The Study of Factors on the Heat Transfer Characteristics of Interface between Cast-in-Place Concrete and Frozen Soil

JI Yanjun, HU Yupu, LUO Tao
(Shaanxi Key Laboratory of Safety and Durability of Concrete Structures, Xijing University, Xi’an 710123, China)

Author's brief introduction: JI Yanjun (1979-), male, graduated from the University of Chinese Academy of Sciences in 2008, an associate professor. He is mainly engaged in the study of frozen soil engineering and materials in cold regions.

E-mail: 59772029@qq.com.

Abstract: The heat transfer characteristics of cast-in-place concrete-frozen soil contact surface directly affect the surface freezing strength of cast-in-place pile, and it is important to study the heat transfer characteristics of cast-in-place concrete-frozen soil contact surface for Pile Foundation design and construction in frozen soil area. Based on the small model pile test, a numerical analysis model is established to calculate the heat transfer characteristics during concrete poured in situ. The results show that the heat flow of 0.5h concrete and the contact surface of frozen soil increases by 381.2% when the pouring temperature raised from 5 to 30℃. The water-cement ratio increased from 0.4 to 0.6, and the heat flux of 0.5h contact surface is reduced by 23.7%. The temperature of the contact surface increased first and then decreased, and the peak is near the liquid limit of soil. When the temperature of frozen soil decreased from -1 to -3℃, the temperature of the contact surface increased with the decrease of the temperature of the frozen soil. The thermal conductivity and transformation of the thermal effect of phase transition have played a decisive role. 0~1h (especially 0~0.5h) is the main time for the heat released from concrete to frozen soil.

1. Introduction
In order to support the economic and social development of Tibet and Qinghai, the state has invested a great deal of manpower and financial resources to build a number of major projects, such as the Qinghai-Tibet Highway, the Qinghai-Tibet Railway, ±400kV DC interconnection project, and the Beijing-Tibet Expressway under construction. With the improvement of engineering construction grade and ecological protection requirements, the design concept of "Bridge for Roadway" has been widely used in large-scale, and pile foundations (especially cast-in-place piles) have also been widely used. Cast-in-place pile foundation has many advantages, such as high mechanization of construction, reliable quality of pile body, wide application range and environmental protection[1-4].

For the pile foundation in frozen soil area, the influencing factors of frozen strength mainly include the roughness of interface, soil temperature, water content and particle size distribution[5]. Zhang Wen et al.[6] from laboratory tests on typical soil samples of Fenghuo mountain in the Qinghai-Tibet Plateau showed that the frozen strength of coarse-grained soil is greater than that of fine-grained soil.
in the range of -7℃. Wang Yuping\cite{7} chose silt and aluminium, concrete, plexiglass and wood to carry out direct shear tests under different water content and temperature conditions, and studied the attenuation law of interfacial strength parameters. Wen Zhi et al.\cite{8}, Dong Shengshi et al.\cite{9} measured the freezing strength of prefabricated concrete blocks and Qinghai-Tibet silt at different temperatures and moisture content. Lu Peng et al.\cite{10} measured the mechanical properties of the interface between precast concrete block and silty clay by using the self-developed fully automatic direct shear test system. From the analysis results of influencing factors of freezing strength, it can be seen that the existing research is mainly aimed at fixed and existing contact surface, not applicable to cast-in-place piles in frozen soil area.

The construction technology of cast-in-place concrete pile is adopted\cite{11}. Its characteristics are that the temperature of cast-in-place concrete and the heat released by the hydration heat of concrete will cause thermal disturbance to the frozen soil around the pile, resulting in different degrees of melting of the pile base and surrounding soil\cite{12,13}. Ji Yanjun et al.\cite{14} adopted the method of making frozen soil samples first, then pouring concrete on the basis of frozen soil samples, which simulated the forming process of cast-in-place piles in frozen soil area more truly and effectively, and the test results of frozen strength obtained were closer to the actual situation. The test results show that the frozen strength of cast-in-place piles depends on the thermal invasion ability of concrete to frozen soil. If the intrusion ability is strong, the rough contact surface will be formed, and the freezing strength will be increased; if the intrusion ability is weak, the opposite will be true. The roughness of contact surface is controlled and influenced by two factors, concrete and frozen soil. The roughness of the interface increases with the increase of concrete pouring temperature and the decrease of water-cement ratio, and increases with the decrease of frozen soil temperature between -1℃ and 3℃. The roughness increases first and then decreases with the increase of frozen soil ice content, and the inflection point is near the liquid limit of frozen soil.

When concrete is poured in frozen soil, how the above factors affect the heat transfer process is a key problem in the formation of frozen strength of cast-in-place pile surface in frozen soil area. However, little research has been done. In this paper, the heat transfer process of small-sized cast-in-place piles under test conditions is calculated by numerical simulation method. The characteristics of heat flow and temperature change at the interface between piles and frozen soil are analyzed with the increase of water content in frozen soil. The variation law is preliminarily analyzed and discussed from the angle of thermal conductivity and phase change heat of frozen soil. The results provide data support for the formation of freezing strength.

2. Numerical Method

2.1. Numerical Model
According to the experimental conditions of small-scale cast-in-place piles, silty clay, a typical soil type in Qinghai-Tibet Plateau, is selected as the frozen soil around the piles, and the numerical simulation is carried out by using ANSYS analysis software and cylindrical coordinate system. The physical model of numerical calculation is established as shown in Fig.1(a) and the finite element model as shown in Fig.1(b) (the thick black line in soil represents the contact surface).
2.2. Thermophysical Parameters

In addition to heat conduction, there is a large amount of ice in the soil when analyzing the heat conduction process of pile foundation in permafrost region. When the soil temperature changes near 0°C, it will cause the phase transformation of water molecules, which will have a greater impact on the soil temperature. In the calculation process, the phase transformation of ice-water must be considered\[^{[15]}\], and the phase transformation of frozen soil should be solved by enthalpy method\[^{[16]}\].

In the calculation process, assuming that the phase change of water in soil only occurs in a certain temperature range (T), the phase change process can be expressed by the change of specific heat and thermal conductivity of soil (formula (1) and formula (2))\[^{[17]}\]:

\[
C = \begin{cases} 
C_f \frac{L}{2\Delta T} + \frac{C_f + C_u}{2} & T < T_e - \Delta T \\
\frac{C_f + C_u}{2} & T_e - \Delta T \leq T \leq T_e + \Delta T \\
C_u & T > T_e + \Delta T 
\end{cases} 
\]  

(1)

\[
\lambda = \lambda_f + \lambda_u - \frac{\lambda_f - \lambda_u}{2\Delta T} [T - (T_e - \Delta T)] \\
\quad \quad T_e - \Delta T \leq T \leq T_e + \Delta T \\
\lambda_f & T \geq T_e + \Delta T 
\]  

(2)

In the formula, \( C_f \) and \( C_u \) are the specific heat of frozen soil and unfrozen soil, \( \lambda_f \) and \( \lambda_u \) are the thermal conductivity of frozen soil and unfrozen soil, and \( L \) is the latent heat of phase transformation of frozen-thawed free water contained in unit mass soil, taking \( L = 334.56 \text{ kJ} \cdot \text{kg}^{-1} \).

Referring to the existing research results\[^{[12,18]}\] and the author's preliminary study on the thermophysical parameters of concrete, the values of the thermophysical parameters of each soil layer in the calculation are shown in Table 1.

| Soil Types     | Water Content/% | Dry Density/kg·m\(^{-3}\) | \( \lambda_f \) \text{[J·(h·m·K)\(^{-1}\)]} | \( \lambda_u \) \text{[J·(kg·K)\(^{-1}\)]} | \( C_f \) \text{[J·(kg·K)\(^{-1}\)]} | \( C_u \) \text{[J·(kg·K)\(^{-1}\)]} |
|----------------|-----------------|---------------------------|---------------------------------|-----------------|----------------|----------------|
| Silty Clay     | 15              | 1600                      | 3672                            | 3996            | 906           | 1170           |
|                | 20              | 1560                      | 4977                            | 4474            | 1108          | 1344           |
|                | 30              | 1280                      | 6022                            | 3931            | 1275          | 1730           |
|                | 40              | 1050                      | 6320                            | 4165            | 1441          | 2024           |
| Ice            | /               | 650                       | 8064                            | 2016            | 2090          | 4180           |
| Water-Cement ratio | 0.4            | /                         | 9756                            | 1050            | 9756          | 1050           |
|                | 0.5             | /                         | 8208                            | 1250            | 8208          | 1250           |
|                | 0.6             | /                         | 6264                            | 1550            | 6264          | 1550           |
2.3. Control Equation and Boundary Conditions

In the cylindrical coordinate system, the heat conduction process in soil and concrete follows the equation:\[19]\:

\[
\frac{\partial}{\partial t}
\left(
\frac{\rho C}{r^2} \frac{\partial T}{\partial t}
\right)
+ \frac{1}{r} \frac{\partial}{\partial r}
\left(
\lambda r \frac{\partial T}{\partial r}
\right)
+ \frac{\partial}{\partial z}
\left(
\lambda \frac{\partial T}{\partial z}
\right)
+ \Phi = 0
\]

Formula (3): \(C\) denotes volume heat capacity; \(\lambda\) is coefficient of heat conduction; \(\rho\) is density of soil; \(T\) is temperature; \(t\) is time; \(\Phi\) is heat source.

For a two-dimensional model, formula (3) can be simplified as follows:

\[
\frac{\partial}{\partial t}
\left(
\frac{\rho C}{r} \frac{\partial T}{\partial t}
\right)
+ \frac{1}{r} \frac{\partial}{\partial r}
\left(
\lambda r \frac{\partial T}{\partial r}
\right)
+ \frac{\partial}{\partial z}
\left(
\lambda \frac{\partial T}{\partial z}
\right)
+ \Phi = 0
\]

The variation of total heat released during cement hydration with time is in accordance with:

\[
Q = Q_0 (1 - e^{-mt})
\]

Formula (5) \(m\) is an empirical coefficient related to the type of cement and injection temperature. The values are shown in Table 2. \(Q_0\) is the heat dissipation of 1 kg cement, and the main mineral contents are: 39% tricalcium silicate, 28% dicalcium silicate, 11% tricalcium aluminate and 22% tetracalcium ferrialuminate. According to the heat released during hydration of mineral composition per unit mass, the final hydration heat of 1 kg cement \(Q_0 = 400\ \text{kJ}^{[20]}\).

| Molding Temperature/°C | 5     | 10    | 15    | 20    | 25    | 30    |
|------------------------|-------|-------|-------|-------|-------|-------|
| \(m\) (1/d)            | 0.295 | 0.318 | 0.340 | 0.362 | 0.384 | 0.406 |

The variation of hydration heat generation rate per unit mass concrete with time is obtained by calculating the derivative of heat \(Q\) released in equation (5). The variation of hydration heat generation rate per unit volume of cement with time is obtained by multiplying the derivative by unit volume of cement and reduced mixture. See 6:

\[
\theta(t) = (W + kF) \frac{\hat{Q}}{\hat{t}} = (W + kF) mQ_0 e^{-mt}
\]

Formula: \(W\) is the amount of cement in each cubic meter of concrete; \(F\) is the amount of mixture; \(K\) is the reduction factor, take 0.25.

For the adiabatic boundary shown in Fig. 1(a), the boundary conditions can be expressed as (7):

\[
\frac{\partial T(x, y, t)}{\partial x} = \frac{\partial T(x, y, t)}{\partial y} = 0
\]

3. Discussion

According to the above calculation model, the pouring temperature, water-cement ratio, frozen soil temperature and water content of different concrete are simulated. The calculation results are shown in Figure 2-5.

In Figure 2, the positive heat flux denotes that the heat flux is a horizontal heat flux from concrete to frozen soil, which is used later.
Fig. 2 Relationship between heat flux, temperature and pouring temperature

It can be seen from Fig. 2(a) that the heat flux of the contact surface decreases unidirectionally at different pouring temperatures, which is basically the same as the previous research results\[12\]. At the same time, from the point of view of heat release time, 0-1 h (especially 0-0.5 h) is the main time for heat transfer between concrete and frozen soil. After this time, the heat release rate slows down obviously, and the difference is not obvious.

From Figure 2(b), it can be seen that the temperature of the contact surface increases first and then decreases during the pouring process. The temperature of the contact surface is 1.86℃ at the beginning of pouring at 20℃, which is affected by the temperature of frozen soil. Then the temperature rises rapidly and reaches the maximum value of 5.53℃ at 0.5 h, which corresponds to the maximum heat flow released by the concrete at that stage. Then the temperature begins to decrease, drops to 4.77℃ at 1.0h and to 1.73℃ at 3.0h. It can be seen from this that increasing the pouring temperature can significantly increase the heat release and promote the "thermal invasion" of concrete into frozen soil.

Fig. 3 shows the heat flow and temperature curves of the interface when the pouring temperature is 20℃ and the water-cement ratio is 0.4, 0.5 and 0.6 respectively when the concrete is poured in the frozen soil with 30% water content and -3℃. The experiment is mostly based on the pouring at room temperature, so the simulation results of 20℃ are mainly introduced in the following paper.

Fig. 3 Relationship between heat flux, temperature and water-cement ration of concrete

It can be seen from Fig. 3(a) that at the beginning of concrete pouring, the heat flow of three water-cement ratios is basically the same at the interface; but after 0.5h, the heat flow of 0.4, 0.5 and 0.6 water-cement ratios of concrete is 18 482, 16 497 and 14099 kJ·m⁻²·h⁻¹, respectively; after 0.5h, the heat flow of the interface begins to decrease, while 0.4 water-cement ratio is the fastest, 0.5 water-cement ratio is the second and 0.6 water-cement ratio is the highest slow. It can also be seen from Fig. 3(b) that the temperature of the interface increases in an equal proportion with the water-cement ratio of concrete within 0.5h, but the temperature decreases differently after 0.5h, that is, the temperature decreases of 0.4 water-cement ratio of concrete are greater than 0.5 water-cement ratio of concrete; the heat flow of 0.6 water-cement ratio of concrete is the smallest.

This is mainly due to the different thermal conductivity and specific heat of three kinds of
water-cement ratio concrete. If the thermal conductivity of 0.4 water-binder is larger than that of concrete, the heat of concrete itself can be transferred to the frozen soil around the pile in a short time, resulting in a significant increase in the temperature of the contact surface. The thermal conductivity of 0.6 water-cement ratio is smaller than that of concrete, and the specific heat of 0.6 water-cement ratio is larger than that of concrete. Because of its slow heat transfer, the temperature of the contact surface rises slightly within 0.5h, but the exothermic process lasts longer and the rate of decline is slower.

Figure 4 shows the heat flow and temperature curves formed at the interface of concrete with temperature of –3°C, water content of 15%, 20%, 30%, 40% and pure ice, respectively.

**Fig 4 Relationship between heat flux(a), temperature(b) and water content of frozen soil**

From Fig. 4(a), it can be concluded that the heat flux of the interface is basically the same when the pouring temperature is constant and the water content of the frozen soil is different, that is to say, the heat released by concrete is mainly related to the pouring temperature, but less related to the water content of the frozen soil.

It can be seen from Fig. 4(b) that at 0.5h, under the conditions of 15%, 20%, 30%, 40% and pure ice, the contact surface temperatures reach 5.67, 5.53, 5.21, 4.83 and 1.75°C, respectively. It can be seen that when the heat transfer of concrete is basically the same, with the increase of ice content in frozen soil, the temperature of contact surface first increases and then decreases, and the inflection point is near the liquid limit of frozen soil. Moreover, when the water content increases to the pure ice state, the temperature will appear "lag" phenomenon, which is mainly due to the need for large phase change heat to melt pure ice, making its maximum temperature appear in 1.0 H.

The change of phase change heat and thermal conductivity of ice molecule in frozen soil is the main reason for the above phenomena. Phase change heat refers to the heat released or absorbed by the phase change of water in a unit volume of soil, which can be calculated by the following formula\(^\text{[18]}\):

\[
Q = L \cdot \rho_d \cdot (W - W_u)
\]  

(8)

In formula Q is phase change heat, unit kJ·m\(^{-3}\); L is latent heat of crystallization or melting of water, 333.51 kJ·kg\(^{-1}\) is taken for the determination of water phase composition in soil by calorimetry, 334.56 kJ·kg\(^{-1}\) is taken for general engineering thermal calculation; \(\rho_d\) is the dry density of soil; W is the total moisture content of soil, in decimals; \(W_u\) is the content of unfrozen water in frozen soil, in decimals. It can be seen from the formula that with the increase of ice content W, the phase change heat Q also shows an increasing trend. According to the relevant data, with the increase of ice content, the thermal conductivity also shows an increasing trend\(^\text{[21]}\).

Limit of liquid refers to the important limit water content of soil mass\(^\text{[22]}\). When the soil is frozen within the limit of liquid, the frozen soil is mainly composed of soil particles, supplemented by ice. With the increase of ice composition, the thermal conductivity and phase change heat increase, but the effect of thermal conductivity on the roughness of the contact surface is smaller and smaller, and the effect of phase change heat on the contact surface is greater and greater. When the water content is greater than the liquid limit, the soil structure changes, water is the main component in the soil, and soil particles become the secondary component. As the distance between soil particles becomes longer, the free gravity water is dominant among the particles, which makes the soil in a flow state\(^\text{[23,24]}\).
Because the soil is mainly ice and the soil particles are supplemented at this time, the phase change heat of ice plays a decisive role.

Fig. 5 shows the heat flow and temperature curves formed on the contact surface of concrete with water content of 30% and temperature of -3°C, -2°C and -1°C.

Fig. 5(a) shows again that when the pouring temperature is fixed and the frozen soil is poured at different temperatures, the heat flow on the contact surface is basically the same, that is to say, the temperature dependence of the frozen soil released heat by concrete is small.

In Fig. 5(b), the temperature of the contact surface increases rapidly with the release of heat from concrete in the period of 0-0.5 h, reaching a peak value near 0.5 h, and then decreases gradually with the decrease of heat flow of concrete, which is basically consistent with the temperature and time changes mentioned above. It can also be seen from the figure that the lowest peak temperature -1°C is 4.33°C, -2°C is 4.77°C, while the frozen soil temperature -3°C is the largest, reaching 5.52°C. This is mainly because as the temperature decreases, more liquid water in the frozen soil is converted into ice crystals, thus increasing the thermal conductivity of the frozen soil, which promotes the heat transfer process of the frozen soil in the shorter heat transfer process of concrete, that is, increasing the "thermal invasion" ability of the frozen soil.

It should be pointed out that, from the relationship between the roughness of the interface and the moisture content of frozen soil, it can be inferred that, with the decrease of temperature, the effect of thermal conductivity on the roughness of the interface becomes smaller and smaller at the initial temperature, and the effect of phase change heat on the interface becomes larger and larger; when the temperature drops to a certain temperature, i.e., the critical value, the phase change heat of ice in frozen soil plays a decisive role, thus the interface. Roughness tends to decrease. Therefore, the roughness of the contact surface increases with the decrease of temperature, only in the range of test temperature.

4. Conclusion

Based on the experimental conditions of small model piles, this paper establishes a numerical model to study the heat transfer characteristics of concrete-frozen soil interface during concrete pouring. The heat flow and temperature changes of concrete pouring temperature, water-cement ratio, frozen soil temperature and frozen soil moisture content are analyzed. The main conclusions are as follows:

1) The heat flux of the contact surface decreases unidirectionally at all pouring temperatures, and increases significantly with the increase of pouring temperature, which increases by 381.2% at 30°C compared with 5°C. Increasing pouring temperature can obviously increase heat release and promote thermal invasion of concrete into frozen soil.

2) The roughness of the contact surface increases first and then decreases with the increase of water content in frozen soil. The peak value is near the liquid limit of frozen soil, and the transformation of thermal conductivity and phase transformation plays a decisive role. When the water content increases within the liquid limit, the thermal conductivity increases with the increase of ice
molecules, which promotes the thermal intrusion of concrete. Water content continues to increase from liquid limit, ice molecules are dominant in soil, and soil particles are supplemented by phase change heat, which can inhibit the thermal invasion of concrete.

(3) When the temperature decreases between -1°C and -3°C, the ice molecules in the frozen soil increase, which increases the thermal conductivity of the frozen soil and promotes "thermal invasion".

(4) The heat transfer process occurring during the initial setting time of concrete plays an important role in the formation of the contact surface. Generally speaking, 0-1h, especially 0-0.5h, is the main time for heat transfer between concrete and frozen soil.

Acknowledgments
Foundation projects: National Natural Science Foundation of China: 51879207; High-level Talents Foundation of Xijing University: XJ17B05

References:
[1] MINISTRY of Housing and Urban-Rural Development of the People’s Republic of China. Code for design of soil and foundation building in frozen soil region(JGJ5118-2011)[S]. Beijing: China Architecture & Building Press, 2011: 8-9.
[2] PENNER E, Gold L W. Transfer of heaving force by adfreezing to columns and foundation walls in frost susceptible soils[J]. Canadian Geotechnical Journal, 1971, 8: 514-526.
[3] SADOVSIKIY A V. Adfreeze between ground and foundation materials[C]//Proceedings of 2th International Permafrost Conference. Yakutsk: [s.n.], 1973: 650-653.
[4] PERAMESWARAN V R. Creep of model piles in frozen soils[J]. Canadian Geotechnical Journal, 1979, 16: 69-77.
[5] CHEN Xiaobai, LIU Jiankun, LIU Hongxu, et al. Frost action of soil and foundation engineering[M]. Beijing: Science Press, 2006: 284-296.
[6] ZHANG Wen, ZHANG Weihong, PAN Qilai. Factors affecting intensity of the aged frozen earth[J]. Journal of Qinghai University (Nature Science), 2005, 23(4): 26-29.
[7] WANG Yu Ping. Experimental Research on the Shear Characteristics of Pile-soil Interface in Permafrost Region[M]. Lanzhou: Lanzhou Jiaotong University, 2014.
[8] WEN Zhi, YU Qihao, ZHANG Jianming, et al. Experimental study on adfreezing bond strength of interface between silt and foundation of Qinghai-Tibetan transmission line[J]. Chinese Journal of Geotechnical Engineering, 2013, 35(12): 2262-2267.
[9] DONG Shengshi, DONG Lanfeng, WEN Zhi, et al. Study of constitutive relation of interface between frozen Qinghai-Tibetan silt and concrete[J]. Rock and Soil Mechanics, 2014, 35(6): 1629-1633.
[10] LÜ Peng, LIU Jiankun. An experimental study on direct shear tests of frozen soil-concrete interface[J]. Journal of the China Railway Society, 2015, 37(2): 106-110.
[11] MINISTRY of Housing and Urban-Rural Development of the People’s Republic of China. Technical code for building pile foundations(JGJ94-2008)[S]. Beijing: China Architecture & Building Press, 2008: 102-114.
[12] CHEN Zhaoyu, LI Guoyu, MU Yanhu, et al. Impact of molding temperature and hydration heat of concrete on thermal properties of pipe foundation in permafrost regions along the Qinghai-Tibet DC Transmission Line[J]. Journal of Glaciology and Geocryology, 2014, 36(4): 818-827.
[13] GUO L, Yu Q, Li X, et al. Refreezing of cast-in-place piles under various engineering conditions[J]. Sciences in Cold and Arid Regions, 2015, 7(4): 376-383.
[14] JI Yanjun, JIA Kun, YU Qihao , et al. Direct shear test of freezing strength at the interface between cast-in-situ concrete and frozen soil[J]. Journal of Glaciology and Geocryology, 2017, 39(1): 86-91.
[15] CHEN Zhaoyu, LI Guoyu, QU Qihao, et al. Study of the thermal stability of cast-in-place pile foundation of the Qinghai-Tibet DC Transmission Project in permafrost regions[J]. Journal
of Glaciology and Geocryology, 2013, 35(5): 1209-1218.
[16] YANG Yongping, ZHOU Shunhua, WEI Qingchao. Numerical analysis of proper thermosyphon inclination angle used in permafrost regions[J]. China Railway Science, 2006, 27(3): 1-7.
[17] ZHANG M, Lay Y, Zhang J, et al. Experimental and numerical investigation on temperature characteristics of in-cuts roadbed in Qinghai-Tibetan railway[J]. Cold Regions Science and Technology, 2006, 46(2): 113-124.
[18] MINISTRY of Housing and Urban-Rural Development of the People’s Republic of China. Standard for test method of mechanical properties on ordinary concrete[S]. Bei Jing: China Architecture & Building Press, 2003: 4-13.
[19] HOLMAN J. Heat Transfer(10th Edition)[M]. Singapore: Mc Granw-Hill Book Company, 1986.
[20] SHI Huisheng, HUANG Xiaoya. Researchi progress of hydration heat in cement and concrete [J]. Cement Technology, 2009, 6: 21-26.
[21] XÜ Xiaozu, WANG Jiacheng, ZHANG Lixin. Physics of frozen soil[M]. Beijing: Science Press, 2010: 75-90.
[22] MINISTRY of Housing and Urban-Rural Development of the People’s Republic of China. Code for investigation of geotechnical engineering[S]. Bei Jing: China Architecture & Building Press, 2009: 10-13.
[23] CHEN Xizhe. Soil mechanics and foundation[M]. Beijing: Tsinghua University Press, 1998: 40-41.
[24] ZHOU Yuming, JIANG Jie, SU Yugu. The variation of soil water content affection the soil engineering Property from the microcosmic nature[J]. Shanxi Architecture, 2006, 32(24):7-8.