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Analytical and experimental investigation of dynamic behaviour of rock-fill dam model

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ABSTRACT: For the purpose of determination of the dynamic behaviour of rock-fill dam structures under the effect of strong earthquakes and to define the failure mechanisms for them, analytical and experimental investigations of a fil-dam model has been carried out. First, the physical model of the dam was designed applying dimensional analysis as well as preliminary mathematical analyisis in order to obtain approximate values of some physical values, relevant for the construction of the model. On the basis of a series of laboratory tests, it was obtained the material having physcal and mechanical properties most adequente for construction of the model. The process of the dynamic shaking table testing of the physical model was performed in several phases, applying several types of real earthquake motions. According to the instrumental data, as well as the visual effects observed during testing, some conclusions have been drawn on the model behaviour under the effect of strong earthquakes. These conclusions, with some limitations, could be applied to the real structure, i.e., the prototype.

1. INTRODUCTION

Considering the importance of the fill-material structures, particularly fill dam type structures, they have been paid significant attention lately. Their behaviour under the effect of strong earthquakes is of special importance, since their heavier damage or failure causes tremendous material damages and losses of human lives. Consequently, the basic task of design engineers is to provide proper design of such structures, which will ensure sustaining of strongest earthquake effects without damage, i.e., with minimum damage.

During the last decade, the problem of the dynamic behaviour of these structures has been sufficiently studied theoretically. Unlike theoretical studies, experimental studies are very few, model testing of such types of structures even fewer, since it is elated to the specific nature of the material for model construction as well as the specific equipment and instrumentation required for such tests performance.

In order to extend the existing and to attain new knowledge on the dynamic behaviour of rock-fill dams and to define the possible failure mechanisms, within the scope of a wider scientific and research project, shaking table model testing of a rock-fill dam has been carried out at the Dynamic Testing Laboratory of the Institute of Earthquake Engineering and Engineering Seismology, Skopje, Macedonia. The physical

Table 1. Physical values and dimensions.

No.	Physical values	Symbol	Dimension
1.	Linear dimension of structure	D	L
2.	Gravity acceleration	g	LT^{-2}
3.	Bulk density of material	γ	$(ML^{-2}T^{-2})$
4.	Bulk density of fluid	γ'	$(ML^{-2}T^{-2})$
5.	Inertial force	P	(MLT^{-2})
6.	Modulus of elasticity	E	$(ML^{-1}T^{-2})$
7.	Compressive strength of material	S	$(ML^{-1}T^{-2})$
8.	Viscous damping coefficient	C	(MT^{-1})
9.	Coefficient of friction	μ	1

model is characterized by loose fill of sand and small grain stones of different shape and size. The dam model was constructed according to the design of a real dam to be constructed in future.

2. DESIGN OF FILL MATERIAL DAM MODEL APPLYING DIMENSIONAL ANALYSIS

Considering the material to be used for the construction of these models, the design of such a model is a complex and time consuming process.

First, it was necessary to determine the relationships between the model and the prototype with respect to their proportions, the material properties and the loads. In this case the best way is the method of dimensional analysis by means of which it is possible to come to the general relationships without relating to the actual vibration equations, when these relationships would apply to any structural vibration problem, whose general values are already entered in the dimensional analysis. The main equation for a system in dynamic equilibrium condition

$$f(D, g, \gamma, \gamma', P, E, S, C, \mu) = 0 \qquad (1)$$

applying the Buchingham's theorem can be transformed into dimensionless form as

$$F(\Pi_1, \Pi_2, \Pi_3, \Pi_4, \Pi_5, \mu) = 0 \qquad (2)$$

The dimensionless Π values are expressed through previously adopted quantities, in the considered case the line dimension D, the acceleration due to gravity g and the bulk density of the material γ. The physical meaning of the values given in equation (1) is given in Table 1.

Assuming the dam model in scale $Dm/Dp=\lambda$, the relationship of the bulk densities $\gamma_m/\gamma_p=\alpha$ and that it is tested under normal gravity conditions, i.e., $g_m/g_p=1$, using the expressions for the corresponding, Π values, the relationships for the different physical values of the model and prototype are determined, as presented in Table 2.

3. CONSTRUCTION OF PHYSICAL MODEL OF DAM

On the basis of the relationships between some physical quantities of the model and prototype, obtained by dimensional analysis, the most adequate scale and material to be used for construction of the model were selected.

During the determination of the most appropriate scale several alternative models were considered, taking care that the outline of the selected model does not exceed the size of the dynamic testing shaking table (5m x 5m) as well as that its weight together with the modelled terrain and part of the water reservoir do not exceed its maximum bearing capacity of 400 Mp. Having in mind these limitations, the most appropriate scale length was determined to be 1:100 (Fig. 1).

The selection of the materials for construction of the model dam body as well

Table 2. Relationship between values of model and prototype

No.	Physical value	Relationship	Value
1.	Linear dimension of structure	D_m/D_p	λ
2.	Bulk density of material	γ_m/γ_p	α
3.	Gravity acceleration	g_m/g_p	1.0
4.	Special weight of fluid	γ'_m/γ'_p	α
5.	Inertial force	P_m/P_p	$\lambda^3\alpha$
6.	Modulus of elasticity	E_m/E_p	$\lambda\alpha$
7.	Compressive strength of material	S_m/S_p	$\lambda\alpha$
8.	Viscous damping coefficient	C_m/C_p	$\lambda^{5/2}\alpha$
9.	Coefficient of friction	μ_m/μ_p	1.0
10.	Acceleration	a_m/a_p	1.0
11.	Velocity	V_m/V_p	$\lambda^{1/2}$
12.	Time (period of vibration	T_m/T_p	$\lambda^{1/2}$
13.	Frequency	f_m/f_p	$\lambda^{-1/2}$
14.	Shear modulus	G_m/G_p	$\lambda\alpha$
15.	Stress	σ_m/σ_p	$\lambda\alpha$
16.	Unit deformation	$\varepsilon_m/\varepsilon_p$	1.0
17.	Displacement	δ_m/δ_p	λ
18.	Rigidity P/g	K_m/K_p	$\lambda^2\alpha$
19.	Mass P/g	M_m/M_p	$\lambda^3\alpha$
20.	Cross-section area	A_m/A_p	λ^2
21.	Moment of inertia of section	I_m/I_p	λ^4

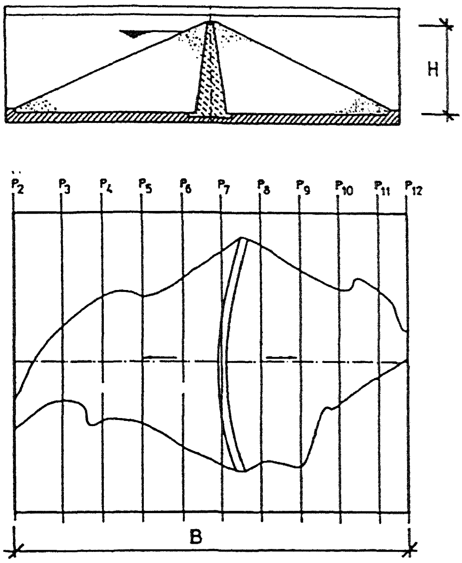

Figure 1. Cross-section and plan of rock-fill dam model.

Table 3. Main characteristics of the model, i.e., prototype.

Physical quantities	Prototype	Model
Height (H)	126 m	1.26 m
Crest length (L)	300 m	3.00 m
Foot length (B)	500 m	5.0 m
Elasticity modulus(E)	2000 MPa	16.8 MPa
Sliding modulus (G)	734 MPa	6.15 MPa
Bulk density (γ)	20.0 KN/m^3	19.8 KN/m^3

as the central clay core was performed based on a series of laboratory tests of the physical and mechanical properties of these types of materials, such as sands, varying grain size stone detritus and several mixtures of sands and detritus. During this selection, care was taken to satisfy the relationships of the sliding modulus G and the bulk density γ, i.e., the density ρ, as the main parameters, which ensures a realistic interpretation of the strength characteristics between the model and the prototype as well as a realistic simulation of the seismic inertial forces.

The main proportions of the model and prototype as well as the corresponding material properties are shown in Table 3.

On the basis of the so determined values for the construction materials of the dam model, as well as the remaining physical quantities, Table 1, preliminary mathematical analysis of the model has been carried out in order to obtain approximate data for its dynamic behaviour, which is very important for further organization of the testing as well as for determination of the most appropriate type of testing equipment and instrumentation set-up.

4. SHAKING TABLE TESTING OF FILL DAM MODEL

The main objective of this testing was to obtain some knowledge on the dynamic behaviour of an actual dam, which is going to be constructed soon, as well as to determine its dynamic response under the effect of various intensity earthquakes. It was of particular interest the behaviour of the model under the effect of an earthquake with an intensity up to 0.3g, accepted as design earthquake, as well as the behaviour of the model for the expected maximum probable earthquake of 0.46g, which are criteria, accepted during the design of the actual structure.

In order to obtain the most possible volume of information relevant to the dynamic behaviour of the model, a set of accelerometers and displacement transducers were distributed at characteristic points of the model. Most of these instruments were placed at the dam crest and the downstream slope. For data recording during the testing, a 32 channel data acquisition system installed as a peripheral sub-system within the existing computer center was used.

The testing was performed in several phases. First, determination of the dynamic characteristics, resonance frequencies and vibration mode shapes of the model was performed using low intensity harmonic excitation. The next step was testing the model under the seismic effect of various intensity earthquakes. Several real earthquake motion records were applied: El Centro, Bregin, Ulcinj, Petrovac, sufficiently "dense" to comply with the requirements of the similitude theory.

5. EXPERIMENTAL RESULTS OBTAINED BY DYNAMIC TESTING MODEL

The experimentally obtained fundamental resonance frequency (Fig. 2) and the corresponding mode shape (Fig. 3), show very good correlation with the analytically obtained results.

The tests with the earthquake effects have showed that slight and moderate earthquake, up to 0.20g, have not practically any effect, i.e., not any changes were observed on the tested model. For an excitation level of up to 0.30g, design level, no cracks to the model or slope sliding was observed, which means that for this excitation level the model behaves still in elastic range.

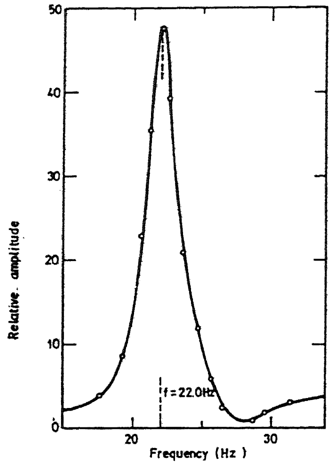

Figure 2. Resonance frequency curve of model.

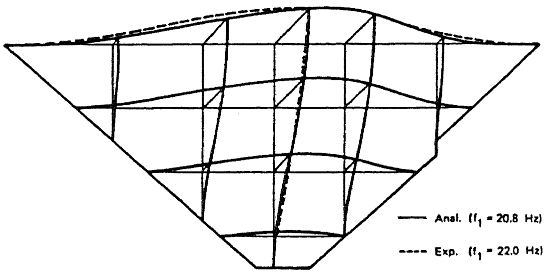

Figure 3. First vibration mode shape of model determined in an analytical, i.e., experimental way.

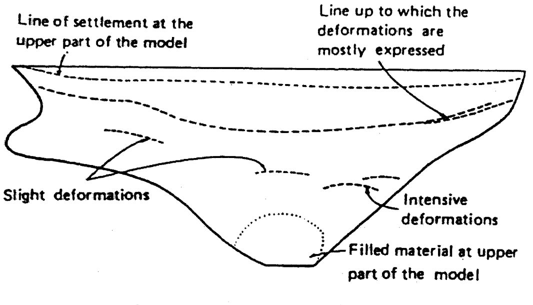

Figure 4. Damage to downstream slope of model, final state.

By increase of the excitation beyond 0.30g, certain deformation began to occur, in terms of sliding of material in the upper part of the model. For the effect of the maximum probable earthquake intensity of 0.46g, besides intensifying of the sliding in the upper part of the models, some deformations to the downstream slope of the model occur, in terms of individual sliding areas of limited length. For earthquake effects exceeding 0.50g intensive damages to the upper third part of the dam occur in terms of sliding surfaces affecting the clay core of the model and intensive deformations to the side of the dam where the contact slopes are with larger inclination. The final state of the dam is presented in Fig.4.

The previous statements are also proved by the analysis of the experimental results, Fig. 5, which shows the relationships between the relative displacements recorded at the dam model crest and the corresponding accelerations, that is proportional to the inertial force, for different earthquake excitation levels, 0.23g, 0.35g, 0.43g and 0.75g of the El Centro earthquake.

On the basis of the experimental results, the analytical model of the tested physical dam model was developed. The analytically determined dynamic response of the model to the seismic effect of the individual earthquakes showed very good correlation with the dynamic response of the model recorded during the testing, when the model was subjected to the effect of the same earthquake, Fig. 6.

6. CONCLUSIONS

According to the considerable volume of data obtained by experimental and analytical study of the dam model, the following conclusions can be drawn:

- There is a fairly good correlation between the experimental data on the model response to the earthquake effect - the analytically obtained dynamic response of the model.
- No occurrence of any deformation to the model was observed up to the design level of earthquakes with 0.30g, meaning that for this level of excitation the model behaves in elastic range of deformation.
- For a maximum possible earthquake level of 0.46g the model suffers some damage to the upper third along the height of the dam, in terms of cracks, sliding of material and occurrence of limited length sliding surfaces on the downstream slope.
- For excitations higher than 0.50g, the model deformations are intensified with the intensity of the excitation. They are expressed in terms of development of sliding areas both on the downstream and upstream slope, with the highest deformations to the upper part along the height of the dam as well as the side of the model on the more inclined side of the canyon.
- The failure mechanism is characterized, first, by the occurrence of moderate intensity sliding on the upper part of the model. With increase in the excitation the sliding on the upper part is intensified and new deformations appear to the downstream

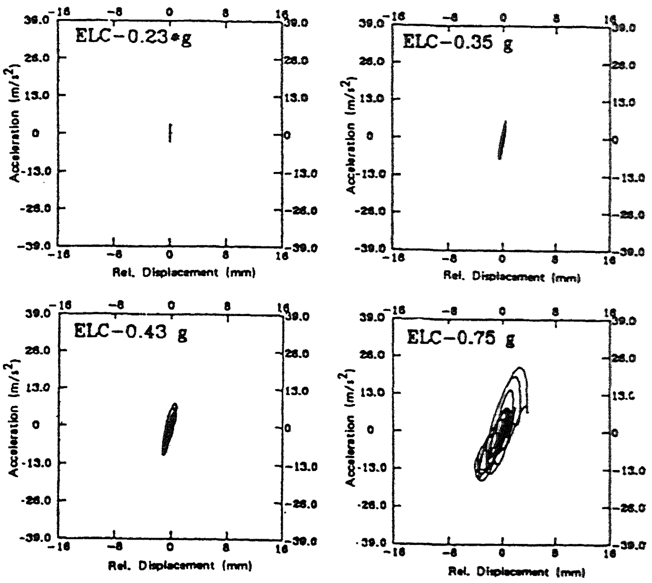

Figure 5. Relative displacement-acceleration relationship, recorded at the dam model crest.

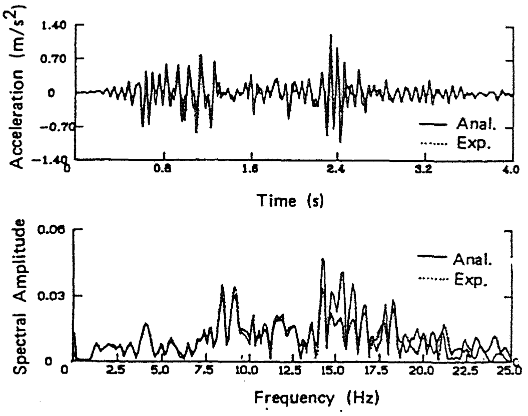

Figure 6. Dynamic response of the model to earthquake effect determined in an analytical and experimental way.

slope in terms of initial sliding areas of limited length. Further increase in excitation causes occurrence of more intensive failure, i.e., sliding, concentrated at the upper part of the model and the side of the dam on the steeper part of the canyon.

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