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Dam safety in China and the life span evaluation of old concrete dams

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ABSTRACT: More and more old dams are operated for more than 50 years. Evaluation on the life span and the real safety status becomes a challenging task for the dam society, especially for China because of more than 6000 dams to be evaluated and rehabilitated within the next 3 years. Based on the investigation on FENGMAN gravity dam, which is 91.7 m high, operated from 1943 and suffered too much up lift pressure, freeze and thaw problem, etc., discussions on the life span evaluation of the old concrete gravity dams have been made. The reasonable coefficient of dam safety has been discussed and rehabilitation schemes have been recommended. Meaningful results have been achieved based on the case study.

Keywords: Dam safety, Life span, Rehabilitation.

1 LIFE SPANS OF OLD CONCRETE DAMS AND DAM SAFETY IN CHINA

For concrete gravity dams built since the 20th century, there are no standards for the normal working period (life span) in China or other countries. According to literatures, a large number of dams lower than 30 meters were built 1000 years ago, but few of them exist nowadays. Most of these dams have failed and their life span was short. The main reason is that the level of design, construction, and reinforcement was very low, for example, flood control standard was low, or there were obvious shortcomings in dam structures and construction quality, or the technology of operation and maintenance were limited. Since the 20th century, the design and construction of concrete gravity dams have been standardized and technologies in reinforcement are getting more and more advanced, which have led to longer life span of concrete dams. Life span of a dam not only depends on the quality of dam but on the environment and the needs of the society. At the same time, it also has close relationship with the reinforcement. Life span of concrete gravity dams can be divided into natural life span, environmental life span and economic life span. Natural life span mainly lies on the own conditions of dams. Because of structures, materials, earthquakes, floods or other reasons, some dams may become defective and need to be rebuilt, disused or removed, which can be considered to reach their natural life span. For those which are breached due to natural reasons (excluding wars or terrors, etc.), it can also be considered to have reached their natural life spans. For example, more than 3,000 dams in China and 1,000 dams in United States were breached and arrived at their natural life span. One gravity dam with height over 50 meters in Canada was reported that it had seriously problems after operating for more than 50 years, the cost of reinforcement may be higher than that of rebuilding a new one and the final decision is to rebuilt it in 2003. This can also be considered for the dam to reach its natural life span. When a dam need to be abolished because of reservoir silt or the needs of environmental protection or the changing of dam purpose, it can all be considered that the dam has already reach its environmental life span. After a period of operation, the security and functions of a dam are far below compared with a new dams, we can consider that the dam has already reach its economic life span. During the natural life span of a dam, there could be several economic life span cycles. Different dams have different economic life span. The normal service period of concrete structure is 50 years defined by some countries, but according to operation status of gravity dams around the world since 20th century, the economic life spans of gravity dams may be over 50 years. Besides, there are also some with service period less than 50 years. Considering the technology related and behavior of dam changing obviously with time, it has practical significance to carry out comprehensive evaluation and studies on dam safety at their economic life span and try to make the safety recover to the level of a new dam.

Another factor which affects reinforcement is the environmental life span of dams. Sometimes, the environmental life span may be obviously shorter than the natural life span and it will also have impact on the economic life span of the dam. For example, many rivers in the world are sediment-laden river and the sediment in reservoir will reduce the capacity of reservoir directly. Although measures have been taken to alleviate siltation to some extent, life span of such reservoirs sometimes is limited, even shorter than 100 years, which will affect the schemes of reinforcement. The reservoir abolishing will cause the ending of economic life span of dams.

According to statistics, among 87,076 reservoirs in China, there are about 37,800 with safety problems. To ensure the security, studies and reinforcement have been carried out in recent years. In the new schemes (2007–2009), the reinforcement of 6240 dams will be conducted. Some of them are very difficult to deal with. The main problems are as following,

(1) Flood control problems: Due to increasing of hydrology data and safety requirement, flood control standard of reservoirs can not meet with the new operation conditions and the discharge ability of reservoirs becomes insufficient.
(2) Seismic problems: According to "Seismic Parameter Distribution Map of China" (GB18306-2001) and current Specification, Safety considering seismic loading cases of many reservoirs can not meet with the current requirements.
(3) Stability of dams: Because of insufficient in dam section or cracks existed or joints openning, many dams have to be rehabilitated.
(4) The leakage and uplift problems.
(5) Crack and Aging problems.
(6) The metal structures and electrical equipment problems: Metal structures and electrical equipment are aging or seriously eroded that they can hardly operate normally, which have seriously affected the safety of reservoirs.
(7) Management facilities and observation equipments are not in good conditions.
(8) Reservoir silt and landslide.
(9) Freezing and sawing problems.
(10) others.

The large-scale construction and management on hydro projects have been conducted for 50 years in China and many effective methods and experiences on reinforcement and heightening have been accumulated. But problems of how to determine the economic life span, how to carry out the long-term safety evaluations of the dams should be further studied.

2 MAIN PROBLEMS AFTER NEW COMPREHENSIVE EVALUATION ON FENGMAN DAM

Fengman concrete gravity dam is situated at the main stream of the second Songhua River, 24 km to downstream Jilin City, Jilin Province. It is situated in severe cold area. Its mean annual temperature is 5.3°. The highest mean monthly temperature is 24.3° and the lowest is −19.7°. The maximum height of the dam for its original design was 90.5 m and the dam crest elevation is 266.5 m. Dam construction started in April 1937 and water impounding started in Nov. 1942. The project was completed and operated in Oct. 1953. By the end of reinforcement in 1996, the maximum dam height is 91.7 m and the dam crest elevation is 267.7 m. The dam crest is 1080 m long, divided into 60 dam sections, each of which is 18 m long. Arranged from the left to the right bank, the 9th to 19th dam sections of the dam are overflow dam sections, the 21st to 31st are intake sections for power generation. The upstream slope of dam section is 0.05 and downstream slope is 0.78. During the construction, the dam cross section was divided into A, B, C and D blocks by the longitudinal joints. The typical cross section after reinforcement is as shown in Fig. 1.

In order to guarantee the safety of old concrete dams over 50 years, it is really necessary to do the comprehensive evaluation based on studies on Fengman dam in China. Main problems and main achievements from evaluation up to now for the project are as following,

(1) Problems of stability related to seismic assessment

Original conclusion: With weak longitudinal joints and sub-longitudinal joints, the stress level of some position of Fengman dam is higher than the allowable value and the safety can not be guaranteed for seismic load and some parts of Fengman dam may be destroyed for used earthquake parameters. Based on results of original analyses, anchoring have to be installed and had been installed before 1997 from the top to foundation and the dam had been added to 91.7 m high (1.2 m higher than original dam) for improving the stability of the dam. With considering the reliability of anchoring and other issues, it is still a safety problem under seismic loading cases.

New conclusion: Considering new progresses made in past 20 years, seismic parameters have been comprehensively evaluated based on current standard. It is found that the acceleration coefficient can be decreased from 0.161 to 0.131 and not to 0.22 or even higher as early estimated. The new results have significant influence on future rehabilitation work.

(2) flood control

Original conclusion: The spillway consists of eleven 6m by 12 m orifice sluice ways. Discharge capacity of

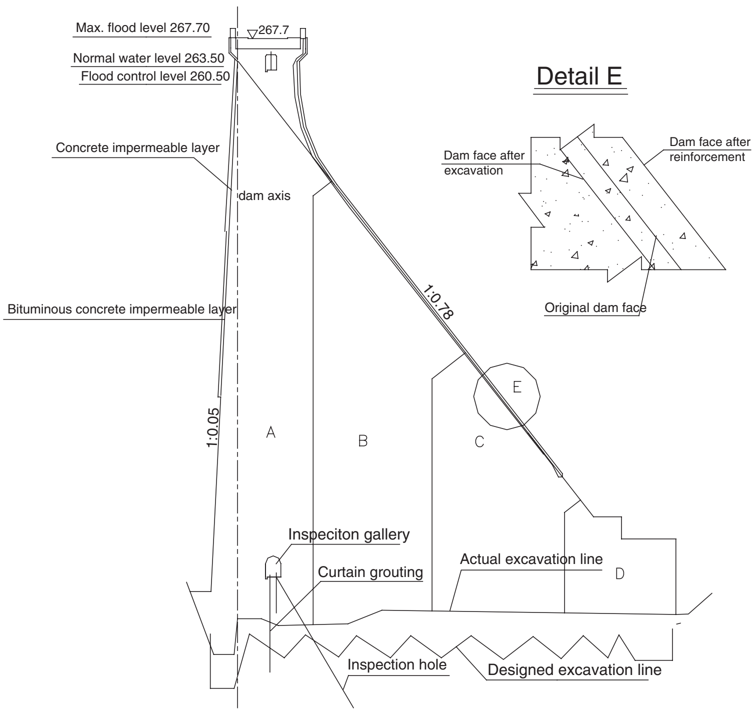

Figure 1. Typical cross section of dam.

1300 m^3/s by the 10 turbines in the powerhouse is used for flood control before for the reservoir at El. 266.5 and El. 267.7.

New conclusion: The discharge capacity of the plant would not be allowed to use when the reservoir level at 267.7 to guarantee the safety. The flood control problems will be more critical for the current design standards compared with original ones in histories. It should be carefully evaluated to consider the possibility to use pre-discharge based on reliable hydrological monitoring and prediction system. Further measures to increase the capacity for flood control should be studied.

(3) Serious Leakage of the Dam and high uplift pressure

Original conclusion: With poor integrity and defects, such as crack and honeycomb, serious leakage from the dam body and joints occurred after impoundment, which affected the integrity and durability of dam. When the reservoir water level reached El. 255 m in 1950, leakage measured in the galleries reached 16,380 L/min and the wet area in the downstream surface was about 24947 m^2. After rehabilitation for many times, leakage today reduces to 39L/min totally and wet area in the downstream surface at El. 256.55 m is about 440 m^2 in 2004, most of which is located at spillway sections. While average uplift pressure coefficients for blocks of 8, 14, 22, 28, 35, 40, and 47 at different position monitored in 1996 are 0.84, 0.48, 0.63, 0.16 and 0. The distances between test holes to the dam axis are 2.9 m, 6.5 m, 12 m, 39 m and 51.6 m respectively. Monitor data at block 15 in 2005 give similar results. Grouting measure could be reliable and has been done many times to decrease the leakage and uplift.

New conclusion: High uplift pressure is still a big problem to be solved in the future. Grouting measures can be used but not enough especially for decreasing the uplift in the body. Geomembrane installation under water can be a reasonable choice for further rehabilitation.

(4) Poor Quality of Concrete

Original conclusion: Strength of dam concrete of 90d in the original design should be 150 kg/cm^2, but actual strength of concrete was only 120 kg/cm^2, 90 kg/cm^2 or even 60 kg/cm^2 at different parts of dam. Aggregate and cement used were not in good quality. Water reducing admixture and air-entraining admixture agent were not used and there was no freezing resistant consideration for all concrete even though the dam locates at extremely cold area. Concrete mix proportion in construction had problems and there was no temperature control. Outer concrete of 0.6 m thick has been replaced in recent years during rehabilitation. While most part of concrete in upper and downstream side of dam have very low strength of about 50 kg/cm^2. Grouting measure can improve the situation.

New conclusion: Grouting measure is not enough. Drainage measure, thickening the dam body and etc. are necessary for further action.

(5) Longitudinal joints of Dam

Original conclusion: Fengman dam was divided into blocks by transverse joints, longitudinal joints, sub-transverse joints and sub-longitudinal joints. No special treatment was done to most of these joints. No shearing resistant structure and joint grouting was made in AB longitudinal joints from EL.220 to EL. 242 (Fig. 1). Although grouting was carried out during operation for many times, unbounded longitudinal joints of the dam body are still a problem. Model test, static and dynamic analyses made before show that the joints have big influence on stress distribution and stability. Strong anchoring measures should be carried out considering possible higher seismic load.

New conclusion: Strong anchoring measures are not so important as before.

(6) Freezing and Thawing Problem

Original conclusion: With poor quality of concrete and serious uplift pressure of the dam, some surface concrete was destroyed by freezing and thawing condition, especially for spillway sections. In 1986, the damaged concrete of the upstream surface above elevation 245 m and of the downstream surface from top to ground level were excavated 0.4 m and were covered by 1 m reinforced concrete with high strength and frost resistance. The dam crest was heightened by 1.2 m. For spillway, the downstream surface was replaced by new concrete with 1.5 m thickness and was fixed with lots of anchorage (3.5 m deep).

New conclusion: The freezing and thawing problem is still a big and challenging problems up to now and it will decrease the safety obviously. The original measures are not enough and concrete with thickness more than 4m should be put on the surface downstream to achieve similar safety standard as a new dam.

Main rehabilitation work finished before 1997 is following,

(1) Bituminous concrete lining with a thickness of 10 cm was placed on the upstream surface between El.245 m to El. 226 m before the flood season in 1990.
(2) Grouting to dam body and foundation was one of the main measures adopted for reducing the seepage and uplift pressure. Grouting was carried out in 37 dam sections in different years.
(3) Pre-stressed anchors were installed to improve the dam safety under earthquake loading cases. 378 pre-stressed cables in total with different loading grades were installed in No.7 to 49 dam sections, in which 361 cables were installed in dam body (excluding the test anchors) and 17 cables, in the dam foundation.
(4) Heightening of dam. According to the dam reinforcement design, the dam crest has been raised by 1.2 m to improve stability of dam and increase flood control ability.

The work above is reasonable but enough to achieve a new economic life span for the old dam.

3 SAFETY EVALUATION BASED ON NUMERICAL ANALYSIS BY FEM FOR FENGMAN DAM

To truthfully reflect the practical safety situation of the Fengman dam and achieve clear results compared with current dam, simulation analyses have been made with considering construction processes and longitudinal joints and construction joints. Whole course simulation analysis of BL47 from the construction period to the operation period is conducted. A three-dimensional FE model is built, which takes into account of all factors that will affect the stressing and deformation of the dam.

In simulation analysis process, the construction process is simulated according to construction data recorded, using measured data of air temperature and water level as boundary conditions. The calculation period is from October, 1941 to December 2005. In the concrete construction period, the minimum calculating step is 0.5d, while the maximum calculating step is 5d. In operation period, calculating step is 10d. There are 2,707 calculating steps in the whole simulation analysis process in total.

In whole course simulation, the adiabatic temperature rise of the concrete material in simulation analysis is determined according to practical mixing ratio of the concrete and the maximum internal temperature observed on site. The final elastic modulus, coefficient of linear expansion and coefficient of temperature conductivity are determined according to observed data of displacement and temperature by back analysis. Main parameters can be seen in Table 1.

According to the whole course simulation calculation, temperature field, stress field and displacement field of BL47 at any time can be obtained. Comparing the horizontal displacement at dam top obtained by simulation analysis with measured data (See Fig. 2), it can be found that these two are consistent with each other, which indicates that the simulation analysis can reflect the practical operating condition of the dam.

According to the envelope diagram of minimum temperature field during operation from 1990 to 2005 (Fig. 3), negative temperature may occur in concrete of dam top and downstream side during winter, which may cause frost thawing fracture due to sever seepage in dam concrete. The depth of negative temperature zone of downstream side is about 4.5 m. According to the contour diagram of$\sigma_1$in winter (Fig. 4), tensile

Table 1. Value of material thermodynamic parameters.

Material	E (GPa)	Specific gravity (kg/m^3)	Poisson's Ratio	Coefficient of temperature conductivity (m^2/h)	Specific heat (kJ/kg·°C)	Coefficient of linear expansion (10^{-6}/°C)
Bedrock	15	2750	0.21	0.00342	0.967	7
Concrete	11	2350	0.25	0.0043	0.978	7

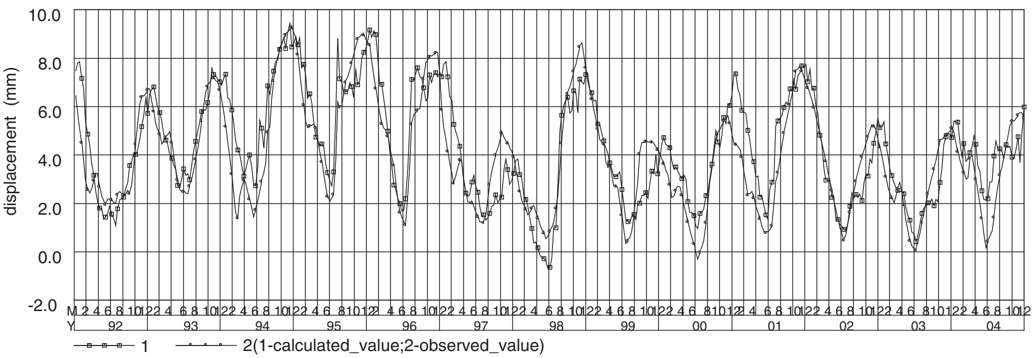

Figure 2. Calculated horizontal displacement compared with observed data at dam top of BL 47.

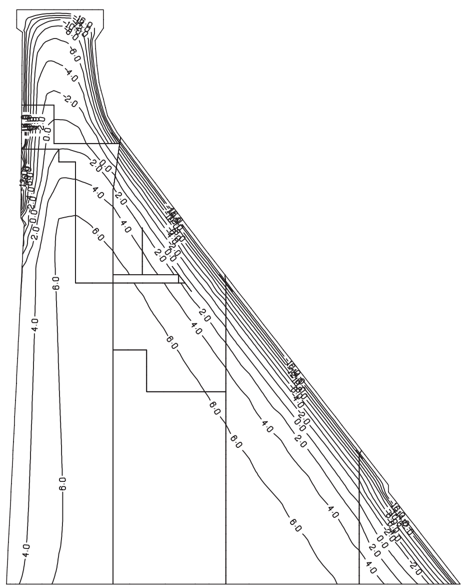

Figure 3. Envelope diagram of minimum temperature during operation (°C).

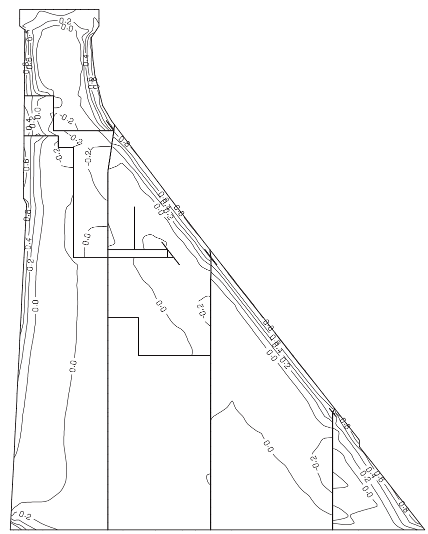

Figure 4. Contour diagram of σ_1 in winter (MPa).

stress with maximum value of 0.8 MPa is distributed in area of dam shell, in most part of which concrete has low tensile strength of about 0.5 MPa. The depth of tensile stress zone of downstream side is about 3.2 m. Furthermore, tensile stress of 0.2–0.8 MPa is distributed in dam heel with width of 6 m or so. Calculated results show that the value and distribution area of tensile stress in dam heel may decrease, while tensile stress distributed in concrete of dam center way cause longitudinal joints and construction joints to open.

Results of simulation analysis show that most part of longitudinal joints of Fengman dam have opened gradually even during the construction period. More

Table 2. Results of overloading analysis.

Items	Case 1	Case 2	Case 3
Overload coefficient	3.26	1.67	1.11–1.14

than 70% of longitudinal joints are opened up to now, which makes it impossible for the dam to bear load as a whole and has deteriorated the work behavior of the dam. According to calculation, safety factor of sliding resistance along dam base, when considering the affect of longitudinal joints and stress history, is 10–20% less than that evaluated by traditional methods, in which no such factors are taken into account. To some blocks of Fengman dam with faults passing through bedrock, potential risk of unstability under some work condition may exist.

Over loading analysis under different conditions has been carried out to evaluate the safety of Fengman dam compared with a similar new dam: (1) Case 1: overloading analysis on a newly built dam in nowadays which has the same dam section as Fengman dam and longitudinal joints are well dealt; (2) Case 2: overloading analysis on a dam with the same dam section and concrete quality as Fengman dam while longitudinal joints are well dealt; (3) Case 3: overloading analysis on Fengman dam under work conditions of nowadays. The results can be seen in Tab. 2. Obviously, poor concrete quality and affect of longitudinal joints are two important factors, which have led to the decrease of dam safety.

To increase the safety of Fengman dam, it is an option to add new concrete on the downstream face. When 4-meter-thick concrete layer is added, overload coefficient will increase to 2.33–2.47 even no reinforcement is done to longitudinal joints and safety factor of sliding resistance along dam base will increase more than 17%, which will meet the requirements of sliding resistance.

4 MAIN SUGGESTIONS FOR FUTURE REHABILITATION FOR FENGMAN DAM

(1) Adding new concrete with 4 to 6-meter-thickness on the downstream face

Thickening the dam along downstream face will increase the safety of the whole dam and also make negative temperature and tensile stress transfer to new high strength concrete, which will improve safety of the dam to a similar new one.

(2) Decreasing the leakage and uplift measures

Leakage, high uplift pressure, freeze and thaw situation are serious problems that can't be ignored. Fengman reservoir with more than 10 billion cubic meter's storage capacity is very difficult to empty. According to feasibility studies, several options have been put forward: (a) Install Geo-membrane on upstream surface with Carpi tech, which can be done partly under water; (b) Design and build a special removable coffer dam used to form a dry site so that it is possible to rebuild an upstream surface of dam; (c) Using New concrete core method to replace concrete of some distance to upstream face with new concrete part by part so as to form a concrete impervious wall; (d) others. Geo-membrane installation on the upstream face is the first choice combined with other measures up to now.

(3) New drainage system to decrease uplift pressure

It is clear that if new drainage system could be constructed, the uplift pressure especially for spillway sections will be decreased. Based on FEM analyses, to construct a drainage system and a new drainage tunnel 2 m under the downstream surfaces and about 40 m away from the dam axis could function well. This method has been used by Shuifen Gravity dam in China and demonstrated well for about 40 years operation located in similar condition.

(4) Further grouting on dam body

Grouting on dam body is still an option to improve the strength of concrete and control seepage. Experiment has been done on dam section 14 and 36, the results is not as good as estimated. Further studies will be made for achieving better results.

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