Geomechanics and Engineering, *Vol. 22, No. 4 (2020) 339-348*
DOI: https://doi.org/10.12989/gae.2020.22.4.339

Estimation of spatial autocorrelation variations of uncertain geotechnical properties for the frozen ground

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(Received April 4, 2020, Revised July 2, 2020, Accepted July 21, 2020)

Abstract. The uncertain geotechnical properties of frozen soil are important evidence for the design, operation and maintenance of the frozen ground. The complex geological, environmental and physical effects can lead to the spatial variations of the frozen soil, and the uncertain mechanical properties are the key factors for the uncertain analysis of frozen soil engineering. In this study, the elastic modulus, strength and Poisson ratio of warm frozen soil were measured, and the statistical characteristics under different temperature conditions are obtained. The autocorrelation distance (ACD) and autocorrelation function (ACF) of uncertain mechanical properties are estimated by random field (RF) method. The results show that the mean elastic modulus and mean strength decrease with the increase of temperature while the mean Poisson ratio increases with the increase of temperature. The average values of the ACD for the elastic modulus, strength and Poisson ratio are 0.64m, 0.53m and 0.48m, respectively. The standard deviation of the ACD for the elastic modulus, strength and Poisson ratio are 0.03m, 0.07m and 0.03m, respectively. The ACFs of elastic modulus, strength and Poisson ratio decrease with the increase of ratio of local average distance and scale of fluctuation. The ACF of uncertain mechanical properties is different when the temperature is different. This study can improve our understanding of the spatial autocorrelation variations of uncertain geotechnical properties and provide a basis and reference for the uncertain settlement analysis of frozen soil foundation.

Keywords: frozen soil; spatial variations; uncertain geotechnical properties; autocorrelation distance; autocorrelation function

1. Introduction

Over the past decade, the field measurement data of permafrost roadbed of Qinghai-Tibet Railway show that, even if the permafrost under the roadbed does not melt, the permafrost layer in the range of annual temperature variation had a great compression deformation due to the action of roadbed filling and driving load. Especially in warm and ice-rich frozen soil and high embankment area, the settlement and deformation of roadbed has considerable magnitude (Mu *et al.* 2018, Chen *et al.* 2018, Wang *et al*. 2018, Luo *et al*. 2018, Yu *et al.* 2019). Due to the absorptive heat of embankment slope, a warm frozen soil interlayer is gradually formed in the frozen soil foundation. The existence of this warm frozen soil interlayer poses a serious threat to the long-term stability of the permafrost roadbed of Qinghai-Tibet Railway, and it has caused roadbed settlement, cracking and other hazards (Ghiasi and Moradi 2018, Li *et al.* 2019, Wu *et al*. 2018, Liu *et al.* 2019a). Therefore, whether the foundation strength of warm permafrost region can meet the requirements and maintain the overall stability is an important issue concerned by scientists and engineers. Reasonable mechanical parameters of warm frozen soil are the key to calculate the strength and deformation of foundation in warm permafrost regions (Ming *et al.* 2018, Tang *et al.* 2018, Wang *et al*. 2019, Li *et al.* 2018). However, the warm frozen soil is composed of solid mineral particles, ice, unfrozen water and gas. Its properties are relatively complex, which are closely related to the soil property, water content, salt content, compactness, load history, temperature and other factors of the material. The ice content can contribute to the thermal properties and mechanical properties of frozen soil (Fang *et al.* 2018, Liu *et al.* 2019b, Zhang *et al.* 2019, Zhou *et al.* 2018, Ji *et al.* 2019). These complex geological, environmental and physical effects can lead to the result that the frozen soil exhibits obvious spatial variations (Lai *et al.* 2012, Liu *et al.* 2017). The spatial variations may result in unexpected deviations and unpredictability for the analysis and design of geotechnical structure (Elachachi *et al.*2012, El *et al.* 2019, Hamidpour *et al.* 2017, Lee *et al.* 2015). Therefore, considering the spatial variations of mechanical properties is very important for the frozen soil engineering in QTP.

RF theory could be applied to quantify the correlation and uncertainty characteristics of geotechnical materials at different spatial locations (Vanmarcke 2010, Chenari *et al*. 2019). Its essence is to use spatial RF to simulate the geotechnical parameters. The variance, variance function, correlation function, fluctuation scale and correlation distance are used to describe spatial variability and

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ISSN: 2005-307X (Print), 2092-6219 (Online)

Table 1 Grain size distribution

Number	Particle sizes and their percentages (%)				
	< 0.002 mm	0.002 mm~0.005 mm	0.005 mm~0.05 mm	0.05 mm~0.075 mm	> 0.075 mm
1#	6.34	23.09	37.20	18.73	14.64
2#	5.76	23.29	36.63	18.88	15.44
3#	6.41	22.46	34.72	23.89	12.52
4#	6.49	23.44	34.81	22.10	13.16
5#	6.43	24.28	36.57	21.56	11.15
6#	6.77	24.76	31.48	21.14	15.85
7#	6.40	27.46	37.68	18.36	10.10
8#	6.71	23.16	36.55	19.47	14.11
9#	5.28	25.50	35.33	20.62	13.28
10#	5.99	25.92	34.30	21.60	12.20

Table 2 Basic parameters of warm frozen soil

Number	Depth (m)	Density (g/cm^3)	Dry density (g/cm^3)	Water content (%)	Plastic limits (%)	Liquid limits (%)	Plasticity Index (%)
1#	0.9~1.0	1.88	1.54	22.58	15.49	27.41	11.93
2#	1.9~2.0	1.98	1.61	22.67	16.46	27.54	11.09
3#	2.9~3.0	1.82	1.46	24.46	17.72	29.26	11.54
4#	3.9~4.0	1.75	1.44	21.55	15.75	28.88	13.13
5#	4.9~5.0	1.79	1.48	20.51	16.44	29.84	13.39
6#	5.9~6.0	1.89	1.55	21.72	16.72	30.47	13.75
7#	6.9~7.0	1.77	1.44	23.57	15.64	27.11	11.46
8#	7.9~8.0	1.7	1.41	20.53	15.36	28.05	12.68
9#	8.9~9.0	1.83	1.49	22.84	17.91	29.47	11.56
10#	9.9~10.0	1.81	1.5	21.21	15.59	27.73	12.14

correlation of soil properties (Alhasan *et al.* 2018, Yi *et al.* 2020, Pan *et al*. 2018, 2019, 2020). Because the RF model can scientifically reflect the uncertain spatial variations of geotechnical materials, it is recognized that it can effectively describe the randomness of soil materials (Guellil *et al.* 2017, Khemis *et al.* 2016, Leung *et al.* 2018). At present, many literatures focus on the spatial variations and correlation structure for the uncertain soil properties (Titi *et al.* 2018, Yao *et al.* 2019, Fei *et al*. 2019). In warm permafrost regions, the spatial variations and correlation characteristics of mechanical parameters can lead to the result that the mechanical properties of engineering geology exhibits obvious randomness. A series of numerical studies reveals the statistical characteristics and dynamic development process of stochastic mechanical properties for frozen soil engineering in warm permafrost regions under global warming (Liu *et al.* 2014, Wang *et al.* 2018a, b, 2019a, b). However, due to the lack of actual statistical data in previous studies, some assumptions have been made on the statistical properties, spatial changes and related characteristics of uncertain mechanical parameters. According to the RF theory and local average (LA) method, the spatial autocorrelation variations of uncertain mechanical parameter are the important aspects for the stochastic analysis, which directly affects the stochastic mechanical properties of frozen soil engineering in QTP. Therefore, more analysis is necessary to estimate the spatial variations of uncertain mechanical properties.

This paper aims to estimate the spatial autocorrelation variations of uncertain mechanical properties for frozen soil in warm permafrost regions. The frozen soil samples are taken from QTP. It is located in the south of Kaixinling in Northwest China. A series of mechanical parameters tests of the warm frozen soil are carried out, and the statistical data of elastic modulus, strength and Poisson ratio under different temperature conditions (-2.0ºC, -1.5ºC, -1.0ºC, -0.5ºC and 0ºC) are obtained. Then the ACD and ACF of the uncertain mechanical parameters are estimated on the basis of the RF method. According to the statistical characteristics, ACD and ACF, the spatial autocorrelation variations of uncertain mechanical parameters for the warm frozen soil are analyzed in detail. This study can provide important basic data for the uncertain analysis of frozen soil engineering in QTP.

2. Materials and methods

2.1 Site description and soil collection

The frozen soil samples were collected from the south of Kaixinling on QTP (K1254+500 of Qinghai- Tibet Railway and K3181+000 of Qinghai-Tibet highway). The site used in this study is the Kaixinling section. This section has flat terrain, piedmont diluvial, and good vegetation coverage. The overall vegetation coverage is between 50% and 60%. The distance between highway and railway is about 305m, and the oil pipeline, telecommunication cable and 400KV transmission and transformation are all located in the section. There is a seasonal river in the section. The width of the river is about 8 m, and the width of water crossing is about 3 m, and the water depth is about 0.2 m~0.3 m. There are water pit and water flow caused by construction on the right side of the highway. Hence the engineering geological conditions are very complex. In this section, a series of temperature measuring holes are arranged on the left shoulder, right shoulder, left slope foot and natural ground. Field test data show that the average annual ground temperature of the site is about -0.6°C (Mu *et al.* 2018, Luo *et al*. 2018). Therefore, it is the warm permafrost regions, and the mechanical properties of the warm frozen soil are poor.

The spatial autocorrelation variation in horizontal direction is much smaller than that in vertical direction because the soils are layered. Therefore, the spatial autocorrelation variation in vertical direction has the larger effect on uncertain mechanical properties of frozen soil engineering in warm permafrost regions. This study investigated the spatial autocorrelation variations in vertical direction, and the frozen soil samples were collected along the vertical direction. The results can provide an important theoretical basis and reference for the uncertain settlement analysis of frozen soil engineering in QTP. First, the permafrost core was drilled with a drilling machine and the warm frozen soil cutter was used for preliminary dressing. During the drilling process, the hole was drilled vertically downward, and the sampling depth of warm frozen soil was also recorded. Then, in order to prevent the moisture loss, the frozen soil samples were put into the earthen pot to be stored. Finally, the frozen soil samples were numbered in sampling order, and then they were placed in the freezer to keep the frozen soil samples frozen. One frozen soil sample was collected every one meter, and ten frozen soil samples were collected from 1.0 to 10 meters. In this study, three groups of warm frozen soil samples were taken from the south of Kaixinling on QTP. Different soil classification has a large influence on mechanical properties. The soil index properties such as grain size distribution, water content, density, dry density, liquid limits, plastic limits and plasticity index had been tested by the basic geotechnical test. Table 1 and Table 2 are the detailed test results of the grain size distribution and basic parameters, ranging from 1.0 meters to 10.0 meters under the ground. It can be seen that the main component is silty clay and it is mainly in plastic state.

2.2 Sample preparation and test procedure

The soil samples were taken from QTP and each sample were obtained by hole-drilling method. All samples with preservative film were quickly put into the foam box. The ice bags were necessary in every foam box. The frozen soil samples were prepared in low temperature laboratory. The first step was to distinguish the upper and lower layers after opening the package of undisturbed samples. The second step was to use a steel saw to smooth the top and bottom of the sample. The third step was to cut and shape the frozen soil with a cutter. After these three steps, the diameter of frozen soil sample was 61.8 mm and the height of frozen soil sample was 125 mm. An experimental test apparatus was used exclusively for testing the warm frozen soil (Lu. 2015). This apparatus was equipped with a digital camera. It was used to perform a series of compression tests on frozen soils at temperatures close to 0°C. Two refrigeration circulators with a temperature fluctuation of ±0.05°C were connected to copper plates. A high-power fan and improved duct of heat exchange were utilized. This can reduces temperature fluctuations around the specimens. Using this system, the temperature was controlled to ±0.05°C in the incubator. The temperature at upper refrigeration plate was the same as the bottom plate. All the temperatures in incubator were monitored using the thermistors, and the precision is 0.01°C. Five different temperatures were imposed on the frozen soil samples, i.e. -2.0°C, -1.5°C, -1.0°C, -0.5°C, and 0°C. The mechanical parameters were measured after the temperature was constant. In this study, multistage loading method was adopted for undisturbed frozen soil. The final confining pressure was set as 0.5 MPa, 1.0 MPa and 1.5 MPa, and the triaxial test was conducted on each sample. The elastic modulus, strength and Poisson ratio are the key parameters of most constitutive model of frozen soil. Therefore, this study focused on the spatial autocorrelation variations of elastic modulus, strength and Poisson ratio. In detail, they could be tested by following steps.

(1) Sample installation. The thermostatic chamber and cryogenic thermostatic circulation tank were opened. The temperature was -1.0°C. The ambient temperature was lowered for more than an hour. The undisturbed samples were coated with latex film. They were put into the pressure chamber after the constant temperature test chamber and low temperature circulation tank were stable. The upper and lower surface of undisturbed samples should be closely contacted with the upper and lower surface of circulation tank.

(2) Temperature setting and mechanical scheme. The upper and lower ends were used to control the temperature of soil samples. The constant temperature box provided the external low temperature environment. Five mean temperatures were imposed on the soil samples, i.e. -2.0°C, -1.5°C, -1.0°C, -0.5°C, and 0°C. The temperature control time was over 12h. After the temperature had stabilized, the first final confining pressure was 0.5 MPa by adjusting the precision pressure controller. The triaxial test was carried out after confining pressure was stabilized for 5min. The axial loading rate was 1.25 mm/min.

(3) Data logging. After the measured differences of principal stress were basically stable, the loading was stopped and unloading was carried out. The axial load and strain value were recorded. The increments of confining stresses of the apparatus are 100 kPa, 200 kPa and 300 kPa when adjusting the final confining pressure. The final confining stresses are different for the different temperatures. In our study, the final confining stress of 0.5 MPa, 1.0 MPa and 1.5 MPa were applied for repeating the process of mechanical scheme. According to the recorded

Table 3 Elastic modulus of warm frozen soil

Number	Elastic modulus/MPa				
	-2.0℃	-1.5℃	-1.0℃	-0.5℃	0℃
1-1#,1-2#,1-3#	72.3,65.6,74.7	65.0,67.1,56.3	62.0,63.0,57.4	42.2,47.0,46.9	40.5,39.6,44.1
2-1#,2-2#,2-3#	60.6,69.3,70.9	62.7,66.8,58.4	67.2,59.2,58.8	48.6,44.2,49.1	42.5,36.3,36.7
3-1#, 3-2#,3-3#	67.3,71.0,76.5	64.1,58.1,60.9	58.6,59.2,63.2	42.6,45.2,53.6	45.3,41.5,37.0
4-1#,4-2#,4-3#	64.6,77.2,69.9	57.6,52.7,64.6	56.6,50.8,58.4	44.6,42.3,47.7	46.1,43.7,39.5
5-1#,5-2#,5-3#	63.1,61.6,76.1	67.7,68.7,63.1	60.5,58.6,55.5	46.2,45.5,49.4	39.7,42.0,36.3
6-1#,6-2#,6-3#	62.1,63.1,66.1	63.4,63.2,56.4	55.7,60.4,64.2	47.4,45.2,48.8	45.0,47.4,43.7
7-1#,7-2#,7-3#	69.0,72.3,62.5	54.2,61.8,67.5	65.1,55.1,61.0	46.4,52.1,48.4	41.1,40.5,40.7
8-1#,8-2#,8-3#	65.7,65.9,66.7	63.5,60.1,61.8	62.1,53.7,58.6	52.1,49.0,49.8	40.5,44.5,37.0
9-1#,9-2#,9-3#	67.9,61.5,73.0	66.6,55.7,69.0	52.8,56.9,60.4	51.7,46.9,50.6	43.6,38.9,38.5
10-1#,10-2#,10-3#	66.0,69.1,62.7	64.2,62.5,57.0	55.0,53.5,55.6	48.6,45.8,46.8	45.0,37.1,38.1

Table 4 Strength of warm frozen soil

Number	Strength/MPa				
	-2.0℃	-1.5℃	-1.0℃	-0.5℃	0℃
1-1#,1-2#,1-3#	1.62,1.52,1.63	1.60,1.44,1.40	1.14,1.41,1.18	0.87,0.95,0.85	0.57,0.72,0.54
2-1#,2-2#,2-3#	1.34,1.60,1.50	1.47,1.47,1.49	1.31,1.45,1.37	0.91,0.88,0.98	0.48,0.65,0.50
3-1#, 3-2#,3-3#	1.55,1.59,1.72	1.35,1.40,1.50	1.58,1.43,1.28	0.85,1.03,0.88	0.67,0.59,0.61
4-1#,4-2#,4-3#	1.46,1.49,1.69	1.53,1.38,1.48	1.31,1.20,1.34	0.85,0.71,0.96	0.47,0.49,0.40
5-1#,5-2#,5-3#	1.67,1.70,1.57	1.65,1.43,1.46	1.12,1.33,1.43	0.84,0.78,0.95	0.51,0.50,0.42
6-1#,6-2#,6-3#	1.70,1.66,1.56	1.53,1.32,1.28	1.31,1.38,1.33	0.78,0.80,0.86	0.46,0.70,0.78
7-1#,7-2#,7-3#	1.65,1.59,1.54	1.55,1.49,1.50	1.12,1.16,1.19	0.90,1.10,0.87	0.69,0.70,0.57
8-1#,8-2#,8-3#	1.62,1.74,1.74	1.47,1.47,1.44	1.30,1.30,1.36	1.00,0.92,0.89	0.51,0.52,0.84
9-1#,9-2#,9-3#	1.31,1.82,1.60	1.44,1.46,1.52	1.09,1.36,1.26	0.82,0.84,0.80	0.41,0.66,0.56
10-1#,10-2#,10-3#	1.63,1.50,1.61	1.56,1.20,1.53	1.36,1.14,1.19	0.83,0.88,0.86	0.66,0.60,0.60

Table 5 Poisson ratio of warm frozen soil

Number	Poisson ratio				
	-2.0℃	-1.5℃	-1.0℃	-0.5℃	0℃
1-1#,1-2#,1-3#	0.22,0.23,0.16,	0.28,0.31,0.30,	0.33,0.23,0.26,	0.34,0.28,0.23,	0.32,0.29,0.26
2-1#,2-2#,2-3#	0.29,0.26,0.27,	0.22,0.33,0.34,	0.37,0.25,0.25,	0.27,0.35,0.27,	0.36,0.35,0.31
3-1#, 3-2#,3-3#	0.21,0.31,0.19,	0.26,0.25,0.16,	0.35,0.31,0.34,	0.33,0.29,0.32,	0.36,0.32,0.29
4-1#,4-2#,4-3#	0.19,0.13,0.16,	0.23,0.22,0.22,	0.33,0.22,0.32,	0.25,0.35,0.25,	0.39,0.37,0.28
5-1#,5-2#,5-3#	0.20,0.30,0.22,	0.19,0.27,0.27,	0.30,0.24,0.17,	0.34,0.28,0.31,	0.38,0.25,0.33
6-1#,6-2#,6-3#	0.25,0.22,0.22,	0.24,0.24,0.29,	0.28,0.29,0.26,	0.19,0.30,0.36,	0.37,0.34,0.25
7-1#,7-2#,7-3#	0.20,0.24,0.18,	0.24,0.26,0.23,	0.21,0.36,0.31,	0.31,0.32,0.31,	0.24,0.24,0.34
8-1#,8-2#,8-3#	0.32,0.28,0.18,	0.25,0.17,0.27,	0.26,0.23,0.20,	0.26,0.36,0.31,	0.27,0.25,0.22
9-1#,9-2#,9-3#	0.27,0.27,0.25,	0.24,0.34,0.20,	0.28,0.31,0.27,	0.26,0.33,0.32,	0.35,0.33,0.35
10-1#,10-2#,10-3#	0.26,0.19,0.18,	0.18,0.28,0.25,	0.29,0.24,0.26,	0.31,0.29,0.36,	0.27,0.31,0.34

data of deviatoric stress, axial strain and volumetric strain and the relation curve of $(\sigma_1\text{-}\sigma_3) \sim \varepsilon_1$ and $\varepsilon_v \sim \varepsilon_1$, the elastic modulus, strength and Poisson ratio can be calculated and obtained. The strength of frozen soil is defined as the deviatoric stress $(\sigma_1\text{-}\sigma_3)$ when the axial strain is 15%. Tables 3, 4 and 5 are the measured data of mechanical parameters of warm frozen soil under different temperature.

2.3 Data processing and statistical method

There are thirty values for each mechanical parameter under each temperature condition, and the maximum and minimum values can be obtained by drawing a scatter plot. The mean and standard deviation can be calculated by statistical technique. It is obvious that the elastic modulus, strength and Poisson ratio of warm frozen soil under same temperature conditions are uncertain. The warm frozen soil is composed of solid mineral particles, ice, unfrozen water and gas. Its mechanical properties are relatively complex, which are closely related to the temperature, grain size distribution, water content, density, dry density, liquid and plastic limits. Especially for temperature, it is the most important factor. The relationships between the statistics, spatial autocorrelation functions and temperature need to be clarified. It is the basis of uncertain mechanical analysis of frozen soil engineering in QTP. According to the RF theory and LA method (Vanmarcke 2010, Parinaz and Ehsan 2016, Rosemary *et al*. 2017, Sadouki *et al*. 2018, Mouyeaux *et al*. 2019), the ACD and ACF are the most important parameter for estimating the spatial autocorrelation variations. The variance reduction function is related to the autocorrelation variations and average range of soil properties. In this study, the variance reduction function along the depth can be defined as follows

$$\Gamma^2(r)=\begin{cases}1 & r\le L_r\\ \dfrac{L_r}{r} & r>L_r\end{cases} \tag{1}$$

In Eq.(1), r represents the LA distance of any two points in depth direction. L_r represents the scale of fluctuation and it can be expressed as follows

$$L_r=\lim_{r\to\infty} r\times\Gamma^2(r) \tag{2}$$

The statistical characteristics, ACD and ACF of warm frozen soil are closely related to the temperature. This is the differences for the statistics and functions compared to the other geotechnical fields. The ACD and ACF of common soil properties can be estimated by spatial recurrence method, curve fitting method, correlation function method and so on. However, these methods are not convenient to apply to warm frozen soil because of the difference in temperature. It is very difficult to find the stable point of variance function accurately, and the deviation of abscissa and ordinate can directly affect the ACD and ACF of warm frozen soil. To improve the accuracy and convenience of optimization fitting, an array transformation method was proposed in this study. First, the array $[r,\Gamma^2(r)]$ need to be converted to the array $[r,r\Gamma^2(r)]$. The fitting function can be expressed as follows

$$z=\frac{y^2}{a+by^2} \tag{3}$$

where $y=r$ and $z=r\Gamma^2(r)$

The fitting function satisfies the definition of variance reduction function and scale of fluctuation (Leng 2000). According to Eq.(2) and Eq.(3), the scale of fluctuation of uncertain mechanical properties can be rewritten as follows

$$L_r=\lim_{r\to\infty} z=\lim_{r\to\infty}\frac{y^2}{a+by^2}=\frac{1}{b} \tag{4}$$

It can be seen that the fitting function can be transformed into linear form. The linear equation can be expressed as follows

$$\frac{Y}{z}=a+bY \tag{5}$$

where $Y=y^2$.

Therefore, the spatial autocorrelation variations could be evaluated by following steps.

(1) LA processes. r is a LA distance along the vertical direction and it is an integral multiple of the actual sampling distance, namely, $r=n\times\Delta r$. A set of data is composed of the mean test values of the sampling points within the range of LA distance. The local mean value and local mean variance of this group of data can be calculated by mathematical statistics method. After obtaining the standardized mechanical parameter by standardization process (Wang *et al*. 2018b), the variance reduction coefficient of uncertain mechanical parameter corresponding to different LA distance can be expressed as follows

$$\Gamma^2(r)=\frac{D^2(r)}{\sigma^2} \tag{6}$$

where r is the local mean distance, $D^2(r)$ is the local mean variance, σ^2 is the point variance of the total sample.

(2) Linear fitting. A coordinate system is set up with r^2 as the x-coordinate and $r/\Gamma^2(r)$ as the y-coordinate. The discrete points of uncertain mechanical parameters are plotted in the coordinate system. Three straight lines are used to fit the discrete points of elastic modulus, strength and Poisson ratio, respectively. The reciprocals of the slopes of the three straight lines are the scales of fluctuation of elastic modulus, strength and Poisson ratio, respectively.

(3) Autocorrelation characteristics. One dimensional squared exponential can be used to describe the spatial variations of uncertain mechanical properties for the warm frozen soil. The relationship between ACD and scales of fluctuation can be expressed as follows

$$l_h=\frac{L_r}{\sqrt{\pi}} \tag{7}$$

where l_h is the ACD of uncertain mechanical properties for warm frozen soil along the depth.

The ACF of uncertain mechanical properties along the depth can be expressed as follows

$$\rho(r)=\exp\left[-\left(\frac{r}{l_h}\right)^2\right] \tag{8}$$

3. Results and analyses

3.1 Statistical characteristics

According to the test procedure, the uncertain mechanical properties under different temperature conditions could be obtained. Fig. 1 shows the measured mechanical properties of the warm frozen soil. From Fig. 1(a), the maximum elastic modulus at -2.0ºC and -1.5ºC is 77.18 MPa and 68.97 MPa, respectively. The maximum elastic modulus and minimum elastic modulus are 67.16 MPa and 50.84 MPa when the temperature is -1.0ºC. The minimum elastic modulus at -0.5ºC and 0ºC is 42.19 MPa

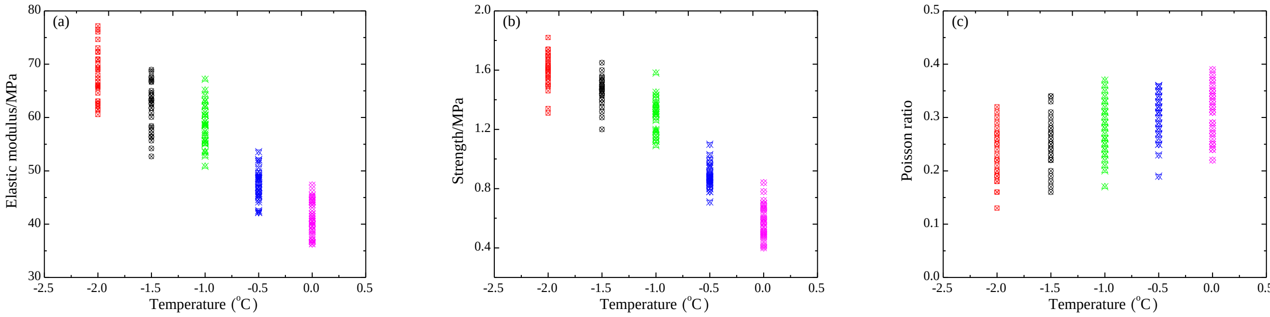

Fig. 1 Measured mechanical properties of the warm frozen soil: (a) Elastic modulus, (b) Strength and (c) Poisson ratio

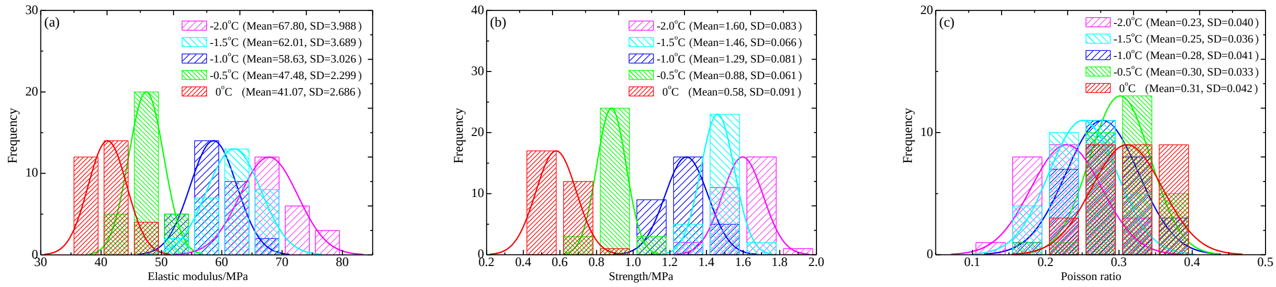

Fig. 2 Statistical characteristics of test values for mechanical properties of warm frozen soil: (a) Elastic modulus, (b) Strength and (c) Poisson ratio

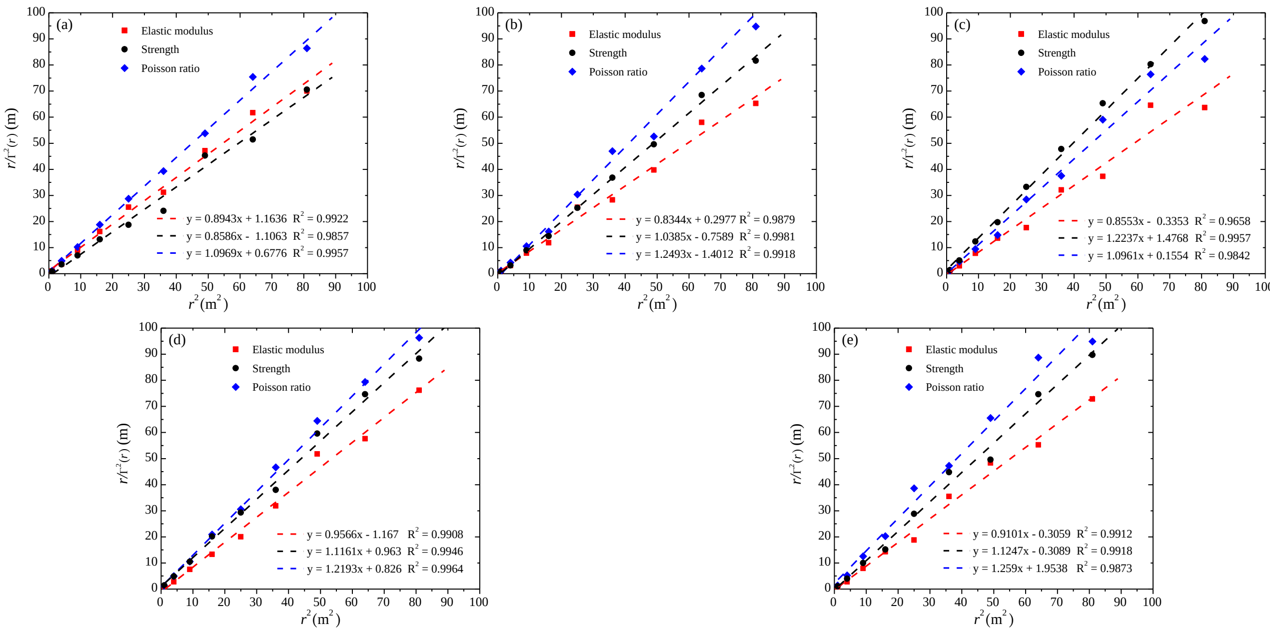

Fig. 3 Fitting curve of uncertain mechanical properties of warm frozen soil for variance reduction coefficient and local average distance. (a) -2.0ºC, (b) -1.5ºC, (c) -1.0ºC, (d) -0.5ºC and (e) 0ºC

and 36.28 MPa, respectively. It can be seen from Fig. 1(a) that the elastic modulus decreases with the increase of temperature. Fig. 1(b) show that the maximum strength at -2.0ºC and -1.5ºC is 1.31 MPa and 1.20 MPa, respectively. The maximum strength and minimum strength are 1.58MPa and 1.09MPa when the temperature is -1.0ºC. The minimum strength at -0.5ºC and 0ºC is 0.71 MPa and 0.40 MPa, respectively. It can be seen from Fig. 1(b) that the strength decreases with the increase of temperature. From Fig. 1(c), the minimum Poisson ratio at -2.0ºC and -1.5ºC is 0.13 and 0.16, respectively. The maximum Poisson ratio and minimum Poisson ratio are 0.37 and 0.17 when the temperature is -1.0ºC. The maximum Poisson ratio at -0.5ºC and 0ºC is 0.36 and 0.39, respectively. According to the data processing of uncertain mechanical properties for warm frozen soil, the mean and standard deviation under different temperature conditions could be calculated. Normal distribution was assumed for the elastic modulus, strength and Poisson ratio, and the statistical characteristics of normal distribution can be obtained. In fact, according to the analysis method of this paper, the distribution type had no effect on the spatial autocorrelation variations (ACD and

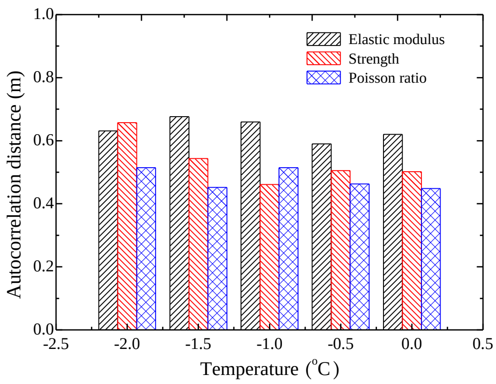

Fig. 4 Autocorrelation distance of uncertain mechanical properties of warm frozen soil at different temperature

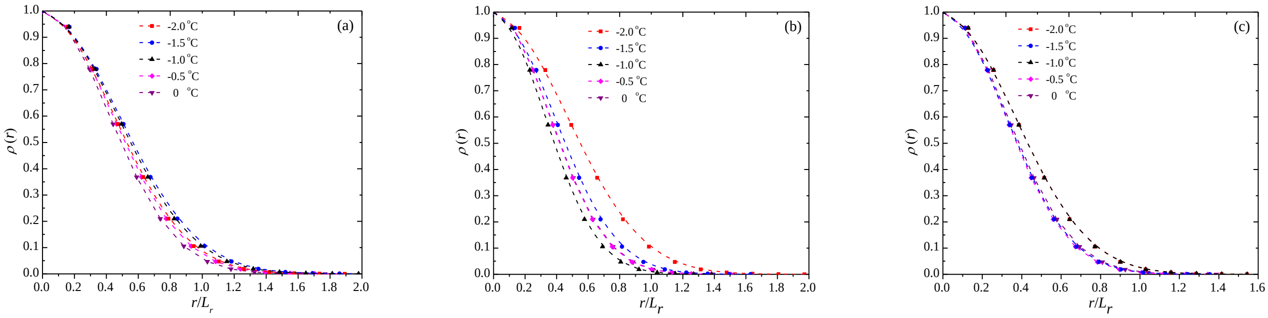

Fig. 5 Autocorrelation function of uncertain mechanical properties of warm frozen soil at different temperature. (a) Elastic modulus, (b) Strength and (c) Poisson ratio

ACF) of uncertain mechanical properties of warm frozen soil. Fig. 2 shows the mean and standard deviation of uncertain mechanical properties. From Fig. 2(a), the maximum mean of elastic modulus is 67.80 MPa and the temperature is -2.0°C. The minimum mean of elastic modulus is 41.07 MPa and the temperature is 0°C. The maximum SD of elastic modulus is 3.988MPa and the temperature is -2.0°C. The minimum SD of elastic modulus is 2.299 MPa and the temperature is -0.5°C. Fig. 2(b) shows that the maximum mean of strength is 1.46 MPa and the temperature is -1.5°C. The minimum mean of strength is 0.58 MPa and the temperature is 0°C. The maximum SD of strength is 0.091 MPa and the temperature is 0°C. The minimum SD of strength is 0.061 MPa and the temperature is -0.5°C. From Fig. 2(c), the maximum mean of Poisson ratio is 0.31 and the temperature is 0°C. The minimum mean of Poisson ratio is 0.23 and the temperature is -2°C. The maximum SD of Poisson ratio is 0.042 and the temperature is 0°C. The minimum SD of Poisson ratio is 0.033 and the temperature is -0.5°C.

3.2 Autocorrelation distance

According to the LA processes and linear fitting, the scales of fluctuation of uncertain mechanical properties under different temperature conditions could be obtained. Fig.3 shows the fitting curve of uncertain mechanical properties for variance reduction coefficient and LA distance. From Fig. 3(a), the slopes of the three fitting lines are 0.8943, 0.8586 and 1.0969, respectively. Hence the scales of fluctuation of elastic modulus, strength and Poisson ratio are 1.12 m, 1.16 m and 0.91 m when the temperature is -2.0°C, respectively. It can be obtained from Fig. 3(b) that the scales of fluctuation of elastic modulus, strength and Poisson ratio are 1.20 m, 0.96 m and 0.80 m when the temperature is -1.5°C, respectively. Fig. 3(c) shows that the scales of fluctuation of elastic modulus, strength and Poisson ratio are 1.17 m, 0.82 m and 0.91 m when the temperature is -1.0°C, respectively. Similarly, the slopes of the three fitting lines can be obtained from Fig. 3(d) and Fig. 3(e), and the scales of fluctuation of uncertain mechanical properties for the warm frozen soil can be calculated when the temperature is -0.5°C and 0°C. According to the relationship between ACD and scales of fluctuation, the ACD of uncertain mechanical properties of the warm frozen soil under different temperature conditions could be obtained. Fig.4 shows the ACD of uncertain mechanical properties for the warm frozen soil in permafrost regions. The ACD of the elastic modulus fluctuates between 0.59 m and 0.68 m; the ACD of the strength fluctuates between 0.46 m and 0.66 m, and the ACD of the Poisson ratio fluctuates between 0.45 m and 0.51 m. To estimate the statistical characteristics of the ACD, the average value and the standard deviation of are calculated. The results indicated that the average values of the ACD for the elastic modulus, strength and Poisson ratio are 0.64m, 0.53 m and 0.48 m, respectively. The standard deviation of the ACD for the elastic modulus, strength and Poisson ratio are 0.03 m, 0.07 m and 0.03 m, respectively.

3.3 Autocorrelation function

According to the LA distance and ACD, the ACF of uncertain mechanical properties under different temperature conditions could be obtained. Fig. 5 shows the ACF of uncertain mechanical properties for the warm frozen soil. From Fig. 5(a), the ACF of elastic modulus decreases with the increase of LA distance. The absolute value of the slope for the ACF is greater when the ratio of LA distance and scale of fluctuation is from 0.2 m to 0.8 m. In detail, the ACF of elastic modulus is the maximum when the temperature is -1.5ºC, and the ACF of elastic modulus is the middle when the temperature is -2.0ºC, and the ACF of elastic modulus is the minimum when the temperature is 0ºC. Fig. 5(b) shows that the ACF of strength decreases with the increase of LA distance. The absolute value of the slope for the ACF is greater when the ratio of LA distance and scale of fluctuation is from 0.3 m to 0.7 m. The ACF of strength is obviously the maximum when the temperature is -2.0ºC while it is the minimum when the temperature is -1.0ºC. The ACF of strength is basically the same when the temperature is -0.5ºC and -0ºC. It can be seen from Fig. 5(c) that the ACF of Poisson ratio also decreases with the increase of LA distance. The absolute value of the slope for the ACF is greater when the ratio of LA distance and scale of fluctuation is from 0.3 m to 0.6 m. The ACF of Poisson ratio is basically the same when the temperature is -2.0ºC and -1.0ºC. Fig. 5(c) shows that the ACF of Poisson ratio is greater when the temperature is -2.0ºC and -1.0ºC, and it is smaller when the temperature is -1.5ºC, -0.5ºC and 0ºC.

4. Discussion

The mechanical properties of warm frozen soil are closely related to the soil property, water content, salt content, compactness, load history, temperature and other factors. These can lead to the result that the warm frozen soil exhibits obvious spatial variations. This study aims to estimate the spatial autocorrelation variations of uncertain mechanical properties for warm frozen soil in QTP. Based on the site description and soil collection, sample preparation and test procedure, data processing and statistical method, the statistical characteristics, ACD and ACF are calculated and analyzed. The results can provide important basic data for the assumptions of the spatial variation characteristics in warm permafrost regions (Liu *et al.* 2014, Wang *et al.* 2018a, b, 2019b). However, with the deepening of the understanding of this problem, the authors realize that there are still some issues in current research. Firstly, the controlling accuracy of experimental temperature on uncertainty of mechanical properties is very important. It can directly affect the experimental process of triaxial test, the elastic modulus, strength and Poisson ratio of frozen soil under different temperature conditions. The measurement errors and system precision of uncertain mechanical properties of warm frozen soil are subsistent. The trend component of the elastic modulus, strength and Poisson ratio of warm frozen soil under different temperature conditions needed to be deleted. After obtaining the standardized mechanical parameter by standardization process (Wang *et al.* 2018b), the statistical characteristics, ACD and ACF could be calculated and analyzed. The standardization process can reduce the measurement errors and system precision of uncertain mechanical properties because of the controlling accuracy of experimental temperature. Secondly, the internal structure of undisturbed frozen soil is very important and it can directly affect the test results of mechanical properties. The interference is inevitable and totally undisturbed samples are impossible after transporting from the site to the laboratory. It would be really useful if the samples taken from the field were frozen and tested without altering its internal structure, and the results would be more useful for engineering geology in warm permafrost regions. Thirdly, this study estimates the spatial autocorrelation variations of uncertain mechanical properties for the warm frozen soil in permafrost regions. In fact, the spatial crosscorrelation variations of uncertain mechanical properties are subsistent. The spatial variability of elastic modulus can affect spatial variability of strength and Poisson ratio; the spatial variability of strength can affect spatial variability of elastic modulus and Poisson ratio; the spatial variability of Poisson ratio can affect spatial variability of elastic modulus and strength. The interaction processes of different mechanical properties are very complicated, and the further research is needed. Nevertheless, this study clarifies the statistical characteristics, ACD and ACF of uncertain mechanical properties for warm frozen soil, and it is an important development compared with previous study (Lai *et al.* 2012, Liu *et al.* 2017). The spatial autocorrelation variations can provide a reference for the uncertain mechanical analysis of frozen soil engineering in QTP.

5. Conclusions

The warm frozen soil has the strong spatial variations and correlation characteristics, and the uncertain mechanical properties are the key factors for the uncertain analysis of frozen soil engineering in QTP. The statistical characteristics, ACD and ACF of uncertain mechanical properties for warm frozen soil were investigated in this paper. The frozen soil samples were collected from the QTP, and the statistical data of three different mechanical properties under different temperature conditions were obtained. The evaluation method of spatial autocorrelation variations was presented, and the statistical characteristics, ACD and ACF for the uncertain mechanical properties were obtained and analyzed. According to this study, the following conclusions can be drawn:

- The mean elastic modulus and mean strength decrease with the increase of temperature. The maximum mean of elastic modulus is 67.80 MPa and the maximum SD is 3.988 MPa and the temperature is -2.0ºC. The maximum mean of strength is 1.46 MPa and the temperature is -1.5ºC. The maximum SD of strength is 0.091MPa and the temperature is 0ºC. The mean Poisson ratio increases with the increase of temperature. The maximum mean of Poisson ratio is 0.31 and the maximum SD is 0.042 and the temperature is 0ºC.

- The ACD of the elastic modulus fluctuates between 0.59 m and 0.68 m under different temperature conditions; the ACD of the strength fluctuates between 0.46 m and 0.66 m, and the ACD of the Poisson ratio fluctuates between 0.45 m and 0.51 m. The average values of the ACD for the elastic modulus, strength and Poisson ratio are 0.64m, 0.53m and 0.48m, respectively. The standard deviation of the ACD for the elastic modulus, strength and Poisson ratio are 0.03 m, 0.07 m and 0.03 m, respectively.

• The ACFs of uncertain mechanical properties decrease with the increase of the ratio of local average distance and scale of fluctuation. The ACFs are different when the temperature is different. The ACF of elastic modulus is the maximum when the temperature is -1.5°C. The ACF of strength is basically the same when the temperature is -0.5°C and -0°C. The ACF of Poisson ratio is greater when the temperature is -2.0°C and -1.0°C.

Acknowledgments

This research was supported by the Graduate Education Project of China University of Mining and Technology (Grant No.2019YJSJG042), the National Natural Science Foundation of China (Grant No. 51604265), the China Postdoctoral Science Foundation funded project (Grant No. 2019M660134) and the Major State Basic Research Development Program (Grant No. 2012CB026103). The authors wish to thank two anonymous reviewers and editor for their comments and advice.

References

Alhasan, A., Ali, A., Offenbacker, D., Smadi, O. and Lewis-Beck, C. (2018), “Incorporating spatial variability of pavement foundation layers stiffness in reliability-based mechanistic-empirical pavement performance prediction”, *Transport. Geotech*., **17**, 1-13. https://doi.org/10.1016/j.trgeo.2018.08.001.

Chen, L., Yu, W.B., Yi, X., Hu, D. and Liu, W.B. (2018), “Numerical simulation of heat transfer of the crushed-rock interlayer embankment of Qinghai-Tibet Railway affected by aeolian sand clogging and climate change”, *Cold Reg. Sci. Technol*., **155**, 1-10. https://doi.org/10.1016/j.coldregions. 2018.07.009.

Chenari, R.J., Fatahi, B., Ghoreishi, M. and Taleb, A. (2019), “Physical and numerical modelling of the inherent variability of shear strength in soil mechanics”, *Geomech. Eng*., **17**(1), 31-45. http://doi.org/10.12989/gae.2019.17.1.031.

El Haj, A.K., Soubra, A.H. and Fajoui, J. (2019), “Probabilistic analysis of an offshore monopile foundation taking into account the soil spatial variability”, *Comput. Geotech*., **106**, 205-216. https://doi.org/ 10.1016/j.compgeo.2018.10.011.

Elachachi, S. M., Breysse, D. and Denis, A. (2012), “The effects of soil spatial variability on the reliability of rigid buried pipes”, *Comput. Geotech*., **43**, 61-71. https://doi.org/10.1016/j.compgeo.2012.02. 008.

Fang, J.H., Li, X., Liu, J.K., Liu, C.Y.N., Liu, Z.Y. and Ji, Y.J. (2018), “The crystallization and salt expansion characteristics of a silty clay”, *Cold Reg. Sci. Technol*., **154**, 63-73. https://doi.org/10.1016/j. coldregions.2018.06.009.

Fei, S., Tan, X., Wang, X., Du, L. and Sun, Z. (2019), “Evaluation of soil spatial variability by micro-structure simulation”, *Geomech. Eng*., **17**(6), 565-572. https://doi.org/10.12989/ gae.2019.17.6.565.

Ghiasi, V. and Moradi, M. (2018), “Assessment the effect of pile intervals on settlement and bending moment raft analysis of piled raft foundations”, *Geomech. Eng*., **16**(2), 187-194. https://doi.org/10.12989/gae.2018.16.2.187.

Guellil, M. E., Harichane, Z., Berkane, H.D. and Sadouk, A. (2017), “Soil and structure uncertainty effects on the soil foundation structure dynamic response”, *Earthq. Struct*., **12**(2), 153-163. https://doi.org/10.12989/eas.2017.12.2.153.

Hamidpour, S., Soltani, M. and Shabdin, M. (2017), “Probabilistic seismic assessment of structures considering soil uncertainties”, *Earthq. Struct*., **12**(2),165-175. https://doi.org/10.12989/eas.2017.12.2. 165.

Ji, Y.K., Zhou, G.Q., Zhou, Y. and Vandeginste, V. (2019), “Frost heave in freezing soils: A quasi-static model for ice lens growth”, *Cold Reg. Sci. Technol*., **158**, 10-17. https://doi.org/10.1016/j.cold regions.2018.11.003.

Khemis, A., Chaouche, A.H., Athmani, A. and Kong, F.T. (2016), “Uncertainty effects of soil and structural properties on the buckling of flexible pipes shallowly buried in Winkler foundation”, *Struct. Eng. Mech*., **59**(4), 739-759. http://doi.org/10.12989/sem.2016.59.4.739.

Lai, Y.M., Li, J.B. and Li, Q.Z. (2012), “Study on damage statistical constitutive model and stochastic simulation for warm ice-rich frozen silt”, *Cold Reg. Sci. Technol*., **71**(2), 102-110. https://doi.org/10.1016/j.coldregions.2011.11.001.

Lee, J., Jeong, S. and Lee, J.K. (2015). “3D analytical method for mat foundations considering coupled soil springs”, *Geomech. Eng*., **8**(6), 845-857. http://doi.org/10.12989/gae.2015.8.6.845.

Leng W.M. (2000), *Reliability Analysis and Design Theory of Foundation Engineering*, Central South University Press, Changsha, China (in Chinese).

Leung, Y.F. and Lo, M.K. (2018), “Probabilistic assessment of pile group response considering superstructure stiffness and three-dimensional soil spatial variability”, *Comput. Geotech*., **103**, 193-200.https://doi.org/10.1016/j.compgeo.2018.07.010.

Li, A., Niu, F., Xia, C., Bao, C. and Zheng, H. (2019), “Water migration and deformation during freeze-thaw of crushed rock layer in Chinese high-speed railway subgrade: Large scale experiments”, *Cold Reg. Sci. Technol*., **166**, 102841. https://doi.org/10.1016/j.coldregions.2019.102841.

Li, Q.L., Ling, X. Z., Hu, J.J. and Xu, X.T. (2018), “Experimental investigation on dilatancy behavior of frozen silty clay subjected to long-term cyclic loading”, *Cold Reg. Sci. Technol*., **153**, 156-163. https://doi.org/10.1016/j.coldregions.2018.05.008.

Liu, W., Yu, W., Hu, D., Lu, Y., Chen, L., Yi, X. and Han, F. (2019a), “Crack damage investigation of paved highway embankment in the Tibetan Plateau permafrost environments”, *Cold Reg. Sci. Technol*., **163**, 78-86. https://doi.org/10.1016/j.coldregions.2019.05.003.

Liu, Y., Hu, J., Xiao, H.W. and Chen, E.J. (2017), “Effects of material and drilling uncertainties on artificial ground freezing of cement-admixed soils”, *Can. Geotech. J*., **54**(12), 1659-1671. https://doi.org/ 10.1139/cgj-2016-0707.

Liu, Z.Q., Yang, W.H. and Wei, J. (2014), “Analysis of random temperature field for freeway with wide subgrade in cold regions”, *Cold Reg. Sci. Technol*., **106-107**, 22-27. https://doi.org/10.1016/j.coldregions.2014.06.004.

Liu, Z.Y, Liu, J.K., Li, X. and Fang, J.H. (2019b), “Experimental study on the volume and strength change of an unsaturated silty clay upon freezing”, *Cold Reg. Sci. Technol*., **157**, 1-12. https://doi.org/ 10.1016/j.coldregions.2018.09.008.

Lu, G.L. (2015), “Experimental study on mechanical properties for warm frozen soils in permafrost regions”, Master Dissertation, China University of Mining and Technology, Jiangsu, China (in Chinese).

Luo, J., Niu, F., Wu, L., Lin, Z., Liu, M., Hou, Y. and Miao, Q. (2018), “Field experimental study on long-term cooling performance of sun-shaded embankments at the Qinghai-Tibet

Railway, China", *Cold Reg. Sci. Technol.*, **145**, 14-20. https://doi.org/10.1016/j.coldregions.2017.09.010.

Ming, F., Yu, Q.H. and Li, D.Q. (2018), "Investigation of embankment deformation mechanisms in permafrost regions", *Transport. Geotech.*, **16,** 21-28. https://doi.org/10.1016/j.trgeo.2018.06.003.

Mouyeaux, A., Carvajal, C., Bressolette, P., Peyras, L., Breul, P. and Bacconnet, C. (2019), "Probabilistic analysis of pore water pressures of an earth dam using a random finite element approach based on field data", *Eng. Geol.*, **259**, 105190. https://doi.org/10.1016/ j.enggeo.2019.105190.

Mu, Y., Ma, W., Li, G., Niu, F., Liu, Y. and Mao, Y. (2018), "Impacts of supra-permafrost water ponding and drainage on a railway embankment in continuous permafrost zone, the interior of the Qinghai-Tibet Plateau", *Cold Reg. Sci. Technol.*, **154**, 23-31. https://doi.org/10.1016/j.coldregions.2018.06. 007.

Pan, Y.T., Liu, Y., Lee, F.H. and Phoon, K.K. (2019), "Analysis of cement-treated soil slab for deep excavation support-A rational approach", *Geotechnique*, **69**(10), 888-905. http://doi.org/10.1680/ jgeot.18.P.002.

Pan, Y.T., Liu, Y., Tyagi, A. Lee, F.H. and Li, D.Q. (2020), "Model-independent strength-reduction factor for effect of spatial variability on tunnel with improved soil surrounds", *Geotechnique*, 1-17. https://doi.org/10.1680/jgeot.19.P.056.

Pan, Y.T., Liu, Y., Xiao, H.W., Lee, F.H. and Phoon, K.K. (2018), "Effect of spatial variability on short-and long-term behaviour of axially-loaded cement-admixed marine clay column", *Comput. Geotech.*, **94**, 150-168. http://doi.org/10.1016/j.compgeo.2017.09.006.

Parinaz, J. and Ehsan, J. (2016), "Reliability sensitivities with fuzzy random uncertainties using genetic algorithm", *Struct. Eng. Mech.*, **60**(3), 413-431. http://doi.org/10.12989/sem.2016.60.3.413.

Rosemary, F., Indraratne, S.P., Weerasooriya, R. and Mishra, U. (2017), "Exploring the spatial variability of soil properties in an Alfisol soil catena", *Catena*, **150**, 53-61. https://doi.org/10.1016/j.catena.2016.10.017.

Sadouki, A., Harichane, Z., Elachachi, S.M. and Erken, A. (2018), "Response of anisotropic porous layered media with uncertain soil parameters to shear body-and Love-waves", *Earthq. Struct.*, **14**(4), 313-322. https://doi.org/10.12989/eas.2018.14.4.313.

Tang, L., Cong, S.Y., Geng, L., Ling, X.Z. and Gan, F. (2018), "The effect of freeze-thaw cycling on the mechanical properties of expansive soils", *Cold Reg. Sci. Technol.*, **145**, 197-207. https://doi.org/10.1016/j.coldregions.2017.10.004.

Titi, H.H., Tabatabai, H., Faheem, A., Tutumluer, E. and Peters, J.P. (2018), "Spatial variability of compacted aggregate bases", *Transport. Geotech.*, **17**, 56-65. https://doi.org/10.1016/j.trgeo.2018.06.007.

Vanmarcke, E. (2010), *Random Fields: Analysis and Synthesis*. MIT Press, Cambridge, U.K.

Wang, C., Zhou, S., Wang, B. and Guo, P. (2018), "Time effect of pile-soil-geogrid-cushion interaction of rigid pile composite foundations under high-speed railway embankments", *Geomech. Eng.*, **16**(6), 589-597. https://doi.org/10.12989/gae.2018.16.6.589.

Wang, S.H., Wang, Q.Z., Xu, J., Ding, J.L., Qi, J.L., Yang, Y.G. and Liu, F.Y. (2019), "Thaw consolidation behavior of frozen soft clay with calcium chloride", *Geomech. Eng.*, **18**(2),189-203. http://dx.doi.org/10.12989/gae.2019.18.2.189.

Wang, T., Zhou, G., Wang, J. and Yin, L. (2018a), "Stochastic thermal-mechanical characteristics of frozen soil foundation for a transmission line tower in permafrost regions", *Int. J. Geomech.*, **18**(3), 06017025. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001087.

Wang, T., Zhou, G., Wang, J., Zhao, X. and Yin, L. (2018b), "Stochastic analysis for uncertain deformation of foundations in permafrost regions", *Geomech. Eng.*, **14**(6), 589-600. https://doi.org/10.12989/gae.2018.14.6.589.

Wang, T., Zhou, G., Wang, J., Zhou, Y. and Chen, T. (2019b), "Stochastic coupling analysis of uncertain hydro-thermal properties for embankment in cold regions", *Transport. Geotech.*, **21**, 100275. https://doi.org/10.1016/j.trgeo.2019.100275.

Wang, T., Zhou, G., Yin, L. and Zhou, L. (2019a), "Estimation on the influence of seepage on stochastic thermal regime of frozen ground surrounding the crude oil pipeline", *Cold Reg. Sci. Technol.*, **157**, 13-20. https://doi.org/10.1016/j.coldregions.2018.09.007.

Wu, X.Y., Niu, F.J., Lin, Z.J., Luo, J., Zheng, H. and Shao, Z.J. (2018), "Delamination frost heave in embankment of high speed railway in high altitude and seasonal frozen region", *Cold Reg. Sci. Technol.*, **153**, 25 32.https://doi.org/10.1016/j.coldregions.2018.04.017.

Yao, K., Xiao, H., Chen, D.H. and Liu, Y. (2019), "A direct assessment for the stiffness development of artificially cemented clay", *Geotechnique*, **69**(8), 741-747. https://doi.org/10.1680/jgeot.18.t.010.

Yi, J.T., Pan, Y.T., Huang, L.Y., Xu, S.J., Liu, Y. and Phoon, K.K. (2020), "Determination of limiting cavity depths for offshore spudcan foundations in a spatially varying seabed", *Mar. Struct.*, **71**, 102723. https://doi.org/10.1016/j.marstruc.2020.102723

Yu, Q., Mu, Y., Yuan, C., Ma, W. and Pan, X. (2019), "The cold accumulative effect of expressway embankment with a combined cooling measure in permafrost zones", *Cold Reg. Sci. Technol.*, **163**, 59-67. https://doi.org/10.1016/j.coldregions.2019.04.009.

Zhang, Y., Cheng, Z. and Lv, H. (2019), "Study on failure and subsidence law of frozen soil layer in coal mine influenced by physical conditions", *Geomech. Eng.*, **18**(1), 97-109. https://doi.org/10.12989/gae.2019.18.1.097.

Zhou, Z., Yang, H., Xing, K. and Gao, W.Y. (2018), "Prediction models of the shear modulus of normal or frozen soil-rock mixtures", *Geomech. Eng.*, **15**(2), 775-781. http://doi.org/10.12989/ gae.2018.15.2.783.

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