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The 3D finite element analysis of cold wave impact effect

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Abstract

In April, 1999, Guangdong Changsha arch dam application new technique of MgO-Admixed concrete arch dam without transverse joints, Changsha arch dam is only 90 d complete high 55.5 m, 31000 m3 concrete dam body, the reservoir filling and power generation, is initiative at home and abroad in the history of arch dam. In January 2000, downstream dam surface appear fine cracks, crack width only 0.2 ~ 0.3 mm, depth 1.3 ~ 4.2 m, all did not throughout the dam upstream face. With the hyperbolic model based on MgO-admixed concrete and APDL language, 3 d finite element in simulation analysis, cleared that design conditions of the stress of MgO-admixed concrete compensation accord with the stress state of conventional arch dam structure. Downstream dam surface crack and using the MgO-mixed concrete dams of new technology without necessarily linked. Before to the stationary temperature field in the dam, the role of heat preservation measures template made of polystyrene foamed plastic board for stress improvement is significant. Cold wave impact cracks appear to great effect, worsened the dam stress state greatly, and put the dam in a high stress state. The original design dam stress state is not ideal, crack resistance caused by concrete quality of dam project is reduced, especially heat preservation measures is invalid during the cold wave impact, caused cracks of ChangSha dam. 1 ~ 2 mm tiny cracks of Changsha arch dam used under no harmful effects. Concrete crack resistance of Changsha arch dam is improved greatly after dam grouting, the main performance indexes is also improved obviously, and dam is used has been more than 12 years under safety operation. The analysis of cold wave impact provides important basic material to promote the new technology application, and reference value to similar projects.

Keywords: MgO-mixed concrete, arch dams without transverse joint, cold wave, crack, 3 d finite element analysis

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1. Preface

MgO expansive concrete, characterized by delayed-expansion, is applicable to offsetting the concrete shrinkage [1] caused by concrete hydration heat due to temperature drop designated to fulfill the key purpose of improving temperature stress and controlling temperature crack. It has already been successfully applied [2] into dozens of large- and medium-sized water conservancy and hydropower projects such as: Dongfeng, Qingxi as well as Tongjiezi, etc. in China. Guangdong Changsha arch dam [3] fast established by initially applying MgO-mixed concrete without transverse joint at home and abroad has already put into use. With total storage capacity of 13.0 million m^3, Changsha arch dam is 55.5m high (excluding filling pond). 0.031 million m^3 concrete pouring of the main body of the dam only in 90 days from Jan. 6, 1999 up to Apr. 5, 1999. The gate was closed for storing water on Nov. 8, 1999. It was impacted by the cold wave on Dec. 25, 1999. It was found that there were numerous cracks generated on the face of the downstream dam under routing inspection on Jan. 18, 2000

The case of similar cracks emerged upon the establishment of the arched concrete dam but Changsha arch dam is the first project of fast constructing arch dam by applying MgO mixed concrete irrespective of transverse joint technique at home and abroad. The crack problem is closely focused by in the field: crack is resulted by MgO mixed concrete, whose stress compensation effect shall be truly manifested in Changsha arch dam. It is urgently necessary to study and solve a series of problems, like the influences of cold wave impact on the reasons for causing crack.

The emergence and treatment of cracks on the downstream dam face of Changsha arch dam and the current running state of the dam will be introduced in this paper. Through establishment of 3d finite element model, the compensation effect of MgO-mixed concrete on arch dam stress is simulated, discussed and defined. The simulation analysis of the influences of cold wave impact on cracks is started and the reasons for causing cracks are studied to provide further adequate scientific argument grounds and experience summary for the successful practice of the first case of Changsha arch dam, so that the development tending perfection of the new technique of arch dam establishment without transverse joint is facilitated.

2. Cold wave and crack of Changsha arch dam

Chinese mainland belongs to monsoon climate. A cold wave often spreads to most regions across the country from the north to the south, more palpable in Guangdong regions. According to relative data, the maximum temperature drop of Guangdong provincial maple dam reaches 20.7 ℃. On Dec. 24, 1999, Changsha arch dam was impacted by the uncommon cold wave. On the same day, the maximum temperature was 18.5 ℃, the minimum air temperature was 2 ℃; the daily maximum temperature drop amplitude reached 16.5 ℃. It was found that there were numerous micro cracks and visible traces of the water seepage on the downstream dam face under the routing inspection on Jan. 18, 2000. It was initially found that there were inclined cracks on the foundation part of the ▽207m high elevation bank slope of the right bank; thenceforward, it was successively found that there were inclined, vertical and horizontal cracks on the dam abutment of the left bank and crown cantilever with water marks found at the earliest period and water seepage at later period.

The schematic diagram of the crack distribution on the downstream face of Changsha arch dam with overall length of crack of about 100m. There is a oblique crossing crack almost perpendicular to the foundation respectively on the right and left bank slopes 207m nearby the elevation, basically showing up symmetric type distribution; there is a vertical crack on the arch crown extending to the 213m of the elevation from the bottom of the dam foundation; there are vertical cracks, horizontal cracks and inclined cracks on the downstream face of the arch dam nearly perpendicular to the two bank slopes. Moreover, above 213m of the elevation, there are horizontal cracks distributed on the different elevations (original construction pouring lay). The width of crack is 0.2～1mm. through ground penetrating radar and geological prospecting, the depth of crack is 2.2～4.3m, not running through the upstream face of the dam body. The width of crack opens and closes according the changes in air temperature. The lower of air temperature, the bigger of width. The maximum width is about 0.5～1mm. The water seepage is evident. When the air temperature is high, it is inclined to be closed. For seepage water volume decreases or showcases the phenomenon of showing up water mark, for the specific details, refer to the table 1.

Table 1 Table of the Crack Length of Changsha Arch Dam (Unit: m)

identifier	*A*	*D*	*E*	*J*	**K**
elevation	201	210.5	207	200	195
length	6.95	3.70	8.78	24.62	3.85

The grouting treatment is carried out for the crack by application of modified epoxy from Mar. 2000 until May 2000. According to the typical image result typical image result of the ground penetrating radar before and after crack grouting, it indicates that the overall effect of the grouting consolidation is good, basically eliminating the influences of the crack on the structure integrity. According to the long-term prototype observation data, it indicates [5][6] that there are no abnormal reflections for the prototype observation. The temperature field of the dam and the autogenous deformation field have already basically been stable and normal; no adverse changes have been led to the trend of the stress field; as for the displacement field, it is at the rational state. The displacement of dam body basically manifests the influences of various load factors. It's already been running for 12 years ever since the crack was treatment from Mar. 2000 until May 2000. Nowadays, the dam is running in the safe state.

3. 3D finite element numerical model of cold wave impact

3.1. Calculation scheme of numerical simulation

As for the new technique of fast constructing arch dam by applying MgO-mixed concrete without transverse joint, its key is whether the application of MgO-mixed concrete stress compensation effect in the arch dam satisfies the rational application and the compensation effect meets the requirements of the stability and durability of the engineering. As for the calculation schemes at two periods, they will be respectively listed as below:

(1) Is it necessary to analyze the crack generation for the MgO-mixed concrete? Utilize the APDL language of ANSYS software for secondary development; mainly discuss the two working conditions: not adding MgO and completely adding MgO; perform simulation calculation of the stress of the concrete arch dam without transverse joint and analyze the rules of stress compensation dosage of MgO-mixed concrete to comply with the stress state of the arch dam structure under the design condition. Namely

Working condition 1: assumed working condition (nmgo: without MgO). The arch dam is analyzed with no MgO-mixed concrete added.

Working condition 2: actual working condition (mgo: with MgO). The arch dam is analyzed with 3.5% and 4.5% MgO-mixed concrete added.

(2) Among the arch dam projects, to which the accident occurs at home and abroad, as for more than 70%, the accidents happen at the initial period of water storage and in the first winter upon that. It is further necessary to pay heed to MgO-mixed concrete arc dam. Therefore, the heat preservation and maintenance of arch dam concrete surface is the key measure for the dam concrete to prevent from cracking, especially prevent form being cracked due to the cold wave impact.

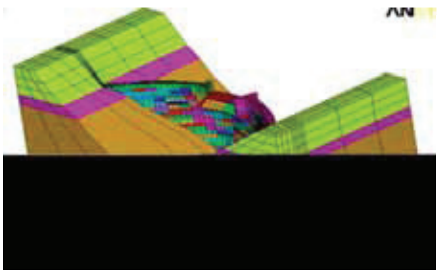
In the original design, Changsha arch dam project the dam concrete surface is pasted with 2cm thick polystyrene foam board within 5 days after mould removal for surface heat preservation. After the concrete is solidified, the artificial watering will be initiated for maintenance, no less than 28 days. It is required that the heat preservation board on the upstream surface of the dam should be dismantled before the water is stored in the reservoir. As for the heat preservation board on the downstream surface can be dismantled after Apr. 2000 (equivalent to the first winter upon initial water storage). However, it is fully focused and carried out during the process of implementation. The heat preservation board is not paved on the dam face immediately and the outside sticking craftsmanship fails to reach the close sticking effect and the heat preservation board of the downstream dam face was dismantled on Jun. 4, 1999, ahead of 1 year.

With aim at the cold wave impact during the initial water storage period, the two calculation working conditions are discussed:

Working condition 1: the heat preservation layer was dismantled in late Apr. 2000, namely the thermal insulation scheme regulated by the original design; (DC: the original design of heat preservation condition)

Working condition 2: the heat preservation layer was dismantled on Jun 4th 1999, namely the actual heat preservation condition of the project; (AC: the actual heat preservation conditions)

3.2. Establishment of finite element model and determination of simulation parameter



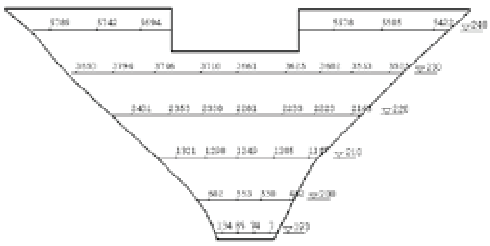


Fig.1 3D Finite Element Model of Changsha Arch Dam

Fig.2 Schematic Diagram of Stress Node Number Label of Different Elevations at the Downstream Dam Face

As shown by the Fig. 1, given the bed rock function, it is necessary to establish 3D finite model of arch dam by adopting ANSYS commercial software, perform secondary development by applying APDL language and simulate the influences of cold wave impact on MgO-mixed concrete dam. The hexahedron eight-node unit is adopted for all, totally 8796 units and 11450 nodes, among which there are 5236 units of dam body and 6716 nodes.

Adiabatic temperature rise of concrete *θ(℃)=24.653t/(1.108+t)*. Coefficient of thermal conductivity: *α=0.00355m2/h*; specific heat: *c=0.96kJ/(kg. ℃)*. Concrete design strength grade: *C9020*; seepage resistance grade: *W6*.

According to the data, it indicates that when the air temperature is -18℃～-18.6℃, the temperature of the concrete surface under the protection of polystyrene plastic foam board is -1～-3℃. The heat preservation effect is good. It is applicable for façade of the concrete dam, especially the heat preservation effect of the upstream and downstream surface of the dam is more evident. The corresponding coefficient of thermal conductivity is *λ=0.1256kJ/m.h. ℃*; surface heat release coefficient: *β=82.2kJ/m2.h. ℃*; equivalent heat release coefficient: *βs=5.834kJ/m2.h. ℃*.

Tthe corresponding MgO addition amount at different elevations respectively are:190~207.5m is 3.5%, 217.5~230m is 4.2%, the rest is 4.5%.

3.3. Manifestation of hyperbolic model of autogenous deformation in the stress compensation

In 3D finite element simulation calculation of Changsha arch dam, the considerations are given to many factors such as: the autogenous deformation of MgO-mixed concrete, concrete construction pouring order, concrete placement temperature, air temperature, ground temperature, reservoir water temperature material heat preservation, sunlight as well as impounding state, etc. In stress compensation, hyperbolic model is introduced for the autogenous deformation.

According to the research, the autogenous deformation of added MgO mixed-concrete is stable. Under the same MgO adding amount, the autogenous deformation value is mainly associated with the march of temperature and age. Adopting hyperbolic model [8] (1)

$$\varepsilon(T,t)=t/(a_1T^{a2}\,t+ b_1T^{b2}) \qquad (1)$$

Through fitting, the autogenous deformation expression of 4.5% MgO-mixed concrete added (2):

$$\varepsilon(T,t)=t/(0.0194T\ \text{-}0.3538t+ 3082T\ \text{-}2.6724) \qquad (2)$$

4. Influences of stress compensation of MgO-mixed concrete and cold wave

4.1. Stress compensation of MgO-mixed concrete

By combining two working conditions of with MgO and without MgO, the comparative analysis of stress compensation is carried out. Table 3 indicates the stress compensation table of type nodes before and after the occurrence of crack. Fig. 3-4 respectively refer to the line graph of the comparative process of the stress compensation at the typical part of the arch dam at different elevations. Nmgo in the Fig. indicates without MgO function.

(1) The stress of each node inside the dam body is complicated and the stress compensation is varied at each elevation point. The three-dimensional function of the arch is extremely evident. The influences of the external temperature on the thin arch dam are relatively obvious.

(2) The stress status of the downstream dam face is quite complication. The principle tensile stress value is higher. During the arch dam construction, the stress of the dam body is large due to the influences of concrete hydration heat. After the water storage period, due to the influence of the upstream water level, the stress is reduced at a certain extent but the main changes are led to the temperature load. The later period is quite sensitive to the temperature.

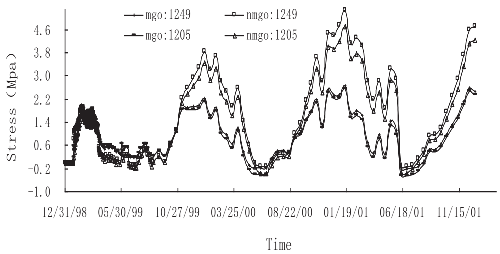
Table 3 S1 Stress Compensation Table of Typical Node before and after Occurrence of Crack (Unit: MPa)

node	*conditions*	*Dec 7,1999*	*Dec. 22,1999*	*Jan.6,2000*	**Jan.21,2000**
1147	nmgo	2.42	2.59	3.02	2.41
1147	mgo	1.84	1.86	2.17	1.54
1147	Compensation Stress	0.58	0.73	0.85	0.87
1249	nmgo	2.95	3.29	3.85	3.21
1249	mgo	1.95	1.99	2.24	1.64
1249	Compensation Stress	1.0	1.3	1.61	1.57

(3) The radial stress of arch crown shows up annual change with the stress enlarged in summer and decreased in winter. The stress of the downstream dam face is enlarged (stress value is within 1.5MPa) due to the compensation effect except the early period of the construction completion while decreased at later period remarkably.

(4) The stress compensation effect is remarkable under the design MgO addition. The compensation effect in winter is better than that in summer. As shown by the table 6, the principal tensile stress compensation value of the representative point of the downstream dam face is 0.58～1.61MPa.

Therefore, MgO-mixed concrete arch dam is very favorable to the stress of the dam. The stress compensation effect of the whole dam body is very obvious. It can be asserted that MgO-mixed concrete is not the reason for causing crack.



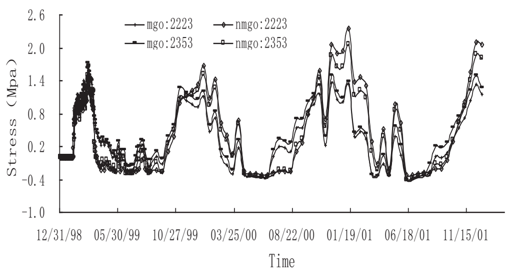


Fig.3 S1 stress process line of representative points (1249, 1205) at 210m downstream of crown cantilever (unit: MPa)

Fig.4 S1 stress process line of representative points (2223、2353) at 220m downstream of 1/4 crown cantilever (unit: MPa)

4.2. Analysis on influences of cold wave impact

Table 3 indicates the comparison table of the principal tensile stress of the downstream dam face before and after the occurrence of crack in different working conditions. Fig. 5, 6 and 7 respectively refer to the line graph of the comparison process stress working condition of the typical part of the different elevation cracks.

(1) The principal tensile stress of the heat preservation working condition of the original design is controlled within 1.5MPa. The principal tensile stress at the cracking position has been reduced greatly and even transformed into the state of pressure stress when the heat preservation layer was dismantled on Apr. 7, 2000.

(2) The principal tensile stress extremism value of the crack occurred on Dec. 25th, 1999 but its principal tensile stress value has been reduced slightly when the crack was found under the routing inspection on Jan. 18, 2000. On Apr. 7, 2000, its principal tensile stress value has already been controlled at the normal stress level.

(3) The principal stress extremism value of the actual construction is enlarged more greatly than that of the heat preservation working condition of the original design. The stress increment of each typical pint is 1.9~2.65 MPa. The influences of cold wave on the occurrence of crack are great, greatly deteriorating the stress state of the dam body, thus the dam body is at the state of higher stress. The principal stress of the crack representative point reaches 3.08～3.93 MPa， far exceeding the design anti-tensile extremism strength of the original dam body concrete.

(4) Before the dam body fails to reach stable temperature field, the function of the pattern plate is extremely obvious. In case of temperature rise, especially the cold wave impact, the improvement of the stress of the downstream dam face by the pattern plate is remarkable.

(5) In calculation of arch dam, the principal tensile stress extremism value of the finite element method is larger than the specified value (arch-cantilevers analysis) of the existing standard. As for its stress standard, there shall be new formulation method.

Therefore, the heat preservation layer can be dismantled after the winter is over of the first year upon the completion of the dam mixed-concrete pouring.

Table 3 Comparison Table of Principal Tensile Stress (MPa) of the Crack Representative Point in Different Working Conditions

time	*condition*	*crown cantilever*	*Left bank Cracks*	*Right bank Cracks*	*Horizontal crack*
	Elevation(m)	215	202.5	202.5	198.0
	node	1707	673	709	422
Dec.25, 1999	DC	3.63	3.37	3.93	3.08
Jan.10, 2000	DC	3.08	2.84	3.31	2.47
April.30, 2000	DC	-0.05	0.02	-0.3	-0.18
Dec.25, 1999	AC	1.42	0.93	1.28	0.8
Jan.10, 2000	AC	1.24	0.79	1.09	0.55
April.30, 2000	AC	-0.05	0.02	-0.3	-0.17

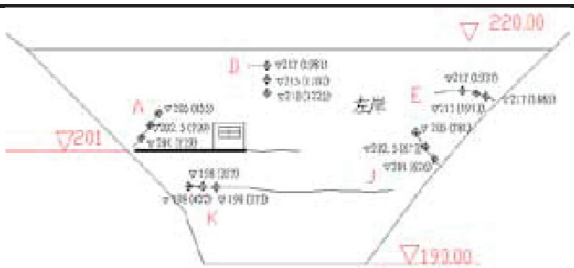
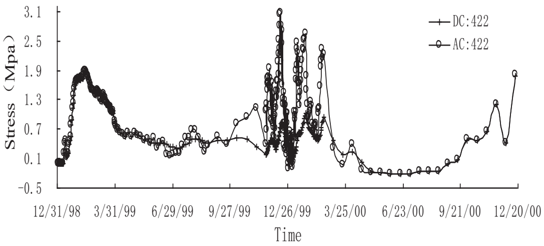


Fig. 5 Schematic Diagram of Finite Node of the Representative Point of Downstream Face Crack of Changsha Arch Dam



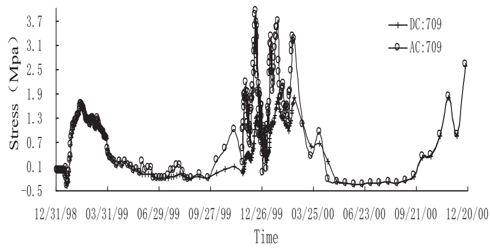


Fig.6 S1 stress process line of representative points (422) at 198m downstream of horizontal crack (unit: MPa)

Fig.7 S1 stress process line of representative points (709) at 202.5m downstream of Right bank Cracks of arc dam(unit: MPa)

4.3. Crack resistance performance of Changsha arc dam with MgO-mixed concrete added

According to a large quantity of laboratory tests and researches, they indicate that [2][5][6] the mechanical strength of the concrete with MgO added is improved if compared to the strength of routing concrete without MgO. The compressive strength can be generally improved by 3～6%; the tensile strength can be increased by around 10%; the limit stretch can be increased by around 12%; creep degree can be increased by around 12%; air shrinkage can be reduced by around 20%. Concrete with MgO added is more favorable to the crack resistance of arch dam than routing concrete.

Construction quality is vital to the influences on crack. In practice of Changsha arch dam project, according to the prototype concrete detection result, it indicates [7] that the laboratory test and machine interface specimen test is basically in line with the requirement of the design indicate. However, the crack resistance performance of concrete fails to reach the design indicator. As shown by the Tab. 4, the prototype core extraction test result is obviously lower than the design indicator, especially the tensile strength and extremum tensile value is only 40～34% and 56 %, so that the crack resistance performance of the prototype concrete is reduced greatly, providing conditions for generation of crack. After strengthening grouting is performed for the dam body concrete, its main indicator performance is increased obviously.

Table 4 Result Table of MgO-mixed Concrete Prototype Body Mechanics of Changsha Arch Dam Strength

Item		90d	1a (Before dam grouting)	3a (After dam grouting)
Compression Strength(MPa)	Average value	26	33.4	39.7
	Not less than 80% assurance value	20.7	26.6	31.5
Axial tensile Strength (MPa)	Average value	0.92	1.29	1.92
	Not less than 80% assurance value	0.66	0.93	1.31
Limiting Tensile((×10-4)		0.646	0.694	0.830

4.4. Analysis on main factors caused by crack

The similar crack occurs to a lot of routing concrete (with MgO routing concrete added, the construction transverse joint is set for the dam body, longitudinal joint pouring) arch dams at home and abroad just like that of the downstream dam face of Changsha dam. The greater crack perpendicular to the slope dam foundation also ever occurred to Boundary thin arch dam and Stevenson Creek in American Seattle. The reason for crack involves wide area and the influence factors are extremely complicated. Through analysis, the main factors leading cracks to Changsha arch dam:

(1) In case of engineering design in 1997 [6], due to many historical conditions such as: engineering experience, design parameter as well as calculation measures, etc. there was inadequate understanding depth of the compensation effect of the fast constructing arch dam without transverse joint. The principal tensile stress value of the downstream dam face of the arch dam was higher. MgO addition amount design scheme and stress state selected appropriately for arch dam concrete is not ideal enough. No complete consideration was given to the influences of the heat preservation and cold wave impact and no sufficiently safe margin was left, so that the dam body gained appropriate compensation effect.

(2) The actual concrete construction quality of the project obviously reduces the crack resistance performance of prototype concrete, not far reaching the requirement of the original design. Owning to the actual factor, the actual stress of the dam body is enlarged and deteriorated and the downstream face of the dam body is at higher stress state and the crack can be caused easily.

(3) Due to the improper Surface temperature maintenance of the dam body, the cold wave impact worsened the stress of the downstream dam face. The principal stress increased by 2.21-2.65 MPa, thus the crack was generated.

Therefore, crack is not the inevitable product of new technique of constructing arch dam without transverse joint. The crack on the downstream dam face of the arch dam has no inevitable association with the new technique taken. The stress state of the original design dam body is not ideal. The dam body engineering quality makes the crack resistance performance is reduced, especially in case of cold wave impact, many factors such as: no effective heat preservation measures, etc. lead crack to Changsha arch dam.

5. Conclusion

Guangdong Changsha arch dam as the first engineering practice of applying new technique of fast constructing arch dam without transverse joint with MgO-mixed concrete at home and abroad. The compensation effect of MgO-mixed concrete on the stress of arch dam is explicit. The crack of the downstream dam face has no inevitable association with the new technique of constructing dam with MgO-mixed concrete added.

The cold wave impact imposes great influences on emergence of crack, deteriorating the stress state of the dam body, so that the dam body is at the state of higher stress. The principal stress of the representative point of crack reaches 3.08～3.93 MPa, far exceeding the ultimate tensile strength of the prototype concrete. The stress state of the original design dam body is not ideal. The engineering quality of the dam body makes the crack resistance performance reduced, especially in case of cold wave impact, many factors such as: no effective heat preservation measures, etc. lead crack to the Changsha arch dam.

1~2mm tiny crack of Changsha arch dam causes no serious harm to the safe operation of dam body. After the strengthening grouting is carried out for the dam body concrete, its main performance indicate is increased obviously. Nowadays, it's already operated for more than 12 years. The finite element analysis of cold wave impact of Changsha arch dam provides main basis for the research on development and perfection of new technique of constructing arch dam without transverse joint with MgO-mixed concrete added.

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