Study on Stability and Reliability of Cement-Sand-Gravel Dam

Xiwun Li\textsuperscript{1}, Shunfu Zhang\textsuperscript{1,2*}, Hao Wu\textsuperscript{1}, Dongcheng Tian\textsuperscript{1},
\textsuperscript{1}China Institute of Water Resources and Hydropower Research, Beijing, 100038, China
\textsuperscript{2}Research Center on Flood&Drought Disaster Reduction of the Ministry of Water Resources, Beijing, 100038, China
*Corresponding author’s e-mail: 553592704@qq.com

Abstract: The cement-sand-gravel (CSG) dam is a new type of dam between the rockfill dam and the gravity dam, with advantages of both these two types of dams. The materials used to build the CSG dams have low shear strength and large dispersion. To study the stability and reliability of equal-height gravity dams and SCG dams, finite element software was used to conduct static analysis on the 100 m gravity dams and SCG dams, and the JC method was used to compute the reliability of dams based on the analysis result. The research results show that under the same working conditions, the CSG dam has better reliability and better adaptability to the foundation than the gravity dam. The study is expected to provide a basis for the design and application of CSG dams.

1. Introduction
The CSG dam is a new type of dam built with lean roller compacted concrete that meet less strict requirements, and the structure of the dam is between the rockfill dam and the concrete gravity dam [1]. CSG dams have the advantages of both rockfill dams and concrete gravity dams: compared with rockfill dams, the CSG dams require less engineering work and have stronger resistance against erosion; compared with roller compacted concrete (RCC) dams, the CSG dams consume less volume of cement, reduce the cost and have lower requirements for the aggregates, mix ratios and temperature control [2]. In recent years, the CSG dam has been gradually promoted in China and abroad. The highest CSG dam in the world is the 107-meter-high Cindere Dam in Turkey. The Shanxi Shoukoubao Dam built in China is the first permanent CSG dam in China.

Reliability analysis can provide a basis for evaluating the building failure probability with clear physical meaning. Based on shear strength tests of geotechnical materials, Chen et al. [3] proposed the idea of relative safety ratio of reliability and its calculation formulas, and verified the method with a gravity dam as an example. Wang [4] introduced the reliability analysis method combined with the strength failure method to analyze the shear resistance of the CSG dam, and carried out the reliability analysis of the shear resistance, finding that the CSG dam has high shear reliability.

Aiming at the characteristics of low shear strength and large dispersion of the materials of CSG dam, the reliability and stability of the foundation was analyzed. The finite element software was used for static analysis of 100 m CSG dams and gravity dams, and the JC reliability analysis method was employed to study the reliability and stability of the two dam types of dams under different working conditions. The research results can provide a basis for the design of CSG dams.
2. Finite element calculation

2.1. Calculation model

A CSG dam is 100 m high, and the slope ratio of the upstream and downstream slopes is 1: 0.7. In this paper, a first-grade gravity dam is designed and compared with this dam.

The dam body is subjected to its own weight, hydrostatic pressure and uplift pressure. In order to study the stress variation of the CSG dam under different water level conditions, three working conditions: an empty reservoir (Condition 1), 1/3 of the dam high water level (Condition 2) and full storage (Condition 3), with no water in the downstream, was analyzed. It is assumed that the lifting pressure was reduced to 1/2 of the water head at the anti-seepage curtain and 1/4 of the water head at the drainage hole. The lifting pressure was linearly distributed at the bottom of the dam, the normal restraints were used on both sides of the dam foundation, and the base was hinged constraint. The calculation parameters are shown in Table 1:

| Materials        | Density (kg/m$^3$) | Elasticity modulus (MPa) | Cohesion (MPa) | Poisson's ratio | Internal friction angle (°) |
|------------------|--------------------|--------------------------|----------------|----------------|----------------------------|
| CSG              | 2300               | 10000                    | 0.255          | 0.2            | 43                         |
| Concrete         | 2400               | 25000                    | 1.5            | 0.167          | 50                         |
| Dam foundation   | 2300               | 12000                    | 1.1            | 0.25           | 50                         |

The calculation area included: the dam foundation area extended twice the length of the dam height towards the upstream, the downstream and the dam foundation. The grid was divided into four-node units. The CSG dam had a total of 5,100 nodes and 4,280 units. The gravity dam had a total of 4,134 nodes and 3,720 units.

The gravity dam had a total of 4,134 nodes and 3,720 units. Under the full reservoir condition (Condition 3), the grid division of the CSG dam and the gravity dam is shown in Figure 1.

![Figure 1](image-url)
2.2. Static analysis
The Mohr-Coulomb failure criterion was adopted as the yield condition of the building materials, and the ideal elastoplastic constitutive model was used for the dam foundation and gravity dam body materials. The stress calculation showed that the compressive stress was negative and the tensile stress was positive. The maximum principal stress and minimum principal stress of these two types of dams are shown in Table 2, and the stress distribution under the full reservoir condition is shown in Figures 2, 3.

Table 2. Maximum and minimum principal stresses

| Condition | value | CSG Dam | Gravity Dam |
|-----------|-------|---------|-------------|
|           |       | Maximum principal stress | Minimum principal stress | Shear strength | Maximum principal stress | Minimum principal stress | Shear strength |
|           | Site  | Downstream dam top | Dam toe | Dam toe | Dam heel | Dam heel | Dam heel |
| Condition 1 | 0.00033 | -1.48 | 0.709 | 0.0535 | -4.409 | 2.231 |
| Condition 2 | 0.00033 | -1.533 | 0.727 | 0.0526 | -4.407 | 2.073 |
| Condition 3 | 0.188  | -2.399 | 0.975 | 0.958  | -4.262 | 2.096 |

As the figures show, the stress distribution of the gravity dam changed greatly with the increase of the water level. When the reservoir was empty, the maximum stress concentrated in the dam heel; when the reservoir was full, the maximum stress was located in the downstream dam toe area and there was a
large tensile stress in the upstream dam heel area. As the water level increased, the minimum principal stress of the gravity dam decreased due to the increase of water pressure and uplift pressure.

In Conditions 1 and 2, there was no tensile stress in the CSG dam, and the entire section was compressed; when the reservoir was full (Condition 3), the stress concentrated at the heel of the dam, but only one node had tensile stress, which was much smaller than 0.86 MPa, the tensile strength of the cemented gravel material at 90 d. The minimum principal stress of the CSG dam was low, and the maximum stress at the toe of the 100 m CSG dam was 2.399 MPa. In most areas of the dam, the stress did not exceed 1.50 MPa. Only when the reservoir was full, there was a small range of stress concentration at the heel of the dam, and no tensile stress appeared in the dam. At the same height, Oyuk Dam in Turkey was reinforced with high-strength cemented gravel materials and concrete during construction of the dam heel and toe [5].

When the reservoir is full, the gravity dam needed 4.262 MPa compressive strength and the CSG dam needs 2.399 MPa to resist compressive stress. The required compressive strength by the CSG dam is about 56% of that required by the gravity dam. The tensile stress generated in the heel area of the gravity dam is 0.958 MPa, while the tensile stress of the CSG dam is 0.188 MPa. Because the dam body needs to have sufficient tensile stress resistance, the concrete tensile stress is generally 10% of the compressive stress, the gravity dam obtains a tensile stress of 0.958 MPa, a compressive strength of 9.58 MPa, and the compressive stress of the CSG dam is 1.88 MPa, that is, the strength requirement of the CSG dam under the full reservoir condition is only 19.6% of the gravity dam’s.

The shear stress of the CSG dam is very small and is evenly distributed. The shear stress of the gravity dam is large. In order to resist the shear stress, it is necessary to integrate the bedrock and the dam body when building the gravity dam, which is not required in construction of the CSG dam.

A comprehensive comparison of the values and distribution of the maximum principal stress, minimum principal stress and shear stress shows that the CSG dam under the same working conditions has a lower stress than the gravity dam, and the distribution of stress is reasonable.

3. Analysis of reliability of the CSG dam

When the basic variable X contains abnormal random variables, the checkpoint method must be used to process these abnormal random variables in advance. The JC method is an equivalent normalization checkpoint method [6].

Matlab is used in this study for calculation. Table 3.1 shows the reliability indicators and damage probability under different work conditions.

|                         | CSG dam          | Gravity dam       |
|-------------------------|------------------|-------------------|
| β                       | Condition 1      | Condition 2       | Condition 3   | Condition 1 | Condition 2 | Condition 3 |
|                         | 5.6053           | 5.351             | 3.302         | 1.87        | 2.07        | 0.9586      |
| p_f                     | 1.0394×10^8      | 4.3727×10^8       | 4.7993×10^4   | 3.07×10^2   | 1.88×10^2   | 1.689×10^1  |

As Table 3 shows, as the water level load increases, the reliability index decreases and the probability of failure increases. Under the same working conditions, the CSG dam has a higher reliability index and lower probability of sliding failure than the gravity dam.

The gravity dam has a high probability of damage when the reservoir is full. To prevent slippage, it is necessary to integrate the bedrock with the dam body when building the gravity dam. In the construction of gravity dams, the foundation rock must have strong shear strength, while in the case of CSG dams, the foundation rock only needs to have friction. Therefore, CSG dams can be built where the strength of the bedrock is relatively weak, but gravity dams have higher requirements for the foundation.
4. Conclusions
Static analysis and reliability analysis on the CSG dam and the gravity dam were performed in this study, and the following conclusions are reached:

(1) Comparison of distribution of maximum principal stress, minimum principal stress and shear strength between the CSG dam and the gravity dam shows that under the same height, the CSG dam has lower stress, better distribution of stress, higher stability and better adaptability to foundation than the gravity dam;

(2) For both CSG dams and gravity dams, the reliability index decreases and the probability for damages increases as the water load increases. Under the same working condition, the CSG dam has a higher reliability index and a lower probability for slippage damages than the gravity dam.

Acknowledgments
This paper was jointly supported by National Key R&D Program of China (Mechanism of Landslide due to Seepage in expansive soil bank slope and dam;2017YFC1501201)

References
[1] Peng Yunfeng, He Yunlong, Wan Biao. Hardfill Dam - A New Design RCC Dam [J]. Water Power, 2008, 34(2): 61-63,70.
[2] Peng Yunfeng, He Yunlong, Xiong Kun. Study on the structure safety of Hardfill dam [J]. CHINA WATER RESOURCES, 2007,(21):55-57.
[3] CHEN Zuyu, XU Jiacheng, SUN Ping, WU Chao,et al. Reliability analysis on sliding stability of gravity dams: Part I, an approach using criterion of safety margin ratio [J]. JOURNAL OF HYDROELECTRIC ENGINEERING, 2012, 31(3): 148-159.
[4] Jia J,Wang S, Zheng C, et al. FOSM-based shear reliability analysis of CSGR dams using strength theory [J]. Computers & Geotechnics, 2018, 97(MAY):52-61.
[5] Liu Junlin, He Yunlong, Xiong Kun, Li Jiancheng. Study on nonlinear elasticity constitutive model of Hardfill material [J]. Journal of Hydraulic Engineering, 2013, 44(04):451-461.
[6] ZHAO Jingang, ZHAN Yulin, JIA Hongyu, LI Xi, et al. Probability analysis for plastic hinge formation of a RC high pier under near-field seismic action based on JC method [J]. JOURNAL OF VIBRATION AND SHOCK, 2019, 38(13):64-72,94.