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Effects of dynamic properties of rockfill materials on seismic response of concrete-faced rockfill dams

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Effects of dynamic properties of rockfill materials on seismic response of concrete-faced rockfill dams

The objective of this study

- With application of large-scale dynamic testing apparatus which are capable to implement complex loading and improvement of in-situ freezing sampling techniques, a number of test results on gravels become available. Based on these collective data, the sensitivity of seismic response on dynamic properties of rockfills should be clarified.---Complexity of dynamic tests
- Numerical results presented will be instructive to gain a better understanding on earthquake-resistant behavior of CFRDs and the effects of dynamic properties of rockfills.---Numerical Technique
- By changing rockfill lithology and by adjusting grading and gravel content---Engineering construction

Finite element mesh

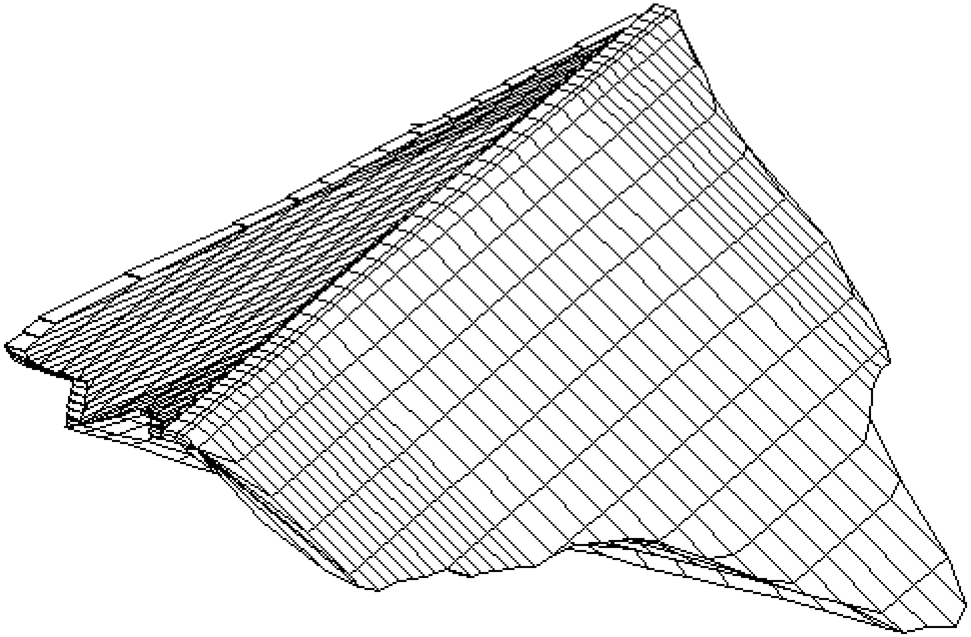


Fig. 4-1 The three-dimensional finite element discretization of Hongjiadu dam

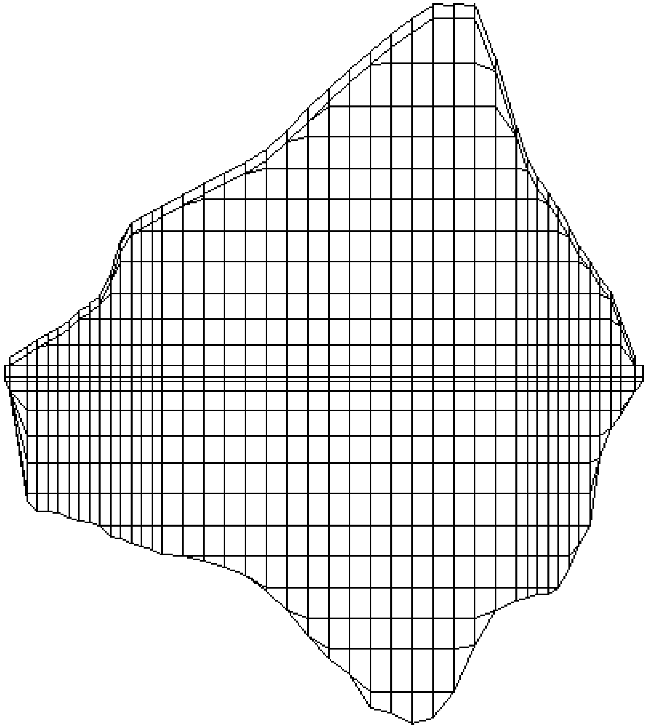


Fig. 4-2 The plan-view of finite element discretization of Hongjiadu dam

Types of elements

Rockfill → strain-dependent

Facing slab → Elastic model

Interface Elements： → Experimental Equation

Peripheral joints elements → Experimental Equation

Dynamic water pressure → Modified Westergaard’s formulation

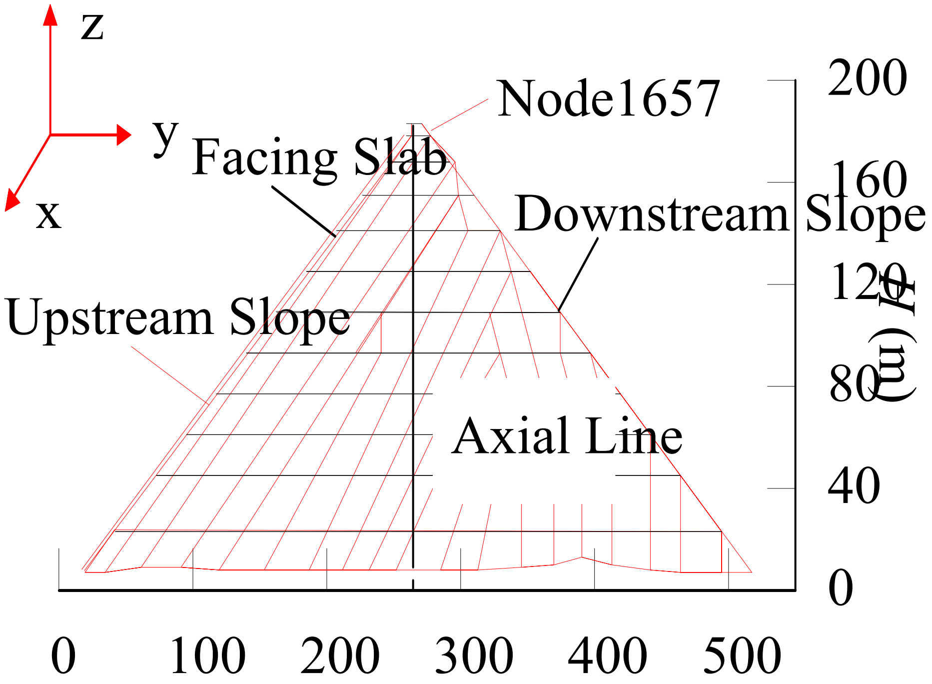
Global iteration number → Three times

Types of elements and maximum Section

The height of dam is 182.3m.

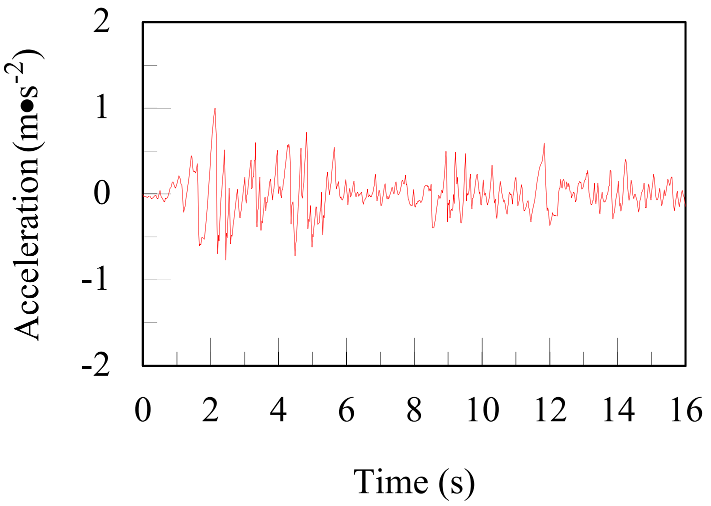
The total number of nodes is 3801

The total number of elements is 3463 with 263 face elements, 263 interface elements and 42 joint elements.

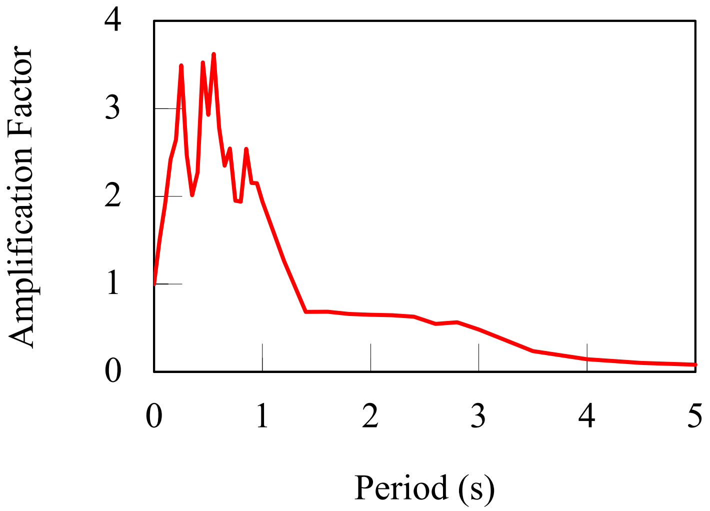


Finite element discretization of Hongjiadu Dam for the maximum section

Input Wave



Time history of El Centro record



Standard response spectrum

Three direction

Equivalent Linearalization procedure

- In this method, approximate nonlinear solutions can be obtained by a series of linear analyses provided the updated stiffness and damping are compatible with current effective shear strain amplitudes.
- The equivalent effective strain is estimated as a fraction (i.e., 0.65) of peak shear strain in order to define modulus and damping ratio for each iteration from the experimentally-achieved curves.
- Successive iterations are required until compatible dynamic parameters with strain level are acquired.
- Rayleigh’s concept of proportional damping is used to represent hysteric damping of soil
- Wilson-θ’s numerical integration scheme is combined with equivalent linearization procedure to solve the dynamic equations of the system step-by-step in time domain.

Contents

- Dynamic properties of rockfill

  1. Small-strain shear modulus；
  2. Shear modulus varying with shear strain；
  3. Hysteretic damping varying with shear strain；
  4. Confining-Pressure-Dependency of shear modulus

- comparative aspects

  1. Natural frequency；
  2. Peak acceleration；
  3. Peak shear strain；
  4. Peak dynamic stress along slab；
  5. Acceleration response spectra

Influence of Initial Shear Modulus of Rockfills

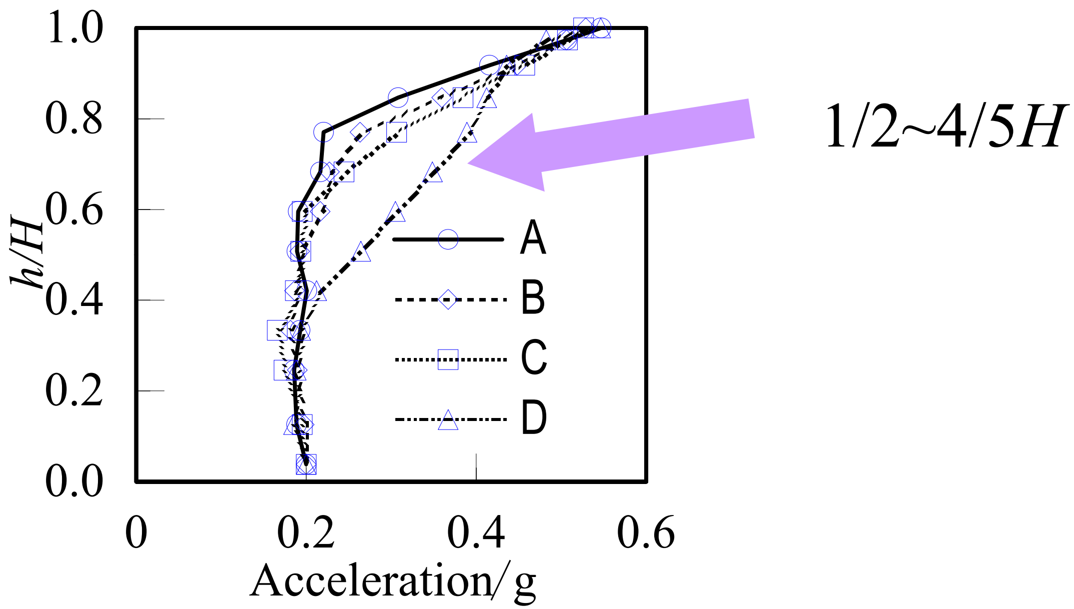
$$G_{\max} = G_0 p_a F(e) \left(\frac{\sigma_c}{p_a} \right)^m$$

Calculated fundamental natural frequencies for different values of G_0

Cases	G_0	References	Frequency（Hz）
A	312.2	Chen and Gu (1987)	1.0790
B	416.3	Chi and Lin (1998)	1.2282
C	499.1	Kong and Zou (1999)	1.3456
D	786.0	Uddin (1999)	1.7056

The test data of modulus ratio and damping ratio curve was used in these cases

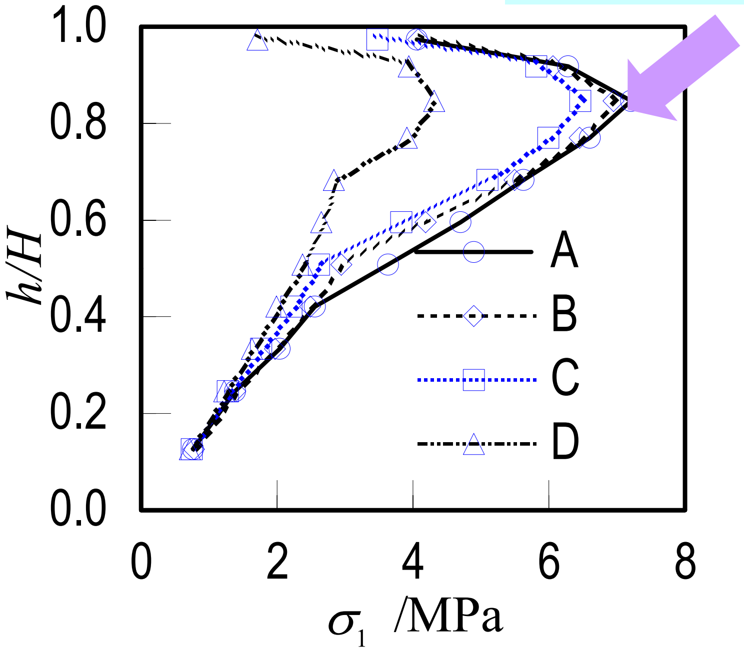
Influence of Initial Shear Modulus of Rockfills



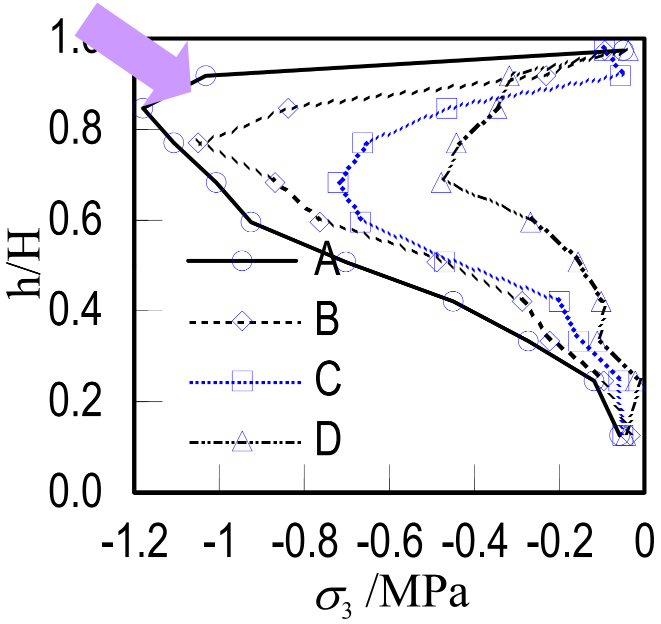
Distribution of peak absolute acceleration in axial line along depth

Influence of Initial Shear Modulus of Rockfills

3/4~4/5*H*==shaking-table tests

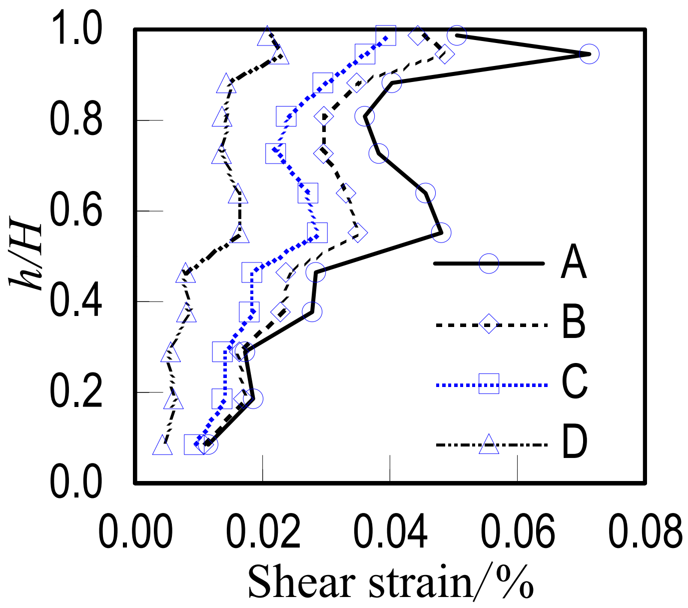


Peak major principal stress along slab

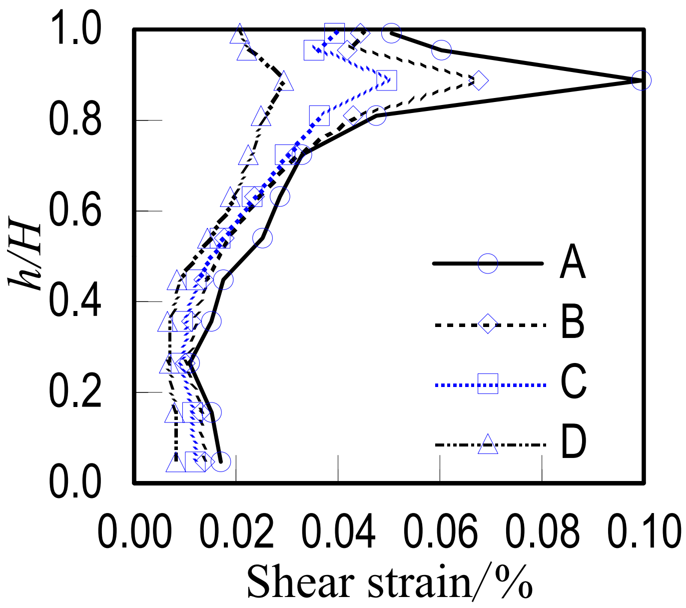


Peak minor principal stress along slab

Influence of Initial Shear Modulus of Rockfills

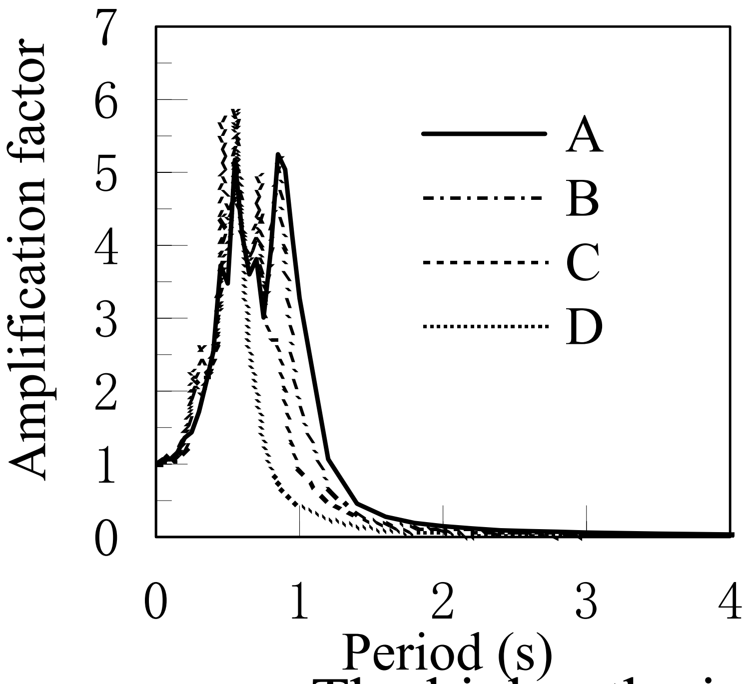


Peak shear strains in axial line



Peak shear strains in upstream slope

Influence of Initial Shear Modulus of Rockfills



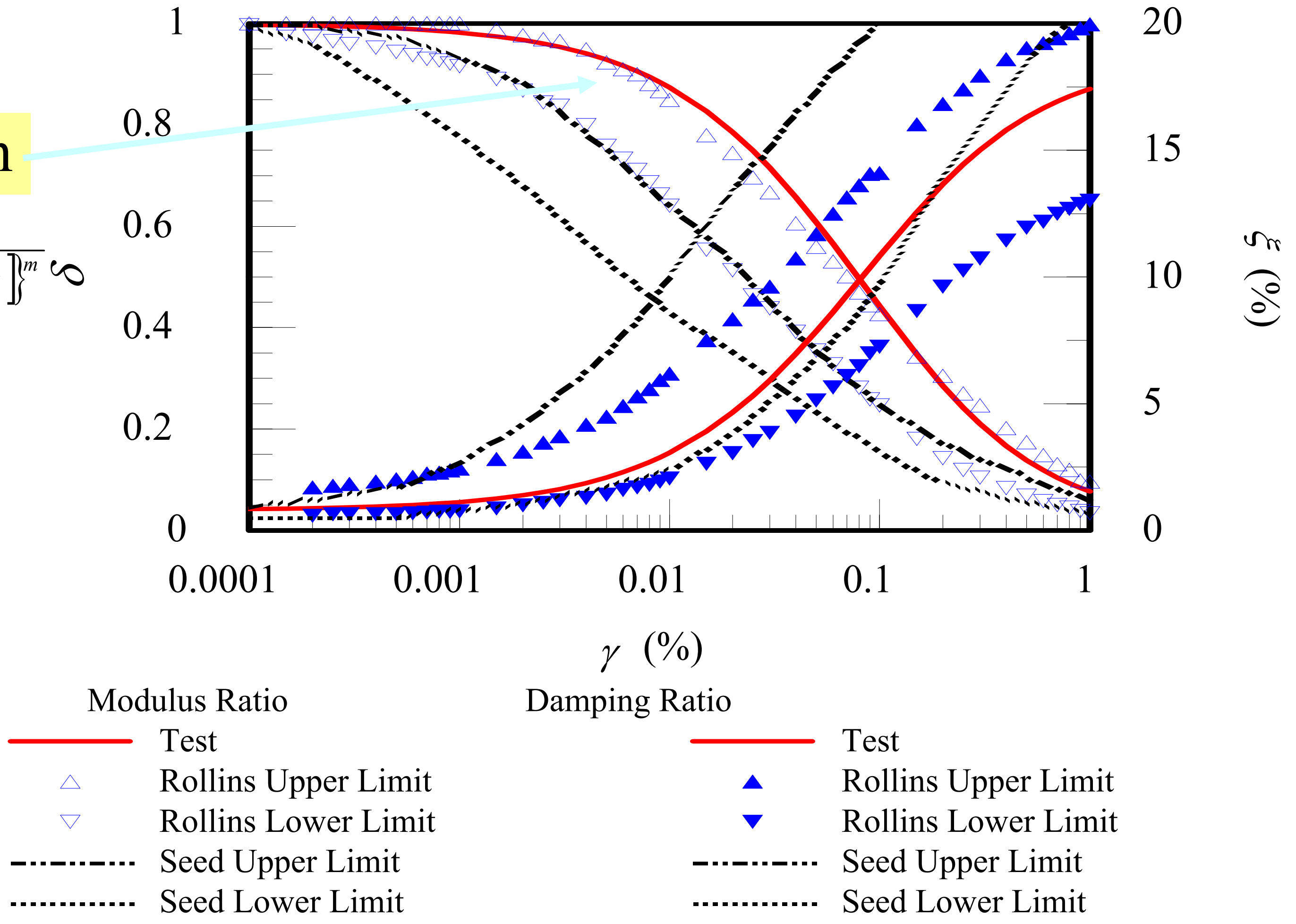
Acceleration response spectra of node 1657(at the dam crest)

The higher the initial modulus, the more narrow the frequency band. The lower the initial modulus, the more plentiful the frequency components contained.

Influence of Variation of Shear Modulus and Damping Ratio with Strain of Rockfills

Equation

$$\delta = \frac{1}{\left\{\ln\left[e + (\gamma / a)^n\right]\right\}^m}$$



Influence of Variation of Shear Modulus and Damping Ratio with Strain of Rockfills

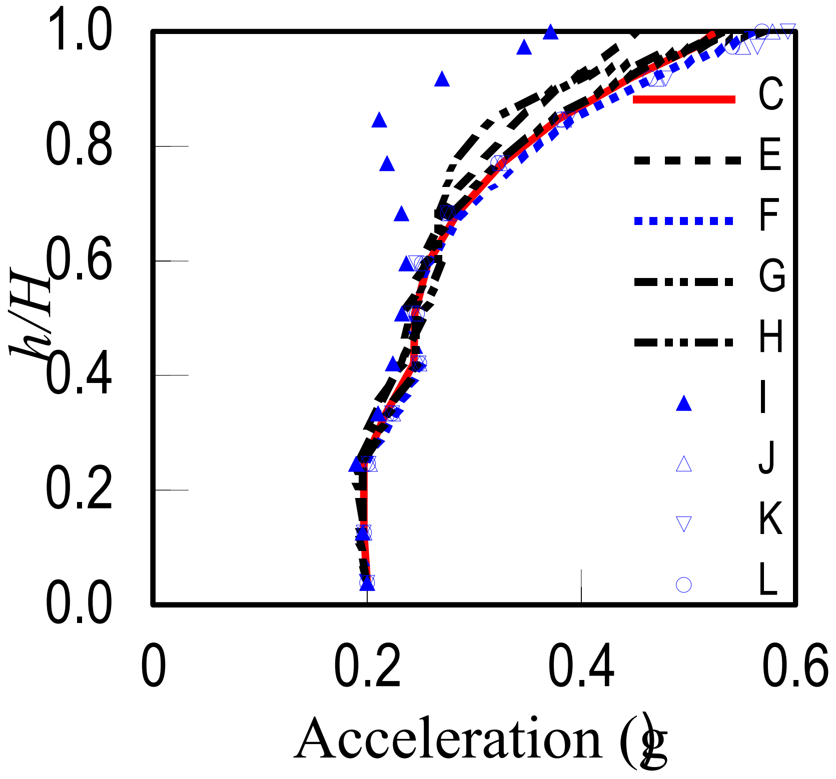
Dynamic property parameters for different cases

Case	δ	ξ	Frequency (Hz)
C	Test	Test	1.3456
E	Test	Rollins Upper	1.3557
F	Test	Rollins Lower	1.3407
G	Rollins Upper	Test	1.3214
H	Rollins Lower	Test	1.1189
I	Seed Lower	Seed Upper	0.9519

G_0=499.1

The natural frequency increases with increasing modulus curve toward the upper bound. The value of damping ratio has little influence on the frequency of dam.

Influence of Variation of Shear Modulus and Damping Ratio with Strain of Rockfills

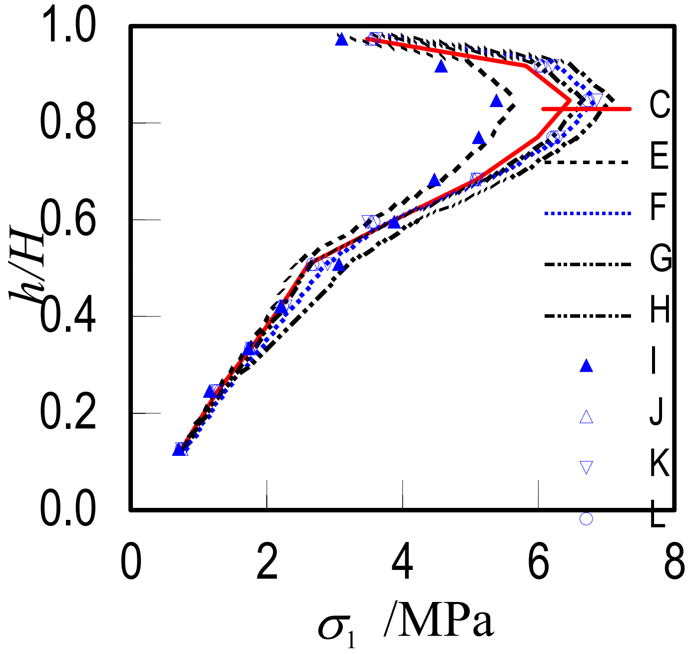


The acceleration in case I with a low modulus and a high damping ratio is smaller than those in other cases.

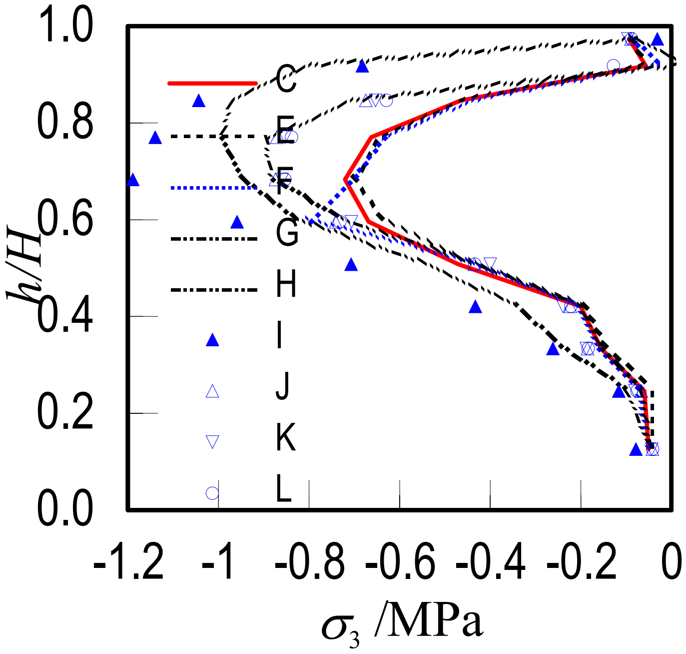
Peak accelerations in upstream slope

figure

Influence of Variation of Shear Modulus and Damping Ratio with Strain of Rockfills



Peak major principal stresses along slab



Peak minor principal stresses along slab

figure

Influence of Variation of Shear Modulus and Damping Ratio with Strain of Rockfills

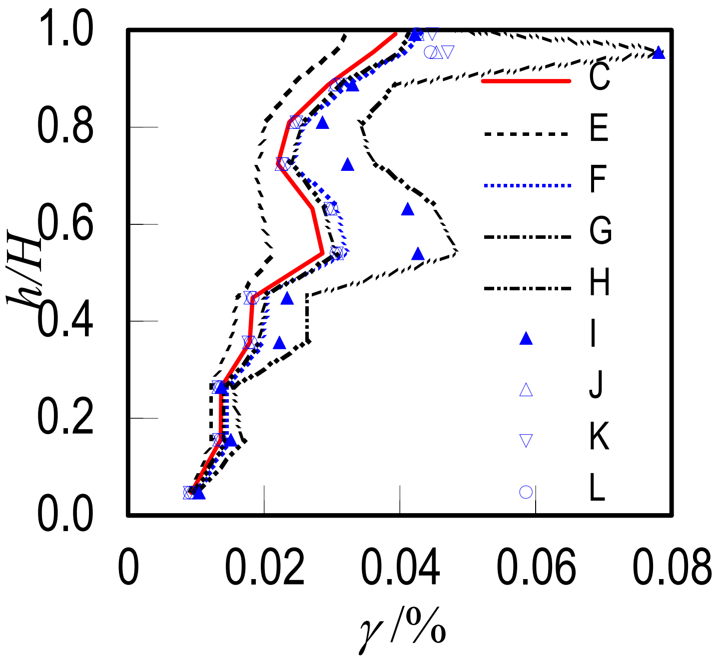
Major stresses in case E and case I are relatively lower;. Major stresses decrease with increasing damping ratios.

Minor stresses in case H and case I are relatively higher and tensile stresses increase with descending modulus reduction curve of rockfills.

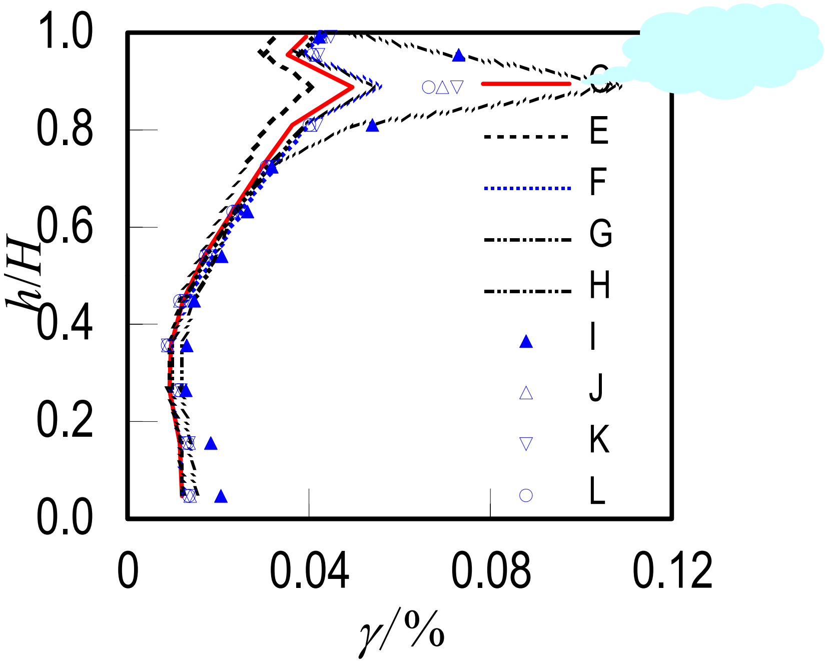
Therefore it is necessary to carry out optimum design especially for face slab on the basis of dynamic properties of rockfills and stress state of facing.

figure

Influence of Variation of Shear Modulus and Damping Ratio with Strain of Rockfills



Peak shear strains in axial line

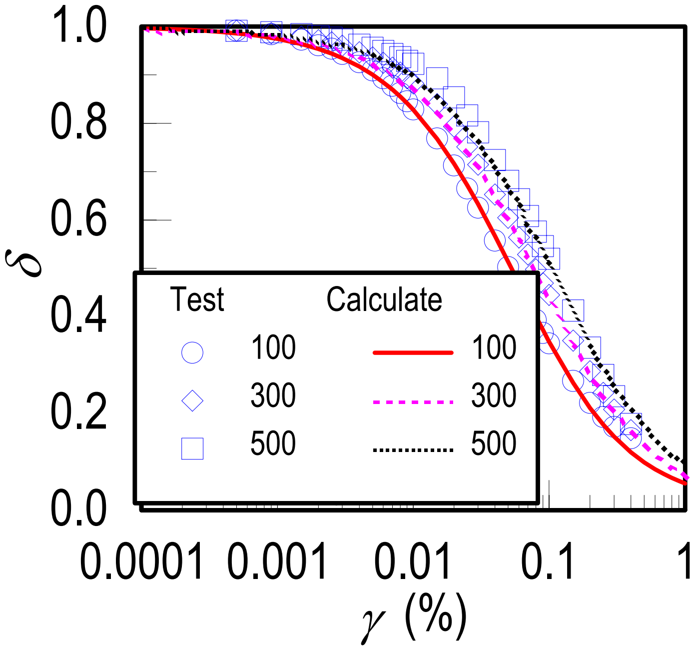


Peak shear strains in upstream

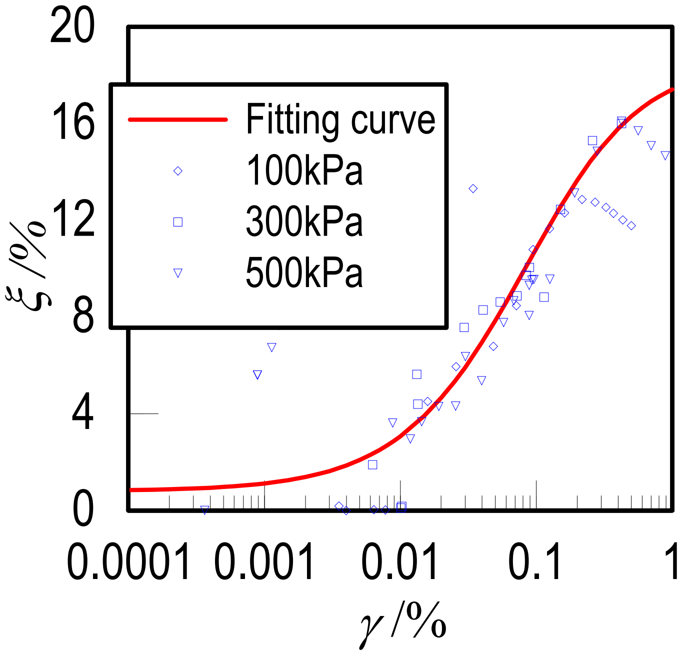
shear strains increase with decreasing modulus.

Effect of Confining-Pressure-Dependency of Shear Modulus

As confining pressure increases, the relations of δ and γ move from the lower bound of testing data range towards the upper.



Modulus ratio of main rockfill at various confining pressure



Damping ratio of main rockfill at various confining pressure

Effect of Confining-Pressure-Dependency of Shear Modulus

$$G/G_{\max} = \delta(\gamma,a,n,m) = \frac{\delta_{\mathrm{s}}}{\{\ln[e+(\gamma/a)^n]\}^m} \tag{4}$$

Simulated by adjusting parameter *a*

linear

$$a = 0.05 + 0.00017\sigma_{\mathrm{c}} \tag{5}$$

Polynomial function

$$a = 0.045 + 0.00024\sigma_{\mathrm{c}} - 1.75*10^{-7}\sigma_{\mathrm{c}}^2 \tag{6}$$

$$\xi = \xi_{\max}(1-\delta) \tag{7}$$

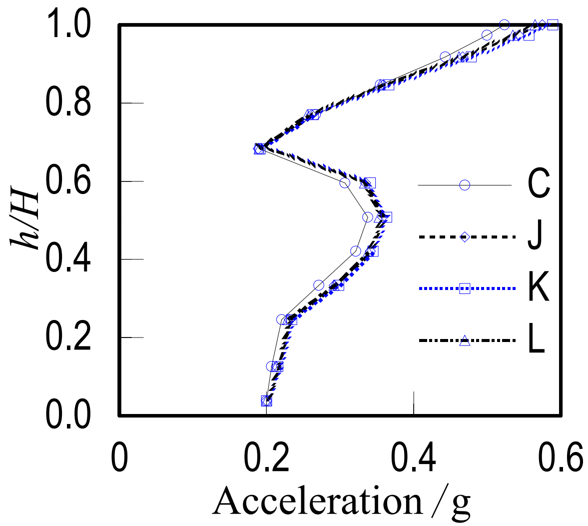
detail

Table 3. Dynamic property parameters and calculated natural frequencies for cases

Case	a	δ	ξ	Frequency (Hz)	Note
C	0.101	Test	Test	1.3456	n =0.89;
J	Eq.(6)	Eq.(4)	Eq.(7)	1.3422	m =3;
K	Eq.(6)	Eq.(4)	Test	1.3411	$\xi_{\max}$ =18%
L	Eq.(5)	Eq.(4)	Eq.(7)	1.3335	G_0=499.1

detail

Effect of Confining-Pressure-Dependency of Shear Modulus



Distribution of peak absolute acceleration in downstream slope along depth

figure

the difference between distribution of peak accelerations along depth in downstream slope and in upstream slope is noticeable. The amplification increases gradually from bottom to crest in upstream slope. However, another amplification region of acceleration occurs at the depth of 1/2H in downstream slope due to reflection of surface waves.

Some Conclusions

- (1) The effect of shear modulus on the natural frequency is stronger compared with that of damping ratio curve. The natural frequency of the equivalent linear vibration system of dam increases with increasing shear modulus. Both the initial shear modulus and modulus reduction curve have considerable influence on acceleration response spectra characteristics at the dam crest. The frequency band is narrow when the higher moduli are used. However the spectra curves is almost independent of damping ratio curve.
- (2) Peak major principal stresses of slab decreases with the increase of damping ratios of rockfills while absolute values of minor principal stresses (tensile stresses) of slab increases with decreasing modulus curve.

Some Conclusions

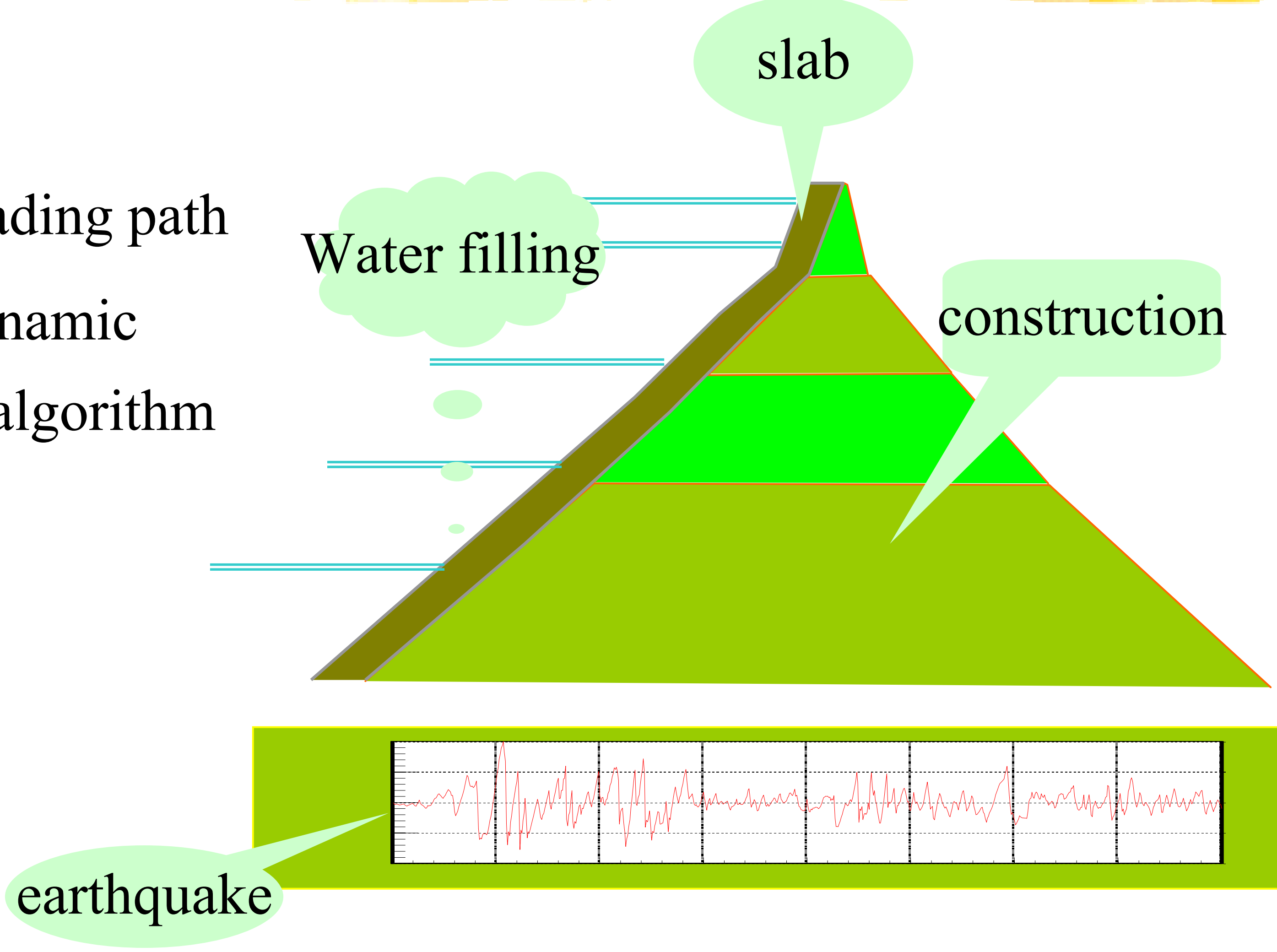
- (3) Shear strains at the dam crest increase with descending modulus curve and peak shear strains decrease with increasing damping ratios.
- (4) The effect of the dependency of shear modulus reduction curve on confining pressure on seismic response can be overlooked as usual.
- (5)Reasonable selections of dynamic parameters of rockfills should be made prudently in order to confidently evaluate earthquake-resistant behavior of CFRDs from three-dimensional equivalent-linear seismic analysis.
- (6)The three parameters equation provides a good fit for soil dynamic behavior over the wide range of shear strain.

Hypoplasticity Bounding Surface model of rockfill materials and static-dynamic incrementally-iterative algorithm for CFRD

Complex loading path

static dynamic

Model and algorithm



slab

Water filling

construction

earthquake

Acknowledgements

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