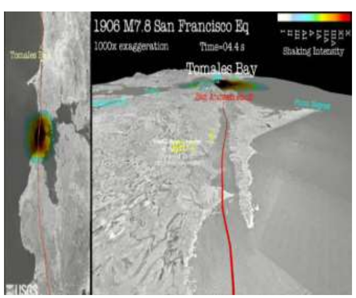
2016.11.19

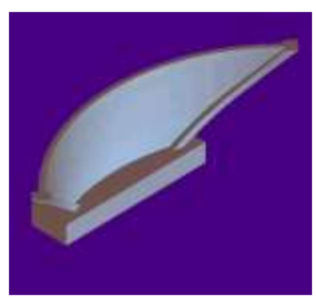
Contents

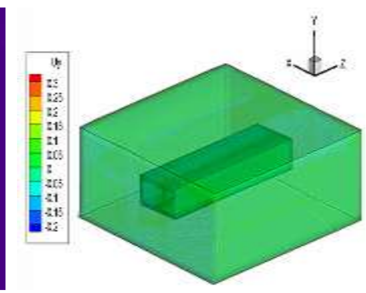
1. Objectives

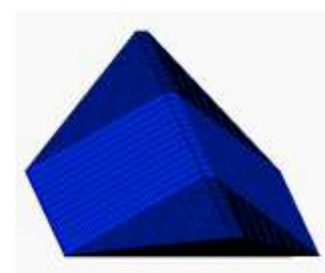
1) Simulation of wideband strong ground motions with both high and low frequency contents, and reproduction of seismic motions fields of the Wenchuan earthquake;
2) Whole-process simulations of earthquake disasters of high dams, underground structures and large-scale cavern groups;

3) Reconstruction of earthquake damages of typical key projects and reveal of their seismic damage mechanism and failure modes.

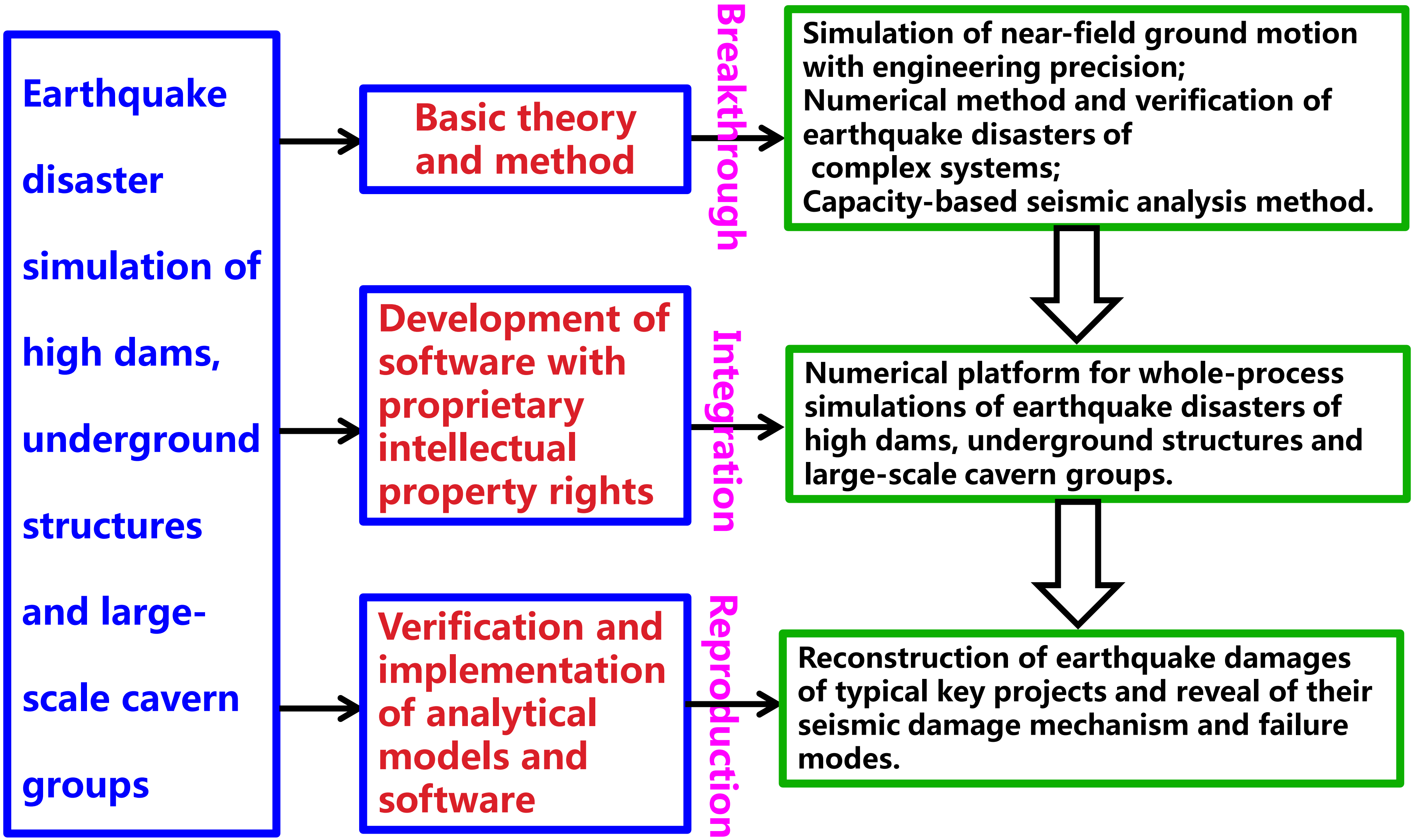








2. Main research contents



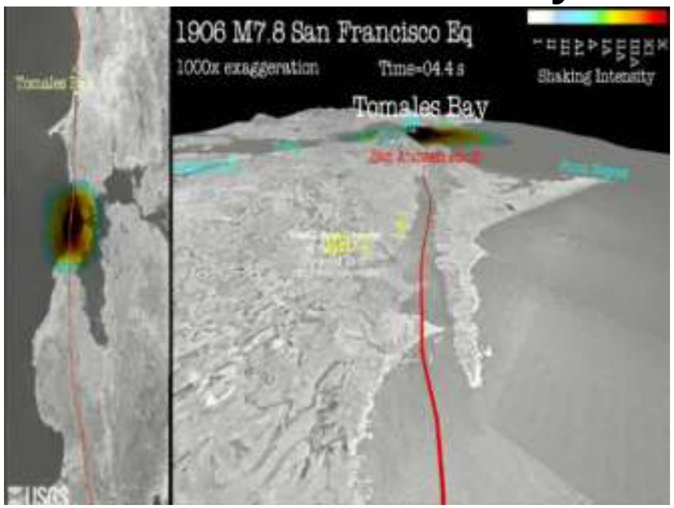
3. Key scientific problems

1) **Investigation of characteristics of near-filed ground motions and simulations of broadband earthquake motions;**
2) **Mechanical behaviors and constitutive models of rock and soil materials, and contact interfaces;**
3) **Seismic failure mechanisms of high dams, underground structures and large-scale cavern groups;**
4) **Development of efficient calculation techniques in software for seismic simulations of earthquake disasters.**

Contents

II. Overall research methodology

Seismic source rupture + Propagation of energy in a semi infinite medium → Dynamic response of Structures

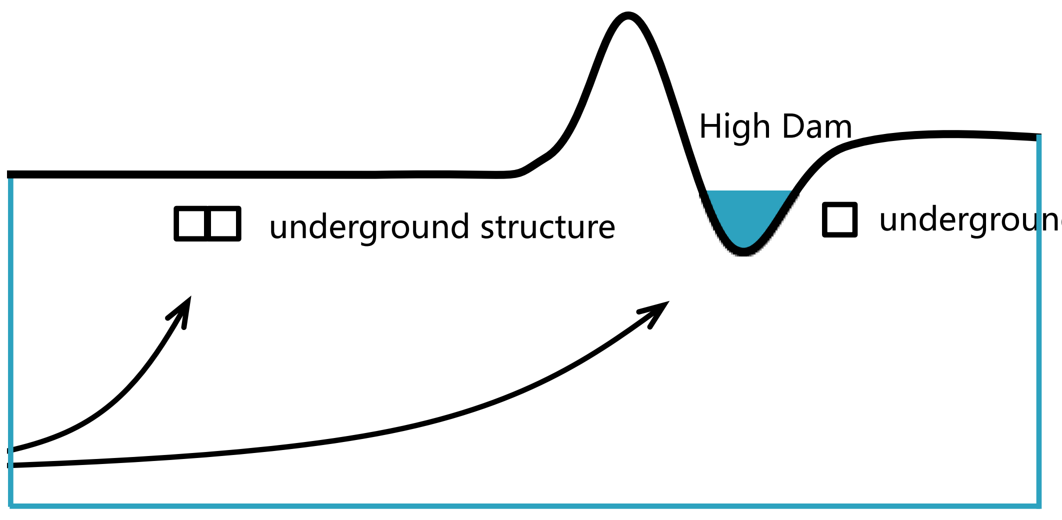



concrete arch dam


earth-rock dam


underground cavern


urban underground structure



Exogenous problem: seismic input+ artificial boundary

Endogenous problem: hypocenter model+ artificial boundary

II. Overall research methodology

Strong ground motion → Independent development

(Subproject 1)

concrete arch dam	earth-rock dam	underground structure	cavern group
(concrete, rock)	(rockfill)	(earth, concrete)	(jointed rock)
(Subproject 2)	(Subproject 3)	(Subproject 4)	(Subproject 5)
Opensees platform ABAQUS	Independent development	Independent development ABAQUS	Independent development DDA

5 sets of special analysis software (platforms)

Contents

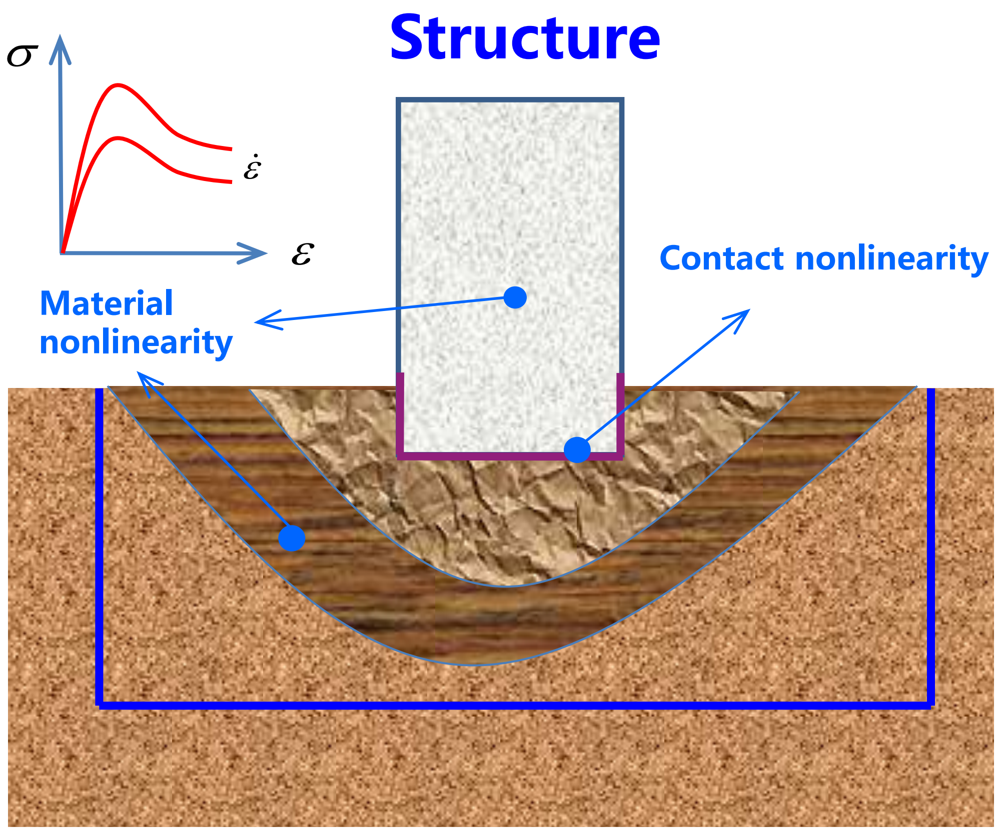
III. Important progress and innovation

1. Seismic disaster simulation theory and method and system integration

2. Theory and method of broadband seismic field simulation and implementation

3. Seismic failure mode and damage mechanism of key structures

1.1 Numerical simulation theory and method



Question 1 :
Artificial boundary -finite processing of infinite models

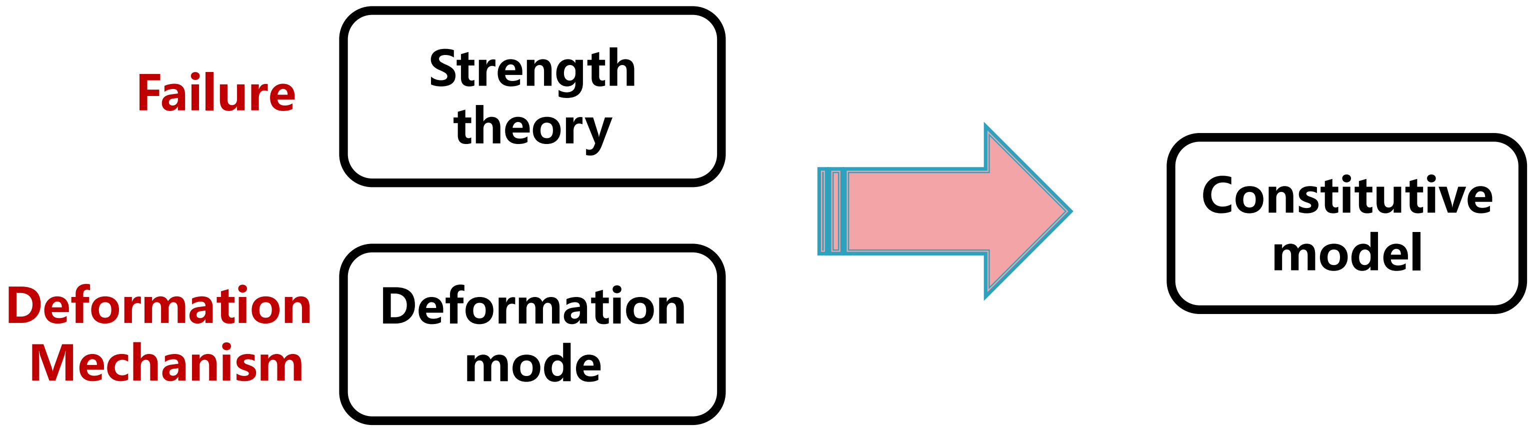
Question 2 :
The establishment of non - linear mechanics model of material and contact

Question 3 :
Efficient algorithm for nonlinear fluctuation analysis(coupled) of large - scale complex

Dynamic Failure Behavior and Surface Contact Model

(1) Dynamic Failure Behavior Model

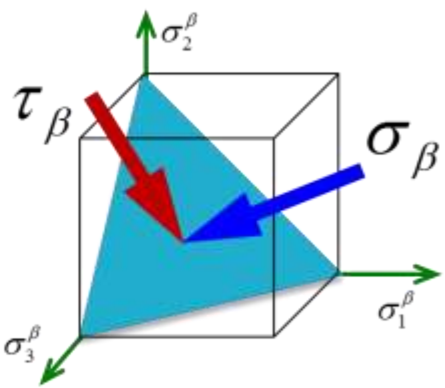
Plastic deformation, strain softening, cycle loading, stiffness degradation and etc.

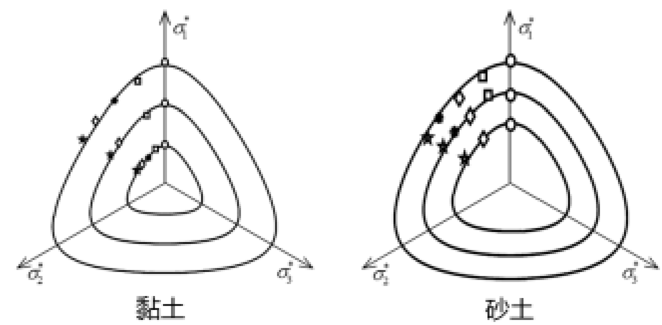


(Damage) constitutive model of geotechnical materials such as overconsolidated soil, rockfill material and concrete

Achievement 1 : Proposed a nonlinear unified strength theory based on the concept of characteristic stress.

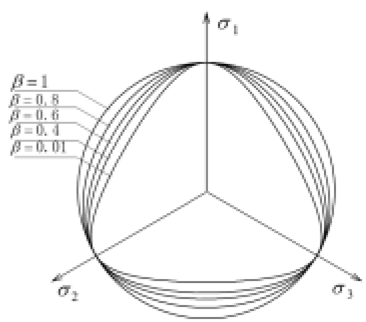
Principal stress effect/Shear sliding surface → Shear sliding surface/Characteristic stress → Simple and clear physical definition

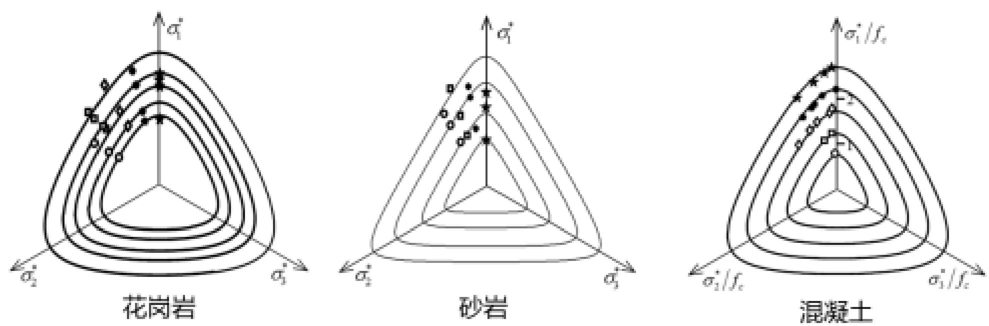




$$\sigma_i^\beta = p_a\left(\frac{\sigma_i}{p_a}\right)^\beta$$

$$\tau_\beta = M_\beta \sigma_\beta + \sigma_0$$



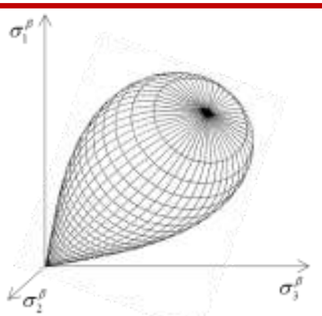


Achievement 2 : Established elasto-plastic (damage) constitutive model of geo-materials for different deformation characteristics

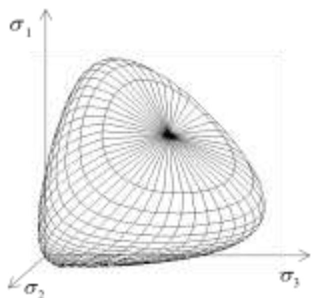
1) Proposed an elastoplastic constitutive model of overconsolidated soil considering strain softening and cyclic loading.

(Less parameters/**5**, clear physical definition, True 3D, Dilatancy properties, Strain softening, Cyclic loading)

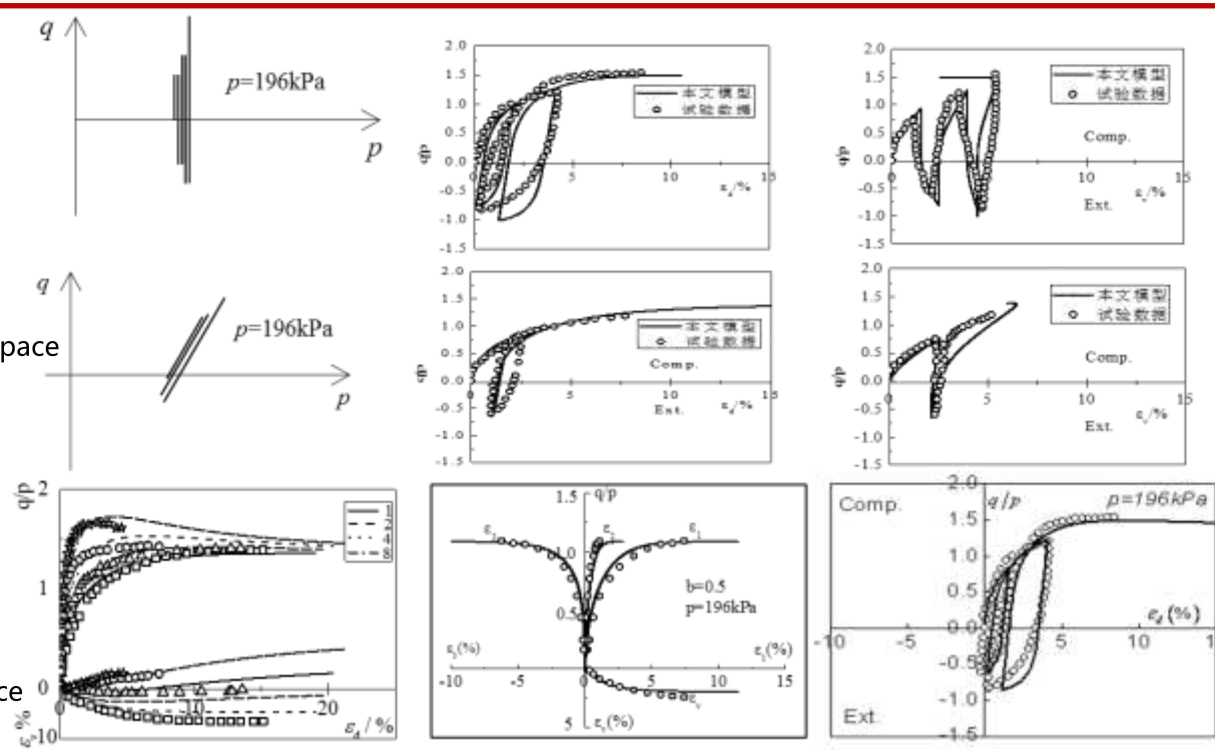
3-axis compression + Three-dimensional method → Direct true 3-D elasto-plastic model → Simple, stress induced heterosexual



The Yield Surface in Characteristic Stress Space



The yield surface in principal stress space

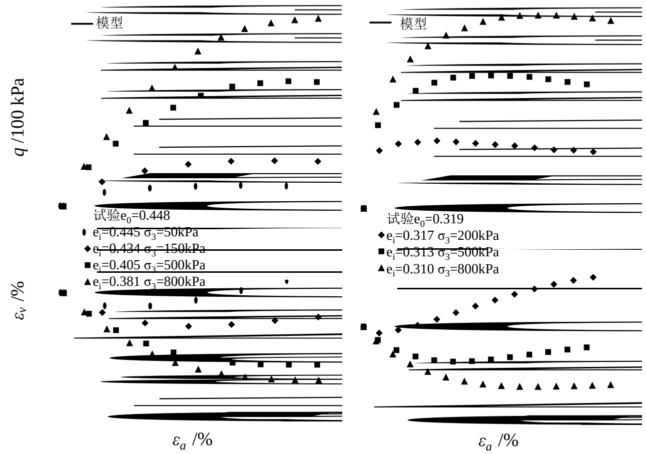


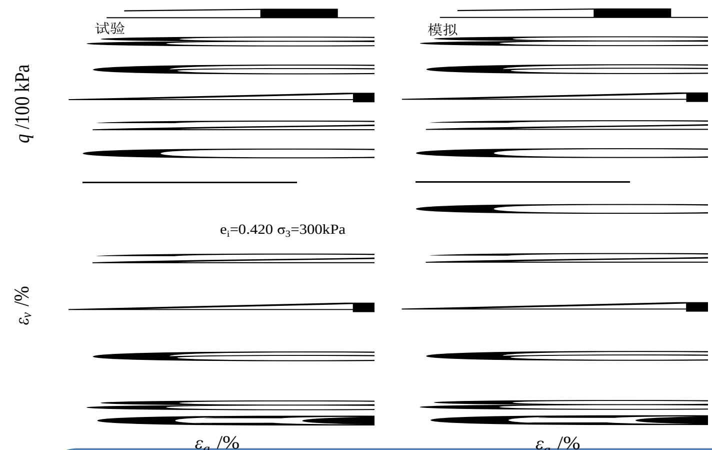
1. Seismic disaster simulation theory and method and system integration

Achievement 2： Established elasto-plastic (damage) constitutive model of geo-materials for different deformation characteristics

2) Established elasto-plastic constitutive model of rockfill considering the particle break and dilatancy.

(Cyclic loading, particle breakage)





- Many Models, and poor correlation of parameters
- Cannot respond to residual deformation
  time-course changes
- Cannot reflect the impact of particle fragmentation
- Cannot reflect state dependencies

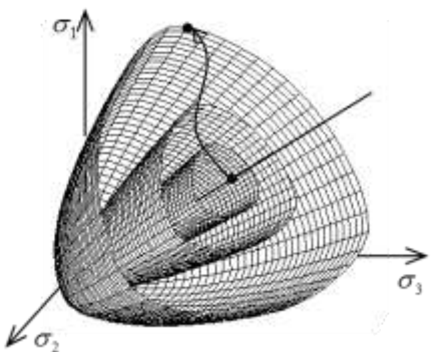
- Monotonic and cyclic use of a set of parameters
- Consider dilatancy and stress softening
- Consider complex loading and stress history
- Consider the effect of particle breakage
- Reflecting the state of relevance

Achievement 2 : The elasto-plastic (damage) constitutive model of geomaterials is established for different deformation characteristics

3) Established elasto-plastic damage constitutive model of concrete considering strain softening, stiffness degradation and cyclic loading.

Single strength criterion→ Generalized nonlinear strength theory → Elasto-plastic, damage

$$D=\frac{1}{1+\left(\frac{1}{D_0}-1\right)\exp\left(-\alpha\left(\varepsilon_p-\varepsilon_{p0}\right)^c\right)}$$

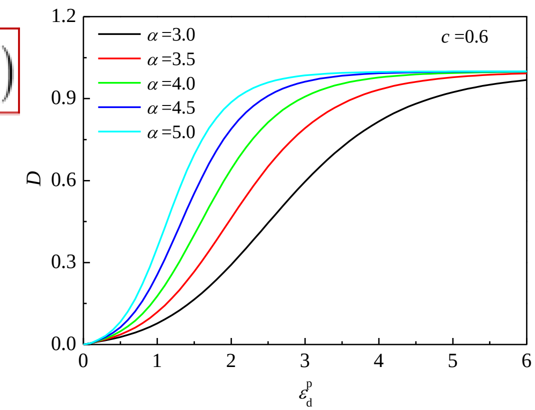


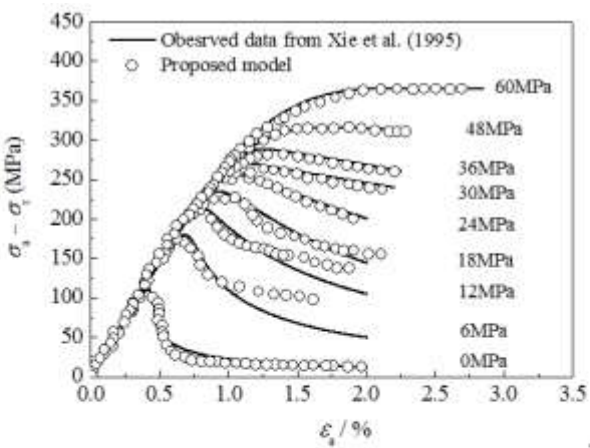
$$\sqrt{\left(\bar{\sigma}_1^{\beta}-\bar{\sigma}_2^{\beta}\right)^2+\left(\bar{\sigma}_2^{\beta}-\bar{\sigma}_3^{\beta}\right)^2+\left(\bar{\sigma}_3^{\beta}-\bar{\sigma}_1^{\beta}\right)^2}=H\left(\varepsilon_d^p\right)$$

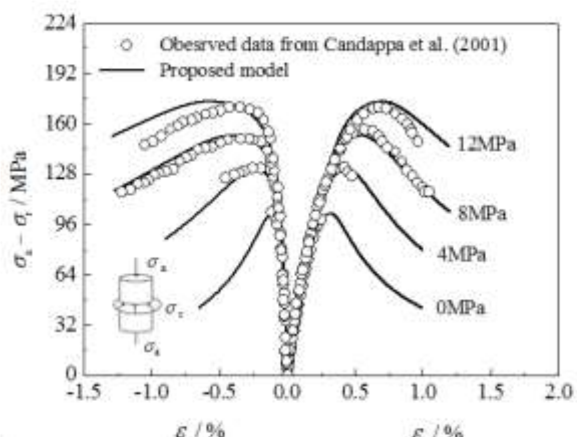
$$x=\varepsilon_d/\varepsilon_{d0} \qquad y=q/q_g$$

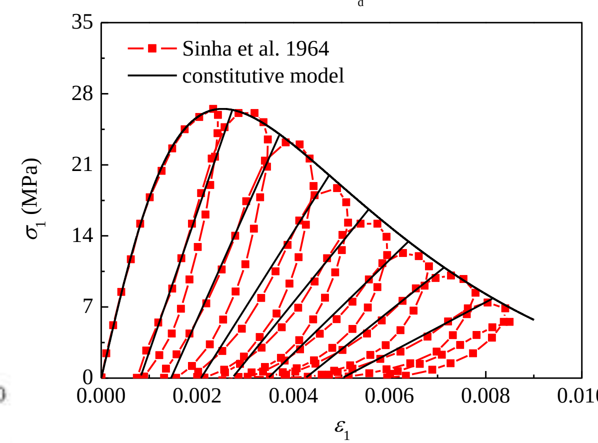
$$x\le 1 \qquad y=\frac{x}{\beta x+1-\beta}-(1-\beta)\left(x-x^2\right)$$

$$x>1 \qquad y=\frac{x}{\gamma(x-1)^2+x}$$









Achievement 2 : The elasto-plastic (damage) constitutive model of geomaterials is established for different deformation characteristics

4) Established elasto-plastic damage constitutive model of rock considering strain softening, stiffness degradation and cyclic loading.

New model (cyclic loading, permanent deformation)

Cyclic shear test dilatancy curve of Joint

↓

Experimental expression of average dilution

↓

Relation between average dilatancy angle shear rate and other physical quantities

↓

Ladanyi-Archambault Shear strength model

$$\tau_i = \frac{\sigma_n\left(1-a_s^i\right)\cdot\left(\tan\alpha_i + \tan\varphi_i\right) + a_s^i\tau_{rock}}{1-\left(1-a_s^i\right)\cdot\tan\alpha_i\cdot\tan\varphi_i}$$

$$\varphi_i = \frac{\alpha_i\left(\varphi_0 - actg\frac{\sigma_n}{\tau_r} + \alpha_r\right) + \alpha_0\left(actg\frac{\sigma_n}{\tau_r} - \alpha_r\right) - \varphi_0\alpha_r}{\alpha_0 - \alpha_r}$$

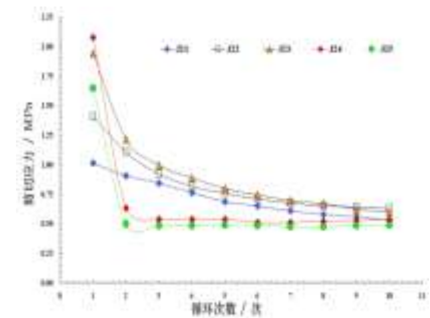
$$\tau_{rock} = \sigma_c\frac{\sqrt{n-1}-1}{n}\sqrt{1+n\frac{\sigma_n}{\sigma_c}}$$

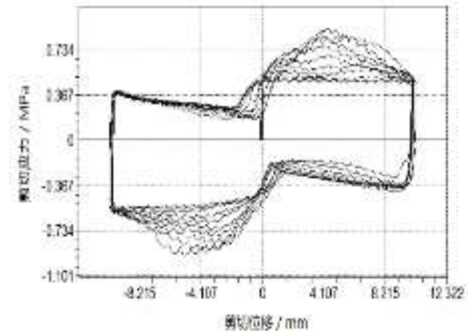
$$\alpha_i = \alpha_0\cdot R_S = \alpha_0\cdot\left[A\left(e^{-\frac{i}{B}}-1\right)+1\right]$$

$$\alpha_s^i = \frac{\left[\left(2H-L\cdot\tan\alpha_i\right)^2\cdot\left(\sin\alpha_0+\frac{\cos\alpha_0}{tg\left(\alpha_0-\alpha_i\right)}\right)-\left(2H-L\cdot\tan\alpha_{i-1}\right)^2\cdot\left(\sin\alpha_0+\frac{\cos\alpha_0}{tg\left(\alpha_0-\alpha_{i-1}\right)}\right)\right]\cdot\cos\alpha_0}{16S_0}$$

↓

Cycling Shear strength model of joint





◻ Dynamic Failure Behavior and Interface Contact Model

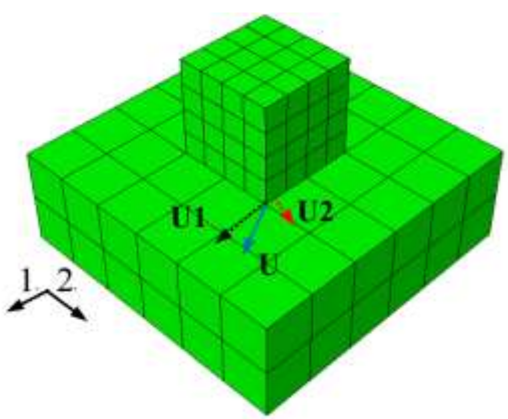
(2) Interface model between soil and structure

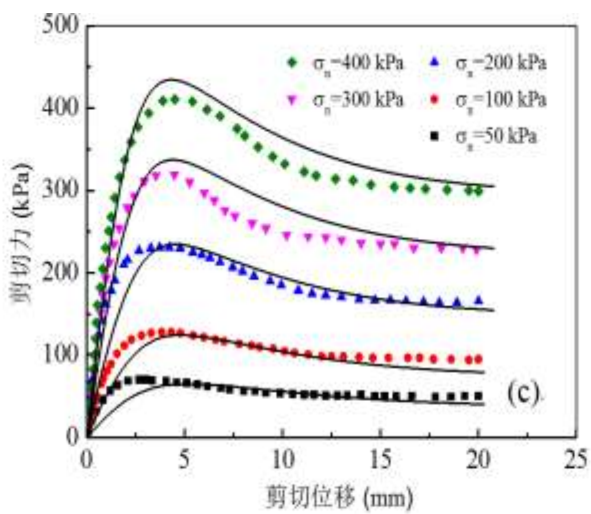
Interface element : Goodman element   Desai element   Shear stiffness ?

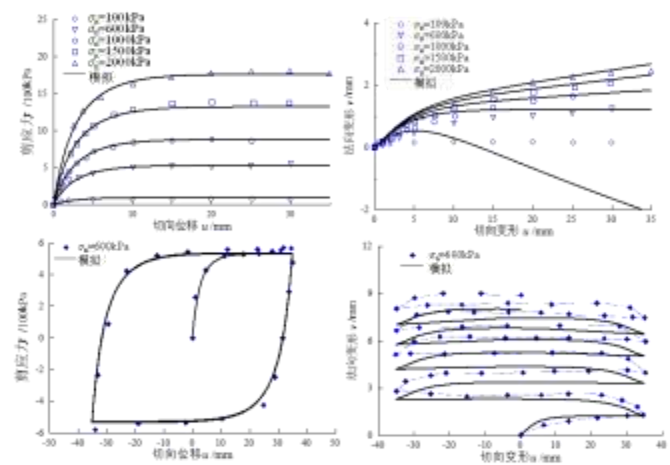
Solution: taking usage of the relationship between the shear stress and the shear strain on the sliding surface of the constitutive relationship of soil

Achievement 1 : Based on the constitutive model of overconsolidated soil, the contact shear stiffness model was established

Achievement 2 : Based on plasticity constitutive model of rockfill material, the model of interface contact shear stiffness was established





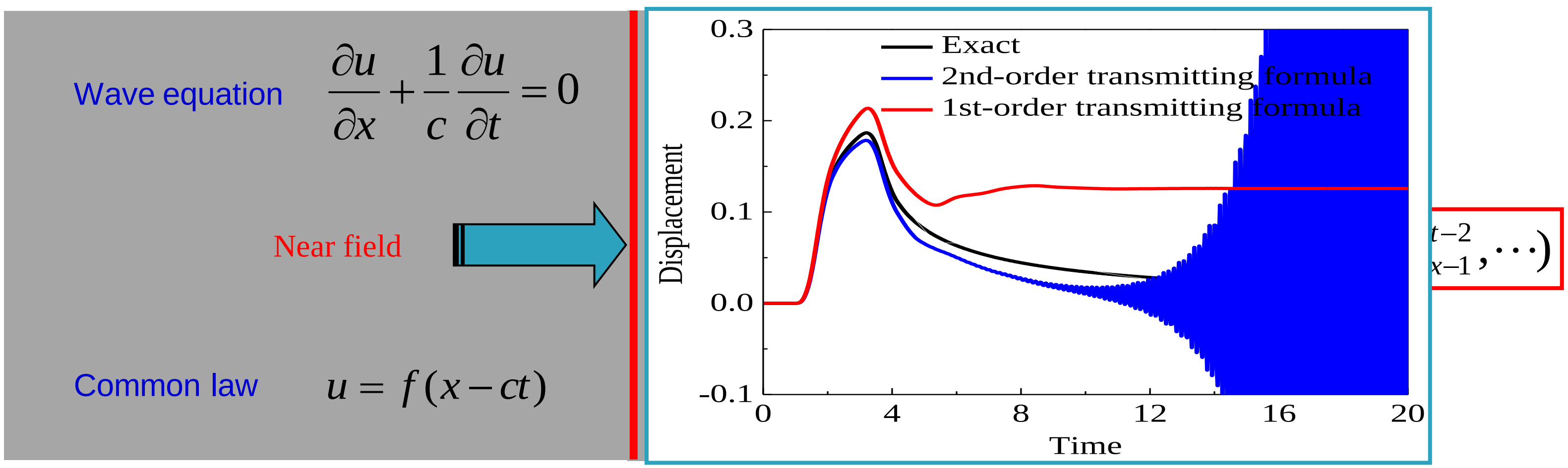


Artificial Boundary and Input of Ground Motion

(1) Artificial Boundary

Major achievements of international studies in the last 4 decades

---- Displacement Artificial Boundary Condition



Artificial boundary

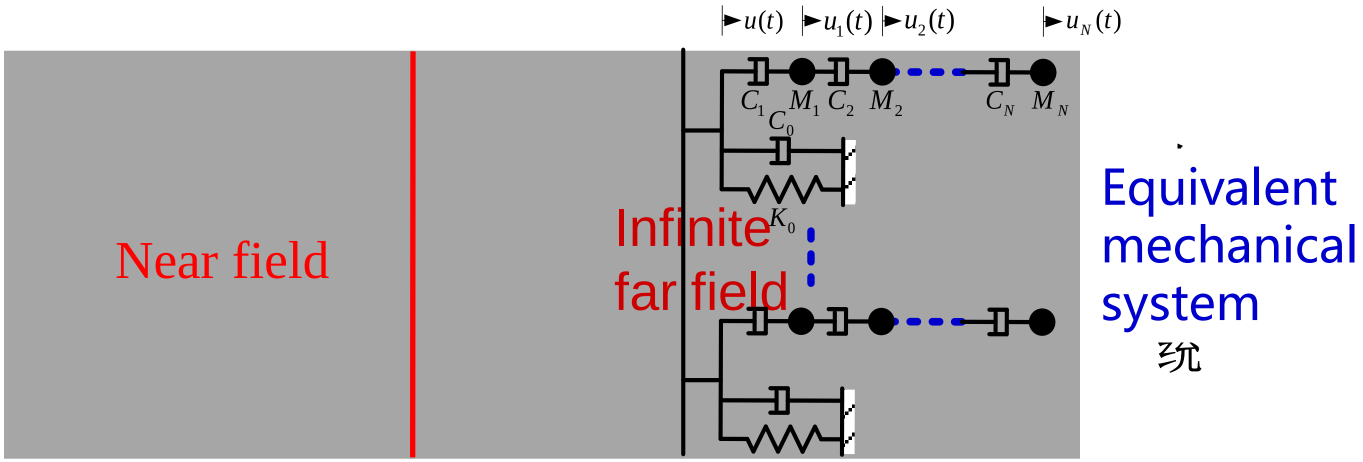
① Low-frequency drift and high-frequency oscillation instability phenomenon

② Inconvenience in the commercial finite element software

Artificial Boundary and Input of Ground Motion

(1) Artificial Boundary

Important development direction ---- High Order Precision Stress Artificial Boundary Condition



Artificial Boundary

① The equivalent mechanical system is consistent with the finite element equation

② To avoid low-frequency drift and high-frequency oscillation instability

1. Seismic disaster simulation theory and method and system integration

Achievement 1 : A Systematic Method for Constructing High - Precision Time Domain Artificial boundary is proposed

Boundary force-Displacement relationship(Frequency domain)

Scalar $F(\omega) = S(\omega)U(\omega)$

Vector $\mathbf{F}(\omega) = \mathbf{S}(\omega)\mathbf{u}(\omega)$

Force-displacement relationship Approach to the Stability of a High Order Linear System

$$S(\omega) \approx \frac{p_0 + p_1 \mathrm{i}\omega + \ldots + p_{N+1}(\mathrm{i}\omega)^{N+1}}{q_0 + q_1 \mathrm{i}\omega + \ldots + q_N(\mathrm{i}\omega)^N}$$

Rational function

$$\mathbf{S}(\omega) = \mathbf{g}_0 + \mathrm{i}\omega\mathbf{h}_0 - \mathrm{i}\omega\mathbf{S}_1^{-1}$$

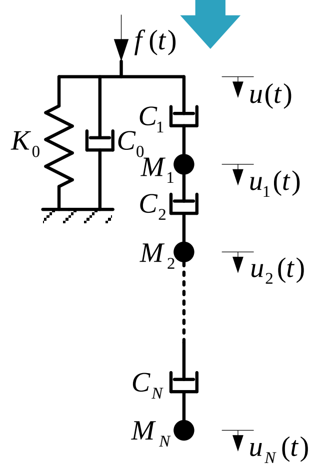
$$\mathbf{S}_j = \mathbf{g}_j + \mathrm{i}\omega\mathbf{h}_j - \mathrm{i}\omega\mathbf{S}_{j+1}^{-1}$$

$$j = 1, \ldots, N$$

Continuous fraction

equivalence

Containing internal variables (reduced order) Time - domain state space system



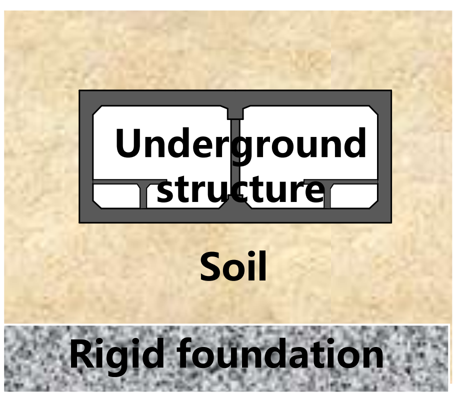
$$\begin{bmatrix} \mathbf{C}_{bb} & \mathbf{C}_{bc} \\ \mathbf{C}_{cb} & \mathbf{C}_{cc} \end{bmatrix} \begin{Bmatrix} \dot{\mathbf{u}} \\ \dot{\bar{\mathbf{u}}} \end{Bmatrix} + \begin{bmatrix} \mathbf{K}_{bb} & \mathbf{K}_{bc} \\ \mathbf{K}_{cb} & \mathbf{K}_{cc} \end{bmatrix} \begin{Bmatrix} \mathbf{u} \\ \bar{\mathbf{u}} \end{Bmatrix} = \begin{Bmatrix} \mathbf{f} \\ \mathbf{0} \end{Bmatrix}$$

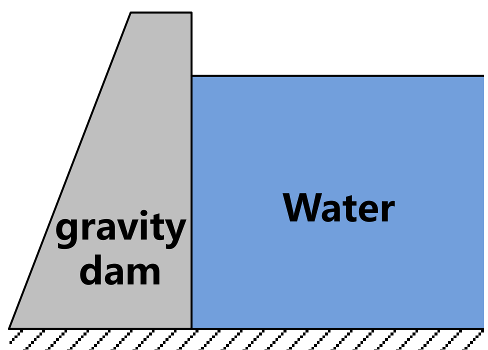
1. Seismic disaster simulation theory and method and system integration

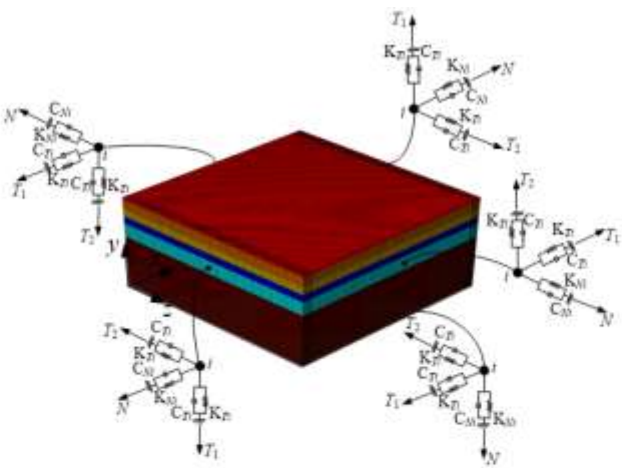
Achievement 2 : Established high-order time-domain artificial boundary conditions for several classes of problems

- **Wave propagation problem**
- **Exterior problem**
- **Cylindrical and spherical elastic wave radiation**
- **…**

Achievement 3 : Low order stress type artificial boundary-viscoelastic artificial boundary condition
(Single-phase and liquid-solid coupling saturated two–phase materials)





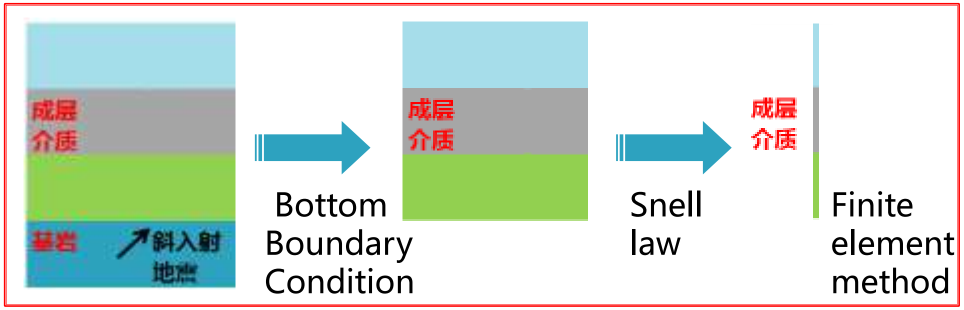


Artificial Boundary and Input of Ground Motion

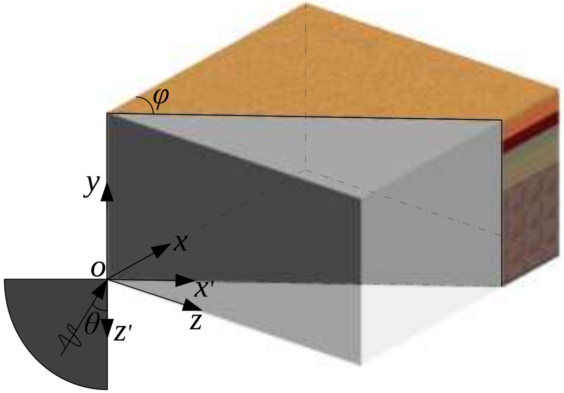
(2) Ground motion input

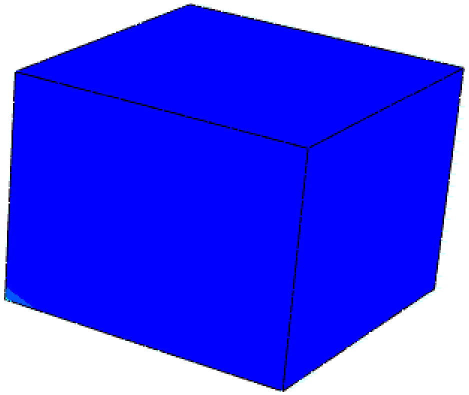
Results: established seismic oblique incidence input method for stratified half-space field

Algorithm to achieve:



Calculation model
With results :

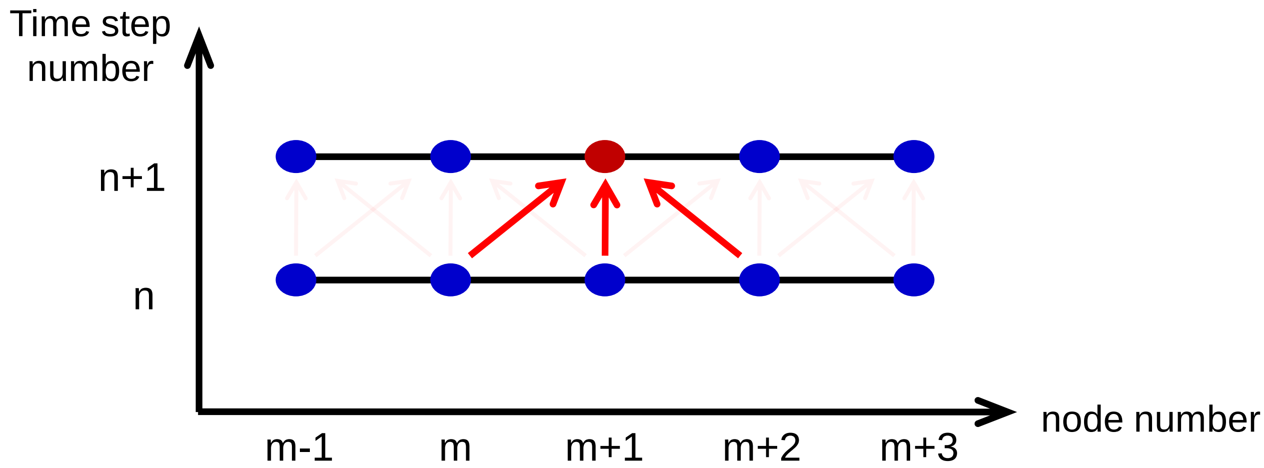




Efficient and high precision numerical method

(1) Efficient algorithm—Space - time Localization Method

- **Based on the concept of finite velocity, the current time response of a node is only related to the reaction of the first few moments of the neighboring nodes.**
- **It is not necessary to solve the coupled equations, and the computational efficiency is high, saving memory and being suitable for parallel computation.**



a) Differential equation--Finite difference Space-time decoupling

b) Integral equation--Finite element method Necessary Conditions for Space - Time Decoupling Time domain difference Centralized quality model

Efficient and high precision numerical method

Achievement 1： The explicit finite element method of viscoelastic solid medium of D'Alembert was developed

Achievement 2： The explicit finite element method of saturated two-phase media is developed

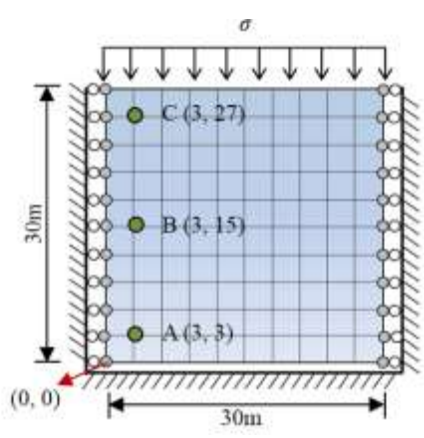
Achievement 3： An explicit algorithm for the dynamic contact force and the dynamic contact force of the solid medium is established

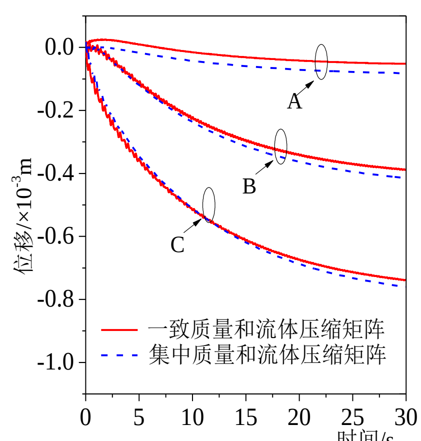
$$u_{k+1}=M^{-1}\left(f_{uk}-K_d\cdot u_k+Q\cdot p_k\right)\cdot\Delta t^2+2\cdot u_k-u_{k-1}$$

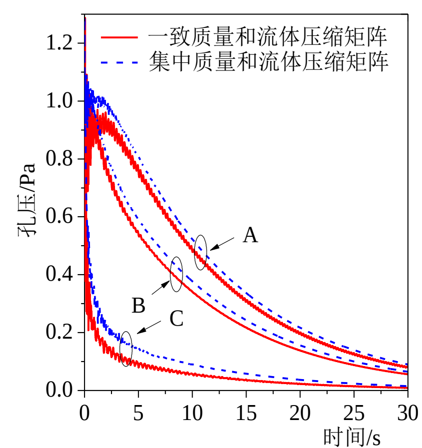
$$p_{k+1}=T\cdot p_k+\frac{\Delta t}{2}\sum_{i=1}^{n}\omega_i\cdot T\left(\frac{\Delta t}{2}(1-\zeta_i)\right)\cdot S^{-1}\cdot f_q\left[t_k+\frac{\Delta t}{2}(1+\zeta_i)\right]$$
$$+\frac{\Delta t}{2}\left[\frac{S^{-1}Q^T}{\Delta t}u(t_{k+1})+\frac{S^{-1}Q^T(T-1)}{\Delta t}u(t_k)-\frac{TS^{-1}Q^T}{\Delta t}u(t_{k-1})\right]$$

Quality matrix M
Fluid compression matrix S

Using a unified diagonal processing







◻ Efficient and high precision numerical method

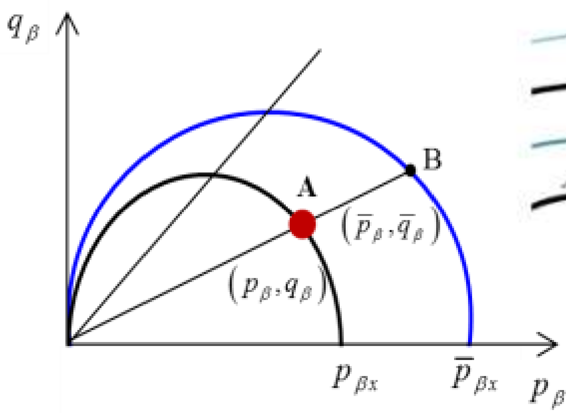
(1) Efficient algorithm—Elastic - Plastic Stress Updating Algorithm

Existing stress update algorithm：Elastoplastic iteration (Increment)+Nonlinear iteration→ high calculation cost, low precision

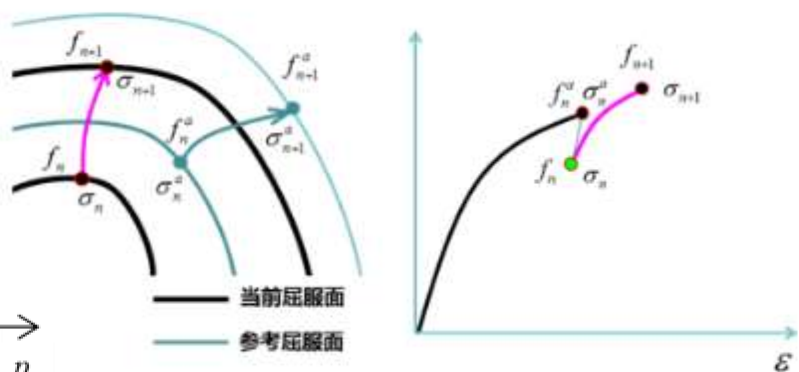
Proposed stress updating algorithm: loading and unloading judgment+Nonlinear iteration→ Small calculation amount, high precision

Strain hardening + Strain softening=Judged by the over-consolidation ratio

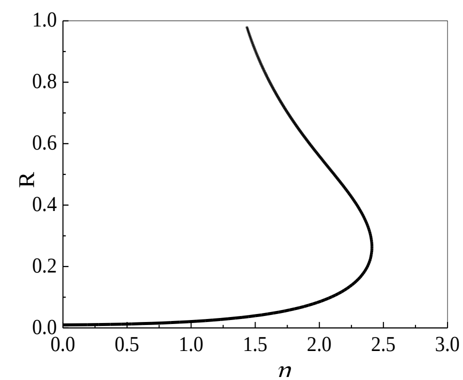
Suitable for large-scale computing



3- Dimensional Elastic - Plastic Model of Lower Loading Surface



Elastic - Plastic Stress Updating Algorithm

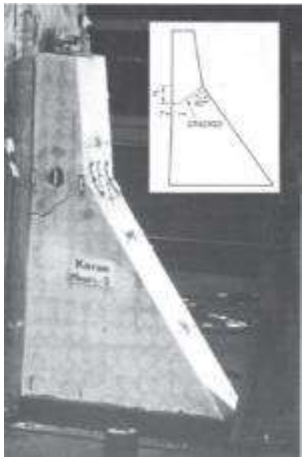


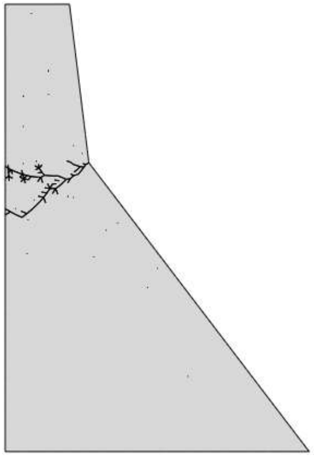
Loading and unloading guidelines

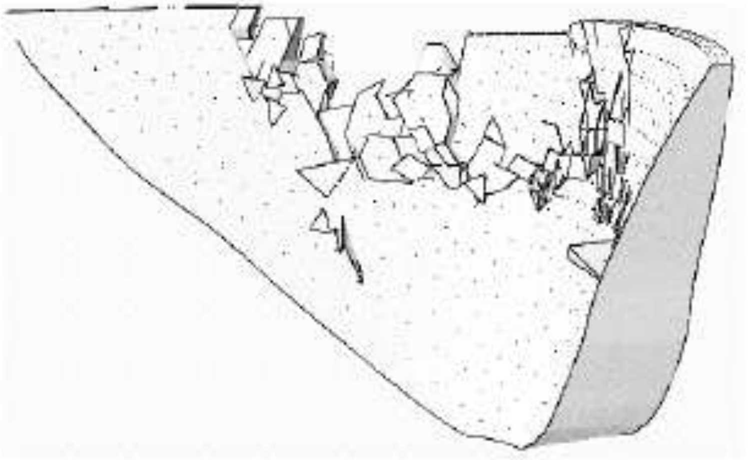
Efficient and high precision numerical method

(2) Grid Dependency—Strain softening, cracking and stress concentration etc.

Achievement ：Apply extended finite element model and thickness-free bonding element model to the analysis of high dam





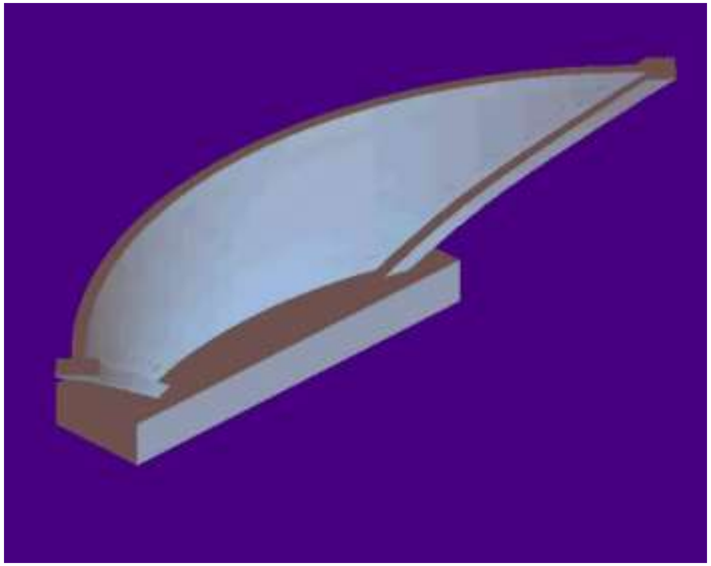


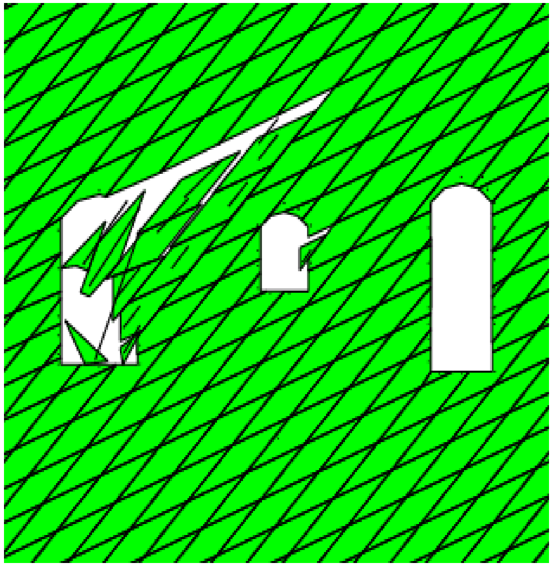
Efficient and high precision numerical method

(3) Discontinuous deformation problem

DDA, Discrete element and Manifold etc.

Achievement : Apply DDA and discrete element method to seismic hazard analysis of high dam and underground cavern





1.2 Physical Simulation Theory and Methodology

- test means-shaking table (1-G,N-G)

defect : Uniform similarity can not be satisfied

advantage : Physical Modeling of Large - Scale Target Structures

defect : Small size and Coriolis effect

advantage : meet the stress similar

1. Multi - media coupling similarity ; 2. Weakening Design of Model Materials ; 3. Selection of ground motion

1、semi qualitative - quantitative analysis。

2、Validation of mature numerical algorithms , to provide technology support for the simulation sets.

1.2 Physical Simulation Theory and Methodology

- The structural damage characteristics and test focus of each sub-project model

Local stress concentration and properties of concrete materials

sub-project 2 : concrete dam

Stress Distribution and Damage Cracking Process in Dam Body

panel suspended and bended, interior wall bended during shaking

sub-project 3 : Panel dam, Earth - rock dam

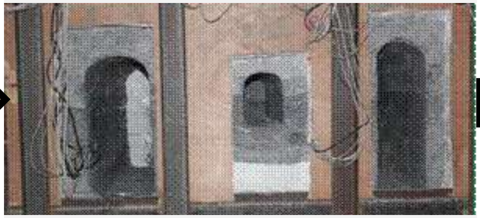
Similarity of dam - breaking process and its macroscopic phenomena

Underground structure controlled by the surrounding soil displacement

sub-project 4 : Underground structure

Development of Soil Box Simulation of free shear properties of soil layers

Stability of surrounding rock and relative sip of surrounding rock blocks

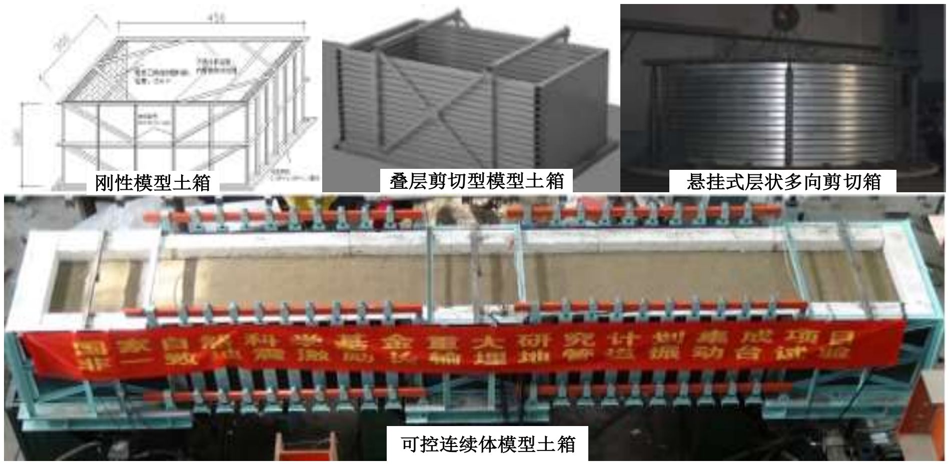


sub-project 5 : Underground caverns

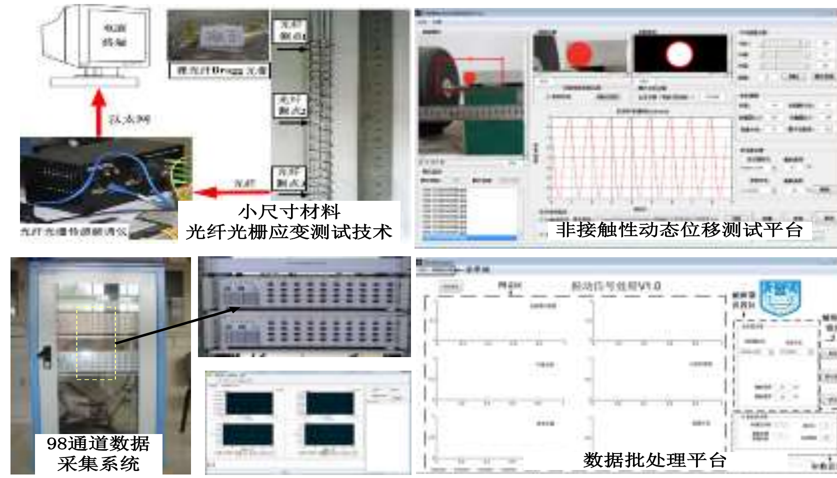
Development of model soil box and accurate simulation of surrounding rock material

1. Seismic disaster simulation theory and method and system integration

Achievement 1：New model box design, test technology, measurement and data transmission technology



Subproject 4



Subproject 4

Subproject 2

Subproject 3

1. Seismic disaster simulation theory and method and system integration

Achievement 2 : Development of Model Materials

Subproject 2

Water ：cement : lime : sand = 0.5:1:0.58:5

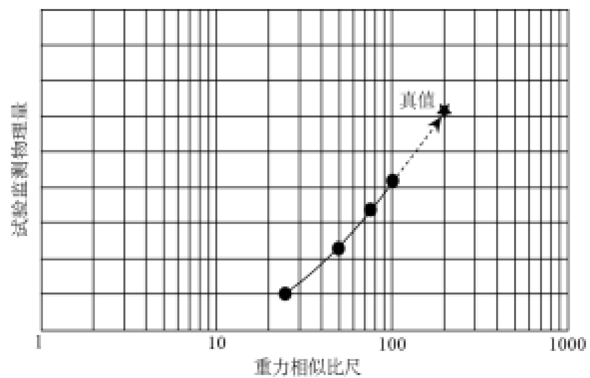
Subproject 5: new materials for underground cavern

Plaster, Barite powder, Quartz sand, water and Gypsum retarder

1. Seismic disaster simulation theory and method and system integration

Achievement 3 : Model similarity ratio design

01 A small-scale centrifugal model test method by stress approximation(N-G)

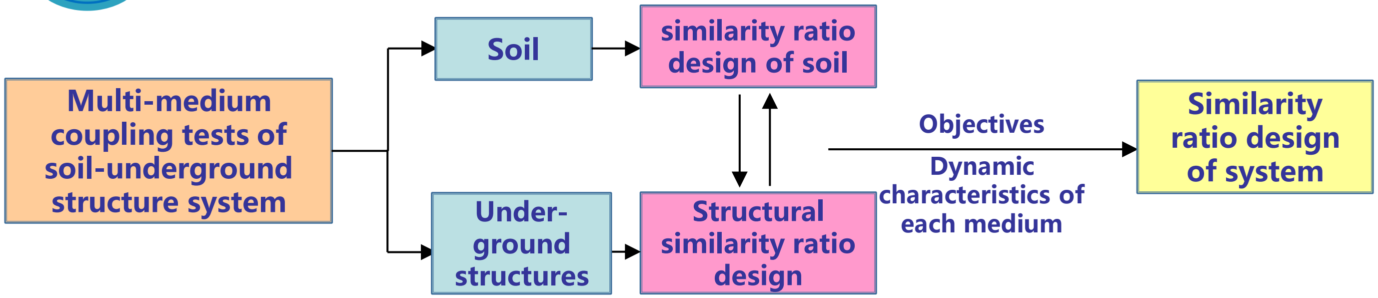


A similar method with good feasibility is obtained by extension analysis by sub project 3

Numerical simulation

Model similarity ratio design

02 Similarity design method of multi-medium coupling soil-structure system (1-G)



The soil-structure similarity ratio design problem could base on the dynamic characteristics of the foundation soil by Subproject 2

1. Seismic disaster simulation theory and method and system integration

1.3 System integration

① Developed a software platform for seismic time history synthesis and seismic field simulation

② Developed a high concrete dam seismic analysis software

③ Improve and develop the high earth and rock dam seismic simulation software platform (GEODYNA6.0)

④ Developed a large-scale underground structure earthquake simulation software (GDA)

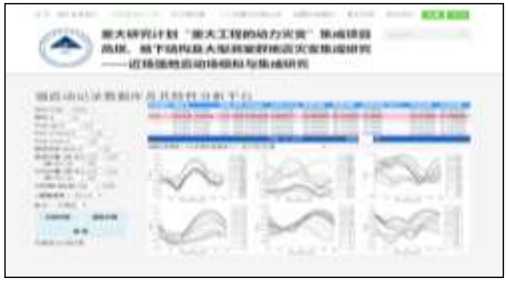
⑤ Developed a large-scale underground caverns earthquake simulation software

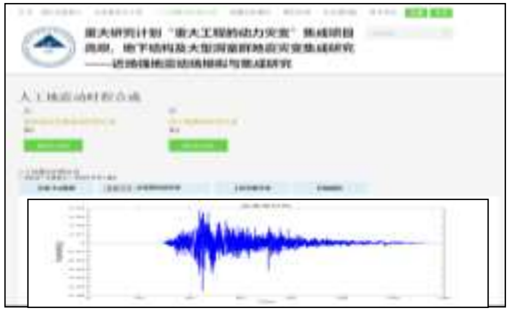
1. Seismic disaster simulation theory and method and system integration

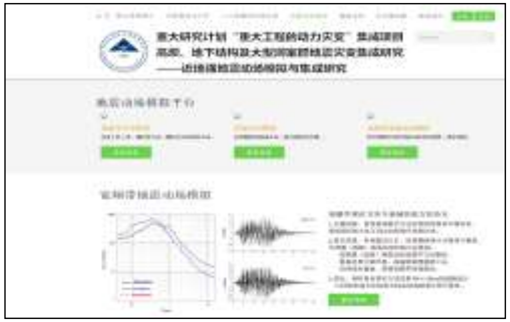
Achievement 1: Seismic Ground Motion Synthesis and Seismic Field Simulation Platform

Ground motion synthesis and seismic dynamic field simulation integration platform

- **Strong vibration database and characteristic analysis platform**
  - Multi-parameter ground motion record query
  - Real-time display of analysis results
- **Artificial ground motion time history synthesis platform**
  - Time history synthesis of ground motion with random phase method
  - 随机相位法地震动时程合成？
- **Seismic dynamic simulation platform**
  - Theoretical method of seismology
  - Empirical statistical method
  - Wide band synthesis method







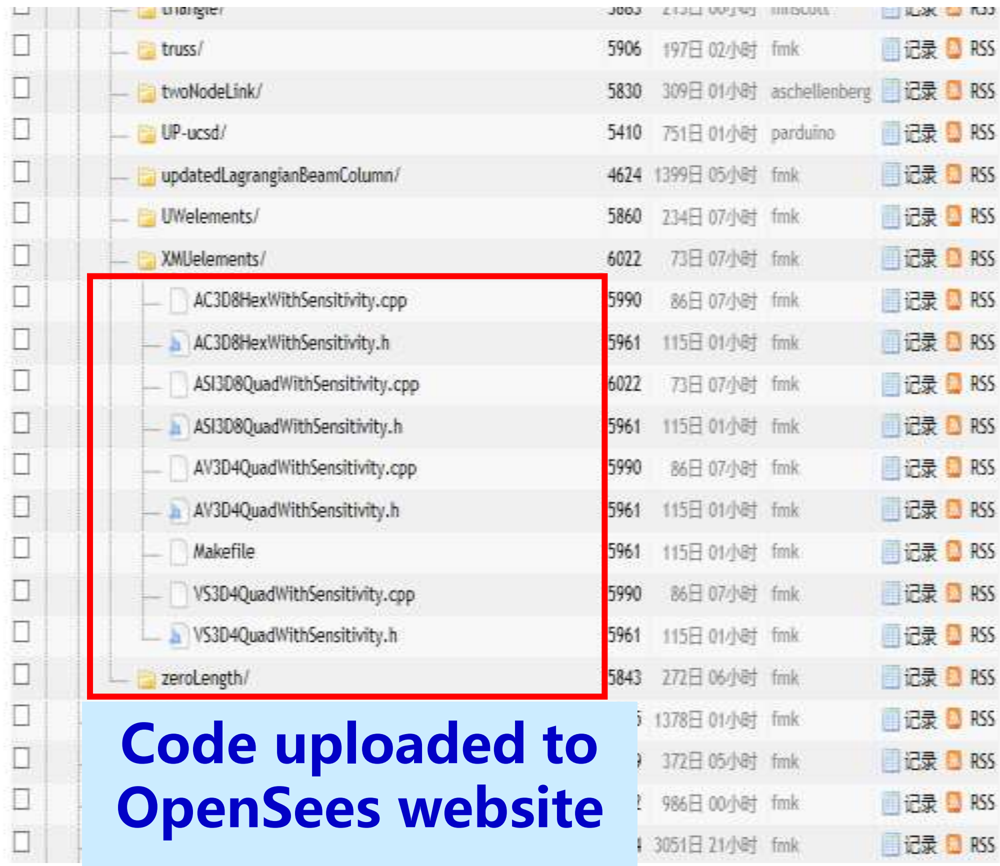
1. Seismic disaster simulation theory and method and system integration

Achievement 2: high concrete dam seismic analysis software

The analysis software of earthquake disaster of high concrete dam is developed and verified by the model test and the actual earthquake damage based on ABAQUS and OpenSees.

Basic function

- Infinite foundation radiation damping
- Dam-water interaction
- Energy dissipation in upper reaches of reservoir
- Nonlinearity of dam material
- Nonlinearity of transverse joints of dam
- Seismic reinforcement measures of dam



Code uploaded to OpenSees website

1. Seismic disaster simulation theory and method and system integration

Achievement 3: High earth and rock dam seismic simulation software platform (GEODYNA6.0)

- ✓ High development efficiency
- ✓ Easy transplant and maintenance
- ✓ ●●●

object-oriented programming

High performance and large scale computing

- ✓ 64 bits
- ✓ multi-threading
- ✓ multi-core parallel process
- ✓ GPU acceleration

3-D nonlinear static and dynamic finite element analysis GEODYNA6.0

- ✓ Seismic wave
- ✓ Hydrostatic pressure
- ✓ Node change
- ✓ ●●●

12 types of loadings

9 types of analyses

- ✓ Dynamic
- ✓ Consolidation
- ✓ Static
- ✓ ●●●

- ✓ Block element
- ✓ Interface element
- ✓ Coupling element
- ✓ Beam element
- ✓ ●●●

28 elements

Integration of seismic disaster simulation methods

- ✓ Complex seismic motion input
- ✓ Fluid-solid coupling of dam and water
- ✓ Damage and crack of concrete
- ✓ ●●●

14 constitutive models

- ✓ Generalized plasticity
- ✓ Plastic damage
- ✓ Equivalent linear
- ✓ state-dependent;
- ✓ ●●●

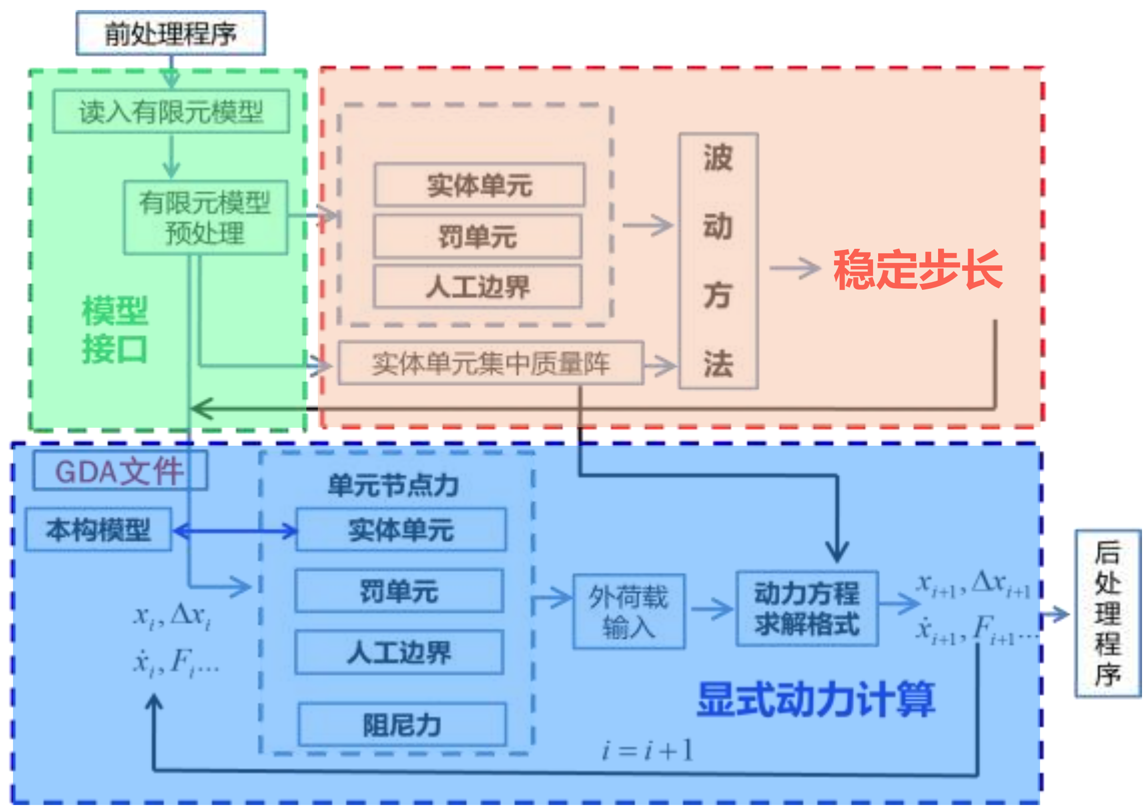
The calculation scale breaks through 50 million degrees of freedom (static problems) and 10 million degrees of freedom (dynamic problems), is able to solve large-scale, non-linear and earthquake-destroying calculation problems of the 300-meter high earth-rock dams.

Achievement 3 : Large-scale underground structure earthquake simulation software (GDA)

Geotechnical Dynamic Analysis(GDA) program

Complete independent development of GDA effectively handled the technical difficulties e.g. high computational costs and high nonlinearity during the nonlinear dynamic analyses of underground structures.

GDA has the characteristics of high scalability, ease of development of new algorithms and models, providing excellent software platform for the integration of research achievements.



Fine and efficient nonlinear finite element analysis of underground structures and software platform for research

1. Seismic disaster simulation theory and method and system integration

Achievement 5 : Developed a large-scale underground caverns earthquake simulation software

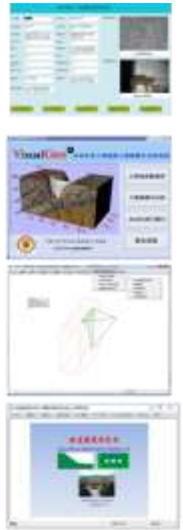
高效并行计算平台

动态试验数据与震害调查资料 → 岩石动态力学参数与震害数据库 RSDB

地质结构精细建模方法与技术 → 三维地质结构精细模型构建软件 VisualGeo

关键块体地震动力响应时程分析方法 → 关键块体动力响应分析软件 S-Key Block

不连续变形的动力时程分析方法 → 不连续变形动力响应分析软件 S-DDA



非线性动力有限元分析理论

岩体材料动力本构模型

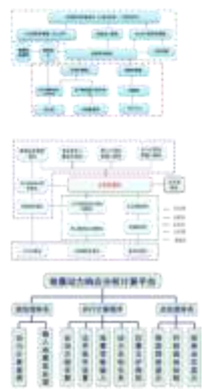
高效并行求解算法

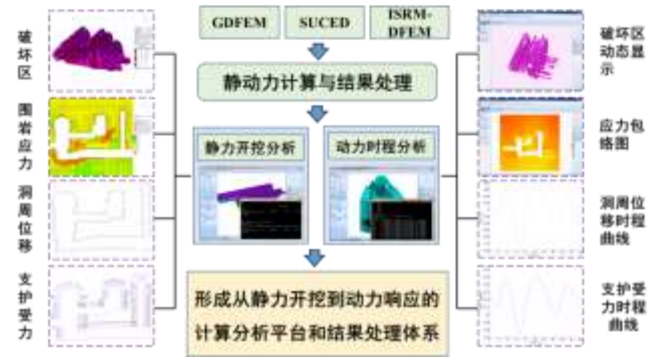
→

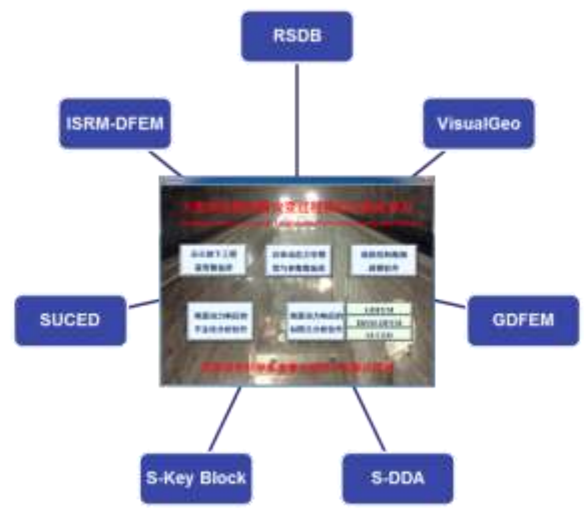
岩土工程静动力弹塑性有限元分析软件系统 GDFEM

大型地下洞室群地震灾变模拟系统 SUCED

岩石工程非线性有限元动力分析软件 IRSM-DFEM

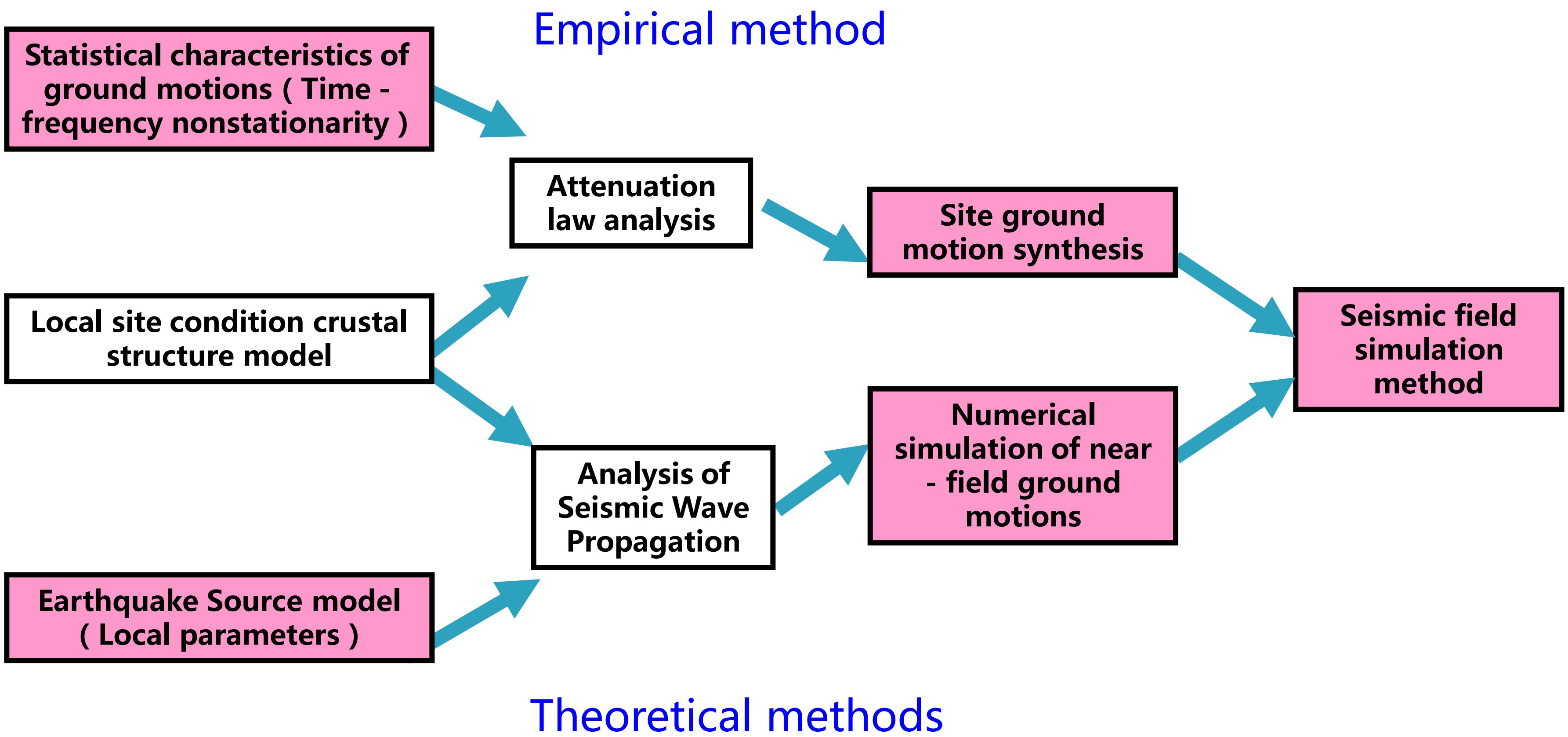






Local and overall combination of efficient, fast, multi-level seismic response and disaster simulation platform

1. Seismic disaster simulation theory and method and system integration



IV. Summary and prospect

1. Study on the theories and methods of earthquake disaster simulation.

2. Several progress on physical model tests and a series of destructive tests in this research.

3. New recognitions on the seismic damage mechanism and failure modes.

Acknowledgement

Thanks !