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A Progressive Methodology for Three-Dimensional Seismic Safety Assessment of Spillway Piers

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ABSTRACT

Concrete spillways are three-dimensional structures that are particularly vulnerable to earthquakes with a strong component occurring in the direction of the weak axis of the piers. This paper presents a progressive three-dimensional structural analysis methodology to assess the seismic stability of spillway piers. The methodology is based on four structural analysis levels of increasing complexity considering (i) the pseudo-static (seismic coefficient), (ii) the pseudo-dynamic (response spectra), (iii) the linear time history, and (iv) the nonlinear time history methods. A three-dimensional extension of the gravity method using stick models is developed to account for bi-axial moment interactions (P-Mx-My), considering in-plane concrete cracking and uplift pressures for unreinforced concrete sections. Three-dimensional seismic analyses of a 30 m high gated spillway built 95 years ago is presented as an application example. Seismic analyses were performed using stick models and 3D solid finite element models as reference solution to compare resultant shear forces and moments at the base joint and an upper joint. These resultant forces were then inputted into proposed post-processors to evaluate concrete cracking and sliding stability (safety factor and residual sliding displacement). The proposed methodology is very useful in practice as it bridges the gap between 3D seismic solid finite element analyses of spillways and a 3D extension of the gravity method to compute global safety indicators accepted by the profession.

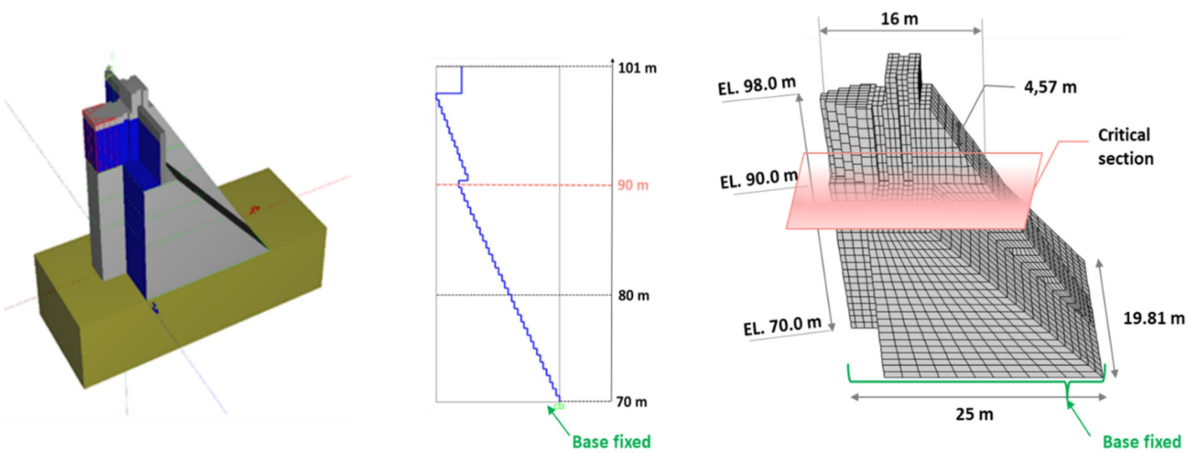
Keywords: Progressive seismic analysis, spillway piers, finite elements, sectional analysis, performance criteria.

INTRODUCTION

Concrete dams and spillways are critical infrastructure, often build years ago, with minimal consideration for seismic loads. This is particularly true in the context of three-dimensional analysis of spillway piers where the upstream-downstream (us/ds) excitation is acting simultaneously with the cross-valley excitation promoting cracking around the weak axis of the piers [1]. Concrete hydraulic structures are usually analyzed by methods of increasing complexity ranging from the pseudo-static method to linear or nonlinear transient dynamic analyses using finite element (FE) models [2-3]. Previous research and applications have shown that, prior to using complex FE model made of 3D solid elements (or 3D shell elements), a simplified 2D model of made of beam-column elements with rigid offset link elements could be used effectively to compute performance indicators accepted by the profession [4] (cracked area, sliding safety factors) [5-6-7]. This paper presents a 3D extension of this approach to analyse spillway piers and to compute seismic performance indicators including residual sliding displacements. An existing concrete spillway built 90 years ago is used in the application example (Figure 1). The seismic behaviour of the central pier 2 (Figure 1) will be assessed with different FE models.

Figure 1. Spillway analyzed.

A two-dimensional stick model is first generated using the computer program CADAM3D (https://cadam3d.com/ Figure 2a). The stick model is then extended in 3D by adding cross-valley characteristics as well as torsional stiffness and mass moment of inertia. The 3D stick model (Figure 2b) is then used with the software SAP2000 to perform seismic analyses of increasing complexity to compute acceleration, shear forces and moments at the base joint (level H=70m), and an upper joint located above the spillway chute (level H=90m). That upper joint is identified as a critical section under seismic load. The resultant forces are inputted to a post-processor to evaluate performance indicators such as concrete cracking, sliding stability and residual displacements. Comparisons are made with a 3D solid FE model (Figure 2c) using the software ABAQUS to assess the accuracy of the seismic performance indicators computed with the stick model.



(a) *(b)* *(c)*

Figure 2. Different spillway pier models : (a) CADAM3D model, (b) Stick model (SAP2000), (c) 3D FE model (ABAQUS).

PROGRESSIVE METHODOLOGY FOR SEISMIC STABILITY OF GATED SPILLWAYS

Progressive analysis approach

Traditionally, the static and dynamic internal forces could be computed with a progressive methodology divided in four basic analysis levels of increasing complexity as shown in Table 1. These analysis levels are (1) the pseudo-static (seismic coefficient method), (2) the pseudo-dynamic (response-spectra) method, (3) linear transient dynamic finite element methods, and (4) nonlinear transient dynamic finite element methods including transient rigid body dynamic analysis for cracked components. The objective is to gradually increase the complexity of analyses by including more precisely the effect of dynamic amplification and non-linearities.

Table 1. Levels of the traditional progressive analysis approach.

Method	Excitation	Characteristics	Software
1. Pseudo-static (Seismic coefficient)	PGA (cracking) Sustained Acc. (stability)	Equivalent static forces Rigid body 2D gravity method No dynamic amplification	CADAM3D
2. Pseudo-dynamic (Chopra, 1988)	Design spectrum	Equivalent static forces Rigid body 2D gravity method Dynamic amplification	CADAM3D SAP2000
3. Linear time-history dynamic analysis	Accelerogram	Finite element / Linear Dynamic amplification	EAGD-84 SAP2000 ABAQUS
4. Nonlinear time-history dynamic analysis	Accelerogram	Finite element / nonlinear Rigid body / Flexible Cracking Dynamic amplification	RS-DAM ABAQUS

Typically, the pseudo-static analysis, which does not recognize the dynamic amplification of ground motion, is only used in preliminary assessment. This approximate method is not recommended for the analysis of structures in high seismicity regions [8]. The second level of analysis is a pseudo-dynamic analysis using design response spectrum (RS) as seismic loads. If an unsatisfactory behaviour is computed from a response spectrum analysis, time history analysis should then be considered [2-4]. Linear analyses are always performed prior to nonlinear analysis. The objective of the analysis is to compute cross-sectional axial force, bending moments and shear forces (P, M_x, M_y, V_x, V_y, T) to evaluate the performance indicators.

Verification and validation of the proposed stick model approach

The proposed method is based on a simplified stick model. The objective is to have a simple model, easy to build and giving good approximation of the seismic forces developed at critical sections of the pier. For this, it is necessary to have a sufficient level of confidence on this model. Validation analyses ensure that the behaviour of the pier and the internal forces developed are sufficiently close to those of a more complete 3D FE model that will serve as a reference. Figure 3 shows the validation process used in this study.

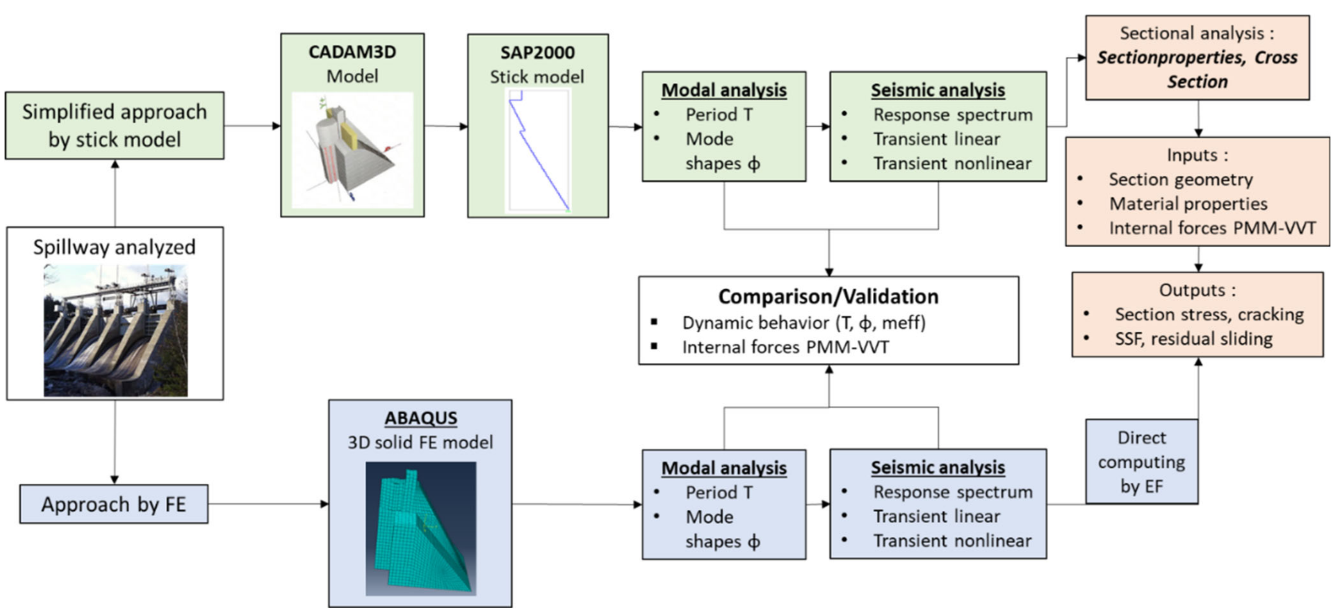


Figure 3. Flowchart of the stick model approach and its validation methodology.

The first step is to model the spillway using CADAM3D software. A simplified 2D stick model fixed at the base is then exported from the CADAM3D model into SAP2000. As this model must be representative of the structure, it is validated by comparing the dynamic behaviour (mode shapes) and response under seismic loading with the reference 3D FE model. For the seismic analysis, the internal forces at selected joints ("control sections") along the height of the pier are used for validation. The choice of the control sections depends on the geometry of the pier. Generally, they coincide with joints or pier elevation with a significant variation in sectional inertia leading to stress concentrations.

When the stick model validation is not satisfactory, i.e., the dynamic behaviour or the forces obtained with the stick model do not correlate with the reference 3D FE model response, the boundary conditions of the stick model are changed. These boundary conditions are the elevation of fixity of the pier and the restriction of the cross-valley displacement degree of freedom (DOF). Thus, it is an iterative process to define the stick model that most closely approximate the reference 3D FE model. The internal seismic forces computed, the geometry of the section and the material properties are the inputs to the sectional analysis that determines the stress distribution and stability of the control section.

DEVELOPMENT OF A 3D STICK MODEL OF A GATED SPILLWAY

The first step is to create a model of the spillway pier on CADAM3D. That model is then exported in a 2D model with rectangular section beam-column elements ("stick elements") using an exportation option directly implemented in the software. The spillway is discretized in slices of constant height. Each slice is represented by a stick element with the same section area and positioned at the center of gravity of the slice. In the case of the pier shown in Figure 4, it is exported with 51 vertical sticks. The vertical stick elements are linked by infinitely rigid horizontal beam elements. The discretization, i.e., the number of stick elements along the height of the pier and the consideration of the hydrodynamic pressures by adding Westergaard masses are given as exportation options. The sectional properties (area, moments of inertia, shear area) of each stick element are computed from the geometry of the slice represented by the stick. The material properties (volumetric weight, modulus of elasticity) are directly transferred to the SAP2000 stick model. As default boundary condition, the pier is embedded at its base, meaning the relative rigidity of the foundation is not considered. Figure 4 shows the process of development of the stick model.

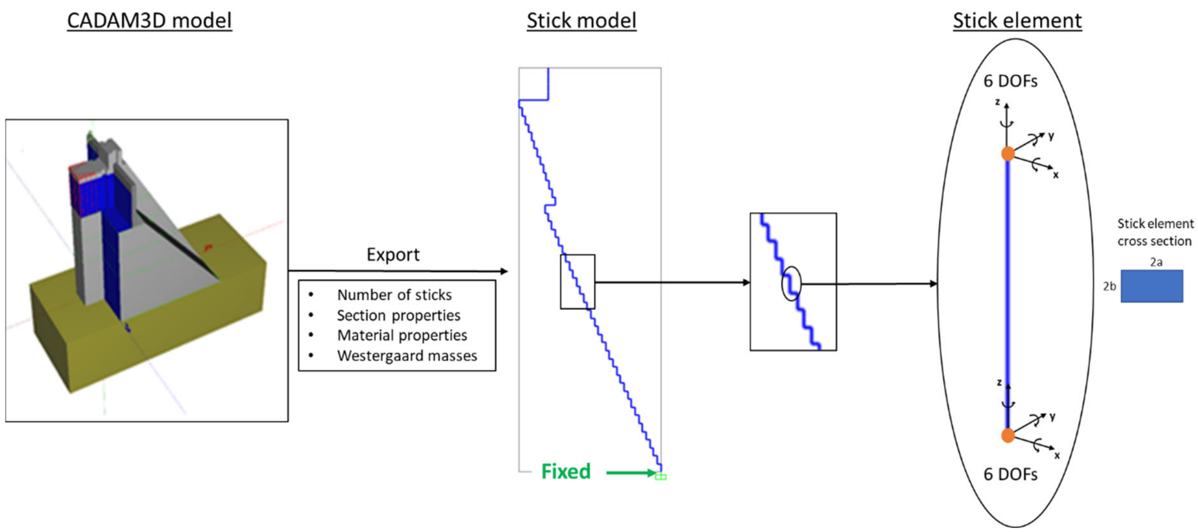


Figure 4. Creation of a stick model from a CADAM3D model.

As CADAM3D allow analysis only in the upstream-downstream direction, the stick model exported does not consider cross-valley DOFs by default. All the DOFs must be activated in SAP2000 to allow a 3D analysis. Thus, each stick element will have 12 DOFs, 6 per node.

The representation of a 3D structure subjected to three-dimensional loading by stick elements implies important approximations, especially for the consideration of the torsion. Some properties of the model are modified to allow a better evaluation of the torsional force by the stick elements. The torsional stiffness is considered by adding the mass moment of inertia to the nodes of the stick element. For a rectangular cross-section b x d, the polar moment of inertia is calculated as :

$$I_z = I_x + I_y = \frac{bd\,(b^2 + d^2)}{12} \tag{1}$$

Then, the mass moment of inertia is computed as :

$$I_c = \bar{m} I_z \tag{2}$$

where $\bar{m}$ is the surface area mass : the stick element total mass divided by the section area. Half of the mass calculated is affected to each node of the stick element. The masses, I_c ,are only activated for the vertical axis rotation DOF.

To evaluate the St-Venant torsional stiffness constant, the formula proposed by Roark and Young [9] for a rectangular cross-section is used :

$$J = ab^3 \left(\frac{16}{3} - 3.36 \frac{b}{a} \left(1 - \frac{b^4}{12a^4} \right) \right) \tag{3}$$

where *a* is half the length of the longest side and *b* is half the length of the shortest side.

The effect of warping is not considered in the calculation of torsional forces.

COMPUTATION OF STRUCTURAL PERFOMANCE INDICATORS

Stress analysis – cracked area

With the forces obtained from a seismic response analysis, a stress analysis of the section is carried out using the software *Cross Section Analysis and Design* [10]. This software performs sectional analysis and design verification of reinforced and unreinforced concrete sections. Among other things, it allows to calculate and illustrate the normal stresses distribution for a combination of axial force and biaxial moments (P, M_x, M_y), considering the tensile resistance of the materials. In addition to predefined conventional materials, the user can define a specific material by its stress-strain curve. The cracking can then be calculated when a limit tensile resistance is specified. The outputs of the stress analysis are the final stress distribution the section and an estimation of the section cracked area.

As acceptance criteria, the CDA (2013) recommends that the maximum compression stress should not exceed 0.9f'c and the resultant force stay within the section for an extreme earthquake [4].

Sliding stability

The second assessed performance indicator is the sliding stability of the joint. The sliding safety factor (SSF) and the residual sliding displacement are computed. When the surface cohesion is neglected as in our study case, the SSF is computed, using the Mohr-Coulomb approach, as :

$$SSF = \frac{P * tan\varphi}{\sqrt{{V_x}^2 + {V_y}^2}} \tag{4}$$

Where P is the axial force (including uplift pressure) applied to the joint cross-section, tan φ is the friction coefficient of the surface and V_x, V_y are the shear forces in horizontal x and y directions. If the SSF is smaller than 1 using linear dynamic transient analysis, it is then possible to estimate the residual sliding displacement at the time step Dt+Δt by finite difference method (FDM):

$$D_{t+\Delta t} = \frac{F_t * \Delta t^2}{M} + 2 * D_t - D_{t-\Delta t} \tag{5}$$

$$F_t = F_{stabl} - F_{destabl} \tag{6}$$

The stabilizing force F_{stabl} is the frictional resistance of the section due to the axial compression force P*tanφ. The destabilizing force $F_{destabl}$ is the resultant shear force $(V_x^2+V_y^2)^{0.5}$ or the shear force V_x or V_y in the direction considered if the sliding is computed for only one direction.

The CDA recommends a SSF superior to 1.1 post-earthquake as acceptance criteria [4].

Another way to evaluate the sliding displacements is by using RS-DAM. This computer program is based on rigid body dynamic equilibrium. It performs transient rigid body dynamic analysis of a cracked dam section [11]. In our case study, RS-DAM is used to estimate the upstream-downstream and the cross-valley residual sliding at the control section. Figure 5 shows the definition of the RS-DAM block model and the seismic excitation applied.

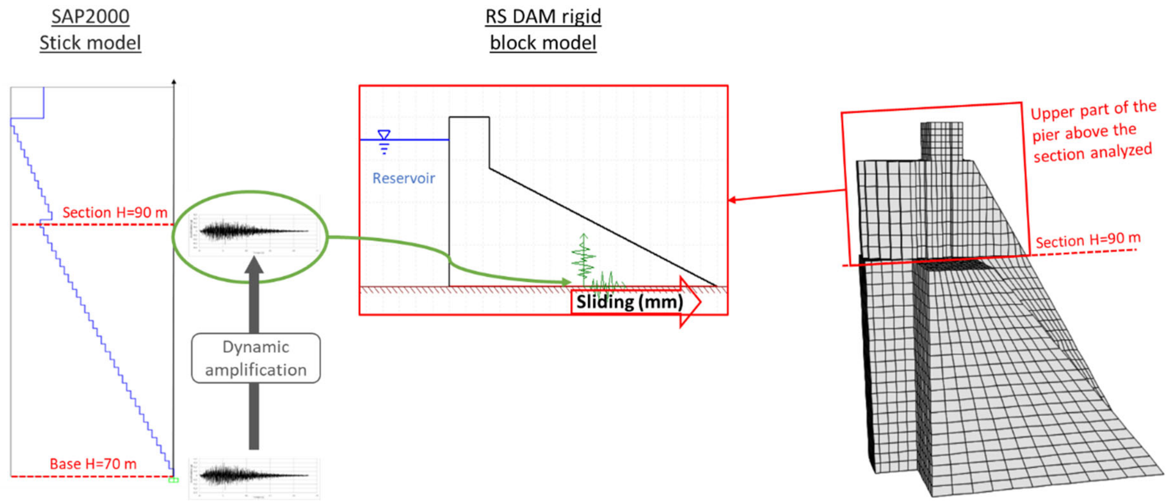


Figure 5. Crest block model and sources of excitation for the sliding stability analysis with RS-DAM.

The first step is to model only the upper part of the pier above the section analyzed. The contact properties of the joint are assigned to the base of the pier in RS-DAM. The friction coefficient is 1 and there is no cohesion. The amplified accelerograms at the joint (H=90m) of the linear stick model are the sources of excitation applied to the base of the RS-Dam block model in the horizontal and vertical directions. To obtain the amplified accelerograms, a transient linear analysis is first performed with the stick model.

CASE STUDY: SEISMIC ANALYSIS OF A SPILLWAY PIER

Description of the spillway

The analyzed gated spillway is located in Canada and was built in 1927 [12]. The structure is approximately 38 m high including the lifting structure (steel towers and hoist bridge) and 100 m wide (Figure 1). The piers are 31 m high. The spillway has five 15.86 m x 8.47 m Stoney gates weighing 500 kN each and driven by two hoists. The spillway rests on a good quality granitic rock foundation.

Description of the models

Different finite element models are analyzed in SAP2000. The objective is to evaluate the response of the central pier n°2 shown in Figure 1 with different modelling assumptions.

The simplified approach is based on the 51 vertical beam-column element (stick model) noted model P1L (Figure 6a). A 3D solid FE model of the pier is developed (Figure 6b). The last model is a three piers 3D solid FE model (Figure 6c). The adjacent piers n°1 and n°3 are also modelized and contribute to the lateral support of the pier n°2. The lateral cross-valley displacements of the adjacent piers are blocked up to the level of the section control. That three-piers model, which is the most representative of the real geometry of the spillway, is considered as the reference for the preliminary validation study of the stick model. All models are fixed at the base.

Single pier models P1L and S1L show similar dynamic behaviour. The first fundamental vibration period is 0.068s for both models. The reference model S3F has a shorter fundamental period (0.052s) due to the lateral support brought by the adjacent piers.

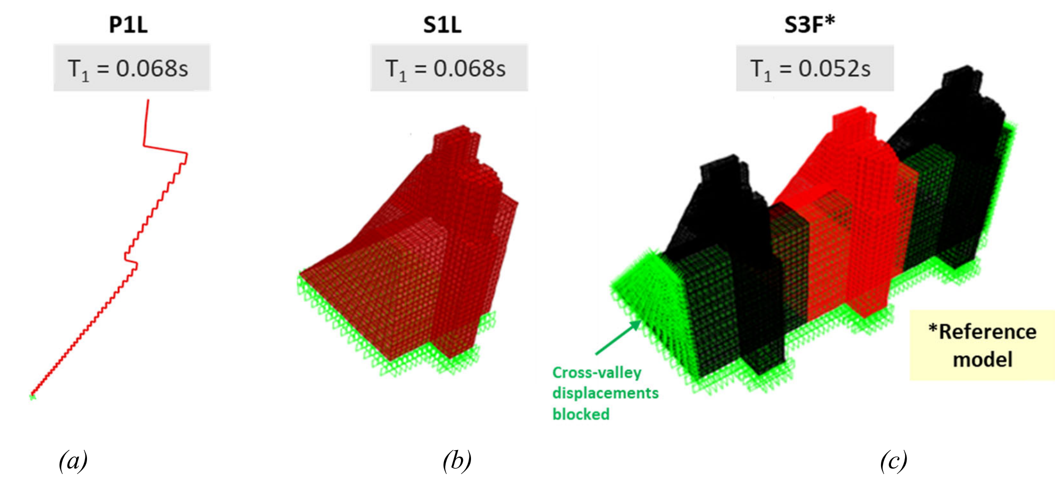


Figure 6. SAP2000 models analyzed and fundamental vibration periods: (a) stick model, (b) one pier solid model and (c) three piers solid model.

Ground motions

The 3D pseudo-dynamic response spectrum analysis is carried out using a horizontal and vertical spectrum developed for the "Ottawa Valley" area by Ko and Schellenberg [13] and Limoges [14] (Figure 7b). For the transient analysis, 3D spectrum-compatible accelerograms applied in the 3 directions with a return period of 10 000 years, as shown in Figure 7c, are used.

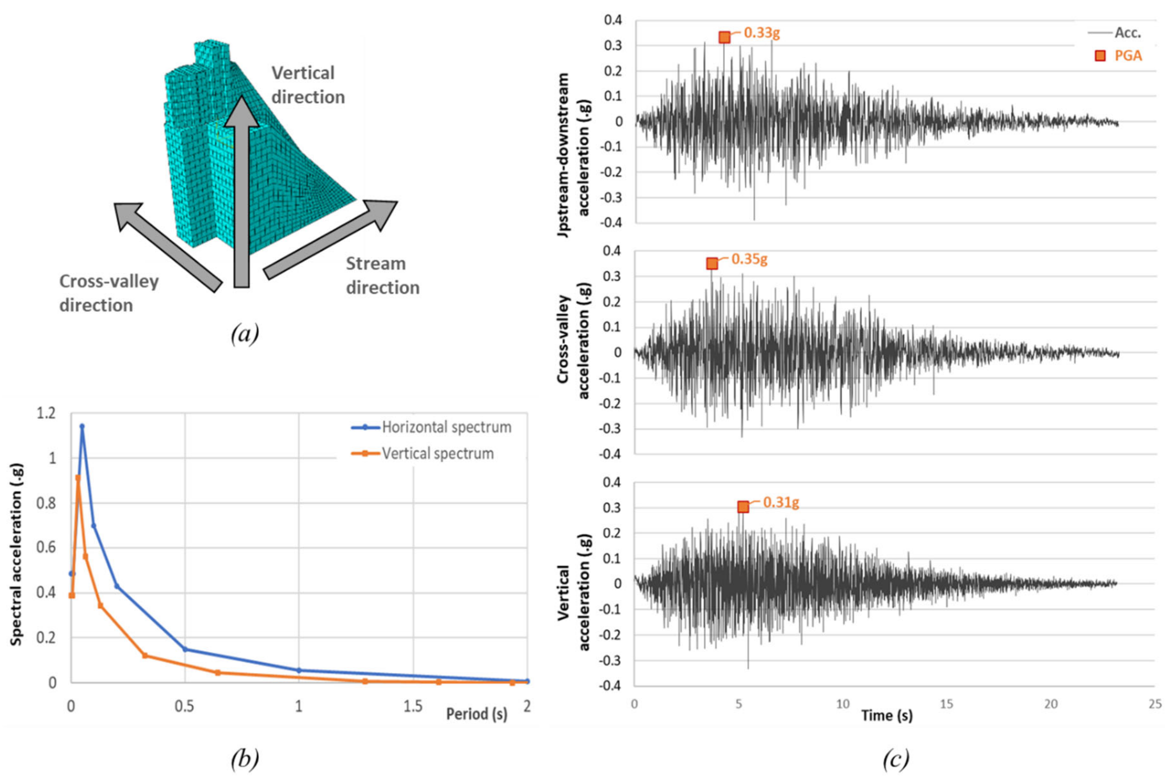


Figure 7. (a) Analysis directions, (b) 10,000 years return period response spectra and (c) compatible accelerograms.

Table 2 summarizes the characteristics of the spectrum and accelerograms.

Table 2. PGA of accelerograms and PSa at the fundamental vibration period.

Direction	PGA (g)	PSa (g)
Upstream-downstream	0.33	1.10
Cross-valley	0.35	1.10
Vertical	0.31	0.74

Each accelerogram has a total duration of 23 s for a time step of 0.00566 s. However, most of the strong vibrations are between 2 s and 10 s. The PSa is given for the fundamental vibration period of the pier (0.068s) and a damping of 5%.

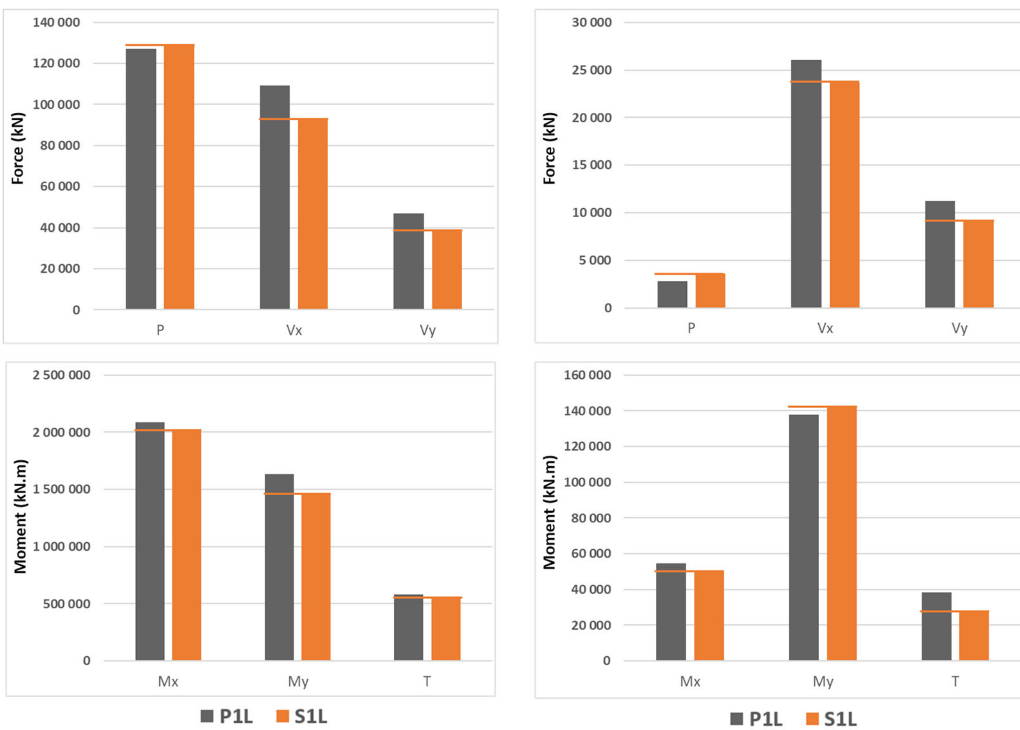
The static loads considered are the pier dead load D, the reservoir hydrostatic pressures H and the uplift pressures U. The hydrodynamic pressures are considered by adding Westergaard masses in the upstream/downstream direction. For the response spectrum analysis, the directional responses are combined according to the "30% rule" considering the cross-valley direction as the main direction. The seismic loads are combined as:

- 100% of the horizontal RS applied in the cross-valley direction,
- 30% of the horizontal RS applied in the stream direction,
- 30% of the vertical RS applied in the vertical direction.

EARTHQUAKE RESPONSE ANALYSIS : SAP2000 STICK MODEL VS REFERENCE SOLID MODEL

This section presents the results of the stick model preliminary validation study. First, a response spectrum analysis is carried out with the response spectra shown in Figure 7.b. The maximum internal forces obtained at the base joint (H=70m) and at the control section (level H=90m just above the spillway chute) are compared.

Figure 8 shows a comparison of internal forces and moments (P, M_x, M_y, V_x, V_y, T) obtained for the stick model (P1L, Figure 6a) and the solid elements model (S1L, Figure 6b).



(a) *(b)*

Figure 8. Comparison of internal forces and moments of the stick model P1L and the solid model S1L: (a) at the base joint level H=70 m, (b) at the joint level H = 90m.

Overall, there is a very good correlation between the force resultants of the models. For the axial force, the difference is less than 10%. The differences are slightly more important for the shear forces but remain generally less than 15%. At the control section, the torsion is overestimated by the stick model (38,000 kN.m vs 27,000 kN.m), a difference of nearly 40%. The torsion value difference is reduced to 7% at the base of the pier. In general, the stick model gives more conservative values, which is acceptable for a preliminary seismic safety assessment.

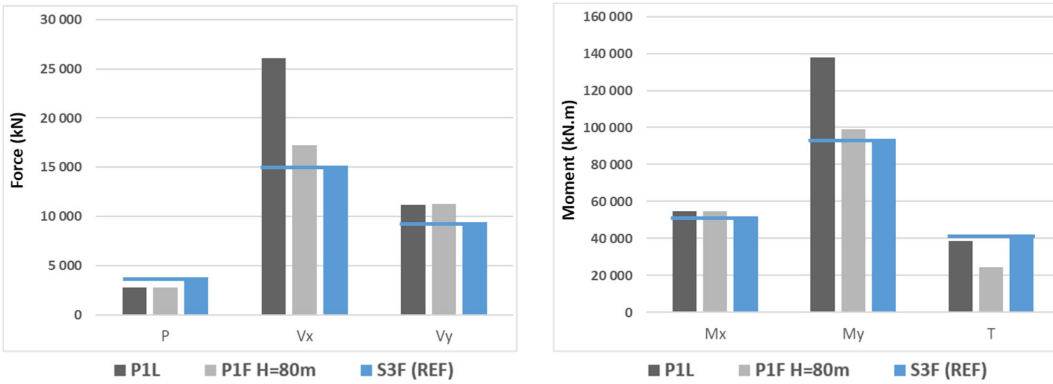


Figure 9. Comparison of internal forces and moments at the joint level H = 90m of the stick model P1L, the stick model fixed up to the level H=80m (P1F H=80m), and the reference model S3F.

The second comparison study is aimed to determine the most suitable stick model, considering the three piers solid elements model (S3F) as reference. The iterative comparison process shows that a stick model fixed at the level H=80m (halfway up the chute) instead of the base level H=70m gives a better approximation of the reference model response (S3F). The axial forces and the moments are better approximated by the modified stick model. The approximations are on the conservative side except for the torsion which is underestimated by about 40%.

EARTHQUAKE RESPONSE ANALYSIS : PROGRESSIVE APPROACH

This section presents the result of the progressive approach analyses applied to the SAP2000 single stick model (Figure 2b) and a 3D FE model in ABAQUS (Figure 2c). That 3D FE model with a fine mesh will be used as the reference model.

Pseudo-static analysis (seismic coefficient)

Traditionally, the seismic response of the pier is assessed using the PGA for stress analysis, and a sustained acceleration of 1/2*PGA for stability analysis. That does not consider the dynamic amplification provided by the flexibility of the structure. The ICOLD recommends using the spectral pseudo-acceleration (PSa) related to the fundamental mode of vibration instead of the PGA to account for the dynamic amplification [15]. In this case study, both accelerations have been used as input load in CADAM3D. The acceleration values used are shown in Table 3.

Table 3. Acceleration used for the seismic coefficient method analysis.

Analysis type	Direction	PGA (g)	PSa (g)
Stress analysis	Horizontal	0.35	1.10
	Vertical	0.23	0.73
Stability analysis	Horizontal	0.18	0.55
	Vertical	0.12	0.37

The stress and stability results are summarized in Table 4.

Pseudo-dynamic analysis (response spectrum)

The elastic response spectrum method evaluates the structure response for each vibration mode using mode-related spectral acceleration. The responses of the modes are combined according to the CQC method and considering 200 vibration modes. The CQC method allows a better estimation of the dynamic response of structures with close vibration modes as it is the case for the pier analyzed [15]. A constant damping of 5% is considered for all modes. The section stress distribution is directly obtained for the 3D FE model in ABAQUS. For the stick model, the linear forces (P, M_x, M_y) are used as input in *Cross Section* to determine the stress distribution, cracked area, and to compute the SSF.

Table 4 summarizes the stability and stress analyses results with the seismic coefficient method and the response spectrum analyses for the control section (level H=90m).

Table 4. Stability and stress analyses results of the seismic coefficient and the response spectrum analyses.

Method	Software	Acceleration / Model	SSF	Tensile area %
Seismic coefficient	CADAM3D	PGA	0.899	18%
		PSa	0.420	39%
Response spectrum	SAP2000	Stick model	0.587	29%
	ABAQUS	3D EF	0.615	12%

The reference SSF computed with the 3D FE model is 0.615. The seismic coefficient method provides a higher (0.899) and a lower (0.420) bound estimation of the SSF, respectively for the calculation with the PGA and the calculation with the PSa. The response spectrum analysis provides a better approximation (0.587) with a difference of less than 5%. For all the SSF estimations, the sliding stability is not ensured because the SSF are less than 1. For the stress analysis, the seismic coefficient method with the PGA gives a tensile area of 18% which the closest to the reference response (12%). The tensile area is largely overestimated with the other methods.

Linear transient analysis

A linear elastic transient analysis was carried out using the ground motions (Figure 7c) as seismic sources of excitation. At each time step, the internal forces are extracted. The SSF is then computed for each step time as given in Eq. (4). Figure 10 shows the SSF variation for the stick model and the reference 3D FE model. Also, the weighted moving average (WMA) on 100 time steps (WMA100) are computed for a better visualization of the correlation between the SSF curves.

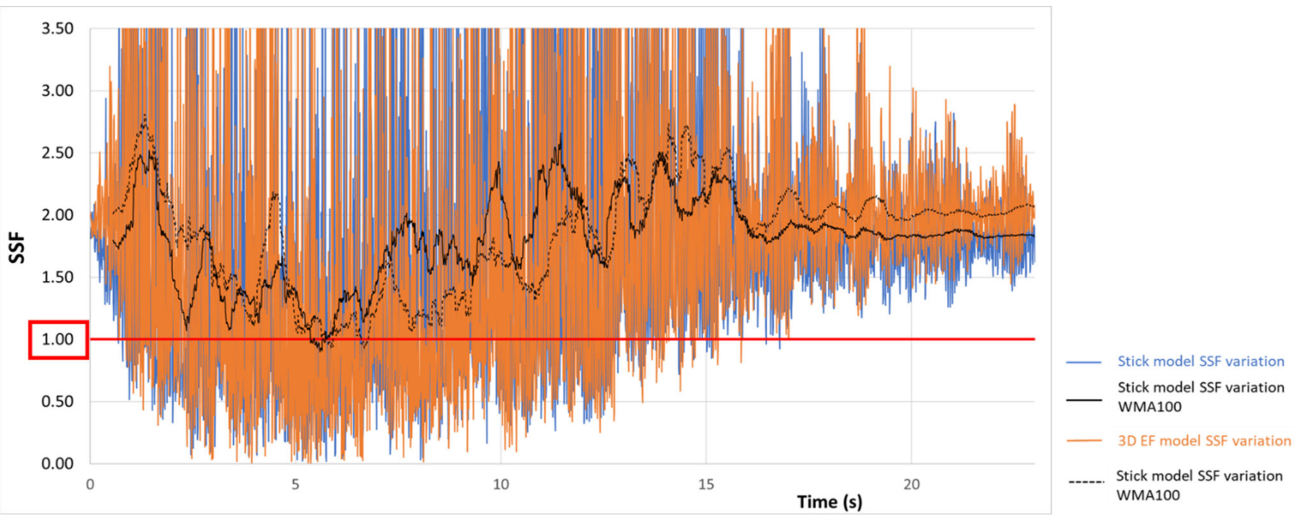


Figure 10. Comparison of the SSF variation curves of the stick model (in blue) with associated WMA curve (full black line) and the 3D FE model (in orange) with associated WMA curve (dotted black line).

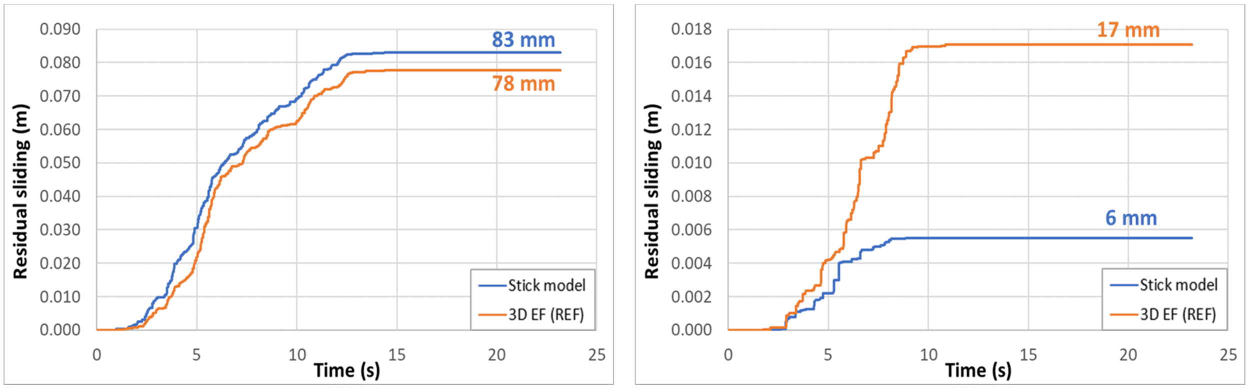
Table 5 summarizes the characteristics of the SSF variation curves.

Table 5. Characteristics of SSF variation curves

Parameters	Stick model	3D FE model
Minimum SSF	0.018	0.004
Average SSF	1.894	1.949
% SSF <1	24%	26%

For both models, the minimum SSF is almost zero. These minimum SSFs are reached respectively at time steps 5.745s for the stick model and 5.371s for the FE model. At those time steps, the resultant shear force induced at the joint exceed largely the section frictional resistance. The sliding resistance becomes almost zero for these time steps. In general, Figure 10 shows a good correlation of the SSF variations for the stick and the solid FE model. The WMA curves allow to better visualize the good correlation between the curves. However, the stick model gives slightly higher SSF values between 7s and 12s.

The proportion of SSF below 1 is similar for both models (24% and 26%). Whenever the SSF is less than 1, there is a short moment of instability that induce a sliding of the top block relatively to the lower part. Without resorting to a non-linear analysis, it is possible to estimate this residual sliding at the joint with the forces obtained from the linear analysis. The residual sliding is computed with the Eq. (5) in a post-processor. Figure 11 shows the residual sliding estimated.



(a) *(b)*

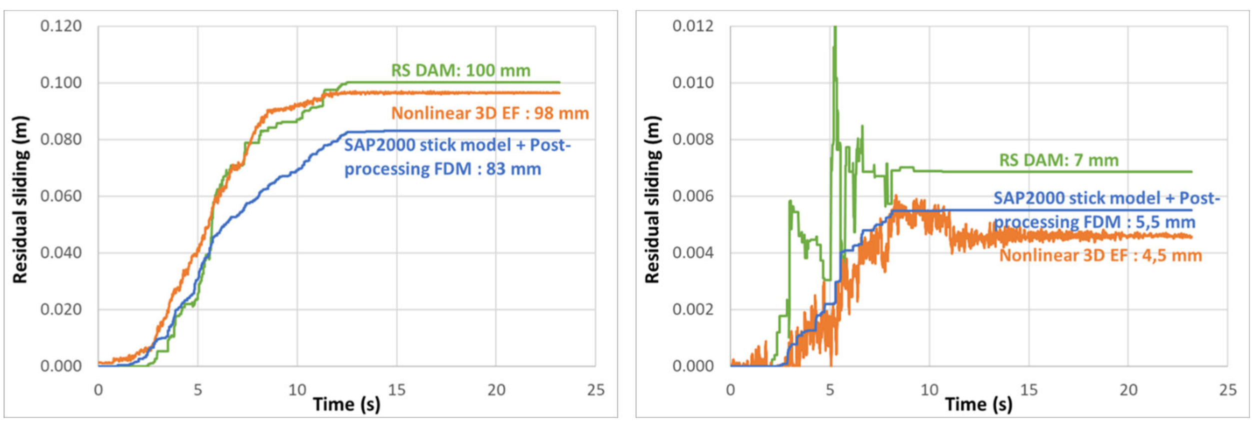
Figure 11. Comparison of the residual sliding at the joint H=90m computed with the FDM post-processor using linear forces from a linear transient analysis : (a) upstream-downstream and (b) cross-valley

In the upstream-downstream direction, the residual displacement is similar for both models (83 mm compared to 78 mm). The difference is less than 7%. In the cross-valley direction, the difference of is more important. The 3D FE reference model estimated residual sliding is almost three times the estimation with the stick model (17 mm vs 6 mm). However, these cross-valley estimated residual sliding are negligeable compared to the upstream-downstream residual sliding.

Nonlinear Transient analysis

The last level of analysis is a nonlinear transient analysis using RS-DAM with seismic input motions from linear stick model. To compute the reference sliding value, the 3D FE model in ABAQUS is modified by introducing a *surface-to-surface* interaction type at joint (level H=90m). The friction is introduced by the *penalty* method.

Figure 12 shows the residual sliding estimated with the nonlinear 3D FE model, the linear stick model (FDM) and RS-DAM.



(a) *(b)*

Figure 12. Comparison of the residual sliding at the joint H=90m : (a) upstream-downstream and (b) cross-valley

In the upstream-downstream direction, the reference residual sliding is 98 mm. RS-DAM provides a very close estimate (100 mm). The Finite Difference Method estimation based on the stick model linear forces (83 mm) underestimates the residual sliding. In the cross-valley direction, the residual sliding is around 5 mm, which is almost negligible compared to the upstream-downstream direction. With 5.5 mm, the stick model gives a good estimate of the reference residual sliding (4.5 mm). RS-Dam gives a slightly higher value (7 mm). However, since the cross-valley sliding is very small, the differences do not allow to conclude on the accuracy of one method compared to the other.

CONCLUSIONS

The progressive methodology proposed is based on a model of beam-column elements (sticks) developed in the software SAP2000 and imported from CADAM3D. To validate the model proposed, the seismic response have been compared to the seismic response of 3D solid finite element models used as reference. As case study, the traditional progressive approach with four levels of analysis was applied to an existing spillway. The reference model is a fine meshed 3D FE model in ABAQUS.

The principal conclusions of this work are listed below :

- For a better computation of a 3D pier seismic behaviour, some modifications are applied to the stick model. Those are (i) the activation of all DOF, (ii) the addition of rotational mass moments of inertia and (iii) the addition of a torsional stiffness constant to approximate the effect of torsion on the vertical stick elements.

- The proposed stick model approximates well the seismic behaviour of a more complete solid model. The stick model gives close but conservative values of internal forces and moments (P, M_x, M_y, V_x, V_y, T) for two control sections: the base of the pier and an upper joint located above the spillway chute. When the lateral support due to the presence of adjacent piers is considered, a modified stick model embedded up to halfway up the chute provides the best approximation of internal forces and moments.

- The seismic coefficient method with CADAM3D gives SSF estimate values of 0.899 and 0.420 respectively for a calculation with the PGA and with the PSa. Those estimation provides a limit interval of the reference SSF (0.615). The response spectrum analysis of the stick model gives an SSF of 0.587 which is a good approximation of the reference SSF. The estimate of the stress distribution is conservative with an overestimation of the tensile area.

- For the residual sliding estimation, it is recommended to use RS-DAM with the amplified accelerograms at the section analyzed. Those accelerograms are obtained from a transient linear analysis of the SAP2000 stick model. This method gives an estimate of 100 mm very close to the reference response 98 mm (difference of less than 2%). This recommendation applies mainly to the upstream-downstream sliding. In the cross-valley direction, RS-DAM overestimates the sliding (7 mm compared to 4.5 mm). However, given the low value of this cross-valley residual sliding, the differences between the models are not representative to conclude on the better accuracy of a method.

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