A numerical study on Flow Regime Process of Liquefiable Cargo based on Finn Constitutive Model

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Abstract: The safe transportation of liquefiable cargo is an important topic in the research on modern transportation safety of watercraft. The current study on this topic is mainly focused on the research after the liquefiable occurs. A numerical analysis model for the liquefiable of flowing particles is established using the Finn liquefiable constitutive relation, and the kinetic equation analysis module of finite difference method is adopted to analyze the liquefiable problem. The result shows that applying the Finn constitutive model to the analysis of liquefiable of flowable cargo can better predict the increase of pore water pressure and decrease of effective stress under the action of external load.

1.Introduction:
The liquefiable cargo is a kind of very special bulk solid cargo and in the process of liquefiable cargo at sea, due to the small particle size of liquefiable cargo, its water permeability is relatively poor. Under the assumption of no water drainage, the cargo becomes dense due to the sinking due to external loads such as wind and waves. The failure to drain the interpore water among the particles of cargos results in increased pore water pressure and decreased effective stress [12]. If the cargo in this state continues to be subjected to an external load, when the water content exceeds the specified value of IMSBC, the flow of the liquefiable cargo occurs. The accident of liquefiable happens suddenly with huge hazard and large difficulty in rescuing.

The most representative category of the liquefiable cargo is the laterite nickel ore, which essentially belongs to soil. Currently the shipping interests are mainly studying the ship's transportation security for the liquefiable-prone cargo from following aspects: One is analyzing the flow regime phenomenon of cargo from the perspective of ship supervision and control. For example, Zhao Yabin et al. analyzed the concrete risk factors for the liquefiable-cargo in the ship and determined the possibility of risk, to facilitate the maritime authority's direction according to the inspection and analysis of marine surveying, so as to prevent the accident when the ship transports the liquefiable cargos [7], etc. Another is taking the study from the aspect of soil mechanics. For example, Wang Wenshao studied the liquefiable mechanism of soil from the aspects of stress condition when the soil liquefies and the stress evolution in liquefying, etc. [8].

The Finn liquefiable constitutive relation is used to establish a numerical analysis model and the dynamic equation analysis module of finite difference method is adopted. It is found that applying the Finn constitutive model to the analysis of liquefiable of flowable cargos can better predict the change of pore water pressure and effective stress under the action of external load.
2. liquefiable mechanism of soil
The saturated sand soil will largely deform when its shearing force tapers due to increased pore water pressure owing to thickened components under the reciprocating dynamic stress, coupled with appearing of water and sandblasting, etc., which is called liquefiable\(^3\). According to the principle of effective stress, the shearing strength of soil mass can be expressed as:

\[
\tau_f = \sigma' \tan \varphi = (\sigma - \mu) \tan \varphi
\]  \hspace{1cm} (1)

Where, \(\tau_f\) is the shearing strength, \(\sigma'\) is the effective normal stress, \(\varphi\) is the angle of internal friction, \(\sigma\) is the normal stress on the failure plane, \(\mu\) is the pore water pressure.

The ore sand usually has a very firm internal structure in the stable state, and now the effective stress is equal to the total stress, while in a vibrating state, the pore water pressure bears the force originally assumed by the sand framework, which results in increased pore water pressure, thereby reducing the effective stress.

3. Finn liquefiable constitutive model
FLAC3D can be used to make a coupling analysis of dynamic and vadose to simulate the accumulation of pore pressure of sand soil under the dynamic action till liquefiable of the soil mass. FLAC3D provides two formulae for plastic volumetric strain increment, including the Finn mode and the Byrne mode. This accumulated effect is described using the Finn model herein. which model essentially adds the rise mode of dynamic pore pressure to the Mohr-coulomb model.

Martin et al. proposed the Finn model to solve the volumetric strain and change of pore water pressure under the cyclic loading action according to the experimental result, finding that the relation between plastic volumetric strain and cyclic shear strain amplitude is not related to the consolidation pressure\(^4\). In the real application, the plastic volumetric strain increment \(\Delta \varepsilon_{vd}\) is only a function of total accumulated volumetric strain \(\varepsilon_{vd}\) and shear strain \(\gamma\).

\[
\Delta \varepsilon_{vd} = C_1 (\gamma - C_2 \varepsilon_{vd}) + \frac{C_3 \varepsilon_{vd}^3}{\gamma + C_4 \varepsilon_{vd}}
\] \hspace{1cm} (2)

Wherein, Martin regressed the experimental data to derive that \(C_1, C_2, C_3, C_4\) are constants. The most standard values are \(C_1 = 0.80, C_2 = 0.79, C_3 = 0.45, C_4 = 0.73\). \(\gamma\) is the shear strain, \(\varepsilon_{vd}\) is the volumetric strain. \(\Delta \varepsilon_{vd}\) is the increment of volumetric strain.

As the basic model of the Finn model is Mohr-Coulomb mode, the parameters of Finn model comprise all the parameters of Mohr-Coulomb, such as bulk modulus, shear modulus, frictional angle, etc.

The dynamical analysis module of FLAC3D software is adopted to apply the Finn model to numerical analysis and calculation to more effectively reflect the change rule of increase in pore water pressure and decrease in effective stress under the action of external load.

4. Numerical simulation

4.1 Computation model and parameters
A 3D model is established, with a height of 8m, a width of 10m and a length of 32m. The schematic diagram of numerical simulation grid for liquefiable analysis is shown in Fig.1. Wherein, the monitoring points are four, being a \((16,5,0)\) b \((16,5,2)\) c \((16,5,4)\) d \((16,5,6)\) respectively. The time-variation of the pore water pressure and effective stress of this unit under the action of dynamic load is recorded.
The property parameters of the laterite nickel ore are as shown in Table.1 according to the repeated dynamic load triaxial tests \[11\], and the local damping is adopted. The coupling mode considers the coupling of dynamic and vadose.

| Internal friction angle | Dry density          | Elastic modulus | Shear modulus | Poisson ratio | Permeability |
|-------------------------|----------------------|-----------------|---------------|---------------|--------------|
| 37.89°                  | 2.75x10³ kg/m³       | 12.8 MPa        | 4.26 MPa      | 0.3           | 10⁻⁹         |

4.2 Input of dynamic

The elastic model is used in the calculation to make the liquefiable cargo reach a balance under the gravity action to derive the initial stress field, then a sinusoidal velocity boundary is applied to the horizontal direction (X-direction) of bottom and two sides of the model to enable the rolling motion of ship. The peak acceleration reaches 0.2g within 2s, and has stepped down since 15s, reaches 0 at 17s. The action time is 20s. The acceleration-time curve of input external load input in calculation is as shown in Fig.2.

4.3 Calculation process

The rationale of the FLAC3D software is the Lagrangian difference method. The Lagrangian method is a numerical method that drags the coordinate system to analyze the large deformation problem.

1. The initial node velocity determines the new rate of strain, strain increment and rotation rate. (2) The unit stress increment and the new one are calculated on the constitutive equation. Under the mode of large deformation, the stress increment must be calculated via the constitutive equation and the rotation stress increment must be corrected. (3) Obtaining the mass of node, unbalanced force and damping force (The damping needs to be introduced in the solving of the static problem to make the system gradually decay to a steady state), can then obtain the new node velocity. The motion equation of node is determined by the Newton's second law. The node mass is equal to the sum of mass of multiple neighboring units agglomerated to this node. The unbalanced force of node is equal to the contribution of the neighboring units to the unbalanced force of node and the sum of external force received by the node.
5. Analysis of simulation results

Fig. 3 and Fig. 4 respectively represent the change of pore water pressure at monitoring points a-d, and the change of effective stress at monitoring points a-d. It is observed from the figures above that the pore water pressure increases with the increase of time, while the effective stress reduces to 0 with time increase. In Fig. 3, the pore water pressure steps down, from which it is judged that the pore water pressure is largest on the bottom layer of the model and smallest on the top layer, while the effective stress at this moment reduces to 0. This conforms to the regulation that pore water pressure increases and effective stress reduces to 0 in the definition of liquefiable in the soil mass liquefiable theory, so it can be judged that the cargo begins to liquefy at this moment.

6. Conclusion

The finite difference method program FLAC3D to analyze the change of pore water pressure and effective stress of liquefiable cargo under the action of external load according to the Finn liquefiable constitutive model, and takes the increase of pore water pressure being accompanied with the reduction of effective stress to 0 as the distinguishing mark for liquefiable, with main conclusions as shown in the following:

1. Applying the Finn liquefiable constitutive model to the numerical analysis and calculation can well reflect the change rule of pore water pressure and effective stress of laterite nickel ore when the external load acts on the laterite nickel ore, i.e. the increase of pore water pressure is accompanied with the reduction of effective stress to 0.

2. The pore water pressure and effective stress are changed sharply in early period when the external load acts on the ore, indicating that the initial stage of occurring of external load witnesses the most significant change of liquefiable cargo.

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