The Impact of Lift Joint on the Mechanical Properties of Cemented Sand and Gravel Material

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Abstract. Cemented sand and gravel (CSG) material is a new kind of geotechnical material. Layered rolling technology is always adopted in the construction of CSG dam, which inevitably creates a weak layer between adjacent CSG material layers. This weak layer is called lift joint. In order to investigate the influence of lift joint on material properties, a discrete micromechanical model of CSG material with lift joint is established based on Lattice Discrete Particle Model (LDPM). Through the three-point bending tests, compression tests and triaxial tests, the parameters for this model are calibrated. Then the impact of lift joint on mechanical properties of CSG material, including compressive, tensile, and shear behavior is studied qualitatively from mesoscopic view. The result shows that the weaker the lift joint is, the lower the material strength is, the more impact of the lift joint on the mechanical properties of CSG material is.

1. Introduction

CSG material is a new kind of geotechnical material. It is made up with sand and gravel, which come from the project site without screening and washing, and mixed with a small amount of cementitious materials (cement, fly ash, etc.) and water. In this way, it can reduce the cost of raw materials as well as reduce damage to the environment. The CSG dam use less cementitious materials, so the hydration heat is reduced and the construction speed is accelerated. With the deepening of research on the material properties and construction process, the CSG material gradually became a new star in the dam material field after roll compacted concrete (RCC). As a new dam type, the CSG dam has been fully recognized and highly appraised by many countries. It is called the "safest dams"[1].

Layered rolling technology is always adopted in the construction of CSG dam, which inevitably creates a weak layer between adjacent CSG material layers. This weak layer is called lift joint. Compared with the CSG material, lift joint is more porous and weaker, which makes it more prone to fracture and seepage damage and reduces the overall mechanical properties of CSG dam. Although there is less research on the properties of lift joint, experience can be drawn from the research of lift joint in RCC.

By comparing the direct shear experiments of normal concrete and RCC under the same circumstances, McLean [2] got the conclusion that the influence of lift joint to the mechanical properties of RCC is greater than that of normal concrete. For the same height dam, the number of lift joints in RCC dams is five times of that in concrete dams, which makes RCC dams more likely to the
phenomenon of level failure [3]. With the experimental researches, Dolen [4] pointed out that the bonding strength of lift joint is related to the mix proportion, the interval time and the level treatment of RCC. Fronteddu [5] focussed on the relation between the shear strength and level treatment method. Martin [6] proved that freezing and thawing cycle is another factor to reduce the shear strength of the lift joint. By water absorbing power method and scanning electron microscopy, Yadong [7] observed that microscopic structure in lift joint is loose and porous than that of other part. Xuezhi [8] and Xiaogang [9] conducted the wedge-splitting test on RCC with lift joint, and obtained the fracture parameters for different lift joints. The elastic modulus, compressive strength, tensile strength and impermeability of RCC with lift joint were also studied with experiments by Changlong [10] and Hongjun [11].

Besides experimental studies, many scholars tried to use numerical simulation to figure out the influence of lift joint. Based on the principle of composite element method, Chen et al. [12] developed the thermal algorithm for the massive concrete containing lift joint, in which the lift joint segments are embedded within the composite elements. Mazloumi, A., et al. [13] used nonlinear seismic analysis to evaluate the seismic safety of RCC dams with lift joints. Yijiang [14] established a mesoscale model of RCC with lift joint, and pointed out that cracks tend to develop firstly from the lift joint. With FEM, Yuwen [15] pointed out that this layer also has impact on the stress distribution. Shu [16] studied the influence of shear parameters of lift joint on the stability of RCC combining annealing algorithm and nonlinear finite element method. Schrader [17] carried out an evaluation method of the construction quality of lift joint in RCC.

In this work, a discrete micromechanical model of CSG material with lift joint is established based on Lattice Discrete Particle Model (LDPM). The impact of lift joint on mechanical properties of CSG material, including compressive, tensile, and shear behavior was studied from mesoscopic view.

2. Discrete Micromechanical Model

A CSG dam can be regarded as a combination of lift joints and normal CSG layers, shown in Figure 1. To investigate the impact of lift joint on mechanical behavior of CSG material, a discrete micromechanical model was built based on LDPM. The LDPM, formulated, calibrated, and validated by Cusatis and coworkers, is a meso-scale discrete model that simulates the mechanical interaction of coarse aggregate pieces. Randomly distributed grains are modeled by a system of polyhedral cells created through generation of meso-structure tessellation. Then parameters represented the properties of lift joint are introduced. Finally, the whole structure is represented by 3D discrete particles. Details of model generation can be found in Cusatis et al [18].

The relationship between stresses and strains are calculated at each facet by the meso-scale constitutive law. Details of the constitutive law can be found in Cusatis et al [18].

In elastic region, the stresses are proportional to the strains.

\[
\begin{align*}
\sigma_N &= E_N \varepsilon_N ; \\
\sigma_M &= E_M \varepsilon_M ; \\
\tau_L &= E_L \varepsilon_L 
\end{align*}
\] (1)

Figure 1. Discrete micromechanical model (S is layered rolling thickness, \(t_m\) is the thickness of lift joint).
where $t_N$ and $\varepsilon_N$ are the normal component of stress and strain, and $t_M, t_L$ and $\varepsilon_M, \varepsilon_L$ are two shear components of stress and strain in each facet. $E_N$ and $E_T$ are the effective normal and shear modulus respectively.

The elastic behavior of lift joint can be acquired by introducing the reduction factors $C_N$ and $C_T$. The normal and shear modulus of lift joint can be expressed as:

$$E_N^b = C_N E_N; E_T^b = C_T E_T$$  \(2\)

Usually the elastic modulus of lift joint is smaller, so $0 < C_N, C_T < 1$ can be obtained, and for the simplicity of the model, it is assumed that $C_N = C_T$, which makes the macroscopic stiffness matrix of lift joint proportional to that of the original material.

For inelastic behavior, there are three different mechanisms to describe the mesoscopic damage mechanics.

(1) For $\varepsilon_n > 0$ (tension or tension/shear)

The effective stress is assumed to be the function of the effective strain.

$$i = E_0 \varepsilon, 0 \leq t \leq \sigma_{ib}(\varepsilon, \omega)$$  \(3\)

where the parameter $\omega$ indicates the interaction degree between shear stress and normal stress $\tan \omega = \varepsilon_N / (\sqrt{\alpha} \varepsilon_t) = \sigma_N \sqrt{\alpha} / \sigma_T$; $\alpha = E_T / E_0$. The boundary $\sigma_{ib}(\varepsilon, \omega)$ is the function of strain.

$$\sigma_{ib}(\varepsilon, \omega) = \sigma_0(\omega) \exp[-H_0(\omega) \left(\varepsilon_{max} - \varepsilon_0(\omega)\right)]$$  \(4\)

where $\left\{x\right\} = \max\{x, 0\}$, $\varepsilon_{max} = \sqrt{\varepsilon_{N, max}^2 + \alpha \varepsilon_{T, max}^2}$, $\varepsilon_{N, max}(t) = \max_{\tau \leq t} \varepsilon_N(\tau)$, $\varepsilon_{T, max}(t) = \max_{\tau \leq t} \varepsilon_T(\tau)$; $H_0(\omega)$ is the softening modulus governing the post peak slope; $\sigma_0(\omega)$ is the strength limit of effective stress.

$$\sigma_0(\omega) = \sigma_i - \sin(\omega) + \frac{\sqrt{\sin^2(\omega) + 4\alpha \cos^2(\omega) / r_s^2}}{2\alpha \cos^2(\omega) / r_s^2}$$  \(5\)

where $r_s = \sigma_s / \sigma_i$, $\sigma_s$ is the shear strength, and $\sigma_i$ is the tensile strength.

The mesoscopic tensile strength and shear strength of lift joint can be defined by a method similar to that used in defining elastic modulus, namely:

$$\sigma_i^b = C_N \sigma_i; \sigma_s^b = C_T \sigma_s$$  \(6\)

The lift joint is usually a weaker area, where cracks firstly generate and expand, so there is $0 < C_N, C_T < 1$.

(2) For strain-hardening behavior (under high confinement pressure)

The normal stress is assumed to be the function of the normal strain.

$$i_N = E_N \varepsilon_N, -\sigma_{ib}(\varepsilon_D, \varepsilon_V) \leq i_N \leq 0$$  \(7\)

The boundary $\sigma_{ib}$ can be described using section function to represent three different mechanical behaviors: pores collapse, densification and rehardening.
Parameters for CSG material can be calibrated according to the following steps:

1. **Material parameters including** Cement content $c$, Water to cement ratio $w/c$, Aggregate to cement ratio $a/c$, MinAggregate size $d_0$, MaxAggregate size $d_a$, and Fuller coefficient $H_F$ can be determined from the real constituents of material. In the experiments, $c = 80kg/m^3$, $w/c = 1.0$, $a/c = 26.6$, $d_a = 40$ mm and the MinAggregate size is set to be a quarter of $d_a$, that is, $d_0 = 10$ mm.

2. **Normal modulus** $E_0$ and Alpha $\alpha$ are relevant to the elastic behavior of material, i.e., $E_0 = E / (1−2\nu)$, $\alpha = (1−4\nu)/(1+\nu)$, $E$ and $\nu$ are macroscopic Young’s modulus and Poisson’s ratio. From the experiments, $E_0 = 800$ MPa and $\alpha = 0.167$ can be calibrated.

3. **The Tensile strength** $\sigma_t$ and Tensile characteristic length $l_t$ are calibrated by simulating the three-point bending tests. The three-point bending tests were performed on $300 \text{ mm} \times 100 \text{ mm} \times 100 \text{ mm}$ beams, and span between two bearing is $240$ mm. During the entire test run, the applied load and the load-line displacement were collected for comparison with the simulation data. The simulated load-displacement curves of best fit compared with the corresponding experimental data are presented in Figure 2 (a). $\sigma_t = 0.55$ MPa and $l_t = 85$ mm can be calibrated.

4. **Shear strength to tensile strength ratio** $\sigma_s / \sigma_t$ is identified from the unconfined compression tests. The unconfined compression tests were performed on $150mm \times 150mm \times 150mm$ cubes. Five specimens were prepared. The test loading speed was controlled by displacement and loaded at a speed of 0.002 mm/s until the specimen was broken. The simulations were conducted following the same setup. Two rigid loading platens were placed on top and bottom of the specimens and the sliding with high friction boundary condition parameters were applied to bond the platens to the specimen surfaces. The macroscopic axial stress and axial strain were calculated as $\sigma_{33} = P/A$ and $\varepsilon_{33} = \Delta L / L$, respectively, in which $P$ is the applied load recorded during the simulations, $A$ represents the initial cross-sectional area of the specimen, $\Delta L$ is the specimen length change, and $L$ is the initial specimen length.
length. The simulated stress-strain curves were compared with experimental data for model calibration. A good fit can be observed in Figure 2 (b). $\sigma_s / \sigma_t = 2.5$ can be calibrated.

(5) Compressive yielding strength $\sigma_{c0}$ and Shear soft modulus ratio are calibrated against the triaxial tests with different confining pressures. In the triaxial tests, experiments were performed on $\Phi 300 \text{mm} \times 700 \text{mm}$ cylinders. The prepared specimens were covered with rubber membrane and placed in a closed pressure vessel. Four different confining pressure values, $\sigma_c = 300 \text{kPa}, 600 \text{kPa}, 900 \text{kPa},$ and $1200\text{kPa}$, were considered. The specimens were first consolidated to the set $\sigma_c$ under hydrostatic equilibrium. The pressure in the vertical direction was applied by a dowel steel in a loading rate of 2 mm/min. The simulations were performed in the same manner. The loading was introduced by applying velocity on the top face and confining pressure on the cylindrical surface. The load and displacement data were recorded, and the axial stress and strain were calculated in the same way as that used for unconfined compression tests. The simulation results of best fit and the experimental data are compared in Figure 2 (c). $\sigma_{c0} = 12 \text{MPa}$ can be calibrated.

(6) Due to lack of experimental data, other parameters are set to the reference value for normal concrete proposed by Cusatis[21], namely, Initial hardening modulus ratio $H_{c0} / E_0 = 0.6$, Transitional strain ratio $\kappa_{c1} = 1.0$, Deviatoric strain threshold ratio $\kappa_{c2} = 5.0$, Initial friction $H_0 = 0.2$, Asymptotic friction $\mu_\infty = 0$, Transitional stress $\sigma_{N0} = 600 \text{MPa}$, Densification ratio $E_d / E_0 = 2.5$, Volumetric deviatoric coupling $\beta = 0$, and Softening exponent $n_t = 0.2$.

Figure 2. Parameter calibration. (a) three-point bending tests; (b) unconfined compression tests; (c) triaxial tests.

In the discrete micromechanical model, parameters for lift joint include layered rolling thickness $S$, the thickness of lift joint $t_m$, reduction factor for elastic modulus $C_N$ and $C_T$, reduction factor for tension $C_{Nt}$ and for shear $C_{Ts}$. In practical engineering, there is no clear boundary between the CSG layer and the lift joint in practice, so it is hard to accurately measure the thickness of the lift joint. It is assumed that the thickness of lift joint $t_m$ is equal to the maximum aggregate size, i.e. $t_m = 4 \text{cm}$.

Because there is little research on the lift joint in CSG material, the influence of lift joint on the behavior of CSG materials can only be qualitative researched. To simplify the simulation, four reduction factors are set to be a same parameter $C$, namely, $C_N = C_T = C_{Nt} = C_{Ts} = C$. The lift joint is simply divided into three categories: weak layer, weaker layer and weakest layer. For the weak lift joint, it is set that $C = 0.9$. For weaker lift joint, it is set that $C = 0.7$. For weakest lift joint, it is set that $C = 0.5$.

4. Numerical modeling

In this section, $\Phi 300 \text{mm} \times 600 \text{mm}$ cylinder which contains one lift joint was adopted to model
uniaxial compression test, Brazilian disk splitting tests and triaxial test. The impact of coefficient $C$ and incline angle $\theta$ of lift joint on the mechanical properties of CSG material is studied qualitatively. Incline angle $\theta$ is defined as the angle between the loading direction and the normal direction of lift joint. It is set to be $0^\circ$, $15^\circ$, $30^\circ$, $45^\circ$, $60^\circ$, $75^\circ$ and $90^\circ$, respectively.

4.1. Compressive behavior

By simulating the uniaxial compression test, the impact of lift joint on the compressive behavior of CSG material is studied. The specimen is shown in Figure 3. Two rigid loading platens were placed on top and bottom of the specimens and the sliding with high friction boundary condition parameters were applied to bond the platens to the specimen surfaces. The macroscopic axial stress and axial strain were calculated as $\sigma_{33}=P/A$ and $\varepsilon_{33}=\Delta L/L$, respectively, in which $P$ is the applied load recorded during the simulations, $A$ represents the initial cross-sectional area of the specimen, $\Delta L$ is the specimen length change, and $L$ is the initial specimen length. The peak stress is regarded as the compressive strength of the specimen, recorded as $\sigma_{bc}$.

![Figure 3](image)

Figure 3. Cylindrical specimens in the uniaxial compression tests. (a) incline angle $\theta$, (b) specimen in 3D, (c) longitudinal section in center plane

![Figure 4](image)

Figure 4. $\sigma_{bc}-\theta$ curves for different $C$

$\sigma_{bc}-\theta$ curves for different $C$ are shown in Figure 4. For $C=0.9$, the compressive strength is almost constant with the increasing of $\theta$. For smaller value of $C$, compressive strength decreases first and then increases with the increase of $\theta$, and it achieves the minimum value when $\theta$ is between $45^\circ$ to $75^\circ$. When $\theta$ is in this region, there is larger difference in compressive strength for different coefficient $C$. When $\theta=60^\circ$ and $\varepsilon_{33}=0.7\%$, the crack opening for different $C$ is shown in Figure 5. With the increase of coefficient $C$, the maximum crack opening width decreases gradually, and the failure modes are not the same. For smaller coefficient, the main failure mode is the sliding failure, and it eventually forms a major crack along the lift joint. For larger coefficient, the crack is almost parallel to
the loading direction, the properties of lift joint has less influence on the compressive behavior of CSG material.

4.2. Tensile behavior

By simulating the Brazilian disk splitting tests, the impact of lift joint on the tensile behavior of CSG material is studied. The specimen is shown in Figure 6. In the simulation, the bottom steel plate is fixed, and the load is applied through the top steel plate. The applied load $P$ and the radial deformation $ΔD$ were monitored. The macroscopic axial stress and axial strain were calculated as $σ=2P/(πDL)$ and $\varepsilon=ΔD/D$, respectively, in which $L$ is the initial specimen thickness, and $D$ is the initial specimen diameter. The peak stress is regarded as the tensile strength of the specimen, recorded as $R_m$.

$R_m - θ$ curves for different $C$ are shown in Figure 7. For the same $θ$, the value of $R_m$ decreases with the decrease of the coefficient $C$. The larger the coefficient $C$, the smaller rangeability of the $R_m - θ$ curve. For the same coefficient $C$, $R_m$ decreases as the increases of $θ$, and it achieves the minimum value when $θ=90°$. This is due to the fact that when $θ$ is small, the cracks first appear in the loading direction. The tensile strength is mainly determined by the properties of the CSG material, and the influence of lift joint is limited. The failure mode is a major crack along the loading direction. As the increase of $θ$, in addition to cracks in the loading direction, there will be fracture along the lift joint. when $θ=90°$, lift joint coincides with loading direction, the tensile behavior of the material is totally determined by the properties of the lift joint. When $θ=0°$ and $ε=0.5%$, the crack opening for different $C$ is shown in Figure 8. The major crack is along the loading direction. However, in the case of a small coefficient $C$, there will be cracks along the lift joint. With the increase of coefficient $C$, the maximum crack opening width decreases gradually.
4.3. Shear behavior

By simulating the triaxial tests, the impact of lift joint on the shear behavior of CSG material is studied. The model is the same as that in Figure 3. Four different confining pressure values, $\sigma_c = 300$ kPa, $600$ kPa, $900$ kPa, and $1200$ kPa, were considered. The specimens were first consolidated to the set $\sigma_c$. The loading was introduced by applying velocity on the top face and confining pressure on the cylindrical surface. The load and displacement data were recorded, and the axial stress $\sigma_{33}$ and strain $\varepsilon_{33}$ were calculated in the same way as that used for unconfined compression tests. The maximum value of $\sigma_{33}$ is recorded as $q_m$.

When $C=0.5$, for different $\sigma_c$, $q_m-\theta$ curves are shown in Figure 9. These curves are almost paralleled. With the increase of $\theta$, $q_m$ decreases first, and then increases gradually. It obtains the minimum value when $\theta = 60^\circ$. According to Mohr-Coulomb rule, the relation between the peak stress
\[ q_m = \frac{2c \cos \phi + 2\sin \phi \sigma_c}{1 - \sin \phi} \]  

(10)

where, \( c \) is the cohesive strength; \( \phi \) internal friction angle.

The value of \( c \) and \( \phi \) for different \( \theta \) is listed in Table 1. As the increasing of \( \theta \), the value of \( \phi \) is always around 30° and \( c \) obtains the minimum value when \( \theta = 60° \). When \( \varepsilon_{33} = 5.4\% \), the crack opening for \( \theta = 0°, 60° \) and 90° is shown in Figure 11. The final failure mode is almost independent of the lift joint for \( \theta = 0° \) and 90°. However, for \( \theta = 60° \), it forms a main crack along with the lift joint. The strength of the lift joint is crucial to the properties of material.

| \( \theta (°) \) | 0   | 15  | 30  | 45  | 60  | 75  | 90  |
|-----------------|-----|-----|-----|-----|-----|-----|-----|
| \( c \) (kPa)   | 914.9 | 916.6 | 922.6 | 924.7 | 822.5 | 833.2 | 891.9 |
| \( \phi \) (°)  | 30.2 | 30.1 | 29.7 | 28.5 | 29.7 | 30.5 | 30.0 |

Figure 11. Crack opening (m) (\( \varepsilon_{33} = 5.4\% \), \( C = 0.5 \)). (a) \( \theta = 0° \); (b) \( \theta = 60° \); (c) \( \theta = 90° \).

When \( \sigma_c = 300kPa \), for different \( C \), \( q_m - \theta \) curves are shown in Figure 10. For \( C = 0.9 \), \( q_m \) is almost constant with the increasing of \( \theta \). For smaller value of \( C \), \( q_m \) decreases first and then increases with the increase of \( \theta \), and it achieves the minimum value when \( \theta = 60° \). And for the same \( \theta \), the larger the coefficient \( C \), the greater \( q_m \) decreases with the increase of the coefficient \( C \). The crack opening when \( \theta = 60° \) and \( \sigma_c = 300kPa \) for different \( C \) is shown in Figure 12. When the coefficient is small, a major crack along with the lift joint is formed when the specimen is destroyed. With the increase of \( C \), the maximum crack opening width decreases gradually, and the position of the major crack is no longer located in the lift joint. This shows that the worse the properties of the lift joint are, the greater its impact on the shear behavior of the CSG material is.

| \( \theta (°) \) | Shear parameters | \( C = 0.5 \) | \( C = 0.7 \) | \( C = 0.9 \) |
|-----------------|-----------------|----------------|----------------|----------------|
| 0               | \( c \) (kPa)   | 914.9          | 951.7          | 973.5          |
|                 | \( \phi \) (°)  | 30.2           | 30.3           | 30.4           |
| 60              | \( c \) (kPa)   | 822.5          | 919.9          | 964.5          |
|                 | \( \phi \) (°)  | 29.7           | 30.1           | 30.4           |
5. Conclusion

In order to investigate the influence of lift joint on material properties, a discrete micromechanical model of CSG material with lift joint is established based on Lattice Discrete Particle Model (LDPM). Through the three-point bending tests, compression tests and triaxial tests, the parameters for this model were calibrated. Then the impact of lift joint on mechanical properties of CSG material, including compressive, tensile, and shear behavior, was studied from mesoscopic view. The results are shown as follow:

(1) By simulating the uniaxial compression test, the impact of lift joint on the compressive behavior of CSG material is studied. The weaker the lift joint is, the lower the compressive strength is, the more impact of the lift joint on the compressive behavior of CSG material is. For strong lift joint, the compressive strength is almost constant with the change of incline angle. For weak lift joint, compressive strength decreases first and then increases with the increase of incline angle. It achieves the minimum value when incline angle is between 45° to 75°.

(2) By simulating the brazilian disk splitting tests, the impact of lift joint on the tensile behavior of CSG material is studied. The weaker the lift joint is, the lower the tensile strength is, the more impact of the lift joint on the tensile behavior of CSG material is. Tensile strength decreases as the increases of incline angle, and it achieves the minimum value when the direction of lift joint coincides with loading direction.

(3) By simulating the triaxial tests, the impact of lift joint on the shear behavior of CSG material is studied. The weaker the lift joint is, the lower the peak strength and cohesive strength is, the more impact of the lift joint on the shear behavior of CSG material is. For strong lift joint, the peak strength is almost constant with the change of incline angle. For weak lift joint, peak strength decreases first and then increases with the increase of incline angle. It achieves the minimum value when incline angle is around 60°.

Because there is little research on the lift joint in CSG material, the influence of lift joint on the behavior of CSG materials can only be qualitative researched. In the future, experiment researches on CSG material with lift joint should be carried out to verify the results in this article.

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