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Study on Influence Factors of Nonlinear Finite Element Analysis for High Arch Dams

Xiaoqing Liu[1], *Tongchun Li*[1], *Zhiqiang Wang*[1] *and Lanhao Zhao*[1]

[1]College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, 210098 P. R. China

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Abstract: In communication network, WDM optical backbone network has become the primary long-distance options. In this paper, the structure of WDM optical networks are analyzed, the add-drop system in the architecture of WDM optical networks is discussed. In order to improve network efficiency, we analyzed the characteristics of network routing, and proposed a new routing design method. In communication network, a good routing is very important for network operation. Routing technologies manage the flow of data between network segments in optical communication network. In addition, we also discussed the WDM optical network switching technology.

Keywords: High arch dam, mesh size, strength criterion, iterative method, convergence control standard

1. Introduction

Recently, there are some high arch dams being built in China, such as Xiluodu (278m), Xiaowan (292m), Jinping (305m), etc. Simulation and analysis of arch dam should be done by using various methods to ensure the structural safety and reliability. Common methods include model testing method, experience decision method and numerical analysis method [1].

Numerical analysis method is widely used method in arch dam safety evaluation. In a variety of numerical methods, nonlinear finite element method can more accurately simulate the actual work state of the dam. It mainly carries on the whole safety evaluation based on the distribution and value of stress and distortion and the failure situation of the dam and foundation, considering material nonlinearity, construction process, all kinds of load, dam and rock defects and so on [8].

Nonlinear finite element static analysis for arch dam has been extensively studied. Zheng [14] used an elastic-plastic-fracture model to describe the behaviors of concrete and rock and the three types of fracture modes of crack, crush and the mixed type. An incremental changeable Kp method was proposed for nonlinear iteration. John and David [4] presented linear and nonlinear static analysis using AIDNA84. The load path selected for comparison produced high tensile stress in linear model and significant cracking in nonlinear model. Fu and Zheng [3] used an elastic-plastic-fracture model to describe the mechanical properties of concrete and foundation rock, obtaining the extent of crack zone in the dam-foundation interface, the changes of arch dam deformation and the stress redistribution of arch dam. Liu and Yang [10] implemented Villappan 3-d anisotropic constitutive model in finite element analysis based on damage mechanics, built an 3-d anisotropic damage evolution law according to strain-damage criterion, applied the improved distributed-crack model to simulate concrete element damage failure, and made anisotropic nonlinear elastic analysis of an arch dam with the aid of the three-dimensional finite element method. Faouzi and Rene [2] presented damage-mechanics models for predicting the nonlinear static response of concrete dams. An anisotropic formulation of the damage because of cracking was proposed. Lan and Yang [5] studied the concretes cracked constitutive relationship, gave the general steps of the nonlinear finite element analysis, and developed the corresponding calculation program. Tian and Xia [12] studied the dam heel cracking mechanism of high arch dam with nonlinear finite element method using the elastic-plasticity hardening model as foundation and concrete constitutive model and the distributed crack model for crack. Zhang and Liu [13] studied the load, material

* Corresponding author: e-mail:ltchhu@163.com

strength, safety analysis methods and real work condition of arch dam. However, non-linear finite element method for evaluation of the safety of high arch dam also has some problems, for instant, influence of mesh size, how to choose of constitutive relationship and strength criterion of dam concrete, iteration method and convergence control standard of nonlinear equations and so on. These factors have significant impacts on calculated results. Therefore, the standard research is necessary. A determination method for reasonable mesh size is proposed in this paper. Three kinds of dam constitutive relationship of linear elasticity, elasticity brittle and damage are introduced, and three kinds of strength criteria of uniaxial, biaxial and triaxial strength criterion are also given. An iterative convergence criterion based on two kinds of iteration method of Newton method and modified Newton method is present. Taking a high arch dam as an example, the problems above had been discussed, and some beneficial conclusions are obtained.

2. Basic Principles

2.1. Reasonable Mesh Size

It is a difficult problem when the finite element method is used to analyze the arch dam. Namely, different mesh sizes will result in different results, so losing objectivity of the results [11]. About the reasonable mesh, it is suggested in the paper that the dam is taken as an elastic structure and different mesh size is used. The maximum mesh size that stress converges of major part region to fixed value is taken as the initial mesh size. Meanwhile, local mesh refinement method is used to analyze the stress concentration of the elements, and then nonlinear finite element analysis is obtained. If the concrete failure or damage range has surpassed the original local refinement area, refinement range should be expanded until the failure or damage range is remained within the local refinement range.

2.2. Constitutive Law

Different result is come from different constitutive relationship. Three kinds of constitutive relationship for dam concrete are adopted in the paper as following:

- Linear elastic constitutive relationship
- Elastic brittle constitutive relationship
- Damage constitutive relationship [2]

2.3. Strength Criterion

When the dam linear elastic and elastic brittle constitutive relationship are applied, if the strength criterion of concrete is different, the dam failure range will be different. The following three kinds of strength criteria are used for calculation:

- Uniaxial strength criterion
- Biaxial strength criterion
- Triaxial strength criterion

2.4. Iterative Method and Convergence Control Standard

For the material nonlinear finite element problem, the stress-strain relationship is nonlinear, and the stiffness matrix is not constant and relative to the strain and displacement instead, which can be written as $K(\delta)$. The structural overall balance equation is as following:

$$\psi(\delta) = K(\delta)\delta - R = 0 \tag{1}$$

Where: δ is displacement vector, $K(\delta)$ is stiffness matrix, R is unbalanced force vector. There are three methods of nonlinear finite element equations, namely incremental method, iterative method and mixed method. The mixed method takes advantage of the incremental method and iterative method, the load in mixed method is divided into several increments, and the iterative computation in each load increment is carried on. Because the advantage of incremental method and iterative method has been included in mixed method, and the drawback of them is avoided. The mixed method is used here. Comparison with Newton and modified Newton method in incremental step is made. When using iterative method or mixed method to solve nonlinear equations, in order to study the convergence of solutions, the iterative convergence criterion must be given, otherwise iterative calculation cant be terminated. At present, the iteration convergence criteria commonly used in the nonlinear finite element calculation are as following.

- Unbalanced force criterion

$$\| \psi(\delta^i) \| \leq \alpha_q \| R \| \tag{2}$$

Where α_q is unbalanced force convergence tolerance.

- Displacement criterion

$$\| \Delta\delta^i \| \leq \alpha_d \| \delta^i \| \tag{3}$$

Where d is displacement convergence tolerance. First unbalanced force convergence is applied in the paper. If unbalanced force convergence is satisfied, then displacement convergence is reached. After determining convergence criterion, a suitable convergence tolerance should be chosen. If convergence tolerance is too small, the convergence rate will be reduced. If convergence tolerance is too big, the true solutions do not be achieved although equations have converged. A comparison on convergence tolerance taking10^{-4},10^{-5}, and 10^{-6} is obtained.

3. Influence Factors of Nonlinear Element Analysis

An arch dam is taken as an example. The dam height is 278m, its dam crest elevation is 610m, and maximum dam bottom thickness is 60m. Dead weight, upstream and downstream hydrostatic pressure of normal water level, sediment pressure, and temperature load are considered.

3.1. Computation Parameters

- Hydrostatic pressure Water load and sediment load

Upstream normal water level is 600m and the corresponding downstream water level is 382m; Sediment elevation is 490m, sediment floating bulk density is $0.5kN/m^3$, and sediment internal friction angle is 0^o.

- Material parameters

The dam concrete material parameters are shown in TABLE 1, the rock material parameters of dam foundation are shown in TABLE 2.

- Temperature Action

The temperature load is one of the main design loads of arch dam. According to design specification for concrete arch dams SD145-85, average temperature is only considered and equivalent linear temperature difference of dam section in operation period and the influence of non-linear temperature difference have not been considered. The simplification can not reflect spatial effect of larger temperature gradient changes in the upstream and downstream water level change area, and can not reflect heat conduction of dam and foundation intersection. After the influence of dam concrete hydration heat and the initial temperature difference disappear, the quasi-steady temperature state is reached. The temperature difference between quasi-steady temperature field and arch closure temperature field is taken as temperature load. According to the actual air temperature and water temperature, etc [9], the quasi-steady temperature field can be calculated by the finite element simulation. Considering sunshine influence in site, annual average temperature is 21.74 and annual temperature amplitude is 9.25. The closure temperature of arch dam with elevation above 560m is 16 while the temperature of arch dam with elevation below 560m is 13. Referring design specification for concrete arch dams SD145-85, each segment temperature boundary of upstream and downstream face is described in functional form. The corresponding boundary average temperature distribution is shown in Figure 1, and the corresponding boundary temperature amplitude distribution is shown in Figure 2. The computing time of temperature field using finite element method is 50 years and the temperature tends to be stable after 20th year. The difference between temperature in mid-February of the 49th year and arch closure temperature as temperature drop load is utilized.

Table 1 DAM CNONCRETE MATERIAL PARAMETERS

Parameter	Value
Bulk density	$24kN/m^3$
Elastic modulus	24.0GPa
Poisson's ratio	0.17
Linear expansion coefficient	1.010^{-5}
Compressive strength	23.5MPa
Tensile strength	2.25MPa
Fracture energy	0.2kN/m
Thermal diffusivity	$0.0023m^2/h$

Table 2 DAM BASE ROCK MATERIAL PARAMETERS

Rockclass	II	III1	III2	IV	Weak Structural plane
Deformation modulus(GPa)	19	13	6	3.5	0.5
Poisson's ratio	0.20	0.25	0.28	0.30	0.30
Friction coefficient	1.35	1.22	1.2	1.02	0.05
Cohesion(MPa)	2.5	2.2	1.4	1.0	0.35

- Load Combination in Construction Period

In order to simulate the actual situation more reasonably, how the dam dead weight applies during construction should be taken into account when calculating the dam dead weight. Considering the progress arrangement of dam concrete placement, dam joint grouting and stage impoundment, the calculation in the construction period is generalized into seven stages.

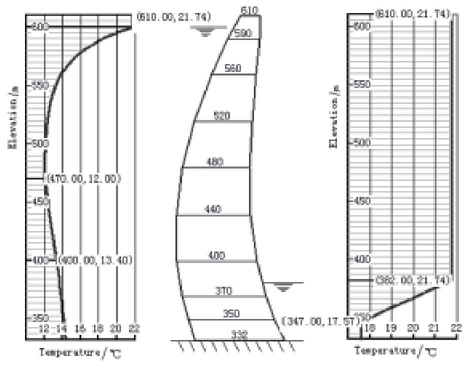

Figure 1 Boundary average temperature distribution

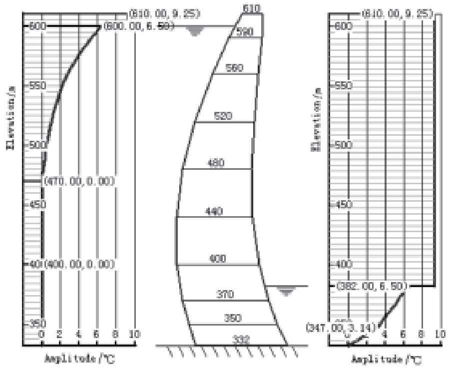

Figure 2 Boundary temperature amplitude distribution

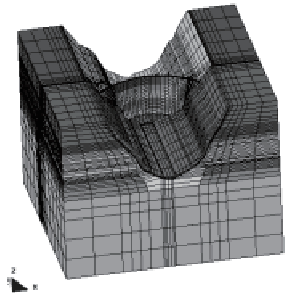

Figure 3 Overall model of initial mesh

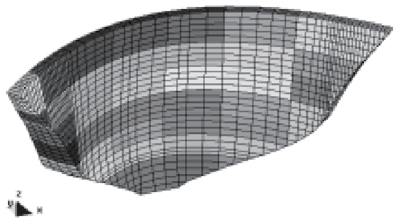

Figure 4 Dam model of initial mesh

3.2. Reasonable Mesh Size

Because the accuracy of three-dimensional iso-parametric element is high, eight-node hexahedral iso-parametric element is used to simulate the dam and foundation, six-node tri-prism element is used to simulate the junction of dam and foundation, and thin layer element is used to simulate the joint and interface of dam and foundation. In order to obtain reasonable analysis result, eliminating the impact of mesh size.

- Determination of initial mesh

Three kinds of different mesh are utilized to carry on elastic analysis in the paper. The dam is divided into 2 layers along dam thickness direction and every 10m layer along dam height direction in Mesh I; 4 layers along dam thickness direction and every 10m layer along dam height direction in Mesh II; 8 layers along dam thickness direction and 5m each layer along dam height direction in Mesh III. Foundation among tensile range corresponding to three kinds of different mesh is shown in TABLE 3.

Table 3 THREE MESH SIZES NEAR FOUNDATION FOR TENSILE AERA

Mesh	Mesh I	Mesh II	Mesh III
Relative tensile range	0.28	0.24	0.23

It is shown from TABLE 3 that the difference of foundation among tensile range between mesh II and mesh III is small, and most region stress of mesh II converges to fixed values. In this article, mesh II as initial mesh is applied. For the initial mesh, there are points of 25459 and elements of 21256. The overall model is shown in Figure 3, and the dam model is shown in Figure 4.

- Determination of refinement mesh

About linear elastic constitutive relationship, because stress concentration exists nearby foundation plane and the computing precision of small mesh is higher than large mesh, the local mesh of the dam and foundation nearby foundation plane is needed to be refined. For incompatible problem caused by local mesh refinement, compatible displacement solution of local incompatible mesh is used (Li et al. 2003). For the determination of refinement mesh size, characteristic length lck which reflects the material equalization characteristic, is usually 1-3 times of the mesh size, and lck =GfE/ft2≈0.9m, so mesh size of failure position should be between 0.3m and 0.9m. The failure may be focused on occurring near the base plane, considering dam tensile failure and compressive failure comprehensively, elements nearby foundation plane which are located in 1/8 dam thick of upstream and downstream side are refined by 10 elements along dam thickness direction and 4 elements along dam high direction and horizontal river direction. The mesh size along dam thickness direction after refinement is 0.30-0.94m. For the refinement mesh, there are points of 79301 and elements of 63112. The overall model is shown in Fig.5, and the dam model is shown in Fig. 6. It is noted that the concrete failure range of three kinds of strength criteria has not surpassed the local refinement range; it means that when the linear elastic constitutive relationship is used, the refinement mesh is reasonable. For elastic brittle constitutive relationship, the same refinement mesh is used. The concrete failure range of three kinds of strength criteria has not surpassed the local refinement range; it means that the refinement mesh is also reasonable when the dam elastic brittle constitutive relationship is applied. For damage constitutive relationship, the same refinement mesh is also used. The concrete damage range has not surpassed the local refinement range. It means that the refinement mesh is also satisfied when the dam damage constitutive relationship is utilized. Therefore, when three kinds of constitutive relationship of dam linear elastic, elastic brittle and damage, the same refinement mesh can be used to do the analysis of nonlinear finite element of concrete arch dam.

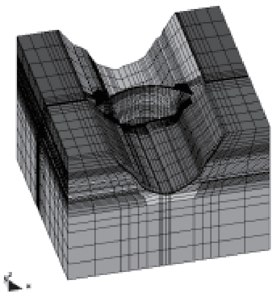

Figure 5 Overall model of refinement mesh

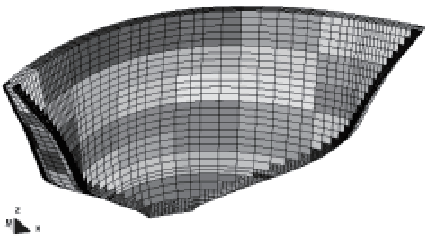

Figure 6 Dam model of refinement mesh

3.3. Constitutive Relationship

When using dam linear elastic and elastic brittle constitutive relationship, foundation plane relative failure range of three kinds of strength criteria is shown in TABLE 4. When using dam damage constitutive relationship, relative damage range of foundation plane is 0.09, the maximum damage value is 0.85. It is obvious from Tab. 5 that (1) the maximum damage value is less than 1, indicating that complete cracking in the dam does not appear under the situation of temperature drop normal load combination; (2) the relative damage range of foundation plane when damage constitutive relationship is applied is slightly bigger than that which linear elastic constitutive relationship is used, but is smaller than that when elastic brittle constitutive relationship is used. This is because both the stress release of dam damage region and the softening effect after concrete bearing load in the damage analysis are considered, project actual situation is simulated more reasonably. So dam constitutive relationship using damage constitutive relationship is more reasonable.

Table 4 RELATIVE FAILURE RANGE ON INTERFACE BETWEEN DAM AND FOUDATION

	Uniaxial	Blaxial	Triaxial
Linear elastic	0.077	0.082	0.081
Elastic brittle	0.143	0.153	0.150

3.4. Strength Criterion

It is shown from TABLE 4 that the relative failure range of foundation plane under blaxial strength criterion is slightly larger than the result under uniaxial strength criterion when constitutive relationship of linear elastic or elastic brittle is used, and is basically the same as the result under triaxial strength criterion. This is because the influence of the third principal stress works on the dam crack when the compressive stress is taken into account under multiaxial strength criterion. Under the effect of dead weight and water load, a large part region of the upstream at the bottom of the dam is under the stress combination of tension and compression. Therefore, multiaxial strength criterion used is reasonable. E. Iterative Method and Convergence Control Standard For damage constitutive relationship, Newton iterative method and modified Newton iteration method with unbalanced force are applied, respectively, and displacement convergence tolerance is taken10^{-4}, 10^{-5}, 10^{-6}. Thus the relative damage rang of foundation plane is obtained (TABLE 5). It is shown from TABLE 5 that the results of two iterative methods are the same when convergence tolerance is the same. The foundation plane relative damage rang of foundation plane with convergence tolerance 10^{-5} is slightly smaller than the result with convergence tolerance 10^{-4}, and is the same as the result with convergence tolerance 10^{-6}. Considering the computation time and accuracy, modified Newton iteration method with unbalanced force should be used in nonlinear finite element analysis, and displacement convergence tolerance 10^{-5} is reasonable.

Table 5 RELATIVE DAMAGE RANGE FOR DIFFERENT ITERATION METHOD AND CONVERGENCE TOLERENCE

	10^{-4}	10^{-5}	10^{-6}
Newton iteration method	0.093	0.09	0.09
Modified Newton iteration method	0.093	0.09	0.09

4. Conclusion

Taking a high arch dam as an example, standard research on reasonable mesh size is done in the paper. Constitutive relationship and strength criterion of dam concrete, iteration method and convergence control standard of nonlinear equations are studied by nonlinear finite element analysis of arch dam safety evaluation. The main conclusions are as following:

1) For reasonable mesh size, the initial mesh with a division of 4 layers along dam thickness direction and 10m each layer along dam height direction is reasonable; the refinement mesh using elements nearby foundation plane which are located in 1/8 dam thick of upstream and downstream side are refined by 10 elements along dam thickness direction, 4 elements along dam high direction and horizontal river direction is also reasonable. When three kinds of constitutive relationship of linear elastic, elastic brittle and damage are employed, respectively, the same refinement mesh can be used to compute.

2) For constitutive relationship, damage constitutive relationship is reasonable; for constitutive relationship of dam linear elastic or elastic brittle, multiaxial strength criterion is reasonable.

3) For iterative method and convergence control pipe and its influence on temperature field and temperature stress field of concrete around in construction period. And the best time to start water cooling and the reasonable water temperature are mainly studied in this paper. It is suggested in the construction of RCC dam that water be passed when the concrete is roller-compacted and the scheme of low temperature in early period and higher temperature in late period be adopted, thus reducing the highest temperature rise and tensile stress of concrete. Standard, modified Newton method with unbalanced force should be used in nonlinear finite element analysis, and displacement convergence tolerance of 10^{-5} is reasonable.

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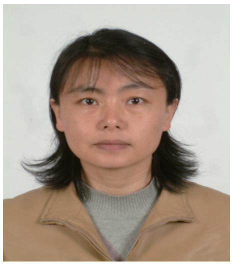

Xiaoqing Liu obtained her PhD from Hohai University in 1997. She participated in research projects between Chinese and Spain Western from October, 1994 to July, 1997 in CEDEX,.Madrid. She is currently engaged in teaching and research work of hydraulic structures.

Tongchun Li obtained his PhD from Hohai University in 1989. He was awarded by the Ministry of water resources of Dayu award in 2011. His research interests are in the areas of hydraulic structure, disaster prevention and reduction engineering, Water-related disasters and water security. He introduced a new technique, now called as finite element internal force method based on stress analysis of arch dam.