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Experimental study on uniaxial compression of sandstone-mudstone interbedded rock mass

Lin Zhong

Department of Railway Engineering, Sichuan College of Architectural Technology, Chengdu, 610399, China

Abstract: *FLAC3D software is used to simulate sand-mudstone interbedded rock mass in various conditions, and the results of its regularity are obtained. The similarity between uniaxial simulation and theoretical results is more than 99%.*

Keywords: *FLAC3D; simulation; surface; sand-mudstone*

1. Introduction

The study of vertical bearing capacity of sandstone-mudstone interbedded rock mass is carried out by means of uniaxial compression test, however, the sampling of sand-shale interbedded rock mass with inclined interface is very difficult, and the samples taken are usually at the same dip angle of structural plane. The other direction is to study the material ratio of sand-shale interbedded rock mass by studying the material ratio of sand-shale interbedded rock mass, the material with similar physical and mechanical properties is selected to cast the mixture, and then the experiment is carried out. There are obvious deficiencies in these two directions. The study on bearing capacity of sand-shale interbed is not complete by in-situ rock sample test, and the correctness of test results cannot be guaranteed by using mixture test.

2. Methodology

2.1 Brief introduction of FLAC3D software and its contact surface model

FLAC3D is a three-dimensional explicit finite difference program for applied mechanics computation. The explicit Joseph-Louis Lagrange computational scheme and hybrid discretization partitioning techniques used in FLAC3D ensure that plastic collapse and flow modeling are very accurate because there is no matrix formation, therefore, it is possible to perform large-scale three-dimensional computations without excessive storage requirements, through automatic inertial scaling and automatic damping that does not affect failure modes, it can overcome the disadvantages of the explicit formula (i. e. the problem of limited time step and required damping). The software has built-in fish language. The user can modify the software with fish language to make the calculation of the numerical model more accord with the engineering practice. FLAC3D provides an ideal analytical tool for solving three-dimensional problems in geotechnical engineering.

FLAC3D provides 12 constitutive models for solving various geotechnical problems. The mohr-Cullen constitutive model is the most universal constitutive model in geotechnical mechanics. The Maurs-coulomb strength envelope is taken as the yield line, and the stress lord angle is applied to the three-dimensional stress space, which is an ideal elastoplastic model. When the stress in the soil is less than the yield surface, the soil is elastic deformation, and when the stress in the soil is greater than the yield surface, the stress in the soil exceeds the yield point, and the soil is plastic deformation. The parameters of the mohr-coulomb constitutive model include Siméon Denis Poisson ratio (μ), elastic modulus (E), cohesion (c) and internal friction angle (φ). The four parameters above are used to calculate the shear modulus (g) and bulk modulus (K) of FLAC3D, where the shear modulus (g) is used to indicate the shear deformation resistance of rock and soil after loading, the volumetric modulus (K) is used to express the resistance of rock and soil to volumetric deformation after loading. For the contact problems of different materials such as interbedded rock, pile-soil, pile-rock, FLAC3D provides a contact surface model that satisfies the moore-Cullen constitutive model and assumes that the contact surface has no thickness. The contact surface element is formed by a series of triangular

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elements and contact surface nodes, as shown in Fig. 1.

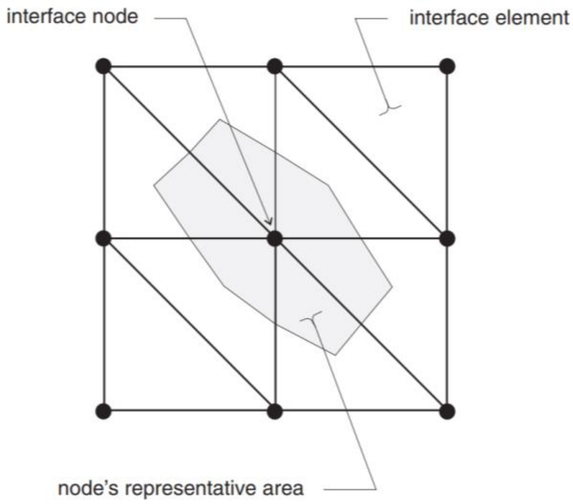

Figure 1: The contact surface represents the region and node distribution

The working principle of the contact surface is shown in figure 2. In FLAC3D, the contact surface is one-sided, and the contact surface is built between two entities. The contact surface can be regarded as a “Contraction belt”, and can be stretched on the designated surface, so that the contact surface and the entity unit surface are fully extruded, thus, the contact surface element and two solid surfaces are connected by using the contact surface node.

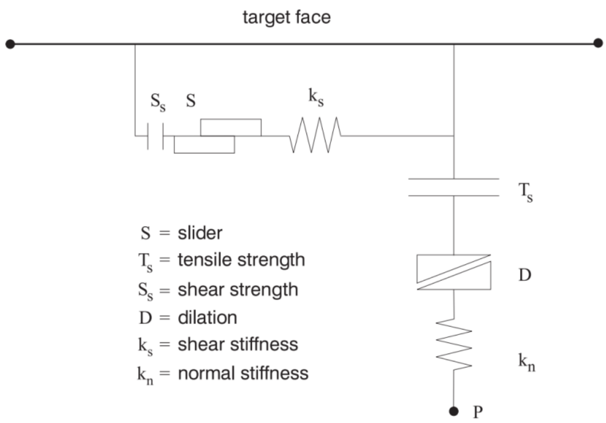

Figure 2: Schematic diagram of FLAC3D contact surface

At the time t+Δt, the normal and shear forces at the contact surface are calculated by the following relation:

$$F_n^{(t+\Delta t)}=k_n u_n A + \sigma_n A \tag{1}$$

$$F_{si}^{(t+\Delta t)}=F_{si}^{(t)} + k_s \Delta u_{si}^{(t+(\frac{1}{2})\Delta t}A + \sigma_{si} A \tag{2}$$

Formula: $F_n^{(t+\triangle t)}$——$t+\triangle t$ time normal force vector, unit N;

$F_{si}^{(t+\triangle t)}$—— $t+\triangle t$ time tangential l force vector, unit N;

u_n——The absolute displacement of the contact surface node penetrating the target surface, unit m;

$\triangle u_{si}$——Relative shear displacement increment vector, unit m;

σ_n——Additional normal stress at contact surface, unit Pa;

σ_{si}——Additional tangential stress at the interface, unit Pa;

k_n——Normal shear stiffness of contact surface, unit Pa/m;

k_s——Tangential shear stiffness of contact surface, unit Pa/m;

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A——The area represented by the contact surface nodes, units m^2.

The maximum shear force is controlled by the mohr-Cullen strength criterion and is calculated as follows:

$$F_{smam} = cA + \tan \emptyset \,(F_n - pA) \tag{3}$$

Formula: *c*—The cohesion of the contact surface;

φ—The friction angle of the contact surface

p—Void pressure

As shown in figure 3, sample commands are provided to illustrate each analysis step. To model the simulation using FLAC3D, you must specify the three basic components of the problem:

(1) finite difference mesh;

(2) constitutive behavior and material properties;

(3) boundary conditions and initial conditions.

The mesh defines the geometry of the problem, and the constitutive model and associated material properties determine the type of response the model will display when disturbed (for example, deformation response due to excavation) , the boundary condition and the initial condition define the in-situ state (that is, the condition before introducing the change or interference of the problem state).

After these conditions are defined in FLAC3D, the initial equilibrium state is calculated for the model. Changes are then made (for example, mining material or changing boundary conditions) and the final response of the model is calculated. For an explicit finite-difference program like FLAC3D, the actual solution to the problem differs from the traditional implicit solution. FLAC3D uses an explicit time-forward method to solve algebraic equations. The solution is found after a series of computational steps. In FLAC3D, the number of steps required to reach a solution can be controlled either by the code or by the user manually, but ultimately the user must determine whether the number of steps is sufficient to reach the solution state.

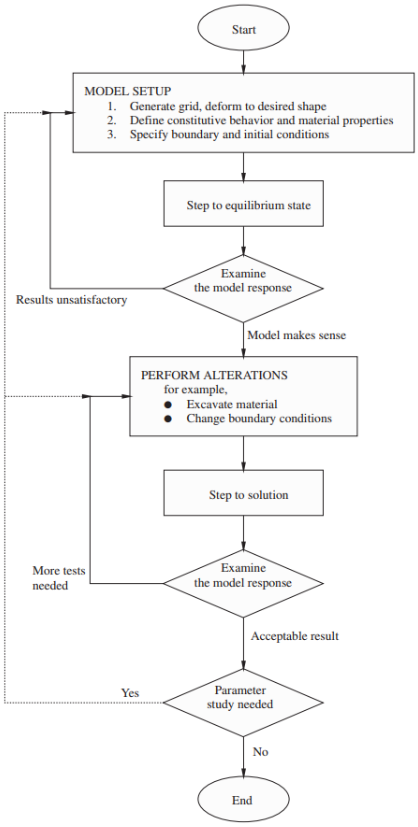

Figure 3: Flow chart of simulation calculation

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2.2 Modeling and parameter selection of sand-mudstone interbedded rock mass

Due to the different physical and mechanical parameters of sandstone-mudstone interbedded rock mass in different areas, in order to select better simulation parameters, this paper investigates and studies many literatures, the physical and mechanical parameters of sandstone-mudstone and sandstone-mudstone interbed in 6 related researches are calculated. The concrete parameters are shown in table 1.

Table 1: Statistical table of mechanical parameters of sand-mudstone interbeds

Author	Rock type	Young's Modulus/MPa	Poisson's ratio	cohesion/kPa	Angle of internal friction/	D/ kg/m^3	Kn/ GPa	Ks/ GPa
Ma Furong[1]	Mudstone	11	0.38	32	11	1.85	-	-
	Sandstone	22	0.26	355	34	2.2	-	-
Zhou Yong[2]	Sandstone	233	0.26	41	38.8	2.3	-	-
	Mudstone	7.83	0.28	28	22.4	1.94	-	-
	Structural plane	5.61	0.31	24.5	11	20.5	-	-
Dong Jinyu[3]	Mudstone	4000	0.3	300	32	2.35	-	-
	Sandstone	-	-	-	-	2.5	-	-
	Structural plane	-	-	100	25	-	1	0.1
He chunmei[4]	Mudstone	19.1	0.42	200	41.8	2.22	-	-
	Sandstone	4200	0.3	4000	33	2490	-	-
	Structural plane	-	-	2	15	-	2	1
Kang Jin Tao[5]	Mudstone	582.184	0.311224	2280	34.8	2258.79	-	-
	Sandstone	9194	0.22588	10100	45.1	2596.06	-	-
	Structural plane	-	-	45	27	-	5.2	0.68
Cao Yungang[6]	Structural plane	-	-	6.5	24.62	-	-	-

By collecting and analyzing the structural plane parameters of sand-mudstone and sand-mudstone interbedded in literature, the most complete structural plane parameters of sand-mudstone and sand-mudstone interbedded in this paper are determined as shown in table 2.

Table 2: The parameters of numerical simulation of rock and discontinuity

	c/MPa	φ/°	G/GPa	K/GPa	D/kg/m^3
Mudstone	2.28	34.8	0.222	0.514	2258.79
Sandstone	10.1	45.1	3.75	5.59	2596.06
-	-	-	Kn/GPa	Ks/GPa	-
Structural plane	0.045	27	5.2	0.68	-

The related calculation steps of numerical simulation of uniaxial compression tests of sandstone-mudstone interbedded discontinuities are as follows:

(1) The FLAC3D model was used to establish the uniaxial compression test model, and the test model was assigned to the Moore-cullen model, and then the basic mechanical parameters of sand-mudstone and interbedded structural plane were assigned to the test model.

(2) Define the analysis step. The uniaxial compression simulation test consists of two steps, namely, the analysis step of in-situ stress balance and the analysis step of applying vertical load. FLAC3D analysis step will judge whether the initial stress and the corresponding load, boundary conditions between the balance, so as to simulate the initial state, after in-situ stress balance, then will return to zero displacement, re-value parameters, impose vertical load.

(3) Define boundary conditions. Constraint boundary is an indispensable condition in simulation. If there is no boundary condition, the whole model will produce displacements under the action of external force, which will reduce the accuracy of simulation results. Only the vertical displacement at the bottom of the model is defined, and then the vertical displacement at the top of the model is defined after the earth stress is balanced. The load is divided into force load and displacement load. In this paper, a more accurate displacement load is selected to be applied.

(4) Set the time step and stop the calculation when the time step reaches the limit. Because the simulation conditions are different, the time step required is also different. The total time step is between 100,000 and 2,500 steps.

(5) Export the recorded data and curves for careful analysis.

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2.3 Verification of uniaxial compression test scheme for sandstone-mudstone interbedded rock mass

Many scholars have also done a lot of rock uniaxial compression test simulation, but many have not carried on the reasonable verification to its simulation test. For the sake of the correctness of the uniaxial compression simulation test of sandstone-mudstone interbedded rock mass, especially the comparison between the uniaxial simulation test of sandstone-mudstone interbedded rock mass with single structural plane under ideal condition and the theoretical formula [53] is made in this paper, see equations 4 and 5.

$$k = 1 + \tan(\varphi j)\tan(\beta) \tag{4}$$

β is the angle between the vertical direction and the structural plane, is the angle of friction in the structural plane, as shown in Formula 4, the stress of rock mass before failure is isotropic. When k > 0, the structural plane begins to fail, and the compressive stress conforms to the mohr-coulomb failure criterion.

$$\sigma_1 = \frac{-2cj}{k\sin(2\beta)} \tag{5}$$

Formula 5: Cohesion of structural plane

σ1: peak stress

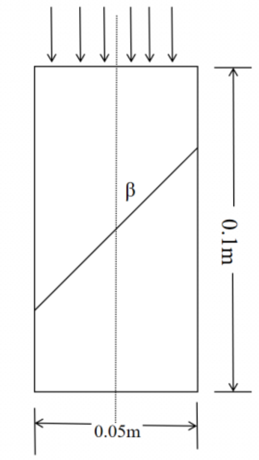

Figure 4: Stress diagram of interbedded rock mass under uniaxial test

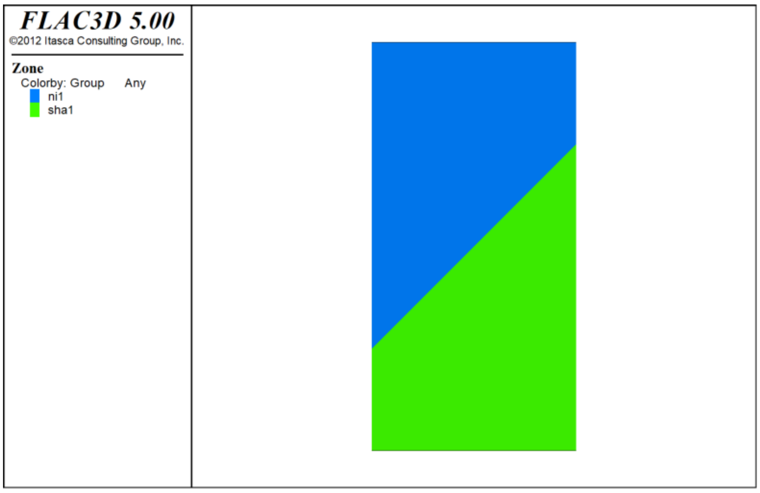

Figure 5: The calculation model of single structural plane with inclination angle of 45 °

Simulation test scheme for uniaxial compression of sandstone-mudstone interbedded rock mass:

According to GB/T 50266-2013, rock samples should be made into standard rock samples with diameter of 50mm and height of 100mm, but in order to better divide the grid and calculate the

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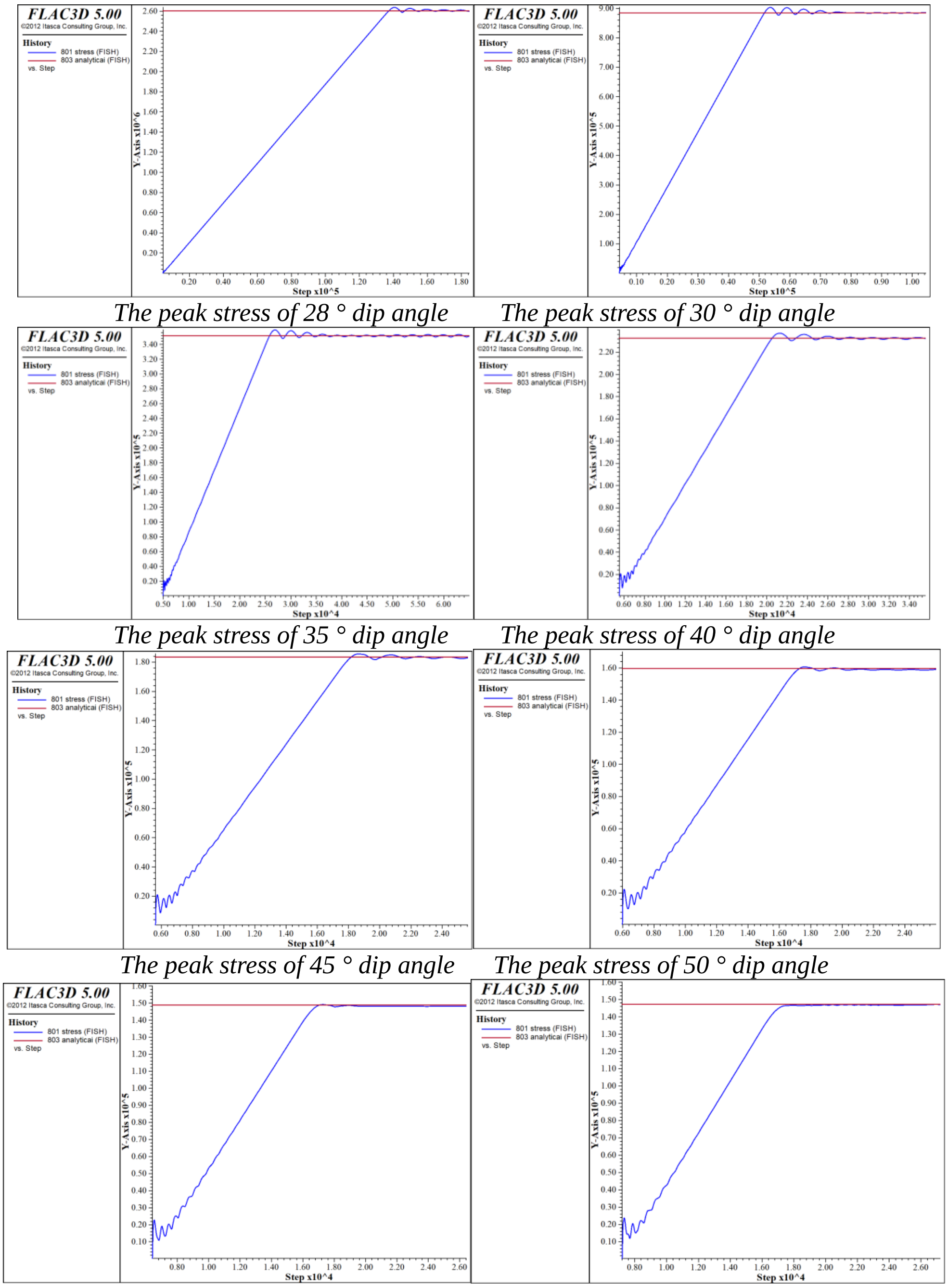
structural area, by simulating the uniaxial compressive behavior of sandstone-mudstone rock mass with a single structural plane, the simulated size is determined as 0.05m×0.05m×0.1m square column, ni1 as mudstone, sha1 as sandstone, mudstone and sandstone, the simulation model is divided into 10 grids along the x-axis, 10 grids along the y-axis and 20 grids along the Z-axis, as shown in figure 4 and figure 5. According to the requirement of $K > 0$ in formula 1,8 angles (28°, 30°, 35°, 40°, 45°, 50°, 55°, 60°) are selected for verification. The rock mass parameters for simulating uniaxial compressive strength tests are those in table 2. The simulation results and their comparison with the calculated values of the theoretical formula are shown in Fig. 6.



The peak stress of 28 ° dip angle *The peak stress of 30 ° dip angle*

The peak stress of 35 ° dip angle *The peak stress of 40 ° dip angle*

The peak stress of 45 ° dip angle *The peak stress of 50 ° dip angle*

The peak stress of 55 ° dip angle *The peak stress of 60 ° dip angle*

Figure 6: The compressive stress curves and theoretical values of each dip angle

3. Results and Discussion

In figure 6, for each dip, the “stress” curve is the stress recorded by fish on the top of the sandstone-mudstone interbedded rock mass, and the “analyticai” line is the theoretical value calculated

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by formula 1,2, from Fig. 6, it can be seen that the stress curve “stress” of sand-mudstone interbedded rock mass with different dip angles shows linear growth at the initial stage, and when the calculation reaches a certain time step, the stress curve “stress” of sand-mudstone interbedded rock mass with different dip angles shows linear growth at the initial stage, the curve shows a small and negligible fluctuation near the calculated value. After a certain amount of time, it tends to be a straight line parallel to the x-axis, and the second half of the “stress” line basically coincides with my theoretical “analyticai” line. In order to more accurately compare the uniaxial compressive strength calculated by FLAC3D software with the calculated values. The exact values of the curve “stress” and “analyticai” are listed in table 3, and the approximate values of the two values can be found more intuitively by comparing the sizes of the two values in table 3, the ratio of the strength value to the theoretical value of the structural plane dip angle of all the simulated sand-shale interbedded rock masses is more than 99%, which proves the correctness of the uniaxial compression test scheme adopted in this paper.

Table 3: Comparison of simulated and theoretical strength values of sandstone-mudstone interbedded rocks with different dip angles

	28°	30°	35°	40°	45°	50°	55°	60°
Analog numerical value (Pa)	2598502	885413	350912	232375	182700	159024	148034	147069
Theoretical value (Pa)	2601975	884632	351701	232676	183496	159642	148899	147236
Compare values	99.87%	100.09%	99.78%	99.87%	99.57%	99.61%	99.42%	99.89%

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