Determination of optimum moisture content of a clay using nonlinear ultrasonic technique

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ABSTRACT

The determination of optimum moisture content is very important for soil materials. Conventionally the optimum moisture content is estimated by the measurement of void ratio (or dry density) of soil samples, which is sometimes time-consuming and tedious. This paper proposes a nondestructive evaluation (NDE) technique based on the nonlinear ultrasonic theory to determine the optimum moisture content of clay. It is found the nonlinear parameter of material defined by the nonlinear ultrasonic technique presents a similar variation trend with the void ratio of clay, corresponding to the increased moisture content. The same optimum moisture content is found by observing the variation of nonlinear parameter and void ratio. The results indicate the developed nonlinear ultrasonic technique could be a fast and convenient testing method for the determination of optimum moisture content of soil materials.

Keywords: soil, moisture content, nonlinear ultrasonic, dry density

1 INTRODUCTION

In the foundation treatment engineering, the moisture content of clay has significant influence on its engineering properties. The different moisture content in clay not only leads to the variation of physical properties such as void ratio and density, but also alters the mechanical properties such as bearing capacity, cohesion, shear strength and deformation (Lin, 1994).

As moisture content is an essential parameter in foundation treatment engineering, the fast determination of optimum moisture content is very important in practice. Currently, the most commonly used methods are oven-drying method and alcohol combustion method which are developed by China Ministry of Water Resources (1999). They both evaporate moisture in clay and get the dried clay by thermal treatment. According to the weight of wet and dried clay, moisture content can be calculated. However, these traditional methods are usually time-consuming and tedious. In this paper, we propose a nondestructive evaluation (NDE) technique based on the nonlinear ultrasonic theory to determine the optimum moisture content of the clay. It presents a new idea of idea measuring the moisture content of clay and provides a possibility for the in situ measurement of optimum.

2 THEORETICAL BACKGROUND

Since 1960s, researchers have tried to evaluate material properties using nonlinear ultrasonic. Based on the nonlinear ultrasonic theory, when a frequency (f) ultrasonic wave travel through propagating media which possess a nonlinear constitutive behavior, the energy of ultrasonic wave is subjected to a redistribution among different frequency components, which is present as the generation of second harmonic of probing frequency (Buck et al., 1978; Van Den Abeele et al., 1996; Morris et al., 1979). The experimental technique based on the second harmonic principle has been well developed and used for the assessment of health condition of various materials (Yan et al., 2009; Zhu et al., 2009; Herrmann et al., 2006; Shui et al., 2008).

For cementitious materials and granular materials, the material nonlinearity in one dimension can be described in terms of higher orders of strain (second order only in this work) in the constitutive relationship (Jhang, 2009) as:

$$\sigma = E(\varepsilon + \frac{\beta}{2} \varepsilon^2)$$  \hspace{1cm} (1)

where $E$ is the modulus of (linear) elasticity, $\beta$ is the quadratic nonlinear parameter. Many experimental results show that the quadratic nonlinear parameter is sensitive to the microstructural features in concrete and rock, i.e., pores, voids and defects (Nagy, 1998; Kim et al., 2006; Viswanat et al., 2011; Shah et al., 2009; Chen et al., 2014).

If the nonlinear constitutive equation (1) of material is integrated into one dimensional wave equation, the nonlinear wave equation can be described as...
\[ \frac{\partial^2 u}{\partial t^2} - c^2 \frac{\partial^2 u}{\partial x^2} = \beta c^2 \frac{\partial \sigma}{\partial x} \]  

(2)

where \( u \) is the particle displacement at \( x \) and \( c \) is the phase velocity of wave, which can be related to the elastic modulus \( E \) and the density \( \rho \) of the material.

\[ c = \sqrt{\frac{E}{\rho}} \]  

(3)

If the initial condition of the nonlinear wave equation is

\[ u(x, t) = A_0 \cos(\omega t) \]  

(4)

where \( \tau = t - x/c \), the approximate solution can be obtained for the nonlinear wave equation is

\[ u(x, t) = A_0 \cos(\omega t) - \beta x \frac{A_0^2 k}{8} \cos(2\omega t) \]  

(5)

so the amplitude of fundamental and second harmonic is

\[ A_1 = A_0 \]  

(6)

\[ A_2 = \beta x \frac{A_0^2 k}{8} \]  

(7)

\( \beta \) can be obtained from (7) is

\[ \beta = \frac{8A_1}{xA_0^2 k} \]  

(8)

where \( k \) is wave number and \( x \) is the relative coordinate of propagating distance of wave. Provided that \( k \) and \( x \) are constant, the nonlinear parameter is equivalent as a ratio of \( A_2 \) and the square of \( A_1 \),

\[ \beta \sim \frac{A_2}{A_1^2} \]  

(9)

The second harmonic wave theory and the nonlinear parameter have been well developed and used for the microstructural characterization of consolidated materials. For the clay, the moisture content is directly correlated with the void in the materials, which causes the material nonlinearity. Therefore, the variation of the moisture content means different void ratio in clay, which provides the possibility for the estimation of moisture content using the second harmonic method and the nonlinear parameter.

3 EXPERIMENT

3.1 Material samples

The wet clay (specific gravity \( G_s = 2.7 \text{ g/cm}^3 \)) is dried at 110°C for 24 hours in an oven to prepare different moisture content of clay. After drying, the dried clay is spread on an impervious disk. Then water whose amount is calculated according to the moisture content is uniformly sprayed into the dried clay and mixed with a blender. The prepared clay is remolded and compacted by a sledgehammer with the same impact energy. This work examines 5 groups of clay cubes (5mm×5mm×5mm), with 3 cubes prepared for each group, for a total of 15 cubes, with different moisture content. The material used is shown in Table1:

| Moisture content | 6% | 9% | 12% | 15% | 18% |
|------------------|----|----|-----|-----|-----|
| Dried clay (g)   | 770| 820| 870 | 920 | 920 |
| Water (g)        | 46.2| 73.8| 104.4| 138.0| 165.6|

3.2 Experimental setup and procedure

The experimental setup of second harmonic is shown in Fig1. A tone burst of 100 cycles at the frequency of 25 kHz is generated by a function generator (Rigol DG1022). The signal is amplified by a wideband linear amplifier (Krohn Hite7500). The amplitude of the tone burst increases from 2V to 20V. From 2V to 10V, the increase step is 2V. From 10V to 20V, the increase step is 1V. Therefore, a total of 15 signals pass through and used to calculate the nonlinear parameter for one clay specimen.

![Fig.1. Experimental system of second harmonic ultrasonic wave](image)

The signals are recorded and processed with Matlab program. In order to obtain \( A_1 \) and \( A_2 \) in formula (9), the signals in time domain are transformed into frequency domain by fast Fourier transform (FFT). For 15 different amplitude of signals, the 15 points \((A_1^2, A_2)\) are drawn and fit with a linear line in graph (i.e., Fig 4). The slope of the line is the nonlinear parameter \( \beta \).

4 RESULTS AND DISCUSSIONS

Fig.2 is a typical time domain of ultrasonic wave across clay cubes, which can be transformed to frequency domain using fast Fourier transform (FFT), as shown in Fig.3. It is seen that the amplitude has obvious peaks at fundamental frequency of 25kHz(\(A_1\))
and second harmonic of 50kHz($A_2$).

Fig.2. Time domain signal

Fig.3. Frequency domain signal

In order to calculate the nonlinear parameter of clay cube, the 15 points ($A_1, A_2$) based on frequency domain signal are drawn and regressed with a linear line, the slop of which is nonlinear parameter. Fig 4 shows $\beta$ of one of the cubes with 6% moisture content.

Fig.4. Nonlinear parameter of one cube with 6% moisture content

To explore the variation trend of nonlinear parameter, Fig.5 presents five fitting straight-line of clay cubes with different moisture content. It can be observed in Fig.5 that when the moisture content is under 15%, the nonlinear parameter decreases with the increasing moisture content and reaches the minimum value corresponding to the 15% moisture content. The nonlinear parameter increases when the moisture content changes from 15% to 18%.

Fig.5. Comparison of $\beta$ of clay cubes with different moisture content

It is interesting to observe the inverse variation trend of nonlinear parameter before and after the moisture content of 15%, which may indicate a significant change in the material microstructure. To further understand the experimental phenomenon, the typical parameter describing the moisture content of soil – void ratio is also calculated in experiments and plotted with respect to the change of moisture content, as shown in Fig. 6. With the moisture content increasing from 6% to 18%, the void ratio of clay cubes decreases at first and then increases. The 15% is a turning point. This kind of phenomenon is linked to the interaction between water and clay particles. When the moisture content is relatively small, the wedging force between clay particles caused by hydration film is weak. However, the adsorption force between clay particles is large, which leads to the high strength of clay aggregates. As a result, the clay is difficult to be compacted and the pore is relatively large. It is the reason why the moisture content increases from 6% to 15%, the void ratio of clay cubes decreases. When the moisture content is over turning point, the water is too much to drain instantly, which make it difficult to clay compaction. As a result, the void ratio of clay cubes increases when the moisture content increases from 15% to 18%. Therefore, the optimum moisture content of clay can determined by finding the turning point of void ratio, which is also the most commonly used method in practice. The method we use is using nonlinear ultrasonic method to get the turning point of void ratio.
To explore the relationship between the nonlinear parameter and optimum moisture content, the nonlinear parameter is plotted together with void ratio against moisture content, as shown in Fig. 7. It is seen that nonlinear parameter presents a good agreement with void ratio with the increased moisture content, particularly where a common optimum moisture content at 15% is found. The result confirms the feasibility of estimating the optimum moisture content with nonlinear parameter defined in the second harmonic technique.

Fig. 7. Comparison of nonlinear parameter and void ratio with different moisture content

5 CONCLUSION

In this paper, a nondestructive evaluation technique based on the nonlinear ultrasonic theory is proposed to estimate the optimum moisture content of clay. The nonlinear parameter defined in the developed second harmonic technique is found to have a positive correlation with the void ratio of clay when the moisture contents increase from 6% to 18%, and a same optimum moisture content occurs in the variation trend of nonlinear parameter and void ratio. The results in the work suggest the feasibility of proposed second harmonic technique as a fast and convenient testing tool for the determination of optimum moisture content of soil materials.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support from National Natural Science Foundation of China (Grant No. 51308020) and Major Fundamental Research of China (973 Program, Grant No. 2014CB047003).

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