Dynamic Centrifuge Modelling Tests for Asphalt Concrete Core Dam

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Abstract. Dynamic centrifuge modelling tests are carried out to study the seismic behaviour of a sand-gravel dam with asphalt concrete core wall. The acceleration response, deformation, core wall stress and stability are analysed under design and check seismic intensity. The crest acceleration amplification factor is 2.7~3.0. The crest settlement rate is 0.442% and 0.481%, respectively under design and check intensity. Maximum seismic stress is recorded in core wall of 2/3~4/5 dam height. Under design intensity, failure cracks appear in crest and upstream dam revetment at water level. Under check intensity, more cracks are found. Furthermore, landslide occurs in upstream slope above 2/3 dam height under check intensity. Downstream slope is stable. No evident separation is observed between dam shell materials and core wall. The dam is unstable under design and check earthquake. Aseismic measures are necessary according to test results.

1. Introduction
Sand-gravel dam with asphalt concrete core wall is employed in a hydropower project. The maximum dam height is 129 m. The dam zone of the project is with high earthquake intensity. The design aseismic intensity is IX degrees. It is necessary to study the seismic response, deformation, core wall stress and stability by means of dynamic centrifuge modeling tests.

2. Dynamic centrifuge modelling tests
The technique of centrifuge shaking table has been developed since around 1980 for dynamic centrifuge modeling test of earthquake problems[1]. The use of dynamic centrifuge modelling tests is particularly important for hydraulic engineering as it offers high gravity field for scaled models by centrifuge and earthquake loading using a centrifuge shaking table in flight. The technique has been recognized as one of the most effective and advanced research methods[2]. Dynamic centrifuge modeling tests has shown its advantages in research of dam seismic failure mode, aseismic design and numerical model verification, etc.[3-6].

2.1 Similarity laws
The similarity laws for dynamic centrifuge modeling are shown in table 1[7]. according to the third law of similarity theory and based on the similarity laws for shaking table test. η is defined as scaling factor of model to prototype for parameters.
Table 1. Similarity laws of dynamic centrifuge modelling

| Symbol | Parameter            | Dimension | Centrifuge model |
|--------|----------------------|-----------|------------------|
| $L$    | Length               | $L$       | $\eta_l$        |
| $\rho$ | Density              | $ML^{-3}$ | $\eta_\rho$     |
| $g$    | Acceleration         | $LT^{-2}$ | $\eta_g$        |
| $C$    | Modulus              |           | $\eta_C$        |
| $\sigma$ | Stress              | $ML^{-1}T^{-2}$ | $\eta_\sigma=\eta_l\eta_\rho\eta_g$ |
| $E$    | Elasticity modulus   | $ML^{-1}T^{-2}$ | $\eta_E=\eta_l^{1/2}\eta_\rho^{1/2}\eta_g^{1/2}\eta_C$ |
| $c$    | Cohesion             | $ML^{-1}T^{-2}$ | $\eta_c=\eta_l\eta_\rho\eta_g$ |
| $\phi$ | Friction angle       |           | $\eta_\phi=1$   |
| $\varepsilon$ | Strain               |           | $\eta_\varepsilon=\eta_l^{1/2}\eta_\rho^{1/2}\eta_g^{1/2}\eta_C^{-1}$ |
| $u$    | Displacement         | $L$       | $\eta_u=\eta_l^{3/4}\eta_\rho^{1/4}\eta_g^{3/4}\eta_C^{-1/2}$ |
| $v$    | Velocity             | $LT^{-1}$ | $\eta_v=\eta_l^{3/4}\eta_\rho^{1/4}\eta_g^{3/4}\eta_C^{-1/2}$ |
| $k$    | Coefficient of permeability | $LT^{-1}$ | $\eta_k=\eta_l^{3/4}\eta_\rho^{1/4}\eta_g^{3/4}\eta_C^{-1/2}$ |
| $T$    | Time                 | $T$       | $\eta_T=\eta_l^{3/4}\eta_\rho^{1/4}\eta_g^{3/4}\eta_C^{-1/2}$ |
| $f$    | Frequency            | $T^{-1}$  | $\eta_f=\eta_l^{3/4}\eta_\rho^{1/4}\eta_g^{3/4}\eta_C^{-1/2}$ |
| $\xi$  | Soil damping ratio   |           | $\eta_\xi=1$     |

2.2 Facilities
The tests are carried out in Nanjing Hydraulic Research Institute (NHRI). The NHRI-400gt large centrifuge and its shaking table are engaged. The centrifuge has a maximum radius of 5.5 m and can accelerate a maximum payload of 2000 kg up to 200 g. Indexes of the shaking table are as table 2. Inner space of the model container is 700 mm long, 350 mm wide and 650 mm high.

Table 2. Indexes of centrifuge shaking table

| Centrifugal acceleration | Seismic acceleration | Payload | Duration | Frequency | Wave mode      | Direction |
|--------------------------|----------------------|---------|----------|-----------|----------------|-----------|
| 80 g                     | 20 g                 | 500 kg  | 3 s      | 20~200 Hz | Sinusoid, Site wave, Random | Horizontal |

2.3 Modelling tests
In centrifuge modeling, $\eta_l$ is normally equal to $1/\eta_g$, meaning that the prototype gravity field is fully modelled. Here the prototype dam is too large to be fully scaled in any centrifugal shaking table in the world. Therefore $\eta_l$ is not equal to $1/\eta_g$ and the prototype gravity field is partially simulated. Also reasonable simplification is made.

2.3.1 Mosel setup. The section of maximum dam height is partly simulated. The berms are ignored and dam shell material is treated as uniform. The model is scaled in 1/450 and centrifugal acceleration is 40 g. 2 tests of the same model setup (figure 1) are carried out, under design ($P_{50}=2\%$) and check ($P_{100}=2\%$) seismic intensity respectively. The peak acceleration is 516.5 gal and 643.3 gal for design and check intensity.
2.3.2 **Dam material simulation.** The maximum size is 40 mm for model dam material considering scale effect of footings and boundary effect in centrifuge modelling [8]. Model dam material is simulated according to Specification of soil test: SL237—1999 [9].

2.3.3 **Core wall and revetment simulation.** The thickness is 700~1400 mm and modulus is 500 MPa of prototype asphalt concrete core wall. Model core wall is a perspex sheet of 1.2 mm thick and its modulus is 2.3 GPa. Thus the flexural rigidity ratio meets the similarity laws. The model revetment is a thin layer of plain concrete.

3. **Analysis of test results**

All given results are converted to prototype according to similarity laws.

3.1 **The acceleration response**

Figure 2 gives recorded and aim waves at basement for design and check earthquake. The peak acceleration is 516.5 gal and 643.3 gal of aim waves. The recorded peak acceleration is 501.9 gal and 523.1 gal for design earthquake. The recorded peak acceleration is 645.0 gal and -645.0 gal for check earthquake. Also the frequency responses are satisfying. The shaking table simulates the earthquakes accurately.

![Figure 2. Recorded and aim waves (left for design and right for check earthquake)](image)

Figure 3 shows peak acceleration and amplification factor profiles at dam axis. Table 3 gives detailed data. \( H \) is the dam height and \( h \) is the height of acceleration transducer to basement.

The acceleration increases with elevation in dam body under input earthquake loading. The acceleration amplification effect is obvious. The acceleration response of the dam can be divided into 2 linear lines at 2/3 dam height. The acceleration amplification effect is stronger for the upper part of dam body. The acceleration amplification factor is lower for the stronger earthquake. The crest acceleration amplification factor is about 2.7~3.0.
Figure 3. Acceleration amplification effect at dam axis

Table 3. Acceleration response data at dam axis

| Elevation/m | h/H | Peak acceleration /gal | Amplification factor | Peak acceleration /gal | Amplification factor |
|-------------|-----|-------------------------|----------------------|-------------------------|----------------------|
| 2176        | 0   | 501.937                 | 1                    | 646.388                 | 1                    |
| 2202.4      | 0.20| 680.152                 | 1.355                | 839.462                 | 1.299                |
| 2224.8      | 0.38| 783.289                 | 1.560                | 1034.831                | 1.601                |
| 2246.9      | 0.55| 924.614                 | 1.842                | 1178.099                | 1.822                |
| 2269.8      | 0.73| 1185.229                | 2.361                | 1387.335                | 2.146                |
| 2290.1      | 0.89| 1362.938                | 2.715                | 1628.741                | 2.520                |

3.2 The crest settlement

Figure 4 shows the crest settlement development under design and check earthquake. It is obvious from the data that the crest settlement waves and increases with earthquake wave and tends to be stable. The stronger the earthquake is, the larger settlement is recorded. The crest settlement is 568 mm and 618 mm, and the settlement rate is 0.442% and 0.481%, respectively under design and check seismic intensity.

Figure 4. Crest settlement during earthquake (left for design and right for check intensity)

3.3 The seismic stress of core wall

Figure 5 is a typical core stress curve. Figure 6 shows the core stress profiles after earthquake. Some text.

Maximum seismic stress is recorded in core wall of 2/3–4/5 dam height. The maximum seismic tensile stress during and after design earthquake is 232 kPa and 192 kPa, respectively. The maximum seismic tensile stress during and after check earthquake is 501 kPa and 474 kPa, respectively.
Figure 5. Typical core stress curve

Figure 6. Core stress profiles after earthquake

3.4 The seismic failure mode

Figure 7 and figure 8 show model dams after design and check earthquake.

Figure 7. Cracks in upstream revetment and crest (left for design and right for check earthquake)

Figure 8. Material settlement (left for design and right for check earthquake)

Under design intensity, failure cracks appear in crest and upstream dam revetment at water level. Under check intensity, more cracks are found. Furthermore, landslide occurs in upstream slope above 2/3 dam height. Downstream slope is stable. No evident separation is observed between dam shell materials and core wall. The seismic failure mode is mainly the separation between upstream revetment and rockfill material induced by settlement, causing revetment to crack or even collapse. The dam is unstable under design and check earthquake.
4. Conclusions
According to test data analysis, conclusions are as follows.

(1) The acceleration increases with elevation in dam body under input earthquake loading. The acceleration amplification effect is obvious. The acceleration response of the dam can be divided into 2 linear lines at 2/3 dam height. The acceleration amplification effect is stronger for the upper part of dam body. The acceleration amplification factor is lower for the stronger earthquake. The crest acceleration amplification factor is about 2.7~3.0.

(2) The crest settlement waves obviously during earthquake. The settlement increases and tends to be stable. The stronger the earthquake is, the larger settlement is recorded. The crest settlement is 568 mm and 618 mm, and the settlement rate is 0.442% and 0.481%, respectively under design and check seismic intensity.

(3) Maximum seismic stress is recorded in core wall of 2/3~4/5 dam height. The maximum seismic tensile stress during and after design earthquake is 232 kPa and 192 kPa, respectively. The maximum seismic tensile stress during and after check earthquake is 501 kPa and 474 kPa, respectively.

(4) Under design intensity, failure cracks appear in crest and upstream dam revetment at water level. Under check intensity, more cracks are found. Furthermore, landslide occurs in upstream slope above 2/3 dam height. Downstream slope is stable. No evident separation is observed between dam shell materials and core wall.

(5) The seismic failure mode is mainly the separation between upstream revetment and rockfill material induced by settlement, causing revetment to crack or even collapse.

(6) Aseismic measures are necessary under design and check seismic intensity.

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