

Research Article

Simulation Analysis of Temperature Effects on the Shear Behavior of Gassy Sand

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The gas in gassy sand is enclosed in the pores of soil skeleton mainly in the form of dissolved in water or free gas bubbles, which is considered to be a perfect equilibrium composed of soil particles, pore water, gas, temperature, and overlying pressure. If any of these elements changes, this balance will be destroyed, resulting in disturbance in its mechanical properties. It is generally assumed that the existence of closed gas bubbles will not affect the soil skeleton but increase the compressibility of pore fluid. Assuming that the closed gas bubbles follow Boyle's law and Henry's law, the relationship between pore pressure change and volume strain is established. On the basis of the constitutive model which can reflect the temperature characteristics of saturated sand proposed by the author previously, combined with the special characteristics of gassy sand, the effect of temperature effects on the shear behavior of gassy sand is preliminarily explored and analyzed. The results show that under the condition of drained shear, the increase of temperature will increase the shear strength of gassy sand, and the simulation results are in good agreement with the test data. Under the condition of undrained shear, the shear strength of loose gassy sand increases with the increase of temperature, while that of dense gassy sand decreases. Moreover, the larger the gas volume, the more obvious these phenomena tend to be. However, only qualitative simulation analysis is carried out for undrained shear, which needs further verification in combination with relevant tests.

1. Introduction

As a kind of special unsaturated soil, gassy soil is widely distributed in coastal areas and alluvial plains. During the construction of subway, foundation pit, large sea crossing bridge, deep-water port wharf, and slope engineering in these areas [1–3], some engineering accidents have been caused due to the lack of understanding of the engineering mechanical properties of gassy soil [4–8]. Different from the general unsaturated soil, the gas in the gassy soil is in a closed state, that is, there are gas bubbles in the soil. Moreover, the existence forms of bubbles are also different in coarse-grained soil and fine-grained soil [9]. Generally, for fine-grained gassy soil, the size of gas bubbles is larger than that of soil particles and exists in the fully saturated soil matrix in the form of discrete large bubbles [10, 11], as

shown in Figure 1(a), while for coarse-grained gassy soil (such as gassy sand), gas bubbles are surrounded by pore water and exist freely in the pores of soil skeleton due to the size of bubbles is smaller than that of soil particles [12, 13], as shown in Figure 1(b). At present, there are many literatures on the research of fine-grained gassy soil [14–16]. This paper mainly studies the basic mechanical properties of coarse-grained gassy soil (gassy sand), especially the effect of temperature on its shear behavior.

At present, some achievements have been made in the research on the basic mechanical properties of gassy sand in terms of laboratory test and theoretical model [17–24]. It is found that under undrained conditions, gassy sand is easier to compress than saturated sand, and it is difficult to produce excess pore water pressure [20]. The existence of gas bubbles can increase or decrease the undrained shear

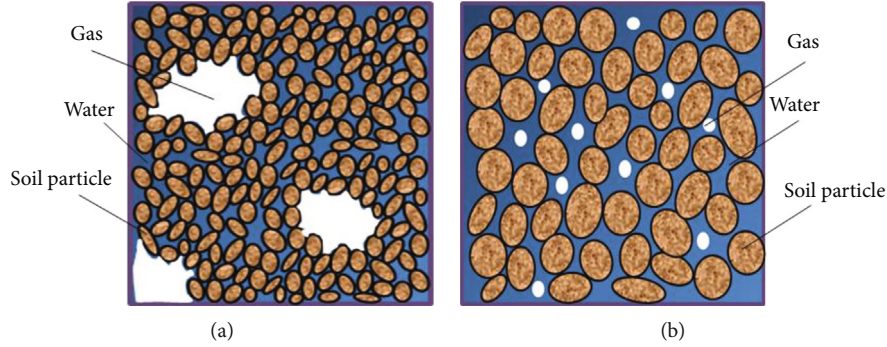


FIGURE 1: Existence forms of gas bubbles in gassy soil: (a) fine-grained soil; (b) coarse-grained soil.

strength of gassy sand, which is related to the initial state of sand, including initial pore water pressure and relative density [17–20, 24]. Under drained conditions, the shear strength of gassy sand is basically consistent with that of saturated sand [20]. Moreover, some theoretical models of gassy sand developed based on saturated sand models can well reflect the basic mechanical properties of gassy sand to a certain extent [22, 23, 25–27].

Because the gas in gassy sand is mainly sealed in the pores of soil skeleton in the phase state of dissolved in water or free gas bubbles, it is considered to be a perfect equilibrium composed of soil skeleton, pore water, gas, temperature, and overlying pressure [28]. If any one of these elements changes, this balance will be destroyed, resulting in changes in its mechanical properties. What is more, temperature has a very significant impact on soil [29–31]. Global warming, thermal decomposition of organic matter, and thermal injection exploitation of natural gas, as well as the construction of some underground projects, will change the temperature of the occurrence conditions of gassy soil, thus affecting its engineering mechanical properties [32–35]. For example, in energy pile foundation, the temperature range of surrounding soil is 5–50°C. Therefore, it is very important to study the temperature effects of gassy soil. Carry out the research on the engineering characteristics of gassy soil in complex environment, and master the evolution law of engineering properties of gassy soil disturbed by temperature change, so as to give the corresponding constitutive theory to reveal its catastrophe mechanism. Now the research on the temperature effects of gassy sand is in the preliminary exploration stage, and there are few reports in the existing literature. Yang and Bai [16] put forward a constitutive model that can simulate the thermal mechanical coupling characteristics of gassy soil and made a qualitative exploration and analysis on the temperature characteristics of gassy soil. However, the model is aimed at fine-grained gassy soil, and the influence of gas on soil skeleton deformation is considered. Zhu et al. [36] considered the effects of gas bubble thermal expansion, saturation degree, and distance from soil to water surface and established a constitutive model to simulate and study the mechanical behavior of gassy marine soil. The results show that with the increase of temperature, the pore pressure of gassy marine soil increases and dissipates gradually with the passage of time. And the larger the gas content, the larger the peak value of

excess pore pressure. Wang et al. [24] explored the drained shear characteristics of gassy sand at different temperatures through an improved temperature controlled multifunctional integrated triaxial instrument. It was found that the drained shear strength of gassy sand also increases with the increase of temperature.

Since most of the current theoretical models of gassy sand are improved based on the theoretical model of saturated sand, this paper attempts to give a constitutive model that can reflect the temperature characteristics of gassy sand based on the theoretical model that can reflect the temperature characteristics of saturated sand proposed by the author [37]. The influence of gas bubbles is considered in the model, and the temperature effects on gassy sand are discussed and analyzed based on the model.

2. A Model Reflecting Temperature Effects of Gassy Sand

The mechanical properties of gassy sand will be affected by pore fluid pressure, and the external load is an important factor causing the change of pore fluid pressure. Especially under undrained conditions, the applied stress will be borne by soil skeleton, pore gas, and pore water, and the proportion depends on their relative compressibility.

Therefore, the pore gas ratio e_g , pore water ratio e_l , and total pore ratio e can be defined as

$$\begin{aligned} e_g &= \frac{V_g}{V_s} = (1 - s_r)e, \\ e_l &= \frac{V_l}{V_s} = s_r e, \\ e &= e_l + e_g, \end{aligned} \quad (1)$$

where V_g , V_l , and V_s are the volumes of gas, liquid, and solid, respectively.

In addition, the surface tension of gas bubbles is generally ignored in gassy sand, that is, the air pressure is equal to the sum of external atmospheric pressure and pore water pressure [12, 13, 38], and assume that the gas phase follows Boyle's law and Henry's law as follows:

$$(p_{\text{atm}} + u_{l0})(V_{g0} + hV_{l0}) = (p_{\text{atm}} + u_l)(V_g + hV_l), \quad (2)$$

where $P_{\text{atm}} = 101.325 \text{ kPa}$ is a standard atmospheric pressure; u_{l0} , V_{l0} , and V_{g0} are the reference pore water pressure, pore water volume, and pore gas volume, respectively; u_l is pore water pressure; h is the dissolution coefficient (Henry constant), which can be taken as 0.02 for water gas fluid mixture [17].

Also, assuming that the gas satisfies the ideal gas equation, there is

$$u_g V_g = n_{\text{mol}} RT, \quad (3)$$

where n_{mol} is the molar weight of the gas, R is a constant, and T is the absolute temperature.

When the temperature and gas content are constant, Equation (3) can degenerate into Equation (2). The ideal gas equation shows that although the gas with the same content has different values of $u_g V_g$ at different temperatures, for gassy sand, when the temperature increases, the pore water pressure will also increase. As the temperature tends to be stable, the pore water pressure will dissipate with time and finally stabilizes. In other words, the increase of temperature will cause the excess pore water pressure of the gassy sand, and it will dissipate slowly with the passage of time [36]. In this process, according to the assumptions, the pore gas pressure also experiences the same change. According to Equation (3), when the pore pressure is completely dissipated, the gas volume will increase and be proportional to the temperature, that is, $V_1/V_0 = T_1/T_0$, where V_0 and T_0 are the reference temperature and the gas volume at the reference temperature, respectively, and V_1 and T_1 are the temperature value and the gas volume after heating, respectively.

Under undrained conditions, pore gas and pore water are not allowed to drain, so any external disturbance will cause the change of pore pressure. Different from saturated soil, although it is under undrained conditions, due to the large compressibility of gas, external disturbance will also cause volume change. Hilf [39] established the relationship between pore gas pressure and pore gas volume under undrained loading based on Boyle's law and Henry's law as follows:

$$\Delta u_g = \left(\frac{\Delta n}{(1 - s_{r0} + h s_{r0}) n_0 - \Delta n} \right) u_{g0}, \quad (4)$$

where Δu_g is the change of gas pressure, u_{g0} is the initial absolute gas pressure, s_{r0} is the initial saturation degree, n_0 is the initial porosity, and Δn is the change of porosity.

Hilf [39] established the above equation by assuming that the change in pore water pressure is equal to the change in pore gas pressure. For gassy sand, according to Equation (2), the change in pore gas pressure can be regarded as the same as the change in pore water pressure [40], which satisfies Hilf's hypothesis. Therefore, through appropriate transformation, Equation (4) can be expressed as the relationship between pore water pressure and volumetric strain as follows:

$$\Delta u_l = \frac{u_l + P_{\text{atm}}}{(1 - s_{r0} + h s_{r0}) n_0} \Delta \varepsilon_v = \frac{(u_l + P_{\text{atm}})(1 + e)}{e_g + (e - e_g)h} \Delta \varepsilon_v, \quad (5)$$

where $\Delta \varepsilon_v$ is the change of volumetric strain.

For gassy sand, the gas bubbles are relatively small and the occluded bubbles are surrounded by water within the void space, as shown in Figure 1(b); thus the soil matrix will not be disturbed. Then, the pore gas pressure u_g is generally assumed to be equal to the sum of atmospheric gas pressure P_{atm} and the pore water pressure u_l , i.e., $u_g = P_{\text{atm}} + u_l$, which implies that the surface tension is neglected. Therefore, the effective stress of gassy sand generally adopts the same form as that of saturated soil, that is, Terzaghi's effective stress principle is still applicable [12, 13].

The authors previously proposed a thermodynamic constitutive model [37], which can reflect the temperature characteristics of saturated sand. The model considers the energy dissipation at the granular level caused by temperature change [41], and the relationship between the energy dissipation process of gassy sand and the macro mechanical behavior is established through the migration coefficient and energy density function model. In addition, the dilatancy equation considering state parameters is combined with model parameters, which can effectively describe the influence of temperature on the strength and deformation characteristics of gassy sand under different relative densities and effective confining pressures. Assuming that the change of gas phase caused by heating does not affect the deformation of soil skeleton (gas bubbles are still free in the pores of soil skeleton), on this basis, combined with the special characteristics of gassy sand, the temperature effects on the mechanical properties of gassy sand can be analyzed.

3. Temperature Effects on Gassy Sand

The model parameters can be determined following the procedure shown in Yang et al. [37] on saturated sand and Yang et al. [27] on gassy sand. In order to fully verify the effectiveness of the proposed model, several groups of test data of gassy sand are used [17, 19, 42, 43], including drained and undrained shear tests. The specific model parameters are listed in Table 1.

3.1. Drained Shear Behavior. With the increase of temperature, the drained shear strength of saturated sand also increases. Since the shear characteristics of the gassy sand are similar to those of saturated sand under the drained condition [20], the shear strength of the gassy sand will also increase. Wang et al. [24] conducted an experimental study on the drained shear behavior of saturated sand and gassy sand by using an improved temperature-controlled triaxial test device and found that the drained shear strength of both saturated sand and gassy sand increases with the increase of temperature. Under the same temperature condition, the drained shear strength of gassy sand is higher than that of saturated sand as shown in Figure 2.

During the shear process, the closed gas bubbles in the pore water of gassy sand are forced to migrate and trapped

TABLE 1: Model parameters.

Meaning of parameters	Parameters	Rad et al. [17]	Grozic et al. [42]	He and Chu [19]	Liu [43]
Stress ratio at the critical state	M	1.4	1.19	1.22	1.434
Slope of CSL	λ_c	0.04	0.0159	0.04	0.012
Intercept of CSL	e_T	0.886	0.92	0.806	0.404
	ξ	0.7	-	-	0.7
Parameters of dilatancy function	m	3.5	3.5	3.5	3.5
	d_0	15	50	50	15
Slope of compression curve in e - $\lg p$ plane	λ	0.03	0.25	0.2	0.036
Specific gravity	G_s	2.63	2.67	2.67	2.63
	ζ	15	7	7	9.5
Material parameter	B_0 (kPa)	1.653×10^{14}	2.128×10^{12}	2.128×10^{12}	5.718×10^{14}
	b_1	0.6	1.1	1.1	0.6
	c_3	9×10^4	8×10^4	8×10^4	9×10^4
Thermodynamic parameters	c_4	4.0×10^{-5}	4.0×10^{-5}	4.0×10^{-5}	4.0×10^{-5}
	c_5	800	800	800	800

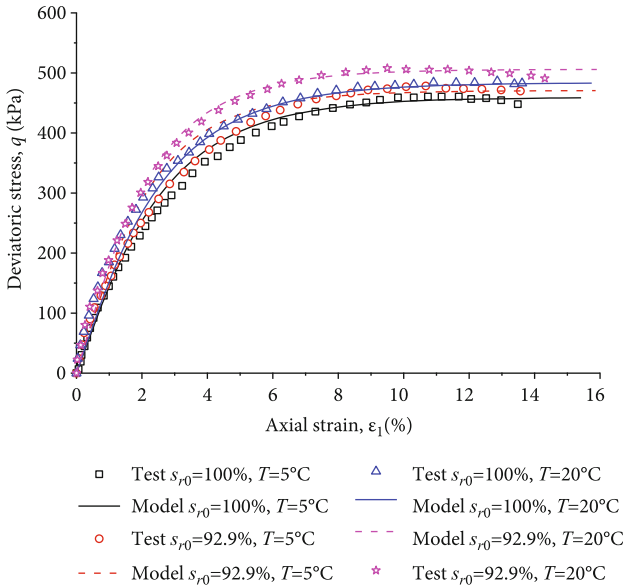


FIGURE 2: Simulation of stress-strain relationships of drained shear of gassy sand at different temperatures (test data after Wang et al. [24]).

in one place due to capillary resistance. With the increase of shear, more and more gas bubbles gather and form large bubbles around the particle contact part, resulting in suction and increasing shear resistance, so as to increase the shear strength [24]. In addition, with the increase of temperature, the thermal expansion of gas bubbles and the dissolution of dissolved gas lead to the increase of gas volume. Therefore, the increase of temperature further increases the drained shear behavior of gassy sand, which can be well simulated by the model as shown in Figure 2.

3.2. Undrained Shear Behavior. As the gassy sand is generally located in marine sedimentary soil, which is approxi-

mately in the condition of undrained, so more research is focused on its undrained shear behavior. Some scholars have studied the undrained shear behavior of gassy sand under ambient temperature and found that gassy sand shows strain softening or strain hardening during undrained shear, depending on its initial state (loose or dense), initial saturation degree, pore ratio, and so on. When the initial saturation degree is large ($>90\%$), that is, the bubble volume content e_g is small, the loose gassy sand soil generally shows strain softening and even liquefaction; while when the saturation degree is small (80%-90%), that is, the bubble volume content e_g is large, the gassy sand generally shows strain hardening. In addition, under the same initial conditions, the undrained shear strength of gassy sand is slightly higher than that of saturated sand [19, 42]. What is more, the excess pore water pressure caused by the undrained shear is smaller than its saturated equivalent value because the stiffness of the gas-water mixture in the former is reduced. Therefore, for loose gassy sand, the existence of gas bubbles is “beneficial” to its undrained shear strength, and the more the gas volume is, the more obvious this benefit is [23].

However, for the dense sand, when it is completely saturated with water, it generally shows strain hardening. And when it contains gas bubbles, the shear strength decreases significantly, with slight shear softening. Moreover, when the gas bubble volume is larger, the corresponding shear strength is slightly lower [17]. And the induced excess pore water pressure is less than its saturated equivalent value because the stiffness of gas water mixture in the former is reduced. The accumulated negative pore water pressure intensifies this effect, resulting in gas dissolution and expansion, which further reduces the saturation degree of gassy sand. This indicates that for dense sand, the existence of gas bubbles is “detrimental” to the undrained shear strength of gassy sand [23].

Therefore, according to the test data, it can be concluded that the bubble volume content has an enhancement effect

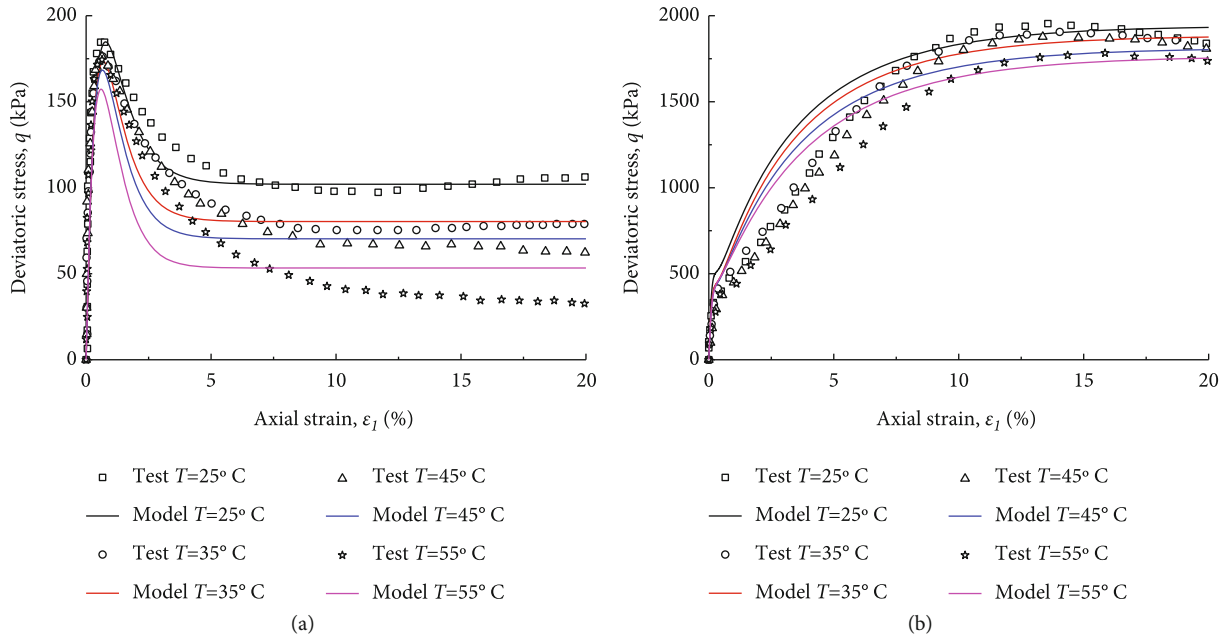


FIGURE 3: Simulation of undrained shear stress-strain relationships of saturated sand with different relative density at different temperatures ($p' = 400$ kPa, $u = 300$ kPa): (a) $D_r = 20\%$; (b) $D_r = 70\%$ (test data after Liu [43]).

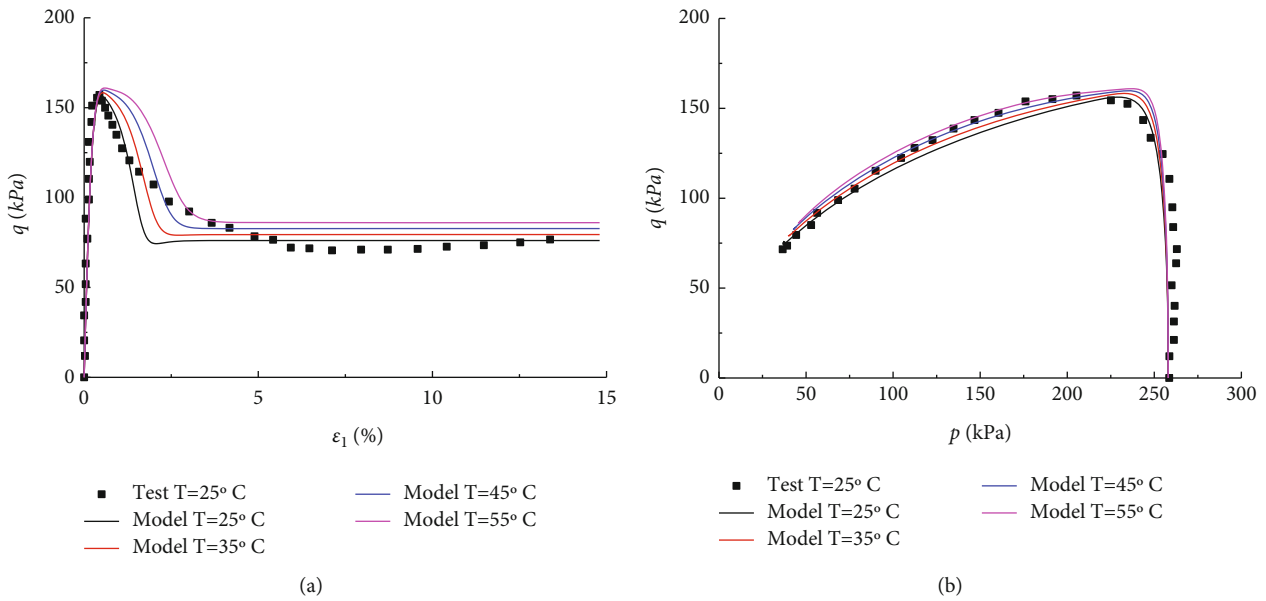


FIGURE 4: Simulation of undrained shear properties of loose gassy sand at different temperatures ($s_{r0} = 0.98$): (a) stress-strain relationship; (b) effective stress path (test data after Grozic et al. [42]).

on the shear strength of loose sand, but a weakened effect on the shear strength of dense sand.

The test data show that the undrained shear strength decreases with the increase of temperature for both loose and dense saturated sand [43, 44], as shown in Figure 3. The undrained shear test is conducted after thermal consolidation, regardless of loose or dense samples, and with the increase of temperature, test soil samples produce negative thermal bulk strain (thermal expansion) after thermal consolidation. Therefore, at the beginning of undrained shear, the soil sample with high temperature has a larger initial

porosity ratio, that is, the soil sample is more loose. The theoretical model proposed in this paper can capture this temperature characteristic of saturated sand as shown in Figure 3.

However, in the existing literature, the author has not found any direct correlation study on temperature effect of undrained shear characteristics of gassy sand. Therefore, based on the model given in this paper, the temperature characteristics of undrained shear of gassy sand are only qualitatively simulated and analyzed, and further analysis can be carried out in combination with relevant tests.

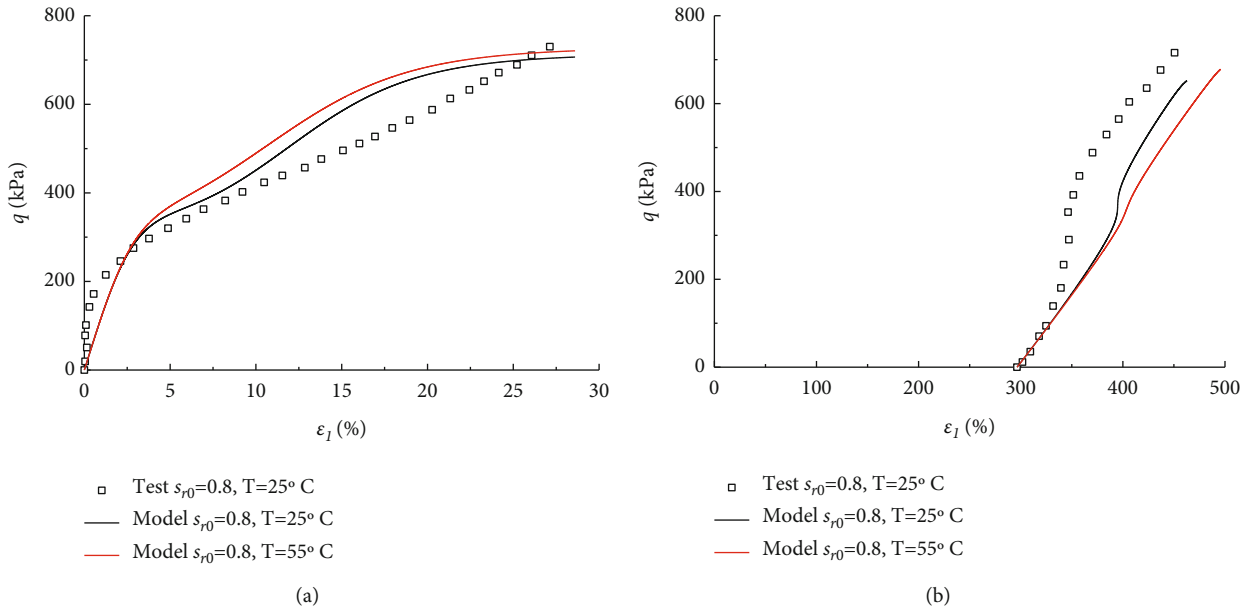


FIGURE 5: Simulation of undrained shear properties of loose gassy sand at different temperatures ($s_{r0} = 0.81$): (a) stress-strain relationship; (b) effective stress path (test data after Grozic et al. [42]).

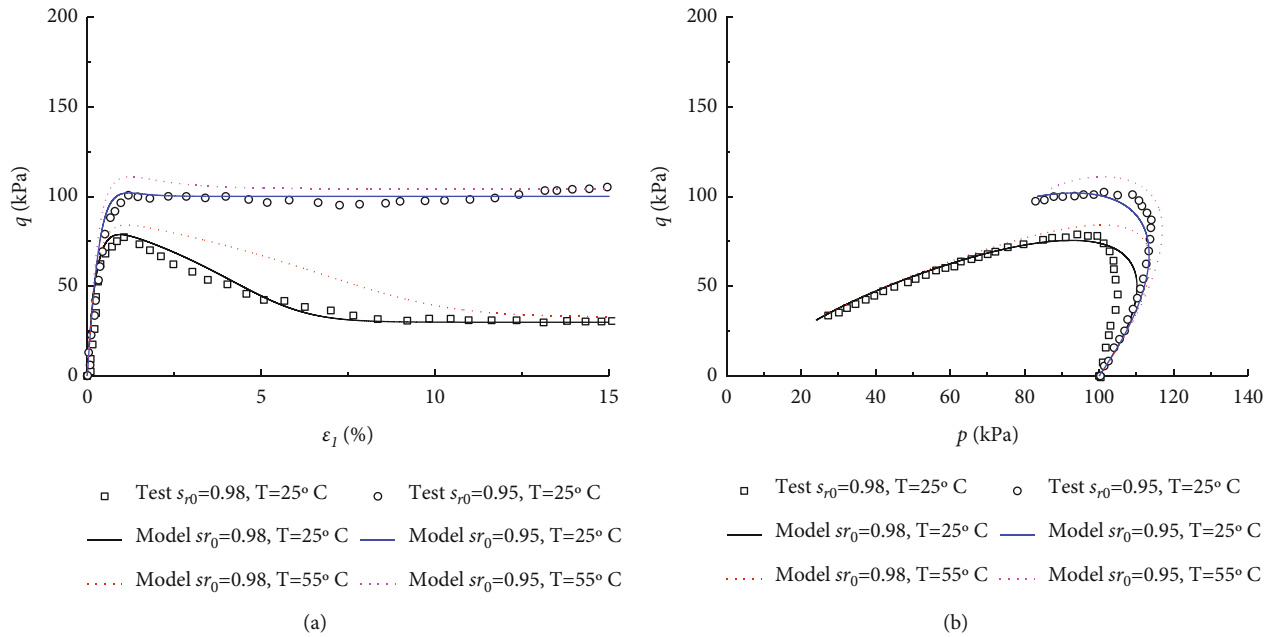


FIGURE 6: Simulation of undrained shear properties of loose gassy sand with different initial saturation at different temperatures: (a) stress-strain relationships; (b) effective stress path (test data after He and Chu [19]).

(1) Temperature characteristics of loose gassy sand

In the process of thermal consolidation of gassy sand, when the temperature increases, the excess pore pressure will be generated, and the excess pore pressure will dissipate slowly with the passage of time [36]. According to the above assumptions, during the heating process, the pore gas pressure also increases first and then decreases, and the volume of pore gas will increase after stabilization. As mentioned above, for loose gassy sand, the increase of gas volume

content (decrease of saturation degree) is beneficial to the increase of undrained shear strength. However, from another perspective, similar to saturated sand, the increase of temperature leads to the decrease of undrained shear strength, which is detrimental to the increase of shear strength. Therefore, the effects of gas volume and temperature on the undrained shear strength of gassy sand cancel each other out, and their specific effect degree is related to the initial conditions and the applied temperature, which should be statistically analyzed in combination with the test

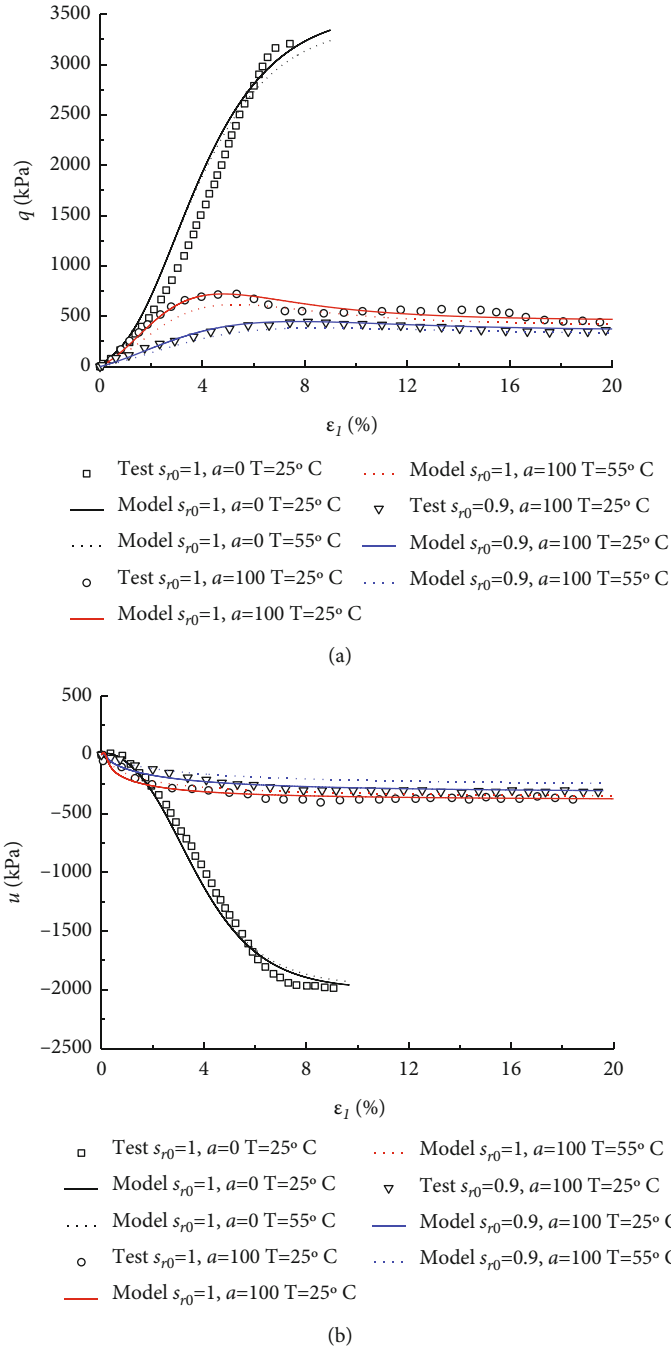


FIGURE 7: Simulation of undrained shear properties of dense gassy sand with different initial saturation at different temperatures: (a) stress-strain relationships; (b) excess pore water pressure (test data after Rad et al. [17]).

data. According to the test data of saturated sand affected by temperature change and the change of undrained shear strength of gassy sand under different gas volume, it can be inferred that the increase of undrained shear strength caused by the increase of gas volume is greater than the decrease of shear strength caused by the applied temperature, and it is more obvious when the saturation degree is small.

According to the simulation results of the proposed theoretical model, with the increase of temperature, the peak strength and final critical state of undrained shear of loose

gassy sand will increase slightly as shown in Figures 4 and 5, which is the same as the rule deduced above. Figure 4 shows the simulation results of strain softening when the saturation is high ($s_{r0} = 0.98$). It can be seen that with the increase of temperature, the difference between the peak strength and the final critical state strength becomes smaller and smaller, and the softening phenomenon decreases. Figure 5 shows the simulation results of strain hardening when the saturation is small ($s_{r0} = 0.81$), and the hardening phenomenon also increases with the increase of temperature. However, no matter strain

softening or hardening, the increase amplitude of undrained shear strength is small, which is the result of the cancellation of the influence degree of temperature and gas bubble volume mentioned above.

Similarly, He and Chu [19] also conducted an experimental study on the undrained shear characteristics of gassy sand with different initial saturation. It is also concluded that the undrained shear strength of gassy sand increases with the decrease of saturation (the increase of gas volume). The model simulation results show that when the temperature increases, the undrained shear strength of gassy sand also increases slightly, which is the same as the previous conclusion as shown in Figure 6.

(2) Temperature characteristics of dense gassy sand

For dense gassy sand, it is found that the existence of gas bubbles will reduce the undrained shear strength. As shown in Figure 7, Rad et al. [17] conducted undrained shear test on dense gassy sand ($D_r = 85\%$) and found that when it is completely water saturated ($s_{r0} = 1$, $\alpha = 0$, where α represents the amount of dissolved gas, and $\alpha = 0$ means there is no dissolved gas), the undrained shear strength of dense sand is very high, and the negative pore pressure generated by shear dilatancy is also relatively large. When there is dissolved gas in pore water ($s_{r0} = 1$, $\alpha = 100\%$), the undrained shear strength decreases obviously, and there is a slight shear softening. When free gas exists ($s_{r0} = 0.9$, $\alpha = 100\%$), the undrained shear strength further decreases, indicating that the gas bubbles reduce the undrained shear strength of dense gassy sand, which means that the gas has a “detrimental” effect. From the above analysis, it can be seen that the increase of temperature will also reduce the undrained shear strength of dense sand. At this time, temperature and gas bubbles play the same role. Therefore, increasing the temperature will reduce the undrained shear strength of dense gassy sand and the corresponding negative pore pressure, as shown in the model simulation results in Figure 7.

4. Conclusion

According to the existence state of gas bubbles in gassy sand and the hypothetical conditions satisfied by the gas, based on the thermal mechanical coupling model of saturated sand previously proposed by the author, this paper presents a theoretical model that can describe the temperature characteristics of gassy sand. Based on the model and the law summarized by relevant test data, the temperature characteristics of gassy sand are discussed and analyzed. The results show that the effect of temperature on the shear characteristics of gassy sand is also different under different conditions. Under the drained condition, when the temperature increases, the corresponding shear strength also increases, and it is related to the increase of gas volume caused by the increase of temperature, which is verified by relevant tests. Under the undrained condition, for loose gassy sand, the effects of temperature and gas volume cancel each other out, and the effect of temperature is larger. Therefore, the increase of temperature can improve the undrained shear

strength to a certain extent, while for dense aerated sand, both temperature and gas volume can reduce the undrained shear strength, so the increase of temperature can weaken the undrained shear strength. Moreover, the larger the gas volume, the more obvious these phenomena tend to be.

In recent years, although the research on the basic mechanical properties of gassy sand has attracted more and more attention, there are few reports on the temperature characteristics of gassy sand. This paper attempts to give a theoretical model that can reflect the temperature effects on gassy sand and makes a preliminary theoretical analysis on it under different conditions. The relevant conclusions need to be further verified by corresponding tests.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

G.Y. proposed the theoretical model and wrote the manuscript; P.C. collated and analyzed the test data; Y.L. reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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