SIGNIFICANCE OF STRESS-SENSITIVITY ANALYSES AND MONITORING OF STRUCTURAL BEHAVIOR OF CONCRETE DOUBLE CURVATURE ARCH DAMS USING FINITE ELEMENT MODELLING FOR THE SAFETY EVALUATION OF EXISTING DAMS

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ABSTRACT

Arch dams though constitute a diminutive proportion compared to the total count of dams worldwide, analyses for the safety of these spectacular structures on various criteria of failures, viz., structural, hydrological, operational etc. are of paramount importance. They are prominent when height more than 150m is considered. First arch dams during nineteenth century followed the design of arch bridges. Arch dams started increasing by first decade of twentieth century and by 1950, there were numerous large arch dams in the World, one of the prominent being the Hoover dam constructed in 1936.

Dam safety inspections and monitoring for the safety of concrete dams shall take into consideration the significant parameters for monitoring the behavior of the dam, foundation and abutments etc such as structural deformations, special movements, dam-body temperatures, uplift pressures, and stresses at salient points, etc. This is more important for a concrete doubly curved arch dam.

Analyses for safety of an arch dam begin with simple analysis techniques and conservative assumptions whereas rigorous analysis would be necessitated when a concern on any aspect is brought up. Apart from that, the rationale for monitoring safety and behavior is becoming pronounced on various counts.

Safety evaluation of arch dams shall address issues of strength, stability, and vibrations, as well as distinctive behavior of arches and arched structures when subjected to the anticipated loads. Computational models using the finite element method (FEM) are capable of modelling and simulating the dam structure as well as the dam-fluid-foundation interaction. Linear, Non-linear, static, dynamic analyses can be incorporated in computational analyses. Though possibilities of new arch dams are not so prospective, imbibing the risk associated, the safety of the existing ones are to be continuously and periodically monitored using the advancement of technology.

This paper studies advancement in analyses techniques and research activities and emphasizes the need of a rigorous stress-sensitivity analyses and monitoring the peculiar behavior through FEM for these complex structures when various safety concerns are taken into consideration.

1. INTRODUCTION

1.1 Arch dams

An arch dam (Fig.1) can be a concrete or masonry retaining (water) structure curved upstream so that the major portion of the load applied to it is carried by the abutments by thrust. The important criteria for deciding in favor of the construction of an arch dam are the favorable valley shape and the foundation as well as abutment rock capabilities to withstand the loads/stresses transferred to it. Though by count, arch dams constitute about 4%, the proportion would increase remarkably when dams of height 150m or more are considered.

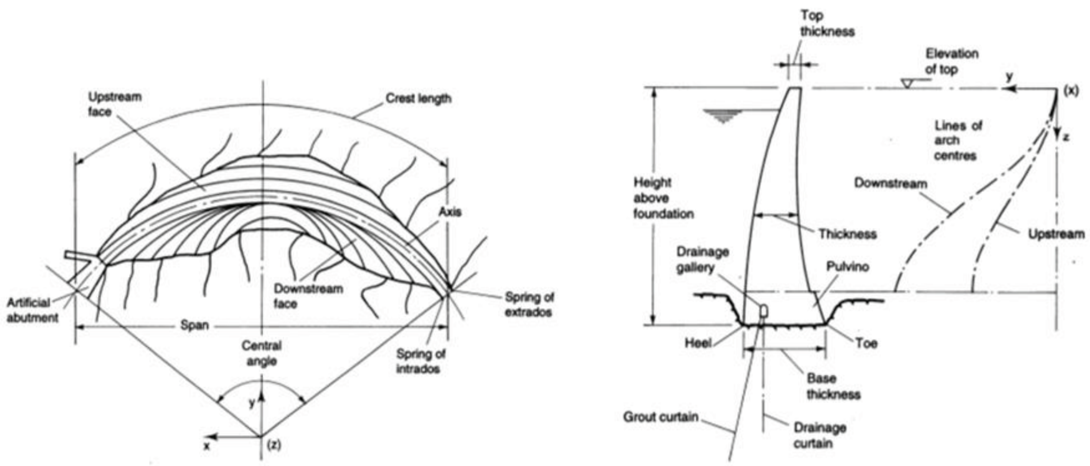

Fig. 1 : (Left) Plan of an arch dam; (Right) Central Cantilever of the arch dam (Source: CISM courses and Lectures No. 367[26])

Arched structures have an inherent safety and arch dams capitalize this major advantage. Certain Model tests carried out, up to failure, proved that if the foundation resist, the arches will also. Some tests showed that arches burst only when the membrane stresses throughout the thicknesses are attained by complete plastification of the dam body by increasing the combined load of hydrostatic pressure & weight by ten times or more.

An ideal dam site (Fig. 2) for an arch dam would be practically impossible and accordingly a final design for an arch dam will be resulted through judicious evaluation and selection of physical properties which best satisfy site conditions, stress requirements, and design criteria. This final design is arrived at by several cycles of layout, analysis, evaluation, and improvement

1.2 Double curvature Arch dams

Initially arch dams were of single curvature, constant angle, variable curvature etc. The development of effective methods for analyses and continuous design interventions for measures for distribution of stresses, reduction of tensile stresses, paved way to the adoption of the principle of double curvature by Andre Coyne, France, in 1935. In 1938, US Bureau of Reclamation published Trial Load Method of Analyses, a widely used analysis method. Better methods of analyses of stresses and behaviour led to higher sized and thinner arch dams. There are thinner dams with base width/Height ratio 0.054 to 0.1. Development of Finite Element Method and its' wide use in analyses, advent of digital computers and its' advancement saw more powerful analysis techniques, 3-Dimensional modeling simulating actual scenarios etc. and this contributed much towards the rigorous analyses and research in double curvature arch dams.

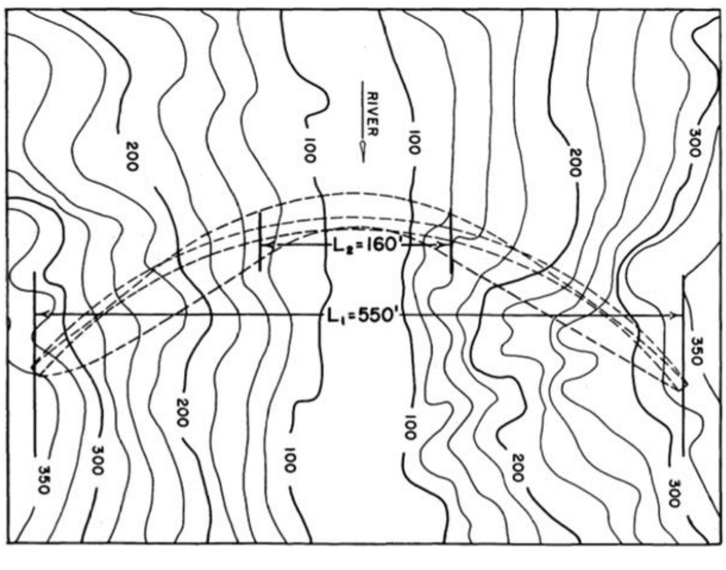

Fig. 2 : Typical dam site of an arch dam (from which the basic parameters for the preliminary design are drawn)(Source: EM36, Guide for preliminary design of arch dams, Bureau of Reclamation, United States Department of the Interior[2])

Based on height, geometry, thickness (base thickness/Height, i.e., b/H ratio), symmetry with respect to crown, extrados-intrados curves, etc., arch dams can be of many types. The prominent and probably the best among these is the double curvature arch dam, which are curved both in plan and elevation.

In double curvature arch dam, the cantilevers are arched from bottom to crest giving better support to horizontal arches and a reduction in tensile stresses at the upstream will be resulted, when compared to single curvature ones. The improved distribution of stresses paves way for effective utilization of concrete.

2. BEHAVIOUR OF ARCH DAMS

Arch dams varies in their behavior responding to the loads acted upon and per the classification of these dams; the predicted response to loads varies vis-à-vis the classification such as, based on theory used for computation of stresses; cylinder theory dams and elastic theory dams [3,10] or as the case may be. Their behavior is monitored by the movements at salient locations of the dams and analyzing for the stresses developed and the consequent development of any cracks or crack propagation, in response to the static, dynamic and temperature loads. Strength and behavior are affected by materials and methods adopted for construction. Reasons such as Alkali-aggregate reaction and its' effects, presence of ettringite in concrete and fracture pattern etc. are all factors deciding the strength and behavior of an arch dam [27]. These considerations and factors would often call for a sensitivity analyses on stress pattern during the safety evaluation of existing dams.

The tendency in these dams are to develop tensile stresses are at the bottom upstream face and the upper 1/3rd portion at the downstream face when the reservoir is at Full Reservoir Level(FRL) and with minimum temperature. At the upper ends, the top arch may offer greater restraint to deflection of the vertical elements. The tensile stresses at the bottom upstream can be reduced by an upstream overhang whereas the tension at the top 1/3rd can be reduced by a downstream overhang. The vertical curvature may increase as the valley shape becomes wider. The stability of the individual block during construction as well as the tensile stresses developed at the downstream top third height is dependent on the downstream overhang[33].

When there is anisotropy in the foundation and differential movement of abutments are likely, double-curvature arch dams are not the preferred ones.

Doubly curved dams are the best one normally but not so in conditions where, (i) appurtenant structures are to be integrated, (ii) construction constraints are there, (iii) economy cannot be achieved due to complexities in form work and construction and (iv) when materials such as roller compacted concrete (RCC) or faster method of construction without joints are to be resorted to, etc.

3. STRUCTURAL ANALYSES ON ARCH DAMS

Conventional analyses of arch dams (trial load analyses developed by Bureau of Reclamation, United States etc.) take into account many assumptions such as the dam material, foundation/abutment rock as homogeneous, isotropic and elastic materials and accordingly the general assumptions of the elastic analyses are considered. Such analyses also normally do not take into account the variation of temperature across the thickness of the arch, relief from tensile stresses due to cracking etc. These analyses consider the dam structure as a monolith, despite the presence of contraction joints. There are various conventional methods of analyses and these analyses do not consider the non-linearity, the simulation of the geometry, discretization etc. Analyses re-creating almost similar conditions become possible due to the advancement of technology and intervention of 3D finite element analyses. Non-linearity in material properties and joints can be introduced, various loading such as dynamic and thermal loading can be simulated, dam-foundation/abutment interaction, water compressibility and fluid-structure interaction etc. can be incorporated in the analyses and the behaviour can be studied.

It requires various favorable conditions for the construction of arch dams and the construction of high arch dams are not so common or frequent. Still, the analyses for development of compressive and tensile stress at salient locations and movement of the existing arch dam structures in response to the applied loads and its' combinations are to be necessarily done in many a situations. Apart from the design perspective, this is an important activity in the safety evaluation of the existing dams. Research and studies on such behaviour and sensitivity analyses on arch dams would help ensure proper attention on the safety of these complex structures housing huge volume of water with a devastating potential to cause damages. The safety of the structure have to be analyzed for the continued normal operation under unusual and extreme loading so as to draw the envisaged benefits for a prolonged life without causing risk to the stakeholders downstream[13]

Arch dams though constitute a diminutive proportion (Table 1) compared to the total count of dams worldwide, analyses for the safety of these spectacular structures on various criteria of failures, viz., structural, hydrological, operational etc. are of paramount importance.

Table 1 : Synthesis of large dams by type

Sl. No.	Type of dam	Number
1.	Earthen dams	37537
2	Rock fill dams	7729
3	Gravity dams	8115
4	Buttress dams	415
5	Barrages	299
6	**Arch dams**	**2352**
7	**Multiple arch dams**	**129**
8	Others	1409
	Total	57985

(*Source*: ICOLD website, https://www.icold-cigb.org), (Updated as on September 2019)

3.1 Loads to be considered in the analyses

Various types of loads acting on the arch dams have different impacts and response. Apart from the analyses involving the static loads such as weight of the structure, reservoir water loads, uplift loads, and effect of temperature/solar radiation, loads and combination for dynamic analyses for seismicity/ground motion are also to be conducted.

3.2 Stresses in arch dam

Maximum allowable compressive stresses in arch dams shall not exceed as for concrete gravity dams but if approximate methods are used for analyses generally a decrease of 25% to 35% in allowable compressive stress values are seen suggested. To the possible extent, the tensile stresses may be avoided though it may occur at certain points, say, at upstream face or downstream face due to various loading situation or its' combination during usual loading or during construction or due to temperature loading or due to extreme loading combination including MCE and on those situations the tensile stresses should not exceed the stipulated values(1.055MPa for usual and 1.583MPa for unusual loading combinations). The Elasticity values of Rock (Er) and that of concrete (Ec) are influential parameters on the value of tensile stresses.[33]

Presence of loading scenario causing development of tensile stresses may lead to cracks in arch dams. The important consideration is that whether these cracks would make the structure incapable of transferring the load to the abutments with adequate factor of safety. Even though the cracks relieves tensile stresses, the cause and its' development are important aspects to be investigated and monitored.

3.3 Potential failure modes in Arch dams

Many literatures about arch dams emphasize that one of the potential cause of failure of arch dams/double curvature arch dams is the failure of the abutment due to various factors. There can be faults, joints vulnerable to cause failure in shear. Joints and fissures parallel to the direction to the thrust are detrimental to the stability of the abutment. Safety of the arch dam prominently lies in the strengths of the abutments and foundation rock and as such, the design as well as safety evaluation shall incorporate the parameters that may cause vulnerabilities to these areas. FEM analyses, parametric methods and geo mechanical analyses shall have such an emphasis.

For having a stable arch dam, the direction of the thrust and the geological features of the abutting rock mass deserve utmost careful consideration. There should not be any possibility of a sliding failure along weak planes. Stability analyses of the possible failure wedges governed by the shearing planes and geological conditions are able to find out the safety factors. The factor of safety should be greater than 4.0, 2.7, and 1.3 for usual, unusual and extreme loading conditions respectively. The failure of Malpasset dam in 1959 is a case study in many literatures about arch dam and the importance of abutment stability is emphasized clearly and explicitly in them.

In order to increase the factor of safety, and to avoid the development of the tensile forces, the building up of pore pressure in the rock mass have to be reduced and for intercepting the seepage water from upstream, drainage galleries at the end of tension zones are to be provided

3.4 Role of abutments in arch dams

Transmission of the arch thrust to rock abutments is an important criterion in arch dam design. Transmission of the thrust in full width to the abutment normal to the axis of the dam is very much advantageous but it would require more excavation. The strength, stability, excavation required, slope of abutment, symmetry and continuity, geological characteristics of the abutment rock etc. all play crucial role in the design as well as construction of arch dams.

Thrust blocks at the abutment would be necessitated in certain situation to reduce the length of the top arch, reduce the non-symmetry, distribution of stresses at a weaker abutment and to serve as an abutment where no natural rock abutments are there. The foundation pads, known as pulvino, in Italy, are provided between arches and foundation to distribute the load to the foundation, to take care of foundation irregularities or to obtain symmetry to the dam. The joint provided between dam and the foundation pad is often referred to as the perimetral joint and this kind of joint relieves the tensile stresses occurring at the extrados areas in abutment and these joints perform well with the behaviour of arch dams[33].

Based on the behaviour, improvement in design can be achieved through the introduction of thrust blocks, foundation pads and perimetral joints etc. which are a few features adopted in arch dams/ double curvature arch dams for obtaining specific advantages in certain situations.

Automatic computer aided shape optimization and reduction in concrete volume of the double curvature arch dam could be facilitated using the strength of computer aided analyses and design but the above aspects of abutments are to be met with in order to avoid stress concentration, instabilities etc. of the abutment which may lead to failure of the dam. The volume of concrete criteria is only one factor among many other important criteria for a competent design.

4. NEED OF REVIEW OF ANALYSES OF EXISTING ARCH DAMS

Safety evaluation of the existing dam is often emphasized through the respective Codes or Manuals of the country, federal agency or the dam owning department. Accordingly, the safety evaluation shall analyze the original design and the parameters considered vis-à-vis the prevalent design consideration and parameters required to be incorporated. Besides, the performance of the arch dam structure vis-à-vis the designed performances also need to be investigated for ensuring safety and mitigating any potential risk associated. The performance or behaviour of an existing dam is obtained from the instrumentation data of the structure. Structural Health Monitoring (SHM) of the arch dams plays a crucial role in obtaining such data. The revised analyses or the design review and connected investigations would be able to find out whether the structural behaviour of stresses and movements against the loads and load combinations are in anticipated lines or any potential risk is associated or the structure is safe against any case. The behaviour of a doubly curved high arch dam too is complex due to its' complex geometry. The effects of aging of the structure with respect to structural (material) parameters and any possible changes in hydrological, geological, climatological and seismological parameters are to be investigated. A sensitivity analysis considering all the above aspects would be able to identify the factors having impact on the behavior of the structure and its' safety.

5. SENSITIVITY ANALYSIS

Computational modeling has become the lead activity in many research and modeling process; the complexity in the problem is to be modeled using various input parameters or factors affecting the results of the model. The sensitivity analysis helps to identify how sensitive the model results are with respect to the input parameters. Identification of relative 'sensitivity' of parameters helps in better monitoring strategies and experiment design, say, finding the priority and amount of data to be collected [35]. A.Saltelli et al (2019) stated that sensitivity analysis is deriving the relative importance of model input parameters and assumptions and is distinct from uncertainty analysis. Sensitivity Analysis involves modeling of the problem which requires much skills through experience and skills in statistical analysis and ability to interpret. According to F.Ferretti et al (2016) sensitivity analysis is critical to gauge the relevance and plausibility of models.

Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be divided and allocated to different sources of uncertainty in its inputs.

R. Kitching et al (1975) stated that sensitivity analysis as an alternative technique for identifying the errors in the model in which overall variations in most of the parameters are made individually and the effect on the readings is noted. An important consideration is the reliability that can be placed on the model results, particularly when they are based on uncertain data. A sensitivity analysis, in which the magnitudes of certain parameters are varied, can indicate the confidence with which the model can be used. Even though a model has been devised and tested it should be continuously updated in the light of new data. The ease with which sensitivity tests can be carried out is one of the main advantages of simulation models

Sensitivity analysis is intended to evaluate the fractional change in the performance estimates in response to alternative models or changes to the parameters of those models. Sensitivity analyses enables the analyzer to refine the model from preliminary to more sophisticated ones and established methodologies besides getting detailed insights on risks associated through better understanding of features, events, and processes. Mohanty et al, (2011) stated sensitivity analysis in the case of a performance assessment as a methodology to determine the importance of its' various parts to the modelers' results. This allows the modeler to focus their efforts to improve the performance assessment. A sensitive parameter, generally, is the one that produces a relatively large change in the output variable for a change in the input parameter within the range of uncertainty. There can have hundreds of parameters sampled from their probability distributions and the parameter sensitivity analysis finds those parameters that make the largest contribution to the chosen outcome, or its' variability.

5.1 Sensitivity Analysis techniques

There are various traditional techniques based on parametric methods. There can be statistical or non-statistical methods. Statistical methods may rely on the Monte Carlo results generated from the uncertainty analyses. It may use random sampling of input parameters to generate a set of responses and statistical hypothesis testing to analyze the relationships between the input parameters and the responses to make inferences about the most sensitive one. There are regression methods, viz., single linear regression based on one variable, stepwise multiple linear regression, etc. and certain statistical test based methods for non-monotonic relationship. Non-statistical methods develop models specifically to address the sensitivity. The Morris method, Fourier Amplitude Sensitivity Technique (FAST), and Factorial Design of Experiments etc. are a few of them. Apart from those, there are certain advanced special case sensitivity techniques such as Cumulative Distribution Function Sensitivity Analysis, Genetic Algorithms, Regionalized Sensitivity Analyses, Fractional Factorial Method, Iterated Fractional Factorial Method, Parameter Tree and Distribution Partitioning Intercept Methods, Barrier Performance Evaluation by Signal Processing Techniques which deploy convolution and de-convolution using the Fourier Transform, Component Sensitivity Analysis, Strategic Partitioning of Assumption Ranges and Consequences Methodology and Distributional Sensitivity Analysis etc. [24].

5.2 Sensitivity analysis-Areas of application

Sensitivity analyses can be performed on a variety of problems. W. Liu et al (2018) developed a novel hybrid approach to perform global sensitivity analysis in order to reduce the randomness and uncertainty underlying the structural safety risk analysis in operational tunnels. The deterministic and stochastic finite element model was used to develop the approximate relationship between input and output parameters with a high level of accuracy. They used the steps, viz., i) tunnel-soil modeling and generation of simulation data, including deterministic Finite Element model analysis by ABAQUS and stochastic Finite Element model analysis by ABAQUS, ii) establishment of meta-model, including the implicit function fitting of risk factors by Particle Swarm Optimization-Least Square Support Vector Machine (PSO-LSSVM)technique, and iii) the global sensitivity analysis, including Monte Carlo method simulation and global sensitivity analysis by EFAST algorithm. Through this work, they were able to establish a sensitivity relation and distinguish the influence degree of parameters on the tunnel engineering safety of this project and similar projects. In their research, they studied the influence of various parameters (fig.3) on the output parameter, viz., Maximum Bending Moment, Maximum Axial Force and Maximum bolt strain

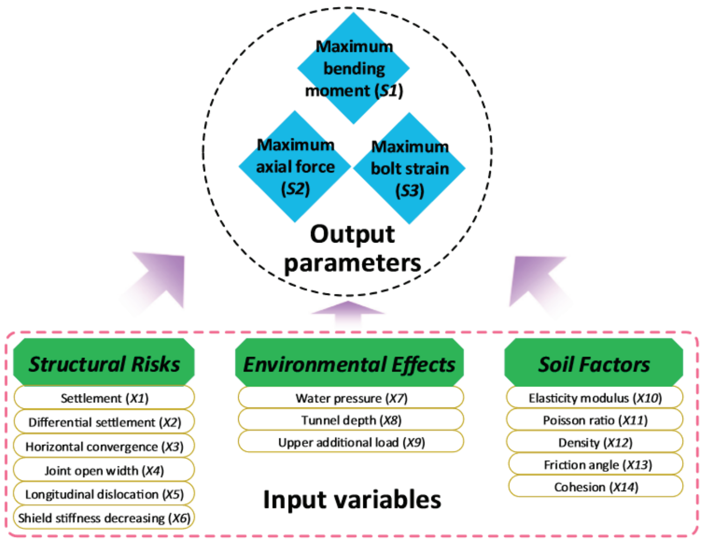

Fig. 3 : A representative Indicator system for Sensitivity Analysis as used in a operational tunnel problem (Source: W.Liu et al, Sensitivity analysis of structural health risk in operational tunnels)

S. Sabermahani & P. Ashjanas (2019) through the sensitivity analyses using Sobol and Delta Moment Independent Measure showed that the most effective parameters in determining the Ground Motion Prediction Equation having a key role in seismic hazard assessment are moment magnitude and shear wave velocity. They used ridge regression method to find relation between input seismic parameters and targets (PGA, PGV, PGD and SA (T=0.02s,T=1s)). Z.Wu et al (2017) used the regional sensitivity analysis method, Monte Carlo filtering (MCF), for the analysis of a typical three layer flexible pavement structure based on Mechanistic-Empirical Pavement Design Guide which compared well with Global Sensitivity Analysis methods. E.Pisoni et al (2018) evaluated, a policy steered (Screening for High Emission Reduction Potentials on Air quality (SHERPA) module - predicting air quality improvement linked to emission reduction scenarios - by means of sensitivity analysis to identify the most influential input sources of this uncertainty and the results provided relevant information about the key variables. R.Thapa et al (2018) in their study on ground water vulnerability zones in Birbhum Dt., India, single parameter sensitivity analysis and map removal sensitivity analysis to test the sensitivity of the various hydrogeological parameters were conducted and concluded that net recharge is the most influential parameters for ground water vulnerability. M.Jeon et al (2018) estimated the changes of the dynamic characteristics of an underwater vehicle performing a specific mission due to the change of the design parameters by sensitivity analysis. They calculated sensitivities of the dynamic characteristics with respect to the hull form parameters and based on the analyses, four sensitive design parameters were selected. Q.D. Boersma et al (2019) performed a numerical sensitivity analysis in layered materials, the impact of changes in sedimentary facies and alternations in mechanical properties to the deformation style, orientation, confinement, and 3D connectivity of natural fractures, to investigate and quantify the relation between contrasting material properties, the principal horizontal stresses and fracture behaviour. The results showed that tensile stresses develop in the stiffer layers and these stresses are dependent on the ratio of elastic parameters of stiffer and softer layers. S.Yang et al(2015) performed Sensitivity analysis in building energy assessment to determine the key factors influencing energy use or carbon emissions for buildings comparing the characteristics of four global sensitivity analysis, viz., Standardized Regression Coefficient), Morris design, Extended Fourier Amplitude Sensitivity Test and Treed Gaussian process) method.

M.A. Hariri-Ardebili & V.E. Saouma (2016) in a probabilistic-based safety assessment of structures responses of which is primarily governed by cohesive cracking studied sensitivity and uncertainty quantification (fig.4) of the cohesive crack model by performing pushover analysis of a simple interface element under mode I and II, and dynamic analysis of a dam with joint elements subjected to mixed-mode fracture[15].

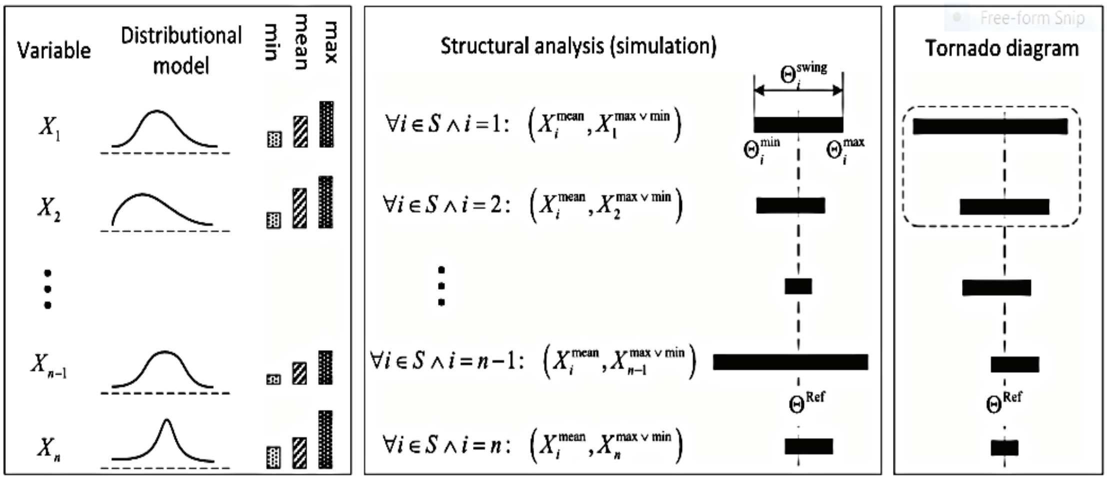

Fig. 4 : Sensitivity Analyses using Tornado diagram
(Source : M.A. Hariri-Ardebili, V.E. Saouma/Engineering Fracture Mechanics 155 (2016) 18–35)

5.3 Sensitivity Analysis in Arch dams

Before computers started reigning the modeling and analyses field, the structural analysis & design of doubly curved arch dam was indeed a difficult task. Intervention of digital computers eased the complexities. Sharpe (1969) presented the arch dam optimization as a mathematical programming problem. Parameters describing the shape, location, height and material properties of the dam are set as design variables. Constraints are placed on the design variables and behaviour characteristics such as maximum stresses and boundary forces to ensure that the structure is feasible, safe and functionally useful. A merit function expressing the cost and functional usefulness of the dam in terms of the design variable set is maximized subject to the design constraints.

Wassermann (1983) in his optimization problem used eight-node iso-parametric solid finite elements to model a double-curved arch dam with the design parameters as the positions of certain key points and tangent vectors of the surfaces and solved by a sequential linear programming method. T.M.Yao et al(1989) used a higher-order finite element approximation. A continuum-based shape design sensitivity analysis is applied to obtain the gradients of cost and constraints. Interfacing of the sensitivity analysis program with analysis data files was done using the data management subroutines of ANSYS. In the optimization process, design automation is achieved by systematic adjustment of design bounds. total volume of the dam is reduced from the Wassermann's optimal volume of 8.5%. Also, the maximum tensile stress on the upstream surface is reduced from the original value of 3.9 MPa to 1.981 MPa. Shape design sensitivity expressions were obtained also by Choi (1985), Mortenson (1985), Haug (1986) and Yao (1989) by different methods. Since then there have been many shape optimization research work and studies aligned to specific problems of arch dams.

Micevska V. et al (2019) performed arch dam design and analyses for the shape optimization of the complex geometry which involved structural evaluation and sensitivity calculation for critical parameters such as stresses and displacements in the dam body, foundation and abutments; the effectiveness of the final shape obtained after the complex analyses and sensitivity analyses depends on the accuracy of the software used.

H.Liang et al (2019) in their seismic stability sensitivity and uncertainty Analysis of a high arch dam-foundation system, observed that arch dam abutment is the supporting and transmitting mechanism, and is often the weak part of the dam and the seismic performance of arch dams depends largely on the seismic stability of the abutment rock mass, an important issue in the safety assessment of concrete dams subjected to severe earthquake hazards. In their study they quantified the variation in the seismic stability of an arch dam affected by the parameter uncertainties. The arch dam abutment and the dam are coupled as a system. Nonlinear behaviors, including the contraction joint opening and closing, the failure of the dam-foundation interface and the boundary of the probable sliding block of the dam abutment, are considered comprehensively. The dynamic contact model based on the Lagrange multiplier method, simulating the opening, bonding and sliding of joints, is adopted to address the contact nonlinearity problem. The main random parameters consist of the friction coefficients and cohesions of the probable sliding block in the dynamic model. Sensitivity analysis is performed first to assess the effect of each of the parameters on the seismic stability and by assigning a probabilistic distribution to these parameters uncertainty quantification is performed using the approximate IDA method with the LHS technique. The results provided a comprehensive understanding of the effects of parameter uncertainties on the seismic stability of arch dam abutments.

Sensitivity studies were conducted on Idukki double curvature thin arch dam in India - analyses of which were originally done using trial load method and Finite Element Method[17]- for studying the behaviour of the dam, gave valuable inputs for dam monitoring [28].].The 3D FEM thermo-static analysis of this dam with vertical block joint and the multi-layered galleries were conducted using the ABAQUS software (fig,5)and the displacement vectors resulted confirmed observed deformation behavior through the instrumentation data of the dam; the dam-foundation compound 3D model was analyzed with the concrete assumed as linearly elastic whereas the rock mass assumed to behave plastically as per the Mohr-Coloumb failure criterion. The Dam-foundation rock interaction was modeled with relative sliding restrained but allowing for opening. The model was analyzed after study on the physical, mechanical and mineralogical properties of the concrete and testing for their values at its' age of 40 years. The analyses were conducted for four different loading scenarios of operating water-level and concrete temperature combination. The FEM analyses were in full agreement with the instrumentation data which validated the FEM modeling and analyses.

6. CONCLUSIONS

The design and analysis of an arch dam, for a construction involves various factors are taken into consideration. To list some of them are, assumptions made in the analyses, canyon shape & topography, peak flood (SPF, PMF, etc..), freeboard, spillway required, dam material and its' properties(say, strength, elastic properties, thermal properties, dynamic properties, etc. of concrete), foundation type and it' properties (strength, deformation and permeability of the rock), abutment properties(Strength, stability, deformation and permeability etc,,), load and load combinations(The loads may be reservoir and tail water loads, temperature, internal hydrostatic pressures, uplift, dead load, ice load, silt load, seismic loads, etc. whereas the loading combinations may be usual, unusual and extreme loading combinations), factor of safety(allowable stresses in tension and compression, shear stresses and sliding stability, foundation stability), earthquake loads and dynamic response, natural frequencies, modes, etc.. The doubly curved dams have more complex behaviour. Considering the potential failure modes and risks, the safety evaluation of the existing dams too is very important and requires care analyses. It can be seen that there are many parameters associated with the design as well as safety evaluation. Various uncertainties would get incorporated in the models. The sensitivity of these parameters on the targeted outputs, viz., the stresses and deformation at various salient points need to be analyzed and carefully reviewed so as to alleviate the risks.

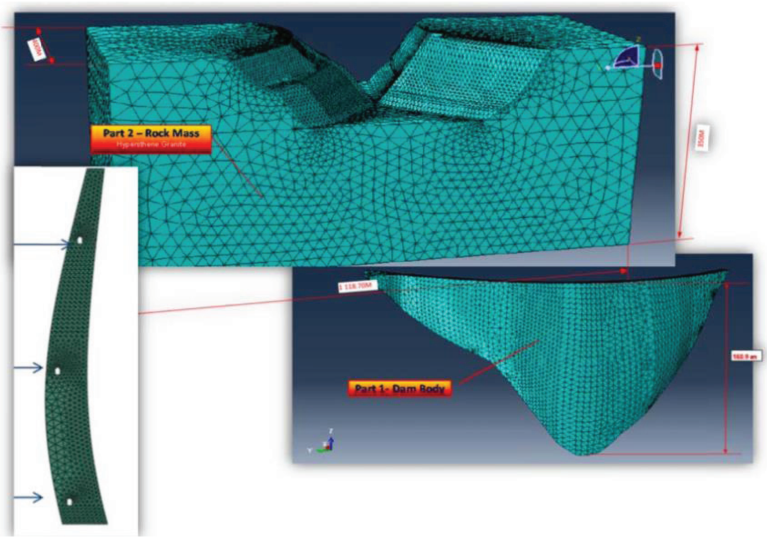

Fig. 5 : The 3D FEM model of the doubly curved thin arch dam and the rock mass.(source: Pillai, B.R.K., et al [28])

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