ASSESSMENT OF THE SEISMIC BEHAVIOUR OF CONCRETE DAMS: FROM SIMPLIFIED TO ADVANCED METHODS

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Abstract: *The evaluation of the structural response of concrete dams to earthquake is carried out by means of numerical simulations generally with the finite element method (FEM), which allow to reproduce with good accuracy the real dynamic behaviour of the system consisting of the dam, the reservoir and the foundation. Different methods of analysis can be adopted, characterized by increasing complexity: the simplest methods, based on some simplifying physical assumptions, generally provide a faster, conservative and more comprehensible response; on the other hand, the most complex methods, although computationally expensive, allow to successfully deal with physical situations that often the simplest methods are not able to represent, providing a more accurate and realistic description of the structural behaviour and reducing the excessive conservativity of the results. An accurate method for the seismic analysis of dam-foundation-reservoir systems should be able to consider the three-dimensionality of the problem, the semi-unbounded size of the foundation, the non-linear behaviour of the system and the dynamic interactions of the dam with the foundation and the reservoir. An advanced approach, to be adopted in the frame of time-history linear or non-linear analyses and able to face all the aforementioned complexities, was recently implemented and tested by RSE: the approach, indicated by the acronym SAM-4D (Seismic Advanced Model for Dams), allows to appropriately simulate the propagation of seismic waves in a realistic massed foundation, considering its semi-unbounded extent. Artificial non-reflecting (or absorbing) boundaries are used to delimit the semi-unbounded foundation and effective earthquake forces (computed with reference to the elastic wave vertical propagation theory) provide the seismic motion. The Pine Flat Dam, used in the frame of the ICOLD 15th International Benchmark Workshop on Numerical Analysis of Dams, is considered as a case study to perform analyses of increasing complexity, starting from the pseudo-static analysis up to the non-linear time-history analysis using the SAM-4D model.*

1. Introduction

Numerical simulations, generally carried out by means of the finite element method (FEM), are nowadays the most widely used and effective tool for assessing the structural safety of complex structures such as concrete dams. The analysis methods have been developed hand in hand with the progressive increase of the computing power and today several methods, characterized by increasing complexity, are available. In the frame of seismic analyses, the time-history analysis based on the direct integration of the equations of motion is now the most powerful method available for evaluating the response of the dams to earthquakes: the advantages of this method are that it can be used for both linear and non-linear analyses and can properly consider the dynamic interactions of the dam with the reservoir and the foundation, providing an accurate and reliable description of the seismic response of the structure. An advanced approach in the context of time-history analyses, that allows to appropriately simulate the propagation of seismic waves considering the dissipation effects through the boundaries of the artificially truncated massed foundation, indicated by the acronym SAM-4D (Seismic Advanced Model for Dams), was recently implemented and tested by RSE (Faggiani et al. 2019, 2020, 2021, 2022). Although the advanced methods can properly simulate important features of the real behaviour of structures, they are complex to use, computationally demanding and require experience and competence for the evaluation of the results and confidence for their comprehension. It could be therefore convenient to adopt a progressive analysis methodology (US Army Corps of Engineers – USACE 2007): this progressive approach is applied to the case study of Pine Flat Dam, already considered in the frame of the ICOLD 15th International Benchmark Workshop on Numerical Analysis of Dams (Salamon et al. 2020).

Section 2 briefly summarizes the progressive analysis methodology with a focus on the methods applied for the case study: the pseudo-static analysis (§ 2.1), the time-history analysis with the massless approach (§ 2.2), the time-history analysis with the SAM-4D model (§ 2.3). Section 3 describes the case study, detailing the numerical model (§ 3.1), the loadings (§ 3.2) and the results (§ 3.3). The main overcomes are summed up in Section 4.

2. Progressive analysis methodology for the seismic safety assessment of concrete dams

The progressive analysis methodology, used to assess the effect of the seismic action, consists in subsequent phases of increasing complexity, starting from the simplest method appropriate to the problem, that provides faster and more easily comprehensible results, and progressing to the more complex methods, that are supposed to provide more accurate and realistic results. The three analysis methods adopted for the case study of Pine Flat Dam, used to show an application of the methodology to the seismic safety assessment of concrete dams, are outlined in this Section: the historical pseudo-static analysis method and two different approaches within the time-history analysis method, based on the direct integration of the equations of motion. The time-history analysis method consists in simulating the entire time history of the behaviour of the structure subject to the ground motion and represents the most robust available method to study the response of structural systems to earthquakes nowadays. One of the main advantages of the method is that it can be used for both linear and non-linear dynamic analyses: it is therefore possible to study the dynamic behaviour of the dam including opening and sliding of the joints and cracking of the concrete. Both the adopted time-history approaches are able to simulate the dynamic interaction between the dam and the reservoir through the classic structural-acoustic coupling on the upstream face of the dam, where the normal component of the dam acceleration is related to the normal gradient of the water hydrodynamic pressure (Zienkiewicz 1977), that allows to consider the compressibility of the water; on the contrary, the two approaches greatly differ in the simulation philosophy of the dynamic interaction between the dam and the foundation.

2.1. Pseudo-static analysis

The pseudo-static analysis method (also referred to as seismic coefficient method), widely used in the past, is considered to be outdated today and should no longer be used for the seismic safety assessment of large dams (Wieland 2008, 2012): nevertheless, it can be useful to get a preliminary estimate of the response of a dam to the seismic action. The method calculates the seismic response with a static analysis, using additional static loads: the inertia forces of the structural mass and the hydrodynamic pressure on the upstream face of the dam. The additional static loads are evaluated considering the whole structure subjected to uniform acceleration (rigid body hypothesis), equal to a fraction of the peak ground acceleration. To better account both for the dynamic characteristics of the dam-foundation-reservoir system and for the characteristics of the ground motion, the spectral ground acceleration corresponding to the fundamental natural frequency of the system can be used.

2.2. Time-history analysis with the massless approach

For a long time, the most used procedure to simulate the dynamic interaction between the dam and the foundation (within the issue of seismic safety assessment of dam-foundation-reservoir systems) was the traditional and consolidated massless approach (Clough 1980) based on the simplifying hypothesis of considering the foundation with zero mass: the input motion is uniformly imposed at its truncated boundaries and reaches instantaneously the dam-foundation interface since the wave velocity tends to infinity. The main deficiency of the approach is that, considering only the flexibility of the foundation, both inertial and radiation damping effects are neglected: consequently, the seismic response of dams results significantly overestimated (Chopra 2014, Hansen and Nuss 2013, Zhang and Jin 2008).

2.3. Time-history analysis with the SAM-4D model

As the massless approach is proved to significantly overestimate the seismic response of dams, it may be important to reduce its excessive conservativeness, that sometimes leads to the wrong conclusion that an existing dam is unsafe according to the current regulations: this purpose can be achieved by adopting advanced structure-foundation dynamic interaction models, able to correctly reproduce the propagation of seismic waves. The dam-foundation seismic interaction model SAM-4D, recently implemented and tested by RSE (Faggiani et al. 2019, 2020, 2021, 2022), allows to ideally reproduce the behaviour of the real semi-unbounded foundation representing the wave propagation in a computation domain delimited by appropriate artificial boundaries and realistically provided with mass: the main properties of the model are deduced from Chen et al. 2012, Liu et al. 2006, Liu and Chen 2013, Zhang et al. 2009; Løkke and Chopra 2019 was considered as important reference too. The semi-unbounded extension of the foundation is achieved using artificial non-reflecting (or absorbing) boundaries at the truncations of the computational domain: one horizontal (the bottom boundary) and four vertical (the side boundaries) planes. The artificial boundaries consist in a layer of normal and tangential dampers and springs; if only dampers are used, the classic non-reflecting boundaries are obtained (Lysmer and Kuhlemeyer 1969). The incoming seismic waves are specified by means of effective earthquake forces, applied at both the bottom and the side boundaries of the foundation and computed, starting from the free-field ground motion, using the theoretical solution of the vertically propagating elastic wave problem in a half-space; the non-reflectivity of the boundaries allows the exit from the foundation of the outgoing waves, scattered by the dam-reservoir system, that propagate towards infinity. In case the half-space is homogeneous and undamped, the incident motion at the bottom boundary is equal to one-half the free surface motion: this simplification may be appropriate if the rock is assumed homogeneous and with no or little (up to 2%) material damping (Løkke and Chopra 2019).

3. The case study of Pine Flat Dam

The seismic analysis of Pine Flat Dam (Fresno, California, USA), a large concrete gravity dam consisting of thirty-six 15.25 m wide monoliths and one 12.2 m wide monolith, was recently proposed in the frame of the ICOLD *15th International Benchmark Workshop on Numerical Analysis of Dams* (Salamon et al. 2020) and before in the USSD Workshop *Evaluation of Numerical Models and Input Parameters in the Analysis of Concrete Dams* (Salamon 2018). The case study only concerns the tallest 15.25 m-wide dam monolith no. 16 (about 122 m hight).

In this paper, Pine Flat Dam is considered to perform an application of the progressive analysis methodology. Several analyses of increasing complexity are carried out: the linear elastic pseudo-static analysis, the linear elastic time-history analysis with the massless approach, the linear elastic time-history analysis with the SAM-4D model, and the non-linear time-history analysis with the SAM-4D model.

3.1. Geometrical and physical model

The 3D FEM model, reported in Figure 1, includes the dam monolith and the relevant portions of the foundation and of the reservoir. The structural problem is schematized as a 2D (plane strain) problem applying appropriate symmetry conditions at side boundaries of the model. The different parts of the mesh (dam, foundation and reservoir) are discretized quite uniformly, with element size ranging from 3 m to 6 m. The fluid domain is obtained by extruding the upstream face of the dam mesh up to the upstream boundary of the foundation. The model of the foundation is characterized by elements of uniform height equal to about 6 m, that allows to describe with good accuracy frequencies up to about 15 Hz (for the time-history analyses with the SAM-4D model). For the non-linear analysis a more refined mesh only for the dam is considered, with element size of about 1.5 m. The case study was approached with the commercial FEM code Abaqus (Dassault Systèmes 2021).

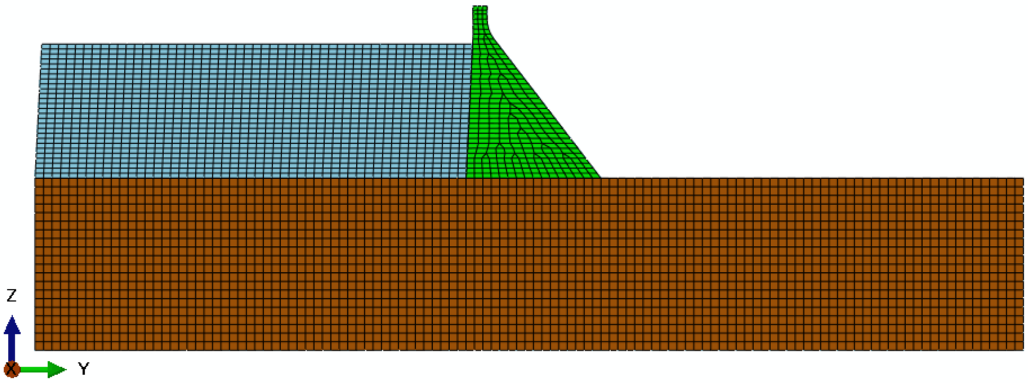

Figure 1. FEM model of the dam monolith, the foundation and the reservoir.

Foundation rock is assumed to behave linear-elastically; depending on the type of analysis (linear or non-linear) dam concrete may behave linear-elastically or according to the Concrete Damaged Plasticity model proposed by Lee and Fenves (1998) and available in Abaqus. According to this model, under uniaxial tensile loading the stress-strain response of concrete is linear-elastic until the tensile strength is attained; subsequent increases of strain cause the progressive damage of the material, characterized by the loss of stress for increasing deformation (softening) and by the reduction of stiffness in the unloading phase. The loss of stress and the growth of damage are assigned as functions of the progressive opening of the crack (Figure 2). The damage variable can take values from zero, representing the undamaged material, to one, which represents total loss of strength.

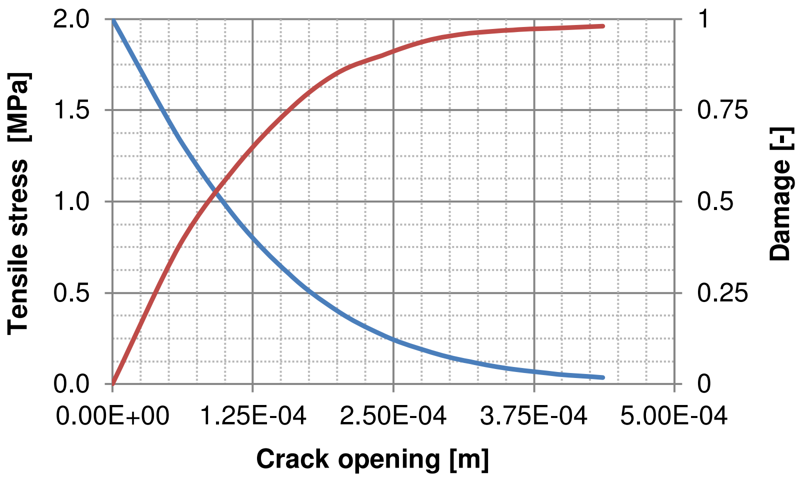

Figure 2. Concrete Damaged Plasticity model. Tensile stress (blue line) and damage variable (red line) versus crack opening.

The dynamic interaction between the dam and the reservoir (for the time-history analyses) is achieved through the classic structural-acoustic coupling (Zienkiewicz 1977); no dynamic interaction is considered between the foundation and the reservoir, while the upstream truncation of the reservoir is provided with non-reflecting acoustic condition.

The dynamic interaction between the dam and the foundation (for the time-history analyses) is approached either with the massless approach or with the SAM-4D model, depending on the type of analysis (foundation without or with mass).

The principal physical-mechanical properties of the materials are summarized in Table 1. The viscous damping, assumed equal to 2% for both the dam and the foundation, is defined using the classic Rayleigh modelling.

Table 1. Material properties.

Parameter	Concrete	Rock	Water
Density [kg/m^3]	2483	2483 (0)	1000
Elastic modulus [MPa]	22410	22410	
Poisson's ratio [-]	0.2	0.2	
Compressive strength [MPa]	28.0		
Tensile strength [MPa]	2.0		
Fracture Energy [N/m]	250		
Shear wave velocity [m/s]		1939	
Compressional wave velocity [m/s]		3167	
Sound velocity [m/s]			1439

3.2. Loadings

The static loads are the self-weight of the dam and the hydrostatic pressure at winter reservoir water level (268.21 m a.s.l.), applied both on the upstream face of the dam and on the surface of the foundation.

The seismic action is the Taft horizontal acceleration time-history record of the M 7.3 Kern County, California, earthquake (peak ground acceleration of 1.77 m/s^2), showed in Figure 3 and considered as a free field ground motion at the surface of the foundation.

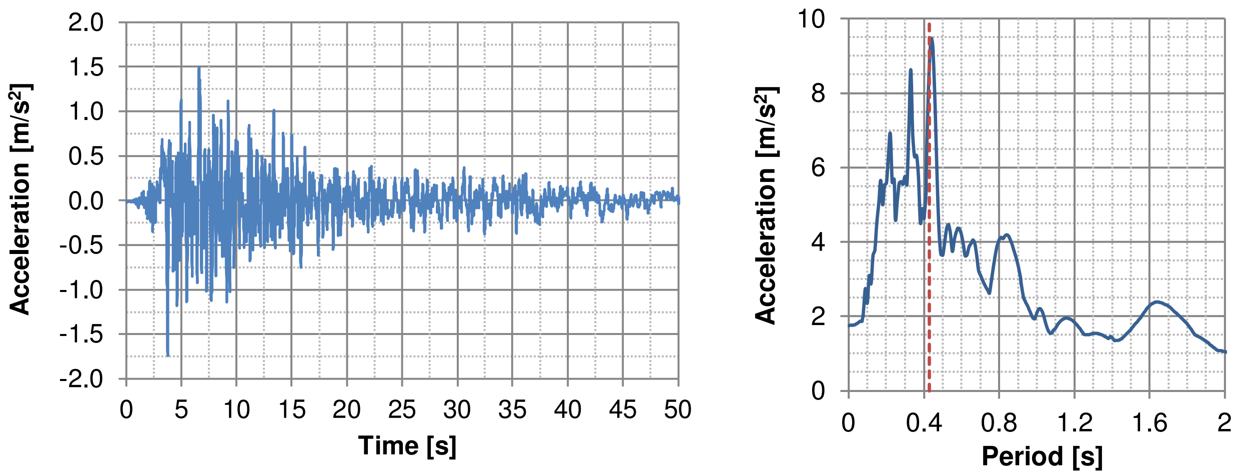

Figure 3. Taft horizontal record: acceleration time-history (left) and response spectrum 2% damping (right).

In the pseudo-static simulations the seismic acceleration (8.77 m/s^2), calculated on the response spectrum at the period 0.43 s (frequency 2.33 Hz) relevant to the first resonant mode of the system (modal participation mass 68%) and evaluated with a modal analysis of the coupled dam-foundation-reservoir system, was applied as inertia load towards either downstream or upstream; the hydrodynamic pressure was calculated according to the Zangar formulation (Zangar 1952), using the same seismic acceleration (8.77 m/s^2), and applied towards either downstream or upstream according to the inertia load.

In the time-history analyses with the massless approach, the acceleration was uniformly applied at the base and side boundaries of the foundation.

In the time-history analyses with the SAM-4D model, seismic action was applied at the base and at the side boundaries of the foundation, provided with damper and spring elements to model the semi-unbounded extent of the foundation, by means of effective earthquake forces computed using the theoretical solution of the vertically propagating elastic wave problem in a half-space, considering the incident motion at the bottom foundation boundary ½ the surface motion.

The transient dynamic coupled problem (for the time-history analyses) is solved using the implicit direct time integration method HHT (Hilber et al. 1977), with integration time step of 0.005 s that well represents frequencies up to 10 Hz.

3.3. Results

The results of the analyses are reported in terms of maximum principal stress (envelope in case of time-history analyses) and maximum and minimum horizontal seismic relative (with respect to dam heel) displacements at dam crest. For the non-linear time-history analysis with the SAM-4D model, also the damage variable is reported.

Figure 4 shows the tensile stress state resulting from the two pseudo-static analyses with the seismic inertia load and the hydrodynamic pressure towards downstream (left) and upstream (right) respectively: in the first case tensile stresses occur mainly on the upstream lower part of the dam, varying from about 1.0 MPa to about 12.5 MPa at dam heel; in the second case tensile stresses state involve mainly the downstream part of the dam, varying from about 1.0 MPa to about 6.4 MPa at dam toe.

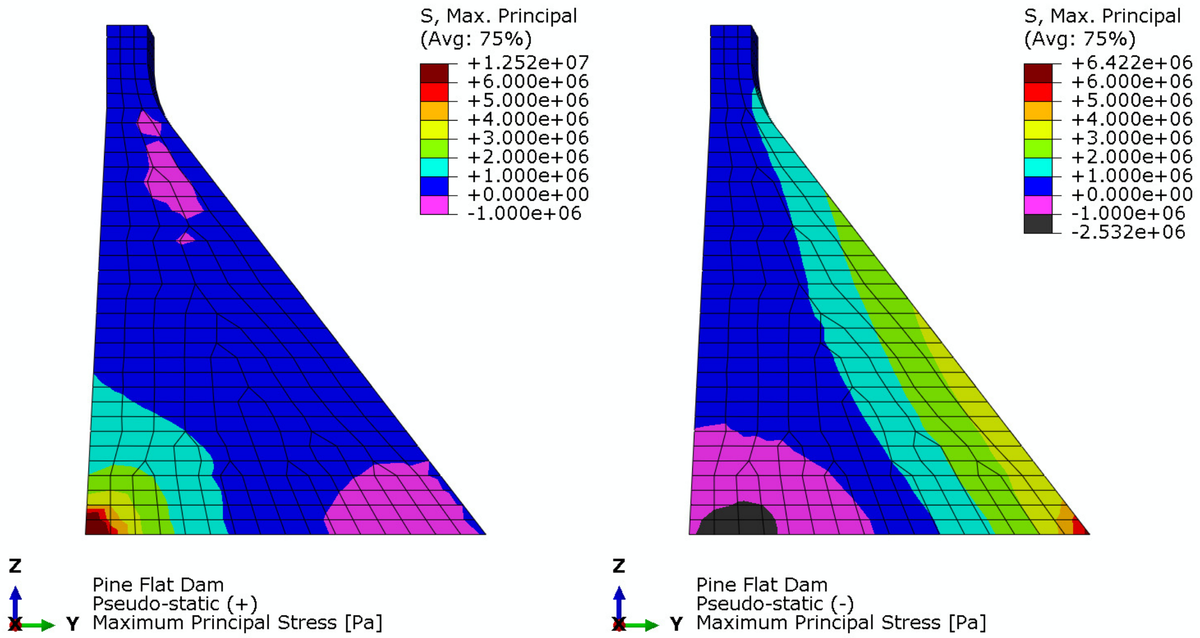

Figure 4. Linear elastic pseudo-static analysis with inertia load towards downstream (left) and upstream (right): maximum principal stress (contour plot).

Figure 5 reports the maximum principal stress envelope resulting from the linear elastic time-history analyses either with the massless approach (left) or with the SAM-4D model (right). In the case with the massless approach a very extensive tensile stress state (higher than the concrete tensile strength) occurs both on the upstream and the downstream face of the dam, also involving a significant depth in the section: the maximum, 11.6 MPa, occurs at dam heel, while at dam toe the tensile stress is a bit lower than 5 MPa. In the case with the SAM-4D model, a quite less severe stress state is observed: tensile stress slightly exceeds the concrete tensile strength only at dam heel, reaching about 3 MPa.

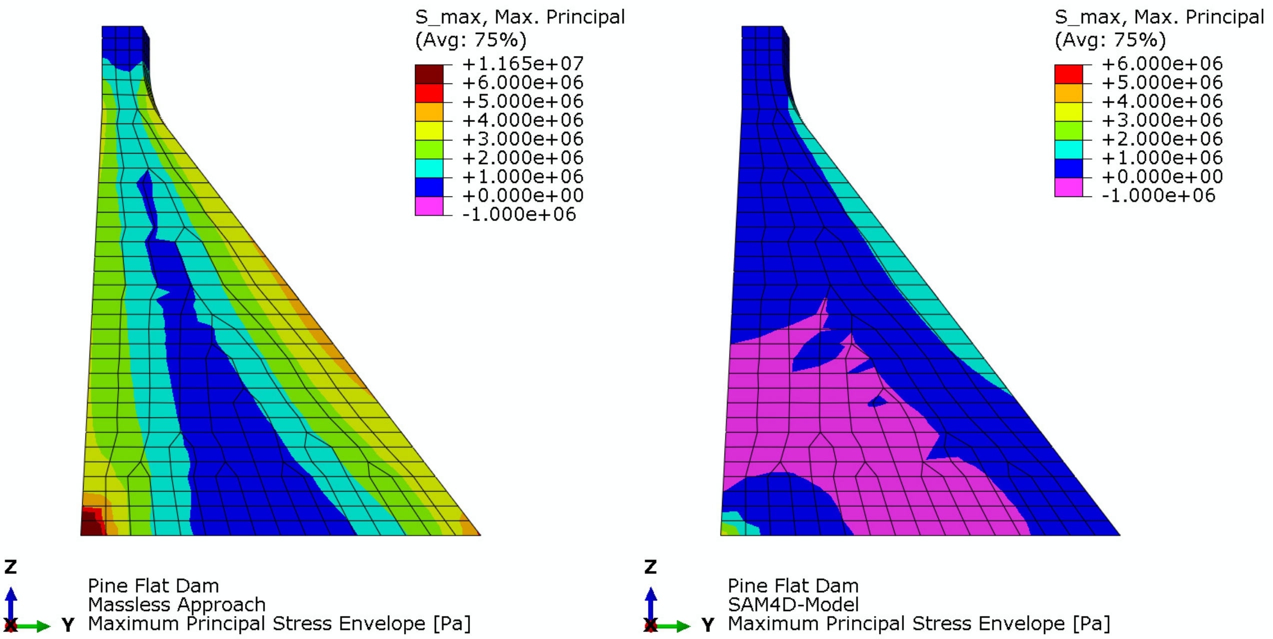

Figure 5. Linear elastic time-history analysis with the massless approach (left) and the SAM-4D model (right): maximum principal stress envelope (contour plot).

In Figure 6 the results of the non-linear time-history analysis with the SAM-4D model are depicted in terms of maximum principal stress envelope (left) and damage variable (right). When the non-linear behaviour of the concrete is considered, a small damaged area occurs at dam-foundation interface in the nearby of dam heel, but the overall structural response of the dam (in terms of stress state) is essentially the same of the linear case as Taft earthquake is not severe enough to highlight significant non-linear effects.

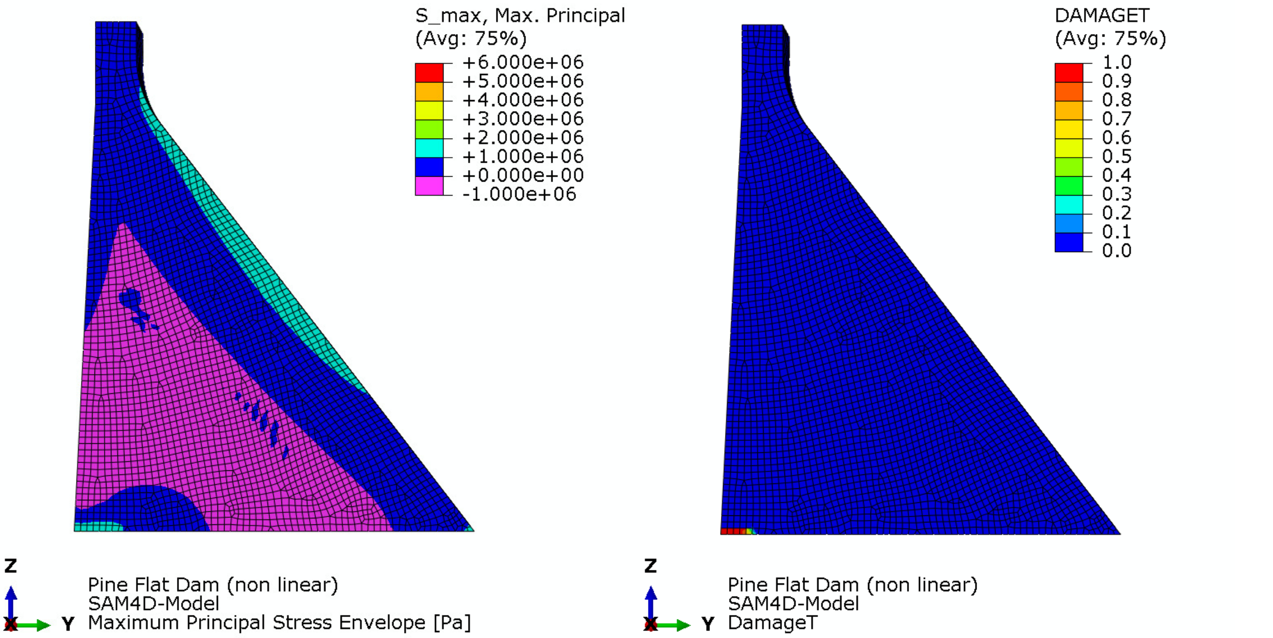

Figure 6. Non-linear time-history analysis with the SAM-4D model: maximum principal stress envelope (contour plot, left) and damage variable (contour plot, right).

Figure 7 summarizes the maximum and minimum horizontal seismic relative (with respect to dam heel) displacements of dam crest resulting from all the performed analyses. As just observed, no difference comes up between linear and non-linear analyses (time-history analyses with the SAM-4D model): displacements are about 0.04 m either downstream or upstream. Using the massless approach, the seismic response of the dam is quite greater than that obtained with the SAM-4D model, as displacements are more than double (0.1 m). The pseudo-static analysis provides displacements of about 0.075 m.

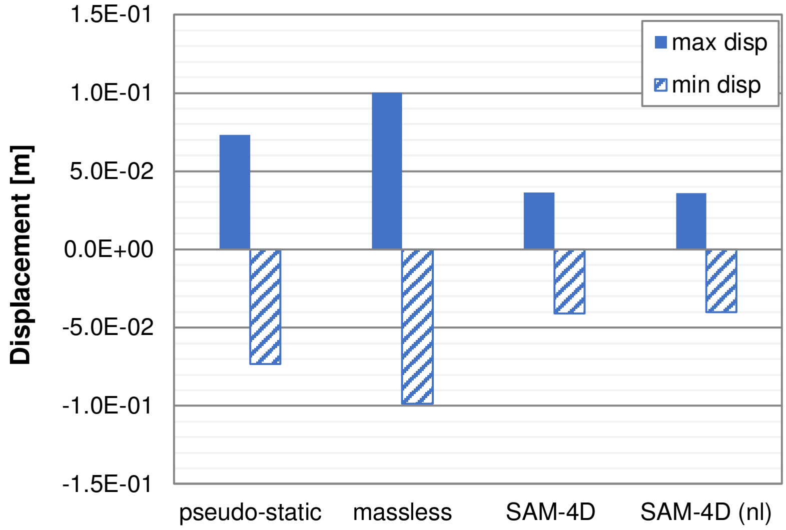

Figure 7. Linear elastic pseudo-static analysis, linear elastic time-history analysis with the massless approach, linear elastic and non-linear time-history analyses with the SAM-4D model: maximum and minimum horizontal seismic relative (with respect to dam heel) displacements of dam crest.

4. Conclusions

The case study of Pine Flat Dam (considered in the frame of the ICOLD 15th International Benchmark Workshop on Numerical Analysis of Dams) was used to apply the progressive analysis methodology, performing analyses of increasing complexity: the linear elastic pseudo-static analysis, the linear elastic time-history analysis with the massless approach, the linear elastic time-history analysis with the SAM-4D (Seismic Advanced Model for Dams) model and the non-linear time-history analysis with the SAM-4D model.

The SAM-4D model was recently implemented by RSE in the frame of the FEM codes used to model the structural behaviour of concrete dams, with the main purpose to reduce the excessive conservativeness of traditional and simplified methods for the seismic safety assessment of dams. It is an advanced structure-foundation dynamic interaction model, in the context of time-history analyses, able to simulate the propagation of seismic waves in a realistic massed foundation, considering its semi-unbounded extent.

The case study of Pine Flat Dam was approached by using the commercial FEM code Abaqus, able to suitably consider both the seismic dam-reservoir and dam-foundation interactions as well as the non-linear behaviour of concrete.

The results of the performed linear elastic analyses show that the seismic response obtained using the SAM-4D model is significantly less severe than that obtained with the traditional approaches. The stress state and the displacements resulting from the SAM-4D analysis are in fact basically consistent with a safe behaviour of the dam under the effect of Taft earthquake: the only exceeding stress, occurring at dam heel, can furthermore be ascribed to the assumption of a monolithic dam-foundation system, without any interface.

The results of the non-linear time-history analysis with the SAM-4D model show that no significant non-linear effect arises: the structural behaviour is pretty unchanged with respect to the corresponding linear case.

The linear elastic time-history analysis with the massless approach provides a structural response, in terms as of stress as of displacement, more than two times greater than that obtained with the SAM-4D model: the tensile strength of the concrete is in this case overcome on both the upstream and downstream entire faces.

The stress state and the displacements calculated with the pseudo-static analysis, although comparable to those resulting from the time-history analysis with the massless approach, are however slightly less demanding: in this regard, it's worth noting that the pseudo-static analysis is able to account only for the fundamental mode of vibration of the system, while also some subsequent modes, instead properly considered in the time-history analysis, could significantly influence the response of the dam to the earthquake.

Anyway, this simplified (pseudo-static) analysis can supply useful hints about the response of the dam, provided that the inertia load is correctly applied in both downstream and upstream directions and that the participating mass of the first resonant mode of the system (used to calculate the seismic action) is significant enough.

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