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Article (Accepted Version)

Zhang, Ji-wei, Murton, Julian, Liu, Shu-jie, Zhang, Song, Wang, Lei, Kong, Ling-hui and Ding, Hang (2020) Sensitivity and regression analysis of acoustic parameters for determining physical properties of frozen fine sand with ultrasonic test. Quarterly Journal of Engineering Geology and Hydrogeology. ISSN 1470-9236

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Accepted Manuscript

Quarterly Journal of Engineering Geology and Hydrogeology

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DOI: <https://doi.org/10.1144/qjegh2020-021>

Received 28 January 2020

Revised 11 May 2020

Accepted 12 May 2020

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Supplementary material at <https://doi.org/10.6084/m9.figshare.12268970>

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Sensitivity and regression analysis of acoustic parameters for determining physical properties of frozen fine sand with ultrasonic test

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Abstract: Determining the development of artificial frozen walls by present methods is challenging where substantial seepage occurs because fixed monitoring points only indicate physical properties in small areas. Here we use ultrasonic acoustic methods to determine the physical properties between two freezing pipes during freezing. Sensitivity analysis indicates that wave velocity is sensitive to physical properties, and the sensitivity rank is water content > temperature > density. The attenuation coefficient has a low sensitivity to physical parameters, whereas dominant frequency is sensitive to temperature and water content but insensitive to density. Wave velocity increases with temperature and density in a quadratic relationship, and with water content in a linear relationship. Dominant frequency increases with temperature and water content in a quadratic relationship. A multiple regression model of wave velocity and dominant frequency established by stepwise regression can be used to predict the relationship between wave velocity and temperature of frozen fine sand in different areas where the soil properties are similar to those reported here. Wave velocity and dominant frequency measured in the laboratory can be used to predict the relationship between acoustic parameters and temperature in field conditions after curve move based on the first data point from field measurements. The procedure of curve moving involves

calculating the difference in value of the first data point between laboratory and field measurements at the same temperature level, and then moving the predicted curve of the laboratory test upward or downward according to the difference.

Key words: frozen sand; acoustic parameters; sensitivity; multiple regression model

Artificial ground freezing (AGF) can be employed as a special construction method to increase soil strength in soft strata such as alluvium and water-rich sand and to isolate groundwater in aquifers (Armaghani *et al.*, 2016; Vitel *et al.*, 2016; Russo *et al.*, 2015; Pimentel *et al.*, 2012). Recently, artificial freezing has become a preferred method of mine shaft construction and urban underground space development in water-rich sand layers, which are characterized by low strength and limited cementation (Liu B. *et al.*, 2018; Kang Y. *et al.*, 2016, Farazi, A. H. *et al.*, 2013). By installing a ring of freezing pipes in unfrozen soil, ground engineers can produce a cylindrical body of frozen soil that is a type of frozen wall (Fig. 1).

Stability problems can beset frozen walls (Alzoubi *et al.*, 2019; Huang *et al.*, 2018). For example, a frozen wall in Ta-shen-dian coal mine, Xinjiang Province, China, developed inadequate strength between two freezing pipes (Z_{22} and Z_{23} in Fig. 1) where groundwater seepage occurred during freezing, which led to water inrush and abrupt subsidence. Therefore, measurement of physical parameters of frozen soil between any two freezing pipes is important in order to identify abnormal development of frozen walls.

Several methods of predicting and determining frozen wall development have been used previously. Real-time temperature monitoring (Dolgov, 1961) and theoretical derivation of stationary temperature fields (Sanger, 1979) were used in the 1950s–60s. In recent decades, numerical simulations of nonstationary temperature fields have developed (Yang P. *et al.*, 2006; Hu J. *et al.*, 2013). Such methods, however, are based on real-time temperature monitoring (e.g. at T_1 , T_2 and T_3 in Fig. 1), which indicate only the temperature near a monitoring point rather than throughout the frozen wall area. Therefore, these methods cannot predict accurately small gaps in the frozen wall between two freezing pipes (e.g. Z_{22} and Z_{23}

in Fig. 1) if the monitoring point(s) is far away. Ground penetrating radar (GPR) has been used to determine the thickness of frozen walls and unfrozen defects within them (Song *et al.*, 2013). Although GPR can reveal the basic characteristics of frozen walls and defects, it is affected by steel freezing pipes, because the electrical conductivity of steel is far higher than that of frozen soil. Additionally, GPR has a limited detection depth (3–30 m).

An alternative method of investigating frozen walls involves ultrasonic measurement of acoustic properties. Soils that are fully or partially saturated with water in the laboratory experience a large increase in wave velocity when they freeze, indicating that changes in the physical properties of frozen soils can be measured indirectly by ultrasonic waves (Kurfurst, 1976; Nakano *et al.*, 1972, 1973; Thimus *et al.*, 1991; Zhang *et al.*, 2019). Ultrasonic acoustic equipment can be inserted into any two freezing pipes and is little affected by the steel pipes, which is an advantage over GPR. Therefore, ultrasonic acoustic methods potentially provide a new and effective way to detect regions of unfrozen or partially frozen soil between two freezing pipes.

Previous studies, under laboratory conditions, have shown the relationships between wave velocity and physical and mechanical properties of frozen soil (Wang D.Y. *et al.*, 2006; Christ *et al.*, 2009; Li D.Q. *et al.*, 2015, 2016; Huang *et al.*, 2015; Wang P. *et al.*, 2017; Wang, Y. *et al.*, 2018). These studies indicate that the ultrasonic technique can be used to evaluate the physical and mechanical properties of frozen soils (Christ *et al.*, 2009). However, most studies have focused on relationships between the time-domain parameters such as P-wave velocity and single physical properties of frozen soils. This makes it difficult for the ultrasonic technique to evaluate the physical properties of frozen walls in different regions under field conditions.

The overall aim of the present study is to provide a theoretical basis of measuring frozen wall development between any two freezing pipes by ultrasonic testing under field conditions.

The objectives are to (1) determine the sensitivity of different acoustic parameters (wave velocity, attenuation coefficient and dominant frequency) to the physical properties (temperature, density and water content) of frozen fine sand; (2) establish the relationships between sensitive acoustic parameters and physical properties of frozen sand; and (3) propose a multiple regression model by laboratory testing to evaluate the physical properties of frozen sand in different geographical regions and countries.

Materials and methods

Specimens preparation and experimental design

Frozen sand was quarried from a depth of 16 m below the ground surface in a tunnel subject to vertical freezing during construction work at Baiyun Airport Guangzhou, located at the southernmost coastal city in China. The stratigraphy of the surficial deposits and the freezing hole arrangement are shown in Fig. 2. The main physical parameters, measured in the laboratory according to the National Standards of the People's Republic of China GB50123-1999, were bulk density = 1.87 g/cm³, water content = 10.31%, and freezing temperature = -0.2 °C. The sand is fine-grained (Table 1).

The experiments were performed in the Deep Coal Mine Construction Technology Laboratory of the National Engineering Laboratory of China, according to two experimental designs. The datasets from the two experiments are available in a supplementary data file (<https://doi.org/10.6084/m9.figshare.12268970.v1>).

(1) Three-factor analysis of variance (ANOVA)

Orthogonal tests are an effective means of multi-factor analysis and lend themselves to assessing the impact of relevant factors (Li Y. *et al.*, 2010; Liu Y.Q. *et al.*, 2016). An orthogonal experiment consisting of nine groups—L₉(3⁴)—selected three physical properties of frozen fine sand (temperature, density and water content) as factors to study the sensitivity of three acoustic parameters (wave velocity, attenuation coefficient and dominant frequency)

to the physical properties. The values of the factors used for the orthogonal test are given in Table 2. Following the industrial standard of the People's Republic of China, MT/T593.8-2011 (State Administration of Production Safety Supervision and Management of the People's Republic of China, 2011), each group of orthogonal test requires three specimens. Two were processed in cylindrical specimens (61.8 mm diameter, 150 mm long) for ultrasonic testing. The remaining specimen (61.8 mm diameter, 130 mm long) was used to calculate the attenuation coefficient.

(2) Control variable test

As shown in Table 3, the control variable test included two types of experiment. One had 16 groups of different levels of water content (4.31, 7.31, 10.31 and 13.31%) at a single level of density (1.87g/cm^3) to study the relationships between sensitive acoustic parameters and physical properties (water content and temperature). The other had 16 groups of different levels of density (1.87, 1.8, 1.76 and 1.73g/cm^3) under a single level of water content (7.31%) to study the relationships between sensitive acoustic parameters and density. Each group was evaluated at four levels of temperature (-5 , -10 , -15 and -20°C), and the results are mean values of two repeated tests.

Experimental procedure

As shown in Fig.3, the experimental procedure had five stages (Wang D.Y. *et al.*, 2006): (1) A specific amount of water was mixed with dry soil to achieve the required uniform density and water content, before the moist soil was packed into a mould and compacted by a press to maximum value of 1.87 g/cm^3 to form a cylindrical specimen. (2) Each remoulded specimen was wrapped in low-density polyethylene ("plastic film") to minimize movements of water into or out of the blocks during freezing and placed into a freezing cabinet and frozen quickly for 48h at the design temperature. (3) The final dimension and mass of the specimen were measured, before the sample was encased with rubber to ensure a stable water content.

(4) Ultrasonic tests were performed. (5) The attenuation coefficient and dominant frequency were calculated based on ultrasonic theories (Yang P. *et al.*, 1997; Ottosen *et al.*, 2004).

Ultrasonic measurement system and procedure

The acoustic parameters of remoulded specimens were measured by the sing-around method (Li D.Q. *et al.*, 2015), using the nonmetal ultrasonic measuring system, NM-4A (KangKeRui Ultrasonic Engineering Co., Ltd., Beijing, China). This apparatus consists of four units: (1) transducers, (2) pulse-receiver, (3) measuring system and (4) wire. The range of launch voltage of the apparatus is 250–1000 V, the measurement accuracy of sound-intervals is $\pm 0.05 \mu\text{s}$, the receiver sensitivity is $\leq 10 \mu\text{V}$, the range of amplitude is 0–177 dB, and the range of amplifier bandwidth is 5–500 kHz. In terms of the test parameters, the sampling interval was $0.4 \mu\text{s}$, the launch voltage was 500V, and the number of sample measurements was divided into 1024.

The ultrasonic apparatus was calibrated before measurement according to the mechanical industrial standard of the People's Republic of China JB/T 8428-2015, to calculate the inherent time delay, t_0 . Petroleum jelly was used to make good acoustic coupling between the soil sample and transducers. Then the frozen soil specimen was placed in a thermostatically controlled tank and an electric pulse propagated through the sample and acoustic parameters were recorded.

Acoustic parameters

The acoustic parameters determined in this study are wave velocity, attenuation coefficient and dominant frequency. The velocity of compressional and shear waves is a basic acoustic parameter of ultrasonic testing and can reflect the physical properties of frozen soil directly by laboratory measurement (Wang D.Y. *et al.*, 2006; Christ *et al.*, 2009; Huang *et al.*, 2015). The compressional wave (p wave) velocity was measured because it is easier to obtain than shear wave velocity in the field. The *p* wave

velocity (V_p) is expressed as:

$$V_p = \frac{L}{t_p - t_0} \quad (1)$$

where V_p is the p wave velocity (km/s), L is the length of the specimen (mm), t_p is the travel time of the head wave in frozen soil (μ s) and t_0 is the inherent time delay (μ s).

The attenuation coefficient is widely used in wave form analysis because it is a fundamental property of soil and rocks that controls the decay in amplitude of ultrasonic waves. The coefficient is sensitive to confining pressure, porosity, degree of fluid saturation and fluid type (Toksöz et al., 1979; Winkler et al., 1979; Johnson et al., 1980; Matsushima, Jun, et al., 2008). Yang et al. (1997) calculated the attenuation coefficient based on the amplitude of head waves measured in long and short specimens, expressed as:

$$\alpha = \frac{1}{\Delta X} \left(\ln \frac{S_2}{S_1} \right) \quad (2)$$

where α is the attenuation coefficient (dB/cm), ΔX is the length difference of specimens (cm), S_1 and S_2 are the head wave amplitudes (dB) of the long and short specimens, respectively.

The dominant frequency is the highest amplitude determined in the frequency component of ultrasonic waves by fast Fourier transform (FFT), which converts data from the time domain into the frequency domain. This acoustic parameter is sensitive to cracks, defects and inter-particle pores (Cote *et al.*, 1988; Alleyne *et al.*, 1992; Ito Y. *et al.*, 1997; Lee H. K. et al. 2004; Hola et al. 2011). Ito Y. *et al.* (1997) found that reduced stiffness due to crack propagation causes a decrease of resonant frequency. Marta *et al.* (2013) proposed that the ultrasonic spectroscopy method was successful in investigating whether the structural integrity of a specimen was impaired. Gheibi *et al.* (2018) observed that dominant frequency relates to changes in volume and distribution of inter-particle pores within a soil. According to the relation given in N. Ottosen et al. (2004), the dominant frequency is expressed as:

$$F(\bar{f}) = \int_{-\infty}^{\infty} f(t) e^{-i\bar{f}t} dt \quad (3)$$

where t is the sound interval (μs), i is an imaginary number and $\bar{f}$ is the dominant frequency (kHz).

Sensitivity analysis

The sensitivity analysis using the $L_9(3^4)$ orthogonal experimental design can be divided into two types: range analysis and analysis of variance (ANOVA). Range analysis avoids a series of complicated processing calculations without reducing the statistical significance. This method uses R values to determine the rank of some factor value change effect on output data variation (Liu Y.Q. et al., 2016). If the R value of factors exceeds the R value of a blank, then the variation of acoustic parameters is caused by changing physical parameters and thus acoustic parameters are highly sensitive to physical parameters (i.e. factors). Conversely, if the R value of a blank is higher than or equal to the R value of the factors, then acoustic parameters have a low sensitivity to the factors. The R value is expressed as:

$$R_j = \max(\bar{K}_{j1}, \bar{K}_{j2}, \dots, \bar{K}_{jm}) - \min(\bar{K}_{j1}, \bar{K}_{j2}, \dots, \bar{K}_{jm}) \quad (4)$$

where R_j is the R value of factor j , $\bar{K}_{jm}$ is the mean value of the power ramp when the factor j is at the m^{th} level. In this way, factors can be ranked in terms of effect strength according to R_j .

ANOVA is a method of model-independent probabilistic sensitivity analysis used to determine if values of the output vary in a statistically significant manner associated with variation in values for factors (Krishnaiah, 1965). The F-test is generally used to evaluate the significance of the response of the output to variation in the inputs (Montgomery, 1997). In the present study, the F-test can identify whether physical parameters significantly influence acoustic parameters and exclude trial errors. According to F-test theory (Frey H. et al., 2002;

Antonio *et al.*, 2004), the criterion formula is expressed as:

$$F > F_{\alpha}(f_1, f_2) \quad (5)$$

where α is prescribed level, f_1 and f_2 are degrees of freedom of between classes and within classes, respectively. If the F value exceeds $F_{0.01}$, the influence of physical parameters of frozen fine sand on acoustic parameters variation can be regarded as highly significant. Similarly, the range of $F_{0.05} < F \leq F_{0.01}$ is significant, the $F_{0.1} < F \leq F_{0.05}$ has limited significance, $F_{0.25} < F \leq F_{0.1}$ is insignificant but has some effect, and $F \leq F_{0.25}$ indicates no effect.

Stepwise regression method

The core idea of stepwise regression is that every independent variable is introduced or removed momentarily from the regression model according to the contribution to the regression equation by the partial F-criterion (Myers et al., 1990; Steyerberg et al., 1999). It can ensure all of the introduced independent variables are highly significant in terms of the forecasting function, whereas the removed variables are non-significant. The F-statistical analysis function of partial F-criterion is:

$$F_{n+1} = \frac{(SSE_n - SSE_{n+1}) / (d_n - d_{n+1})}{SSE_{n+1} / d_{n+1}} \quad (6)$$

where SSE_n and SSE_{n+1} are the error sum of squares for n and $n+1$ of the regression model, respectively, and d_n and d_{n+1} are the degrees of freedom for n and $n+1$. The reasonable removed significance level α_{out} should be given at first (Myers et al., 1990). Then the discussion variables are introduced when $\alpha_i < \alpha_{out}$ is satisfied; otherwise they are removed.

Results

Sensitivity analysis

Range analysis

Table 4 lists the orthogonal test results and R values of the acoustic parameters. The parameters of each group are mean values of three repeated experiments. The R value ranking of wave velocity (R_V) is $R_{VW} > R_{VT} > R_{VD} > R_{VB}$, which indicates the sequence of physical parameter effect on wave velocity variation is water content $\rightarrow$ temperature $\rightarrow$ density. In addition, wave velocity is sensitive to all three physical parameters.

The sensitivity of the attenuation coefficient cannot be determined accurately by range analysis, though the R value rank of R_A is $R_{AT} > R_{AW} > R_{AD} \approx R_{SB}$. The main reason is the value of R_{AB} is close to the R value of all three factors, and the sensitivity rank may be influenced by error and level changes.

The R value ranking of dominant frequency (R_D) is $R_{DW} > R_{DT} > R_{DD} > R_{DB}$, which indicates the sequence of physical parameter effect on dominant frequency variation is water content $\rightarrow$ temperature $\rightarrow$ density. Therefore, the dominant frequency is sensitive to water content and temperature. The sensitivity of dominant frequency to density should be confirmed by ANOVA because the value of R_{DB} is close to R_{DD} , and the sensitivity result may be influenced by errors and level changes.

ANOVA

As noted above, range analysis indicates the sensitivity ranking of physical parameters to acoustic parameters but it cannot determine if data variation results from errors or changes of level. ANOVA uses F-tests that can identify whether physical parameters significantly influence acoustic parameters and exclude trial errors.

The results of the ANOVA (Table 5) indicate a number of influences. First, the F value

rank of wave velocity (F_V) is $F_{VW} > F_{0.01} > F_{VT} > F_{0.05} > F_{0.1} > F_{VD}$, which indicates the influence of temperature, water content and density on wave velocity variation is significant, highly significant and insignificant but with a limited effect, respectively. Thus, wave velocity is highly sensitive to temperature and water content but weakly sensitive to density, and the sensitivity ranking is water content, temperature and density, the same ranking as determined by range analysis.

Second, the F value rank of attenuation coefficient (F_A) is $F_{AT} > F_{0.25} > F_{AW} > F_{AD}$, which indicates the influence of all three physical parameters on the attenuation coefficient is insignificant or has no effect. Obviously, the attenuation coefficient has a low sensitivity to physical parameters of frozen fine sand and cannot be used as a sensitive acoustic parameter to detect freezing fine sand under field conditions.

Third, the F value rank of dominant frequency (F_D) is $F_{DW} > F_{0.05} > F_{DT} > F_{0.25} > F_{DD}$, which indicates the influence of temperature, water content and density on dominant frequency is of little significance, significant and has no effect, respectively. This indicates that dominant frequency is sensitive to temperature and water content but insensitive to density, and the sensitivity rank is same as that obtained from range analysis.

In summary, both wave velocity and dominant frequency are sensitive to the physical parameters of frozen fine sand, though wave velocity weakly sensitive to density, whereas dominant frequency has no effect. Both of the above two sensitive acoustic parameters can be used to evaluate the physical parameters of frozen fine sand after analyzing the relationships between sensitive acoustic parameters and physical parameters.

Correlation analysis

Temperature and acoustic parameters

The relationships between temperature and acoustic parameters were determined by testing at a control density of 1.87g/cm^3 . Wave velocity increased in a nonlinear manner as

temperature decreased (Fig. 4). The increase of velocity was initially rapid at temperatures from 0 to -15°C and became gradually slower from -15 to -20°C . The reason for the observed changes is that the unfrozen water content of frozen fine sand sharply decreases and the ice content correspondingly increases at temperatures from 0 to -15°C , while unfrozen water content gradually diminishes from -15 to -20°C . Wave velocity increases with increasing ice content in fine soil because the increasing volume of ice particles can increase cohesion and elastic properties and reduce acoustic attenuation (Huang *et al.*, 2015).

The nonlinear relationship between wave velocity and temperature was quantified by fitting a quadratic function:

$$V_p = a_1 + b_1 T + c_1 T^2 \quad (7)$$

where a_1 , b_1 and c_1 are characteristic soil parameters (Table 6) and T is the temperature below freezing.

Dominant frequency also increased with decreasing temperature (Fig. 5). The rate of increase at temperatures from 0 to -5°C is greater than from -5 to -20°C . This nonlinear relationship represents the cohesion of freezing soil gradually increasing due to decreasing temperature, which led to reduced acoustic scattering and deflection. The temperature of about -5°C is a tipping point, because the decrease in porosity of frozen fine sand becomes slower at lower temperatures as ice infills the pores.

The nonlinear relationship between dominant frequency and temperature was quantified by fitting a quadratic function:

$$\bar{f} = a_2 + b_2 T + c_2 T^2 \quad (8)$$

where a_2 , b_2 and c_2 are characteristic soil parameters (Table 7).

Water content and acoustic parameters

The relationship between water content and acoustic parameters was also determined by testing at a control density of 1.87g/cm^3 . Wave velocity increased rapidly with increasing

water content, following a linear function in the temperature range of -5 to -20°C (Fig. 6). In addition, the slope of water content is steeper than that of temperature, which indicates that the sensitivity of wave velocity to water content is higher than it is to temperature, consistent with the results of the sensitivity analysis. The main reason for this trend is that the gravitational (free) water is the main type of water among fine sand particles, and it freezes more readily than water in the finest pores. The ice content increases with increasing water content, which leads to a uniform increase in wave velocity. The approximately linear relationship between wave velocity and water content was determined by fitting a linear function:

$$V_p = a_3 + b_3 w \quad (9)$$

where a_3 and b_3 are characteristic soil parameters (Table 8).

The dominant frequency also increases with increasing water content (Fig. 7). The rate of increase at water contents of 4.31 to 7.31% exceeds that from 7.31 to 13.31%, which indicates that dominant frequency is highly sensitive to water contents of 4.31 to 7.31% but less sensitive at higher water contents of 7.31 to 13.31%. The nonlinear relationship can be expressed by the following quadratic function:

$$\bar{f} = a_4 + b_4 w + c_4 w^2 \quad (10)$$

where a_4 , b_4 and c_4 are characteristic soil parameters (Table 9).

The main reason for the above trend is that the bulk, shear and contact stiffness of frozen fine sand increase sharply because the pores are filled and cemented by ice. However, due to the limited variation of volume and distribution of inter-particle pores, the rate of increase of dominant frequency with increasing water content slows down gradually. The lower slope of dominant frequency versus water content compared to wave velocity versus water content indicates that wave velocity is more sensitive to water content than is dominant frequency, consistent with the results from the sensitivity analysis.

Density and acoustic parameters

As dominant frequency is insensitive to density (section 3.1.2), we consider only the relationship between density and wave velocity, at a controlled water content (7.31%). Wave velocity is plotted as a function of density at temperatures of -5 , -10 , -15 and -20°C (Fig. 8). The relationship is nonlinear and can be expressed by the function:

$$V_p = a_5 + b_5\rho + c_5\rho^2 \quad (11)$$

where a_5 , b_5 and c_5 are characteristic soil parameters (Table 10). This relationship is due to the decreasing distance between soil particles as bulk density increases. In addition, wave velocity in mineral soil particles is faster than that in unfrozen water within soil pores.

The trend of wave velocity versus density is similar at different negative temperatures. The slope of wave velocity versus density is flatter than wave velocity versus temperature and water content, which indicates that wave velocity is less sensitive to density than it is to temperature and water content, consistent with the results from the sensitivity analysis. The main reason for the above trend is that the mineral soil particles become closer together as the bulk density increases, leading to a small decrease in the loss of wave energy at the similar temperature and water content.

In summary, wave velocity increases with water content and density in a quadratic relationship, and with temperature in a linear relationship. Dominant frequency increases with temperature and water content in a quadratic relationship.

The results above were obtained by controlled testing of individual variables, which neglects the interaction among different physical properties and may lead to large errors in predicting the relationship between acoustic and physical properties. Therefore, we now establish a multiple regression model of to encompass the interactions between different physical properties and sensitive acoustic parameters (wave velocity and dominant frequency) based on orthogonal test and control variable test results.

Multiple regression analysis

Regression Model

We used the stepwise regression method (Burkholder *et al.*, 1996) to establish a multiple parameter quadratic regression equation model:

$$Y = \beta_0 + \sum_{i=1}^n \beta_i x_i + \sum_{i=1}^n \beta_{ii} x_i^2 + \sum_{i=1}^{n-1} \sum_{j=1}^n \beta_{ij} x_i x_j \quad (12)$$

where Y is the dependent variable (i.e. wave velocity and dominant frequency), $i, j = 1, 2, \dots, n$ are mixed element order coefficients, $x_i x_j$ is the first-order interaction between x_i and x_j , and $\beta_0, \beta_i, \beta_{ii}, \beta_{ij}$ are regression parameters.

Variable selection

The results from 9 groups in the orthogonal test and 16 groups in control water content test (7.31%) were analyzed by stepwise regression. The removed significance level was determined as $\alpha_{out}=0.1$ (Myers *et al.*, 1990). Therefore, the discussion variable i (water content (A), density (B) and temperature (C) of frozen fine sand) was introduced when it met the condition that $\alpha_i < \alpha_{out}$, otherwise they are removed (section 2.6).

The results of independent variable selection of wave velocity and dominant frequency are summarized in Tables 11 and 12 respectively. As shown in Table 11, B^2 , AB , BC were removed from the regression formula of wave velocity by F-statistical analysis. The significant rank of independent variables, which were obtained from F and P values of one-power and quadratic items, were water content > temperature > density, in accordance with the ANOVA results. The coefficient of determination (R^2) increases from 0.742 to 0.999 with an increasing number of independent variables. The final value of the root mean squares was 0.0446, which indicates that the independent variable selection was correct.

The variable selection of dominant frequency is summarized and averaged in Table 12. B ,

A^2 , B^2 , BC and AB were removed from the regression formula by F-statistical analysis. The significant rank of independent variables, obtained from F and P values of one-power and quadratic item, were water content > temperature, also consistent with the ANOVA results. The value of R^2 gradually increased with an increasing number of independent variable, finally reaching 0.9710. The final value of the root mean squares was 0.927, which indicates that the regression precision of dominant frequency is lower than that of wave velocity.

Regression equation and precision test

The multiple regression equations of wave velocity and dominant frequency, respectively, were calculated by the stepwise regression method (Myers et al., 1990) after variable selection based on 9 groups in the orthogonal test and 16 groups in control water content test (7.31%) as follows:

$$V_p = -1.03078 + 0.065092A + 1.35853B - 0.0715C - 0.00107938AC + 0.00261154A^2 - 0.00195229C^2 \quad (13)$$

$$\bar{f} = 28.73024 + 2.05388A - 0.56449C + 0.031065AC - 0.051333A^2 \quad (14)$$

The results of the precision test are shown in Table 13. The F values of wave velocity and dominant frequency are 1843.78 and 100.36, respectively, and the P values are lower than 0.0001. This indicates that both multiple regression equations are highly significant. All values of R^2 , R^2_{Pred} , R^2_{Adj} of wave velocity and dominant frequency are close to 1, indicating that the predictive power of the multiple regressions is high.

Model validation

The multiple regression model was validated by 16 groups in a test at a controlled density (1.87 g/cm³) (Fig. 9). Every point of wave velocity and dominant frequency plots close to the diagonal, which indicates that the predictive power of the multiple regression equation is high. Thus, it can be used to predict wave velocity and dominant frequency of frozen walls in fine

sand. However, the predicted wave velocity and dominant frequency at a low water content (4.31%) is less accurate than at high water contents (7.31–13.31%). The main reason is that the water content data in the stepwise regression model are 7.31–13.31% without 4.31%.

Discussion

The experimental results in the present study are significant for measuring frozen wall development by ultrasonic testing in artificial freezing engineering. This work suggests that the multiple regression model of sensitive acoustic parameters (wave velocity and dominant frequency) is an effective method to determine the physical properties of frozen fine sand in different geographical regions and countries.

Laboratory test analysis

Christ *et al.* (2009) monitored the temperature of frozen fine sand from the Khabarovsk region of southern far eastern Siberia (Russia) by ultrasonic testing in the laboratory. The tested sand had a water content of 15.2% and a density of 1.9 g/cm^3 , and indicated that compressional wave velocity increased quadratically with decreasing temperature. The data range of the multiple regression model in the present study is similar to tests in Christ *et al.* (2009): water content (7.31–13.31%), temperature ($-5 \text{ }^{\circ}\text{C}$ to $-20 \text{ }^{\circ}\text{C}$) and density ($1.73\text{--}1.87 \text{ g/cm}^3$). Therefore, the multiple regression model in the present study can be used to determine the quantitative relationship between wave velocity and temperature in the Christ *et al.* (2009) study.

Values of water content and density from Christ *et al.* (2009) were substituted into the wave velocity multiple regression model equation (13). The predicted relationship between wave velocity and temperature is shown in Fig. 10. The trends of wave velocity versus temperature between predicted and actual values are similar.

The predicted values of wave velocity from eastern Siberia sand were lower than the actual values. The main reason for the prediction error can be divided into physical properties

of fine sand and ultrasonic testing equipment. The physical properties of soils from Eastern Siberia (e.g. water content and density) is larger than the data range of the multiple regression model. This difference may cause prediction errors. In addition, Christ *et al.* (2009) measured ultrasonic velocity by the UVM-2 apparatus, whereas the present study used the NM-4A apparatus, and this difference may cause measurement gaps.

Pearson's correlation test was used by Dzik-Jurasz *et al.* (2002) to measure the linear association between two variables. The correlations refer to wave velocity between predicted and actual values, which we calculated to be 0.986 and the P values to be 0.000049. This indicates that predicted and actual values were highly correlated, which confirms that the predictive power of the multiple regression equation was high and it can be used to predict the relationship between wave velocity and temperature of frozen fine sand in different geographical regions.

Field observations

The laboratory results in the present study can be compared with field observations obtained during AGF engineering of Baiyun Airport, Guangzhou. As shown in Fig.11, the frozen soil at 16 m depth was measured by the ultrasonic wave transmission method, with a distance of 1.36 m between inspection holes J₁ and J₂. Two cylindrical transducers (one emission, the other reception) were placed at the same depth (–16 m) in the inspection holes. Brine was used to ensure good acoustical coupling between each hole and the transducers. The launch voltage of 1000 V and sampling period of 1.6 μ s were selected for this fieldwork observation. Wave velocity and dominant frequency were measured by ultrasonic testing during different freezing periods (60, 80, 100 and 150 days).

Wave velocity values measured in the field and laboratory are compared in Fig.12. The trend of wave velocity between field and laboratory measurements is similar. However, the values obtained from field measurements were 33.67–40.54% higher than those from

laboratory tests, and the slope of field measurements was slightly lower. Therefore, the wave velocity of field measurements can be predicted by the multiple regression model equation (13) and by the quadratic function (6) after applying the curve moving method. The predicted curve moves upward 1.898 km/s and 1.912 km/s, respectively, based on the first data point obtained from field measurements at the same temperature level.

The Pearson correlation coefficients between values predicted by multiple regression and the quadratic function and values measured in the field were 0.968 and 0.964, and the P values were 0.032 and 0.036, respectively. Clearly, the values predicted by both methods and the values measured were highly correlated, and the prediction from the multiple regression equation is slightly better. Thus, the laboratory test results can be used to predict the relationship between wave velocity and temperature of frozen fine sand in the field after the curve moves upward based on first point data of field measurements.

Dominant frequency values in the field and laboratory are compared in Fig. 13. The trend of dominant frequency increasing with decreasing temperature is similar in the field and laboratory, though the field measurements were 39.17–43.93% lower than the laboratory tests. This demonstrates that frozen soil in the field contains more defects and micro-cracks than remoulded specimens used in the laboratory. Therefore, the dominant frequency of field measurements also can be predicted by the multiple regression model equation (14) and the quadratic function (7) after the curve shifting method. The predicted curve moves downward 20.487 kHz and 19.59 kHz respectively based on first point data of field measurements.

The Pearson correlation coefficients between values predicted by multiple regression and quadratic function and measured value in the field were 0.997 and 0.991, and P values were 0.00289 and 0.00915, respectively. These results indicate that the values predicted by the two methods and values measured were highly correlated, and that both methods can be used to predict the relationship between dominant frequency and temperature of frozen fine sand in

the field after curve move downward based on first point data of field measurements.

Several reasons may account for the differences of wave velocity and dominant frequency measured in the field and laboratory. (a) Cylindrical transducers, brine and a launch voltage of 1000 V were used in the field, whereas plane transducers, petroleum jelly and a lower launch voltage (500 V) were used in the laboratory. (b) Numerous defects and micro-cracks occur naturally in frozen soil under field conditions, whereas remoulded specimens were intact and relatively homogeneous. (c) Formation pressure had compacted the frozen soil in the field, whereas frozen soil was detected under unloaded condition in the laboratory. (d) Freezing in the field was unidirectional and perpendicular to the freezing-hole arrangement, whereas freezing in the laboratory was three-dimensional inside a freezing cabinet. (e) Other factors, such as measuring errors during remoulding and ultrasonic testing, may also contribute to the differences.

In summary, the regression equation of wave velocity and dominant frequency measured in the laboratory can be used to predict the relationship between two sensitive acoustic parameters and temperature of frozen fine sand in the field after moving the curve based on first point data of field measurements. This can be used to predict the relationship between acoustic parameters and temperature between any two freezing pipes in field conditions. In addition, we should compare the first data point between laboratory testing and field measurements at the same temperature level before curve moving, in order to ensure reliable prediction.

Conclusions

We draw the following conclusions from this study of ultrasonic testing of frozen fine sand:

(1) Range analysis and ANOVA indicate that wave velocity is sensitive to water content and temperature but has low sensitivity to density. The attenuation coefficient has low

sensitivity to physical parameters. Dominant frequency is sensitive to temperature and water content but insensitive to density. Overall, both wave velocity and dominant frequency are sensitive to the physical parameters of frozen fine sand, though wave velocity is weakly sensitive to density, whereas dominant frequency shows no effect.

(2) Wave velocity increases with temperature and density in a quadratic relationship, whereas it increases with water content in a linear relationship. Clearly, wave velocity is sensitive to the physical properties of fine sand and it can be used to detect directly the development of artificial frozen walls.

(3) Dominant frequency increases with temperature and water content in a quadratic relationship. Dominant frequency can also be used to detect artificial frozen walls but has a lower sensitivity than wave velocity.

(4) A multiple regression model of wave velocity and dominant frequency has been established by the stepwise regression method. The multiple regression model of wave velocity can be used to determine the quantitative relationship between wave velocity and temperature in different areas where the soil properties are similar to those in the present study (Christ *et al.* 2009).

(5) The regression equation of wave velocity and dominant frequency measured in the laboratory can be used to predict the relationship between two sensitive acoustic parameters and temperature of frozen fine sand in the field (Baiyun Airport, Guangzhou, China) after moving the curve based on first point data of field measurements.

Acknowledgments The authors gratefully thank Department of Geography University of Sussex, and the anonymous reviewers for their valuable and constructive comments in improving this study.

Funding The research was financially supported by National Natural Science Foundation of China (Grant No. 51804157; 5177040737; 11702094), the National Key Research and Development Plan of China (Grant No. 2016YFC0600904), the China Scholarship Council (Grant No. 201909110045), the

Science and Technology Innovation Fund of TianDi science and technology co., LTD (Grant No. 2018-TD-QN008; 2018-TD-ZD004; 2019-TD-QN009), and the North China Institute of Science and Technology Applied Mathematics Innovation Team (Grant No. 3142018059), which are all gratefully acknowledged.

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Figure Captions

Figure 1 Horizontal cross section through a frozen wall of water-rich sand between two freezing pipes at Tashendian coal mine, Xinjiang Province, China. Blue dotted area indicates freezing wall.

Figure 2 Vertical section showing the stratigraphy of surficial deposits and the freezing hole arrangement.

All measurements are in metres.

Figure 3 Experimental procedure for ultrasonic testing: (a) remoulded cylindrical specimen after compaction; (b) freezing cabinet in which specimen was frozen for 48h; (c) measured acoustic parameters; (d) waveform; (e) frequency spectrum

Figure 4 Wave velocity versus temperature at different water contents

Figure 5 Dominant frequency versus temperature at different water contents

Figure 6 Wave velocity versus water content at different temperatures

Figure 7 Dominant frequency versus water content at different temperatures

Figure 8 Wave velocity versus density at different temperatures

Figure 9 Predicted and actual values of wave velocity and dominant frequency.

Figure 10 The quantitative relationship predicted between temperature and p-wave velocity of laboratory test. Empirical data are from Christ et al. (2009).

Figure 11 Arrangement of freezing holes and sensors for field observations: (a) plan view showing freezing holes and (b) vertical profile showing ultrasonic sensors.

Figure 12 Comparison of wave velocity between field measurements and laboratory test.

Figure 13 Comparison of dominant frequency between field measurements and laboratory test

Table Captions

Table 1 Grain-size fractions of fine sand

Grain diameter (μm)	>250	250–225	225–200	200–175	175–150	150–125	125–100	100–75	75–50
Percentage	0.59	19.86	26.72	11.75	18.56	11.42	5.78	3.69	1.63

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Table 2 Values of factors for three-factor ANOVA test

Level	Factor		
	Temperature (°C)	Density (g/cm ³)	Water content (%)
1	–5	1.73	7.31
2	–10	1.8	10.31
3	–15	1.87	13.31

Table 3 Summary of test specimen conditions used in control variable test

Control variable	Variable level	Temperature Level (°C)	Repeat number	Total group
Control density test (1.87 g/cm ³)	Water content (4.31%)	-5, -10, -15 and -20 °C for every variable level	Two for every temperature level	16*2(repeat)
	Water content (7.31%)			
	Water content (10.31%)			
	Water content (13.31%)			
Control water content test (7.31%)	Density (1.87 g/cm ³)	-5, -10, -15 and -20 °C for every variable level	Two for every temperature level	16*2(repeat)
	Density (1.8 g/cm ³)			
	Density (1.76 g/cm ³)			
	Density (1.73 g/cm ³)			

Table 4 Orthogonal test results and R values

Experimental scheme	Factor				Acoustic parameters		
	Temperature, T (°C)	Density, D (g/cm ³)	Water content, W (%)	Blank, B	Wave velocity, V (km/s)	Attenuation coefficient, A (dB/cm)	Dominant frequency, D (kHz)
	1	2	3	4			
1	1 (-5)	1 (1.73)	1 (7.31)	1	2.294	19.375	42.09
2	1	2 (1.8)	2 (10.31)	2	2.725	7.081	44.51
3	1	3 (1.87)	3 (13.31)	3	3.215	6.954	47.91
4	2 (-10)	3	1	2	2.604	4.692	44.9
5	2	1	2	3	2.675	2.856	47.17
6	2	2	3	1	3.136	1.935	49.68
7	3 (-15)	2	1	3	2.705	2.998	43.9
8	3	3	2	1	3.275	2.315	48.96
9	3	1	3	2	3.489	1.755	49.34
R_V	$R_{VT}(0.412)$	$R_{VD}(0.212)$	$R_{VW}(0.746)$	$R_{VB}(0.074)$			
R_A	$R_{AT}(8.780)$	$R_{AD}(3.99)$	$R_{AW}(5.47)$	$R_{AB}(3.606)$			
R_D	$R_{DT}(2.563)$	$R_{DD}(1.227)$	$R_{DW}(5.346)$	$R_{DB}(0.66)$			

Table 5 ANOVA results for wave velocity, attenuation coefficient and dominant frequency

Acoustic parameters	Variance sources	III type of quadratic sum	DOF	Mean square	F	F_{α}
Wave velocity	Temperature	0.297	2	0.148	$F_{VT}(35.777)$	$F_{0.05}(24,2) = 19.4$
	Density	0.077	2	0.039	$F_{VD}(9.316)$	$F_{0.1}(24,2) = 9.44$
	Water content	0.835	2	0.417	$F_{VW}(100.681)$	$F_{0.01}(24,2) = 99.4$
	Error	0.008	2	0.004		
	SUM	77.011	8			
Attenuation coefficient	Temperature	141.359	2	70.680	$F_{AT}(5.797)$	$F_{0.25}(24,2) = 3.43$
	Density	27.513	2	13.757	$F_{AD}(1.128)$	$F_{0.25}(24,2) = 3.43$
	Water content	54.629	2	27.314	$F_{AW}(2.240)$	$F_{0.25}(24,2) = 3.43$
	Error	24.386	2	12.193		
	SUM	247.888	8			
Dominant frequency	Temperature	12.417	2	6.209	$F_{DT}(15.884)$	$F_{0.05}(24,2) = 19.4$
	Density	2.650	2	1.325	$F_{DD}(3.390)$	$F_{0.25}(24,2) = 3.43$
	Water content	43.545	2	21.773	$F_{DW}(55.702)$	$F_{0.05}(24,2) = 19.4$
	Error	0.782	2	0.391		
	SUM	59.395	8			

Table 6 Values of the parameters a_1 , b_1 and c_1

Water content (%)	a_1	b_1	c_1	Correlation coefficient
4.31	1.549	-0.067	-0.001	0.996
7.31	2.087	-0.063	-0.001	0.971
10.31	2.435	-0.088	-0.002	0.990
13.31	2.863	-0.077	-0.002	0.992

Table 7 Values of the parameters a_2 , b_2 and c_2

Water content (%)	a_2	b_2	c_2	Correlation coefficient
4.31	35.210	-0.658	-0.015	0.932
7.31	40.325	-0.598	-0.012	0.980
10.31	41.303	-0.877	-0.024	0.999
13.31	46.503	-0.329	-0.008	0.960

Table 8 Values of the parameters a_3 and b_3

Temperature (°C)	a_3	b_3	Correlation coefficient
–5	1.243	0.151	0.991
–10	1.435	0.155	0.992
–15	1.629	0.158	0.982
–20	1.719	0.157	0.973

Table 9 Values of the parameters a_4 , b_4 and c_4

Temperature (°C)	a_4	b_4	c_4	Correlation coefficient
–5	30.143	2.137	–0.061	0.956
–10	31.427	2.517	–0.094	0.986
–15	30.223	3.184	–0.131	0.993
–20	33.159	2.686	–0.108	0.982

Table 10 Values of the parameters a_5 , b_5 and c_5

Temperature (°C)	a_5	b_5	c_5	correlation coefficient
-5	-17.963	21.888	-5.884	0.997
-10	-2.816	5.464	-1.372	0.933
-15	38.880	-41.592	11.943	0.988
-20	19.018	-19.273	5.721	0.998

Table 11 Statistical data relating to wave velocity

Variable	R ²	Root mean squares	P value	F value
A	0.742	1.068	<0.0001	4711.01
C	0.975	0.686	<0.0001	1957.19
B	0.987	0.237	0.0034	230.92
C ²	0.997	0.176	<0.0001	126.65
AC	0.998	0.054	0.0063	11.84
A ²	0.999	0.045	0.0167	8.24

Table 12 Statistical data relating to dominant frequency

Model	R ²	Root mean squares	P value	F value
C	0.558	5.369	<0.0001	139.82
A	0.924	5.100	<0.0001	154.95
AC	0.960	1.587	0.0031	13.56
A ²	0.971	0.927	0.0529	4.61

Table 13 Precision test results for wave velocity and dominant frequency

Acoustic parameters	<i>F</i> value	<i>P</i> value	R^2	R^2_{Adj}	R^2_{Pred}
Wave velocity	1843.78	<0.0001	0.9991	0.999	0.996
Dominant frequency	100.36	<0.0001	0.9710	0.961	0.936