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A systematic assessment of the influence of geometry and materials properties on the performance of arch dams

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ABSTRACT: Arch dams have different properties that play a relevant role in their behavior, although it is not clear to what degree or in what sense. There is some consensus regarding the relevance of certain factors such as length at crown, height, base and crest thickness, or Young modulus of dam and foundation. However, others such as the shape of arcs and cantilevers, which are correlated and whose effect is more difficult to consider, can also be influential.
In this work, a systematic study of the response of arch dams in front of the common loading scenarios has been carried out, taking into account the usual range of variation of their properties. In total, 39 input variables related to geometry, material strength and thermal load were considered. Ranges of variation for each of these parameters have been defined according to the usual design criteria and 3,000 different geometries – together with the corresponding FEM models - have been generated with random values of these parameters.
The resulting displacements and stresses have been used to fit prediction models based on a machine learning technique named 'random forests' that give an estimate of the dam response. The interpretation of these models can be associated with the relative importance of the characteristics of arch dams on each of the behavior variables.

1 Introduction

The first filling and the initial stage of dam operation are critical periods in terms of dam safety; the new loads applied by the presence of the reservoir frequently induce a transient behavior [1]. This is more acute for arch dams, since they transmit higher loads to the foundation and abutments. Moreover, the joints between cantilevers are grouted at that time, hence the structure becomes monolithic and hyperstatic.

Data-based models cannot be applied properly during the first years of operation due to the lack of monitoring data for model fitting [2]. Numerical models are sometimes available, though they need to be calibrated, for which behavior data are also necessary.

As a result, dam safety assessment during that period is mostly based on engineering knowledge and experience from similar cases. This approach is intrinsically subjective and biased by the particular know-how of each practitioner. Moreover, each dam features different properties whose influence on the relevant outcome indicators is not fully understood. It is generally acknowledged that several factors are relevant on dam behavior, such as the crest length/height ratio [3], or that between the elastic modulus of dam and foundation [4]. According to the USBR [5], if the ratio base thickness/height is lower than 0.2, the thermal load is preponderant. However, other variables, whose effect is harder to consider, can also be influential. In addition, some of them are obviously correlated. It can be concluded that the effect of each parameter of the dam on each of the response variables is difficult to determine *a priori*.

The aim of this work is to analyze the effect of the main parameters defining an arch dam – geometry, material strength and thermal properties – on its structural behavior. A database was automatically generated with an ad-hoc application that allows creating and computing numerical models based on the finite element method (FEM). It is integrated in the pre-process software GiD [6] and makes use of "DamApp", a code for thermo-mechanical computation of dams developed in the open-source environment Kratos Multiphysics [7]

The results of these models were employed to fit supervised learning non parametrical models based on random forests (RF), whose interpretation allows identifying the influence of each input variable on dam response, both in magnitude and shape.

2 Methods

2.1 Model generation

The analysis is based on the results of the thermo-mechanical calculation of 3,000 numerical models of arch dams whose geometry, boundary conditions and loads were randomly and automatically defined with an application developed ad-hoc [8]. In this section, the process is succinctly described.

Geometrical parameters

The geometry of the models depends on a total of 10 parameters, representing a compromise between a sufficient degree of detail to obtain useful results and the necessary simplifications to allow the systematic generation and analysis. The selected parameters are summarized in Table 1, which also shows the units and the corresponding range of variation.

Table 1: Geometrical parameters and corresponding ranges.

Parameter	**Symbol**	**Units**	**Range**
Height	H	m	[20 - 305]
Crest chordal length	L_c	m	[40 - 505]
Foundation chordal length	L_f	m	[30 - 400]
Total angle	α	Degrees (º)	[100 - 120]
Central angle	β	Degrees (º)	[20 - 35]
Crest thickness	Th_c	m	[1.01 – 13.4]
Foundation thickness	Th_f	m	[1.5 - 60]
Abutment increment thickness	Th_a	(%)	[0 - 100]
Undercut	O_{max}	m	[0 - 50]
Overhanging	O_{c-f}	m	[0 - 6]

These parameters allow defining the geometry of the dam. The ranges of variation were set according to different criteria, with the purpose of representing a wide range of realistic geometries of arch-dams. The maximum height is that of Jinping-I dam, currently the highest dam in operation worldwide [9]. The lower limit for height was taken discarding *small* dams according to various sources [10], [11]. Other ranges were defined considering data of limited but representative lists of existing dams [5], [12], such as those for crest and foundation chordal lengths and thicknesses, as well as for the relative abutment thickness and overhang. Recommendations extracted from reference guidelines were considered for total and central angles [3], [5].

In each of the 3,000 cases, the values of the geometric parameters are randomly selected. The geometry generation procedure is described in detail in [8], and a brief description of the main steps follows.

1. The slope of the valley is defined as a function of three parameters: H, L_c and L_f. It is verified that the resulting values meet the condition $L_c/H<5$. The range of variation of these parameters allows representing different site shapes, as described by USACE [3]: narrow-V, wide-V, narrow-U, or wide-U.
2. The cross section of the crown cantilever is determined in three steps:
   - Random values of Th_f and Th_c are taken, conditioned to $Th_f>Th_c$. The thickness at intermediate height is linearly interpolated.
   - The crown arch is moved toward downstream a distance equal to $2/3{\cdot}Th_f$, with respect to that at the base.
   - Intermediate arches are placed as a function of a parameter C_f. Its effect was verified and its range of variation determined by generating models reproducing real dams.
3. The horizontal shape is defined following the method proposed by Vallarino [13], in which circular arches are employed both for the intrados (one center, constant radius) and the extrados (three centers, greater radius near the abutments). This results in variable horizontal curvatures along each arch [5], dependent on Th_a, which in turn is defined as the ratio between the thickness at the abutment and that at the crown section for each arch.

The following simplifications were adopted: a) the riverbed axis is straight and b) all models are symmetrical.

Material properties

Table 2 shows the list and corresponding ranges of variation of the material properties involved in the thermomechanical calculations, both for the dam and the foundation. The values were extracted from the technical literature: reference guidelines or technical reports and peer-reviewed papers related to specific case studies. References are included in the last column of Table 2.

Table 2: Material properties and corresponding ranges.

Parameter	**Units**	**Range**		**References**
		Concrete	**Foundation**	
Density (ρ)	kg/m^3	[2400 - 2700]	[2600 – 3000]	[14], [15]
Elastic Modulus (E)	GPa	[20.1 – 41]	[0.5 – 60]	[4], [11]
Poisson’s ratio (ν)	-	[0.2 – 0.28]	[0.14 – 0.25]	[11], [14], [16]
Thermal conductivity (λ)	W/(m·K)	[1.7 – 3.86]	[1.7 – 4.6]	[15], [17]
Specific heat (α)	J/(kg·K)	[837.4 – 1046.7]	[879 – 1000]	[15], [17], [18]
Thermal expansion coef. (β)	$1/K\ (10^{-6})$	[6.3 – 12.6]	[8.3 – 10]	[14], [17], [18]

FEM analysis

Once the random geometries were generated, the definition of the FEM models requires determining (1) the loads, (2) the boundary and initial conditions, and (3) the type and size of mesh elements.

Self-weigh, hydrostatic and thermal loads were accounted for. Two scenarios were considered for the hydrostatic load, namely empty and full reservoir. Thermal load was defined with sinusoidal functions based on three parameters: mean value (T_{mean}), amplitude (T_{amp}) and phase (ε). Water temperature was established according to the empirical depth-dependent law proposed by Bofang [19], dependent on the ambient temperature.

Tetrahedron elements were selected after been validated by previous analysis [20]. The mesh size was defined under the condition of featuring at least three layers of elements across the dam thickness. This assumption was based on expertise knowledge acquired in former projects and other FEM analysis studies [21]. The simulation period was three years, with a time step of one month. It was verified that the yearly cycle of the thermal field was independent on the initial temperature, which in turn was set to T_{mean}.

Finally, a set of behavior variables is obtained from the results of the numerical models, mainly stress and displacement for each mesh node and time step.

2.2 Supervised learning

Once the calculations are run and the results compiled into a data set, they can be used to construct a relation of the form $Y = f\ (X_i)$, being X_i the model parameters (hereinafter constitutive parameters, which include those defining the geometry, materials and loads), and Y the response variable (displacement or stress). With this information, models based on random forests (RF) have been fitted, which allow obtaining an estimate of this function f.

RF models belong to the category of non-parametric algorithms, since they are solely based on data, without any a priori assumptions on the nature or strength of the association between inputs and response. The result of an RF model is computed as the average prediction of a set of simple decision trees. The description of the theoretical basis can be found in several sources (e.g. [22]), as well as in the seminal article by Breiman [23]. Examples of application of models of this type have been published in the field of dam safety [24].

In addition to their predictive capacity, useful information can be extracted on the underlying mechanism through the variable importance measure. Once the model is fitted, each of the predictor variables is randomly permuted and the increase in the prediction error is calculated. It is based on the assumption that if a variable does not affect the response, the model accuracy will be low sensitive to the permutation of the corresponding value, and vice versa.

More information on the phenomenon under analysis can be obtained from the partial dependence plots [25]. This tool can be applied to any black box model, as it is based on the effect of each predictor on the output, as learned by the model and accounting for the average effect of the remaining inputs.

Input variables

Some derived constitutive variable were computed and considered as inputs. They are frequently employed in practice to characterize arch dams and make comparisons [3]. The full input set is included in Table 3.

In both cases, two versions of the RF model were fitted: one with all the input variables listed in Table 1, and another with a set of independent variables. This allows for a more reliable estimation of the variable importance measure, since highly correlated variables can share the importance in the full model (for example, *gCreLen* and *rCreLenH*) [26].

Table 3: Input variables

Variable	Code	Variable	Code
Dam height	*gHei*	L_c/L_b	*rCreLenBasLen*
Dam crest length	*gCreLen*	Th_b/H	*rBasThiH*
Base length	*gBasLen*	Th_c/H	*rCreThiH*
Total angle	*gTotAng*	Th_{mean}/H	*rMeanThiH*
Central angle	*gCenAng*	Young modulus-dam	*mYouDam*
Abutment increment thickness	*gAbuIncThi*	Young modulus-foundation	*mYouFou*
Factor of curvature	*gFacCur*	Conductivity-dam	*mConDam*
Crest increment thickness[1]	*gCreIncThi*	Conductivity-foundation	*mConFou*
Base increment thickness	*gBasIncThi*	Density-dam	*mDenDam*
Crest thickness	*gCreThi*	Density-foundation	*mDenFou*
Base thickness	*gBasThi*	Expansion coefficient-dam	*mExpDam*
Mean thickness	*gMeanThi*	Expansion coefficient-foundation	*mExpFou*
Thickness at H/3	*gThi13*	Poisson coeff.-dam	*mPoiDam*
Thickness at 2H/3	*gThi23*	Poisson coeff. foundation	*mPoiFou*
Thickness at crest abutment	*gAbuCreThi*	Specific heat-dam	*mHeatDam*
Thickness at base abutment	*gAbuBasThi*	Specific heat-foundation	*mHeatFou*
Crest overhang	*gCreOver*	Young mod-Dam/Young mod-Fou	*mYouDamFou*
Undercutting at H/3	*gUnd13*	Mean air temperature Tmean	*tMean*
Maximum undercutting	*gUndMax*	Temperature amplitude	*tAmp*
L_c/H	*rCreLenH*		

3 Results and discussion

The maximum radial displacements at the top of the crown cantilever were analyzed. More precisely, the difference between the maximum displacement toward upstream (recorded for empty reservoir in summer, month 31 in the simulation) and that toward downstream (obtained for full reservoir in winter, month 37). This result was divided by the dam height. Also, the maximum stress at the upstream toe – frequently tensile stress – was analyzed, which is registered for full reservoir at month 37.

3.1 Displacements at the crown cantilever

Figure 1 shows the variable importance of inputs for both models, where crest chordal length stands as the most relevant, followed by Young´s modulus of foundation. Thickness at the base is more important than that at the crown, while the inputs related to temperature – both thermal load and properties – show low relevance.

The partial dependence plot for *mYouFou* (E_f) was also obtained (Figure 2). It can be seen that the high importance of this variable is mostly due to the effect of those cases with $E_f<5$, which is a suggested minimum threshold for arch dams foundation [4].

[1] wrt default value as proposed by USBR [5]

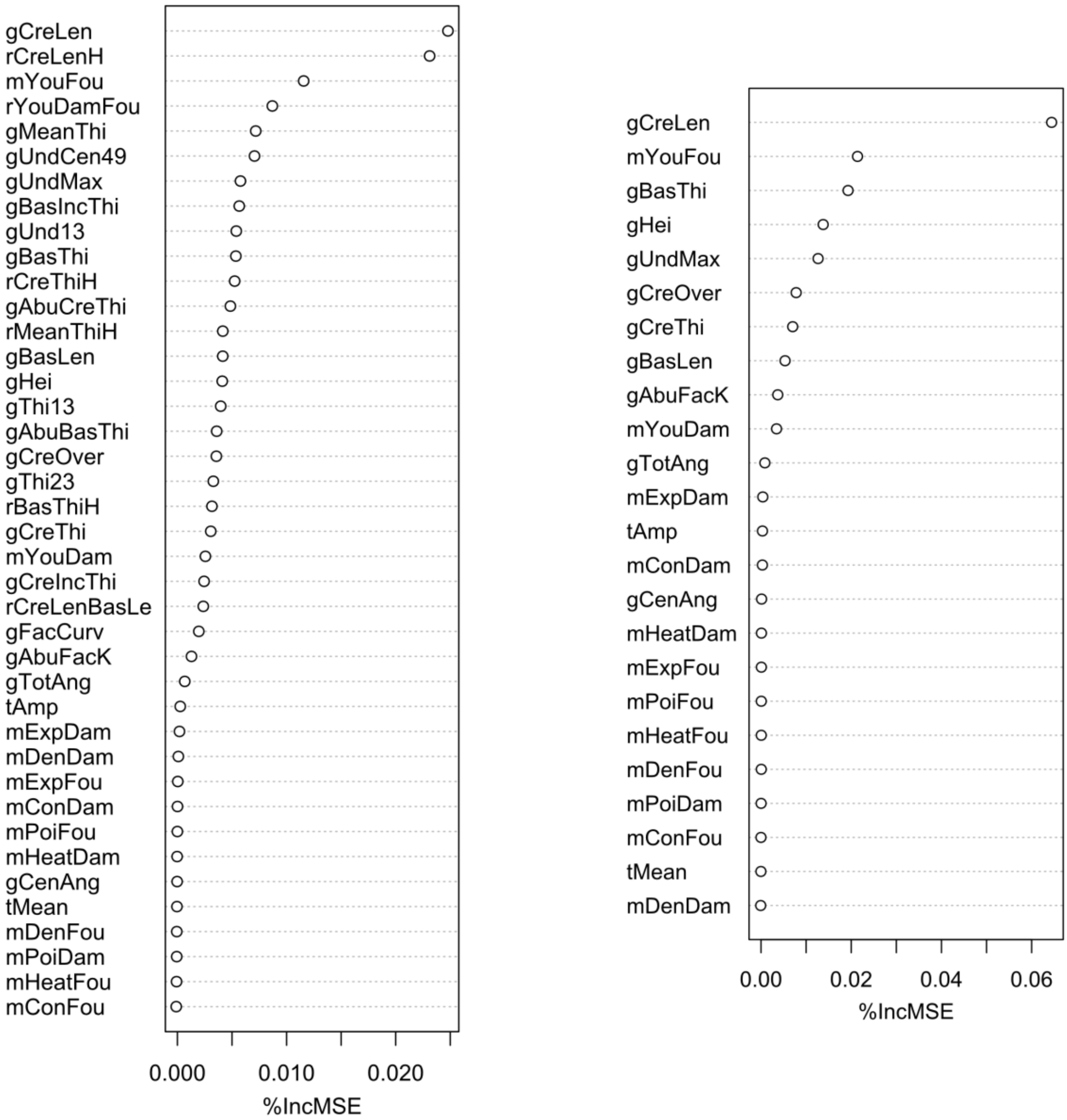

Figure 1: Variable importance on dimensionless displacement at the top of the crown cantilever. Left: all inputs. Right: independent inputs

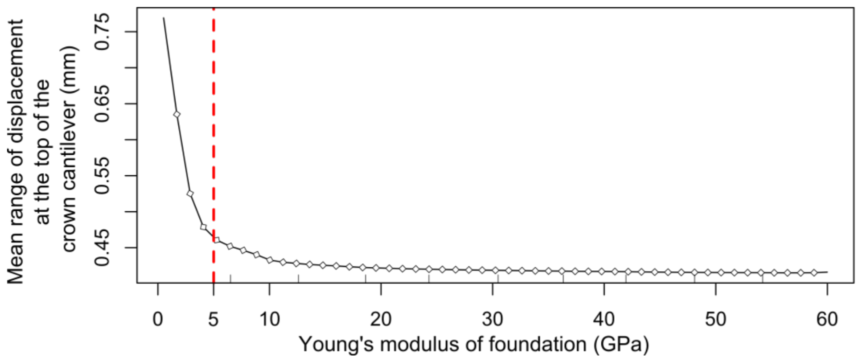

Figure 2: Partial dependence of dimensionless displacement at crown cantilever on Young's modulus of foundation.

The same process was followed without those cases with $E_f<5$ or $E_c/E_f>8$. The latter condition was proposed by Rocha [27] and is frequently taken as a reference limit to avoid serious problems in arch dams [4], [28]. The results are different in terms of the importance of *mYouFou*, much lower in this case (Figure 3).

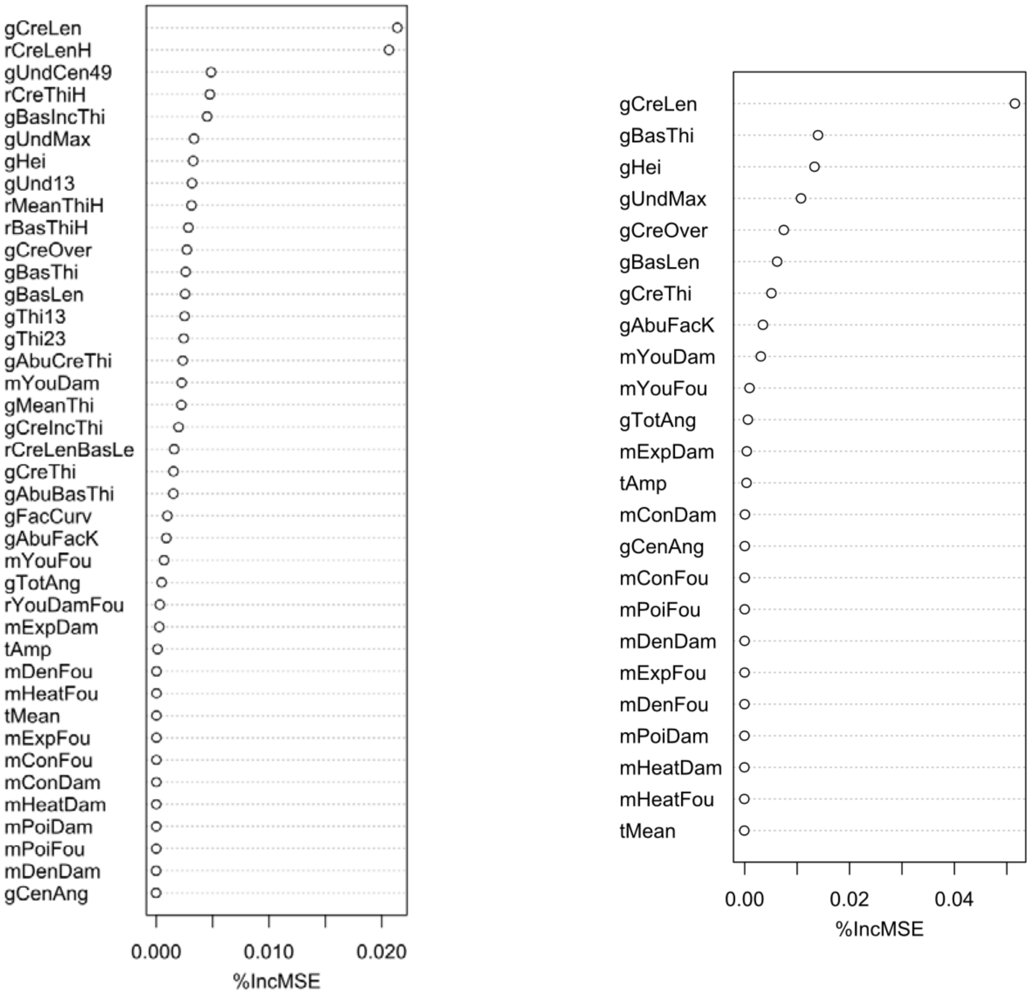

Figure 3: Variable importance of inputs on dimensionless maximum displacement for cases with E_f>5 and E_c/E_f<8. Left: all inputs. Right: independent inputs

Chordal crest length remains at the top, followed by those related to the dam geometry: in decreasing order, base thickness, height, undercutting, overhanging, base length and crest thickness. All feature higher relevance than foundation Young’s modulus for this data set.

It should be remembered that the response variable is the ratio between maximum displacement and dam height. Since *gHei* is highly relevant, its relation with the outcome is not linear. This was verified by computing the partial dependence plot of another RF model (Figure 4), where the output is the maximum displacement (without dividing by dam height).

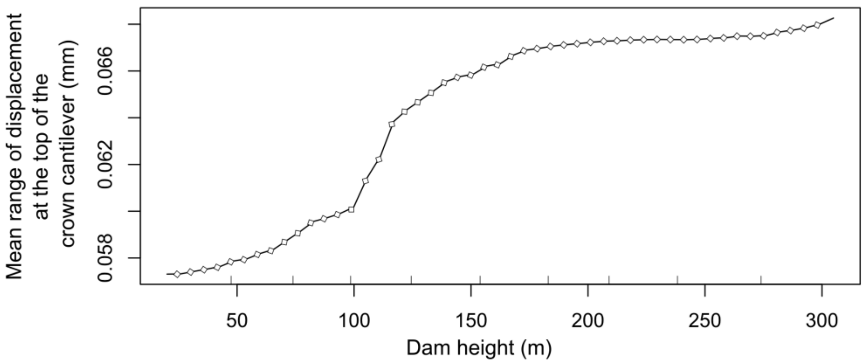

Figure 4: Partial dependence of displacement at crown cantilever on dam height.

3.2 Tensile stress at the upstream toe

A homologous analysis was performed for the stress at the upstream toe, as obtained for the worst load combination among those considered: low temperature, full reservoir. Figure 5 shows the relative importance of inputs.

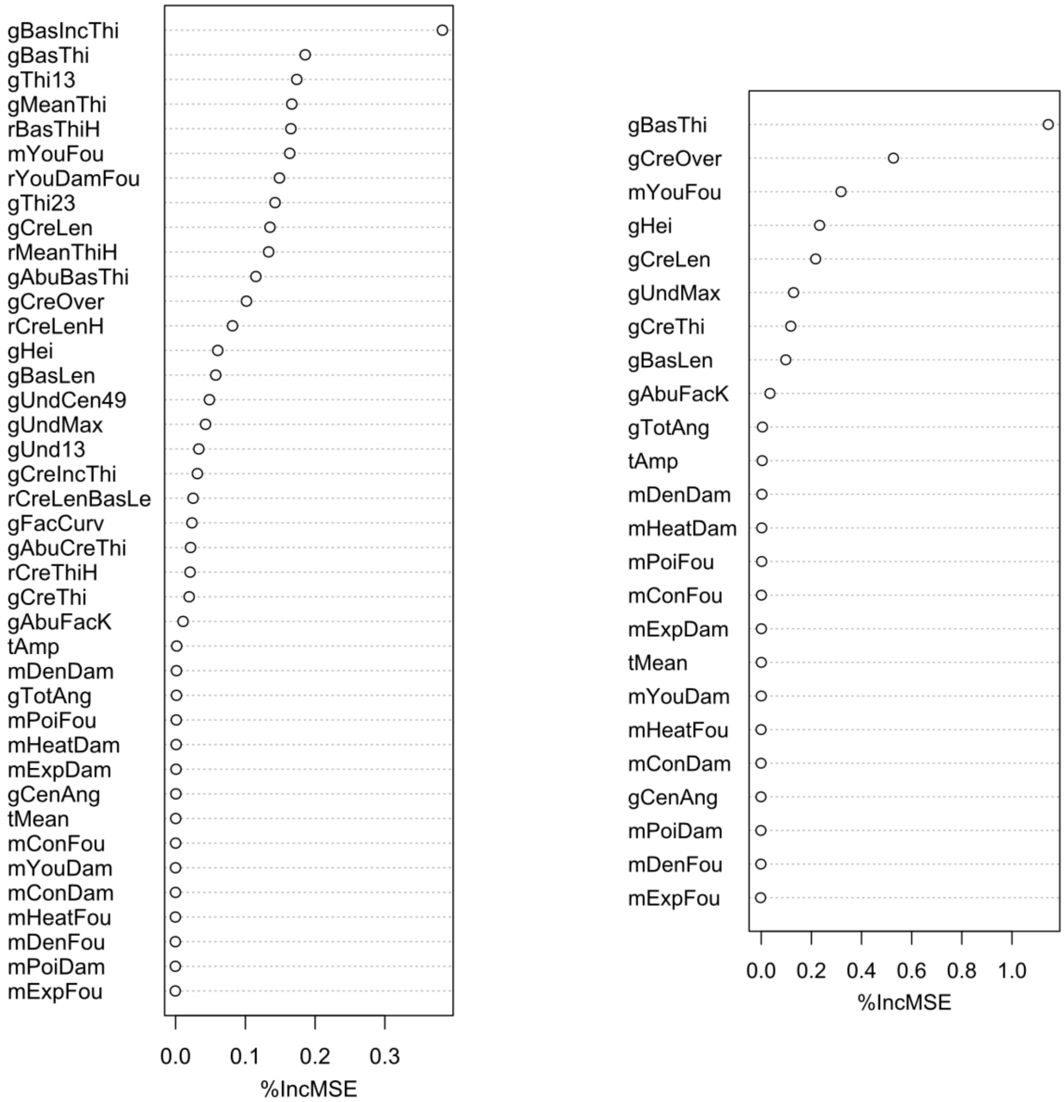

Figure 5: Input variable importance on tensile stress at the upstream toe. Left: all inputs. Right: independent inputs

Base thickness is the most important input in this case, followed by overhanging. These results agree with engineering knowledge, which supports the applied methodology. Nonetheless, this analysis can be interpreted as an objective quantification of the effect of these variables, as compared to others that can also be tuned in the design stage.

4 Conclusions

A methodology for the systematic study of the behavior of arch dams has been presented. It can be used to compute an objective estimate of the effect of each dam variable - geometry, materials - in its response. The results obtained in terms of the influence of the foundation Young’s modulus on the dimensionless displacement at crest is consistent with the values based on experience: soft foundations have great influence on dam response, but a much lower relevance if its value is restricted to the commonly recommended ranges. The geometrical features are clearly preponderant over the thermal and resistant characteristics of the materials, provided that all are within the conventional ranges.

In this sense, the results show a much greater influence of chordal crest length. Among the variables that can be controlled in the design – the length of crown depends basically on the site, generally with low flexibility – base thickness and curvature stand as the most influential.

The presented methodology can be applied to analyze further variables related to dam behavior. Moreover, a degree of similarity can be defined as a function of the difference in terms of the input variables, weighted on the basis of the variable importance. This measure would vary depending on the response variable under consideration: two arch dams can have more similar performance in terms of stress than in terms of deformation.

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6 References

[1] Lombardi, G., Amberg, F., & Darbre, G. R. (2008). Algorithm for the prediction of functional delays in the behaviour of concrete dams. The international journal on hydropower & dams, 15(3), 111.

[2] Salazar, F., Toledo, M. A., Oñate, E., & Morán, R. (2015). An empirical comparison of machine learning techniques for dam behaviour modelling. *Structural Safety*, 56, 9-17.

[3] USACE – US Army Corps of Engineers, editor (1994). Arch Dam Design, capítulo 8, pp. 1:15. USACE, Washington DC, USA.

[4] Romana, M. (2003). DMR, a new geomechanics classification for use in dams foundations, adapted from RMR. 4th International Symposium on Roller Compacted Concrete (RCC) Dams, Madrid, Spain.

[5] USBR – US Bureau of Reclamation, editor (2013). Design of Double-Curvature Arch Dams Planning, Appraisal, Feasability Level. Technical Memorandum No. EM36-86-68110.

[6] GiD the personal pre and post processor. http://www.gidhome.com/, June 2017.

[7] Dadvand, P., Rossi, R., and Oñate, E. (2010). "An Object-oriented Environment for Developing Finite Element Codes for Multi-disciplinary Applications". *Archives of Computational Methods in Engineering*. 17, 253–297.

[8] Vicente, D.J., San Mauro, J., Salazar, F. and Baena, C. M. (2017). An Interactive Tool for Automatic Predimensioning and Numerical Modeling of Arch Dams. *Mathematical Problems in Engineering*, vol. 2017, Article ID 9856938, doi:10.1155/2017/9856938

[9] Shiyong, W., Manbin, S., y Jian, W. (2010). Jinping hydropower project: main technical issues on engineering geology and rock mechanics. Bull Eng Geol Environ, 69(3): 325-332.

[10] Degoutte, G. (2002). *Small Dams, Guidelines for Design, Construction and Monitoring.* French Comittee on Large Dams. Ed. Cemagref editions (France). ISBN: 2-85362-551-6.

[11] USBR – US Bureau of Reclamation, editor (1977). Design Criteria for Arch and Gravity Dams – Engineering Monograph Nº19. US Government Printing Office, Denver, Colorado, USA.

[12] MAPAMA – Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente, website (2017). *Inventario de presas y embalses.* <*http://www.mapama.gob.es/es/agua/temas/seguridad-de-presas-y-embalses/inventario-presas-y-embalses/*http://www.magrama.gob.es/>. {Last access 2017-07-17}
[13] Vallarino, E. (1998). *Tratado Básico de Presas – Tomo I (4ª Edición)*. Ed. Colegio de Ingenieros de Caminos, Canales y Puertos. ISBN: 84-380-0144-0 (In Spanish).
[14] Santillán, D., Salete, E., Vicente, D. J., y Toledo, M. Á. (2014). Treatment of solar radiation by spatial and temporal discretization for modeling the thermal response of arch dams. *Journal of Engineering Mechanics*, *140*(11), 05014001.
[15] Castilho, E.M., Schclar Leitao, N. and Tiago C. (2013). Thermal analysis of concrete dams during construction. *Second International Dam World Conference*, Lisbon, Portugal, LNEC, 21-24 April.
[16] Tatin, M., Briffaut, M., Dufour, F., Simon, A., and Fabre, J. P. (2015). Thermal displacements of concrete dams: accounting for water temperature in statistical models. *Engineering Structures*, *91*, 26-39
[17] Andersson, O. and Seppälä, M. 2015. Verification of the response of a concrete arch dam subjected to seasonal temperature variations. MSc Thesis, TRITA-BKNExamensarbete 458, Department of Civil and Architectural Engenering, KTH Royal Institute of Technology, Stockholm, Sweden, 89p.
[18] FERC – Federal Energy Regulatory Commission Division, editor (1999). *Engineering Guidelines for the Evaluation of Hydropower Projects, Chapter 11 – Arch Dams.* RIDM –Regulations, Guidelines and Manuals. Comission of Dam Safety and Inspections Washington, DC 20426.
[19] Bofang, Z. (1997). Prediction water temperature in deep reservoirs. *Dam Eng*., 8(1), 13–25.
[20] Gracia, L., Salazar, F. and Larese, A. (2016). Development of a Computational Tool for Structural Verification of Dams. Monographs of the International Center for Numerical Methods in Engineering (CIMNE) (2016). URL https://www.scipedia.com/public/Larese_2016a.
[21] Pan, J. (2015). Collapse Modeling of a Masonry Arch Dam Using the Cohesive Interface Elements. *Mathematical Problems in Engineering*, *2015*. Article ID 139586, http://dx.doi.org/10.1155/2015/139586.
[22] Friedman, J., Hastie, T., & Tibshirani, R. (2001). *The elements of statistical learning* (Vol. 1). Springer, Berlin: Springer series in statistics.
[23] Breiman, L. (2001). Random forests, *Machine learning* 45(1) (2001) 05-32.
[24] Salazar, F., Toledo, M. Á., González, J. M., and Oñate, E. (2017) Early detection of anomalies in dam performance: A methodology based on boosted regression trees. *Struct. Control Health Monit*., doi: 10.1002/stc.2012.
[25] Salazar, F., Toledo, M. Á., Oñate, E., & Suárez, B. (2016). Interpretation of dam deformation and leakage with boosted regression trees. *Engineering Structures*, *119*, 230-251.
[26] Strobl, C., Boulesteix, A.L., Kneib, T., Augustion, T, Zeileis, A. (2008). Conditional variable importance for random forests. *BMC Bioinformatics* 2008, 9:307
[27] Rocha, M. (1964). Statement of the physical problem of the arch dam. Proceedings. Symposium on the Theory of Arch Dams. Southampton. 1964.
[28] Shaw, Q., Becerik, M.U. (2016). Structural Design to Accommodate Challenging Rock Mass Conditions at Yusufeli Dam. 10th ICOLD European Club Symposium, Antalya, Turkey, 2016.