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On strength property of gassy fine sand and model tests of pile foundation

Sur la propriété de la résistance d’un sable fin gazeux et le modèle physique de fondation de pieux

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ABSTRACT

Based on the phenomenon of blowout during the engineering geologic surveys in the Hangzhou Bay Bridge, Zhejiang province, China, the influence of shallow biogenetic gas on the engineering properties of sandy soil is measured and analyzed. It is found that the engineering behaviors of gassy sand is determined by its three-phase composition state and special stress path, the gas reservoir pressure of fine sand layer is 515~530kPa and its pressure coefficient is 1.03~1.06. The shear strength of gassy sand can be expressed as the formula $\tau_f=c'+(\sigma_n-u_a)\tan\phi'+\tau_{us}$ and $\tau_{us}=a(u_a-u_w)^b$,and increases with the decrease of the gas pressure level. Moreover, the model tests of steel pipe pile in the gassy sand show that the Q-s curve belongs to the type of steep fall, the ultimate bearing capacity of pile increases with the release of gas even though the increasing amplitude is different at the different stage of gas release, which can be explained by the internal mechanism that the increase of net stress makes predominance over the ultimate bearing capacity of pile compared with the decrease of suction under the condition of gas release slowly.

RÉSUMÉ

En se basant sur le phénomène d’éclatement observé durant l’investigation géologique pour le pont de baie de Hangzhou, Province de Zhejiang, Chine, on a mesuré et analysé l’influence du gaz biogénétique présente à faible profondeur sur les propriétés géotechniques du sol sableux. Il est observé que le comportement du sable avec du gaz est conditionné par sa composition tri-phasique et dépend du chemin de contrainte particulier. La pression de gaz dans le gisement situé dans une couche de sable est de 515~530 kPa,et son coefficient de pression est de 1.03 ~1.06.La résistance au cisaillement du sable de gisement peut être exprimée par la formule $\tau_f=c'+(\sigma_n-u_a)\tan\phi'+\tau_{us}$ et $\tau_{us}=a(u_a-u_w)^b$, et elle augmente avec la diminution de la pression de gaz. De plus, un modèle physique avec des pieux métalliques fichés dans du sable a montré que la courbe Q-s est caractérisée par une forte chute ; la capacité portante des pieux augmente avec le relâchement du gaz, bien que l’amplitude d’augmentation est différente d’une étape à l’autre, ce qui peut être expliqué par un mécanisme interne qui est la prédominance de l’augmentation de la contrainte nette sur la capacité portante des pieux en comparant avec la diminution de la succion sous la condition de relâchement lent de la pression de gaz.

1 ITRODUCTION

The Hangzhou Bay Bridge located at Zhejiang province, China, is the presently longest crossing-sea bridge in the world, which begins in Ningbo City from the south and ends in Jiaxing City to the north with total length of 36.0km and crossing-sea length of 31.5km.The engineering geological condition of bridge site is very complex for deeply buried bedrock and nearly 40m thick clay. Moreover, the biogenetic gas was found at the clay and sand layer of depth 18~60m in the southern beach, which has little influence on the exploration in clay stratum, while in the sand layer, the intense blowout happened so frequently that the exploring work was terminated. Based on the feature of blowout and effect factors analysis, it is considered that the main reasons resulted in blowout are pump of drill pulling and delay of grouting. Blowout is a process of unsaturated seepage damage when the infiltration gradient of gassy soils exceeds its critical air pressure gradient, whose effect on layer lies in damaging and disturbing. The gas at the clay layer will not cause obvious hazard to pile foundation, but at sand layer may severely disturb the soil and brings a reduction of bearing capacity of pile, differential settlement or sinking of pile legs, occurrence of negative friction and influence of insecurity on pile foundation construction. Some measures such as rational selection of pile type, previously-releasing biogenetic gas without disturbing soil, heightening the work platform of pile drilling and increasing specific gravity of mud in the construction should be applied to prevent the occurrence of disaster (Kong et al., 2004).

So far, some researchers not only have studied the gas deposit state of gas-charged sediments and its influence on geotechnical properties (Wheeler, 1988,Brandes, 1999), but also explored the acoustic characteristics of gassy offshore soil and consolidated properties of gassy soft soils (Sills & Gonzalez, 2001), and begun to pay attention to the behaviors and cyclic liquefaction of gassy loose sand (Grozic et al., 2000). However, few documents of shallow gas on geotechnical practice can be found. In this paper, after analyzing the hazard of blowout to the Hangzhou Bay Bridge, the strength properties of gassy sands and bearing capacity of pile foundation are investigated.

2 STRESS STATE OF SHALLOW GASSY SANDS AND ESTIMATION OF GAS RESERVOIR PRESSURE

2.1 *Stress state of shallow gassy sand*

The gassy sands differ from common mainland unsaturated soil in the state of three phases though the gassy sands belong to three-phase unsaturated soil, for the former, the gaseous phase is not air but methane in a closed state, while for the latter, the gaseous phase is open to atmosphere.

Since the strength and deformation properties of unsaturated soils depend on the two independent stress state variables-net stress and matrix suction, and represent apparent dependence on stress path, the stress state of gassy sand is completely different from mainland unsaturated soils. For the gassy sand, unloading and air pressure decreasing always characterize geotechnical engineering condition, while for the common unsaturated soils, the geotechnical engineering condition is mainly characterized by wetting and drying, under the condition of constant vertical pressure and confining pressure, the net stress of the former varies with suction, i.e. pore air pressure changes and pore water pressure keeps constant, but that of the latter does not vary with suction, i.e. pore air pressure keeps constant and pore water pressure changes. Hence, both of the two stress state variables of gassy sands change with the gas releasing or supplying, which differs from the change principle of common unsaturated soils by wetting and drying, and the internal mechanism is determined by its three-phase composition state and special stress path due to the change of three-phase composition.

2.2 *Estimation of gas reservoir pressure in gassy sand*

The disturbed sandy soils come from 50m deep stratums in the Hangzhou Bay Bridge site, and the results of grain-size analysis are given in Table 1,it shows that both of the silty sand and fine sand contain a little clay particles.

According to the laws of natural gas migration and accumulation, the reservoir layer is primarily filled with water, and then water is partly replaced by gas, which is gradually accumulated in the reservoir sand layer. But the replacement of water is not complete and a certain volume of water is reserved to balance capillary pressure and gravity. When the gas reservoir forms to a certain extent, the water content in gas reservoir should at least be close to residual water content. Therefore, based on the soil water characteristic curves of gassy sand, the original gas reservoir pressure p_0 in the Bridge site can be estimated by the suction relevant to residual water content.

In term of mean and maximum index of density provided by the exploration report, water retention characteristics tests are done on silty sand and fine sand with two kinds of density in pressure plate and unsaturated triaxial apparatus, respectively. The test results are shown in Fig.1 and Table 2.

From the results above, it can be seen that the air entry values S_b of silty sand and fine sand are only about 5.0kPa,due to containing a little clay particles, their residual water contents w_r are about 10.0%and higher than that of common sands, the suction relevant to residual water S_d are only 15~30kPa.

Since the static water pressure of gassy sand layer can be assumed as about 500kPa, that the suction S_d equals to 15~30kPa, then the gas reservoir pressure p_0 and pressure coefficient λ of shallow biogenetic gas are obtained as follows:

$$p_0 = S_d + u_w = 515 \sim 530kPa$$
$$\lambda = \frac{p_0}{u_w} = 1.03 \sim 1.06 \qquad (1)$$

Theoretically, the original matrix suction of gassy sands in the Bridge site may be higher or lower than the suction S_d relevant to w_r, however, the tertiary to quaternary biogenetic gas reservoir belongs to normal pressure gas reservoir and the maximum of pressure coefficient is less than 1.20. So, for the gassy sands in the Bridge site, the theoretical maximum gas pressure and matrix suction are given as follows:

$$p_{\max} = 1.20u_w = 600kPa$$
$$S_{\max} = p_{\max} - u_w = 100kPa \qquad (2)$$

In general, the initial gas reservoir pressure and pressure coefficient for sand layer in the Hangzhou Bay Bridge site are 515~530kPa and 1.03~1.06, the gas pressure and matrix suction are less than 600kPa and 100kPa, respectively.

Table 1 Grain size distributions of silty sand and fine sand

Soil sample	Grain composition/%		
	<0.005mm	0.005~0.075mm	0.075~2.0mm
Silty sand	4.0	32.0	64.0
Fine sand	4.0	16.0	80.0

Table 2 Characteristic values of soil water characteristic curves

Soil sample	Dry density /g.cm^{-3}	Air entry Value/kPa	Suction to residual water content	
			Residual moisture content/%	Matrix Suction/kPa
1# silty sand	1.50	4.0	11.6	25.0
2# silty sand	1.58	6.0	12.8	30.0
3# fine sand	1.50	2.5	9.2	15.0
4# fine sand	1.63	3.0	9.6	20.0

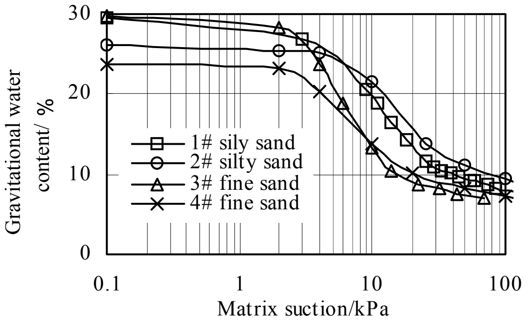

Figure1 The soil water characteristic curves of gassy sands

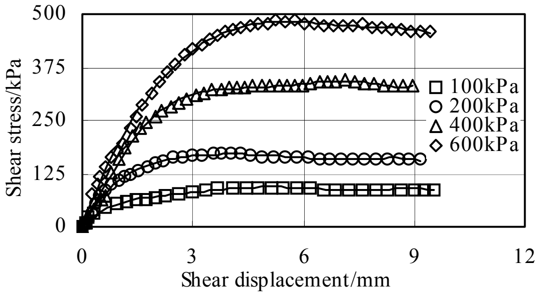

Figure 2 Typical shear stress versus shear displacement curves of gassy sand under various net stress (3# fine sand, u_a-u_w=20kPa)

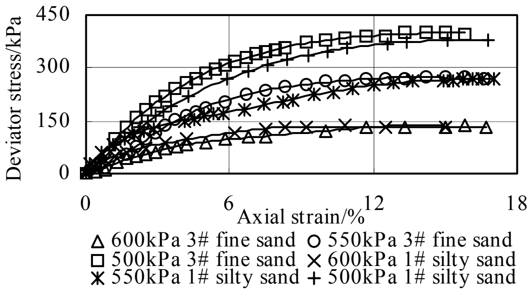

Figure 3 Deviator stress versus strain curves of consolidated drained triaxial tests on saturated sand under various backpressures (σ $_3$=650kPa)

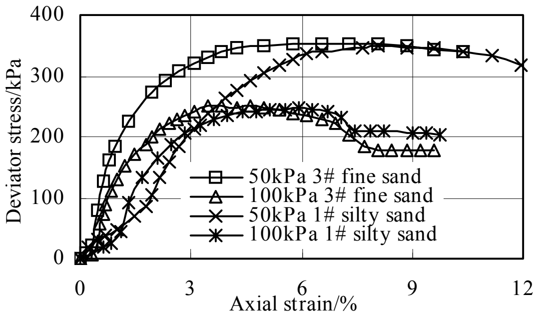

Figure 4 Deviator stress versus strain curves of triaxial tests on unsaturated sand under various matrix suctions (σ $_3$=650kPa,u_w=500kPa)

3 THE STRENGTH PROPERTY OF GASSY SAND

3.1 *Test methods and results*

In order to demonstrate the influence of biogenetic gas on the shear strength of sand, the matrix suction is controlled within 100kPa,and the direct shear tests on the gassy sand are carried out under various suction and net stress. The shear strength formula of gassy sand is established by quantifying relationship between the shear strength, matrix suction and net stress, whose effectiveness is evaluated by the unsaturated triaxial tests.

The results of unsaturated direct shear tests of sand in the bridge site are listed in Table 3, and the typical curves of shear stress and shear displacement are shown in Fig. 2, in which the shear strength parameters is obtained by the regressive analysis of shear stress and net normal stress under various suction. The results of triaxial tests are shown in Table 4, curves of shear stress and axial strain are shown in Fig.3-4.

3.2 *The shear strength formula of gassy sand*

From the Table 3, the variable characteristic of the apparent cohesion τ_{us} of gassy sand with suction (u_a-u_w) can be described by power function, the results are shown in Table 5, it can be seen that it is reasonable to use the power function to describe the relationship of the apparent cohesion and suction of sand.

Comparing the strength parameters in Table 3 and Table 4, it can be found that the ϕ' in direct shear tests are larger 3.5° than that in triaxial tests. Adopting the ϕ' in triaxial tests, the shear strength formula of gassy sand is given as formula (3).

$$\tau = c' + (\sigma_n - u_a)\tan\phi' + a(u_a - u_w)^b \tag{3}$$

In which c'=8.8kPa, ϕ'=32.5°, a=0.7585,b=0.8808 for silty sand and c'=2.0kPa, ϕ'=34.5°, a=1.0098,b=0.7494 for fine sand, respectively.

The results of unsaturated triaxial tests and calculated values are compared in Table 6 so as to evaluate the validity of formula (3), in which the geometric relation of limit Mohr circle is employed. It indicates that the presented formula is practical and reasonable for gassy sand.

Table 6 Comparison between the results of unsaturated triaxial tests and the calculated values for sands

Soil sample	Deviator stress in failure under various matrix suction/kPa			Remark
	0kPa	50kPa	100kPa	
1# silty	379	348	246	Test
	380	351	308	Calculation
3# fine	399	353	251	Test
	400	341	259	Calculation

Table 3 Results of unsaturated direct shear tests and strength parameters of gassy sand

Soil sample	Dry density /g.cm^{-3}	Matrix suction /kPa	Shear stress under different net stress/kPa				Total cohesion /kPa	Internal friction angle/°	Coefficient of correlation	Effective cohesion /kPa	Mean values of internal friction angle/°
			100kPa	200kPa	400kPa	600kPa					
1# silty sand	1.50	0	75	158	292	435	8.8	35.4	0.9990	8.8	36.0
		20	86	164	308	442	19.1	35.4	0.9992		
		50	104	192	323	482	34.3	36.5	0.9978		
		100	123	204	341	497	50.9	36.5	0.9991		
3# fine sand	1.50	0	80	147	293	449	2.0	36.5	0.9993	2.0	38.0
		20	91	170	314	484	11.5	37.9	0.9987		
		50	96	185	328	493	21.1	38.1	0.9988		
		100	119	193	355	524	33.7	39.1	0.9995		

Table 4 Results of triaxial tests and strength parameters of gassy sand

Soil sample	Confining pressure/kPa	Matrix suction/kPa	Deviator stress in failure under various pore water pressure /kPa			Effective cohesion/kPa	Effective internal friction angle/°
			500kPa	550kPa	600kPa		
1# silty sand	650	0	379	268	135	8.8	32.5
		50	348	/	/		
		100	246	/	/		
3# fine sand	650	0	399	273	135	2.0	34.5
		50	353	/	/		
		100	251	/	/		

Table 5 The apparent cohesion versus matrix suction of sand in bridge site

Soil sample	Apparent cohesion under various matrix suction (τ_{us}=c_T-c')/kPa			Regression equation	Coefficient of correlation
	20kPa	50kPa	100kPa		
1#Silty sand	10.3	25.5	42.1	$\tau_{us}=0.7585(u_a-u_w)^{0.8808}$	0.9928
3#Fine sand	9.5	19.1	31.7	$\tau_{us}=1.0098(u_a-u_w)^{0.7494}$	0.9999

3.3 *Shear strength of gassy sand variation with gas release*

We process derivation to the equation (3) and yield the equation (4) for analyzing the shear strength of gassy sand variation with gas release, the parameters of c', ϕ' and the σ_n and u_w are considered to be constants in a certain depth of soil layer.

$$\begin{aligned} \frac{d\tau}{d(u_a - u_w)} &= ab(u_a - u_w)^{b-1} - \tan\phi' \\ \frac{d^2\tau}{d^2(u_a - u_w)} &= ab(b-1)(u_a - u_w)^{b-2} \end{aligned} \tag{4}$$

Based on the criteria of increasing function and decreasing function by first order derivative and second order derivative, and parameters feature of a, b and ϕ', when the matrix suctions is less than 1.54kPa and 1.47kPa for gassy silty sand and gassy fine sand, respectively, the shear strength of gassy sand increases with suction, behaving as an increasing function, otherwise behaving as a decreasing function. In fact, it is difficult for the gassy sand in Hangzhou Bay Bridge site approaches to saturated state with only matrix suction of 1.50kPa during gas release without disturbing soil. Therefore, the shear strength of gassy sand will increase with the decrease of the gas pressure.

4 MODEL TESTS OF STEEL PIPE PILE AND ITS BEARING BEHAVIOR FOR GASSY SAND

4.1 *Test method and material*

Model tests of pile foundation under various matrix suction and dry density of fine sand are done in a developed apparatus for model tests in unsaturated soil, in which the suction is within 300kPa, the pore air pressure and pore water pressure can be controlled independently, the penetration resistance of model pile is measured by load transducer installed in the pressure cell.

A hollow stainless steel pipe with length of 30cm,outside diameter of 18mm and wall thickness of 0.2mm is used as model file to simulate the steel pipe pile. The dry density and matrix suction of fine sand are controlled in 1.50~1.78g/cm^3 and 0~100kPa,respectively, the pore water pressure is set to 500kPa. In order to match the actual construction of steel pipe pile, the model pile is firstly penetrated into 18cm depth of gassy sand layer and then the static-loading test is vertically carried out.

4.2 *Bearing behavior of pile foundation for gassy sand*

The result of model tests of steel pipe pile for gassy fine sand is listed in Table 7 and typical load versus displacement curve is shown in Fig.5, in which the Q~s curve belongs to the type of steep fall and the load to start point of steep drop is considered as the ultimate bearing capacity of model pile. It can be concluded that the ultimate bearing capacity of model pile is evidently influenced by the dry density and matrix suction of fine sand, and increases with the increasing of dry density and matrix suction, however, the former has more influence on the bearing capacity of model pile than the latter for fine sand.

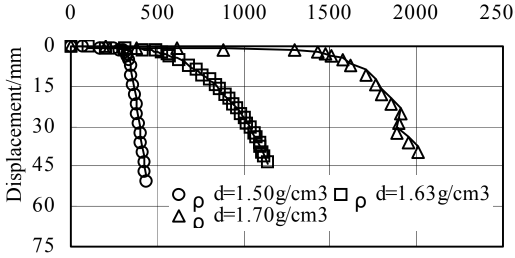

Figure 5 Typical Q-s curve of model pile (u_a-u_w=20kPa)

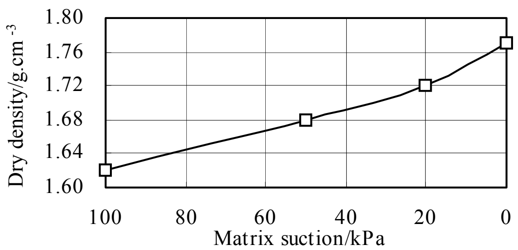

Figure 6 Dry density after consolidation versus matrix suction of fine sand in the unsaturated triaxial apparatus

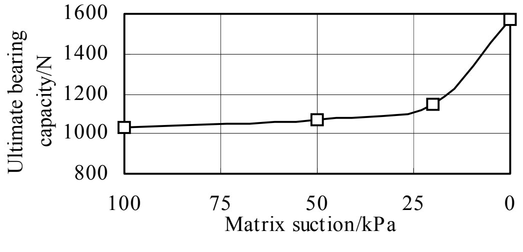

Figure 7 Ultimate bearing capacity of model pile in the fine sand with the gas release

Table 7 Ultimate bearing capacity of model pile for gassy sand

Matrix suction /kPa	Ultimate bearing capacity of model pile under various dry density /N			
	1.50/g.cm^{-3}	1.63/g.cm^{-3}	1.70/g.cm^{-3}	1.78/g.cm^{-3}
0	/	/	789	1680
20	304	495	999	/
50	378	727	1242	/
100	555	1054	1370	/

In order to simulate the variation of dry density of gassy fine sand with gas release, a fine sand sample with 1.50 g/cm^3 of initial dry density is firstly consolidated under the initial condition of σ_3=650kPa, u_a=600kPa and u_w=500kPa in unsaturated triaxial apparatus, then consolidated by decreasing the pore air pressure gradually. The dry density of fine sand after consolidation by gas release variation with matrix suction is shown in Fig.6. From Fig.6 and Table 7, the change characteristic of ultimate bearing capacity of model pile foundation in the fine sand of initial dry density1.50g/cm^3 and initial suction 100kPa under σ_3=650 kPa and u_w=500 kPa with the gas release can be approximately concluded in the Fig.7.

In summary, the bearing capacity of pile in gassy sand layer will increase with gas release though the increasing amplitude is different at the different stage of gas release, which are in accordance with the change of shear strength for gassy sand. The internal mechanism lies in the fact that the increase of net stress makes predominance over the ultimate bearing capacity of pile compared with the decrease of suction.

5 SUMMARY AND CONCLUSION

The influence of shallow biogenetic gas on the engineering behaviors of sand layer in Hangzhou Bay Bridge is determined by its three-phases composition state and special stress path due to due to the change of three-phase composition. The gas reservoir pressure and pressure coefficient for gassy sand layer are 515~530kPa and 1.03~1.06, and the gas pressure and matrix suction are less than 600kPa and 100kPa, respectively. The shear strength of gassy sand can be expressed as the unified formula τ_f=c'+(σ_n-u_a)tanϕ'+τ_{us} and τ_{us}=a(u_a-u_w)^b ,which increases with the decrease of the gas pressure level.

The model tests of steel pipe pile in the unsaturated sand show that the Q-s curves of model pile belong to the type of steep fall and the ultimate bearing capacity of pile in gassy sand increases with the release of gas. However, the increasing amplitude of the ultimate bearing capacity is different at the different stage of gas release, which can be explained by the internal mechanism that the increase of net stress makes predominance over the ultimate bearing capacity of pile compared with the decrease of suction under the condition of gas release slowly.

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