The role of numerical analysis in design and construction of Three-Gorges Cofferdam

Fonction des analises quantites dans le projet et l'execution de l'entournee-digue des Trois Gorges

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ABSTRACT: In the Three-Gorges Project, the second stage Cofferdam (TGC) is a very important and a challengeable structure due to the arduous task and its severe construction condition. The numerical analysis on this cofferdam was executed as long as 16 years starting from 1984 up to now. It was playing an indispensable and important role in the design and construction works. Actually, it has made a great contribution to the every step, almost, of the progression for this cofferdam. The cofferdam has been built and operated for more than three years, including the 98' severe flood period. The comparison of analysis results to the monitoring data and back analysis were carried out. The predictive procedure on the performance of the cofferdam was established. The meaning of this research is not only useful for the safety control of the cofferdam, but offering a new experience of numerical method in geotechnical field, and promoting the development of design theory of earth dam.

RÉSUMÉ: L'entourée-digue de 2^{ième} phase porte des difficiles responsabilités dans la construction, de plus les conditions de exé cution des travanx sont três dures, c'est pourqoi. C'ést une construction qui muni de provoquer an combat. C'est l'analyse de 1998 au present d'ejà a duré 16 ans elle porte une importante comtribution et aussi uon remplacer au projet et aux travaux dans l'entouré e-digue des Trois-Gorges. L'entourée-digue a construé en outre S'est mouvoit 3 ans parmi eux comprend particuliëre grande inondations de 1998 tous les états sont très bonnes. Signification de cette analyse non seulement profitable ō la domination sûre de l'entourée-digue, mais encore pour le développement de la théorie de l'analyse quantité de la domaine de roche et du soe. Et du projet de la digue-sol, en même temps porte sur la fonction favorable.

1. INTRODUCTION

The Three-Gorges Cofferdam (TGC) is a very important structure as it is a guide to ensure the safety of constructions for the main dam and the left powerhouse in Three-Gorges Project (TGP), and also, to ensure the people life at the downstream area during 5 years of construction time. However, it is also a very difficult and challengeable structure since its cross section is very complicated and the construction time schedule is very tight, especially, it has to be built under 60m deep water, which is about 2/3 of whole height of the cofferdam.

The numerical analysis technology was get involved in the matter of TGC during the whole process of design and construction works, even the operating time, from 1984 to 1999. A great contribution has been made for the decisions of many important problems during the building process, which were related to the outline and size of the cofferdam, the detailed cross section structure, the stress and strain state, the material of cut-off walls, the construction procedure, the water table control at the cofferdam body between two cut-off walls, and so forth. It has been realized that a safe, optimum and economic TGC will not be constructed without the relevant base of numerical analysis results.

In general, the numerical analysis (FEM) has become a very popular technology used at technical and engineering field, including the geotechnical area since 70's. However, FEM wouldn't be easy to obtain an ideal result that was tallied with the corresponding real case in geotechnical engineering due to much uncertainties existed. In China, different views on the numerical analysis are still presented in the engineering technical circles and even in the academic circles. Meanwhile, very few good examples that related to the difficult engineering problems solved successfully by FEM have been published in publications up to now.

The experience of TGP cofferdam using FEM would be as a good example to indicate that the numerical analysis could play an important, even indispensable sometimes, role for engineering posers, if some conditions would be considered very careful, such as, the selected constitutive model was reflecting the characteristic of engineering materials, the simplified boundary condition basically tallied with the actual situation, the calculate procedure met the requirement of engineering accuracy, and especially, the calculative parameters were investigated sufficiently and the values were rational.

This is just the view of our experience and also the focus of this paper.

2. THE OUTLINE OF TGC

The cofferdam is actually a big earth-rock dam with the height of near 90m. Its body was formed by dumped completely weathered granite and waste rock chunk into the river water of 60m deep, and then, filled with weathered granite under dry compacting, 30m thick, above the dumped body. Finally, two concrete cut-off walls with the height of near 80m were built in the center of the cofferdam to prevent the water leakage. (Fig.1)

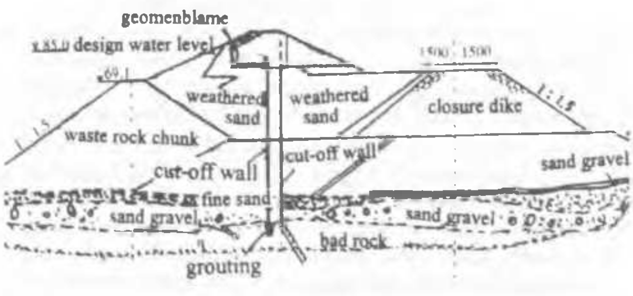

Figure 1 the typical cross-section of TGC

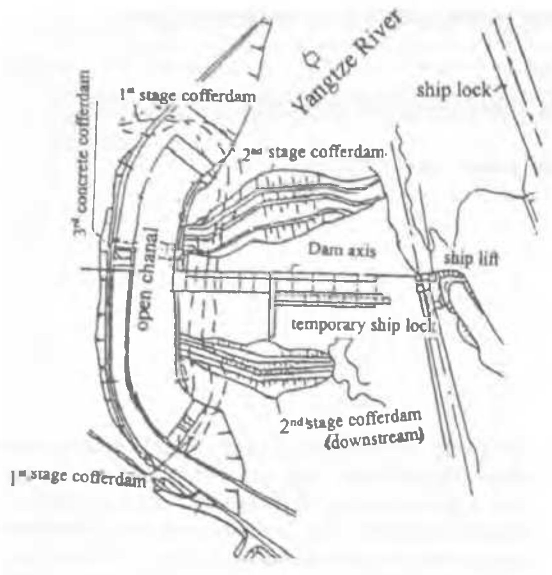

Figure 2 the outline of closure works of TGP

The main features of this cofferdam were:

1. The cofferdam was built under 60m water, as mentioned above, so the construction work was difficult;
2. The fill material was completely decomposed granite, and the dumped body was quilt loose, so the working condition of the cofferdam, especially, the concrete wall was quite severe;
3. There was a fine-sand layer with the maximum thickness of 18m deposited at the foundation of cofferdam, so the dynamic stability of cofferdam should be considered; (Fig.1)
4. The quantities of the body and the concrete walls were quite great. They should be finished at a short period between two flood seasons, so the project schedule was very tight.

With such severe constructing and working conditions, this cofferdam was considered to be one of the most challengeable structures in the TGP.

Not only was the cofferdam a very difficult structure, but also it would be a very important one as it would offer the whole project in a smooth construction condition (Fig.2) and to relief the people from flood threats at the downstream reach during 5 years construction period. Based on the circumstance of such harsh conditions, as well as many variable factors, to search a dependable, rational, economical and prompt design scheme for the cofferdam was a vital task, and the numerical analysis was playing an effective and convenient role for this end. It is not common that the numerical analysis has ever been to be such important role for a large-scale geotechnical structure.

3. OUTLINE OF ANALYTICAL METHODS.

Based on the consideration of the properties of cofferdam materials and of the convenience for use, total 8 constitutive models were selected for this calculation, in which, 4 of them were non-linear elastic models, i.e Duncan-Chang E-μ model, Duncan-Chang E-B model, non-linear K-G model and Spline model; the other was elasto-plastic models, i.e., Tsinghua model, Nanshui model, Hohai model and Lade-Duncan model. The Duncan-Chang E-μ model was selected to be the essential one for whole research project. Many topics of numerical analysis widely related to the outline and size of the cofferdam, the structure of cross-section, the stress and strain state of body and cut-off walls, the materials of cut-off walls, the construction procedure and so on, were considerably studied. In addition, the consequence of the possible defect formed at construction time was predicted, and the shortcoming in design was also evaluated. In short, almost all the important technical problems were decided and adopted in use of numerical analysis results. This research project was performed as long as 16 years starting from 1984 up to 1999. Altogether 15 universities and research institutes in China participated, first and after wards, in the research project group.

The calculating parameters of models, the mesh, the loading procedure, etc. were unified and offered by YRSRI, but the computer programs were selected by the analyzers. 2D or 3D analysis was carried out by different calculators.

4. THE MAIN PROBLEMS SOLVED BY NUMERICAL ANALYSIS FOR TGC.

The FEM analysis was performed for the following main problems of the cofferdam.

1. What was the state of stress, strain (or deformation) and stress level in the cut-off walls, and whether it was expectable in the viewpoint of safety of TGC or not. (The detailed discussion on this point is presented later in this paper);
2. Which one was better, normal rigid concrete or plastic one, for the material of cut-off walls?
3. What thickness was optimum, 0.8m, 1.0m or 1.2m, for the walls?
4. What type was suitable, the whole concrete one or a compound one (i.e. partial concrete wall at lower part and partial geomemblame impervious wall (15m high) above the concrete wall) for the cut-off walls;
5. To set the double walls along the whole axis of cofferdam was necessary or not, between the two walls, which one (front one or back one) was better to be built first;
6. To compact the dumped body of weather granite was meaningful or not for improving the stress and strain state of cofferdam;
7. What was the dynamic stability under the seismic action with the strength of Ⅶ degree and under the blasting during construction period;
8. To set a hinge in the middle point of wall was meaningful or not for reducing the bedding moment in the wall;

The analysis results and the optimum procedure were not only important for safety, but accelerated the structure progression and decreased a large amount of engineering cost for this cofferdam.

5. RESULTS OF ANALYSIS FOR THE SCHEMES OF PRELIMINARY AND TECHNICAL DESIGN STAGE

The horizontal displacement of cut-off wall was concerned the most in the result of analysis. It indicated that the maximum horizontal displacement for the common concrete walls was about 120cm for different models. It exceeded the limited value of tensile strain of the common concrete. Meanwhile, a quite large yield zone, in which the stress level exceeded the value of 1.0, appeared in the water face at the lower part in the walls. It means that the wall was not safe, and this design scheme was untenable.

Based on this situation, a great effort was needed to find a feasible cross section for that cofferdam. After a lot of analysis by FEM, it was realized that the most effective and simple way was to use the plastic (or flexible) concrete instead of common (rigid) concrete to be the material of the impervious walls. The elastic modulus of plastic concrete should be as about 1,000Mpa, the ratio of modulus and compression strength (28 day) should be in the range of 200 to 250. In this case, the working condition of cut-off walls was improved notably, the horizontal displacement, the principal stress as well as the stress level were reduced considerably. According to the results (Table 1), the maximum displacements of first and second walls were about 40cm and 15cm, respectively, the values of

Table 1 the calculation results of maximum deformation & stress for various models

Models	Body		First (front) wall			Second (back) wall		
	Displacement (cm)	Settlement (cm)	Displacement (cm)	σ_{1max} (Mpa)	σ_{3max} (Mpa)	Displacement (cm)	σ_{1max} (Mpa)	σ_{3max} (Mpa)
E-μ(average)	39.7	69.1	34.2	3.58	-0.33	12.4	3.19	-0.11
E-B	62.3	141.9	50.1	3.06	-0.87	14.4	3.60	-0.59
K-G	78	115.0	42.6	4.88	-0.20	17.7	3.11	-0.22
Spline	38.5	56.3	40.4	3.84	-1.71	9.8	1.96	-0.39
Nanshui	17.3	88.8	31.9	3.01	-0.21	12.7	2.56	0.25
Hohai	18.4	75.3	35.0	2.18	-0.26	13.5	2.48	0.26

maximum shear strain was lower than the permitted range, and the plastic zone in walls was almost eliminated and was no longer to affect the safety of cofferdam.

Fig.3 is the comparison of stress and deformation between the alternatives using plastic concrete and using rigid one. So the design scheme was expectable. The comparison of analytical results by FEM for various constitutional models is shown in Table 2.

It can be seen from Table.2, that ① Some difference of the results from the various models are existed, but not very serious; ② The general tendency is that the values from non-linear models are greater somewhat than from elastic-plastic models. Moreover, the values of deformation from Duncan-Chang E-B model is greater than from Duncan-Chang E-μ model; ③ The results from two double yield surface models (Nanjing, and Hohai) are very closed each other. It means, the elastic-plastic models are rational to be used for engineering purpose.

6. THE PERFORMANCE OF TGC DURING 98' SERIOUS FLOOD

At the constructing period, the TGC even stood up a rigorous trial of 98' Flood. At that time, the front wall was just finished,

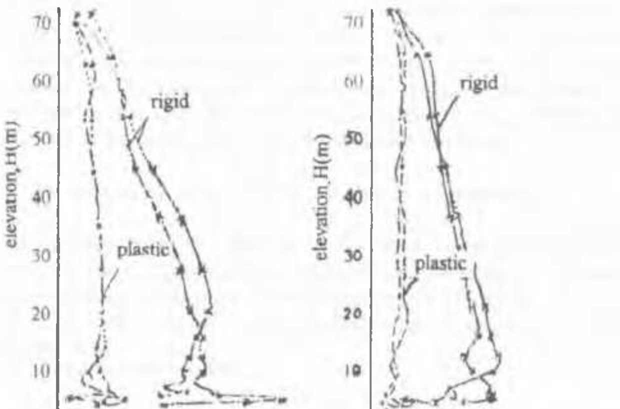

Figure 3 the comparison of stress distribution between plastic and rigid walls

Table 2 comparisons of results for various models

Models	Duncan E-μ	Duncan E-B	Tsinghua	Nanshui	Hohai
Max displacement of wall	100%	109	62	84	87
Max Compression stress of wall	100%	92	92	97	96
Max displacement of body	100%	94	59	75	79
Max settlement of body	100%	125	89	106	99
Max stress level of body	100%	117	99	89	88

but the back (second) one was still under constructing, while the crest of cofferdam hadn't reached the design elevation. It means that the cofferdam was in a critical condition.

During that flood season, the maximum monitoring horizontal displacement of front wall reached up to 45.7cm (1998.8.22) and 55.2cm(1998.9.15). However, the corresponding value for calculation one was only about 40cm. By such abnormal situation, the authorities were worried very much and even considered stopping the construction work for this structure.

Nevertheless, considering the difference between the actual situation and calculation condition, we realized that some factors, e.g. the front wall lost the back support due to back

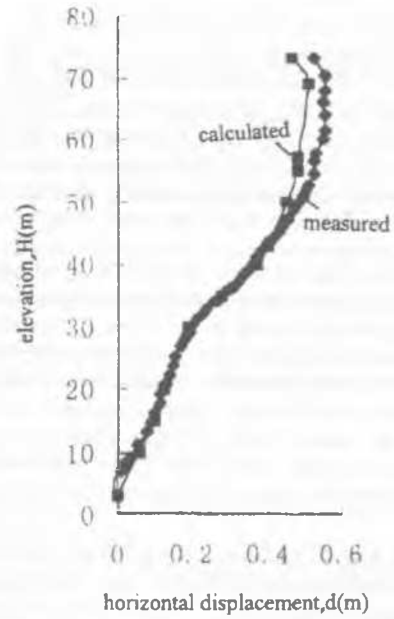

Figure 4 the comparison between measured displacement and calculated one

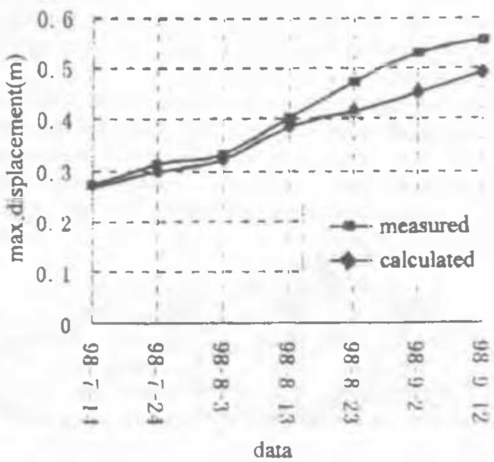

Figure 5 the max horizontal displacement VS data for the cut-off wall

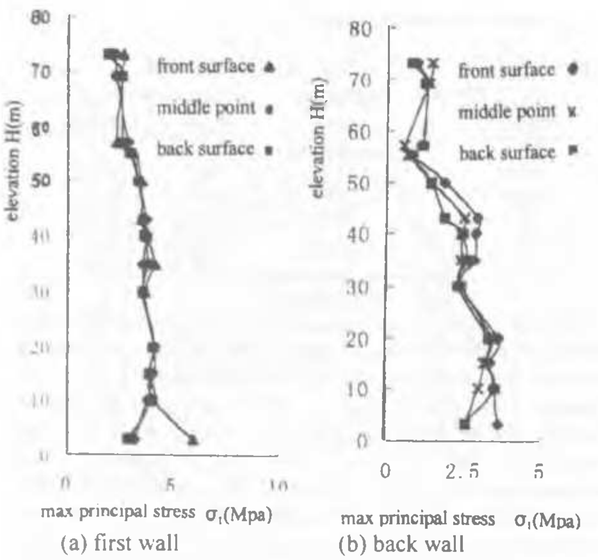

Figure 6 the distribution of max principal stress

wall under constructing (as mentioned at the beginning of this section), the filled material part of body was changed, the earth pressure on the top was not in a balance state, etc, caused the discrepancy of deformation values of the walls. Based on the actual situation, the calculation parameter was regulated, the boundary condition was renewed, and then, FEM procedure was re-performed. The new result of maximum displacement of front wall was 53.7cm, closed to the monitory value (Fig.4 and Fig.5). Moreover, the predicted value of ultimate horizontal displacement in the future for front wall would be not over 60cm.

The maximum vertical stress would be σ_{1max}= 3.14~5.28Mpa (Fig.6), while the permitted unconfined compression strength would be, [R]= 4.62~5.28MPa.

The distribution of stress level in the cofferdam is shown in Fig.7. It can be seen that there is a small zone at the upstream side of body, in which the stress level is exceeded 1.0. However, this is in the active zone of earth pressure due to the deformation of wall. Since the body was formed with cohesiveness granular material, it was not interfered the safe of cofferdam.

The varied analysis of FEM was carried out continuously in 1999. The consistency between analyzed and measured was very satisfied, and the cofferdam operated very well in the past 3 years.

7. CONCLUSIONS

It was not very common that the numerical analysis was playing such a useful role like the TGC did in geotechnical engineering field.

Looking back on the role of that numerical analysis, in the preliminary design stage, it checked the design scheme feasible or not; in the technical design stage, it offered a whole thoughts for the optimum design scheme; in the construction stage, it showed a rational building procedure speeding up the

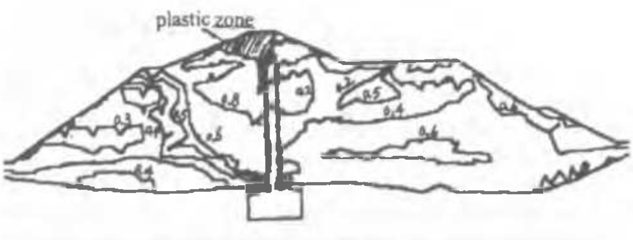

Figure 7 the stress level of the cofferdam body

construction progress and reducing the cost; in the operating period, it judged the safety of the cofferdam and fixing the control water level between the two walls.

It is not too much to say that almost every decision of important problems for the cofferdam could not be made without the numerical analysis.

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