

Strength Characteristics of Shallow Gassy Sand in the Hangzhou Bay

Wang Yong, Kong Ling-Wei, And Guo Ai-Guo

Abstract—In view of geological origin, formation of the shallow gas reservoir of the Hangzhou Bay, northern Zhejiang Province, eastern China, and original occurrence characteristics of the gassy sand are analyzed. Generally, gassy sand in scale gas reservoirs is in the state of residual moisture content and the approximate scope of initial matric suction of sand ranges about from 0kPa to 100kPa. Results based on GDS triaxial tests show that the classical shear strength formulas of unsaturated soil can not effectively describe basic strength characteristics of gassy sand; the relationship between apparent cohesion and matric suction of gassy sand agrees well with the power function, which can reasonably be used to describe the strength of gassy sand. In the stress path of gas release, shear strength of gassy sand will increase and experimental results show the formula proposed in this paper can effectively predict the strength increment. When saturated strength indexes of the sand are used in engineering design, moderate reduction should be considered.

Keywords—Gassy sand, Gas release, Occurrence characteristics, strength

I. INTRODUCTION

SHALLOW biogas refers to methane-rich gas formed by organic matters with the action of anaerobic microorganisms at a reducing environment, which is an important component of natural gas resources [1]. It is also called shallow gas for short due to its shallow buried depth. There is general distribution in about $3 \times 10^5 \text{km}^2$ regions of China, such as the southeast coast, both shores and estuary of the Yangtze River, the Minjiang River and the Pearl River [2]. Among them, the Hangzhou Bay areas had alternatively deposited several organic-rich silt and sand layers in process of the marine transgression- regression in the Quaternary. Biogas produced in the silt layers had formed a number of ultra-shallow gas reservoirs through migration and accumulation in vicinity of the sand lens or at the top of sand layers. The buried depth of these gas reservoirs is generally less than 60m; their original residual pressure ranges from 0.12 to 0.46MPa, and the main gas component is methane occupied above than 90%. They are characterized by the wide extent of

gas-bearing area and thin gas-bearing layer [3].

Most of the past studies on shallow gas were mainly focused on its occurrence mode, geological genesis, exploitation and utilization [4]-[7], and etc. But in recent years, with the expansion of engineer scale and exploitation of underground space, the problems of geological engineering disasters induced by the shallow gas are increasingly prominent in China. For examples, as the project of hydraulic facilities along the Yangtze River in Anhui province, the geology with shallow gas caused the foundation uneven subsidence and cracking of the hydraulic structures [8]; due to the release of shallow gas, the Bamboo outfall tunnel of Shanghai sewage treatment projects had been distorted and fractured, which led to a major engineering accidents [9]; construction project of the Hangzhou Gulf Bridge had encountered accidents of boat damaged and person injured caused by eruption of the shallow gas in early geotechnical investigation and survey [10]. The geology with shallow gas has been regarded as a kind of geological hazard gradually caused more attention [11]. Therefore, it is necessary to identify basic engineering properties of the soil with shallow gas, which is the basis for taking initiative and preventive measures to eliminate geological disasters caused by the shallow gas in engineering construction.

Shallow gas in Hangzhou Bay mainly accumulates in the sand body with larger porosity and better permeability. The sand stored by shallow gas is also known as gassy sand. Gassy sand is a special type of unsaturated soil, whose pore air phase has a clear distinction with the general unsaturated soil. The pore air phase in general unsaturated soil is connected with the atmosphere, but gassy sand is closed, and its pressure is 3-4 times higher than atmospheric pressure. In addition, the gas stored in sand is mainly composed of methane rather than air, and genesis of it is related to the special terrestrial sedimentary environment of marine facies and lacustrine facies. Its engineering properties are often characterized by gas emission, gas pressure reduction and the drop of matric suction [12]. At present, researches [13]-[17] about basic mechanical characteristics and dynamic behaviors of the deposit contained with large gas bubbles in marine environment (generally, its saturation is above 85%) have made some progress, but studies on the soil stored by the closed shallow gas with higher pressure in terrestrial environment are few. This paper is focus on typical gassy sand in the Hangzhou Bay, studying on its basic characteristics of the shear strength and variation law in engineering in order to grasp the nature of it and provide references for engineering design of construction under

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this geological condition.

II. FORMATION MECHANISMS OF GAS RESERVOIRS AND ORIGINAL OCCURRENCE OF GASSY SAND

In view of geological origin about shallow gas of the Hangzhou Bay, a large number of organic matters quickly sealed and got into reducing environment with a continuous subsidence due to the rapid sedimentation of regional stratigraphy, which creates a favorable external environment and material condition for the microbial communities to survive and reproduce [18]. Overlying thick organic-rich silt clay is the main gas source and the sealing layer of shallow gas. Methane produced by the gas source layer firstly is dissolved in stratum water or adsorbed by clay particles, most of which appears in the water-soluble state. Due to the continuous subsidence of silt layer, the pore water is gradually discharged and the water-soluble gas is obliged to flow from the clay with poor permeability to the sand. As solubility of the methane is smaller, when gas is dissolved saturated, the dissociating gas appears. After a constant migration, for the upper silt layer with a larger capillary resistance, it is closed at the top of sand layer. Accumulated gas has diffused into the atmosphere continuously through the upper sealing layer, but the quantity and pressure of dissociating gas have increased constantly because gas production is larger than the lost. As dissociating gas has expelled and replaced the pore water of sand and the air-water interface has declined continuously, then a scale gas reservoir with certain thickness comes into being eventually. It is in the dynamic equilibrium of producing gas, dissolution, adsorption, migration, diffusion and aggregation all along from beginning to end. So it can be concluded that the pore air in scale gas reservoirs is connected with each other and water content of the sand increases gradually from the top to the bottom; the original occurrence of sand transits gradually from unsaturated to saturated state. The phenomenon that many of in-situ penetration holes erupted dry sand and gas firstly, then gas, water and sand was erupted simultaneously provides an strong evidence for the conclusion in process of the engineering investigation.

The typical soil-water characteristic curve of gassy sand in the Hangzhou Bay is shown in Fig.1. It can be seen that air-entry value $(u_a - u_w)_d$ of the gassy sand is about 5kPa, saturated moisture content θ_s for 42%, residual moisture content S_r for 10%, residual saturation nearly for 20%, and the

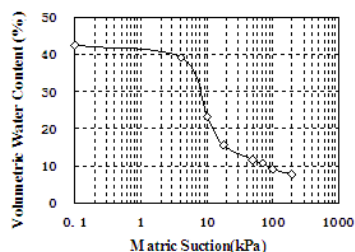


Fig. 1 The typical SWCC of gassy sand of the Hangzhou Bay

corresponding matric suction $(u_a - u_w)$ nearly for 100kPa. Studies have shown shallow gas reservoirs of the Hangzhou Bay are normal pressure reservoirs [19] (original formation pressure coefficient ranges from 0.7 to 1.2). The typical buried depth of gas cap of them ranges 25-50m below the ground, and corresponding hydrostatic pressure near the cap ranges roughly from 250 to 500kPa. If it takes the maximum pressure coefficient of 1.2, the estimated maximum gas reservoir pressure ranges from 300 to 600kPa and the maximum matric suction $(u_a - u_w)_{Max}$ of gassy sand ranges from 50 to 100kPa. It can be inferred that gassy sand in scale gas reservoirs is in the state of residual moisture content and the corresponding suction ranges from 50 to 100kPa. Therefore, the shear strength characteristics of matric suction within 100kPa of gassy sand are the primary concerns for this paper.

III. SHEAR STRENGTH CHARACTERISTICS OF GASSY SAND

Although the gassy sand is considered as a special type of unsaturated soil, its engineering properties can still be studied with the theory of unsaturated soil.

Classical formulas for the shear strength of unsaturated soil fall into two categories. One proposed by Bishop [20] is as follows:

$$\tau_f = c' + (\sigma - u_a) \tan \phi' + \chi(u_a - u_w) \tan \phi' \quad (1)$$

where c' = the effective cohesion, ϕ' = internal friction angle, u_a = pore air pressure, u_w = pore water pressure, χ = an effective stress parameter depending on saturation, and its value ranges from 0 to 1. Another is the double-variable strength formula proposed by Fredlund [21]:

$$\tau_f = c' + (\sigma - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b \quad (2)$$

where $(\sigma - u_a)$ = the net normal stress, $(u_a - u_w)$ is the matrix suction, ϕ^b = shear strength friction angle caused by the matrix suction. Contrasting (1) and (2), it can be seen that two formulas are mainly different in the third item, $\tau_{us} = (u_a - u_w) \tan \phi^b$ caused by matrix suction, and which is also called as the adsorption strength or apparent cohesion; and the complexity of unsaturated soil strength is mainly rooted of this item. In Addition, the relationship between the coefficient χ and ϕ^b is given in (3):

$$\chi \tan \phi' = \tan \phi^b \quad (3)$$

Taking the gassy sand specimen from the typical sections buried shallow gas of the Hangzhou Bay region, the triaxial shear tests of the same initial densities and different initial air pressures are carried out with the GDS triaxial test system of unsaturated soil. The initial pore water pressure of the sample is controlled of 300kPa; initial pore air pressure is controlled of 300kPa, 320kPa, 350kPa, and 400kPa and the corresponding matrix suction $(u_a - u_w)$ of 0kPa, 20kPa, 50kPa and 100kPa respectively. Tests are carried out after the initial suction of samples is relatively close to equilibrium, and test results are obtained according to the shear strength formulas proposed by

Bishop and Fredlund. Strength indexes of the gassy sand with different initial gas pressures are shown in Table I .

TABLE I

THE STRENGTH INDEXES OF GASSY SAND IN THE HANGZHOU BAY WITH DIFFERENT INITIAL GAS PRESSURE

| u_a (kPa) | $(u_a - u_w)$ (kPa) | Strength parameters | | | | |
|----------------|------------------------|---------------------|-------------|-------------------|--------|--------------|
| | | c' (kPa) | ϕ' (°) | τ_{us} (kPa) | χ | ϕ^b (°) |
| 300 | 0 | | | 0.0 | 1 | 33.7 |
| 320 | 20 | 8.0 | 33.7 | 12.1 | 0.91 | 31.2 |
| 350 | 50 | | | 18.8 | 0.56 | 20.6 |
| 400 | 100 | | | 24.4 | 0.37 | 13.7 |

Results show that the higher of the original gas pressure in reservoirs, the larger of the corresponding matric suction, apparent cohesion or the shear strength of gassy sand with the same initial density. As shown in Fig.2 and Fig.3, χ and ϕ^b are all not constants and both of them decrease gradually with

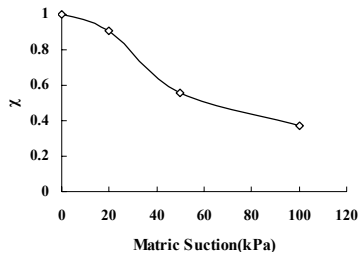


Fig. 2 Variation of χ with the matric suction

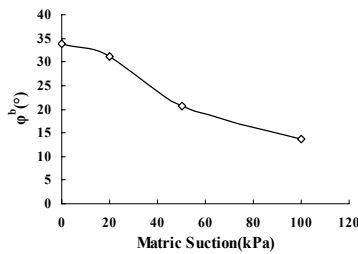


Fig. 3 Variation of ϕ^b with the matric suction

the increasing suction. When matric suction increases from 0kPa to 100kPa, the value of χ decreases from 0.37 to 0, while the value of ϕ^b reduces from ϕ' in saturated state to 13.7°. It indicates that χ and ϕ^b generate by the matrix suction, and they are both variables being dependent on matric suction or moisture content. Therefore, although (1) and (2) may reflect variation laws for the basic shear strength characteristics of gassy sand, they can not describe effectively and be convenient for application because χ and ϕ^b are difficult to determined in practice.

KONG et al. [12] developed a formula to describe the relationship between apparent cohesion and matric suction of

shallow gassy sand in study of influences of the shallow gas on pile foundation in the Hangzhou Gulf Bridge:

$$\tau_{us} = a(u_a - u_w)^b \tag{4}$$

where a and b are constants determined by tests and independent of the matric suction. The corresponding formula for shear strength of gassy sand can be given as:

$$\tau_f = c' + (\sigma - u_a) \tan \phi' + a(u_a - u_w)^b \tag{5}$$

The comparison between τ_{us} derived from (4) and the measured results of tests is illustrated in Fig.4. As can be seen that the relationship between the apparent cohesion and matric suction of gassy sand agrees well with the power function, where $a=3.44$, $b=0.43$. The correspondence between theoretical values and test values proves the validity of (5) to describe the basic shear strength characteristics of gassy sand in original gas reservoirs.

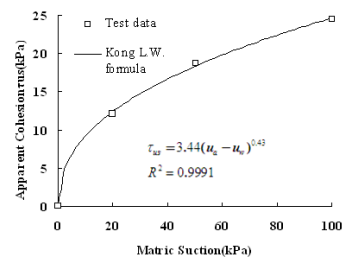


Fig. 4 Relationship between the apparent cohesion and matric suction of gassy sand

IV. STRENGTH PROPERTY OF GASSY SAND IN PATH OF THE GAS RELEASE

The most obvious difference between gassy sand and general unsaturated soil lies in the particularity of its air phase. Influences on its engineering properties of the high pore air pressure are prominent. The gas-water equilibrium in the original gas reservoir is prone to break up due to the release of closed gas. Gas release is one of the most commonly encountered stress paths, and the change of gas-water state directly determines the behaviors of gassy sand in engineering. Therefore, the stress strength of gassy sand after the gas emissions becomes the focus of concern in constructions.

As the external load remains constant in gas release path, changes in the strength of gassy sand originate from the variation of pore air pressure and matric suction. To take differential on both sides for (2), we have

$$d\tau = -du_a \tan \phi' + d(u_a - u_w) \tan \phi^b \tag{6}$$

In the path of gas release, $du_a < 0$, $du_w = 0$, (6) changes to

$$d\tau = du_a (\tan \phi^b - \tan \phi') \tag{7}$$

We can see from the above tests, it has $\phi^b \leq \phi'$ and $\tan \phi^b \leq \tan \phi'$. Therefore, $d\tau \geq 0$. It indicates that gas release will leads to increase the strength of gassy sand. As the net mean stress $(\sigma - u_a)$ and matric suction $(u_a - u_w)$ control the shear strength of gassy sand simultaneously, decrease of the pore air pressure will lead to increase of the net mean stress, while water will enter into the gas reservoir under the pressure

head, which will cause the reduction of the matric suction. They produce contrary effects on the shear strength occurred at the same time. However, contribution caused by the variation of net mean stress to increase the strength is measured by $\tan \phi'$, while the contribution caused by the variation of matric suction to decrease the strength is measured by $\tan \phi^b$. For $\tan \phi^b \leq \tan \phi'$, the stress strength of gassy sand will be enhanced in the path of gas release, which is one of the important reasons for taking the measure of pre-exhausting shallow gas under control to eliminate disasters.

Vanapalli et al. [22] proposed an empirical model to predict the shear strength of unsaturated soil based on its soil-water characteristic curve, which can also be used to predict the increment of the shear strength of gassy sand after gas release.

$$\tau = c' + (\sigma - u_a) \tan \phi' + (u_a - u_w) \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right) \tan \phi' \quad (8)$$

where θ is the volume of soil moisture content; θ_r and θ_s is the residual volumetric water content and saturated volumetric water content respectively.

Differential calculating on both sides of (8), strength variation of gassy sand in path of the gas release can be described by (9),

$$d\tau = d(\sigma - u_a) \tan \phi' + d(u_a - u_w) \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right) \tan \phi' + (u_a - u_w) \tan \phi' d \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right) \quad (9)$$

It is noticed the facts that external total stress σ is a constant in the path of gas release, and $du_w = 0$; if θ_0, θ_1 are the water content volume of gassy sand before and after gas release respectively, and u_{a0}, u_{a1} represent the corresponding pore air pressure, as mentioned above, gassy sand in scale gas reservoirs is in the state of the residual moisture content, $\theta_0 \approx \theta_r$; and gassy sand is close to saturated state after the thorough gas release, $\theta_1 \approx \theta_s, u_{a1} \approx u_w$. Hence, the following expression can be arrived from (9),

$$d\tau \leq (u_{a0} - u_w) \tan \phi' \quad (10)$$

Additionally, according to the fact that coefficient of formation pressure in the Hangzhou Bay region is among 0.7-1.2, if the maximum pressure coefficient of 1.2 is used to estimate the initial pore air pressure of gas reservoirs, there is $u_{a0} \approx 1.2u_w$; and substituting it into (10) results in

$$d\tau \leq 0.2u_w \tan \phi' \quad (11)$$

Equation (11) can be used to predict the increment of shear strength of gassy sand after the gas release. For example, if the gassy sand layer buries in the depth of 25-50m, corresponding to the initial pore water pressure is about 250-500kPa and the effective friction angle of sand in saturated state is about 33.7° , so the shear strength increment of the sand $\Delta\tau$ is about 30 - 60kPa according to (11).

In order to verify the feasibility and effectiveness of (11), a contrast test on shear strength of gassy sand before and after gas release is carried out. With the initial pore air pressure of 360kPa, the pore water pressure of 300kPa, consolidation confining pressure of 500kPa, the initial pore water pressure of 300kPa, consolidation confining pressure of 500kPa, the initial net mean stress of 140kPa and the initial matric suction of 60kPa, pore air pressure of the samples is reduced gradually

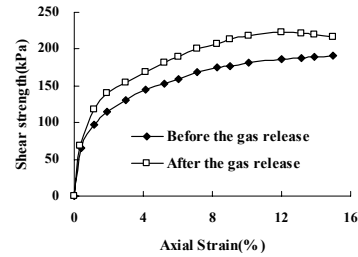


Fig. 5 Triaxial shear tests compared before and after the gas release of gassy sand

from 360kPa to 300kPa by the gas release. Fig.5 shows the stress-strain curves of sand in triaxial shear tests before and after the gas release. As can be seen, before the gas release, taking stress 190.7kPa corresponding to the strain of 15%, and after the gas release, taking peak stress 222.8kPa corresponding to the strain of 12% as the peak strengths, the shear strength increases about 32.1kPa, and $0.2u_w \tan \phi' = 40\text{kPa}$, those indicating that the strength of gassy sand will be enhanced in gas release path, and the value agrees well with the prediction of (11).

It is difficult to achieve the original samples of gassy sand because the gas in pore will be released in the process of field sampling. As the gas release will lead to increase the strength of sand, using the indexes of saturated sand to design in practice may cause of overestimating parameters resulting in insecurity for constructions on the ground buried gassy sand, so moderate reduction should be considered in practical application.

V. CONCLUSIONS

(1) In view of geological origin, the formation of shallow gas reservoirs of the Hangzhou Bay and original occurrence characteristics of gassy sand are analyzed. Generally, the gassy sand in scale gas reservoirs is in state of the residual moisture content. Moisture content of the sand increases gradually from the gas cap to the bottom with the state from the unsaturated to saturated, and the approximate scope of its initial matric suction ranges from 0kPa to 100kPa.

(2) The classical strength formula of unsaturated soil can not effectively describe the basic strength characteristics of gassy sand at the original state. The contribution of matric suction to the shear strength is in line with the power function, and the formula $\tau_f = c' + (\sigma - u_a) \tan \phi' + a(u_a - u_w)^b$ can reasonably describe the strength of gassy sand.

(3) In stress path of the gas release, the shear strength of gassy sand will increase, and the correspondence between theoretical values and test values proves the validity of formula

$d\tau \leq 0.2u_w \tan \phi'$ to predict its shear strength increment. When the saturated strength indexes of the sand are used in the engineering design, moderate reduction should be considered.

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