FOSM-based shear reliability analysis of CSGR dams using strength theory

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**A R T I C L E  I N F O**

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**A B S T R A C T**

The cemented sand, gravel and rock (CSGR) dam is a new type of dam that combines the characteristics of a rigid dam and an embankment dam. Mechanical tests show that the shear strength of CSGR is much lower than that of concrete and present significant discreteness; shear failure of a CSGR dam is more similar to a failure in material than a failure along the contact between two materials and is quite different from the failure of a rigid dam. The rigid equilibrium method (REM), which adopts the parameters \(\phi\) and \(C\), could cause great calculation error when applied to the stability evaluation of a CSGR dam. Because of the uncertainty of the shear parameters, reliability theory should be used to analyze the shearing stability of CSGR dams. In this study, shear criteria based on the theories of Mohr Coulomb and double-shear strength failure and the corresponding limit state equations using uniaxial compressive and tensile strength as random variables are proposed to evaluate the shearing stability of CSGR dams; then, the reliability index of above limit state equations is solved using the reliability method of first-order second moment (FOSM) combined with the finite element method; the failure probability can thus be evaluated on a local scale. The FOSM-based method proposed in this study is applied to the case study of Shou Koubao Dam. The conclusions drawn from the results will contribute to the risk analysis of CSGR dams in the future.

1. Background

The CSGR dam is a new type of dam that has been developed in recent years based on the CSG dam \cite{1,2}. It is built using natural sand, gravel and rock excavated from the riverbed at the dam site in addition to a small quantity of cementitious material (cement, fly ash, etc.) \cite{3}. The profile of this dam adopts a symmetrical isosceles trapezoid and is much smaller than that of a traditional embankment dam. Therefore, this type of dam has the advantages of being environmentally friendly, requiring lower investment, and having a sufficient degree of safety \cite{4}; as a result, such dams were promoted and put into application immediately. As the consumption of cementitious material is much less in this dam than that in a concrete dam, the shear strength of a CSGR dam is much lower and shows greater discreteness than that of a concrete dam, even if the wider cross section provides more safety in resisting the damage caused by shear stress. Therefore, anti-sliding stability analysis is an important aspect in the design of CSGR dams.

The conventional rigid equilibrium method (REM) is often used to calculate the stability of the dam; this method assumes the following: (1) the dam and the foundation are two contacting rigid bodies, (2) the contact between them is the weak surface and is considered as potential sliding surface, and (3) a single safety factor is adopted to evaluate the stability of the dam. The safety factor is defined as the ratio of the anti-sliding force provided by the potential sliding surface and the sliding force. If the anti-sliding force is larger than the sliding force, then the dam is considered as safe. If the sliding force is larger than the anti-sliding force, then the dam is considered as unsafe. However, because of its low shear strength, the failure process of a CSGR dam is different from that of a rigid dam, and the REM assumes that the safety factors of all points on the potential shear sliding surface are the same, which contrasts with actual situations. Because the stress state on the potential shear sliding surface is very likely different, the safety factors of every point are different; as a result, the stability analysis for CSGR dam based on the method of REM could be misleading.

The stability of dams using reliability theory has been studied by many scholars in the last few years; for example, the latest representative articles include Li et al. \cite{5}, Su et al. \cite{6}, Shi et al. \cite{7}, Su et al. \cite{8}, Yang et al. \cite{9,10}, Wang et al. \cite{11}, Sun et al. \cite{12}, Que et al. \cite{13}, Chen et al. \cite{14}, Zhu et al. \cite{15}, Zhang \cite{16}, and Su \cite{17}. However, the objects of these studies are gravity dams, and most of them are based on the method of REM; even though there are also studies of reliability analysis of dams based on the finite element \cite{18}, no research has been conducted on the reliability analysis of the shear stability for CSGR dams based on strength theory.

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The FOSM-based method proposed in this study estimates the failure probability of a dam using mathematical statistics, which not only takes the uncertainties of material parameters into account but also considers the different stress states and material zones, so the reliability indices of shearing resistance at different positions can be obtained. The FOSM algorithm is coded into a computer program using the Matlab programming language. Next, the algorithm is applied to the shear stability analysis of the Shou Koubao CSGR dam. The accuracy of the reliability analysis proposed in this paper, based on the first-order second moment method, is verified using the Monte Carlo method. Although several researchers have conducted studies investigating the material properties of CSGR [19,20], few researchers have investigated the shear stability of CSGR dams using reliability theory combined with strength theory; hence, the conclusions reached in this study are of great importance in applications to risk analysis of CSGR dams.

2. Formulation of performance functions

The performance function of shear failure is assumed to be:

\[ Z = g(x_1, x_2, \ldots, x_n) \]

where \( g(.) \) is the performance function, \( x_i \) are random variables, the structure is in a safe state if \( Z > 0 \), whereas it is in an unsafe state when \( Z < 0 \); \( Z = 0 \) indicates that the structure is in a critical state between safe and unsafe, and the corresponding equation is called the limit state equation.

### 2.1. Performance function of shear failure in plane stress problems

According to Mohr–Coulomb theory, the principal stresses and the principal shear stresses of a point in plane stress problems are shown in Fig. 1. The outer sides of the straight envelope lines are failure zones; an unsafe state is considered when the stress-circle lies in these zones. The inner sides of the envelope lines are safe zones; shear failure will not occur because ultimate stress in these zones will not exceed the allowable value of the material. \( \varphi \) and \( C \) are two shear parameters obtained from the failure envelope curve. \( f_c \) and \( f_t \) are the uniaxial compression and the tensile strength of the material, respectively; their numerical values are chosen as calculation parameters according to the results of mechanical tests [21]; thus, Mohr–Coulomb theory is not applicable to three-dimensional problems.

It is assumed that the stress circle (the red one) of a point is as shown in Fig. 1; its maximum shear stress can be written as follows:

\[ \tau_{\text{max}} = \frac{\sigma_1 - \sigma_3}{2} \]

If \( f_t \) is taken as a reference, the allowable shear stress of the material can be written as follows:

\[ |\tau| = \frac{f_t}{2} \left( \frac{f_t}{2} - \frac{\sigma_1 + \sigma_3}{2} \right) \sin \varphi \]

where \( \sin \varphi = \frac{k - f_t}{k + f_t} \); thus, the allowable shear stress of this stress state can also be written as follows:

\[ |\tau| = \frac{f_t}{2} \left( \frac{f_t}{2} - \frac{\sigma_1 + \sigma_3}{2} \right) \frac{f_t - f_c}{f_t + f_c} \]

Thus, the limit state equation can be obtained:

\[ \frac{f_t}{2} \left( \frac{f_t}{2} - \frac{\sigma_1 + \sigma_3}{2} \right) \frac{f_t - f_c}{f_t + f_c} = 0 \]

The simplified form is:

\[ \sigma_1 - \sigma_3 = f_t \]

The external forces of a structure are assumed to be unchanged; consequently, the inner stresses of a structure are constant, as are the principal stress \( \sigma_1 \) and \( \sigma_3 \) of every point. If the uniaxial compression and the tensile strength of the material, \( f_c \) and \( f_t \) are used as random variables, then the performance function of the strength failure method is written as follows:

\[ Z = g(f_c, f_t) = f_t f_c + C - \beta f_t \]

The limit state equation is:

\[ Z = g(f_c, f_t) = f_t f_c + C - f_t = 0 \]

If the uniaxial tensile strength \( f_t \) is used as a reference, then the same performance function as Eq. (6) can be obtained. The limit state Eq. (7) applies for each point of the model.

### 2.2. Performance function of shear failure in plane strain problems

According to the description from Section 2.1, the maximum shear stress and the corresponding normal stress are chosen as calculation parameters according to the theory of Mohr-Coulomb, and the other component stresses are not taken into consideration. However, the principal shear stresses of the other two directions have an effect on strength according to the results of mechanical tests [21]; thus, Mohr-Coulomb theory is not applicable to three-dimensional problems.

The principal stresses and the principal shear stresses of a point in plane strain problems are shown in Fig. 2. \( \sigma_1, \sigma_2, \) and \( \sigma_3 \) are the three principal normal stresses; they are the intersections of three stress circles with the \( \sigma \) axis, and the vertices of the three stress circles are principal shear stresses \( \tau_{13}, \tau_{12}, \) and \( \tau_{23} \) and the corresponding normal stresses \( \sigma_{13}, \sigma_{12}, \) and \( \sigma_{23}, \) respectively. The maximum principal shear stress is \( \tau_{13}, \) and the other principal shear stress is \( \tau_{12} \) or \( \tau_{23}; \) the relationship between the three principal shear stresses is \( \tau_{13} = \tau_{12} + \tau_{23} \), according to double-shear strength failure theory. The maximum principal shear stress \( \tau_{13} \) and the secondary principal shear stress \( \tau_{12} \) (or \( \tau_{23} \)) are common factors influencing the yield and failure of material; when the influencing function of the two sets of shearing stresses and the normal stresses on the corresponding surface exceed the critical value, yield or failure occurs.

The mathematical expressions of double-shear strength failure theory are as follows:

\[ Z = \tau_{13} + \beta (\sigma_{13} + \sigma_{23}) = C, \quad \text{when} \quad \sigma_{12} + \beta \sigma_{13} \geq \tau_{13} + \beta \sigma_{23} \]

\[ Z = \tau_{13} + \beta (\sigma_{13} + \sigma_{23}) = C, \quad \text{when} \quad \sigma_{12} + \beta \sigma_{13} \leq \tau_{13} + \beta \sigma_{23} \]

where \( \beta \) and \( C \) are material parameters determined by the uniaxial tensile strength and compressive strength as follows:

\[ \beta = \frac{f_t - f_c}{f_t + f_c} = \frac{1 - \alpha}{1 + \alpha} \]

\[ \alpha = \frac{12}{\beta (1 - \beta)} \]

Note: For interpretation of color in Figs. 1 and 9–12, the reader is referred to the web version of this article.
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