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PHYSICAL MODEL METHOD FOR SEISMIC STUDY OF CONCRETE DAMS

BY

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Abstract. The study of the dynamic behaviour of concrete dams by means of the physical model method is very useful to understand the failure mechanism of these structures to action of the strong earthquakes. Physical model method consists in two main processes. Firstly, a study model must be designed by a physical modeling process using the dynamic modeling theory. The result is a equations system which permits to dimensioning the physical model. After the construction and instrumentation of the scale physical model a structural analysis based on experimental means is performed. The experimental results are gathered and are available to be analysed.

Depending on the aim of the research may be designed an elastic or a failure physical model. The requirements for the elastic model construction are easier to accomplish in contrast with those required for a failure model, but the obtained results provide narrow information. In order to study the behaviour of concrete dams to strong seismic action is required the use of failure physical models able to simulate accurately the possible opening of joint, sliding between concrete blocks and the cracking of concrete. The design relations for both elastic and failure physical models are based on dimensional analysis and consist on similitude relations between the physical quantities involved in the phenomenon. The using of physical models of great or medium dimensions as well as its instrumentation creates great advantages, but this operation involves a large amount of financial, logistic and time resources.

Key Words: Concrete Dam; Physical Model; Earthquake; Shaking Table.

1. Introduction

Earthquakes have always been known to be the most destructive and the most unpredictible of all natural calamities and the dams probably were among the earliest major structures created by humans. The arch dam is a structure with a high degree of redundancy, redistributions of loads, and deformations on the structure are usually expected when cracks occur inside of the structure.

In early years of the last century the research methods in structural engineering had consisted in mathematical methods mainly based on Strength of Materials and Theory of Elasticity. Experimental methods started to be developed as a need of the research engineers to check the theoretical results obtained by structural analyses of concrete dams with mathematical methods of that time.

The real progress for both research investigation methods was registered in early 1950's once with the apparition of the computers and also with improvement of experimental techniques. Starting with that decade the both methods have been developed continuously due to the advances which have been made in research area as for static as for dynamic studies.

The last decade of the century was marked by relatively strong earthquakes that stroked countries where there are a great number of high dams (Iran 1990, 1997; USA 1994; Japan 1995). The effects of these earthquakes, on dams in general, and concrete dams in particular, have shown that, more than ever, considerations on the performance evaluation of dams and seismic risk must be taken into consideration. Otherwise, a recent study in Switzerland has shown that about 50% of the risk from the natural environment is caused by earthquakes. The main portion of the seismic risk originates from the strongest earthquakes [1]. It is pertinent to note here, the performance criteria based on the nonlinear response evaluation is particularly important [2].

2. Review about Study Dynamic Methods Used to Study of Concrete Dams

It is well known that the mathematical methods involve idealizations of the structural systems and it is difficult to correlate the results obtained from analysis with the behaviour of prototype especially for actions which take the structure beyond the elastic field. The experimental methods remain a reliable means to evaluate the behaviour of structural systems and to provide information to correlate the mathematical models. The methods frequently used for investigating the dynamic behaviour of concrete dams as well as the connections among them are presented in Fig. 1.

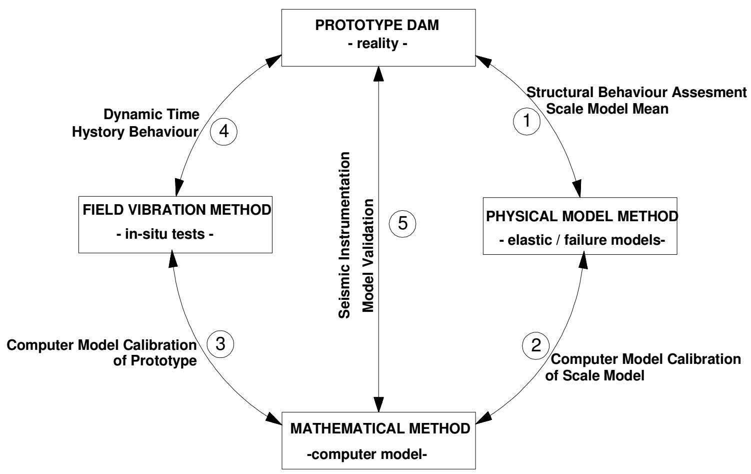


Fig. 1. – Dynamic study methods used for investigating dam prototype.

The methods illustrated in Fig. 1 can be independently used as study dynamic methods, but the information obtained about the behaviour of the prototype may be limited, or the methods can be coupled in order to increase the information.

The physical model method includes processes of physical modelling of the structures and experimental techniques of analysis applied on a physical model. The basis of this study method is the physical model which represents a replica of the prototype to a certain scale. The method can be used, as is shown by the curve 1, for predicting the behaviour of the prototype. The accurate of prediction is in accordance with the capability of the physical model to simulate the dynamic response of the prototype. The capability of the physical model to predict the behaviour of prototype is in close relation with fulfilment of many requirements as: similitude criterions, model material properties, boundary conditions, etc. The physical model method can be equally employed in studies on models under static actions as well as under dynamic actions. In this paper all the remarks will be concerned with the employment of this method into the dynamic studies.

The complexity of the physical model employed within this method depends on the pursued objective. If the objective is to predict the linear-elastic behaviour of the prototype, a continuous elastic physical model will be studied. If the objective is to predict the nonlinear behaviour of the prototype, a failure physical model with discontinuities must be employed into the study.

Three major types of structural nonlinearities, as those illustrated in Fig. 2, can be expected in the response of concrete arch dams to strong earthquake motions [3]. Only by means of the failure physical model is possible to obtain information about these types of structural behaviour of the concrete dams.

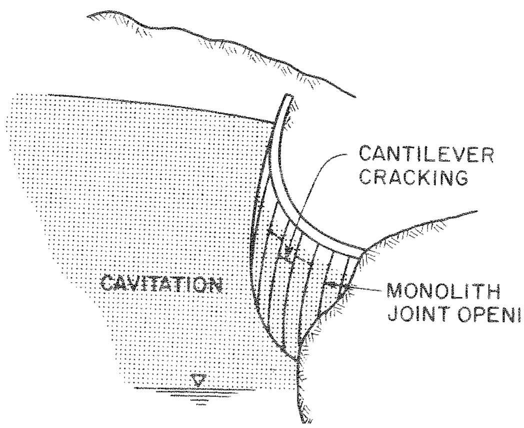


Fig. 2. – Possible nonlinear mechanism of the arch dam response [3].

In the frame of this study method, specific dynamic testing techniques applied on physical models are used. Dynamic tests on models can be performed using mechanical exciters or pulse generators within the pseudo-static testing technique or using a shaking table within the fully dynamic testing technique. For the pseudo-static method, the time effects are eliminated, *i.e.* the inertia forces are replaced by equivalent pseudo-static loads, and effects of the straining rate and damping become negligible applying these loads slowly enough. In the frame of the dynamic testing methods, the shaking table provides a convenient way to undertake experimental studies, since they can be designed as realistic simulations of seismic events from which the dynamic features of the model behaviour can be monitored and measured. Newly-built shake tables are able to undergo simultaneously three or six components of the recorded ground motion, what means an enhanced usefulness. Moreover, dynamic model tests carried out into similitude conditions can improve the fundamental understanding about the behaviour of the prototype and for the sake of convenience this model test is called a "traditional experiment". Many traditional model tests were performed during the 1950, 1960, 1970 decades at ISMES - Italy, LNEC - Portugal, Bureau Reclamation - USA particularly under static actions.

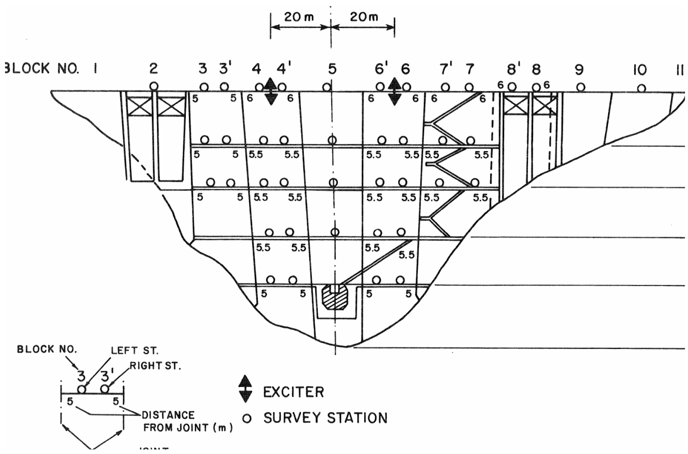


Fig. 3. – Generators position on dam crest and measurement points against all dam face [4].

The physical model method is also used, as is shown by the curve 2, for providing of information for the mathematical methods. This information facilitates the improvement of the computer models. Whenever the similitude laws are fulfilled only partialy, the information provided by model must be cautiously used by engineers with a great experience in the area. In this case the development of a numerical model which will be calibrated on experimental results may aid in many respects. If the similitude relations are ignored or just few involved, then a numerical model is absolutely required and the information provided by the physical model is only used to calibrate the computer model. The physical model method provides accurate data on the behaviour of the prototype when the similitude is fulfilled, but it is recognized that requires a large amount of financial, logistic and time resources. The second category of methods used to study the behaviour of the prototype are field vibration methods which are based on the processing of the dam response to an external excitation, namely to forced or ambient vibrations (Fig. 3). Information provided of the *in situ* tests are resumed to dynamics characteristics of the prototype as: natural frequencies, mode shapes, modal damping and hydrostatic pressure on dam wall. This information may also be used to calibrate the elastic numerical models for prototypes, as indicated in the curve 3. The *in situ* tests will provide reliable reference data in order to obtain accurate values for the dynamic elastic moduli of the whole dam - foundation system by the calibration process.

Performing *in situ* tests in various instances of dam life, (curve 4), information about the variation of dynamic properties with the seasons (winter - summer), water level and opening - closing of the joints can be collected. Using this information time histories of the dynamic behaviour of the prototype can be concluded. *In situ* tests may be also regarded as an instrument of assessment of the structural integrity of the dam.

The mathematical methods in structural civil engineering are the most frequently used and are based on computer models developed using numerical techniques. So far, the finite elements are the most employed in such computer models. From Fig. 1 it may be observed that the mathematical methods can be employed in three directions.

The first, the mathematical method, may be employed to elaborate computer models able to simulate the prototype dynamic behaviour with regard to the dynamic displacement patterns (curve 3), which are conveniently expressed in terms of free vibration mode shapes and natural frequencies of the prototype. The modelling operation is achieved assuming that the response of the prototype to dynamic motions of low or moderate intensity is linear. That is, it is expected that the resulted deformations of the prototype will be directly proportional to the amplitude of the applied excitation. Hence, the elaborated computer model will be an elastic computer model. Summarizing, the elaborated computer model is calibrated in accordance with the experimental information obtained by means of field tests on prototype. These calibrated computer models can be involved with confidence in seismic analysis studies.

The second, the mathematical method may be employed to elaborate computer models able to simulate the behaviour of scale physical models (curve 2), to static, dynamic and seismic actions. The computer model may be an elastic model which fulfils the mean features of an elastic physical model, meaning that the structural continuity is ensured, and the behaviour of model material is elastic - linear. Such computer models are usually used to undertake linear - elastic analyses, whereby the stresses obtained are compared with the model material strengths. In the case of a major earthquake it is probable that the calculated strains would exceed the elastic capacity of concrete, indicating that damage would occur. Therefore, the calibration of the elastic computer model may be done in close relation to the crack patterns of elastic - physical model and to those values of acceleration which produced them. Also, the computer model may be a nonlinear one and must be able to simulate the behaviour up to failure of the physical model. In this case all the geometrical, mechanical and rigidity characteristics of the physical model should be modeled including the correct modeling of boundary conditions and acting loads.

The third, the mathematical method, may be employed to elaborate computer models of the prototype which will be calibrated using the information obtained by means of the dam instrumentation (curve 5). For example, in Fig. 4 is presented the instrumentation with seven accelerometers of Punt-dal-Gall concrete arch dam from Switzerland.

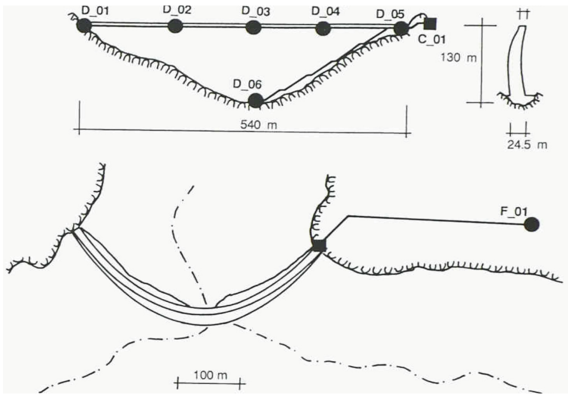


Fig. 4. – Punt-dal-Gall dam instrumentation: accelerometers network [5].

3. Concrete Dams Dynamic Study by Physical Model Method

Several years after the World War II started in all Europe great construction projects in the energetic area, very necessary at that time as: great power plants, concrete dams, and hydraulic works. In the early 1950's the study method started to be applied on large scale at ISMES laboratory under professors Lauletta's and Oberti's supervision on scale models for static actions. At LNEC, in the late 1950's, the method started also to be applied in concrete dam studies for static action. In contrast to the hydraulic models, which provide direct empirical data, the principal function of the structural models was to furnish a checking on the analytical methods of design existent at that time, particularly the trial load method.

The most of tests accomplished in that time were performed on physical models to large scale fulfilling many of similitude relations required. Besides, such traditional experiments had provided information about stresses and strains which couldn't be calculated with trial load method in some part of the dam. This traditional test has always improved the fundamental understanding of the involved phenomena.

Once with the development of computers the goal of the method has known a generalization. As was foregoing mentioned the physical model method may be employed in two directions, and for each direction can be also distinguished linear - elastic and nonlinear studies. Hence many kinds of physical models can be imagined to be tested.

The physical model method consists in two main processes. Firstly, a study model (replica model) must be created by a physical modeling process. The physical modeling process includes simplifications with regard to structural properties and actions adopted in the behaviour model for prototype. The result will constitute a study physical model which includes simplifications with regard to the behaviour model for concrete dam. Secondly, the resulted physical model (replica model) will be subjected to a structural analysis using experimental methods.

One of the goals of the structural analysis by means of laboratory tests on scale physical models within earthquake engineering, is to estimate the dynamic response of the prototype structures or to provide laboratory results to calibrate the mathematical models. These studies can be limited to the elastic response or can comprise the complete history up to failure including the material and geometric nonlinearities. For dynamic and seismic studies the realistic modeling of structural characteristics of the prototype is of the utmost importance in order to achieve an efficient research investigation. Hence in such studies the accurate modeling of mass volumes and implicitly of the prototype weight is very important because the inertial effects are substantial.

3.1. Dynamic Modeling Theory. General Remarks

In order to create a physical model it must be involved a process of physical modeling based on idealisations and simplifications with regard to the behaviour model of the concrete dam. Basically, a scale physical model is represented by a scaled structure which has the same shape with the real structure. The real structure represents the prototype. In order to correlate the results obtained on physical model to the prototype is required as the geometrical dimensions, mechanical characteristics and loads to be in certain ratios. If these ratios are fulfilled, the behaviour of the prototype under loadings can be known using the physical quantities measured on model and the similitude ratios, in ideally test conditions. As these ideally conditions are impossible to be fulfilled the physical model will include some simplifications as regards the behaviour model of the prototype.

3.2. Similitude by Dimensional Analysis

Dimensional analysis constitutes a general formulation to obtain similitude relations for various physical quantities involved in the phenomena study. This analytical method converts a dimensionally homogeneous equation which contains physical quantities and describes the physical phenomenon into an equivalent equation containing only dimensionless products of powers of the physical quantities. Since these dimensionless products describe the same physical phenomena and are independent with respect to the measure units, they must be equal both in prototype and model whether the complete similitude is to be achieved.

The first step in the dimensional analysis is establishing of a preliminary interpretation of the phenomenon in order to estimate the physical quantities which are involved. It is obvious that, if the differential equation of motion is known, the first step above mentioned do not constitute any difficulty. Each physical phenomenon may be generally expressed as a physical multi-quantity function

$$f(A_1,\ldots,A_k,B_{k+1},\ldots,B_n)=0, \tag{1}$$

which represents a dimensionally homogeneous equation, that is no depends on fundamental quantities adopted.

In order to create conditions of applying of Π theorem from all the involved physical quantities are chosen those which are considered fundamental for the phenomenon. The final relationship of physical quantities depends on the selection of fundamental quantities.

Once established the fundamental quantities, the function which express the phenomenon is reduced to relation

$$f(1,\ldots,1,\Pi_{k+1},\ldots,\Pi_n)=0, \tag{2}$$

according to the Π theorem.

Eq. (2) describes the physical phenomenon, and because of its dimensionless form, it must be fulfilled simultaneously for prototype and model, if similitude is to be achieved. Hence a sufficient condition for a complete similitude may be formulated as

$$(\Pi_{k+1})_p=(\Pi_{k+1})_m\,,\,(\Pi_{k+2})_p=(\Pi_{k+2})_m\,,\ldots,(\Pi_n)_p=(\Pi_n)_m\,. \tag{3}$$

Eqs. (3) constitute the design relations of the physical model. Two major difficulties have to face the model analyst. Firstly, he has to manifest an extreme care in specifying of the right number of physical quantities which enter in eq. (1). If there are quantities with an insignificant effect on the structural response of interest, it will impose unnecessary restrains on the model, whereas, if are neglected significant quantities, it can lead to incorrect results. Secondly, as will be seen, particularly for seismic tests, the model analyst is faced with almost insurmountable problems when he tries to replicate at the scale of the model all the design conditions imposed by eqs. (3). In particular, the totally simulation of material properties and loading conditions can be an extremely difficult or an impossible task. Often the difficulties foregoing mentioned leads to the design of distorted models from which one or more of the design conditions are violated [6]. Nevertheless, such models may still be adequate if the prediction can be corrected to account for the violation in the design conditions.

3.3. Elastic Physical Models for Dynamic Tests

a) Design Criteria of Elastic Model

The study of the structural behaviour using elastic scale models is based on assumption that for maximum load conditions the maximum level of stresses, ?, should be always lower than elastic limit of material as for dam as for foundation. Consequently, properties as the compressive and tensile strengths, and also the associated failure strains are not need to be scaled. Besides, nonlinear processes as the opening of contraction joints must not take place and the influence of gravitational force is considered insignificant. The strains and displacements resulted by applying of the load must be susceptible of measurement with available laboratory equipment.

b) Similitude Criteria

For an elastic model subjected to static action, the deformation grows up slowly, the elastic forces are prevalent and the relationship between stresses, σ, and strains, ε, is represented by Hooke's law. Since the elastic strain, ε, is dimensionless and it must be equal in the prototype and in the physical model, then

$$(4)\qquad \frac{\sigma_p}{E_p}=\frac{\sigma_m}{E_m} \text{ and consequently } \frac{F_p}{A_pE_p}=\frac{F_m}{A_mE_m}=H_k \quad \text{(Hooke's number).}$$

Furthermore, for elastic systems which are subjected to dynamic actions the stress field is determined by the equilibrium state between inertial forces, F^i, and restoring forces, F^e, taking into account boundary conditions. Hence is required as the restoring forces ratio between prototype and model must be equal to the inertial forces ratio

$$(5)\qquad \frac{F^e_p}{F^e_m}=\frac{F^i_p}{F^i_m}.$$

Because the gravity forces are neglected, the stress obtained in the physical model is not proportional to the prototype stress.

Taking into account the foregoing affirmations, the dimensionally homogeneous equation of phenomenon can be expressed as follows:

$$f(\sigma,\rho,l,E,\ddot{u})=0. \tag{6}$$

If the relation (6) is developed using Π theorem, as previously, or developing the relations (4) and (5), the similitude relations

$$K_F=\lambda^2 K_E \text{ (Hooke)},\ K_\sigma=K_E,\ K_\rho \lambda K_{\ddot{u}}=K_E,\ \text{(Cauchy)} \tag{7}$$

are obtained.

Within the dynamic studies on dam physical model the test can be performed into full reservoir or empty reservoir approach. In any of these approaches the Cauchy's similitude has to be fulfilled, but, in addition, for the full reservoir approach, the restoring forces, F_e, include the hydrodynamic forces, F_h, (Fig. 5).

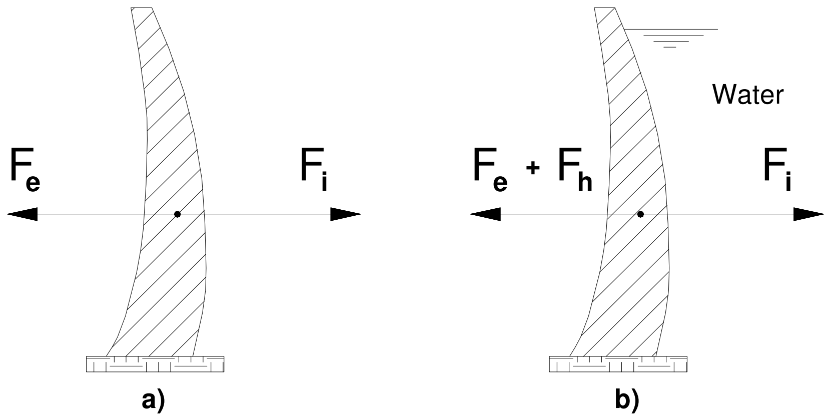


Fig. 5. – Dynamic equilibrium, Cauchy's similitude: *a* – empty reservoir; *b* – full reservoir.

c) Design hypotheses

Design hypotheses of the physical model depends on the purpose of the test but in the same time must take into account the constructive characteristics of the prototype. Obviously, some of these design hypotheses are a consequence of the similitude laws.

The physical model must be a true scalar representation of the prototype.

The length scale which defines the model dimension is considered as fundamental quantity within design of the model.

The entire model is constituted of dam body and a substantial extension of the foundation and reservoir.

The boundary conditions must to enable freedom for model to deform in a manner similar to the prototype.

The dam is considered a homogeneous monolithic body. The vertical and perimetral joints aren't necessary to be reproduced.

The superposition effect is hold true, i.e. the stress analysis can be achieved apart for each action. Consequently, the resultant stress is obtained by addition of all the stresses obtained separately.

The effect of surface waves is neglected whether the test is performed with water in reservoir.

d) Elastic test requirements

The tests which are performed on elastic models no cover the dam behaviour in all complexity. In each model test there are simplified assumptions, as well as the inaccuracies with regard to the geometry, shaping or fulfillment for the similitude criterions. Therefore, the criterions after which the model test is conceived have to take into account the supposed simplified assumptions, inaccuracies with regard to similitude and desired results.

Since the dams are engineering structures with large dimensions, the length scale of the model $(1/\lambda)$ become an important parameter. Hence the designer has to take into account that the dimension of the model must to lead to the measuring of the gathered data accurately using the existent devices.

Within a test on elastic models subjected to dynamic actions can be mainly achieved the identification of natural frequencies, estimation of modal shapes, evaluation of structural damping, and even hydrodynamic pressure measurement. In order to evaluate accurately the dynamic parameters of the model, the design hypotheses with regard to the geometry of the dam - foundation - reservoir system must to be accomplished, and hence, the dynamic parameters obtained in the physical model can be extrapolated to prototype. [7], . . . , [11]

The dynamic model test may be performed considering two approaches: empty reservoir and full reservoir. The excitation of the model may be applied in three directions: horizontal valley course, cross-valley course and vertical. The second hypothesis is considered more unfavourable for tested system. When the physical model consists of the dam body and a large extension of the foundation Cauchy's similitude has to be accomplished. In this case there is more freedom in choosing the model materials. Particularly, when the shaking table is the excitation system model materials with suitable Young‘s modulus are required, in order to make the fundamental frequencies of the model lie in the frequency band of the shaking table. Despite of the enhanced capabilities of the newly-built shaking table this difficulty have maintained up to the present.

When the physical model consists of the dam body, foundation and the full reservoir, Cauchy's similitude must to be accomplished simultaneously as for dam body and foundation as for reservoir. Since in the most situations water is used as fluid in the reservoir, the similitude ratio of the material properties as the density and Young‘s modulus of the dam body are restricted to 1. Hence the possibility to effectuate dynamic tests around the natural frequencies of the model only depends on the geometrical length scale of the model $(1/\lambda)$. In this situation the most suitable are large scale models excited by actuators. It is emphasized, since is no longer necessary to reproduce the hydrostatic pressure and weight action, the density scale, K_ρ, of the material is found to be independent of the Young´s modulus scale, K_E.

The foundation influences the dynamic parameters of the physical model. The natural frequencies of the prototype seem to be correctly produced into physical model when the foundation is modeled one to two times the height of the dam, and it is extended laterally from the dam one to two times the height of the dam [12]. A special care must to be paid with regard to simulation of the boundary conditions. In dynamic model studies a proper simulation of the boundary conditions represents an essential task, but difficult to be achieved.

3.4. Failure Physical Models for Dynamic Tests

a) Design criteria of failure model

It is well recognized that the strong earthquake take the concrete dam beyond the elastic range, and nonlinear properties of the material and structural discontinuities of the concrete dam must be considered [2].

b) Similitude Criteria

Since beyond of the elasticity limit of the material the superposition principle of effects is no longer accepted, it is necessary the simultaneous reproducing of all forces which acts on prototype during the earthquake. Therefore, considering the phenomena in one g field is required as the ratio of the gravity forces, G, between prototype and model to be equal to ratio of the inertial forces, F_i. In addition, it is necessary that the ratio of restoring forces, F_r, to be equal to ratio of the inertial forces, F_i (rel. (5))

$$\frac{F_p^i}{F_m^i} = \frac{G_p}{G_m}. \tag{8}$$

If the relation (8) is developed taking into account the physical expressions of the involved quantities and considering that the physical model is placed in one g field then, the particular Froude’s similitude relation

$$\lambda = \tau^2 \tag{9}$$

is obtained.

As was foregoing mentioned, the model must to fulfil Cauchy’s similitude relation (7), and simultaneously with (9) is obtained the similitude relation

$$\begin{cases} \lambda = \tau^2, \ \text{Froude}, \\ K_\rho \lambda K_{\ddot{u}} = K_E, \ \text{Cauchy}, \end{cases} \text{with } K_\rho \lambda = K_E, \tag{10}$$

of the material properties.

Analysing relations (10), in order to achieve an experimental test using a failure scale model up to dynamic failure seems to be a very difficult task because the concrete dams have great dimensions. The relations (10) express a very severe requirement for physical model and it is very difficult to fulfill it. Moreover, the model materials which are used to construct failure models have to fulfill requirements concerning the strain similitude. All the similitude ratios required for a failure model there are summarized in Table 1.

Table 1

Similitude Requirements for Dam Dynamic Scale Models

Physical quantities	Failure model (Froude similitude) $\left(\frac{F_i}{F_g}\right)_{\text{Dam}} = \text{const.}$	Elastic model (Cauchy similitude)	
		Empty reservoir $\left(\frac{F_i}{F_e}\right)_{\text{Dam}} = \text{const.}$	Full reservoir $\left(\frac{F_i}{F_e}\right)_{\text{Dam}} = \left(\frac{F_i}{F_e}\right)_{\text{Water}} = \text{const.}$
Length	$\lambda = \frac{L_p}{L_m}$	$\lambda = \frac{L_p}{L_m}$	$\lambda = \frac{L_p}{L_m}$
Elasticity modulus	$K_E = \frac{E_p}{E_m}$	$K_E = \frac{E_p}{E_m}$	$K_E = 1$
Mass density	$K_\rho = \frac{K_E}{\lambda}$	$K_\rho = \frac{\rho_p}{\rho_m}$	$K_\rho = 1$
Gravity accel.	$K_g = 1$	neglected	neglected
Acceleration	$K_{\ddot{u}} = 1$	$K_{\ddot{u}} = \frac{K_E}{K_\rho \lambda}$	$K_{\ddot{u}} = \frac{1}{\lambda}$
Velocity	$K_{\dot{u}} = \sqrt{\lambda}$	$K_{\dot{u}} = \sqrt{\frac{K_E}{K_\rho}}$	$K_{\dot{u}} = 1$
Time	$\tau = \sqrt{\lambda}$	$\tau = \lambda\sqrt{\frac{K_\rho}{K_E}}$	$\tau = \lambda$
Frequency	$K_f = \frac{1}{\sqrt{\lambda}}$	$K_f = \frac{1}{\lambda}\sqrt{\frac{K_E}{K_\rho}}$	$K_f = \frac{1}{\lambda}$
Force	$K_F = K_\rho \lambda^3$	$K_F = K_E \lambda^2$	$K_F = \lambda^2$
Stress	$K_\sigma = K_E$	$K_\sigma = K_E$	$K_\sigma = 1$
Strain	$K_\varepsilon = 1$	$K_\varepsilon = 1$	$K_\varepsilon = 1$
Strain rate	$K_{\dot{\varepsilon}} = \frac{1}{\sqrt{\lambda}}$	$K_{\dot{\varepsilon}} = \frac{1}{\lambda}\sqrt{\frac{k_E}{k_\rho}}$	$K_{\dot{\varepsilon}} = \frac{1}{\lambda}$

Equally as for elastic models, the studies on failure models can be accomplished in the approach of empty or full reservoir. Within the first approach the forces as the weight, inertial force, elastic force and damping force must to be reproduced. In addition for full reservoir approach the action of the hydrostatic and hydrodynamic pressure must to be reproduced.

c) Design hypothesis

It is obvious that several design hypotheses required for elastic models will be preserved within the failure models. Besides those preserved there are new hypothesis as follows:

The superposition actions are not more available.

The shape model must to take into consideration the interaction phenomena between dam and foundation and dam and reservoir.

The discontinuities of interest contained to prototype must to be modeled.

It is required as the simultaneous action of all forces which act the prototype as the weight force, the hydrostatic pressure, hydrodynamic pressure, elastic forces, inertial forces, damping forces must to be modeled.

d) Failure test requirements

The failure model is perhaps most useful when is used to investigate nonlinear aspects of the dam response as the joint opening-closing, the sliding behaviour under high compression or cracking, but requires model materials which rise difficulties concerning the mechanical properties. In the most general case of a complex three-dimensional structure as is the concrete arch dam, where gravity and inertia effects are equally important, a true replica model of similitude should be the ideal selection. However, the failure dynamic experimental studies of the concrete dams rise difficulties in fulfilment of the criterions on which are based because the similitude ratios required are very severe.

The most appropriate excitation system is the shaking table. The possibilities to perform the model test up to failure are mainly with regard to the capabilities of the shaking table. Considering that for failure models the frequency similitude ratio, K_f, only depends on the length scale ratio, λ, as for empty reservoir as for full reservoir test, the selection of the size of the model must to take into consideration the maximum capacities of the shaking table. From the same reason the maximum capacities of the shaking table are determined regarding the signal which must be used in order to bring the model up to failure.

At the beginning the dynamics properties of the model must be estimated. This task can be accomplished by means of suitable modal identification techniques taking into account the model dimensions (white noise, spring hammer, shaking table, etc.).

Usually, this kind of experimental investigation consists in the introducing of time history signal, recorded or artificially generated wave acceleration, accordingly with possibilities of the shake table. In a first test phase the intensity of the signal should not overpasses the design spectrum. In accordance with similitude relation the wave acceleration signal must to be compressed by $\lambda^{-1/2}$ (Fig. 6).

By this operation the acceleration level remains unchanged (Fig. 6 *a*), but the frequencies spectrum is translated toward a higher value (Fig. 6 *b*). Evidently, time length of the wave must to be long enough, particularly for dam structures, to avoid a too short time-compressed signal. Time action for a strong earthquake is usually around 30 s. For this phase of the test more dynamic scenario can be considered; various water level and input signals.

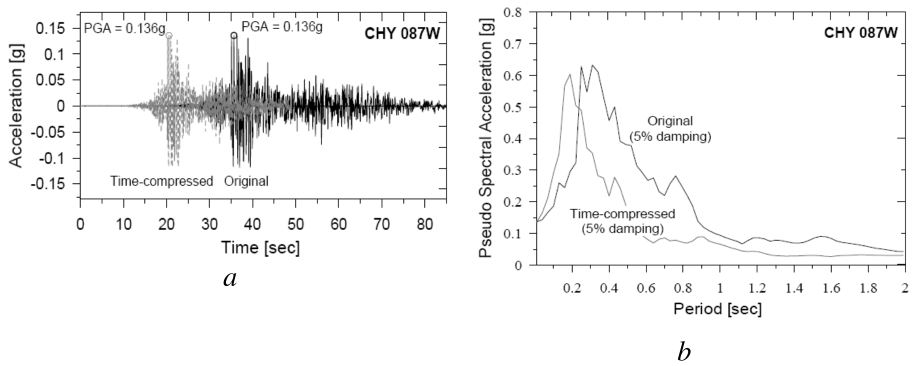


Fig. 6. – *a* – Time-compressed wave acceleration; *b* – translated response spectrum.

The overloading phase requires just one signal, perhaps that caused the highest response of the model, and its intensity is increased stepwise until the failure of the model is achieved. Many times the natural frequencies of physical model are much higher than the superior limit of the frequencies range of the shaking table. That is why, sometimes in the case of the application of an earthquake motion as input signal may no lead to expected results. In consequence, the complex transient signal may be replaced with a simple steady-state motion. The method of generating into the model a stationary sinusoidal vibration having a frequency as close as possible to the most dangerous natural frequency of the model has been considered a basic technique. Higher input accelerations can be accomplished by increasing of the motion amplitude, as well as the increase of the frequency. For seismic studies the most suitable technique from the two is considered that which consist in the increase of amplitude of the steady-state motion and keeping constant the selected frequencies. Evidently, the acceleration of the collapse producing vibration does not simulate the same acceleration at the actual earthquake since the influence of the shape diversity of the two vibrations is all too great [12]

4. Shaking Table 3D Model Design Process of a Concrete Arch Dam

The requirements for failure models, as was emphasized before, are difficult to be accomplished particularly for the modeling material. Based on the similitude requirements from Table 1 the density ratio of the modeling material was fixed to unity considering that the liquid in the reservoir is water, equal as for prototype. Therefore, a special mixture with a density close of the density of concrete was required. A consequence of the aforementioned condition is that the modulus scale of the modeling material must be of the same size with the geometrical scale. It is known that a material with a high density have also high rigidity. However, taking into consideration the past experience at LNEC concerning the preparation of mixtures for modeling materials, a mixture based on cement, diatomite, ilmenite, limestone, and water was prepared. The hardened mixture, with the density around 2,500 kg/m^3, exhibits a low tensile strength and a Young modulus 10…30 times lower than ordinary concrete. The modeling material heterogeneity is confirmed by the mechanical properties of mixture molded into the seven cantilevers and two abutments of the model. Consequently, considering the mechanical properties of the hardened mixture, the geometrical length scale of the model should be around 30.

Since the design process was not constrained of the study of a particular dam, more freedom existed to encounter a concrete arch dam in service life, which can be modeled at this scale. In order to achieve a failure test upon the model, the dynamic characteristics of the prototype as the natural frequencies are of utmost importance. Nevertheless, the appraisal of the length scale of the model was given of the shaking table capacity coupled with the performance of the modeling material and with the requirement to perform dynamic tests near by the natural frequencies. With this requirements established, finally, the Odiaxere's arch dam geometry as prototype was chosen. Odiaxere dam, illustrated in Fig. 7, is located in South-West of Portugal, Faro province, having the crest length of 150 m, the dam high of 41 m about foundation, and 5 m the width at the crest. The computed natural frequencies are appropriate of the target demanded. Nevertheless, the final length scale was set at 1/40 because this provide a model size that could be constructed and tested conveniently on the LNEC shaking table.

a *b*

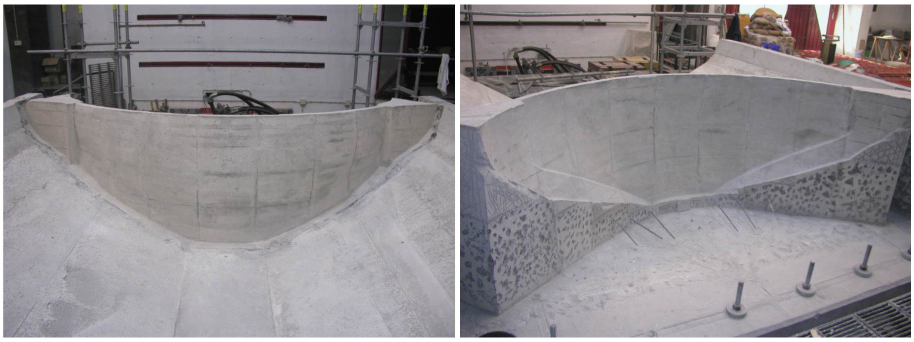
Fig. 7. – Prototype Arch Dam - Odiaxere Dam from Portugal; *a* – downstream view; *b* – upstream view.

Within physical model, the entire dam body and a substantial extension of reservoir of foundation were modeled as shown in Fig. 8. The reservoir was designed in length of 3.15 m in the upstream direction. The canyon shape is almost circular in order to replicate better the hydrodynamic pressure during the test. Thus, the reservoir length is three times at least the high of the dam body. The displacement of the shaking table is transmitted to all points from bottom reservoir through a very rigid plate.

The foundation was extended to maximum in order to reduce the influence on the natural frequencies of the model but accounting as the weight of the model does not overpass the payload of the shaking table for the frequencies required.

The weight of the model with its foundation and empty reservoir was evaluated as approximately 200 kN. The maximum payload of the earthquake simulator enables the inducing of accelerations to the base of the order of 0.95g and velocities of 42 m/s. These capabilities are considered to be adequate to induce an extensive damage into the model.

Since the body dam of the prototype consists of seven cantilevers jointed by eight contraction joints, the physical model contain also these vertical discontinuities, as shown in Fig. 8, created by the construction process. The volume of the dam body was accurately modeled by means of a wood formwork in order to reproduce correctly the action of inertial forces. The surface of joints between the dam body and foundation is naturally created by casting of the cantilevers on the hardened foundation. The shear keys between the adjacent monolithic cantilevers are not incorporated.



a *b*

Fig. 8. – Arch dam failure physical model; *a* – upstream view; *b* – downstream view.

In accordance with the input signal, basically, the principal concern was a suitable earthquake simulation of the physical model, capable to provide a structural excitation necessary to obtain an adequate response for the study. Concerns with the acceleration level required were not raised, since for a failure model the demanded acceleration level is compatible to the real earthquake. Within a failure model, time must be scaled with a ratio of $\lambda^{-1/2}$, illustrating that the input motion and the model response will occur at a much faster rate than for the prototype. Since the frequency scale, f, increases in a ratio of $\lambda^{-1/2}$ it is required a suitable shaking table and a high-speed data acquisition.

In order to evaluate the degree of fulfillment of the similitude requirements, the mechanical properties of a middle class concrete as target values were selected. Considering as reference point the mechanical properties from Table 2, it can be emphasized that, neither material stiffness nor material strength fulfils the similitude relation related to geometrical length scale, λ. However, the material density is well suited and the stiffness scale is nearby of the strength one. The stiffness scale is approximately $k_E = 12$ and the strength scale is around $k_E = 14$. The density scale is very close of target $k_\rho = 0.94$. In addition, the ratio between the compressive and the tensile mixture strength is adequate, approximately 13.5.

Table 2
Model Materials Properties Target Values

Property	Middle class concrete	Scale factor	Target values
Young Modulus, E, N/mm^2	35,000	40	875
Compressive strength N/mm^2	30	40	0.75
Tensile strength N/mm^2	2.5	40	0.0625
Density kg/m^3	2,400	1	2,400
Compressive strain %	2	1	2
Tensile strain %	0.15	1	0.15

5. Conclusions

Although considerable progress has been achieved in the last 50 years much additional research needs to be done to improve the reliability of methods for the seismic design and safety evaluation of concrete dams. Significant experience has been accumulated in the linear-elastic dynamic analysis of concrete dams and also in the interaction phenomena between dam and foundation of respectively dam and reservoir.

The physical model method remains a powerful tool for seismic analysis of concrete dams. However, the accuracy of the response prediction depends strongly on some factors as: suitable model material, accuracy of dynamic input, properly simulate of initial and boundary conditions, resolution of instrumentation system, acquisition rate of measurement system. One major problem encountered to all model studies regardless of scale is the simulation of boundary conditions. Adequate simulation of material properties seems to be the most difficult and important of small scale modeling.

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METODA MODELULUI FIZIC IN STUDIUL BARAJELOR DE BETON SUB ACŢIUNEA SEISMELOR

(Rezumat)

Studiul comportării dinamice a barajelor cu ajutorul metodei modelului fizic poate reprezenta o cercetare edificatoare în înţelegerea mecanismului de cedare al acestor structuri la acţiunea seismelor puternice. Realizarea unei cercetări utilizând metoda modelului fizic implică mai intâi un proces de proiectare a modelului fizic pentru un prototip existent bazat pe teoria dinamică a modelării scriind relaţiile de dimensionare ale modelului fizic. Ulterior construcţiei modelul fizic urmează analiza structurală bazată pe metode experimentale şi interpretări ale rezultatelor achiziţionate experimental.

In funcţie de scopul cercetării se va recurge la proiectarea şi testarea unui model fizic elastic sau de rupere. Constrângerile în privinţa realizării de modele fizice elastice sunt relativ uşor de îndeplinit dar şi rezultatele experimentale ce se pot achiziţiona furnizează informaţii cu caracter limitat. Pentru studiul barajelor de beton la acţiunea seismelor se impune realizarea de modele fizice de rupere capabile să simuleze adecvat eventuala deschidere a rosturilor, lunecarea in rost între blocurile de beton pentru două console alăturate precum şi producerea fenomenului de fisurare. Pentru a studia fenomene cu caracter dinamic relaţiile de proiectare ale modelelor fizice elastice şi de rupere au la bază analiza dimensională ce constă în stabilirea de relaţii de similitudine între diferitele mărimi fizice implicate în fenomenul de studiu.