Seismic Analysis of Pine Flat Concrete Dam

S. Mitovski, L. Petkovski, G. Kokalanov, V. Kokalanov, and F. Panovska

Abstract Pine Flat Dam, located on King's River, east of Fresno, California, was constructed by the US Army Corps of Engineers in 1954 with height of 122 m. The dam's behavior was extensively studied in the 1970's and 1980's at the University of California at Berkeley that provide measured and calculated responses for correlation and comparison. For such purpose the dam was analyzed at action of various seismic excitations by taking in consideration linear and non-linear material properties as well and the effect of wave velocities of the rock foundation. The numerical analysis was carried out by preparation of 3D model of the dam thus applying code SOFiSTiK.

Keywords Pine flat dam · Numerical analysis · SOFiSTiK

1 Introduction

The formulation for Theme A requires case study of the seismic response of Pine Flat Dam at action of various earthquake excitations so called Cases. Namely, the formulators have developed a list of cases in order comparative studies to be performed, including linear and non-linear material models that are to be included in the numerical analysis. Total of 8 case studies were formulated, such as:

– Case A—EMVG Test Simulation (Simulation of the eccentric-mass vibration generator (EMVG) performed at Pine Flat Dam in 1971 is considered for Case A)
– Case B—Foundation Analysis using Impulsive Loads (Investigate the effect of foundation size and analyze the efficiency of non-reflecting boundary conditions in the dynamic analysis of dams. Analyses will use the Impulsive Stress Records)

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– Case C—Dynamic Analysis using Impulsive Loads (Case B, which considers only the foundation, is extended to include the dam and reservoir. Analyses will use the Impulsive Stress Records)
– Case D—Dynamic Analysis for Various Reservoir Levels (Investigate the effect of water levels. The dam-reservoir-foundation model defined in Case C is analyzed for various reservoir water levels and Taft Record)
– Case E—Non-linear Dynamic Analysis (Investigate the effect of nonlinear behavior of the dam. The dam-reservoir-foundation model defined for Case D is extended to include nonlinear properties for concrete. Analyses will use the Taft and ETAF Record)
– Case F—Massless Foundation (Investigate the effect of using a massless foundation. The dam-reservoir-foundation model defined for Case D is modified to use a massless foundation. Analyses will use the Taft Record).

Within the paper are displayed and analyzed some of the output results for Case A, Case C, Case D and Case E.

2 Dam Geometry and Modelling

Pine Flat Dam, located on King's River, east of Fresno, California, was constructed by the US Army Corps of Engineers in 1954. It consists of thirty-six 15.25 m-wide and one 12.2 m-wide monoliths. The length of the straight gravity dam is 561 m and the tallest non-overflow monolith no. 16 is 122 m high (Fig. 1), adopted for the analysis. Within the stage of numerical analysis, following steps must be undertaken, typical for this type of analysis: (1) choice of material parameters and constitutive laws (concrete. rock foundation and interface elements); (2) discretization of the dam and the rock foundation and (3) simulation of the dam behavior for the typical loading states (as required in the topic formulation).

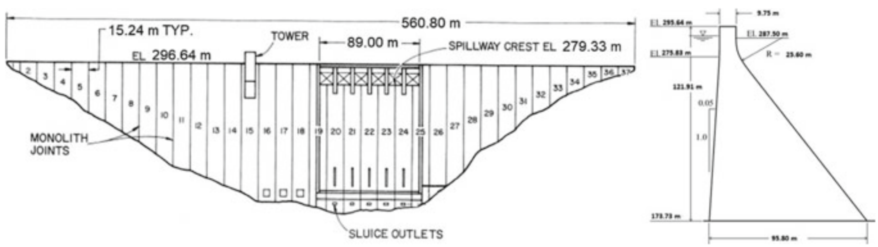


Fig. 1 Downstream view of Pine Flat dam and cross section geometry of Monolith 16

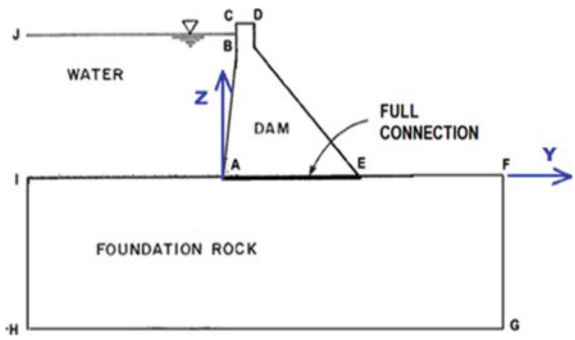


Fig. 2 Model cross section

2.1 Model Base Configuration

The model consists of the 15.24 m-wide dam monolith and a corresponding strip of the foundation. The origin of the axis system and key reference nodes are shown in Fig. 2. The axis and reference nodes are located on the mid-width of the monolith. A "base configuration" of the model is defined according to the dam dimensions (Fig. 1) and foundations dimensions' length: H-G = 700 m, depth: I-H = 122 m, dam heel location: I-A = 305 m (Fig. 2) and reservoir water level at 268.21 m, recorded at Pine Flat Dam in winter 1971.

2.2 Description of Program Package SOFiSTiK

The numerical analysis of Pine Flat dam is carried out by application of program SOFiSTiK, produced in Munich, Germany. The program is based on finite element method and has possibilities for complex modeling of the structures and simulation of their behavior. It also has possibility in the analysis to include certain specific phenomena, important for realistic simulation of dam's behavior, such as: discretization of the dam and foundation taking into account the irregular and complex geometry of the structure, simulation of stage construction, simulation of contact behavior by applying interface elements and etc. in order to assess the dam behavior and evaluate its stability. The program SOFiSTiK in its library contains and various standards and constitutive laws (linear and non-linear) for structures analysis [1].

2.3 Input Parameters and Constitutive Laws for the Materials

The choice of material parameters, as input data for the stress-deformation analysis is complex process, taking into account various factors and influences. A linear constitutive law is applied for the rock foundation and concrete (assumed to be

Table 1 Input parameters of the materials

Parameter	Rock	Concrete (linear)	Water
Modulus of elasticity [MPa]	22 410	22410	0.6
Density [kg/m^3]	2 483	2483	1000
Poisson ratio	0.20	0.20	0.499
Shear wave velocity [m/s]	1 939		
Compressional wave velocity [m/s]	3 167		1439
Compressive strength		28.0	
Shear modulus [MPa]			0.2
Bulk modulus [MPa]			2080
Tensile strength		2.0	
Fracture energy		250.0	
Compressive strain at peak load		0025	
Tensile strain at peak load		0.00012	

homogeneous and isotropic throughout the entire dam), for each Case except for Case E, whereas input data are specified in Table 1.

In Case E is applied non-linear constitutive law for concrete, according to Eurocode 2, concrete grade 30, and input parameters are specified in Chap. 6. The water load is important specific phenomena in case of dams. Rather complex is the water effect simulation in numerical models in case of seismic loads, where there are generally two approaches—by Westergaard method (added masses) or by compressible fluid (applied here below).

2.4 Discretization of Dam Body and Foundation by Finite Elements

Applied finite elements. Numerical analysis in the report are performed by spatial (3D) model, at 1 m' length in X-direction, and it can be approximated as plane analysis. Namely, the applied boundary conditions enable plane state analysis of the models. The dam body and the foundation are modeled with volume elements. A powerful and reliable finite element should be applied in case where an analysis of structure with complex geometry and behavior is required, having in consideration that the correctly calculated deformations and stresses are of primary significance for assessment of the dam stability. Generally, for discretization of the dam body and the rock foundation are applied quadrilateral finite element (as auxiliary elements, type quad, by 4 nodes), volume finite element (type brick, by 8 nodes) and interface element (dampers and water bedding) of type spring.

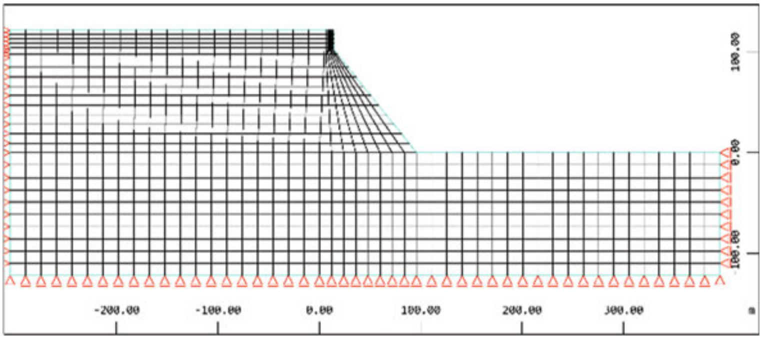


Fig. 3 Display of coarse finite element mesh (N = 816), applied for Case A, Case D, Case E and Case F

Numerical model. The model is composed of dam body, rock foundation and water fluid modeled as compressible, according to the specified geometry (Fig. 3). The model has geometrical boundaries, limited to horizontal and vertical plane whereas are defined the boundary condition of the model, varying for various Cases. The discretization is conveyed by capturing of the zones of various materials in the model—concrete and rock foundation and such model was applied for Case A, D, E and F. The model for Case C is explained in Chap. 4.

2.5 Dam Loading

Static load includes weight of concrete dam and the reservoir without weight of foundation block taken into consideration. The applied water loading includes simulation of the dam behavior for three reservoir levels: (a) winter reservoir water level at El. 268.21 m; (b) summer reservoir water level at El. 278.57 m and (c) normal reservoir level at El. 290.00 m. There are specified demands whether the static weight of the dam, the reservoir and the foundation are to be included in the analysis.

3 Case A—EMVG Test Simulation

In Case A is performed dynamic linear analysis of the dam-foundation-reservoir system for the harmonic force record exerted by an eccentric-mass vibration generator positioned at the dam crest. The boundary conditions are adopted as follows: the horizontal edge in the lowest zone of the model is adopted as non-deformable boundary condition by fixed displacements in XYZ direction, the vertical planes perpendicular on X-axis are boundary condition by applying fixed (zero) displacements in X-direction and the vertical planes perpendicular on Y-axis are boundary

Table 2 Natural frequencies for first 6 models

Water level [m]	1st mode (dam and reservoir)	2nd mode (dam and reservoir)	3rd mode (dam and reservoir)	4th mode (dam and reservoir)	5th mode (dam and reservoir)	6th mode (dam and reservoir)
268.21	1.42	1.65	2.02	2.53	4.07	5.57
278.57	0.96	1.12	1.31	1.54	2.23	3.85

condition by applying fixed (zero) displacements in Y-direction. The input parameters for concrete and rock materials are considered elastic. During the analysis the static weight of the foundation is not included, while the static weight of the dam and reservoir is taken in consideration. The dynamic load is EMVG harmonic-force time history record applied at the middle of the dam crest in the upstream/downstream direction.

The natural frequencies for water levels at 268.21 and 278.57 masl are displayed respectively in Table 2.

The displacement time history of the upstream nodes at dam crest [C] and dam heel [A] for water level at 278.57 masl are displayed on Fig. 4. The obtained value for the relative displacements point out to dominant values of displacements at point C at the dam crest compared with the low values obtained at point A. The diagrams of the time history of the displacements have expected shape of dynamic response of such dam to EMVG record. The amplitude of the relative displacements reaches value of 0.0008 m.

Very similar case is also with the obtained accelerations. Namely, the obtained accelerations at point C are higher than accelerations at point A (Fig. 5), apropos the dam response is more dominant at dam crest.

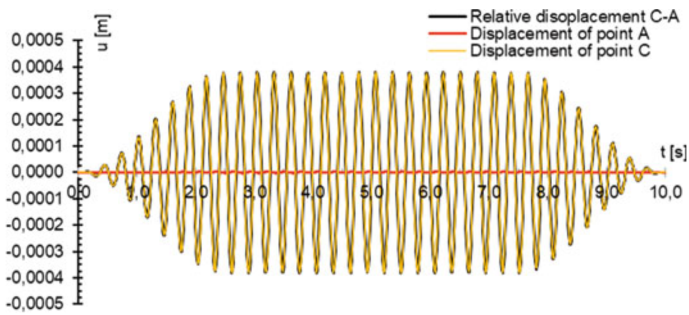


Fig. 4 The displacement time history of upstream nodes A and C and relative displacements

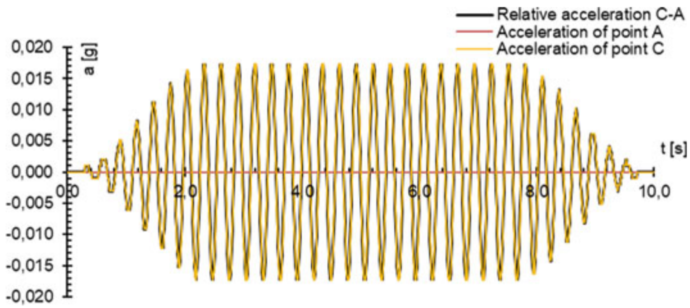


Fig. 5 The acceleration time history of the upstream nodes A and relative acceleration

4 Case C—Dynamic Analysis Using Impulsive Loads

The analysis type for Case C takes in consideration the dam and the reservoir along with the foundation model. The excitation is defined by horizontal (Y-axis) Impulsive Stress record, applied uniformly at the base of the foundation block as specified by the formulator. In this case are applied viscous boundaries that are described briefly here below. Namely, a way to eliminate waves propagating outward from the structure is to use Lysmer boundaries [2, 3]. This method consists of simply connecting dashpots to all degrees of freedom of the boundary nodes and fixing them on the other end. Lysmer boundaries are derived for an elastic wave propagation problem in a one-dimensional semi-infinite bar. The damping coefficient C_x of the dash pot equals (Eq. 1):

$$C_x = A \cdot \rho \cdot c \tag{1}$$

where A is the cross sectional area of the bar, ρ is the mass density and c the wave velocity that has to be selected according to the type of wave that has to be absorbed (shear wave velocity c_s or compressional wave velocity c_p). In two dimensions the equation takes the following form, which results in dampers C_n and C_t (Fig. 4) in the normal and tangential directions (Eq. 2):

$$C_n = A_1 \cdot \rho \cdot c_p;\ C_t C_t = A_1 \cdot \rho \cdot c_s \tag{2}$$

The shear wave velocity C_s and compressional wave velocity C_p are given by Eq. 3:

$$C_s = \sqrt{G/\rho};\ C_p = \sqrt{E(1-v)}/[(1+v)(1-2v)\rho] \tag{3}$$

where G is the shear modulus of the medium and is expressed as specified in Eq. 4:

$$G = \sqrt{E/(2(1+v))} \tag{4}$$

Here E is the Young's modulus and υ is the Poisson's ratio. The procedure leads to the frequency independent boundary conditions that are local in time and space. If the shape functions of the neighboring finite elements are used instead of crude lumping procedure, a narrow banded matrix arises, which is also easy to implement.

In our calculations, the elastic material properties are taken as specified by the formulator, while the A is the dashpot's belonging area which is calculated from the code SOFiSTiK.

The fine finite element mesh was adopted for Case C due to the requirements of the dampers at bottom of the foundation that need to be placed on distance of 1.5 m (Fig. 6).

The velocity time history for Case C1 for upstream nodes C and A for water level at 268.21 masl are displayed on Fig. 7. The maximal obtained value for the velocity are practically equal at the dam crest and dam heel. Similar case is with velocities at points a (middle point of the dam width) and b (middle point of rock foundation bottom). Namely, the obtained values are practically equal, values of 0.0045 m/s and 0.0048 m/s respectively (Fig. 8).

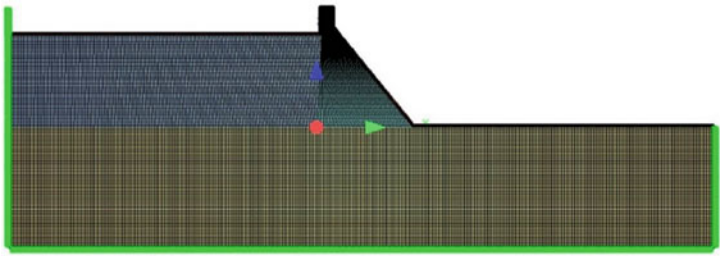


Fig. 6 Fine finite element mesh (N = 54440), applied for Case C (green lines at model edges represent the dampers)

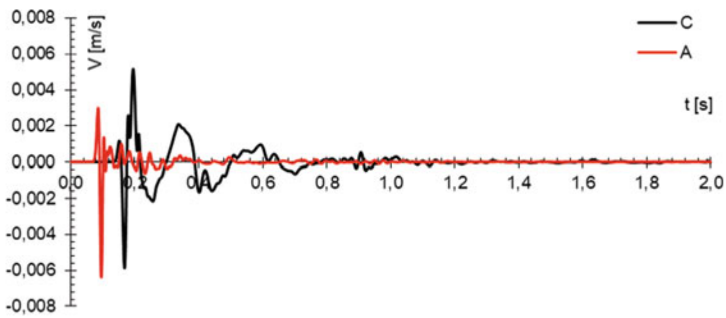


Fig. 7 The acceleration time history of upstream nodes A and C for Case C1

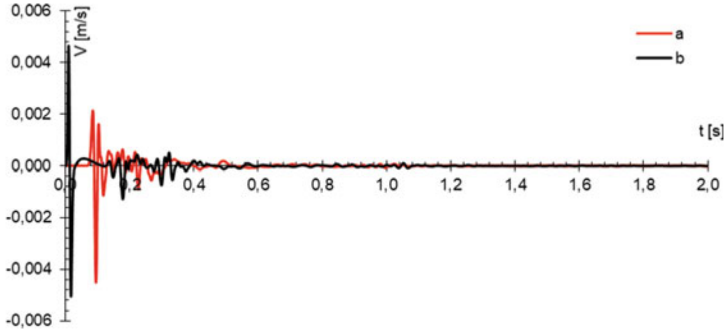


Fig. 8 The acceleration time history of nodes a (middle node of dam width) and b (middle point of foundation bottom) for Case C1

5 Case D—Dynamic Analysis for Various Reservoir Levels

In Case D, a dynamic analysis of the dam-foundation-reservoir system is performed considering the elastic material properties, the Taft earthquake record, and the reservoir water at three different elevations. The Taft record is applied as deconvolved acceleration time history at the base of the foundation block for each different reservoir water levels of 267.21 masl (D1), 278.57 masl (D2) and 290.00 m (D3) respectively. The damping parameters are adopted by Rayleigh damping calculation with input values for frequencies f1 = 4.18 Hz and f2 = 9.95 Hz.

The dam response through the various water level elevations is analyzed by the obtained values for the displacements and the hydrodynamic pressure within the excitation period for Taft record. Namely, on Fig. 9 is displayed displacements time history at point C for Case D1, D2 and D3. By the obtained values for the displacements time history there are no significant differences between analyzed water levels. Namely, the amplitude of the maximal values of the dynamic displacements ranges from 0.014 to 0.017 m for case D1 to case D3 respectively.

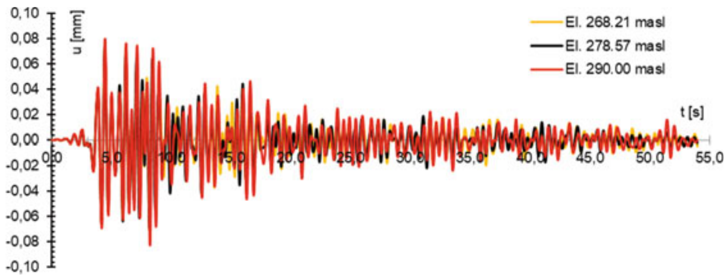


Fig. 9 The displacements time history of upstream node C for Case D1, D2 and D3

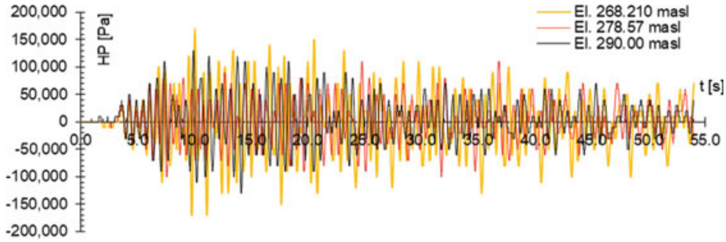


Fig. 10 The hydrodynamic pressure time history of node A for Case D1, D2 and D3

The same analogy is for the hydrodynamic pressure at the dam's heel (Fig. 10), with values ranging from of 3,40,000 Pa for case D1, 2,00,000 Pa for Case D2 and 2,60,000 for Case D3, with initial pressure set to zero.

6 Case E—Non-linear Dynamic Analysis

The analysis of Case E includes carrying out of dynamic analysis with by applying non-linear material properties for the concrete. Two different dynamic loads are applied at the base of the foundation block: The Taft (deconvolved acceleration) and ETAF Record. The non-linear material constitutive model for concrete is adopted according to Eurocode 2, EN 1992 norms [4]. For such applied non-linear law the potentially damage zones occur in case of exceedance of the tension stresses.

For Case E1 and E2 are applied Taft Record (deconvolved acceleration) and ETAF horizontal acceleration time history record at the base of the foundation block. As specified, gravity loads are applied to the dam and reservoir but not to the foundation. The analysis is performed for dam-reservoir-foundation system at water level El. 268.21 m, combined with the static load (Table 3).

The dam response for Case E1 is analyzed by the obtained values for acceleration and hydrodynamic pressure within the excitation period for Taft record. Namely, on Fig. 11 is displayed dynamic response of the dam under action of the specified

Table 3 Concrete non-linear properties

Parameter	SI unit	Value
Modulus of elasticity	MPa	31476
Density	kg/m^3	2500
Poisson's ratio		0.20
Compressive strength	MPa	33.00
Tensile strength	MPa	2.56
Fracture energy	N/m	137.0
Compressive strain at peak load		0.002

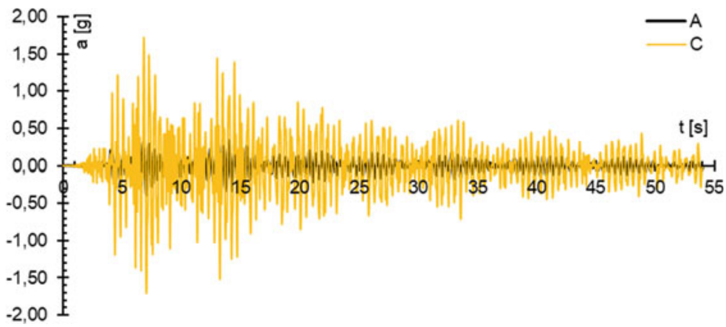


Fig. 11 The acceleration time history at node A and C for Case E1

Taft record at nodes A and C, located at dam heel and crest respectively. Maximal values for accelerations occurs at node C apropos the dam responds to Taft record amplification of the horizontal acceleration in the crest multiplied by 9.5 regarding the peak ground acceleration (dynamic amplification factor of DAF = 9.5). In case E2, on Fig. 12 is displayed dynamic response of the dam under action of ETAF record at nodes A and C. Maximal values for accelerations occurs at node C apropos the dam responds to ETAF record amplification of the horizontal acceleration in the crest multiplied by 16.2 regarding the peak ground acceleration (dynamic amplification factor of DAF = 16.2).

On Fig. 13 are displayed displacements time histories for nodes A and C and relative displacements for Case E2. The diagrams of displacements time history have expected shape of the dynamic response of the dam. The amplitude of the relative displacements has value of 0.8 m.

The hydrodynamic pressure at the dam's heel (Fig. 14), riches maximal amplitude of 9,500,000 Pa for Case E2.

On Fig. 15 is displayed potentially tension zone of the dam, for Case E1. Namely, according to the display of superimposed maximal values of principal stresses II,

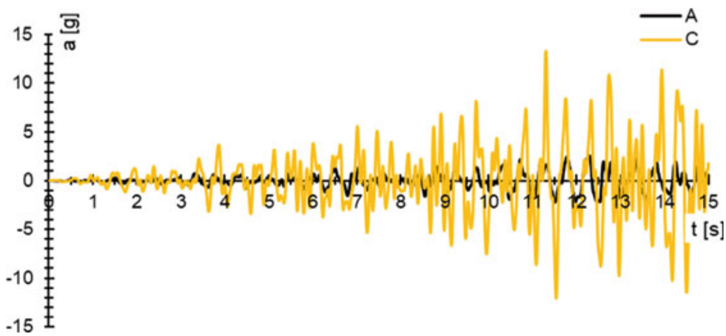


Fig. 12 The acceleration time history at node A and C for Case E2

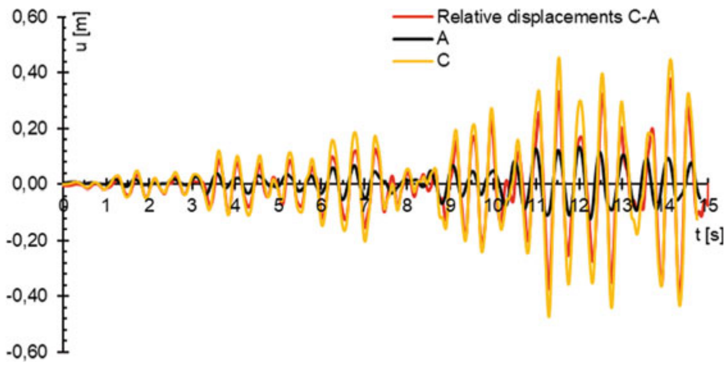


Fig. 13 The displacements time history at nodes A and C for Case E2 and the relative displacements

Fig. 14 The hydrodynamic pressure time history at node A for Case E2

Fig. 15 Display of critical case of damaged zone for Case E1

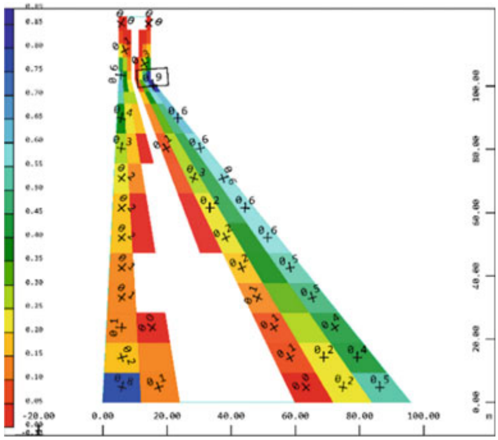
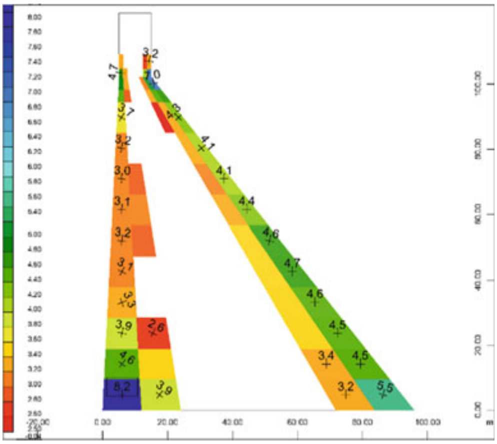


Fig. 16 Display of critical case of damaged zone for Case E2



there is no exceedance of the tension strength of 2.5 MPa, apropos the maximal value is 0.89 MPa.

On Fig. 16 is displayed potentially damaged zone of the dam, assessed as most critical, by superimposed maximal values of principal stresses II from all time steps for Case E2. Namely, within the cross section of the dam are marked zones with exceedance of the tension stress of 2.50 MPa thus assessed as potential zones for crack occurrence. Maximal value of the tension stress is 8.20 MPa, occurring at the zone of the dam's upstream heel at contact with foundation.

7 Conclusions

From the numerical experiment of simulation of the structural behavior of Pine Flat dam at various excitation records, following main conclusions and recommendations are drawn out:

- The prediction of the concrete gravity dams' behavior during construction, after construction, reservoir filling and service period by means of numerical models is of primary importance.
- The gravity dam stability includes determination of potential damaged zones, mainly occurred by exceeding the tension stress of the concrete resulting in plastification of the material. The specification of allowable tension stresses for concrete type should be done by experimental (laboratory or field) testing performed for that purpose and afterwards identification of such critical zones will be precisely determined.
- In Case A1 and A2 of the present case study are determined the first 6 fundamental frequencies of Pine Flat dam for reservoir water levels at 268.21 and 278.57 masl, ranging from 1.42–5.57 Hz and 0.96–3.85 Hz respectively, thus indicating that

the raised water level decreases the frequencies. The dam response is dominant at dam crest, as evaluated by the distribution of the relative displacements and relative accelerations during the excitation record.

- For Case C1 by the analyzed values of the velocities at upstream dam nodes A and C and nodes a (middle node of dam width) and b (middle node of foundation bottom) a modus of velocities lowering can be noticed as the nodes are more distanced then the upstream face of the dam.
- For Case D1, D2 and D3 the impact of the various water elevations results in different initial conditions due to the static load of the dam and the reservoir. The obtained values for the dynamic displacements and hydrodynamic pressure during excitation record are varying approximately for 8% for water level of 268.21 to 290.0 m.
- For Case E1 the dam responds to Taft record with dynamic amplification factor of DAF = 9.5. For case E2 the dynamic amplification factor is DAF = 16.2 for ETAF record. For Case E1 there is no occurrence of damaged zone, while for Case E2 is obtained potentially damaged zone, assessed as most critical for crack occurrence, from all time steps, with tension stress value of 8.20 MPa, occurring at the zone of the upstream heel of the dam at contact with the foundation.

From the numerical experiment of simulation of the structural behavior of Pine Flat dam at various excitation records, following recommendations for future research can be applied:

- We are on opinion that the applied non-linear constitutive law for the concrete has large impact to the obtained results regarding the damaged zones and occurrence of plastification and cracks. Namely, there are few such constitutive laws and they include various parameters for definition and determination of the damaged plasticized zones. We recommend specification of at least two non-linear constitute laws and execution of analysis for further research.
- Long term behavior of dams is extensively analyzed and researched in the recent period. The concrete properties are varying in long time period. Therefore, if possible, we believe that it will be useful to determine the some of the concrete input parameters (modulus of elasticity, compressive and tension strength) of Pine Flat dam by applying non-destructive methods and based on such parameters an innovated analysis to be conducted.
- Temperature effect is important issue in case of concrete dams. So, in the future research and analysis temperature load should be considered, in order to be obtained more comprehensive insight and assessment of the dam's behavior.

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