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NONLINEAR DYNAMIC ANALYSIS OF CONCRETE GRAVITY DAM

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SUMMARY

Pine Flat Dam, located on King's River, California, was constructed by the US Army Corps of Engineers in 1954 with height of 122 m. In the paper is carried out nonlinear dynamic analysis of the dam under action of ETAF (Endurance Time Acceleration Function) excitation record. The numerical analysis was carried out by plane (2D) model, that actually is spatial model at 1m', by application of code SOFiSTiK.

Keywords: Pine Flat Dam, numerical analysis, nonlinear dynamic analysis.

1. INTRODUCTION

The dams, having in consideration their importance, dimensions, complexity of the problems that should be solved during the process of designing and construction along with the environmental impact are lined up in the most complex engineering structures (Tančev, 2005; Novak et all., 2007). The assessment of the structural stability and the behaviour of the dam during construction, at full reservoir and during the service period is of vital meaning for this type of structures.

Structural stability of concrete dams is confirmed with analysis (research) of the response of the structure (dam) under action of static [1-5] and dynamic loading [6-8], different between themselves according to the velocity of application of the loadings. Namely, at earthquake action, the seismic loading is executed in incomparably shorter time intervals compared with the application of the loadings during construction and exploitation of the dam. In this paper are systemized acknowledgments from the nonlinear dynamic analysis of concrete gravity dam, obtained with application of advanced numerical methods, based on finite element method. Namely, here below will be illustrated output data from the dynamic analysis of Pine Flat dam, constructed in 1954 in California, USA (H=122m).

Different acceleration-time history records, which vary in terms of intensity level, shape of the record, and frequency content, can be selected for performing nonlinear time history response analysis. One might expect that uncertainty in the response of a structure would increase as the level of excitation increases; however, there is no guarantee that a particular record will induce a sufficiently large excitation to push the structural response into the highly-nonlinear range. To overcome this issue without the need for repeating the nonlinear time history analysis at increasing excitation levels, the nonlinear dynamic analysis is conducted using an Endurance Time Acceleration Function (ETAF) [9]. The ETAF is an intensifying dynamic load that shakes the structure from low to high-excitation levels (Figure 1). Dynamic analysis conducted using the ETAF acceleration time-history is equivalent to nonlinear dynamic pushover analysis, where the structural response ranges from elastic to highly-nonlinear, and finally to collapse. Over a given period of time, the response spectrum of the ETAF increases proportionately with a selected target spectrum. Namely, the Endurance Time Analysis (ETA) is a dynamic pushover procedure which estimates the dynamic performance of the dam when subjected to a pre-designed intensifying excitation. The simulated acceleration functions are aimed to shake the dam from a low excitation level - with a response in the elastic range - to a medium excitation level - where the dam experiences some nonlinearity - and finally to a high excitation level, which causes the failure. All these response variations can be observed though a single time history analysis. The case study of Pine Flat dam includes carrying out of nonlinear dynamic analysis of the dam in time domain for action of ETAF excitation for plane (2D) model.

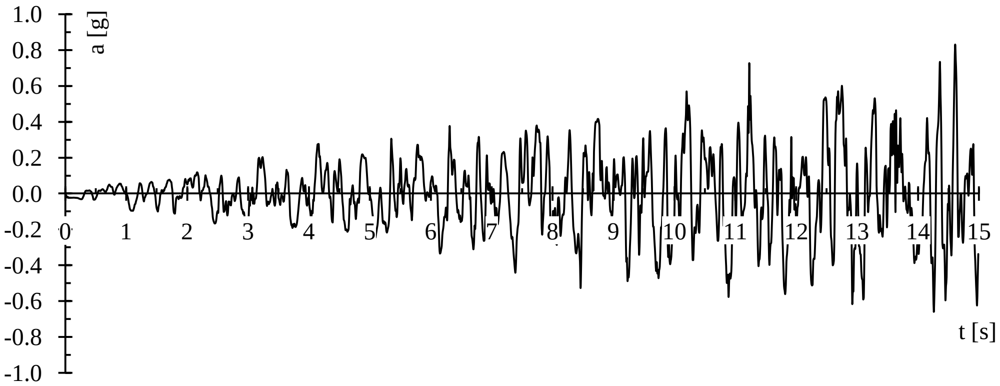

Figure 1. ETAF excitation record

2. PINE FLAT DAM

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 monolith. The length of the straight gravity dam is 561 m and the tallest non-overflow monolith no. 16 is 122 m high (Figure 2), adopted for the analysis. Within the stage of numerical analysis, following steps must be undertaken: (1) choice of material parameters and constitutive laws, (2) discretization of the dam and the rock foundation and (3) simulation of the dam behaviour for the typical loading states.

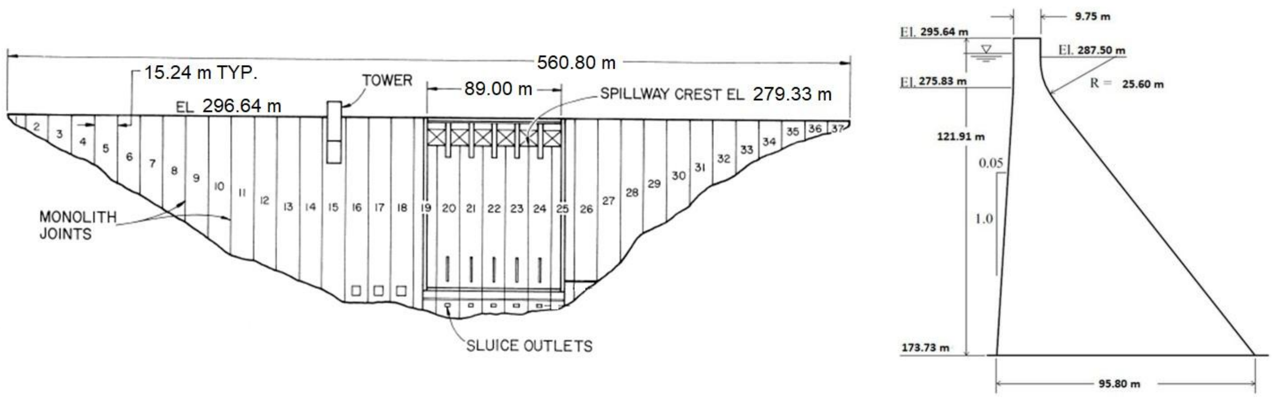

Figure 2. Downstream view of Pine Flat dam (left) and cross section geometry of monolith 16 (right)

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 Figure 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 (Figure 2) and foundations dimensions' length: H-G=700 m, depth: I-H=122 m, dam heel location: I-A=305 m (Figure 3) and reservoir water level at 290.0 m. For the case study is prepared spatial (3D) numerical model at 1m', that can be considered as plane (2D) model.

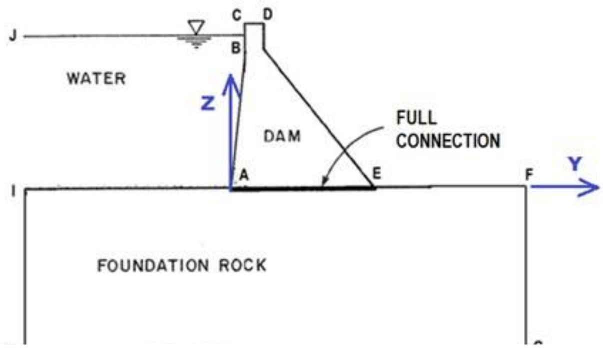

Figure 3. Model cross section

2.2 Short description of code SOFiSTiK

The numerical analysis of Pine Flat dam is carried out by application of SOFiSTiK code, produced in Munich, Germany. The program is based on finite element method and has possibilities for complex modelling of the structures and simulation of their behaviour. It also has possibility in the analysis to include certain specific phenomena, important for realistic simulation of dam's behaviour, 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 behaviour by applying interface elements, non-linear material modelling and etc. in order to assess the dam behaviour and evaluate its stability. The SOFiSTiK code in its library contains and various standards and constitutive laws for structural analysis. The core of the code is powerful and highly efficient CDBASE, in which a set of modules for various modelling problems are called upon by standard textual files combined with graphical user space [10].

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 while for concrete in the dam body is applied nonlinear constitutive law (assumed to be homogeneous and isotropic throughout the entire dam), whereas input data are specified in Table 1. For such applied non-linear law the potentially damage zones occur in case of exceedance of the tension stresses. The nonlinear material constitutive law for concrete is applied according to the input data (Table 1), combined with the LADE elastic plastic material law [10-11]. The water load is important specific phenomena in case of dams. Rather complex is the water effect simulation in numerical models in case of dynamic loads in time domain, where there are generally two approaches – by Westergaard method by added masses [6] or by compressible fluid (applied here below). The damping parameters are adopted by Rayleigh damping calculation with input values for frequencies f_1=4.18 Hz and f_2=9.95 Hz.

Table 1. Input parameters of the materials

Parameter	Unit	Rock	Water	Concrete
Modulus of Elasticity	[MPa]	22 410	0.01248	22410
Density	[kg/m3]	2 483	1000	2400
Poisson Ratio		0.20	0.499999	0.20
Compressive Strength				28.0
Shear modulus	[MPa]		0.00416	
Bulk modulus	[MPa]		2080	
Tensile Strength				2

2.4 Discretization of dam body and foundation by finite elements

Numerical analysis in the report are performed by spatial (3D) model, at 1m' 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 modelled with volume elements. A powerful and reliable finite element should be applied in case where an analysis of structure with complex geometry and behaviour 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.

The model is composed of dam body, rock foundation and water fluid modelled as compressible, according to the specified geometry (Figure 4). 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.

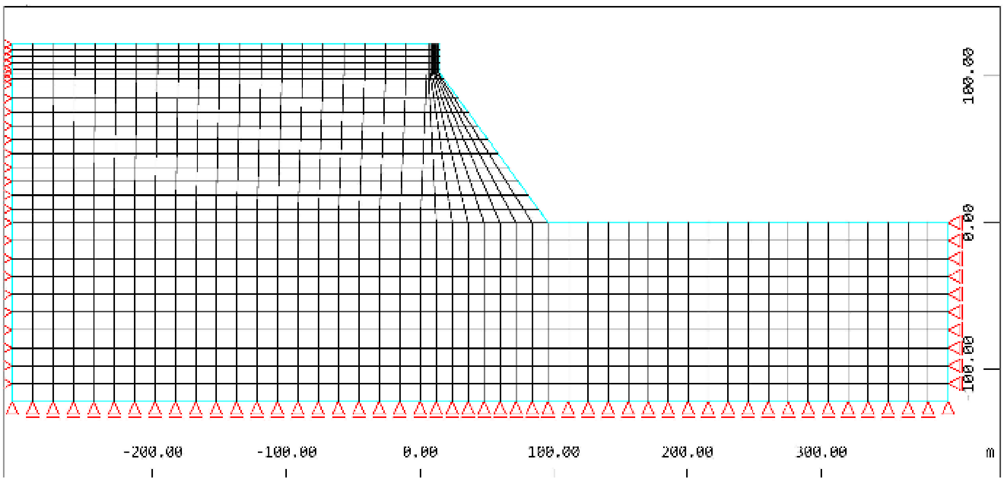

Figure 4. Display of coarse finite element mesh (N=816), applied for the Case Study

2.5 Dam loading

Static load includes weight of concrete dam, reservoir and foundation. The applied water loading includes simulation of the dam behaviour for normal reservoir level at El. 290.00 m.

3. NON-LINEAR DYNAMIC ANALYSIS OF THE DAM

In the Case study a nonlinear dynamic analysis of the dam-foundation-reservoir system is performed considering the elastic and plastic material properties, the ETAF earthquake record and the normal reservoir water level.

The dam response is analysed by the obtained values for the displacements and the acceleration within the excitation period for ETAF record. On Figure 5 are displayed displacements time history at node A and node C as well and the relative displacements (C-A). The diagrams of displacements time history have rather expected shape of the dynamic response of the dam, having in consideration the shape of the ETAF excitation record. The amplitude of the maximal values of the displacements at node C is 1.36 m. The increasing pattern of the displacements time history at node C is mostly influenced by the ETAF record as well and the water reservoir.

On Figure 6 are displayed relative crest displacements at node C from conducted Case study of nonlinear dynamic analysis of Pine Flat dam by 14 participants, that tends to investigate the progressive damage response of the dam subjected to an ETAF [12]. It can be noticed that some of the individual curves show results as high as 4.70m. The median (dotted block line)

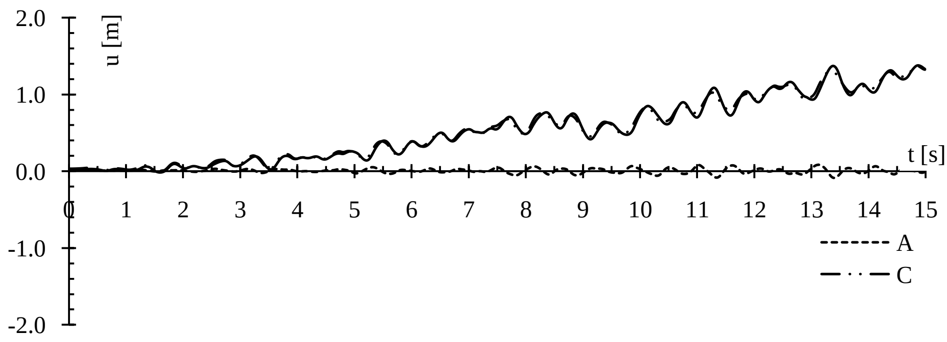

Figure 5. The displacements time history at node A and node C and relative displacements (C-A)

curve shows a total of about 0.4 m displacement at t = 15 s. The obtained displacements at node C (Figure 5) are in similar shape and values compared with the obtained displacements at node C from the conducted case study. However, it is required more detail specification of the non-linear modelling and simulation of water reservoir behaviour.

On Figure 7 is displayed dynamic response of the dam under action of the specified ETAF record at node C. Maximal values for accelerations as expected occurs at node C apropos the dam responds to ETAF record with amplification of the horizontal acceleration in the crest multiplied by 2.57 regarding the peak ground acceleration of ETAF record (dynamic amplification factor of DAF=2.25).

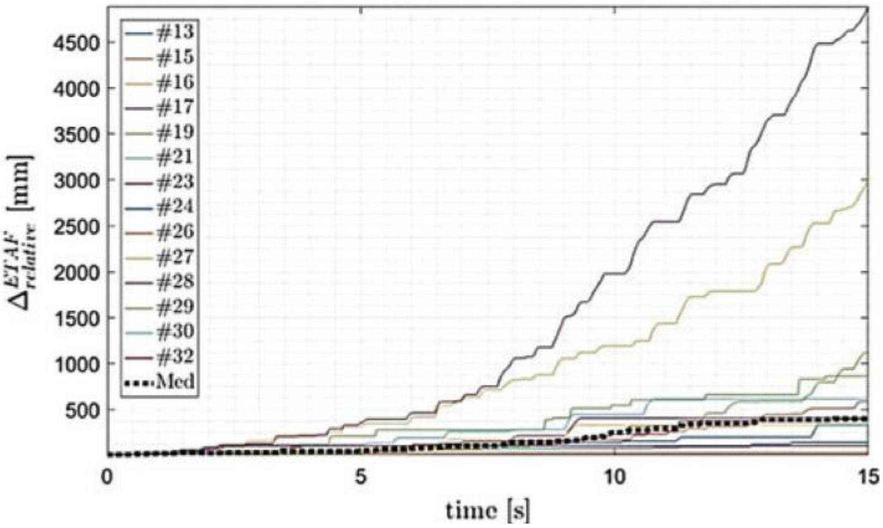

Figure 6. Displacement evolution of the relative crest displacement (node C) under ETAF excitation record [14]

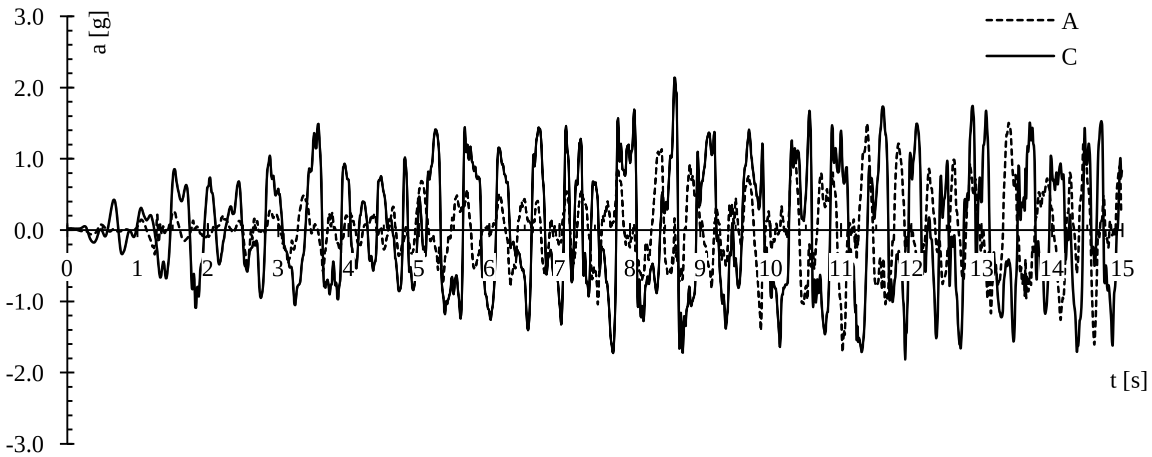

Figure 7. The acceleration time history at node A and node C

On Figure 8 and Figure 9 are displayed assessed potentially critical zones of the dam, by superimposed maximal values of principal stresses I and II from all time steps. Namely, within the cross section of the dam are specified zones with the maximal tension stresses. The permissible tension stresses are specified at 2 MPa, while the permissible compression stress are specified at 10.0 MPa. Exceedance of the specified tension stress value will imply on potential zones for crack occurrence. Maximal value of the tension stress is 1.4 MPa, occurring at the zone of the below the dam crest, where the dam cross section is widening. Maximal value of the compression stress is 9.97 MPa, occurring at the downstream toe of dam.

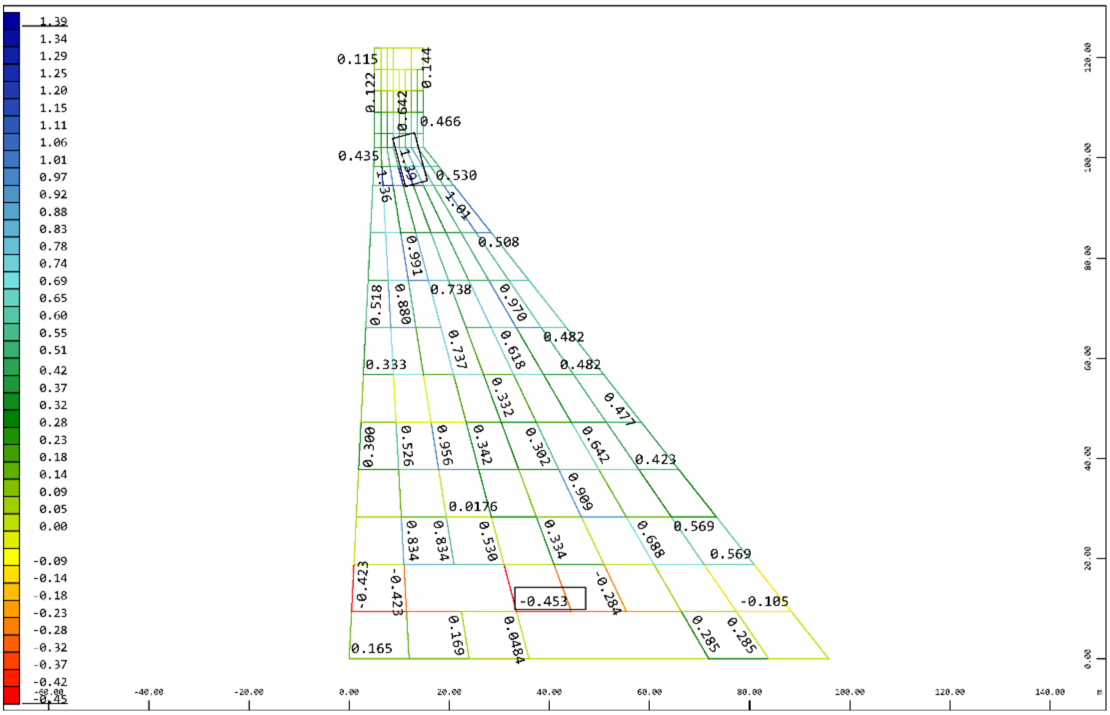

Figure 8. Display of zones of maximal tension stress, $\sigma_{1,max}$=1.40 MPa

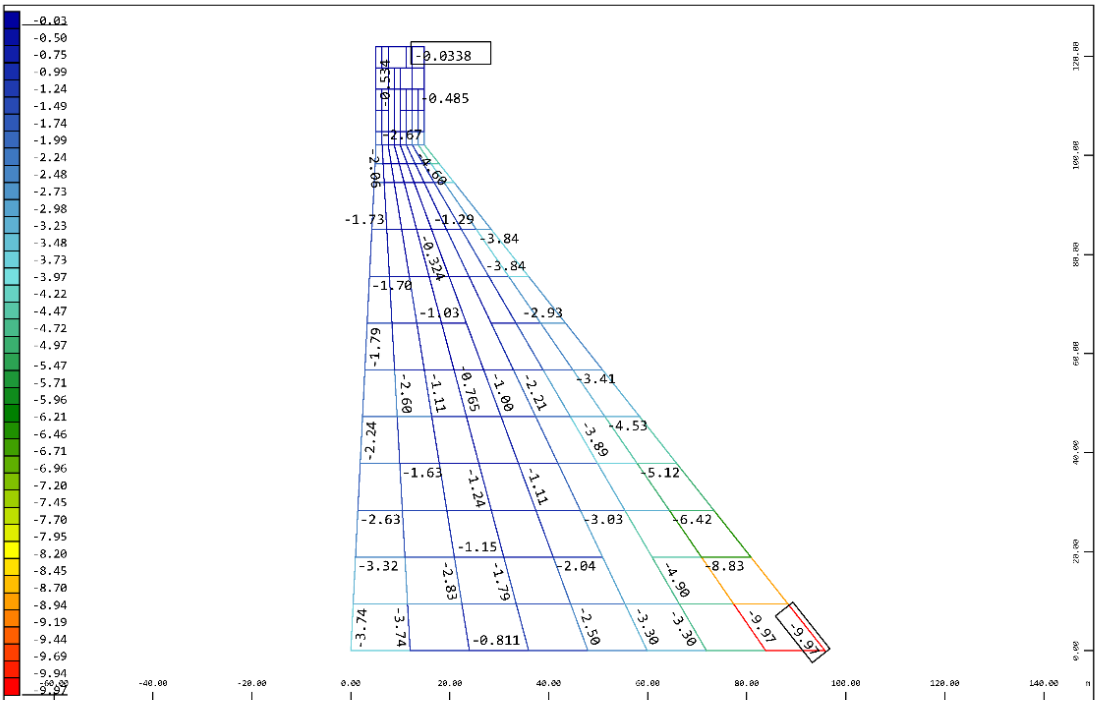

Figure 9. Display of zones of maximal compression stress, $\sigma_{3,max}$=9.97 MPa

4. CONCLUSIONS

From the numerical experiment of simulation of the structural behaviour of Pine Flat dam for ETAF excitation record, following main conclusions are drawn out:

- The displacements time history at node C (dam crest) have rather expected shape of the dynamic response of the dam, having in consideration the ETAF excitation record, with amplitude of 1.36 m. The pattern of the displacements time history at node C is mostly influenced by the ETAF excitation record as well and the water reservoir modelling.
- 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 permissible 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. It can be concluded that there is no exceedance of the permissible tension or compressible stress that implies that the dam stability is achieved regarding cracks occurrence.
- The dynamic amplification factor DAF=2.57 the for ETAF record.
- The applied non-linear constitutive law for the concrete and modelling of the reservoir as compressible fluid has large impact to the obtained output results regarding the displacements, accelerations, damaged zones and occurrence of plastification and cracks. It is of paramount importance to be specified input data for the nonlinear concrete constitutive law and the water based on experimental laboratory investigations in order to be conveyed more accurate dynamic analysis.

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НЕЛИНЕАРНА ДИНАМИЧКА АНАЛИЗА ГРАВИТАЦИОНЕ БЕТОНСКА БРАНА

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Резиме

Гравитациону бетонску брану Pine Flat Dam на реци Кингс, у Калифорнији, висине 122 m, изградио је 1954. године Инжењеријски корпус Војске САД. Браном је формирана значајна вишенаменска акумулација, од којих је једна од важних фукција активна заштита од поплава. Пошто се налази у доста израженом трусном подручју, битно је ажурно оскултационо, али и моделско праћење понашања бране у условима побуде убрзањем ETAF (Endurance Time Acceleration Function). Захваљујући подацима осматрања те бране могуће су свестране анализа њеног понашања. Аутори су своје анализе засновали на 2D моделу, који је, у суштини, 3D модел примењен на 1 m'. Применили су софтверски пакет SOFiSTiK који има врло широку употребљивост. Заснован је на методи коначних елемената и има могућности за сложено моделирање структура и симулацију њиховог понашања. Такође има могућност да у анализу укључи одређене специфичне појаве, важне за реалистичку симулацију понашања бране, као што су: дискретизација бране и темеља узимајући у обзир неправилну и сложену геометрију конструкције, симулацију изградње у више етапа (или етапногграђења), симулацију контакта понашање применом елемената интерфејса, нелинеарно моделирање материјала, итд. Таквим анализама се може априорно проценити понашање бране њена стабилност при разним спољним утицајима. Стабилност гравитационе бране укључује одређивање потенцијално оштећених зона, углавном насталих прекорачењем напрезања бетона на затезање. Спецификацију допуштених затезних напрезања за тип бетона треба извршити експерименталним (лабораторијским или теренским) испитивањима која се изводе у ту сврху, а затим се идентификација таквих критичних зона може прецизно одредити. Може се закључити да не постоји прекорачење дозвољеног затезања или стишљивог напрезања што имплицира да се постиже стабилност бране у погледу појаве пукотина.

Кључне речи: брана Pine Flat Dam, анализа стабилности, нелинеарна динамичка анализа, програмски пакет SOFiSTiK.

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