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Challenges from North to South
Des défis du Nord au Sud

Numerical simulation of wave propagation along a soil nail

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ABSTRACT
This paper presents a numerical simulation of wave propagation along a soil nail in order to develop a non-destructive testing (NDT) technique for quality control of soil nail walls. Soil nailing is a popular retention system where nails are encapsulated in grouted drillholes and contribute to the stability when the reinforced soil mass moves. Due to the fact that many defects could occur, the quality control of soil nail construction is very critical to ensure the safe performance of soil nailed structures. Currently, there are only destructive pullout tests available. This research is to address the need for an efficient and reliable NDT technique for soil nails. This research uses the finite element method (FEM) to study the complex wave propagation along a nail and the influences from various factors, including a radius of a grouted nail, material properties, and necking defects. The findings from this study demonstrate that the guided wave NDT technique is a very promising technique and can be used to detect defects and their locations in a soil nail.

RÉSUMÉ.
Cet article présente une simulation numérique de la propagation des ondes le long d'un clou de sol afin de développer une technique d'essais non destructifs (NDT) pour le contrôle de la qualité des murs à clou de sol. Le clouage des sols est un système populaire de rétention où les clous sont encapsulés dans des forages injectés, ce qui contribue à la stabilité quand la masse de sol renforcée se déplace. Attribuable au fait que de nombreux défauts peuvent se produire, le contrôle de la qualité de la construction de clou de sol est très critique pour assurer la sécurité de fonctionnement des structures de sol cloué. Actuellement, il n'y a que des essais destructeurs d'arrachement disponibles. Cette recherche répond au besoin d'une technique efficace et fiable de CND pour les clous. Cette recherche utilise la méthode d'éléments finis (MEF) pour étudier la propagation des ondes complexes le long d'un clou et l'influence de divers facteurs, y compris le rayon d'un clou injecté, les propriétés des matériaux et les défauts de striction. Les résultats de cette étude démontrent que la technique d'essais non destructifs d'onde guidée est une technique très prometteuse et peut être utilisée pour détecter les défauts et leurs emplacements dans un clou de sol.

1 INTRODUCTION

Soil nail walls have been widely used for supporting excavations or reinforcing existing slopes (FHWA 2003). Soil nailing is a passive reinforcing technique since the regularly spaced nails contribute to the stability of a soil mass only when there is any ground movement. The satisfactory and safe performance of soil nailing has been demonstrated through its successful applications in various ground conditions throughout the world. However, there are still occurrences of failures in soil nailing due to defects in the construction, such as necking due to borehole collapse, voids or defects in the grout column, or misalignment of the nails. Therefore, the success of soil nail walls depends fundamentally on their quality control during construction.

Currently, field pullout tests are required for each project at different stages to verify the design assumptions. On one hand, destructive field pullout tests are superior in identifying the defects of a soil nail; On the other hand, it is a costly and time-consuming method. In addition, pullout tests are sometimes quite limited and constrained to a large extent due to special site restraints. As a result, it is highly necessary to develop a non-destructive testing (NDT) technique as a complementary tool to traditional nail pullout tests.

This paper presents a numerical simulation of guided ultrasonic wave propagating along a soil nail. This study is intended to improve our understanding of wave propagation along a soil nail and eventually help us to develop an NDT technique for soil nail walls in the field.

2 GUIDED WAVE NDT TECHNIQUE

The NDT techniques for quality control on civil structures have received tremendous efforts from around the world. Ultrasound has been applied successfully in many engineering fields. Specifically for soil nails, a few NDT methods were investigated and developed, including the pulse echo method (Salloum et al. 2003, Jayawickrama et al. 2007, Liao et al. 2008), electro-magnetic induction method and time domain reflectometry method (Cheung 2003). Most publications studied the NDTs on determining the lengths of soil nails in field or in laboratory (Thurner 1983, Salloum et al. 2003, Gong et al. 2006, Liao et al. 2008, Zou et al. 2010). However, results show that these studies are still premature for field testing. By taking the rod-like structures as waveguides, guided waves have been studied in rock bolts (Beard and Lowe 2003, Zou et al. 2010) and concrete piles (Finno and Chao 2010). Such attempts revealed promising results in detecting defects in rock bolts and piles. While to date, there is no reported study focusing on applying guided waves for soil nails.

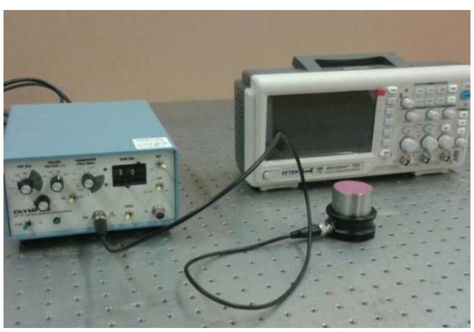
There has been an enormous amount of work devoted to the understanding of wave propagation in cylindrical structures, both homogeneous and composite (Rose

1999). Understandings of wave propagation along cylinders now are applied to develop NDT for inspection of pipe, tube, and so on. Due to the complex physics and wave propagation involved, it is almost impossible to get analytical solutions for most real life problems. This study is to conduct numerical simulation of wave propagation along a composite soil nail and investigate the influences from various factors are investigated, including radial dimension of a nail and deflects.

3 NUMERICAL SIMULATION OF GUIDED WAVES IN SOIL NAILS

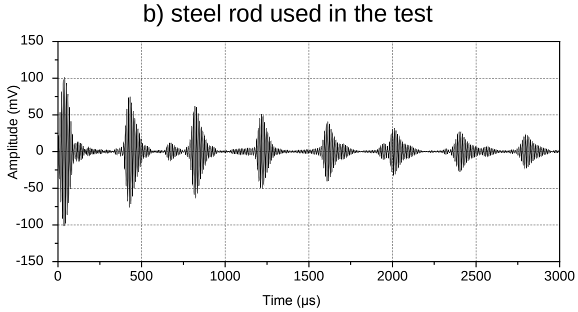
3.1 Laboratory test of guided waves in a soil nail

An ultrasonic guided wave NDT system is developed in this study, which consists of an ultrasonic pulser and receiver, an oscilloscope, an ultrasonic sensor, as shown in Fig. 1a. Three different nail models are used in the tests, including a 10 mm diameter and 905 mm long steel rod, shown in Fig. 1b, a scaled fully grouted nail, and a scaled grouted nail with a necking defect in the middle. The responses from wave reflection at the end of the rod are received and analysed. Fig. 1c is the signal received from wave propagation along the steel rod. The tests show that the response signals are different due to the presence of a necking defect and the system can detect the necking in the nail. More details can be found in Lin et al. (2013) or Liu et al. (2014).



a) ultrasonic NDT system

b) steel rod used in the test



c) signal received from wave propagation along the rod

Fig. 1 Laboratory guided wave NDT test of soil nails

3.2 2-D FEM model for wave propagation modelling

A simulation of laboratory test result on the steel rod is conducted first to verify the modeling method before extending to a parametric study. The FEM software package, ABAQUS, is used in this study. A solid element type, C3D8R, in ABAQUS is selected for the steel rod. A symmetrical mesh is used in this study. To determine the appropriate element size of a FEM model, the wavelength of an input signal with a given centered frequency is used. To solve the wave propagation problems by the FEM, each element length should be no longer than one third of the wavelength. To ensure the computational accuracy and efficiency, the element length should be taken as one tenth of a wavelength for a short strand model and one fourth or fifth for a long rod (Fu 2004). In model verification of experimental result on a steel rod, the element size in the longitudinal direction is chosen as 1 mm, roughly one fourth of the wave length.

To generate a wave, a windowed sinusoidal signal with ten cycles is used with an input frequency of 100 kHz and a duration of 100 μs to simulate the ultrasonic wave pulse generated in the experiment. The uniform pressure signal with an amplitude of 10 N/mm^2 is applied on the left surface of the rod, which is also used in the parametric study, unless noted otherwise.

The output signal based on time-history of deformation at the surface of the steel rod shows perfect periodical variation, as shown in Fig. 2, which resembles almost perfectly the results measured from the experiment, Fig. 1c. It also shows that there is only one longitudinal mode excited for this rod. From time histories of node displacement in the axial direction, one can easily obtain the period of longitudinal deformation and then calculate the group velocity of guided wave.

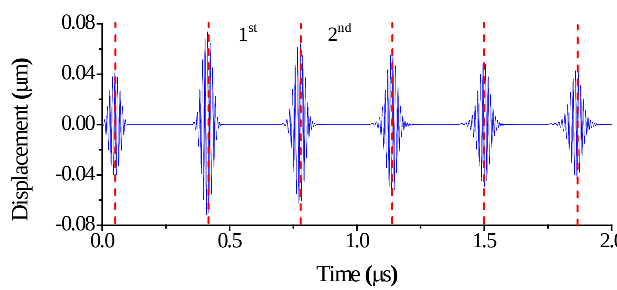


Fig. 2 Time history of node displacement on loading surface of a steel rod

3.2.1 Influence of material properties

Both steel and grout rods are chosen to study the influences of material properties on wave propagation. The diameter and length are kept the same as the steel rod used above. The physical properties that should be given before carrying out calculations are the values of density, ρ, Young's modulus, E, and the Poisson's ratio, ν. Table 1 lists these values used in this study.

The time histories of node displacement for both rods are shown in Figs. 2 and 3. It shows that material property has a significant influence on guided wave propagation. It can be seen that the wave packet is not significantly dispersed in the steel rod in Fig. 2 compared to appreciable dispersions in the grout rod in Fig.3. The lower the elastic modulus; the severer the dispersion of wave packet. The sever dispersion makes the accurate detection of wave packet more challenging.

Table 1 Material properties used in calculation

Material	Density, ρ (kg/m^3)	Young's modulus, E(GPa)	Poisson's ratio,v
steel	7840	210	0.30
grout	2400	17	0.20

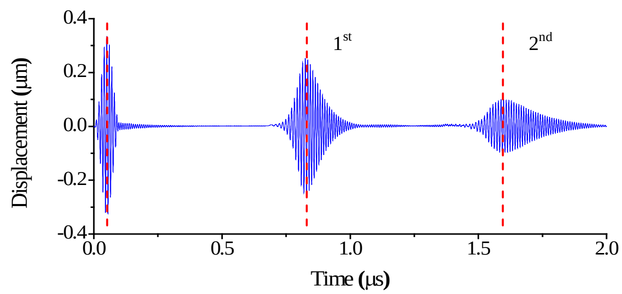


Fig. 3 Time history of node displacement on loading surface of a grout rod

3.2.2 Influence of the geometry of the rod

Two steel rods with diameters of 10 mm and 60 mm are used to investigate the influence of the diameter of a rod on wave propagation. Both rods are set to have the same length of 905 mm. The same element size of 1 mm in the longitudinal direction is used in both FEM models.

Typical wave propagation along a nail rod is shown in Figure 4 for the 10 mm diameter rod and Figure 5 for the 60 mm diameter rod. The time-history response of surface deformation are shown in Figs. 2 and 6. It is found that the radial dimension also has a significant influence on wave propagation. With the increase of a rod diameter, more longitudinal modes even flexural and torsional modes are excited, hence time histories of node displacement are much more complicated. There are apparent wave propagations found in both FEM models. However, there is discernible non-uniform distribution of displacement along its transverse section in the 60 mm rod compared to the more uniform distribution in the 10 mm rod.

Since the node displacement is contributed from multiple modes, it is difficult to distinguish the contributions of different modes from the output signal. Nevertheless, it is possible to find the duration of a complete transmission mode and then determine the group velocity of guided wave.

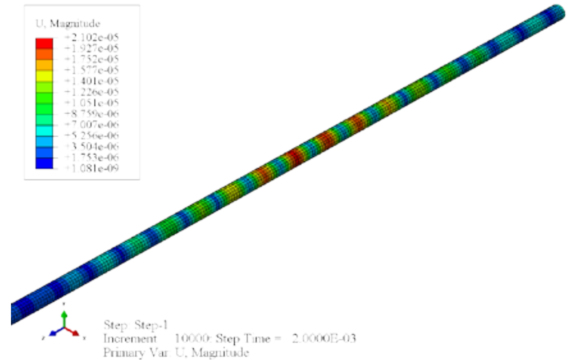


Fig. 4 Wave propagation along a 10 mm diam. steel rod

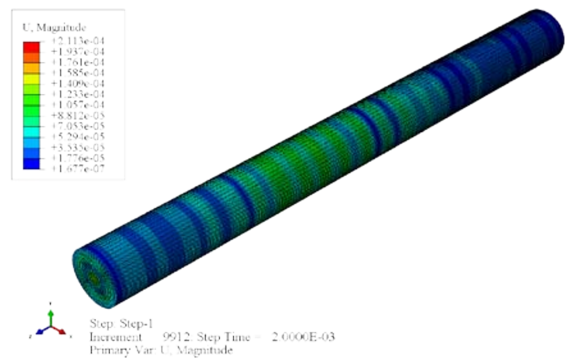


Fig. 5 Wave propagation along a 60 mm diam. steel rod

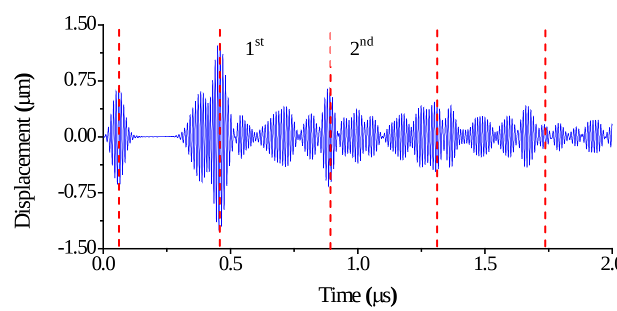


Fig. 6 Time history of node displacement of the 60 mm diameter rod

3.3 Wave propagation in a soil nail

A soil nail consists of a steel rod encapsulated in cement grout and extended at one end for connecting to the facing. A 905 mm long nail with a 156 mm rod extension and a 749 mm grouted length is used in the study, as shown in Fig. 7. The diameter of the steel rod is 10 mm and the thickness of the grout is 25 mm, which makes the grout column have an outside diameter of 60 mm. The same input signal is loaded on the left surface of the steel rod. The element size is the same as 1 mm in the longitudinal direction.

Typical field and time history outputs are shown in Figs. 7 and 8. Due to the extrusion part with different dimensions and the composite material of a soil nail, the propagation of waves becomes so complicated. This is due to the reflection and transmission occurring at the interfaces between the rod extension and the grouted part. From the output signal, it can be found that most waves propagate forward in the steel rod or leak into the grout layer with only minimal waves being reflected and propagating in the rod extension. The magnitude of waves attenuates substantially with time. It is found that waves propagate at different speeds at different parts in a composite nail and their speeds are not significantly influenced by each other. It is possible to obtain the total length of the nail by obtaining the length of each individual part based on corresponding wave speed. This is very useful for detecting the nail length using guided wave NDT technique.

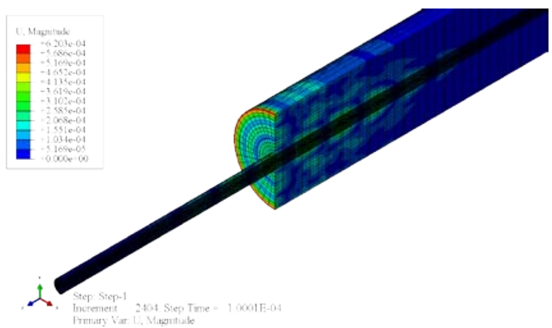


Fig.7 Wave propagation along a soil nail

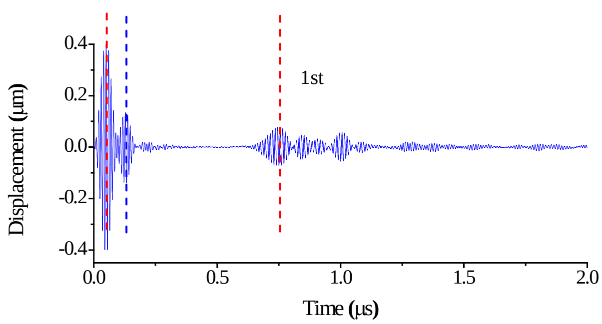


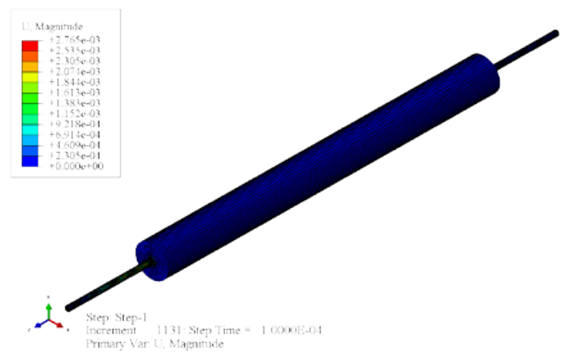
Fig. 8 Time history of node displacement on loading surface of a soil nail

3.4 Wave propagation in a soil nail with necking

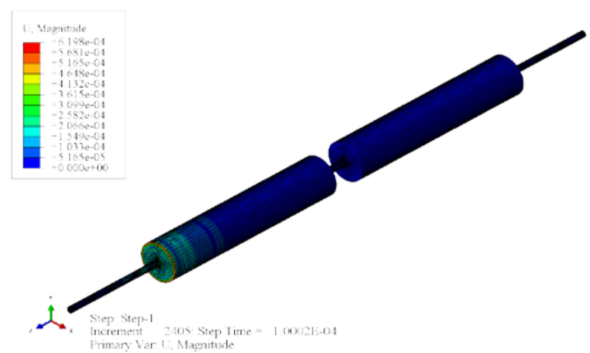
Two FEM models are used to investigate the influence of a necking defect in wave propagation. A fully grouted nail is created, the other is the same geometry except a 45 mm wide necking defect in the middle. The element size in longitudinal direction is chosen to be the same as 1 mm in both FEM models. Typical field outputs for both models are shown in Figs. 9.

It can be seen that the necking defect has a significant influence on wave propagation. The magnitudes of node displacement in the nail with a defect are much smaller than that in the nail without defects. It is found that most waves leak into the annular grout or propagating forward and there are negligible waves being reflected for the nail with a necking defect.

From the time histories of node displacement of the loading surfaces are shown in Fig. 10. Due to the fact that the necking defect significantly increases the acoustic impedance at the interfaces of the defect, it can be found that the amplitude of the node displacement for a soil nail with a necking defect attenuates much faster than that of its counterpart. Hence, there are much more waves propagating into the grout for the nail without a necking defect, which is also consistent with that shown in Fig.10.

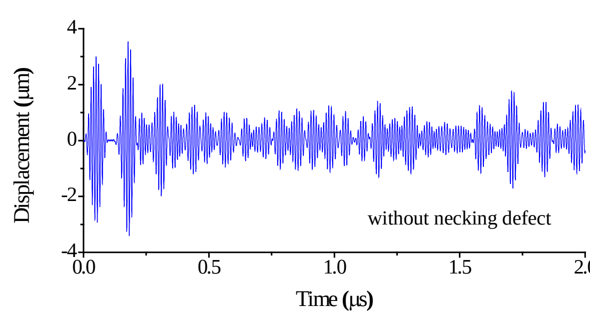


a) a fully grouted nail the same as Fig. 7

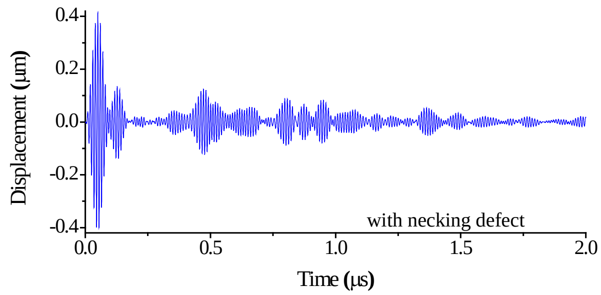


b) a nail with a necking defect in the middle

Fig.9 FEM models of a soil nail with or without a necking defect



a) a soil nail without a necking defect



b) a soil nail with a necking defect

Fig. 10 Time history of node displacement of the nail with or without a necking defect

4 MAIN FINDINGS AND FUTURE RESEARCH

This paper presents a numerical simulation of wave propagation along a soil nail in order to develop an efficient NDT technique for quality control of soil nails. When waves propagate along a wave guide, its properties change during their propagation. Due to complex physics involved, it is impossible to get analytical solutions for such a complex problem. The numerical method presented in this paper shows that it is capable to capture the main features of guided wave propagation along a soil nail. Based on this study, we can draw the following conclusions:

1. A guided wave ultrasonic system is a very promising NDT technique and is possible to detect defects in soil nails since the output signal reveals the influence of necking along the nails.

2. There is a significant influence on wave propagation from material properties. The smaller elastic modulus; the severer the dispersion of guided wave.

3. The radial dimension of the rod has a significant influence on wave propagation. With an increasing rod size, there are more wave modes being excited even flexural and torsional modes.

4. There are significant waves leaking into the annular grout layer. There is a significant attenuation in the magnitude of reflected signals due to the existences of rod extensions and necking defects.

5. Necking defects have significant influences on wave propagation. Based on studies on two scaled soil nails, it can be seen that guided wave ultrasonic NDT is capable of detecting defects and also detecting the whole length of soil nails.

There are still many questions left unknown, for example, the influence of energy leakage to surrounding soil, ground conditions, curvature of nails, etc. More research is needed to develop this innovative guided ultrasonic NDT system to be able to apply in the field testing.

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