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REVIEW

Research review of the cement sand and gravel (CSG) dam

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ABSTRACT The cement sand and gravel (CSG) dam is a new style of dam that owes the advantages both of the concrete faced rock-fill dam (CRFD) and roller compacted concrete (RCC) gravity dam, because of which it has attracted much attention of experts home and abroad. At present, some researches on physic-mechanical property of CSG material and work behavior of CSG dam have been done. This paper introduces the development and characteristics of CSG dam systematically, and summarizes the progress of the study on basic tests, constitutive relation of CSG material and numerical analysis of CSG dam, in addition, indicates research and application aspect of the dam.

KEYWORDS cement sand and gravel (CSG) dam, cement sand and gravel (CSG) material, research review

1 Introduction

The cement sand and gravel (CSG) dam, originated in the 1970 s, is a new style of dam that has been put forward by scholars both at home and abroad, and it owes the advantages both of the concrete faced rock-fill dam (CRFD) and roller compacted concrete (RCC) gravity dam. Its features, for instance, small section, high-speed construction, low-loss materials, convenience in construction diversion, high-quality of seismic resistance, good adaptation for soft foundation and so on, make it reliable and economic, having strong competitive power. This new dam type has been used in abroad, and has just been paid attention in domestic. There is few research on this kind of dam and no essentially application. The research and application of CSG dam is an active promotion for the hydroelectric development of China.

2 Characteristics of the CSG dam

The aggregate of CSG dam is the gravel in riverbed and abandon slag in excavation near the damsite, and then join the additive such as cement to make the CSG dam material. The basic profile on type of the dam is an isosceles trapezoid with symmetric dam slopes. The dam uses panel for seepage control on the upstream face and utilizes the low intensity cementation gravel which is at a low price. Many scholars think the dam type has characters of high security, high vibration resistance and low requirements for foundation, and the construction is simple, fast, and cheap [1]. Due to its requirements for dam material requirements is very low, it makes the construction in the pouring process can make utmost use of the local materials: weathered rock and excavation abandon slag, so as to avoid land vegetation destruction from engineering. So the dam is called “zero emission dam” (dam without pollution) in abroad, and has been known as a kind of environmental protection hydraulic structures. Compared to RCC (roller compacted concrete) gravity dam, the cement content of this dam in the building process is about 40%–50% of cement content in RCC gravity dam; compared to the concrete face rockfill dam, the dam section area can be reduced by 50%. The existing research results show that the displacement of CSG dam weighs against that of RCC gravity dam with same height and is just 1/20–1/10 of the concrete faced rock-fill dam (CRFD) in corresponding place. The internal stress of CSG dam body has a little variation in completion period and operation period, and

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the dam seismic capability increases apparently [2].

Comparing with concrete face rockfill dam, in addition to the smaller dam section, the main differences between CSG dam and concrete face rockfill dam are as follows:

1) Because of been mixed with gelled material, the rockfill becomes stone cementation body, so the dam has larger shear strength, compressive strength and strong ability of resisting impact. During construction period, the dam allows excess of water, so construction diversion standard is lowered; in the operation period it can resist seepage erosion and flooding overtopping, so the safety degree is greatly increased.

2) The deformation modulus of CSG material is about 10–100 times as much as that of ordinary compacted rockfill [3], and the deformation of CSG dam is greatly decreased, improving the workability state of panel and surrounding seam, which makes the upstream anti-seepage system normally work.

3) In the construction of rolling compaction, CSG dam do not need division, so it greatly simplifies the construction process, and the construction speed is obviously accelerated.

Comparing with roller compacted concrete gravity dam, the main differences dam are as follows:

1) The dam seepage control depends entirely on the panel, and it has no seepage prevention requirements to the dam body.

2) CSG dam has larger dam section, and stress distribution is more even; the ability to adapt to the weak foundation is enhanced markedly. The stability and the aseismatic performance are improved.

3) Requirements to dam material are low, and selection scope of aggregate for dam material is wider.

4) Cement admixture is lessened, and the temperature effect is slight, so it should not consider cement hydration heat influence on the structure, which simplifies the construction technology and makes the construction more fast and simple.

3 Development of the CSG dam

The CSG dam can date back to 1970 when J. M. Raphael put forward it first in Rapid Construction of Concrete Conference in California [4]. Raphael suggested use Cement Sand and Gravel material to build dams, and take advantage of efficient cubic meter of earth and stone transport machinery and the compaction machinery to construct. As adding a little cement to the natural graduation rockfill, making the grit stone from scattered grain into a continuum body, and the consolidation function of cement increases the shear strength, so as to narrowed the section of the dam; using continuous construction method that is similar to that of earth dam can shorten the construction time and reduce the construction cost. In the 1970 s, China's Lin Yishan also proposed the rudiment of CSG dam which is constituted by the relatively impervious wall and the fat structure built by low cementing stone, which can keep the dam stable [5]. In 1972, R. N. Cannon raised "building concrete dam by method of soil compaction", which developed the designing concepts of CSG dam. In 1973, A.I.B. Moffat put forward the thought that make the use of poor concrete which had been used to construct roadbed in Britain in the 1950s to build concrete dam in the 11th international dam meeting, and it could realize rapid construction by using road construction machine, so it perfected the thought of CSG dam.

In 1982, Willow Creek dam which is the first full section RCC dam in the world was built in Oregon, USA, and the cement content of roller compacted concrete in the dam body is just 66 kg/m^3, so it is a typical lean concrete dam. This dam saved the dosage of cement greatly; meanwhile the hydration heat was also reduced by a greater degree, so as to simplify the temperature control measures. In the construction process, large-scale mechanical construction technology used for earth dams was applied to achieve the purpose of rapid construction. The concreting job that consisted of 331000 m^3 concrete was done in five months, which is reduced by 1–1.5 years compared to ordinary concrete gravel dams, and the price was just as much as 40% of the ordinary concrete gravel dams, 60% of rockfill dams. This dam could be regarded as the rudiment of CSG dam.

In 1992, French scholars P. Londe published a paper about "The Faced Symmetrical Hard-Fill Dam", which further expounded the characteristics of the dam type, and compared to RCC dam, Londe thought it was a dam with lower cost and higher safety degree [1]. In 2004, Tadahiko Fujisawa gave a report about "Trapezoid-Shaped CSG Dam and Material Properties of CSG" in the first time academic exchanges meeting of "The China, Japan and South Korea Dam the Committee", and the report discussed the relationship between the strength, stability of trapezoid-Shaped CSG dam and character of CSG material, and studied the influences of graduation and water consumption on the strength of CSG dam, introducing a construction example of Nagashima Dam–the first dam took advantage of CSG construction technology in Japan [6].

According to incomplete statistics, there are about 10 already-built CSG dams which have heights from 20 to 100 m overseas. Among them Turkey's Cinderen (107 m high) was the highest, but as to the engineering examples in domestic, the case is so rare, only three. They are respectively: upstream cofferdam of Daotang reservoir (7 m, 2004), downstream cofferdam of Jiemian hydropower station (16.3 m, 2005), and the upstream cofferdam of the Hongkou hydropower station (35.5 m, 2006).

4 Experimental study of the CSG dam and CSG material

In 1997, Lu and Tang added a little gelled material into natural grading application to make the application become "CSG material", and they conducted compressive strength and flexural strength tests on the CSG material to study the compressive strength, tensile strength and elastic modulus characteristics of CSG material [3,7]. In 2003, Omae et al. tested the dynamic properties of dam material in an actual CSG dam by dynamic triaxial test, and the test results showed that dynamic shear modulus of material increased with confining pressure under the effect of pressure in small value circulation, and decreased with increasing shear strain and decreasing strain rate, meanwhile the dynamic constitutive relation of CSG material presented nonlinear properties obviously [8]. Tadahiko did uniaxial compression test and uniaxial reciprocating load test on CSG material, and the test results showed that stress-strain relationship of CSG material had elastic-plastic characteristics [6]. Jia et al. combined downstream cofferdam works of Jiemian hydropower station in Fujian, studying the compressive strength, tensile strength and penetration dissolution performance of CSG material through tests [9]; Sun et al. did triaxial test first on CSG material with different cement content, and the test results showed that the stress-strain curve had obvious nonlinear characteristics and softening feature [10]; Yang et al. combined with upstream cofferdam works of Daotang reservoir in Guizhou, researching the performance of CSG material [11]. Batmaz combined with Turkey's Cinderen dam to conduct strength experimental research on CSG material [12]. Using cofferdam works of Baisha hydropower station, Jiemian hydropower station, and Hongkou hydropower station, Yang conducted compressive strength, tensile strength, modulus of elasticity, Poisson's ratio tests on CSG material with different proportions [2]. Peng et al. conducted an experiment on over lean cemented material (cement content in the range of 0–80 kg/m^3), obtaining the physical, mechanical properties of the material. Peng et al. put forward the basic parameters of mix design and the optimum water cement ratio through experiment, and reasonable exceeding coefficient of the pulverized coal ash were given [13]. He et al. conducted an uniaxial compression test on dam material of a Japanese CSG dam, analyzing the constitutive relation, strength properties, permeability, and thermodynamics characteristics of the dam material [14]. Connecting with cofferdam works of Daotang reservoir, Xiao et al. got some test data and construction technical parameters of CSG dam by material tests and site rolling compaction test, which accumulated experience for the application of CSG technology in China [15]. Combined with "Research on key technology of CSG dam" which was the foundation item of NHRI, Cai et al. have done material tests of CSG material and centrifugal model experiment on CSG dam, studying the influence of cement content on dam settlement [16]. Chen et al. expounded on the penetration dissolution mechanism of CSG material, and conducted contrast test which adopt dissolution concentration of Ca^{2+} and percolation of Ca^{2+} to characterize the penetration dissolution degree of CSG material [17]. Basic material experiment and large scale triaxial tests on CSG material were conducted by Cai and Wu to study the relationship between the collapsing strength, initial tangent modulus of elasticity of the material and confining pressure condition, and the relationship between Poisson's ratio and stress state was also researched, by which Cai et al. raised a nonlinear elastic stress strain relation that could reflect the deformation characteristics and deformation law of CSG material in pulling stage, but the plastic deformation characteristics of the material cannot be reflected [18,19]. According to the results of triaxial tests on over lean cemented material, borrowing ideas from Duncan model, Sun et al. put forward a constitutive model of over lean cemented material which could reflect the softening property of the material, but the Poisson's ratio in the model was only supposed for the constant as the test data of lateral deformation was inadequate [20].

Synthesizing the experimental research achievement thus far, studies on CSG material mainly focus on basic mechanics properties, such as uniaxial compression strength, splitting tensile strength, and flexural strength, however, triaxial tests considering confining pressure and study on dynamic characteristics are rare. So far, there is no loading and unloading triaxial test on CSG material, and there is no literature that reports plastic characteristics tests on CSG material under respective stress conditions. Research on constitutive properties of CSG material is in the initial stage, and the studies generally borrow ideas from Duncan-Chang model to build nonlinear elastic model that cannot reflect the plastic deformation characteristics. Therefore, the lack of a reasonable elastic-plastic constitutive model limits the extent to which CSG dams can be investigated.

5 Numerical analysis of the CSG dam

Li regarded CSG material as an ideal elastoplastic D-P material and performed a finite element analysis on CSG dam by ANSYS to discuss the susceptibility effect on stress and stability, which is connected with cohesion, internal friction angle, and Young modulus of the material [21]; Wang took ANSYS as the main computing equipment to analyze the working condition and stress-strain distribution rule of CSG dam with different dam slopes [22,23]. Shi supposed the stress-strain relation of CSG material fits Duncan-Chang E-μ model, on this basis, Shi expounded the variation trend of parameters, relating to cement content of CSG material, in Duncan-Chang E-μ model, and analyzed the stress and displacement changes of panel and dam body on three kinds of typical CSG dam [24]. Cai et al. adopted nonlinear mathematical programming method to optimize the CSG dam, and the prioritization scheme showed that the dam slope of CSG dam could be steeper than ordinary rockfill dam, based on the satisfaction of stress and stability, CSG dam uses less stone and costs less, meanwhile the section is safe and reasonable [25]. Yang et al. adopted finite element method to compute the composite dam which was composited by CSG material and earth material [26]. Sun et al. described the softening characteristics of over lean cemented material by means of "virtual rigid spring method" and "step iterative algorithm", and they worked out to nonlinear finite element program to simulate construction loading by degrees, on this basis, the stress and strain of over lean cemented dam were computed [27]. Peng et al. adopted the three-dimensional nonlinear finite element numerical simulation method to analyze the panel and dam body of CSG dam [28,29]. Wu et al. made theoretical analysis on CSG dams with different height and density, comparing the analysis with the finite element calculation results, revising the area with major error [30]. Wu applied the nonlinear elastic stress strain relationship based on experiment of CSG material to analyze the workability of CSG dams in different working conditions [19]. Liu et al. researched the seepage field law of Hardfill dam foundations in different permeability conditions, and compared it with the seepage field law of Hardfill dam foundations which were given seepage prevention, organizing the reckoning into flow net figure and seepage slope figure of characteristic points, which lays a foundation for further integrated grasping the seepage field regulation of Hardfill dam [31]. Liu et al. adopted the three-dimensional nonlinear finite element numerical simulation method to analyze the temperature field of Hardfill dam in construction period, and compared it with RCC gravity dam, reaching the changing regularity of Hardfill dam temperature field [32]. They briefly analyzed the influences of adiabatic temperature rise, creep degree, coefficient of linear expansion, modulus of elasticity, ultimate elongation on the thermodynamic properties of Hardfill material, obtaining the conclusion that in the same condition, stress due to temperature of Hardfill material is smaller than that of conventional concrete and rolling compacted concrete, and it has the larger crack redundant, so it is a new type of dam material that is worth being investigated and researched [33]. Le adopted a linear elastic finite element method and response spectrum method to compare the static and dynamic working characteristics of CSG dam and those of gravity dam, and some rules can been found on the impact of static and dynamic working characteristics of CSG dam following the changing of dam slope, and how the permeability of dam and foundation impacts working characteristics of dam was investigated. Le discussed the effects of homogeneous foundation and inhomogeneous pre-post foundation, foundation stiffness on working characteristics of the dam, and the possibility of building CSG dams on soft foundation was also discussed [34]. By utilizing elastic theory, Xiao et al. deduced the stress computational formula of Hardfill dam body under dead load, upstream water pressure, and uplift pressure, and they also deduced the stress computational method of Hardfill dam under osmotic pressure; by comparing with the results of finite element calculation, Xiao proved the computational formula based on elastic theory was reasonable to describe the stress distribution [35].

On the dynamic calculation front, it can date back to 1970 when Londe analyzed the earthquake resistant behavior of Hardfill dam by very brief method which adopted pseudo-static method to estimate the earthquake loading and utilized material mechanics method to calculate the dynamic stress of the dam, finally through research, it proved that unlike the traditional gravity dam, the phenomenon of stress concentration in dam heel and dam toe almost disappeared in Hardfill dam, and the earthquake working condition wouldn't lead the stress state near dam foundation to very serious deterioration [36]; afterward Hirose et al. analyzed the seismic stress and dynamic displacement distribution regulation of a CSG dam in Japan by two-dimensional linear finite element method and response spectrum method, obtaining the conclusion that the deformation of this dam type under earthquake was mainly shearing deformation, and the dam top didn't exist dynamic stress concentrating area, and the increasing amplitude of dam stress under earthquake was much smaller than that of gravity dam, so this dam type was of good seismic safety [37]. Using the 107-m-high Cindere dam, Gurdil et al. conducted seismic analysis on the dam by adopting time history method, and the result proved it had high seismic safety degree, which can resist an earthquake with an 8.0 magnitude [38]. Using a CSG dam of 100 m high, Liapichev conducted two-dimensional seismic analysis, finding that the CSG dam with symmetric figure had very fine earthquake resistant behavior, and the dam can ensure the proper functioning in intact state under the seismic action of which the peak acceleration was 0.4 g, even the peak acceleration up to 0.8 g, the harm to dam was limited to endanger the overall stability safe [39]. On the basis of one-dimensional shear wedge theory for Hardfill dam, He et al. educed the computational formula of natural frequency of vibration and mode of vibration, afterward they adopted a simplified equivalent system to compute the variations of natural frequency of vibration and mode of vibration caused by dynamic water pressure, and then utilized response spectrum method to compute the dynamic response of Hardfill dam; by comparing the natural vibration characters based on shear wedge method with that based on finite element method, He et al. demonstrated the applicability and veracity of adopting shear wedge method to compute the seismic response for

Hardfill dam [40,41]. According to shear wedge method, Yu et al. deduced the differential equation of Hardfill dam with trapezoidalcross-section, and they adopted Liouville function and confluent hypergeometric function to educed the computational formula of natural frequency of vibration and mode of vibration, reaching computational formula of the acceleration, speed, and dynamic displacement of dam body under simple harmonic wave action; through the calculating example, Yu et al. compared the calculated results based on shear wedge method and finite element method, proving it was valid to utilize shear wedge method to set up computational formula of natural vibration and dynamic response for Hardfill dam [42].

At present, in terms of numerical analysis on CSG dam, the constitutive model of CSG material usually refers to linear elastic model of traditional rockfill and concrete, ideal elastic-plastic model, and Duncan-Chang nonlinear elasticity model, which cannot reflect the plastic deformation features of CSG material; the Poisson's ratio of CSG material in computing is generally taken as constant, so it leaves out of consideration the nonlinear variation of Poisson's ratio; the knowledge of loading-unloading rule is still a blank; researches on seepage characteristics and temperature stress field of CSG dam are in the initial stage as well; dynamic characteristics and dynamic calculation of this material are still in exploratory stage, and dynamic constitutive has not yet been reported; dynamic calculation normally utilizes pseudo static method and spectrum analysis method those are based on linear rule, but the calculated results cannot reflect the actual seismic characteristics of CSG dam, and the optimization of cross section can only be found in reference [25] which refers to that of concrete faced rockfill dam. Thus, this method cannot accuratrly reflect the feature of the CSG dam.

6 Conclusions

CSG dam is a new type of dam with great potential, which is widely recognized by domestic and foreign experts. Currently some researches about CSG dam and its material are carried out and some achievements and understanding are obtained, providing good basis for further study. By synthesizing existing research results, there are problems about this kind of dam and dam material, which are worth further exploration.

1) CSG material is a complex new material of engineering, influenced by a serial of factors such as the content of cement, grain gradation, sand ratio and water-cement ratio. The law of impact of those factors to the strength, plastic deformation and failure form of CSG material needs to be further discussed.

2) CSG material has significant nonlinear characteristics and the stress-strain curve is greatly influenced by the stress state. To put forward a widely accepted constitutive model which can truly reflect elastic-plastic deformation characteristics of CSG material is the key issue of CSG dam research.

3) The cross-section optimum design research on CSG dam is still in starting process and suitable failure criterion and control standards for CSG material are premise of it.

4) The understanding of dynamic properties of CSG material is still inadequate, which needs to be studied by special dynamic experiments. Reasonable and effective dynamic constitutive model for CSG material should be put forward to study and better understand seismic properties of this type of dam.

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