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VERY SIMPLIFIED SEISMIC RESPONSE EVALUATION OF AN ASPHALT CORE ROCK-FILL DAM – ITS POSSIBILITIES AND LIMITS

Despite of the intensive development of sophisticated dynamic analysis methods and their implementation in the field of Dam Engineering in the last decades due to the explosive increase of the computational power of modern computers, the pseudo-static equivalent-force approach is still being further developed due to its ability to provide fast and simple estimation of some response parameters of the dam under earthquake excitation. This statement is proved by some recent publications in this field continuing to focus the attention of the practicing engineers on such as far as possible simple tools yet providing realistic results.

The present work deals with the example application of such simple pseudo-static response analysis method to a Bulgarian rock-fill dam with asphalt concrete core. The procedure applied was developed in a series of works by Dr. Max A.M. Herzog for embankment dams under basic operational loads as well as for seismic excitation. The obtained results are compared with the results from sophisticated dynamic analysis procedures for the same dam carried out with well-established finite element analysis software. Based on these comparisons, conclusions are drawn about the applicability of the used simplified method for the case of seismic loading on rock-fill dams with bituminous cores.

Keywords: rock-fill dam, seismic response, simplified method

1. INTRODUCTION AND PROBLEM FORMULATION

In the 21st century, the computational power even of the personal computer systems is already remarkably high, and these systems become more easily affordable. On the other hand, sophisticated methods for static and dynamic analyses of complicated civil engineering systems with complex physical interactions are continuously being developed, and their software implementations become more intuitive and user-friendly. This situation can be observed especially in the field of Dam Engineering where the mentioned overall development already allows for much more realistic modelling of complex physical phenomena such as: the strongly non-linear material and structural behaviour of the dam, dynamic soil-structure and fluid-structure interactions, liquefaction, seepage problems.

Despite of the intensive development of both sophisticated dynamic analysis methods and their hard- and software implementation in the field of Dam Engineering in the last decades, simplified methods for cheap, fast and yet reliable assessment of key response parameters of the dam structure to decisive loads and impacts are further developed and used for independent control and comparison purposes. As examples in this connection, the works [6, 7] should be mentioned. They are dedicated to the computation of particular response parameters of the dam (fundamental period, settlement). Special attention is continuously paid to the pseudo-static equivalent-force method still being further developed due to its ability to provide fast and simple estimation of some response parameters of the dam under earthquake excitation. Here, a series of works by M. Herzog should especially be mentioned, a small part of which is used and cited further below [1-4].

In general, the application of more or less simplified methods can be in many cases important for:

- preliminary assessment of key dam response parameters for various load and impact conditions and orientation about the further computational proceeding based on the obtained results in this way;
- independent qualitative control of the results from more sophisticated models / analyses.

In this presentation, an application of a very simplified calculation procedure is shown to the case of a Bulgarian rock-fill dam with asphaltic concrete core currently under construction. The procedure applied follows in general the approach developed in the above mentioned works of M. Herzog [1-4]. The particular case of this dam was selected mainly due to two reasons. On the one hand, the mentioned simplified calculation procedures have been applied in the corresponding sources to earth- and rock-fill dams. It would be indeed interesting how such an approach holds for a rock-fill dam with asphaltic concrete core. On the other hand, a technical design developed by a renowned consultant already exists based on thorough static and dynamic non-linear analyses with real physical parameters of the fill zones obtained from extensive laboratory studies. Thus, the possibility for a comparison with the results of such sophisticated computations also exists which would allow assessment of the applicability of the discussed simplified approach.

It should be noted here that relatively few references discuss rock-fill dams with asphaltic concrete cores compared to the conventional rock-fill dams. Most of them present either particular projects, as for example [8], or discuss particular issues of the design and construction of this type of dams, however, without going deeper into detail regarding computational procedures (which is of course understandable). In this connection, the milestone report [5] should be noted containing extensive information about practically all main issues related to such a project.

2. CASE STUDY AND IMPLEMENTATION OF A SIMPLIFIED PROCEDURE

In the following, an application of the mentioned simplified approach presented mainly in the works [1-4] to a Bulgarian rock-fill dam with asphaltic concrete core is presented.

2.1 PRESENTATION OF THE DAM

The considered dam is in fact no typical rock-fill dam. Its body consists in fact of a crushed rock, even with similar physical parameters as those of the filters. Further below, average mechanical parameters of the case (crushed rock / ballast fill dam) with asphalt concrete core were used. The design and site investigation works of the dam began in the 80s of the last century. In 2001, the construction of the partly built dam (up to about one third in height) and appurtenant facilities was suddenly stopped. Currently, attempts are made for completing the dam and setting the reservoir and its facilities in operation. Due to the large time gap, new site investigations and re-design of the dam and all facilities were carried out by an internationally renowned consultant who won the tender. The typical cross-section of the dam with both zones – the already built one and the upper one to be newly constructed is shown in Figure 1.

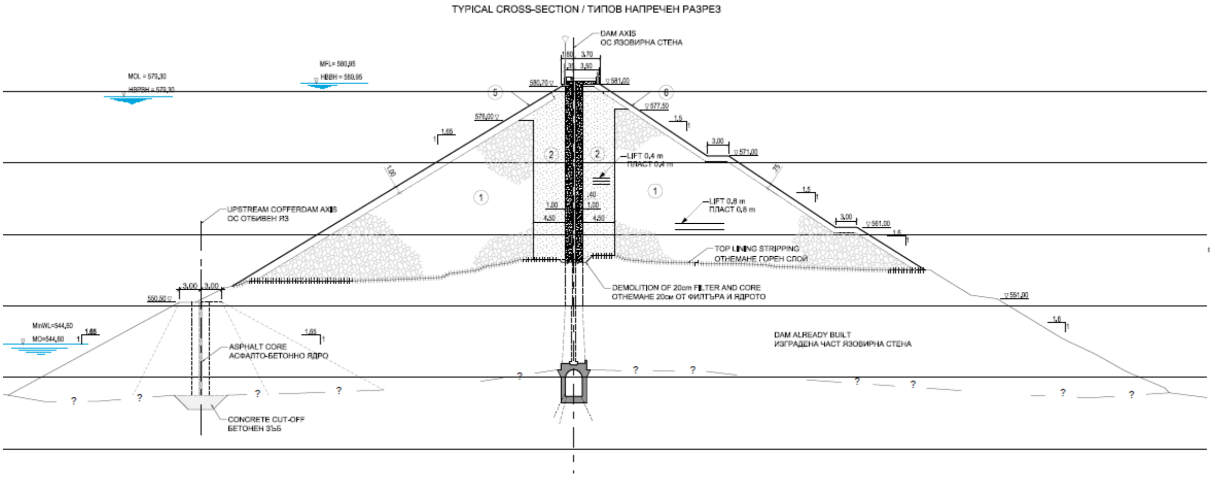

Figure 1. Typical cross-section of the dam

The main design parameters of the dam are as follows:

Type: (crushed) rock fill dam with asphalt concrete core

Height: 47,15 m (maximal, from grouting gallery base to parapet wall crest)

Crest length: 200 m

Crest width: 4,25 m

Gross capacity of the reservoir at maximum operating level: 3841000 m^3

Total volume of the dam: 295500 m^3

Spillway: side channel spillway with stepped chute and stilling basin on the left bank.

According to the requirements of the Bulgarian national code for design of hydraulic structures, the dam was designed as Class II structure. According to the Bulgarian national code for the design of buildings and facilities in seismic regions [10], the site is in a zone of intensity level VII with peak ground acceleration (PGA) of 0,1g corresponding to a return period of 1000 years.

2.2 OUTLINE AND APPLICATION OF THE SIMPLIFIED CALCULATION PROCEDURE

In general, two main lines can be identified in the simplified calculation procedure for earthquake-induced response assessment of the dam according to the works [1-4]. These are:

- calculation of a compound seismic coefficient which can be further used for obtaining of a pseudo-static equivalent-force by multiplication of the weight of the dam (or part of it);
- approximate calculation of some key seismic response parameters of the dam, such as fundamental frequency of the dam, horizontal and vertical earthquake-induced settlement etc.

In the following, the composition of the generalized seismic coefficient according to [3, 4] will be shortly presented. Particular further details are presented in other sources from the series of works by the same author on this problem. Firstly, the fundamental period T_1 (fundamental frequency, respectively) of the dam has to be evaluated. According to [4], the fundamental frequency of the dam can be approximately calculated in (Hz) as:

$$f_1 = \frac{5,6}{\sqrt{w_{stat}}} \qquad (1)$$

where w_{stat} is the maximal transversal static deflection of the dam under the horizontal action of its own dead weight, substituted in (cm). Of course, $T_1 = 1/f_1$, and w_{stat} can be obtained [4] as:

$$w_{stat} = \frac{\gamma H^2}{4G} \qquad (2)$$

with H being the dam height, γ – the unit weight, and G – the shear modulus.

The generalized seismic coefficient consists of 4 components with the following meaning of the corresponding multipliers M_i:

- response parameter of the seismic excitation:

$$M_1 = \frac{T_1}{T_b} \qquad (3)$$

where T_b is the upper bound (with respect to period T) of the plateau of the design response spectrum in the particular case.

- influence of the foundation:

$$M_2 = \left(\frac{2}{\log E_f}\right)^2 \qquad (4)$$

where E_f is the modulus of elasticity of the foundation in (MN/m^2).

- influence of the ductility, i.e. of the relation of the deformation at collapse to the deformation at the limit of linearity (proportionality). This multiplier can be written in the form:

$$M_3 = \frac{3}{F_d} \qquad (5)$$

where the value of the factor F_d can be read from a table given in [3] depending on the dam type.

- accounting for resonance effects, i.e. for possible activating of the fundamental frequency of the dam by the seismic excitation. For this multiplier, an upper limit value is recommended to be set as:

$$M_4 = 10 \qquad (6)$$

Thus, the generalized seismic coefficient finally gets the form:

$$C_s = \frac{a_E}{g} M_1 M_2 M_3 M_4 \qquad (7)$$

where a_E is the design PGA for the dam site.

One more multiplier is further introduced as well to account for the hydrodynamic dam-reservoir interaction. However, since it has to be separately applied to the hydrostatic load and is not directly related to the above presented seismic coefficient it will not be discussed further herewith.

Besides the seismic coefficient, furthermore simple relations and even rules of thumb for some other important parameters of the seismic dam response are introduced in the mentioned sources. These parameters are the maximal horizontal and vertical displacements, values of the dynamic modules as well as the above already mentioned fundamental period / frequency.

The earthquake-induced displacements of the dam body to be expected are of particular interest. The following relations are proposed for them [1-4], respectively:

$$w_{dyn,h} = \frac{a_{E,h}}{g} w_{stat} \qquad (8)$$

where $w_{dyn,h}$ is the maximal dynamic horizontal (transversal) crest displacement, and w_{stat} is to be substituted after Eq.(2);

$$w_{dyn,v} = \frac{a_{E,v}}{g} \frac{\gamma H^2}{2E} \qquad (9)$$

with $w_{dyn,v}$ the maximal dynamic vertical crest settlement.

It would be reasonable, and hence recommended, to use the dynamic values of the corresponding deformation modules in Eqs.(8, 9). Reversibly, these relations can be used for obtaining the average dynamic deformation modules of a dam if measured values of the seismic crest displacements exist.

2.3 RESULTS AND DISCUSSION

In the case of the considered dam in particular, we start the application of the outlined approach with calculation of the fundamental frequency / period of the dam. According to the submitted by the Designer results from the laboratory investigations of the dam materials, the unloading-reloading deformation module is 63 MN/m^2. Further below, we used these values as an approximate average for the dam body without taking into account the mechanical parameters of the asphalt concrete core, i.e. latter's contribution to the deformation behaviour of the dam. Thus, the shear modulus is 26,25 MN/m^2. The average unit weight is 21 kN/m^3. With these values, the maximal horizontal transversal static crest displacement according to Eq.(2) is 44 cm. By means of Eq.(1), the fundamental frequency of the dam is calculated as 0,844 Hz, i.e. the fundamental period is 1,184 s.

For comparison, by means of the empirical relations given in [9], the fundamental period of the dam is calculated as 1,187 s. There is some discrepancy between these values and the computed fundamental period by the Designer by means of the sophisticated FE-model 1,104 s. However, the difference between the obtained values and the interval for the fundamental frequency proposed by the rules of thumb in [2] is much larger – 0,291 s to 0,357 s. This observation just emphasises the need for great caution and independent comparison when any strongly simplified relations are used.

In a next step, the components of the presented above generalized seismic coefficient are calculated as follows:

- response multiplier from Eq.(3):

$$M_1 = \frac{0{,}36}{1{,}184} = 0{,}30 \qquad (10)$$

- influence of the foundation from Eq.(4):

$$M_2 = 0{,}396 \approx 0{,}4 \qquad (11)$$

with modulus of elasticity of the foundation E_f = 1500 MN/m^2 according to the site investigation results;

- influence of the ductility:

$$M_3 = 0{,}43 \qquad (12)$$

with F_d = 7 as read from the table given in [3] for the considered dam type;

- multiplier for resonance effects:

$$M_4 = 10 \qquad (13)$$

Thus, the generalized seismic coefficient gets the value in the considered case:

$$\begin{aligned} C_s &= \frac{a_E}{g} M_1 M_2 M_3 M_4 = \\ &= 0{,}1 * 0{,}3 * 0{,}4 * 0{,}43 * 10 = \\ &= 0{,}1 * 0{,}516 = 0{,}0516 \end{aligned} \qquad (14)$$

with horizontal design PGA for the dam site a_E = 0,1g.

For comparison, calculation of a generalized seismic coefficient according to the Bulgarian national seismic code [10] was performed. If only the fundamental period is taken in to account, the following relation holds:

$$\begin{aligned} C_s^* &= k_c C R \beta(T) = 0{,}1 * 1{,}5 * 0{,}25 * 0{,}8 = \\ &= 0{,}1 * 0{,}3 = 0{,}03 \end{aligned} \qquad (15)$$

Such comparison could only serve general orientation about the results from the quite different approaches since the meaning of the single multipliers is here complete different: in fact, k_c = a_E/g, C = 1,5 represents the importance class of the structure, R = 0,25 is the reciprocal value of the corresponding ductility factor, and the dimensionless function β(T) gives the shape of the design response spectrum with respect to three groups of soil conditions. The used here value is according to the actual conditions (foundation in rock) and fundamental period.

The difference between the results is obvious. As it can be clearly seen, when applying simplified approaches, one should be cautiously aware of all assumptions made as well as of the meaning of every single parameter used.

Finally, the maximal earthquake-induced crest displacements can be calculated:

- The maximal dynamic horizontal (transversal) crest displacement for the design excitation with PGA = 0,1g is 4,4 cm according to Eq.(8). For comparison, the computed horizontal seismically induced displacements by the Designer by means of a sophisticated non-linear FE-model are 14 cm + 4,5 cm (initial + residual value) with maximal amplitude of 7 cm. Although any direct comparison would be impossible and simply non-professional, the accuracy of the dynamic displacement is obviously not bad.
- The maximal dynamic vertical crest settlement for the design excitation with PGA = 0,1g is 3,7 cm according to Eq.(9). For comparison, the computed horizontal seismically induced displacements by the Designer are 22 cm + 5 cm (initial + residual value) with maximal amplitude of 6 cm. Also here, under the above formulated assumptions, the accuracy of the dynamic displacement is fully acceptable, too. If as usual according to [10], the maximum vertical excitation is assumed to be 2/3 of the maximal horizontal one, the maximal vertical crest displacement will become 2,48 cm instead of 3,7 cm.

2. CLOSURE

The above illustrated application of a strongly simplified approach to the seismic response of a rock-fill dam with asphaltic core or to determination of some particular parameters of the dam structural behaviour can be highly efficient with respect to the possibility to obtain in a very short time orientation about quantitative values of key parameters of the dam and its response to different loads and impacts. Such results are especially useful when the obtained values are realistic. In many cases, the latter one can be proved by means of comparison with measured values or with results from rigorous computations with much more realistic sophisticated models of the system.

However, in many cases such comparison possibilities simply do not exist, and just in such cases, obtaining a preliminary realistic assessment is especially important. In such cases the application of heavily simplified approaches can become a problem. In this connection, the following considerations should be taken into account:

- Despite of the theoretical (although based on simple mechanical models) justification of every component of the compound seismic coefficient in the pseudo-static equivalent-force approach or of the relation used for a particular physical effect, the obtained results should be treated with great caution.
- The use of an integral seismic coefficient in the pseudo-static equivalent-force method is a matter of global approach, and the particular calculation procedure should always be applied in its consistency and completeness with respect to the particular assumptions and effects accounted for. The emphasized caution needed here is due to the ambition to describe at the end all substantial physical phenomena of interest by means of a single number.
- In general, it is different when simplified relations are applied to particular response parameters (for example: earthquake-induced crest settlement), however, in such cases one should be quite clearly aware of the assumptions and features of the mechanical system model justifying the used relation(s) as well as of the assumptions and features of the impact describing model.
- Rich experience in the field is inevitably required for any application of any similar simplified approach.
- Last but not least – although simplified approaches are most commonly used for independent control purposes parallel to the use of sophisticated computational procedures, their application also needs an independent control. If measurements and / or sophisticated computational models are not present, an independent comparison with similar cases, data from literature sources etc. will be inevitable.

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