Proc. of the 9th International Symposium on Geotechnical Safety and Risk (ISGSR)
Edited by Zhongqiang Liu, Jian Dai and Kate Robinson
Published by Research Publishing, Singapore.
doi: 10.3850/GRF-25280825_isgsr-206-P239-cd

CYCLIC DYNAMIC CHARACTERISTICS OF GASSY CLAY : EXPERIMENTS, BOUNDING SURFACE MODEL AND SIMULATION

Xuanyu Chen
PowerChina Huadong Engineering Corporation Limited, China;College of Harbour, Coastal and Offshore Engineering, Hohai University, China. E-mail: chen_xy24@hdec.com

Kanming Shen
PowerChina Huadong Engineering Corporation Limited, China.E-mail: shen_km@hdec.com

Yi Hong
College of Civil Engineering and Architecture, Zhejiang University, China.E-mail: yi_hong@zju.edu.cn

Rui He
College of Harbour, Coastal and Offshore Engineering, Hohai University, China. E-mail: herui@hhu.edu.cn

Shenzhou Yi
Zhejiang Huadong Geotechnical Investigation & Design Institute Corporation Limited, China.E-mail: yi_sz@hdec.com

Abstracts: Fine-grained gas marine sediments are widely distributed all over the world. Due to the existence of large gas bubbles, the structure of the soil have been altered which have significant influence on the instability of offshore structures and the occurrence of submarine landslides. However, the existing constitutive models mainly focus on the response of saturated soil under cyclic loading and the response of gassy soil under monotonic loading. To understand the cyclic characteristics of gassy soils, a bounding surface elastoplastic constitutive model is proposed based on the cyclic triaxial test results and critical state soil mechanics. The proposed model has the following three characteristics: (1) The elastic stiffness of soil is modified by intergranular strain theory to make it closer to the stiffness shown in the test, which can also reflect the sudden change of stiffness when the loading direction changes. (2) The variable shape bounding surface equation is used to describe the stress path under different combinations of initial pore pressure and gas content. At the same time, the relationship between the shape parameters with the initial pore pressure and gas content is established to facilitate the calibration of the parameters. (3) Gassy soil is considered as a three-phase composite material. In the process of undrained cyclic shear, a positive volumetric strain increment of saturated soil matrix is introduced to simulate the bubble flooding effect. The cyclic constitutive model quantitatively reproduces experimental results ofmeasured effective stress pathforgassyclay.

Keywords: Gassy clay, Bounding surface model, Undrained shear behavior, three-phasecompositematerial

1. Introduction

Gas-charged marine sediments widely exists in North Sea, Gulf of Mexico, Gulf of Guinea, and Eastern China Sea. With the development of marine engineering in the eastern coastal areas of China, engineering infrastructures are expanding in those regions,it is beneficial for engineering construction to clarify the stress-strain relationship of gassy soil. The deformation and mechanical properties of gassy soil under cyclic loading are the most important factors in engineering design (Hong et al., 2021), because they are the important properties to judge the stability of foundation under cyclic loading such as wind and wave. So far, there are few reports on the deformation and mechanical properties of gassy soil, especially the dynamic properties of gassy soil under cyclic loading.

Some previous studies simulated the stress-strain relationship of gassy soil by establishing constitutive model. Grozic et al. (2005) constructed the constitutive model of gassy soil as soil with compressible fluid, which was physically unreasonable. Because the compressible fluid reduces the positive pore pressure produced in the undrained shear process, this model can only predict the beneficial effect of bubbles on the undrained shear strength. Pietruszczak and Pande (1996) constructed a constitutive model based on the fact that bubbles are larger than soil particle size, but their method still can not capture the damage effect of bubbles on undrained shear strength. Through experimental research, Hong et al (2020) proposed a variable yield surface constitutive model, which can capture the dilatancy characteristics of gassy soil. Gao et al (2020) regarded the gassy soil as a composite material and proposed a new constitutive model. Both these two models can simultaneously describe the strengthening and weakening effects of bubbles on stiffness and undrained shear strength. Huang et al.(2022) proposed a constitutive model for cyclically-loaded clay with entrapped gas bubbles. However, the model neglects to quantify the gas volume change under cyclic loading. Based on the composite material method proposed by Gao et al (2020) and the cyclic test results of gassy soils, a new bounding surface constitutive model is proposed in this study. The new constitutive model can capture the bubble flooding during the cyclic triaxial tests and the influence of stress history on soil stiffness.

2. Constitutive model

2.1.Bubble flooding

As shown in Fig.1, gassy clay can be regarded as a composite material. According to a simple rule of composite mixture, the stress state of gassy clay is assumed as follows (Pietruszczak & Pande, 1996; Gao et al., 2020):

$$p = (1-f)p_{\mathrm{m}} + fu_{\mathrm{g}} \tag{1}$$

$$p_{\mathrm{m}} = p'_{\mathrm{m}} + u_{\mathrm{w}} \tag{2}$$

$$q = (1-f)q_{\mathrm{m}} \tag{3}$$

where$f$ is the volume fraction of the gas cavities (Wheeler, 1986), p_{m} and p'_{m} are total and mean effective stress of the saturated clay matrix, q_{m} is the deviator stress of the saturated soil matrix, u_{g} is the gas pressure, u_{w} is the pore water pressure. Since the bubble has no shear stiffness,the total deviator stress$q$ only depends on q_{m}. The volume fraction of cavities f is expressed as below (Wheeler, 1988). Since the cavity volume fraction f of gassy soil is very small (less than 0.05), the influence of air pressure on the total stress can usually be ignored (Gao et al, 2020).

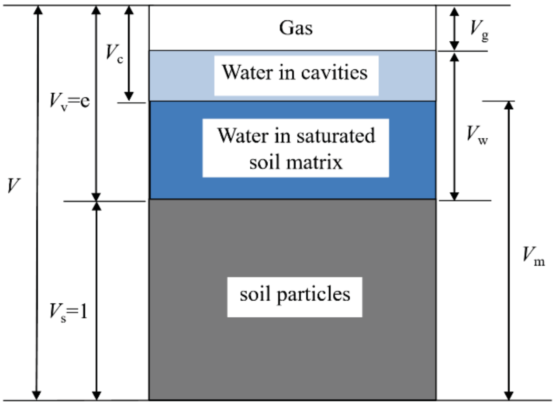

Fig. 1.Phase diagram for fine-grained gassy soil (water in both the saturated matrix and cavity)

The total volumetric strain μ_v and shear strain μ_q of a composite material can be decomposed as below using the rule of mixture.

$$\varepsilon_v = (1-f)\varepsilon_{\mathrm{v}}^{\mathrm{m}} + f\varepsilon_{\mathrm{v}}^{c} \tag{4}$$

$$\varepsilon_{\mathrm{q}} = \varepsilon_{\mathrm{q}}^{\mathrm{m}} \tag{5}$$

where μ_v^{c} is the volumetric strain of gas cavities,μ_v^{m} and μ_q^{m}denote the volumetric strain and shear strainof the saturated clay matrix, respectively.The volumetric strain increment of the saturated clay matrix dμ_v^{m} is dependent on the both the volumetric strain increments ofwater flow at the boundary dV_{b} andbubble flooding dV_{f}(Gao et al., 2020; Wheeler, 1986; Sills et al., 1991):

$$d\varepsilon_{\mathrm{v}}^{\mathrm{m}} = \frac{dV_{\mathrm{b}} + dV_{\mathrm{f}}}{V_{\mathrm{m}}} = d\varepsilon_{\mathrm{v}}^{\mathrm{b}} + d\varepsilon_{\mathrm{v}}^{\mathrm{f}} \tag{6}$$

where V_{m} is volume of the saturated clay matrix, the dμ_v^{b} and dμ_v^{f} denote the volumetric strain increments of water flow at the outer boundary of the saturated matrix and bubble flooding, respectively.In the cyclic undrained shear test of gassy soil, it is found that the partial drainage effect of saturated soil matrix caused by bubble flooding will occur during loading, while the water will flow out of the cavity during unloading, which also result the characteristics of partial drainage. Based on such observation, the following formulation for dμ_v^{f} is proposed:

$$d\varepsilon_{\mathrm{v}}^{\mathrm{f}} = \frac{(1-S_{\mathrm{r}})e}{(u_{\mathrm{w}} + p_{\mathrm{a}})(1+e)} du_{\mathrm{w}} \tag{7}$$

where $S_{\mathrm{r}}$is the degree of saturation, e is the global void ratio, p_{a} denote the standard atmospheric pressure with the value of 101 kpa

Considering Boyle's law and Henry's law, a pressure variation equation considering dissolution is adopted in this paper. At the same time, when the sample is unloading, the water entering the sample is assumed to contain no dissolved gas (Thomas, 1987). Therefore, the gas pressure evolution of bubbles du_g can be expressed by the following formula

$$du_g = \frac{u_g dV_g}{V_g - dV_g + HV_W} \tag{8}$$

where H is Henry's coefficient of solubility, dV_g istotal gas volume change,$V_w$and $V_g$donate the volume of water in gassy soil and gas, respectively.

2.2.Intergranular strain elastic model

Previous studies have found that the high stiffness of soil at very small strain (i.e. less than 10^{-5}) and its strong nonlinear degradation with the increase of strain amplitude are a key aspect of the basic characteristics of soil. Based on the small strain stiffness elastic model proposed by Niemunis and Herle (1997), Shi and Huang (2020) incorporated the intergranular strain concept into the framework of elastoplasticity. They assumed that intergranular strains only played a role in elastic stiffness, so the above compatibility problem can be well solved because the solution of elastoplastic stiffness based on consistency condition is relatively independent of elastic stiffness. The intergranular strain model is simplified to triaxial space and can be written as the following formulas:

$$m = \rho^{\chi} m_T + (1-\rho^{\chi}) m_R + \begin{cases} \rho^{\chi}(1-m_T) g_1(l) & if \quad l > 0 \\ \rho^{\chi}(m_R - m_T) g_2(l) & if \quad l \leq 0 \end{cases} \tag{9}$$

$$g_1(l) = g_2(l) = |l|^n \tag{10}$$

$$K_m = m\frac{(1+e_m)}{\kappa} p' \tag{11}$$

$$G_m = m\frac{3(1-2\mu)K_m}{2(1+\mu)} \tag{12}$$

where m_R and m_T donate the stiffness amplification factors when the stress turns 180° and 90°, respectively. When the stress-reversing angle is between 0°-180°, the value of m can be determined according to the above interpolation function. Same as modified Cam-clay model, K_m is the elastic bulk modulus of the saturated soil matrix, G_m is the elastic shear modulus, e_m is the void ratio of the saturated soil matrix and μ is the Poisson's ratio. Çis the model parameter controlling the stiffness. And the definition of l and Á is the same as in Niemunis and Herle (1997).

2.3.Bounding surface function

Collins (2005) deduced a yield surface equation with firm physical basis according to the modern theory of the thermomechanics. The model not only satisfies the basic laws of thermodynamics, but also has a clear physical explanation in energy storage and dissipation. Therefore, the function form proposed by Collins (2005) is adopted as the bounding surface function in this paper, and the formula is as follows:

$$\bar{F} = \frac{(\bar{p}' - \alpha\bar{p}_0'/2)^2}{[(1-\gamma)\bar{p}' + \alpha\bar{p}_0'/2]^2} + \frac{\bar{q}^2}{M^2\left[(1-\alpha)\bar{p}' + \alpha^2\bar{p}_0'/2\right]^2} - 1 = 0 \tag{13}$$

where $\bar{p}_0'$ is the size of the bounding surface (i.e. the preconsolidation pressure); and $\bar{p}'$ and $\bar{q}$ are the mean stress and deviatoric stress at the image stress point, respectively. In this paper, in order to simplify the bounding surface equation, we assume that ³=±.Based on the above experimental evidence, similar to the findings of Hong et al.(2020), the expression of ± is proposed as follows:

$$\alpha\left(\frac{u_{w0} - u_{w0\_ref}}{p_0'}, \psi_0\right) = (-1.5 \times \Lambda \psi_0^{a+b\Lambda}) \tag{14}$$

where $\Lambda = (u_{w0} - u_{w0,ref})/p_0'$, which measures the normalized difference of initial water pressure u_{w0} from a virtual reference initial water pressure u_{w0_ref}. The a and b are two parameters which control the relative effectiveness of Λ and $\phi_0$in determining the shape of the bounding surface. The constant "1.5" is obtained by back analysis based on the test results of three types of fine-grained gassy soil, which is independent of gas content $\phi_0$and initial pore water pressure u_{w0}.

3. Model validation

The verification of the model is mainly aimed at the undrained shear cyclic test of gassy soil. The comparison between the predicted and measured effective stress path are shown in Fig.2.The model calculation results show the same characteristics as the experimental results, that is, similar drainage phenomenon occurs in the undrained test of gassy soil under initial u_{w0}=0 kPa. It also shows the importance of considering the effect of bubble flooding for the simulation of cyclic characteristics of gassy soil. Considering soil as composite material can well simulate the relationship between bubbles and soil matrix, which is reflected in the behavior of the soil sample under undrained cyclic shear. When the initial pore pressure is high (u_{w0}=600 kPa), the gas pressure in the bubble is also large, and the bubble flooding is not obvious.

4. Conclusion

Based on the results of undrained cyclic triaxial test of gassy soil and the critical state theory, a cyclic constitutive model which can consider the beneficial or detrimental effect of bubbles on gassy soil is proposed in this paper. The model considers the physical mechanism of gassy soil under cyclic shear by treating gassy soil as a three-phase composite material. In order to simulate the volumetric strain of gassy soil during undrained cyclic shear test, the bubble flooding is considered in the model. Due to the phenomenon of partial drainage observed in the test, this method can well explain the occurrence of this phenomenon in the physical mechanism and predict the test results.

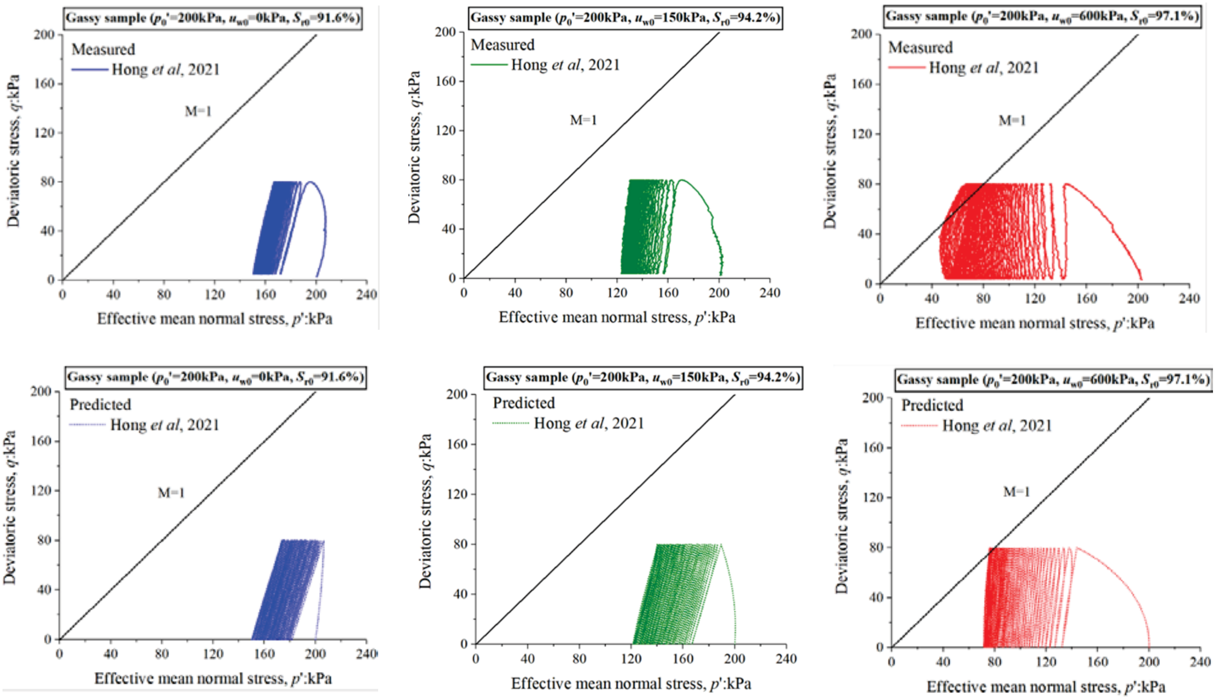

Fig. 2.Comparison between the predicted and measured effective stress path: (a) gassy sample (u_{w0}=600 kPa); (b) gassy sample (u_{w0}=0 kPa) ; (c) gassy sample (u_{w0}=150 kPa)

Acknowledgement

The authors gratefully acknowledge the financial supports provided by National Natural Science Foundation of China (grant No. 52101334).

References

Grozic, J.L.H., Robertson, P.K., Morgenstern, N.R. (2000).Cyclic liquefaction of loose gassy sand. *Canadian Geotechnical Journal 37(4)* : 843–856.

Hong, Y., Chen, X. Y., Wang, L. Z., Yang, B. and Sanchez, M. (2021).Distinct undrained cyclic behavior of fine-grained gassy soil at various initial pore water pressures. *Journal of Geotechnical and Geoenvironmental Engineering147(2)*, 06020027.

Grozic, J. L. H., Nadim, F., and Kvalstad, T. J. (2005).On the undrained shear strength of gassy clays. *Computers and Geotechnics 32(7)*, 483–490.

Pietruszczak, S., and Pande, G. N. (1996). Constitutive relations for partially saturated soils containing gas inclusions. *Journal of Geotechnical and Geoenvironmental Engineering 122 (1)*, 50–59.

Hong, Y., Wang, L.Z., Zhang, J.F. and Gao, Z.W.(2020).3D elastoplastic model for fine-grained gassy soil considering the gas-dependent yield surface shape and stress-dilatancy. *Journal of Engineering Mechanics 146(5)*, 04020037.

Gao Z, Hong Y., Wang L.Z. (2020). Constitutive modelling of fine-grained gassy soil: A composite approach. Numerical and Analytical Methods in Geomechnics

Huang, M.S.,Zou, S.H., Shi, Z.H. and Hong Y. (2023).Constitutive modeling of cyclically loaded clays with entrapped gasbubbles under undrained and unexhausted conditions. *Acta Geotechnica (18)*, 265-278.

Wheeler, S.J. (1988). The undrained shear strength of soils containing large gas bubbles. *Géotechnique 38(3)*, 399–413.

Wheeler, S.J. (1986). The Stress-Strain Behaviour of Soils Containing Gas Bubbles. PhD thesis, Oxford University.

Sills, G.C., Wheeler, S.J., Thomas, S.D. and Gardner, T.N.(1991).Behaviour of offshore soils containing gas bubbles. *Géotechnique 41(2)*: 227–241.

Niemunis A. and Herle I. (1997). Hypoplastic model for cohesionless soils with elastic strain range. *Mechanics of Cohesive-frictional Materials2(4)*, 279–299.

Shi, Z. and Huang, M. (2020). Intergranular-strain elastic model for recent stress history effects on clay. *Computers and Geotechnics 118*, 103316

Collins, I. F. (2005). Elastic/plastic models for soils and sands.*International Journal of Mechanical Sciences 47(4)*, 493–508.