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Characterizing the modal responses of a composite soil nail under axial excitation

Caractérisation de la réponse modale d'un clou de sol composite soumis à une excitation axiale

T. Salloum & K.T. Law
Department of Civil and environmental Engineering, Carleton University, Ottawa, Canada

G. Pernica, L. Neels & R. Glazer
Institute for Research in Constructions, National Research Council Canada, Ottawa, Canada

ABSTRACT

This paper characterizes the waves induced in a grouted soil nail from axial excitations in an attempt to develop a non-destructive field procedure for determining the length of in-situ soil nails. The study comprised experimental tests in which a 3.66-m long grouted laboratory soil nail was built and tested and numerical analyses in which a finite element model (FEM) of the nail was developed and calibrated. The FEM clarified the experimental responses of the nail by providing wave velocities and mode shapes for natural frequencies below 5 kHz, which described the actual dynamic behaviour of the soil nail. The results showed that axial excitations of the composite soil nail induced modes, which displayed both shear and longitudinal behaviour. Wave velocities below 3000 m/s suggested shear wave modes of energy transport whereas the nearly uniform axial displacements within the cross sections of the nail were more in keeping with longitudinal modes of behaviour.

RÉSUMÉ

Cette publication caractérise les ondes induites dans un clou de sol soumis à des excitations axiales afin de développer une procédure de terrain non destructive pour déterminer la longueur des clous de sol. L'étude comportait : (i) des essais expérimentaux dans lesquels un clou de sol d'une longueur de 3,66 m a été fabriqué et testé en laboratoire, et (ii) des analyses numériques dans lesquelles un modèle d'éléments finis du clou a été développé et calibré. La modélisation par éléments finis a permis de clarifier la réponse expérimentale du clou en fournissant les vitesses de propagation des ondes et les formes modales pour les fréquences naturelles inférieures à 5 kHz, qui décrivaient le comportement dynamique actuel du clou de sol. Les résultats ont montré que les excitations axiales du clou de sol induisaient des modes avec des comportements de cisaillement et longitudinal. Les vitesses de propagation d'ondes inférieures à 3000 m/s ont suggéré la présence de modes de cisaillement de transport d'énergie tandis que les déplacements axiaux quasi-uniformes dans la section transversale du clou étaient plus reliés aux modes longitudinaux de comportement.

1 INTRODUCTION

Soil nailing is an in-situ soil reinforcement technique for cut-slope retaining and slope stabilization systems. It is an alternative technique to other conventional supporting systems as it offers flexibility, rapid construction and competitive costs. As a result, a tremendous number of soil nails are installed worldwide every year. Because nails can be rapidly inserted into a slope (up to 10 per hour), satisfactory quality control of the nailing installation has been difficult to achieve in some jurisdictions. A fast and reliable field technique has therefore been sought to satisfy the requirement for comprehensive quality control of soil nailing systems.

This study is a continuation of research undertaken at the Institute for Research in Constructions (IRC) of the National Research Council Canada (NRC) by Salloum et al. (2003) and Pernica et al. (2002). The objective was to characterize the dynamic behaviour of a grouted soil nail under axial excitations to assist in the implementation of a non-destructive field procedure to determine the length of in-situ composite soil nails.

The study comprised experimental tests in which a 3.66-m long laboratory soil nail was constructed and tested using two measurement techniques to obtain the dynamic properties of the nail, impulse response (IR) and steady-state forced vibrations. The two techniques were used to determine the modal frequencies (i.e. resonances) of the soil nail. Forced vibrations were also used to determine the phase velocities of the modes and their dependency if any on frequency.

A finite element model (FEM) of the composite laboratory soil nail was also developed and calibrated by comparing the numerical set of axial natural frequencies to those obtained experimentally. The FEM was then used to examine in detail the modal responses of the soil nail.

2 DESCRIPTION OF SOIL NAIL

The composite soil nail was constructed using a single steel reinforcing bar surrounded by a cover of grout. The bar was 3.66 m long and 25 mm in diameter. The grout cover had a 152-mm circular cross-section and a compressive strength of about 50 MPa. The soil nail was housed in the main structural lab at NRC/IRC and positioned horizontally on rubber mats to isolate it from concrete floor slab of the lab (Fig. 1).

Figure 1 Laboratory composite soil nail

3 EXPERIMENTAL PROGRAM

3.1 *Principles of measurement techniques*

3.1.1 *Impulse-response technique*

The IR technique is a non-destructive sonic method, which is generally used to determine the dynamic properties (frequencies, damping ratios and mode shapes) of structural systems. The technique consists principally of two stages; striking the system being tested with a mechanical device such as a hammer and then monitoring the response by attaching a motion transducer to the system. The impact (force) produced by the mechanical device is transient (short duration). It induces stress waves, which reflect back and forth within the structural system between boundary or material interfaces until the mechanically induced energy is consumed by material damping, dispersion and reflections. Dynamic properties are identified from the normalised response spectra (response-force transfer function) of the structure.

3.1.2 *Steady-state forced vibrations*

Steady-state forced vibrations are conducted by attaching an inertial shaker to the structure being tested. A sinusoidal signal is fed into the shaker and the response of the structure monitored using one or more motion transducers. By varying the frequency of the sinusoidal signal, a frequency response function of the structure can be obtained from which modal properties can be identified. By attaching two or more sensors to a structure, modal responses (amplitude and phase) at monitored locations can be realized.

3.2 *Equipment*

Hammer: A 2-kg instrumented hammer with a steel tip was sufficient to excite the lower modes of the composite soil nail, Salloum et al. (2003). The hammer was equipped with a force transducer to capture the induced force.

Transducer: To monitor the response induced by an impact, a high-frequency piezo-electric accelerometer was firmly attached to the exposed portion of the steel bar. The accelerometer was mounted with its axis of sensitivity aligned with the longitudinal axis of the nail, because the axial response of the nail was the direction of primary interest.

Shaker: A small high-frequency shaker (0.02-20 kHz) was used to perform the steady-state forced vibration tests. The shaker contained a built-in impedance head, comprising a force transducer and an accelerometer and thus was able to monitor both the force imparted to the nail and the nail's response to the force. The shaker was securely connected to the end of the steel bar and had its armature aligned with the longitudinal axis of the nail.

Frequency Analyser: Signals from the instrumented hammer and accelerometer were fed into a 2-channel frequency analyser with signal storage capabilities. The analyser had the ability to display the waveforms generated by the impacts and the frequency spectra (Fourier transforms and transfer functions) derived from the time signals using algorithms built into the analyser.

The analyser was also an integral component of the steady-state vibration tests conducted on the composite nail. Besides monitoring and recording shaker force and nail response, it also served as the signal generator for the shaker, as it had the capability to output a sinusoidal signal and to slowly increase the frequency of that signal over the range selected for the test.

3.3 *Experimental procedure*

3.3.1 *Impulse response technique*

Impact Delivery: Exciting the soil nail was simply accomplished by impacting the exposed end of the steel bar perpendicular to its surface, as the axial response of the nail was the direction of interest.

Accelerometer Attachment: The bottom of each accelerometer incorporated a screw, which was fastened into a previously tapped hole on the end or side of the steel bar.

Frequency Range of Analyser: The frequency range chosen for the IR tests on the soil nail was 5 kHz in an attempt to identify most of the lower modes of the nail from normalised spectra of nail response, Salloum et al. (2003).

3.3.2 *Steady-state forced vibrations*

Steady-state excitations were conducted from 0.1 to 5 kHz on the composite nail to confirm the modal frequencies obtained using the IR technique. The test was then repeated with the signal from the force transducer of the shaker being replaced by an accelerometer mounted at the opposite end of the nail. The phase between the two accelerometers signals at each of the modal frequencies was obtained from the frequency analyser (cross spectrum of the accelerometer signals) and used to calculate the wave velocity of each modal frequency.

3.4 *Estimation of Nail Length*

Accelerometer signals from the two vibration techniques were analysed in the frequency domain to identify the dominant modal frequencies within the induced stress waves, as the waves reflected between the two ends (head and toe) of the nail. At frequencies that corresponded to the resonances of the soil nail, reflections were maximum. The resonant frequencies were thus a function of nail length (L) and the wave velocity (V_c) within the composite nail. By determining the frequency spacing between resonant frequencies, the length of a nail could be estimated from the following relationship, Malhotra and Carino (1991) if the wave velocity within the composite nail were known:

$$L = \frac{V_c}{2 \Delta f} \tag{1}$$

4 EXPERIMENTAL RESULTS

4.1 *Impulse-response technique*

Figure 2 shows the frequency content (Fourier Transform) of the axial response induced in the composite lab nail using the medium instrumented hammer with a steel head. Numerous spectral peaks, which correspond to the resonant frequencies of the soil nail, can readily be identified within this response spectrum. However, the frequency spacing of successive modal peaks is not constant, as would be the case for a soil nail comprising only one constituent, Salloum et al. (2003), or are the spacings commensurate with the longitudinal wave velocity of the grout or the steel bar. Possibilities for the variable and smaller spacings include; a) the axial wave induced in the nail has dispersive components, i.e., modal frequencies within the wave propagate at different velocities (phase velocities); and b) the components within the stress wave system are no longer purely longitudinal, i.e., the stress wave defining the dynamic response of the nail is a combination of longitudinal and shear waves.

In a longitudinal wave, the motion of the particles is parallel to the direction of propagation, whereas in a shear wave the motion is perpendicular to the direction of propagation. The shear wave also propagates at a considerably slower velocity than the longitudinal wave, Malhotra and Carino (1991). To ascertain which of the above possibilities most likely represents the response of the composite nail to an axial excitation, additional experimental tests using steady-state vibrations were conducted and a finite element model developed.

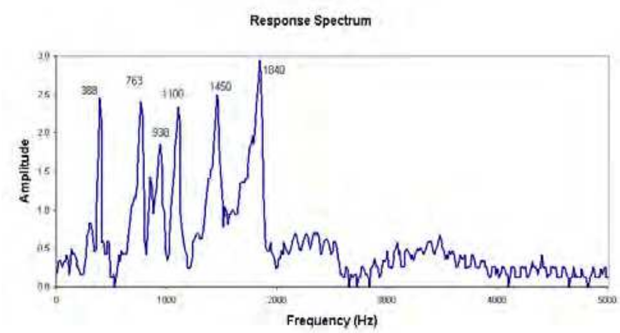

Figure 2 Axial response spectrum obtained on composite laboratory nail using medium instrumented hammer

4.2 *Steady-state vibrations*

Figure 3 shows the phase between frequency components of accelerometer signals recorded at opposite ends of the nail under steady-state shaker excitations. From the phase relationship, the time of travel and thus the phase velocity of each of the modal components within the stress wave can be determined using the equation, Magrab and Blomquist (1971).

$$c = \frac{360 fL}{\phi} \tag{2}$$

where: f = modal frequency [Hz]
L = distance between accelerometer locations on soil nail [m]
Φ = Phase between locations on soil nail [degree]

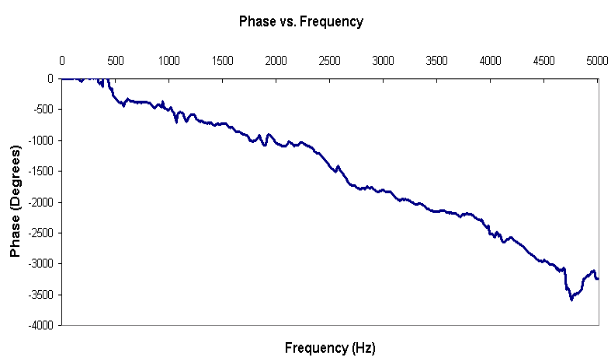

Figure 3 Phase between accelerometer signals recorded at opposite ends of soil nail for steady-state vibrations

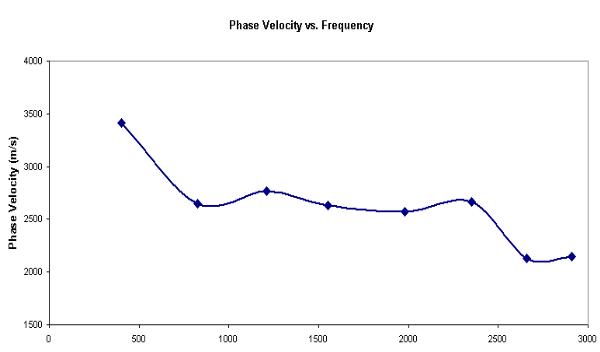

Figure 4 Phase velocities for the first eight modes calculated using experimentally obtained modal phases

Figure 4 shows the calculated phase velocities for the first eight modal frequencies. The fairly constant velocity for the first five modes significantly reduced the likelihood of dispersion. Velocities for these modes were also substantially lower than the longitudinal velocity for either steel or grout. In fact, these experimentally determined phase velocities appeared comparable to the shear velocity of the grout (Table 1). The higher velocity for the first mode and the lower velocities for the seventh and eighth modes were thought caused by experimental error in the determination of phase from the recorded accelerometer signals. To corroborate the phase velocities, a finite element model of the composite nail was developed.

Table 1 Comparison of longitudinal, shear and phase velocities

	Grout	Steel	Soil Nail
Long. Velocity, m/s	4200	5100	------
Shear velocity, m/s	2600	3200	------
Phase velocities, m/s	------	------	~2700

5 FINITE ELEMENT MODEL

A model of the composite nail to obtain its dynamic properties in the axial direction was constructed using ABAQUS, a commercial finite element program. The model replicated the physical dimensions and layout of the nail and was calibrated using the experimentally obtained modal frequencies. The model determined the mode shapes and phase velocities of the nail and thus helped to characterize the nature of the waves propagating in the nail.

The model was constructed using axisymmetric elements, which provided the desired properties for bodies of revolution subjected to axially symmetric loading conditions. Nodes of the steel bar along the axis of symmetry were constrained in the radial direction so as to derive the axial and not bending response of the nail. Typical material properties were also selected for the steel and grout elements. ABAQUS provides different types of contact between discrete bodies. Tied contact between adjoining steel and grout nodes was chosen at the steel-grout interface because no relative motion was envisioned during axial excitations.

6 NUMERICAL ANALYSIS AND RESULTS

Numerically generated mode shapes for deformations in both the axial and radial directions were extracted from the FEM. Figures 5 and 6 show mode shapes for the first three modes for axial and radial deformations along the length of the nail. Based on modal wavelength and frequency, the phase velocity for each mode was calculated using the following well-known relationship:

$$c = \lambda * f \tag{3}$$

where c is the phase velocity, λ is the wavelength and f is the modal frequency.

Table 2 gives the modal frequency, wavelength and calculated phase velocity for the three lowest derived modes of the composite nail.

As seen in the table, the phase velocity extracted from the FEM was in good agreement with the experimental. Again, the low velocities did not correlate with the longitudinal wave velocity of either the grout or the steel.

Table 2 Phase velocities derived from the FEM using modal wavelengths for axial and radial deformations

Mode	Modal Frequency (Hz)	Wavelength (m)	Phase Velocity (m/s)
1	388	7.32	2840
2	755	3.66	2763
3	1160	2.44	2830

Figure 7 shows the cross-sectional axial deformations at a location close to one end of the nail. As can be seen, the axial deformations are not uniform over the cross-section, as would be the case for a purely longitudinal wave. However, the differences are very small when compared to the absolute amplitudes of the deformations. This profile suggests that the wave generated by axial excitations has primarily axial displacements but travels at a velocity comparable to that of a shear wave.

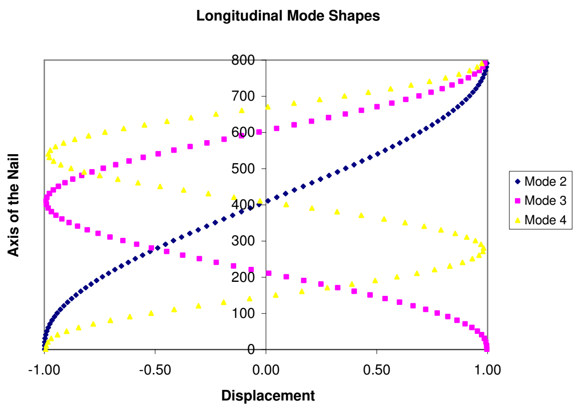

Figure 5 Mode shapes for axial deformations of the first three modes along the length of the nail

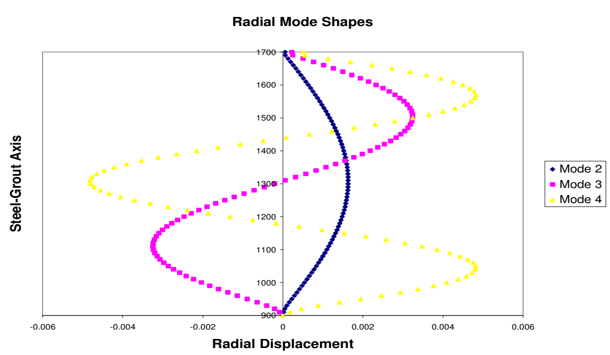

Figure 6 Mode shapes for radial deformations of the first three modes along the length of the nail

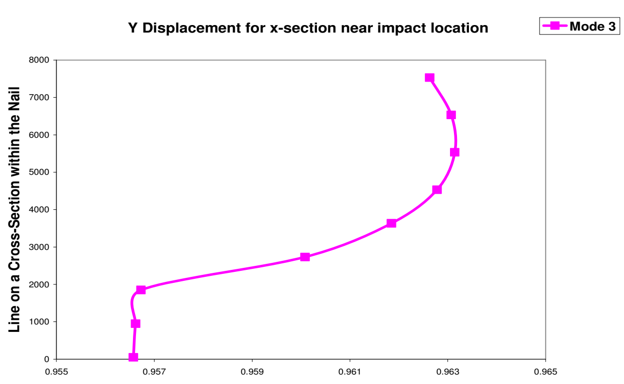

Figure 7 Cross-sectional axial deformations for Mode 2 at a location close to one end of the nail

7 CONCLUSIONS

From the experimental and numerical analyses of the composite soil nail, the following conclusions may be drawn:

- Exciting the soil nail in its axial direction does not generate a purely longitudinal wave within the nail
- Modes containing both shear and longitudinal characteristics define the response of the nail to axial excitations for frequencies below 5 kHz
- The phase velocities of the modes correspond to the shear wave velocity of the grout; modal displacements resemble those of a longitudinal wave.

8 RECOMMENDATIONS

Theoretical and experimental study of guided waves in embedded cylindrical structures is warranted to fully address and characterize the axial modes of composite soil nails with frequencies below 5 kHz.

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