Application of rockfill dynamical characteristic statistic curve in mid-small scale concrete face dam dynamic analysis

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SUMMARY: (10 pt)
After Wenchuan earthquake, China pays more attention to earthquake resistant capability of earth and rockfill dam. The new Specifications require the first and second grade dams whose design intensity exceeds seven degrees should take dynamical analysis with FEM for earthquake resistant capability evaluation. Dynamical characteristics of soil determine the FEM results, which would be acquired by dynamic test. But because of high cost, long period and limited service, which cannot be afforded by numerous mid-small scale dams, they take analogy method. The method greatly depends on personal experience, lacking objective and accurate references. In this paper, the statistic curves of rockfill dynamic characters are established, providing references for dynamic parameters analogies. In order to examine the availability, two mid-small scale concrete face dams' dynamic parameters are determined by the statistic curves. The results of FEM indicate that dynamical responses of dams conform to general rules.

Keywords: rockfill, statistic curve, dynamical character, mid-small concrete face dam

1. INTRODUCTION

After Wenchuan earthquake, China pays more attention to earthquake resistant capability of earth and rockfill dam. The new Specifications for Seismic Design of Hydraulic Structures require that the first and second grade dams whose design intensity is higher than seven degrees should take dynamical analysis with FEM for earthquake resistant capability evaluation. Furthermore, the government announced that the existing dams should check earthquake resistant capability. As we all know that, dynamical characteristics of soil used in dam determine the FEM results, which are generally acquired by dynamic triaxial test. But because of high cost, long period and limited service, only dams higher than 150 meters in China took dynamic triaxial test before Wenchuan earthquake. Most of mid-small scale dams determined dynamical characteristics of the soil by analogy method, which greatly depends on personal experience, lacking objective and accurate references. Moreover, it is still impossible to acquire soil dynamical characteristics of all the mid-small scale dams by dynamic tests in limited period. So a more reliable and effective method should be developed. The dynamical characteristics of soil used in the earth (or rockfill) dam can be described generally by equivalent linear viscoelastic model, which contains initial dynamic elastic modulus G_0, degradation of normalized dynamic elastic modulus G/G_0-γ, and increasing of damping ratio ξ-γ. In the past several decades, many researchers studied the statistic dynamical characters of the soil. Seed and Idriss (1970) provided the ranges of shear modulus and damping ratios for cohesive soil and sand.[1] Seed et al. (1986) developed the shear modulus and damping ratios ranges of sandy and gravelly soils.[2] Rollins et al. (1998) provided gravels' best-fit curves and stand deviation bounds of both normalized shear module and damping relationships.[3] Kong et al (2001) studied equivalent dynamic shear modulus and equivalent damping ratio of rockfill used in several Chinese hydro projects using triaxial tests, combined with elastic waves measured from eight dams both in China and Japan, and proposed a formula for evaluating the maximum dynamic equivalent shear modulus and the range of both equivalent dynamic shear modulus and equivalent damping ratio of rockfill.[4] Zhang (2005) et al. conducted statistical analysis on

Resonant Column and Torsional Shear test for 122 specimens and developed predictive equations for estimating normalized shear modulus and material damping ratio.[5] On the basis of above, the author gathered dynamical characters of many rockfills used in earth (or rockfill) dam both in China and abroad recently, and developed the rockfill dynamical characteristic statistic curves, which were applied in two mid-small scale concrete face dams dynamic analysis. The results of the dynamic analysis demonstrate that the dynamical characteristic statistic curve is effective for mid-small scale concrete face dams' dynamic analysis.

2. DYNAMICAL CHARACTERISTIC STATISTIC CURVE

Since dynamical tests results of rockfill were gathered and arranged, there were generally 35 kinds of rockfill counted as specimens for statistic analysis including main rockfill, secondary rockfill, transition gravel and cushion gravel. Some of these specimens come from earth (or rockfill) dams under-constructed or constructed recently, while the others come from research production published, as shown in Fig.1 and Fig.2. All of these specimens were fitted by symmetrical logistic curve, which is grouped into best-fit curve, one standard division curves and two times standard division curves.

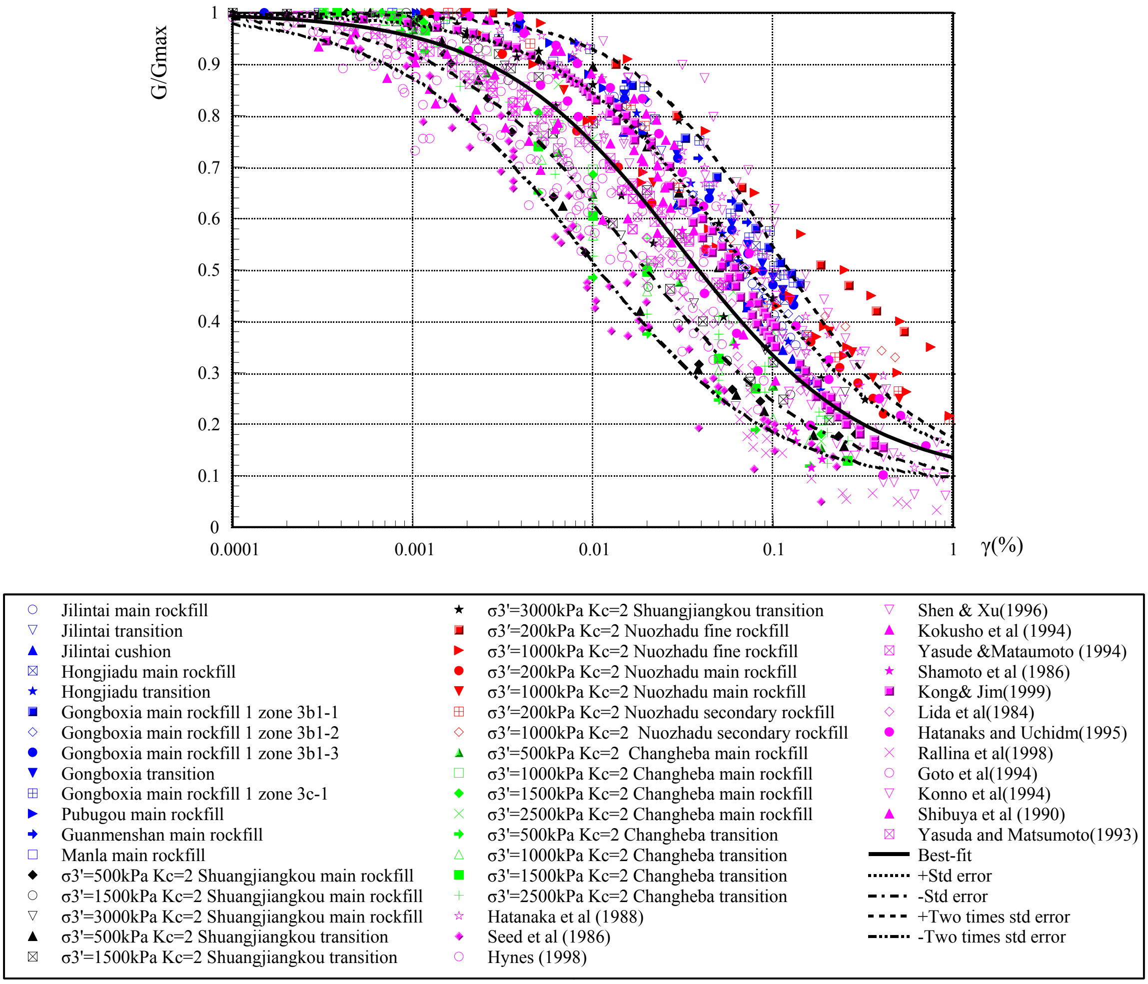


Figure 1. Data points defining G/G_0 versus γ relationships for 35 kinds of rockfills based on testing along with the best-fit curve, ± one standard division curves and two times standard division curves.

The best-fit symmetrical logistic curve and ± one and two standard division curves for these specimens are shown in Fig.1. The equation for these curves is

$$G/G_0 = b + \frac{1-b}{(1+(\frac{\gamma}{x_0})^{m})} \tag{2.1}$$

where G is dynamic shear modulus; G_0 is initial dynamic shear modulus; γ is shear strain; b is minimum G/G_0 versus γ between 10^{-6}~10^{-1}; x_0 and m are fitting parameters. The parameters values are shown in Table.1.

The statistic curves of damping ratio are shown in Fig.2. The equation for those curves is

$$\xi = A_2 + \frac{A_1 - A_2}{1 + a\gamma^{n}} \tag{2.2}$$

where ξ is damping ratio; A_1 and A_2 are maximum and minimum ξ versus γ between 10^{-6}~10^{-1} respectively; a and n are fitting parameters. The parameters values are shown in Table 2.1.

Table 2.1. Parameters For Statistic Curves

Statistic curves	b	x_0	m	A_1	A_2	a	n
Best-fit	0.09123	0.03048	0.85218	0.00819	0.26123	2.90294	0.64172
+ one standard division	0.09345	0.05809	0.89702	0.01209	0.29204	3.95345	0.65595
- one standard division	0.08424	0.01596	0.84206	0.00418	0.21802	1.97530	0.61858
+ two times standard division	0.11093	0.09673	1.08876	0.01526	0.32513	5.20375	0.68162
- two times standard division	0.07955	0.00883	0.83877	0.00076	0.18467	1.30518	0.58710

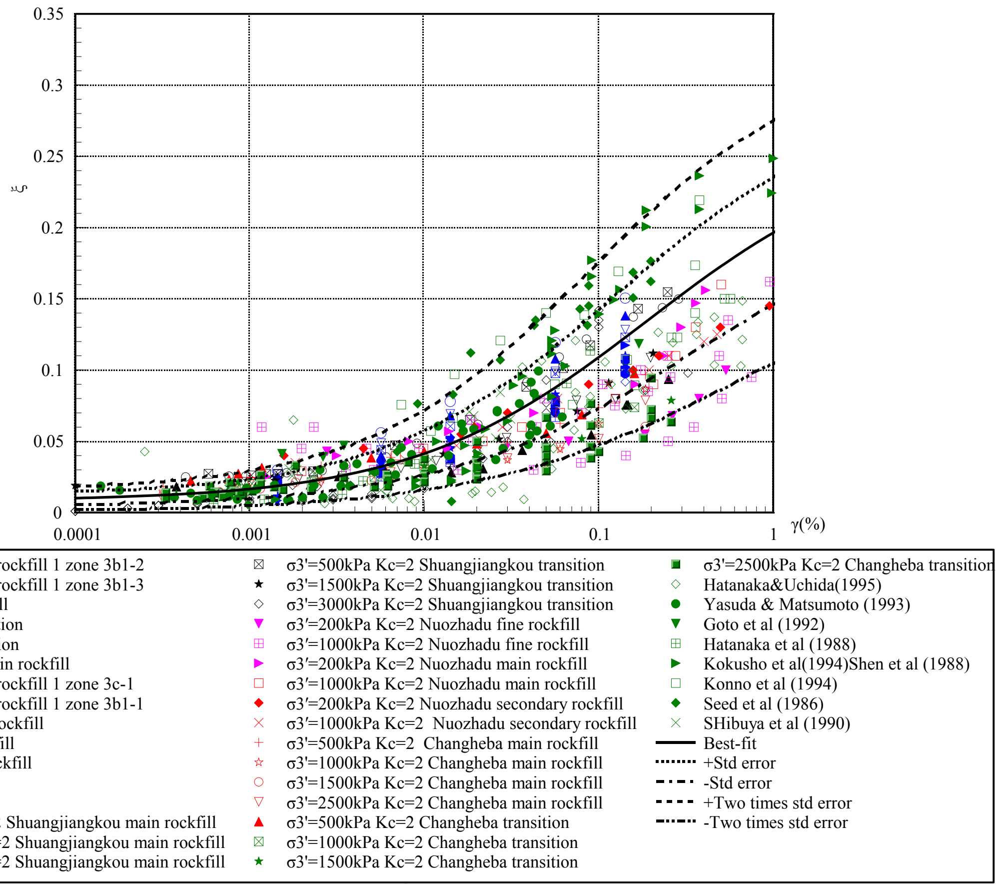


Figure 2. Data points defining ξ versus γ relationships for 35 kinds of rockfills based on testing along with the best-fit curve, ± one standard division curves and two times standard division curves.

3. APPLICATION

3.1. Introduction of projects for application

In order to examine the effect of dynamical characteristic statistic curve, dynamical characteristic curves of soil used in two constructed concreter face dams are analogized on the curve and inspected the dynamical responds of the dams. Yayangshan concrete face dam, 88m in maximum in height with total reservoir capacity of $2.47\times10^8 m^3$, is located on the Babian River, Yunnan province, China (Fig.3). Longma concrete face dam, 135m in maximum in height with total reservoir capacity of $5.986\times10^8 m^3$, is also located on the Babian River (Fig.4). The typical cross section and three dimensional mesh of Yayangshan dam are shown in Fig.5, while Longma dams' are shown in Fig.6.

Figure 3. Yayangshan concreter face dam

Figure 4. Longma concreter face dam

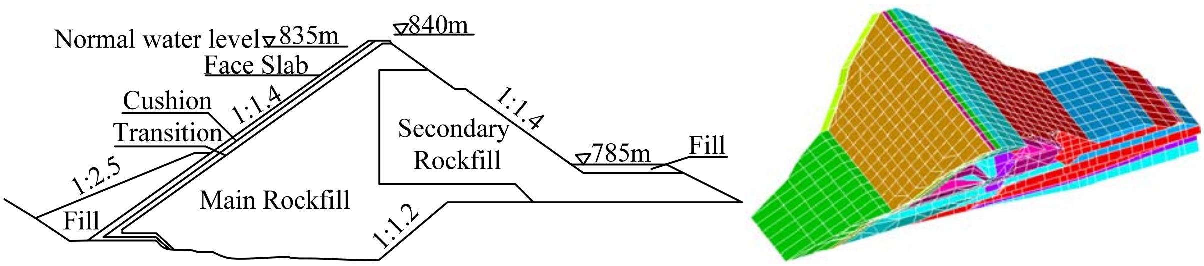


Figure 5. Typical cross section and three dimensional mesh of Yayangshan

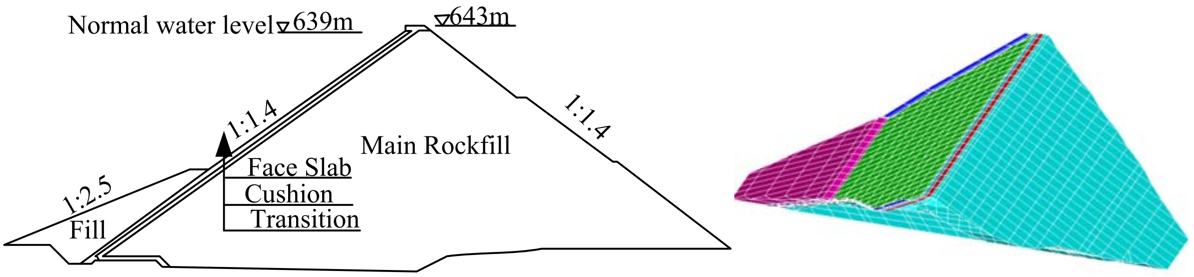


Figure 6. Typical cross section and three dimensional mesh of Longma

3.2. Constitutive model and dynamical characters of the soil used in dams

In the static analysis, the Duncan-Chang's E-B model is carried out for soil and the Goodman interface element is applied to describe interaction between face slab and cushion. The face slab is regarded as linear elastic object and slit elements are located among them in dam axis direction.

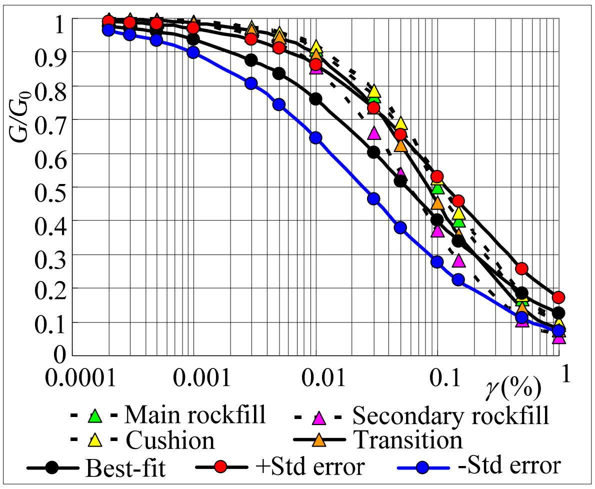
In the dynamic analysis, the equivalent nonlinear viscoelastic model is used, where the dynamic shear modulus and damping ratio can be calculated as followed

$$\frac{G}{G_0}=\frac{1}{1+k_1\gamma} \qquad \xi=\xi_{\max}\frac{k_1\bar{\gamma}}{1+k_1\bar{\gamma}} \qquad \bar{\gamma}=\frac{\gamma}{(\sigma_m/P_a)^{1-n}} \qquad G_0=k_2P_a(\frac{\sigma_m}{P_a})^n \qquad (3.1)$$

where P_a is atmosphere pressure; σ_m is average effective stress; $\bar{\gamma}$ is normalized shear strain; k_1, k_2, n, m and $\xi_{\max}$ are model parameters. The model parameters of the two concrete face dams are listed in Table 3.1. In these parameters, k_2 and n, determined according to static elastic modulus, describe dynamic shear modulus and reflect stiffness of soil. But because of the scale effect of triaxial tests and construction effect in the construction site, the static analysis results always deviate from prototype measurement. So static elastic modulus based on triaxial tests could not accurately describe stiffness of the soil used in the dam. On the other hand, the two projects have been operated for a few years and accumulate some prototype measurement data, by which more accurate static elastic modulus could be determined by parametric inversion. As the amount limitation of the paper, determination of parameters k_2 and n will be stated in another paper. Here just list the values in the Table.3.1. The $G/G_0\sim\gamma$ curve and $\xi\sim\gamma$ curve of the soil used in Yayangshan and Longma are shown in Fig.7 and Fig.8 respectively. As Fig.7 and Fig.8 are shown that, the $G/G_0\sim\gamma$ curves are determined incorporating that arrangement of soil from top to bottom are cushion, transition, main rockfill and secondary rockfill, and that all curves are restricted in the range of one standard division curves. On the other hand, the $\xi\sim\gamma$ curves should be determined mainly incorporating that all curves are restricted in the range of one standard division curves, and it should be made sure that the damping verse shear strain at 1% is less than 0.25, which is the largest damping in Fig.2. $\xi_{\max}$ is chosen based on the material of the soil, incorporating the influence of weathering.

Table 3.1. Parameters For Dynamical Characters

Materials	Yayangshan				Longma			
	k_1	k_2	n	$\xi_{\max}$	k_1	k_2	n	$\xi_{\max}$
Main rockfill	20	1500	0.55	0.18	25	2760	0.204	0.2
Secondary rockfill	28	900	0.59	0.15	\	\	\	\
Cushion	9	1800	0.50	0.28	12	2503	0.305	0.19
Transition	12	1400	0.56	0.24	18	1455	0.324	0.17
Fill	28	900	0.59	0.15	25	2760	0.204	0.2



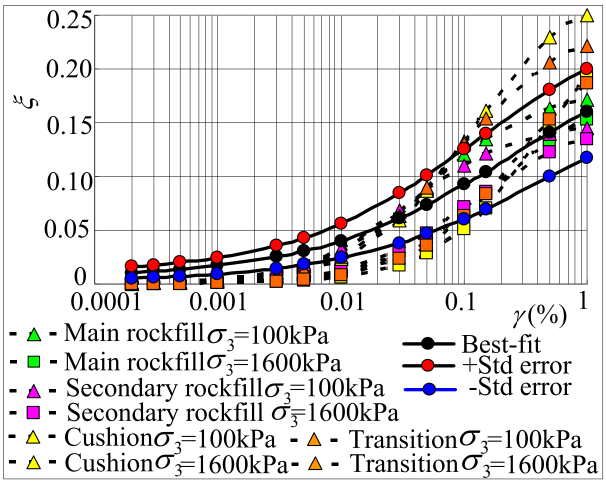


Figure 7. The $G/G_0\sim\gamma$ curve and $\xi\sim\gamma$ curve of the soil used in Yayangshan

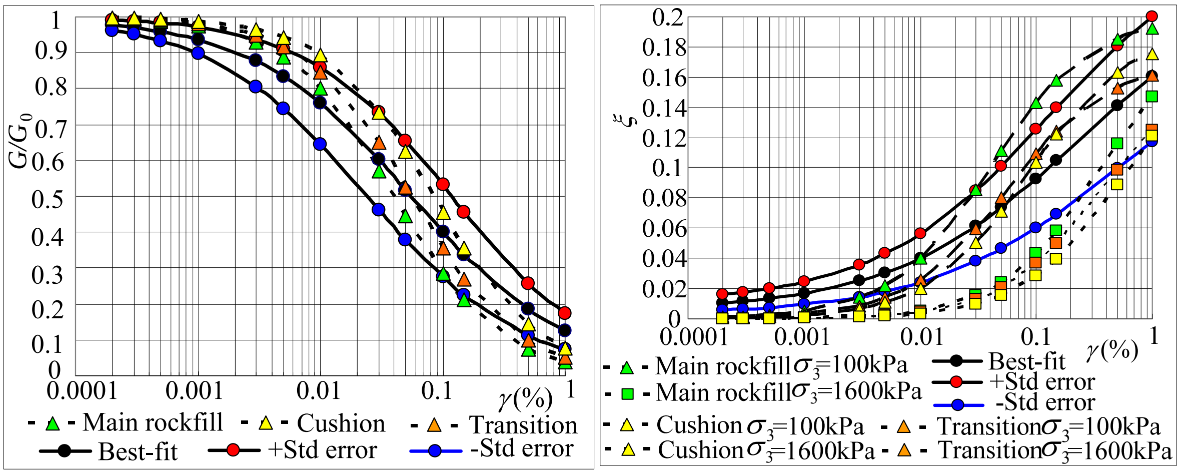
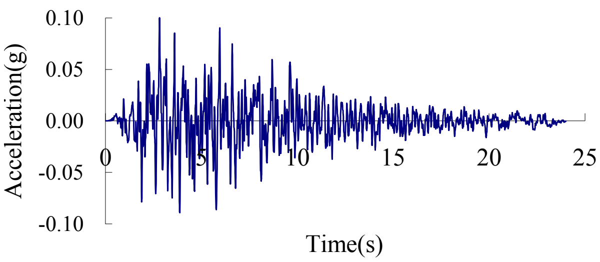


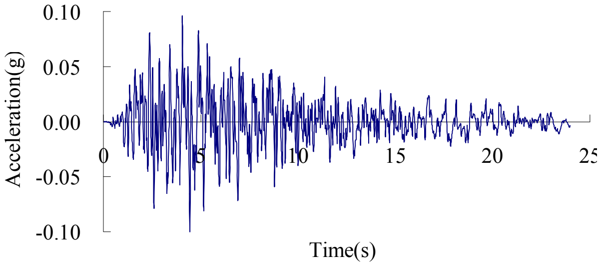
Figure 8. The $G/G_0 \sim \gamma$ curve and $\xi \sim \gamma$ curve of the soil used in Longma

3.2. Earthquake excitation

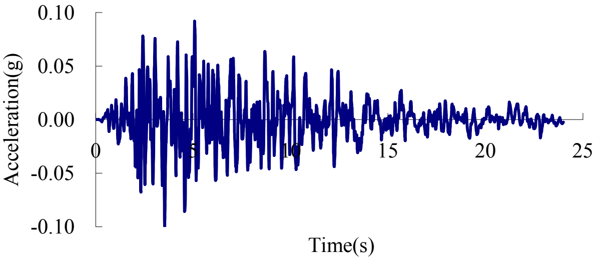
According to the geological inspection, the design earthquake of Yangyashan dam with intensity of 5% transcendental probability for 50 years is 7 degree, and the peak acceleration of ground motion is 101gal. The Longma suffers a design earthquake whose intensity with a 10% transcendental probability for 100 years and the peak acceleration of ground motion is 101gal. The earthquake accelerations of the two dams are applied in upstream-downstream direction, dam axis direction and vertical direction, which are shown in Fig.9 and Fig.10 respectively.



(a) upstream-downstream direction

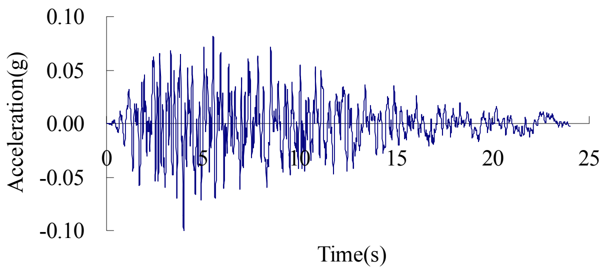


(b) dam axis direction

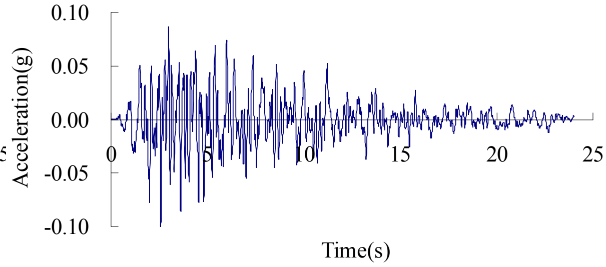


(c) vertical direction

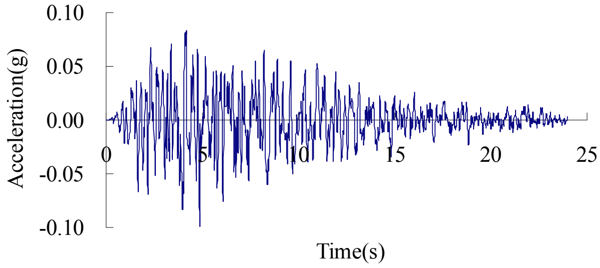
Figure 9. Design earthquake of Yangyashan



(a) upstream-downstream direction



(b) dam axis direction

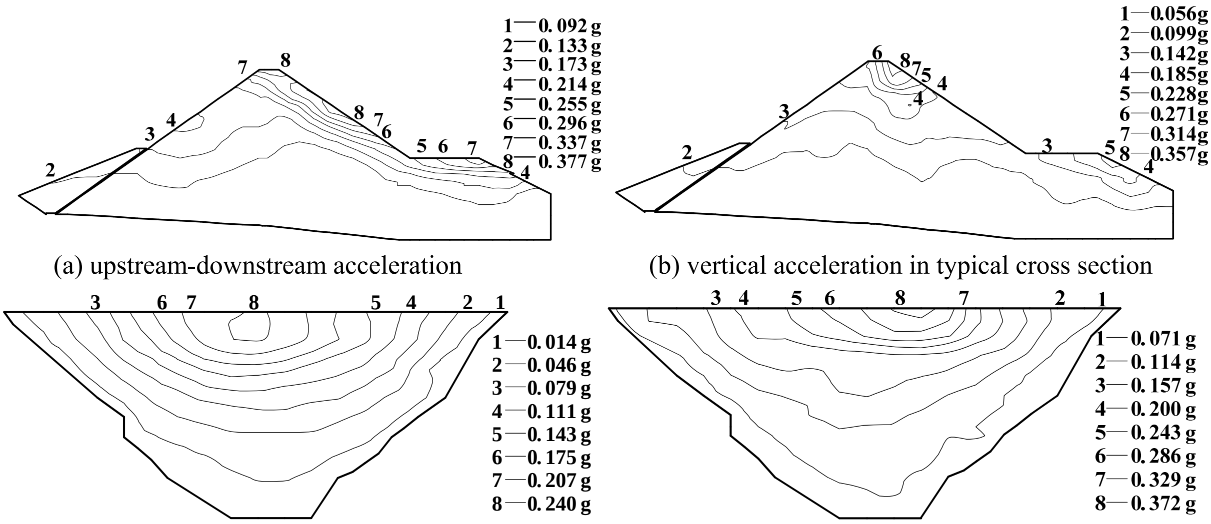


(c) vertical direction

Figure 10. Design earthquake of Longma

3.2. Earthquake response of the dam

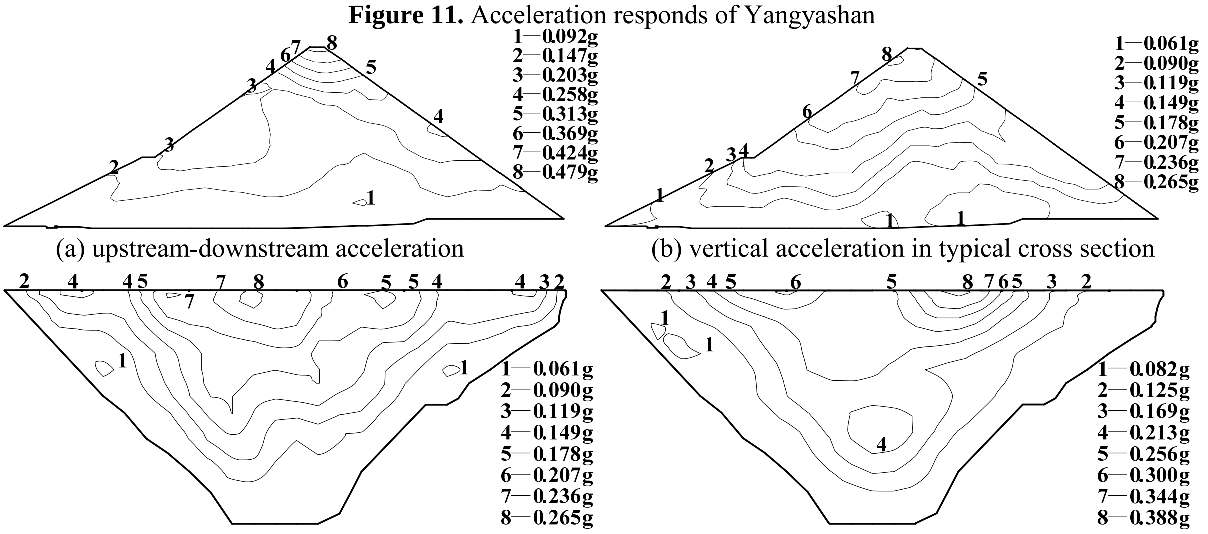
In the processes of construction and impounding, static analysis of the dams is carried on to obtain stress state of soil before dynamical analysis. The design earthquake time-step in calculation is 0.02s, and the value of acceleration in vertical direction is cut down to two thirds. The acceleration responses of Yayangshan are shown in Fig.11, while Longma's are shown in Fig.12. As the responses are shown



(a) upstream-downstream acceleration (b) vertical acceleration in typical cross section

(c) vertical acceleration in dam axis cross section (d) dam axis acceleration

Figure 11. Acceleration responds of Yangyashan

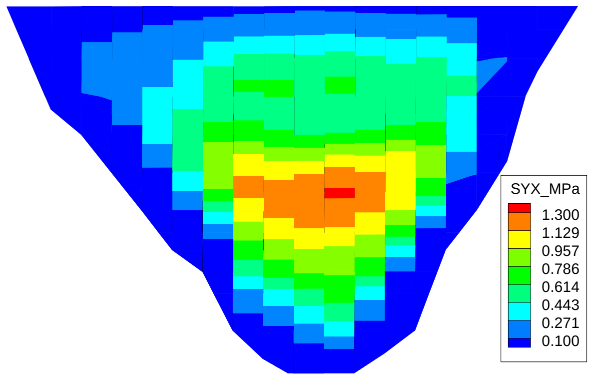


(a) upstream-downstream acceleration (b) vertical acceleration in typical cross section

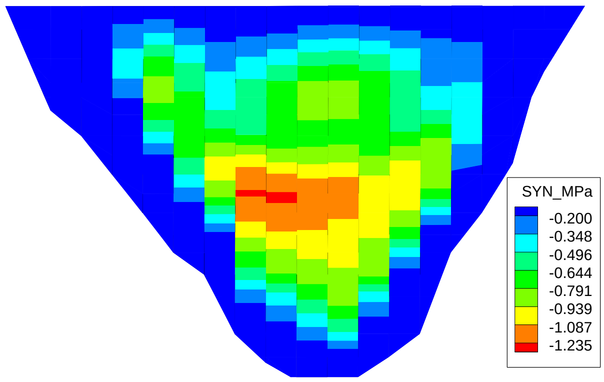
(c) vertical acceleration in dam axis cross section (d) dam axis acceleration

Figure 12. Acceleration responds of Longma

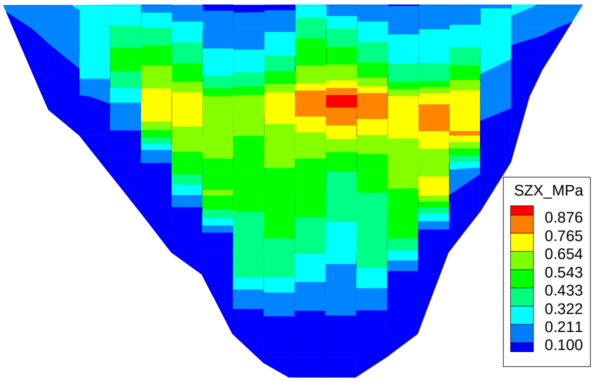
that, the maximum accelerations in every direction of the two dams locate on the top of dams, according with general rules. The maximum accelerations of Yayangshan are 0.377g, 0.357g and 0.372g in the upstream-downstream direction, vertical direction and dam axis direction respectively, while the values of Longma are 0.479g, 0.265g and 0.388g, larger than Yayangshan's in upstream-downstream direction and dam axis direction, and smaller in vertical acceleration. Although the Yayangsha dam is 88m in maximum height, lower than Longma dam, which is 135m in maximum height, yet k_2 and n of Yayangshan are less than Longma. So the Longma dam is firmer than Yayangshan as a whole, and gets larger acceleration. But as Fig.5 shows that, Yayangshan locates on a higher weathering foundation; it equally reduces the height of dam and results in a higher vertical acceleration. The maximum stress responses of face slab are shown in Fig 13 and Fig 14. As the



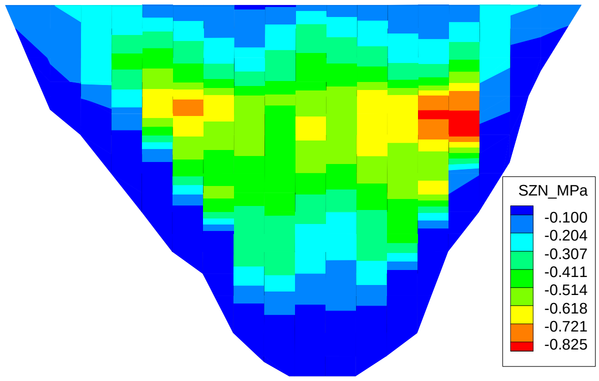
(a) maximum compress stress along dam slop



(b) maximum tensile stress along dam slop

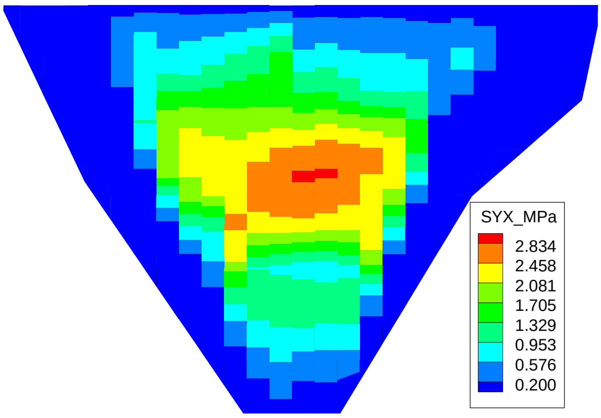


(c) maximum compress stress along dam axis

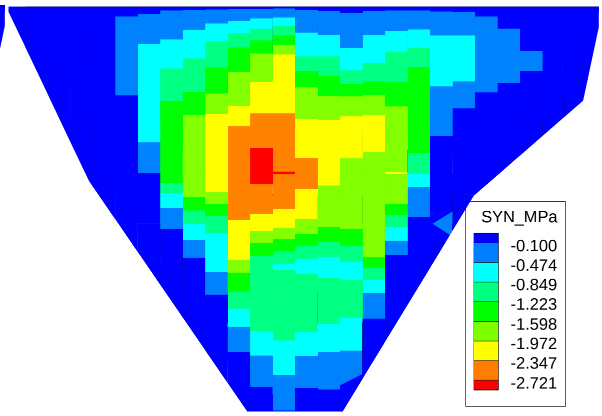


(d) maximum tensile stress along dam axis

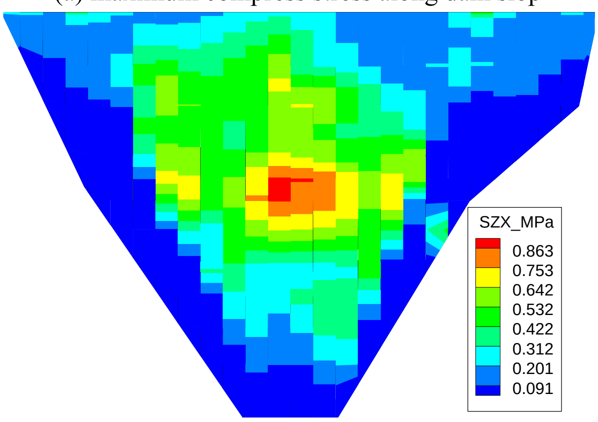
Figure 13. Maximum stress response of face slab distribution of Yangyashan



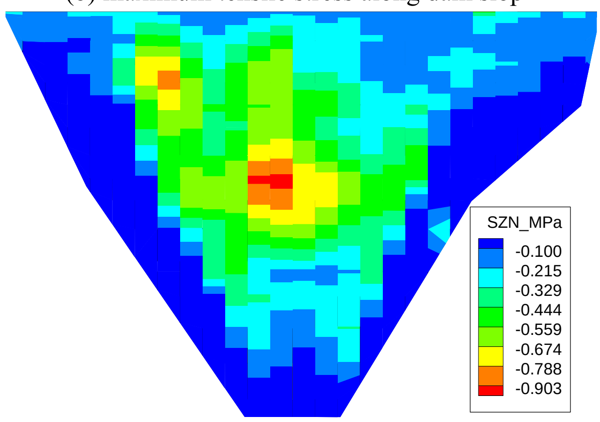
(a) maximum compress stress along dam slop



(b) maximum tensile stress along dam slop



(c) maximum compress stress along dam axis



(d) maximum tensile stress along dam axis

Figure 13. Maximum stress response of face slab distribution of Longma

responses show that, the maximum stress values of the face slab in two dams locate on the middle area. The maximum compress stress and tensile stress are almost equal, and stress along dam slop is larger than dam axis with slit decreasing, which accords to general rules. As the Longma dam is higher, the face slab gets larger dynamical load generated by water, and the face slab stress is larger than Yayangshan. But as Fig.5 and Fig.6 show that, Longma face slab gets more slits than Yayangshan, which results in that the stress difference in dam axis is smaller than that in dam slop.

COCLUSION

According to dynamical characteristic statistic curve, the $G/G_0 \sim \gamma$ curve and $\xi \sim \gamma$ curve of the soil used in two mid-small scale concrete face dams are determined, by which the dynamical analysis are carried on. The dynamical responses of the two dams accord with general rules, indicating that the dynamical characteristic statistic curve is effective. But there is still some questions needing to be resolved, such as methods for quantificational analogy of dynamical characters according to statistic curves, statistic relationship between $G/G_0 \sim \gamma$ curve and $\xi \sim \gamma$ curve, relationship between soil material and dynamical characters, weathering and particle grading influences on dynamical parameters. But the dynamical tests results collected are still limited, and some of tests results are short of $\xi \sim \gamma$ curve and others lacking of $G/G_0 \sim \gamma$ curve, let alone material and weathering information and so on. Nevertheless, we believe it would be resolved with proceeding of research and accumulating of dynamical tests data of the soil.

REFERENCES

Seed H B, Idriss I M. (1970) Soil Moduli and Damping Factors for Dynamic Response Analysis[R]. U.C. Berkeley,Calif.: EERC.

Seed H B, Wong R T, Idriss I M, et al. (1986) MODULI AND DAMPING FACTORS FOR DYNAMIC ANALYSES OF COHESIONLESS SOILS. *Journal of geotechnical engineering* 112:11,1016-1032.

Rollins K M, Evans M D, Diehl N B, et al. (1998). Shear modulus and damping relationships for gravels. *Journal of Geotechnical and Geoenvironmental Engineering.* 124:5,396-405.

Xian-Jing K, Shulian L, De-Gao Z. (2001). The equivalent dynamic shear modulus and equivalent damping ratio of rockfill material for dam. *JOURNAL OF HYDRAULIC ENGINEERING* 08,20-25.

Zhang J, Andrus R D, Juang C H. (2005) Normalized shear modulus and material damping ratio relationships. *Journal of Geotechnical and Geoenvironmental Engineering* 131:4,453-464