USING THE IMPULSE RESPONSE TECHNIQUE TO ESTIMATE THE LENGTH OF IN-SITU SOIL NAILS

by

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Using the Impulse Response Technique to Estimate the Length of In-Situ
Soil Nails

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In partial fulfillment of the requirements
for the degree of Master of Applied Science

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ABSTRACT

Soil nails are used to prevent landslides in man-made or natural embankments. The need to install a large number of soil nails in regions of the world where site inspections are infrequent makes quality assurance difficult to achieve.

The objective of this study was to develop a non-destructive field procedure, which can quickly determine the length of the installed nails using the impulse response (IR) technique.

The study comprised two parts, experimental testing of laboratory and in-situ nails and the development of finite element models for the nails based on the tests.

The study showed that the length of short simple nails (steel bar only) could be readily determined using the IR technique. The study also showed that the mechanical properties and condition of the concrete cover in composite nails dominated the dynamic response and behavior of the nail. Knowing the proper wave velocity of the concrete cover leads to a reasonable estimate of nail length.

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Chapter 1 Summary

1.1 Introduction

Soil nailing is an in-situ soil reinforcement technique for cut-slope retaining and slope stabilization systems. It has been an alternative technique to other conventional supporting systems as it offers flexibility, rapid construction and competitive costs. Therefore, a tremendous number of soil nails are installed worldwide every year.

Due to the large number of soil nails that are installed every year as well as the rate at which they are inserted (up to 10 soil nails can be installed per hour), satisfactory quality control of the nailing technique has been difficult to achieve in some jurisdictions. Pullout capacity has been the primary control test conducted on soil nails to examine bearing capacity and nail length. However, the pullout test suffers from major disadvantages:

- 1) Expensive and time consuming
- 2) Few nails can be tested and thus results may not be indicative of the nailing system
- 3) More care may be taken by the contractor in installing test nails than other nails so that results can be misleading
- 4) The nail is often discarded after the test and not included as a part of the supporting system.

Therefore, a rapid and reliable field technique has been sought to satisfy the requirement for comprehensive quality control of soil nailing systems.

The industry tried to adopt the non-destructive sonic technique that measures the length of in-ground piles (ASTM D5882-00, Standard Test Method for Low Strain Integrity Testing of Piles) but the system showed severe limitations when it was applied to soil nails, (*Pernica et al.*,

2002). This study represents another attempt at developing a sonic technique to determine the length of in-situ nails.

The objective was to develop a sonic field procedure using the Impulse-Response technique, a technique based on the propagation of stress waves in solid materials, to estimate the length of in-situ soil nails. The study comprised two complementary phases, an experimental phase to determine the dynamic properties of 4-m long nails and a numerical analysis phase to develop suitable finite element models for the nails.

Both phases were carried out at the Institute for Research in Constructions (IRC) of the National Research Council Canada (NRC) as the institute was equipped with both scientific instrumentation to conduct the experiments and software to undertake a finite element analysis.

1.2 Experimental Phase

A total of six laboratory and in-ground soil nails were poured and then tested using the Impulse Response (IR) technique.

1.2.1 Laboratory Soil Nails

Four laboratory soil nails were constructed and housed in the structures lab at NRC/IRC (Fig. 1-1). Three laboratory nails were built with a steel bar surrounded by concrete. The bar was 4.03 m long and 28.5 mm in diameter. The concrete cover had a 152-mm square cross-section and a 20-MPa compressive strength. The fourth nail however had only one constituent, the steel bar (4.03m in length and 28.5mm in diameter).

Figure 1-1: Laboratory Soil Nails

1.2.2 In-ground Soil Nails

Two soil nails were also installed in the ground at the NRC campus. The in-ground soil nails had lengths of 3.44 m and 3.66 m. The laboratory and in-ground soil nails were considered as the very first step in developing the non-destructive field procedure to determine the length of in-situ soil nails.

1.3 Numerical Analysis Phase

The numerical analysis was carried out using the ABAQUS finite element program. Finite element models for the laboratory and in-ground nails were developed and calibrated by comparing the numerical set of the longitudinal natural frequencies to those obtained experimentally. The finite element models were then used to obtain the dynamic response of the

nails to actual impacts. From a comparison of the experimental and analytical responses, a comprehensive interpretation of the experimental data was achieved.

1.4 Conclusions

The study showed that the mechanical properties and conditions of the grout cover had a significant effect on the dynamic response and behavior of soil nails. Natural frequencies and mode shapes of the grouted laboratory nails also indicated that the lowest frequency components within the induced stress waves travelled at slightly different velocities. A slight drop in phase velocity for the first four modes also meant that the frequency spacing between modes was no longer constant. Therefore, an appropriate estimation for the length of the grouted laboratory soil nails could only be made if either the phase velocities or the frequency spacings of the vibration modes are known.

A practical approach would be to match numerical and experimental frequency signatures by varying the estimated length of the soil nail and the material properties of the grout.

However, for simple soil nails (steel bar only) or for nails with uncracked grout, good length estimation can be readily achieved by using the constant frequency spacing of the longitudinal modes.

Chapter 2 Review of Soil Nailing

2.1 Definitions

Soil nailing is an in-situ soil reinforcement technique for cut-slope retaining systems and slope stabilization. (Ground Reinforcement-Ground Treatment, Geotechnical special publication NO.69).

A soil nail is a small diameter reinforcing element, passively installed in a slope, with a typical installation angle of 10° - 45° to the normal of the potential failure surface, and therefore working mainly in tension, with shearing/bending forces as a possible but negligible secondary effect, (*Franzen 1998*).

The fundamental concept of soil nailing consists of reinforcing the ground by passive inclusions (i.e. soil nails), closely spaced, to create in-situ a coherent gravity structure and thereby to increase the overall shear strength of the in-situ soil and restrain its displacement, (ISSMFE-TC-17). The basic design consists of transferring the resisting tensile forces generated in the inclusions to the ground through the friction mobilized at the soil-nail interface. This technique has been used for the past three decades as an alternative to traditional earth supporting systems (e.g. gravity walls and sheet piles) for both temporary and permanent applications.

2.2 Applications

The Soil nailing technique has three areas of application:

1. Reinforcement of excavations
2. Stabilization of existing slopes
3. Repair of old retaining structures

The soil nailing technique is considered to be most suitable and economical for soils in which a 1 to 2-m vertical cut can stand unsupported for 1-2 days (the time required to drill holes and install nails).

Therefore, the following soil types are suitable for the soil nailing technique:

1. Weathered rock
2. Naturally cemented sand and gravel
3. Fine to medium homogeneous sand with capillary cohesion (case for sand with a water content of about 5 % according to Byrne et al., 1993).

The method can also be applied to silty soils and till, at least above the ground water table.

Soil nailing is not practical in:

1. Soft, plastic clay
2. Organics
3. Loose ($N=10$; N is the Standard Penetration Test blow count), low density and/or saturated soil.

2.3 System Components

Typical soil-nail systems contain the following components:

a) The in-situ ground

i.e. the ground containing the nails.

b) Nails

Steel bars (15-50 mm in diameter), which essentially work in tension, are placed in holes drilled into the ground (10-20 cm in diameter), and grouted over their entire length. The grout serves as corrosion protection for the bar as well as increases the surface interface between the soil and the nail.

c) Facing

Typically, reinforced shotcrete facing (100-150 mm thick) is applied to the exposed face of the wall after the nails are installed. The shotcrete is placed in the appropriate thickness reinforced with either wire mesh or large tied steel rebars depending on load requirements. The facing of the soil-nailed structure is not a major load-carrying member, but rather ensures local stability of the soil between rows of nail reinforcement and protects the ground from surface erosion and weathering effects. The type of facing not only varies with nail spacing but also depends on whether the soil-nail structure is considered permanent or temporary. In the latter case, geotextile materials are sometimes used, while shotcrete is often chosen for permanent structures.

d) Drainage

Weepholes, typically consisting of 50-mm diameter PVC pipe extending through the shotcrete facing, or strips of drainage fabric extending vertically behind the facing and protruding through the shotcrete at the bottom of the facing, are used for drainage.

2.4 Construction Steps

A soil-nail wall is constructed in successive steps from the top to the bottom of the excavation (Fig. 2-1). Construction comprises the following phases:

1. Excavation, generally limited to 1 to 2-m depth (depends on the ability of the existing soil to temporarily stand without support) and possibly limited in overall length by the type of soil being stabilized
2. Installation of the nails (steel bars and grout)
3. Building the facing of the wall
4. Repetition of steps 1 to 3

Figure 2-1: Construction Steps for Installation of Soil-Nail System

Dewatering of the site must be accomplished prior to excavation and nailing. Effective dewatering prior to excavation is critical to the success of soil nailing as it maintains the stability of the excavation face before support is in place, provides good contact between the soil/shotcrete interface and keeps soil nail boreholes open during drilling, nail installation and grouting operations (Khalil et al).

2.5 Types of Nails

Depending on the installation method, nails can be classified as follows:

a) Driven Nails

Ordinary steel bars or angle bars are often used, which are driven into the soil. The diameter of the bars is normally 15-50 mm and the nails are driven closely spaced at 0.5-4 nails per square meter of wall. The steel should preferably be ductile to avoid brittle failure.

b) Fired Nails

Special types of driven nails can be fired into the soil at speed of 320 km/h using air pressure. These nails have typically a diameter of 25-38 mm and lengths up to 6 m. The installation of nails by means of compressed air is rapid, flexible and economical and produce a minimum of disruption to the site.

c) Grouted Nails

These nails can be either installed in pre-drilled holes or drilled into place during installation. Both types consist of a steel bar with a diameter of 20-50 mm encased in a 30-50 mm thick grout cover. The spacing of the nails normally corresponds to 0.25-1 nail per square meter depending on the type of soil. Commonly used types of grouted nails are those where a hole (75-150 mm in diameter) is pre-drilled into the soil and then filled with grout after the steel core is positioned at the center of the hole. An alternative nail, where the steel core is hollow and therefore can be used as a drill bit during the installation, has also been developed. In the later case, the grout is used as a drilling liquid.

d) Jet-Grouted Nails

Nails are installed using a high-frequency vibropercussion hammer in combination with high-pressure cement grouting. This method has been shown to enhance the pullout resistance, as the high-pressure grouting causes hydraulic fracturing and re-compacting of the surrounding soil.

e) Corrosion-Protected Nails

These nails are used for aggressive soils as well as for permanent structures requiring double protection against corrosion. A minimum grout cover of 40 mm should be achieved along the total length of the nail. Secondary protection is provided by using bars coated with a minimum thickness of about 0.36 mm of electrostatically applied resin-bonded epoxy.

2.6 Advantages and drawbacks of soil nailing

- **Advantages:**

1. A flexible technique that can easily be modified during construction and can be built to follow curved or zigzagged ground profiles.
2. No specially developed equipment is needed.
3. The method can be utilized at construction sites with limited space.
4. Technique causes less noise and traffic closures on highways than other soil supporting systems.
5. The process creates less impact on adjacent or nearby properties than other construction methods.
6. Construction is rapid.
7. Costs are Competitive.

- **Drawbacks:**

1. The method can not be used at sites where ground water is a problem.
2. It is inappropriate for sites with soils having very low shear strength, with sand and gravels that lack cohesion or with other unsuitable soils.
3. Soil must be able to stand unsupported while it is being nailed and before shotcrete is applied.

4. Good drainage is essential, especially for permanent structures and for sites prone to freeze-thaw cycles.
5. Lateral and vertical movements of the soil-nail structure will occur as they are inherent to the very nature of the technique.

2.7 Mechanisms and Behavior

Soil nailing is a well established method for reinforcing soil, through the installation of relatively slender steel reinforcing bars. For a small movement of the front part of the slope (the active zone), the nail will experience both axial, δ_{ax} and lateral δ_L displacements, with respect to the soil. The axial displacement will result in the mobilization of tensile forces in the nail. The tensile forces are, however, limited by the maximum friction that can be achieved between nail and soil. Due to lateral displacements, lateral stresses will be built up in the reinforcement. The maximum lateral stresses are limited by the bearing capacity of the soil. Shear forces and bending moment may be induced in the nail by the lateral displacements, with the level being determined by the inclination and stiffness of the nail (*Franzen, 1998*).

Laboratory tests (Juran et al. 1984) have shown that the locus of maximum tensile forces, mobilized along the nails, coincides with the potential sliding surface in the soil. That surface separates the soil-nail structure into two zones (Fig. 2-2).

1. The active zone (or potential sliding soil): where the friction forces along the nail are directed towards the facing and therefore have a tendency to pull the nail reinforcement out.
2. The resisting zone (or stable zone): where the frictional forces are directed inwards into the slope, and hence prevent the outward movement of the nail. As a consequence, the

induced tensile force in the nail will firstly increase the normal stress acting on the failure surface (in turn increasing the mobilized shear resistance of the soil) and, secondly, since the nail is locked in the resisting zone, retain the movement of the active zone. A lack of nail length in the active zone can, however, be compensated by a more rigid facing (Franzen, 1998).

Figure 2-2: Active and Passive Zones in Nailed Excavation

(CLOUTERRE)

S_v is the vertical spacing between the nails

S_h is the horizontal spacing between the nails

Also, removal of horizontal layers during successive construction excavations results in preferential tensile stresses in rows of nails with higher elevation. Tension in a row of nails starts only when lower levels of the cut are being excavated. For example, it can be seen in Figure 2-3 that the tension in the Nail No.3, which was nil at the end of phase 3, increases progressively as the cut is deepened with the removal of layers 4 to 7. Furthermore, the increase in tension in Nail No. 3 due to excavation j ($j=4, 5, 6$, and 7) lessens with increasing j , as the tension in Nail i

depends mainly on the following three excavation phases, i+1, i+2 and i+3. The result is that the lowest rows of nails are the least subjected to tensile stresses. However, at the end of construction, progressive tensioning of these rows occurs due to long-term deformations of the nailed excavation. (*National research project CLOUTERRE, recommendations 1991*).

Figure 2-3: Tensioning of Soil Nail by Removal of Horizontal Layers at Lower elevations (CLOUTERRE)

2.8 Types of Failures

There are two types of failures of soil-nail wall structures, external failures and internal failures (Fig. 2-4). The difference between the two is that in external failures the reinforced wall moves as a monolithic block.

External failures can occur in one of the following ways:

1. Sliding failure: active pressure from soil on the backside of the block causes the reinforced soil block to slide along a failure surface. Insufficient nail length may also give rise to this type of external failure.

2. Bearing failure: the weight of the reinforced block and the lateral earth pressure acting on its back causes a bearing failure in the foundation.
3. Overturning of the reinforced soil block. Insufficient nail length can give rise to this type of failure.

Internal failure: To prevent this type of failure, there must be a sufficient number of nails to effectively tie the reinforced block together. The nails must have enough capacity and length to avoid the following types of internal failures:

1. Pullout failure due to insufficient friction between the nails and the soil: This type of failure occurs when the frictional forces along the surface of the nails are overestimated by the design engineer. If the lengths of the nails are now too short in the passive zone, tension forces will not be balanced and the nails will be pulled out of the soil.
2. Bearing failure in the soil because of the movement of the nail
3. Breakage of the nail due to tension combined with shearing/bending (Schlosser et al., 1991)
4. Breakage of the nail in tension: This type of failure may occur due to one of the following:
 - An underdesigned cross sectional area for the nail.
 - Corrosion of the steel bars in the nails.
 - Addition of soil surcharge to the top of the wall.
 - Saturation of the wall due to water infiltration (rain or thaw).
 - Formation of ice lenses in frost-susceptible soils, (Clouterre 1991).

Mixed Failure: A mixed failure might occur where the failure surface crosses partly through the nailed block. (*Franzen, 1998*).

Figure 2-4: Types of Failures

2.9 Design of Soil-Nail Structures

Various approaches are available for designing a soil-nail structure:

1-Limit equilibrium design methods

- Limit force equilibrium analysis
- Multi-Criteria limit equilibrium analysis

2-Working stress design methods

- Empirical design earth pressure diagrams
- Finite-element analysis
- Kinematical limit analysis

Although there are various design methods, each approach includes the following steps:

1. Estimating the working forces and the location of the potential sliding surface
2. Choosing the type of reinforcement (type of soil nail, length, inclination of the nail, cross sectional area and spacing) and then verifying that the strength and the pullout capacity of the nails at each level of reinforcement (local stability) are sufficient to withstand the working forces, calculated in step one, with an acceptable factor of safety
3. Verifying that the global stability of the nail-soil structure and the surrounding ground is maintained during and after excavation with an acceptable factor of safety.
4. Designing the wall facing according to the forces acting on it (lateral earth pressure and nail forces at the connections), taking into consideration architectural and durability criteria
5. Selecting corrosion protection (relevant to site conditions) for permanent structures
6. Selecting the drainage system

(Schaefer et al).

In this study, only one method is going to be briefly reviewed, limit force equilibrium analysis.

2.9.1 Limit force equilibrium analysis

This method uses the approach for a slope stability analysis with one difference; τ forces are considered. The global factor of safety for a slope is defined by the equation

$$F = \tau_f / \tau_{mob} \quad \text{Equation 2-1}$$

τ_f available shear resistance to soil movement

τ_{mob} shear stress mobilized in soil by failure mechanism

P nail axial force [kN]

q_s pullout resistance of the nail [kpa]

θ Perimeter [m]

L_i Nail length

T_L Pullout capacity

Figure 2-5: Nail Forces

As seen in the Figure 2-5, the mobilized tensile force in the nail has two components, one normal to the failure surface P_N , and the other parallel to the failure surface P_P . Whether the reinforcement should be considered as an increase in the resisting forces or as a decrease in the disturbing forces, gave rise to a technical dilemma (Jewell 1990). When the contribution from the nail is considered as an increase in shear resistance, the factor of safety can be expressed as:

$$F = \frac{\tau_f}{\tau_{mob}} = \frac{\sum c' + (\sigma'_N + \Delta\sigma'_N) \tan \phi + \Delta\tau_{nail}}{\tau_{mob}} \quad \text{Equation 2-2}$$

Where:

c' cohesion of the soil

σ'_N effective normal stress

$\Delta\sigma'_N$ increase in effective normal stress perpendicular to the

failure surface due to the nail force normal component, P_N

$\Delta\tau_{nail}$ increase in shear resistance due to the nail force parallel components, P_P

ϕ angle of friction or the angle of shearing resistance

τ_{mob} shear stress mobilized in the soil, depends on the weight of the active zone and the size of the external loading

On the other hand, when the contribution from the nail is considered as an decrease in disturbing forces, the factor of safety can be expressed as:

$$F = \frac{\tau_f}{\tau_{mob}} = \frac{\sum c' + (\sigma'_N + \Delta \sigma'_N) \tan \phi}{\tau_{mob} - \Delta \tau_{mob, nail}} \quad \text{Equation 2-3}$$

Where:

$\Delta \tau_{mob, nail}$ decrease in mobilized shear stress due to the nail force component, P_p , parallel to the shear surface

2.10 Pullout capacity of soil nails

Pullout capacity, T_L [kN/m] is defined as the maximum average shear force that can be mobilized per meter of nail, whereas the nail pullout resistance, q_s , is defined as the pullout capacity divided by the perimeter of the nail, (Franzen, 1998). To determine the pullout capacity of a soil nail, pullout tests should be performed. However, if tests cannot be conducted many authors have given several expressions to estimate pullout capacity (Franzen, 1998) and (Schaefer et al). These expressions generally contain four variables:

- The normal stress acting on the nail surface
- The coefficient of friction between the nail and the soil
- The adhesion between the soil and the nail
- The nail perimeter

A typical expression for pullout capacity can be written as:

$$T_L = (c_\alpha + \mu \sigma'_N) \theta$$

Equation 2-4

c_α *adhesion between soil and nail*

μ *coefficient of friction between nail and soil*

σ'_N *effective normal stress acting on the nail*

θ *nail perimeter*

Pullout capacity is an essential tool in the design of soil nails. Therefore, an accurate prediction of the pullout capacity can result in an economical design for soil-nail wall structures.

Chapter 3 Experimental Study

3.1 The Impulse-Response Technique

The Impulse-Response (IR) technique is a non-destructive sonic method, which is used to determine the dynamic properties (frequency, damping and mode shape) of structural systems, (Brueel & Kjaer, Structural Testing-Part 1). The Impulse-Response 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 travel back and forth in the structural system until they decay due to material damping, dispersion and reflection losses.

Initially, the main goal in applying the technique to soil nails was to excite the higher modes of the soil nail, which were originally thought to be primarily associated with the response of the steel bar. (However, this assumption proved later to be incorrect). By determining the resonant frequencies of these bar modes and by knowing the wave velocity in steel, the length of the soil nail could be estimated. To excite the higher modes of the nail, the impact should contain sufficient energy within the frequency range containing the modes. Figure 3-1 shows an impact in the time domain and its Fourier Transform in the frequency domain. The useful frequency range for exciting nail modal (resonant) frequencies is also indicated.

Figure 3-1: Waveform and Frequency Spectrum of a Hammer Impact

The duration and the amplitude of the force depend on the stiffness of the impact head and the mass of the hammer. By varying the hammer weight and the head stiffness, a wide range of impacts with varying frequency content (0-10 kHz) can be obtained. Long-duration impacts, i.e. impacts containing mainly low-frequency energy can be generated by using a heavy hammer with a soft impact head. Whereas, short duration impacts, i.e. impacts containing high-frequency energy, can be generated by using a light hammer equipped with a stiff impact head. Figure 3-2 shows how the frequency spectrum of the impact force can vary by simply changing the impact head of a hammer.

Figure 3-2: Influence of Hammer Head on Impact Force

Nail response induced by an impact can be monitored using a motion transducer. A motion transducer can measure displacement, velocity or acceleration of a vibrating system. A low-sensitivity accelerometer seemed most appropriate for this study because of the high-amplitude, high-frequency accelerations, which would be generated by the impacts. Displacement, velocity and acceleration are interchangeable units; by measuring one, the other two units can be obtained from the waveform.

3.2 Description of Soil Nails

Six soil nails were constructed at NRC/IRC to assist in the development of a non-destructive procedure using the IR technique. Four of the nails were housed in a structures laboratory while the remaining two were installed in the ground.

3.2.1 Soil Nail A

Soil Nail A was built with a steel bar surrounded by concrete. The bar was 4.03 m long and 28.5 mm in diameter and was covered by the concrete except its ends. The concrete cover had a 152-mm square cross-section and a 20-MPa compressive strength. Figure 3-3 shows the layout of the soil nail.

Figure 3-3: Layout of Soil Nail A

3.2.2 Soil Nail B

Soil Nail B had the same material constituents as Soil Nail A but they were arranged somewhat differently. The steel bar was again exposed at the two ends but the concrete cover now possessed a 0.5-m gap at its center. Soil Nail B was built to model the case when soil falls into the predrilled hole during the grouting operation and creates a barrier that eliminates the continuity of the grout. Figure 3-4 shows the layout of Soil Nail B.

Figure 3-4: Layout of Soil Nail B

3.2.3 Soil Nail C

Soil Nail C is another simple variation of the layout of Soil Nail A. In Soil Nail C, the steel bar was only exposed at one end. The other end of the bar remained buried in the concrete cover.

Figure 3-5 shows the layout for Soil Nail C.

Figure 3-5: Layout of Soil Nail C

3.2.4 Soil Nail D

The last of the lab soil nails, Soil Nail D was the simplest of the group of four. It had only one constituent, a steel bar 4.03 m in length and 28.5 mm in diameter. Figure 3-6 shows the layout of this basic soil nail.

Figure 3-6: Layout of Soil Nail D

3.2.5 Soil Nail S1

Soil nail S1 was the basic in-ground nail, consisting only of a single steel bar, which was driven into the ground at the NRC/IRC campus. The bar, about 25-mm in diameter and 3.44 m in length, protruded about 125 mm above the ground. Figure 3-7 shows the layout of the in-ground Soil Nail S1.

Figure 3-7: Layout of Soil Nail S1

3.2.6 Soil Nail A1

Soil Nail A1 was the composite in-ground soil nail consisting of a 25-mm diameter, 3.66-m long steel bar surrounded by a 150-mm diameter concrete cover. The bar was placed into a predrilled hole in the ground at the NRC/IRC and then backfilled with 30-MPa concrete. Figure 3-8 shows the layout of Soil Nail A1.

Figure 3-8: Layout of Soil Nail A1

The lab and in-ground nails were constructed primarily to observe whether variations in the layout of the two soil nail components (steel and concrete) had any significant effect on the dynamic properties of the nail or the IR technique and to calibrate finite element models which were also being developed as part of the study.

3.3 Conducting the experiments

3.3.1 Equipment

Different sizes of instrumented hammers producing forces with various frequency contents were used to impact the lab and in-ground soil nails at the NRC/IRC. The hammers ranged in weight (0.3 kg to 4 kg) and each came equipped with a variety of impact heads (steel, rubber or plastic). By varying both hammer weight and impact head, the duration and the amplitude of the impact force could be controlled. Each instrumented hammer was equipped with a force transducer to capture the induced force. The response of the soil nail was monitored by connecting an

accelerometer to the nail. Signals from the force and accelerometer were fed into a 2-channel frequency analyzer for storage and processing. The analyzer (Fig. 3-9) had the capabilities of presenting the captured signals in both the time and frequency domains.

Figure 3-9: 2-Channel Frequency Analyzer

3.3.2 Procedure

Exciting the soil nail was done by striking the end of the steel bar in one of two ways:

- Direct way, by impacting the end of the steel bar (most of the time)
- Indirect way, by hitting a steel shaft about 100-mm long, held firmly against the end of the steel bar

Impacting the concrete cover was another way, which was initially used to excite the soil nail system. However, this method was dropped after it became apparent that repeated impacts could damage the cover and thus substantially alter the frequency content of the induced and reflected stress waves. Therefore, striking the end of the steel bar was the only impact procedure used throughout the study.

To capture the response induced by the impact, a motion transducer, for this procedure an accelerometer, was attached to either the steel bar or the concrete cover of the soil nail system. Various types of piezo-electric accelerometers were tried. The accelerometers, which had similar physical dimensions and dynamic response characteristics, were selected because of their broadband frequency (1 Hz-20 kHz) and full-scale acceleration ranges (500 to 50000g). The bottom of each accelerometer was fitted with a threaded screw so that it could be firmly attached to any structure with a threaded fitting (e.g. a magnetic base). The accelerometer was attached to either the steel bar or the concrete cover using different systems of attachment. Table 3-1 lists the various mounting techniques for connecting the accelerometer to the soil nail, which were examined throughout the study. Table 3-2 summaries the different combinations of mounting technique and sensor location, which were tested at the start of the study. The final two entries in each table resulted from observed inadequacies in the other mounting techniques following a series of IR tests on both the lab and in-ground nails.

Table 3-1: Techniques for Mounting Accelerometer on Nail

Location on Nail	Mounting Technique
Cover	<ul style="list-style-type: none"> • Accelerometer on magnetic base <ul style="list-style-type: none"> - Base placed on head of steel screw inserted into cover • Accelerometer attached to probe (steel bar with pointed tip) <ul style="list-style-type: none"> -Probe held firmly against cover in direction of nail
Steel Bar	<ul style="list-style-type: none"> • Accelerometer on magnetic base <ul style="list-style-type: none"> - Base placed on end of steel bar • Accelerometer attached to probe <ul style="list-style-type: none"> - Probe held firmly against end or side of bar • Accelerometer screwed directly into end of steel bar <p>Hole drilled into bar and tapped to receive accelerometer</p>
Steel Bar	<ul style="list-style-type: none"> • Small steel disk welded to side of steel bar <ul style="list-style-type: none"> -Hole drilled into disk and tapped to receive accelerometer • Small steel prism screwed into side of steel bar <ul style="list-style-type: none"> - Hole drilled into side of bar and tapped to receive prism screw

Table 3-2: Tested Combinations of Sensor Location and Mounting Techniques

Impact Location	#	Accelerometer Location	Accelerometer Mounting
End of Steel Bar	1	End of Steel Bar	Magnetic Base
	2	End of steel Bar	Steel Probe
	3	End of steel Bar	Steel Screw
	4	Surface of Cover	Concrete Screw
	5	Surface of Cover	Steel Probe
End of Steel Bar	6	Side of Steel Bar	Steel Disk
	7	Side of Steel Bar	Steel Prism

The goal of trying different combinations of sensor location and mounting technique was to determine the IR test procedure, which gave optima response spectra. Optima spectra meant spectra, which contained well-defined resonant frequencies for calculating the length of the nail. This will be further discussed in upcoming sections.

In developing the test procedure, the following two tasks required careful execution:

- **Impact Delivery-** The hammer should impact the steel bar perpendicular to the bar surface i.e. the impact should be in the axial direction because only the axial response of the nail was of interest (Fig. 3-10). For many impacts at the start of the study, that was rather difficult to achieve, as the sensor was placed on the end of the steel bar in close proximity to the impact location.

- **Accelerometer Attachment-** The accelerometer must be firmly connected to the nail so as not to slip or move when the nail is impacted.

Figure 3-10: Impacting End of Steel Bar with Small Instrumented Hammer

Signals from the instrumented hammer and the accelerometer were fed into the 2-channel signal analyzer with signal storage capabilities. The frequency range was initially set to 5 kHz or 10 kHz, because higher modes which were thought to be primarily associated with the response of the steel bar and not the soil nail system, were of interest. However, that assumption turned out to be inaccurate as higher modal frequencies within the induced stress wave were not restricted to the bar but traveled within the composite nail system (steel + concrete). Therefore, the frequency range chosen for the tests on the composite laboratory soil nails was eventually set at 2 kHz to better capture the lower modal responses.

The 2-channel analyzer had the ability to display the waveforms generated by the impact and frequency spectra (Fourier Transform and Transfer Function) derived from the time signals using algorithms built into the analyzer. Not all signals were stored in the analyzer for further display and analysis. After each impact, a decision to accept or reject the measurement for suitability and

usefulness in identifying the desired modal properties of the soil nail was taken, based on the time and frequency signatures of the two recorded signals. In many cases the test was rejected because either the hammer struck the steel bar twice or hit the steel bar at a noticeable angle so as to excite bending modes in the exposed end. Table 3-3 shows the measurement procedure followed since the start of the study to conduct the IR tests (Pernica et al., 2002).

Table 3-3: Overview of IR Measurement Procedure

<p><i>1- Select Hammer Type and Impact Head</i></p> <p style="text-align: center;"><i>Hammer: Small, Medium or Large</i></p> <p style="text-align: center;"><i>Head: Steel or Stiff/Medium Plastic</i></p>
<p><i>2- Attach accelerometer to Soil Nail</i></p> <p style="text-align: center;"><i>Location: Steel Bar or Cover</i></p> <p style="text-align: center;"><i>Mounting: Magnetic Base, Probe or Steel Prism/Disk</i></p>
<i>3- Strike Soil Nail on Steel Bar</i>
<i>4- Capture Force and Acceleration Signals</i>
<i>5- Display Signals in Time and Frequency Domains</i>
<i>6- Accept or Reject Measurement</i>
<i>7- Identify Modes in Response Spectrum useful for Estimating Length of Soil Nail</i>

3.3.3 Testing Difficulties

The same set of equipment (hammers, transducers and 2-channel analyzer) and measurement procedure, which tested the laboratory soil nails, were used for the in-ground soil nails at NRC/IRC. As the stress waves induced by impacting the in-ground nails, decayed at a faster rate (less time to return to ambient conditions) due to the large amount of damping provided by the soil, a considerably large impact was required to suitably excite the desired modes. Unfortunately, these larger impacts gave rise to two undesirable outcomes:

- The response sensor frequently slipped or moved when attached using one of the initial mounting techniques (Table 3-1). Moreover, controlling the strike angle, i.e. the angle between the hammer head and the end of the steel bar, was rather difficult to achieve with the sensor mounted on the end of the bar. Acute angle impacts (less than 90^0) could excite bending modes which were not of interest in this study.
- Acceleration responses in excess of 1000 g were induced in the nail, which saturated the electrical output of the accelerometer selected for the lab nails by considerably exceeding its specified upper response range.

As a result, none of the attachment techniques (Table 3-2, #1 to #5) used with the in-ground soil nails were now considered to have yielded good results. On the one hand, exciting the system with forces from the small hammer produced high-frequency components which died out rapidly and were thus difficult to detect while on the other hand, exciting the system with considerably larger impacts (medium hammer) saturated the accelerometer. A better attachment technique and a more suitable sensor were therefore needed to capture the desired modal responses using the IR technique.

Interest now focused on **a)** how to get a very good connection between the nail and the accelerometer so that large hammer impacts did not cause slippage or saturate the sensor; and **b)** how to minimize the near-field effect caused by the closeness of the sensor to the impact. The nearness of the two had produced large amplitude nail responses which may not have been totally related to the longitudinal response of the nail but which dominated the initial portion of the time signature.

3.3.4 New Sensor Mounting

A small steel disk, about 6-mm thick and 25 mm in diameter was welded perpendicular to the side of the steel bar in Soil Nail S1. The disk contained a small threaded hole near its center for connecting an accelerometer (Fig. 3-11). By removing the sensor from the end of the steel bar, the effect caused by the closeness of the sensor and the impact location was lessened. However, the use of a disk as a mount required that its dynamic properties be determined experimentally. Natural frequencies of the disk could fall within the frequency range of interest, i.e. below 5 kHz, which would be unacceptable.

Figure 3-11: Location of Steel Disk Welded to Side of Steel Bar in Soil Nail S1

To determine the dynamic properties of the welded disk, the following laboratory test was undertaken:

A short steel bar with a welded disk was suspended horizontally in the air on soft supports. Two accelerometers were attached to the bar, one on the disk and the other on the end of the bar closest to the disk. Both accelerometers were screwed into their mounting locations (Fig. 3-12).

Figure 3-12: Test setup to Determine Dynamic Properties of Welded Disk

After impacting the opposite end of the steel bar with a small hammer, frequency spectra of the two response signals were plotted (Figs. 3-13 and 3-14). From the two figures, it can be seen that the dominant resonant frequencies of the bar at the two accelerometer locations are the same. This indicates that the natural frequencies of the disk are above 10 kHz and thus well above the frequency range of interest of the soil nails.

Figure 3-13: Response Spectrum Obtained at End of Bar to Hammer Impact at Opposite End

Figure 3-14: Response Spectrum Obtained on Welded Disk to Hammer Impact at far End of Bar

Chapter 4 Experimental Results

4.1 Laboratory Soil Nails

4.1.1 Soil Nail D

Figures 4-1 and 4-2 show the Fourier Transform of the force and the response induced in Soil Nail D (steel bar) using the small instrumented hammer with a steel head. The spectral peaks in Figure 4-2 correspond to the modal (resonant) frequencies of the unsupported steel bar, (ASTM C 1383-98a). Note that the force (Fig. 4-1) had enough frequency content (sufficient energy) to excite the higher modes (above 5 kHz) of the bar.

From vibration theory, it is known that the resonant frequencies of a soil nail are proportional to the inverse of the time required for the stress wave to travel various lengths of the soil nail (Ronald et al). The resonant frequencies of a nail are, therefore, related to nail length and stress wave velocity. For this simple unsupported nail, the length can be estimated from either the fundamental frequency or the spacing of the resonant frequencies.

$$\text{Fundamental Modal Frequency or Frequency Spacing} = \frac{\text{Longitudinal Wave Velocity}}{2 \times \text{Length Of Bar}}$$

Equation 4-1

Figure 4-1: Fourier Spectrum of Force Produced by Small Instrumented Hammer with Steel Impact Head Striking Soil Nail D

Figure 4-2: Fourier Spectrum of Response of Soil Nail D to Impact Produced by Small Instrumented Hammer with Steel Impact Head

It can be seen in Figure 4-2 that the frequency spacing of the peaks remained constant over a wide frequency range, which means that the stress wave and all its modal components traveled in the steel bar at a velocity of about 5940 m/sec (Equ. 4-2).

$$Velocity = Frequency\ Spacing \times 2 \times Bar\ Length$$

Equation 4-2

4.1.2 Soil Nail A

Figures 4-3 and 4-4 show the Fourier Transform of the force and the response induced in Soil Nail A using the medium instrumented hammer with a stiff plastic head. The force spectrum also shows that very little energy is present in the impact above 1 kHz.

Figure 4-3: Fourier Transform of the Force Produced by the Medium Instrumented Hammer with Stiff Plastic Head Striking Soil Nail A

Figure 4-4: Fourier Transform of the Response of Soil Nail A to Impact Produced by Medium Instrumented Hammer with Stiff Plastic Head

It can be noticed in Figure 4-4 that the first resonance occurred at a very low frequency (near 0 Hz). It arose because Soil Nail A was not directly supported in the axial direction but simply rested on the ground floor lab of the structures laboratory (Davis, et al 1974). Also seen in the figure, are five successive spectral peaks (below 1.5 kHz) with frequency spacings ranging from 160 – 235 Hz. The breadth of these peaks suggests that a high amount of damping is present in Soil Nail A. The frequencies also suggest that the concrete cover has mechanical properties which are below those anticipated for a 20 MPa concrete as both the fundamental frequency and frequency spacing of the modes are considerably less than 375 Hz, which would be obtained for a concrete wave velocity of 3000 m/sec. The apparently low wave velocity combined with the large amount of modal damping indicated that the visible transverse cracks in the concrete had adversely affected the mechanical properties of the cover.

The variable frequency spacing of the peaks also meant that the phase velocities of the modal components within the longitudinal wave varied slightly with frequency.

A verification of this phenomenon is presented in Chapter 6 and an explanation in Chapter 7.

4.1.3 Soil Nail B

Figure 4-5 shows the Fourier Transform of the response induced in Soil Nail B by the medium instrumented hammer equipped with a stiff plastic head.

Figure 4-5: Fourier Transform of the Response of Soil Nail B to Impact Produced by Medium Instrumented Hammer With Stiff Plastic Head

Only three major spectral peaks below 1 kHz could be identified. The modal frequencies are not equally spaced as the nail did not possess a uniform cross-section but one with major material discontinuities at two locations on either side of its midpoints. The small spectral peak at 430 Hz does not appear to be a longitudinal mode based on the shape and frequency spacings of the more dominant peaks. The peaks can be used to estimate the length of the nail provided that the wave velocity and wavelength of each mode of vibration is known.

$$\text{Modal Frequency} = \frac{\text{Longitudinal Wave Velocity}}{\text{Wavelength}}$$

Equation 4-3

as this is unlikely, the length of the nail can only be estimated by matching the experimental spectral peaks with those obtained numerically (see Chapter 8).

4.1.4 Soil Nail C

Figure 4-6 shows the Fourier transform of the response induced in Soil Nail C to an impact produced by the medium instrumented hammer equipped with stiff plastic head.

Figure 4-6: Fourier Transform of the Response of Soil Nail C to Impact Produced by Medium Instrumented Hammer with Stiff Plastic Head

Many spectral peaks below 1.5 kHz can be seen in the response spectrum of the nail.

Similar to Soil Nail A, the fundamental frequency and the frequency spacing of the modes are considerably less than expected. But in contrast to Nail A the modes are nearly equally spaced at about 230 Hz, which suggests a wave velocity (phase and group) of about 1850 m/sec. This low velocity is in keeping with the condition of the concrete cover, which sported many transverse

cracks along the length of the nail. The case of the peak at 290 Hz which departs from the normal modal spacing is unknown.

4.2 In-Ground Soil Nails

4.2.1 Soil Nail S1

Figures 4-7 and 4-8 show the frequency spectra of the force and the response induced in Soil Nail S1 using the medium instrumented hammer with a steel head. For this soil nail, the force produced by the hammer had enough frequency content (sufficient energy) above 5 kHz to excite the higher modes of the embedded steel bar.

The modal peaks are well defined in the response spectrum with the 775 Hz fundamental frequency and frequency spacing corresponding to the length (3.44 m) of the soil nail (steel bar).

(Wave velocity for steel is about 5300m/sec.)

$$Frequency\ Spacing = \frac{Longitudinal\ Wave\ Velocity}{2 \times Length\ Of\ Bar} \quad \text{Equation 4-4}$$

Figure 4-7: Fourier Transform of the Force Produced by the Medium Instrumented Hammer with Steel Head Striking Soil Nail S1

Figure 4-8: Fourier Transform of the Response Induced in Soil Nail S1 to Impact Produced by Medium Instrumented Hammer with Steel Head

The length of a simple nail comprising only a steel bar can thus be obtained using the Impulse-Response technique.

4.2.2 Soil Nail A1

A very large exciting force was needed to excite the desired modes in Soil Nail A1, which saturated the accelerometer initially chosen for the tests. As mentioned earlier, the desired modes were the higher modes which were thought to be primarily associated with the steel response of the bar. To eliminate sensor saturation, a new accelerometer with a much higher acceleration range (10000g) was purchased.

Figures 4-9 and 4-10 show the frequency spectra for the impact force used to excite Soil Nail A1 and the response induced by the force. From Figures 4-7 and 4-9 it can be seen that a very large force was required to excite the nail. Unfortunately, the force did not have sufficient energy to excite modes above 3500 Hz because of the high amount of damping present in the nail system and the poor frequency content of the force above 3500 Hz in spite of the many attempts which were made to correct the impact.

Figure 4-9: Fourier Spectrum of Force Produced by a Medium Instrumented Hammer with Steel Impact Head Striking Soil Nail A1

Figure 4-10: Fourier Spectrum of Response of Soil Nail A1 to Impact Produced by Medium Instrumented Hammer with Steel Impact Head

Four modal peaks below 3500 Hz having various frequency spacings (1180 Hz, 900 Hz and 670 Hz respectively) could be identified from Figure 4-10. Unfortunately, the modal frequencies and frequency spacings appeared to correlate poorly with the known properties of this in-situ soil nail.

Chapter 5 Numerical Analysis- Finite Element Model

5.1 Introduction

Dynamic analyses to obtain the dynamic properties and response of the soil nail system were carried out using the ABAQUS finite element program. ABAQUS is a general-purpose finite element program for non-linear static and dynamic analysis, which was designed and developed by Hibbitt, Karlsson and Sorensen, Inc (HKS). The essential purpose of using ABAQUS was to create a finite element model for a soil-nail system that could be used to determine whether the Impulse Response (IR) technique had the capabilities to accurately estimate the length of soil nails with varying in-situ lengths and cover configurations. Several finite element models (FEM) were built using ABAQUS. The models replicated the physical dimensions and layout of the laboratory and in-ground nails at NRC/IRC.

5.2 Algorithm for building FEM

In creating the finite element models, the following general algorithm was used:

1. Discretization:

This stage consisted of two steps:

- a) Defining Nodes

- b) Defining Elements

2. Defining Materials

3. Defining surfaces

Defining the Type of Contact between the surfaces

4. Defining Boundary Conditions

5. Defining Impulse

6. Defining Steps (Desired Outputs)

a) Frequency Extraction

Modal frequency and mode shape

b) Modal Dynamic

- Applying Load

5.3 Model for Soil Nail D

Soil nail D was the simplest nail system modeled in the study (Fig. 5-1) consisting simply of a steel bar.

Figure 5-1: Layout of Soil Nail D

The creation of the model for this simple nail will be presented and discussed in a step by step manner. Refer to Input File No.1 in Appendix D and Figure 5-2 for assistance in understanding the design and layout of this model.

ABAQUS input files consist of selections from built-in or user-defined element, material, procedure and loading libraries. These selections can be combined in any reasonable way, allowing for a tremendous number of problems to be modeled. In general, any input file consists of two “blocks”, model definition and history definition.

The model definition block includes model geometry, property reference, material data and boundary conditions, whereas the history definition block includes procedure definition (static or dynamic), loads and outputs requests. Each option in ABAQUS must start with a star (*). However, two or more stars (**) at the beginning of a line indicate a non-executable note or remark that ABAQUS ignores during the execution of the file.

MODEL DEFINITION BLOCK

5.3.1 Nodes (*NODE)

Only key nodes such as node # 1 and node # 500 needed to be explicitly defined in the input file. The rest were automatically generated (*NGEN) by ABAQUS. The nodes were divided into groups with each group being assigned a node set name (*NSET). For instance, axial nodes along the Y-axis (longitudinal direction of nail) were assigned to node sets called AXIAL-NODES, whereas, those along the boundary of the bar to sets called BOUNDARY-NODES. This option in ABAQUS allowed specific conditions (load or boundary conditions) to be applied to one set of nodes.

5.3.2 Elements (*ELEMENT)

ABAQUS has an extensive element library, which provides a powerful set of tools for solving many different problems. As shown in Input File No. 1, 4-node bilinear stress/displacement axisymmetric elements (*TYPE=CAX4) were selected because these elements provide the modeling needed for bodies of revolution under axially symmetric loading conditions. This axisymmetric element has four nodes each with two degrees of freedom; displacements in the X and Y directions of the Global coordinate system. Each node is described in cylindrical polar coordinates; r, z and θ at $\theta=0$. The radial r and axial z coordinates coincide with the Global Cartesian X- and Y-coordinates.

Figure 5-2 shows the mesh for Soil Nail D and it also shows the axisymmetric element in a 3-D view. Four hundred elements each with 10-mm element length were used in the longitudinal direction (Y direction). Doubling or tripling the number of elements did not have any significant effect on the derived dynamic properties of Soil Nail D. Therefore, 400 elements were considered sufficient for this simple nail. Comparable to the nodes, the elements were divided into groups with each group being assigned an element set name, (*ELSET).

5.3.3 Materials (*MATERIAL)

For Soil Nail D, there was only one material to be defined, steel. Since the soil nail will only be subjected to “light” hammer impacts its response will fall within the linear elastic range of the steel. As a result, two primary parameters have to be defined for steel through the option (*ELASTIC); Young’s modulus of elasticity, and Poisson’s ratio. Typical properties of 206 GPa and 0.3 were selected for Young’s modulus and Poisson’s ratio. The density of steel was also defined as 7850 kg/m³ through the option (*DENSITY).

5.3.4 Boundary Conditions (*BOUNDARY)

As only the axial response of the nail was of interest, displacements in the X direction were fixed for each node along the axis of symmetry. A spring element with 200 N/m stiffness was also attached in the Y direction to the bottom of the steel bar to eliminate numerical instability in the model. The stiffness of the spring element was chosen exceeding small so as to have minimal effect on the dynamic behavior of the system. In Soil Nail D, there was no contact between elements of different materials and hence contact surfaces did not need to be modeled.

5.3.5 Impulse (*AMPLITUDE)

The same hammer impulse that had been used to excite Soil Nail D was used to excite its FEM. An ASCII file of the time history of the hammer force was obtained from the 2-channel analyzer.

The file contained time and amplitude pairs of the dynamic force, which was modified to suit the ABAQUS format for loads.

HISTORY DEFINITION BLOCK

5.3.6 Analysis Steps and Output Requests (*STEP)

The analysis steps are based on the desired outputs. The outputs can be associated with nodes, elements or surfaces. For Soil Nail D, two outputs response were of major interest; the natural frequencies (*FREQUENCY) of the system and the acceleration response (*NODE FILE) to a hammer impact.

Sometimes the sequence of steps maybe significant in modal analysis. For instance, the natural frequencies have to be extracted before the impulse force is applied and the acceleration response of the nodes determined.

When determining the response of the nail to a dynamic force (impulse), damping ratios must be assigned to all the modes selected for the analysis (*MODAL DAMPING). For Nail D, the damping ratio for the first mode was set at 0.5% and those for the remainder of the selected modes at 0.1%. In the input file shown, only the first 22 natural frequencies were extracted and used to calculate system response.

Figure 5-2: Finite Element Mesh for Soil Nail D Showing Nodes and Element Numbering

Schemes

To check whether the FEM was properly built, numerical natural frequencies were compared to those obtained experimentally and to the closed-form solution for a solid bar (Clough and Penzien):

$$f_i = n_i * \sqrt{\frac{E \cdot A}{m \cdot L}} \quad \text{Equation 5-1}$$

Where $n=0.5, 1, 1.5, 2 \dots$

E, Young's Modulus of elasticity

A, Cross sectional area

L, Length of the steel bar

m, the unit mass of the steel bar

Table 5-1: Natural Frequencies for Soil Nail D Obtained Numerically, Theoretically and Experimentally

ABAQUS	CLOSED FORM	EXPERIMENTAL
Frequency [Hz]	Frequency [Hz]	Frequency [Hz]
<i>0.50102</i>	<i>0.00</i>	<i>0</i>
<i>636</i>	<i>636</i>	<i>624</i>
<i>1271</i>	<i>1271</i>	<i>1274</i>
<i>1907</i>	<i>1907</i>	<i>1898</i>
<i>2542</i>	<i>2542</i>	<i>2548</i>
<i>3177</i>	<i>3178</i>	<i>3172</i>
<i>3813</i>	<i>3813</i>	<i>3821</i>
<i>4448</i>	<i>4449</i>	<i>4446</i>
<i>5083</i>	<i>5085</i>	<i>5095</i>
<i>5717</i>	<i>5720</i>	<i>5720</i>
<i>6352</i>	<i>6356</i>	<i>6344</i>
<i>6986</i>	<i>6991</i>	<i>6993</i>
<i>7620</i>	<i>7627</i>	<i>7618</i>
<i>8254</i>	<i>8262</i>	<i>8267</i>
<i>8887</i>	<i>8898</i>	<i>8891</i>
<i>9520</i>	<i>9534</i>	<i>9541</i>
<i>10153</i>	<i>10169</i>	<i>10165</i>
<i>10786</i>	<i>10805</i>	<i>10815</i>
<i>11418</i>	<i>11440</i>	<i>11439</i>
<i>12049</i>	<i>12076</i>	<i>12063</i>
<i>12680</i>	<i>12711</i>	<i>12688</i>
<i>13311</i>	<i>13347</i>	

It can be seen from Table 5-1 that below 10 kHz the numerical natural frequencies are nearly identical to those obtained experimentally and theoretically which suggests that the FEM for the simple soil nail was properly conceived and built.

5.4 Soil Nail A

As noted in section 3.2.1 Soil Nail A is a composite nail consisting of a steel bar surrounded by a uniform concrete cover (Fig. 5-3).

Figure 5-3: Layout of Soil Nail A

The FEM for Soil Nail A was accomplished by following a procedure similar to that developed for Soil Nail D (see Input File No. 2 in Appendix D). However, a geometric modification to the concrete cover was required to use the axisymmetric elements of the previous model. As Soil Nail A was not axisymmetric with respect to the Y-axis, the square cross-section was simply converted to a circular section with an equivalent area, (Fig. 5-4).

Figure 5-4: Conversion of Square Cross Section to Circular for Soil Nail A

Because Soil Nail A was composite, the surfaces (*SURFACE) between the two materials (the steel bar and the concrete) and hence the interaction (*SURFACE INTERACTION) at their interface had to be modeled. The (*SURFACE) option can be used in ABAQUS to model the interaction of two or more distinct bodies in a mechanical analysis. A surface is created from a set of elements. In our case, two surfaces were defined; a surface associated with the steel bar and a surface associated with the concrete cover (Fig. 5-5).

Figure 5-5: FE Mesh for Soil Nail A Showing ABAQUS Surface Convention

In the surface definition step, an outward normal of the surface must be defined, so that ABAQUS knows the contact direction (Contact direction is always normal to the master surface). The surface interaction step and the contact pair step usually follow the surface definition step. In the surface interaction step, ABAQUS identifies the two surfaces which are in contact, and their interaction properties such as friction. In the contact pair step, points and surfaces on one body are aligned with points and surfaces on the other body. When using (*CONTACT PAIR) step, ABAQUS requires a Master/Slave surface relationship (approach). One significant difference

between Master and Slave surfaces is that the Master surface can penetrate the Slave surface, but the Slave surface can not penetrate the Master surface. In our model the steel surface was defined as the Master surface (much stiffer than the concrete) and the concrete surface was defined as the Slave surface.

Many parameters can be defined in conjunction with the contact pair step, such as small sliding or infinitesimal sliding to simulate the actual behavior of contact surfaces. The major difference between the small sliding and infinitesimal sliding formulation is that infinitesimal sliding ignores the non-linear geometric effect, whereas small sliding takes this non-linear behavior into consideration.

For Soil Nail A the contact between the Slave and the Master surface was defined as a tied contact, since no relative motion between the steel bar and the concrete was assumed. A tied contact formulation constrains each of the nodes on the Slave surface to have the same displacement as the nodes on the Master surface that it contacts. Defining identical nodes at the steel-concrete interface (the steel and concrete share the same nodes) is an alternative modeling approach to the surface option. For that case, surfaces needed not be defined. For tied contact, changing the coefficient of friction at the steel-concrete interface is irrelevant as the relative motion between the steel and the concrete is zero.

Natural frequencies initially extracted from the FEM of Soil Nail A did not match with experimental results. The mismatch appeared to be caused by the condition of the concrete cover. Many transverse cracks were now present in the covers of the lab nails stemming from the numerous moves they had sustained during their stay in main structures laboratory. To account for their deteriorated condition, the modulus of elasticity of the concrete was reduced. The drop to obtain agreement between the numerical and experimental sets of natural frequencies was substantial, from 18 GPa to 1.8 GPa.

Because the FEM for Soil Nails B and C were built in the same manner as Soil Nail A, they are not discussed here. However, their input files are also provided in Appendix D.

5.5 Soil Nail S1

Soil Nail S1 as noted in Section 3.2.5 comprised a single steel bar, which was driven into the ground on the NRC/IRC campus (Fig. 5-6). The input file for Soil Nail S1 is given in Appendix D.

Figure 5-6: Layout of Soil Nail "S1"

The model for Soil Nail S1 comprised two parts. The first part modeled the steel bar which duplicated that produced for Soil Nail D. The second part modeled the soil surrounding the bar. The difficulty encountered in creating the FEM for Soil Nail S1 was modeling the actual contact between the steel bar and the soil, as the difference in properties between these two materials was significant. Many attempts at modeling the soil and the soil-steel interface were tried to obtain the actual response of Soil-Nail S1 to an impact. The first attempt was to model the soil as an elastic

material since the soil-nail system can be considered a linear system for the application of IR technique.

When modeling the soil as an elastic material, regardless of the type of contact selected at the steel-soil interface, only two parameters needed to be defined, Young's modulus of elasticity $E=10E6$ MPa and Poisson's ratio $\nu=0.3$. By doing so, ABAQUS made an assumption that the soil-nail system is a linear system and thus the two components of the system (the steel bar and the soil surrounding the bar) should respond elastically as a composite structure. As a result, hundreds of closely spaced modal frequencies below 500 Hz were extracted from the model. A close examination indicated that these frequencies were primarily associated only with the presence of the soil and not the response of the bar. Increasing the number of elements in the longitudinal direction was thought to give better results. Therefore, 800 elements along the steel bar were tried. However, the same set of closely spaced frequencies was obtained.

Using different contact approaches (small sliding, infinitesimal sliding or tied contact) between the steel bar and the soil produced sets of natural frequencies which were comparable to that obtained by increasing the number of longitudinal elements. Therefore, modeling the soil as an elastic material was abandoned at this point in the numerical analysis.

The second attempt was to model the soil as a porous elastic material. A porous elastic material is valid for small elastic strains ($<5\%$). It is a nonlinear elastic isotropic designation in which the pressure stress varies as an exponential function of volumetric strain. (ABAQUS/Standard, User's Manual, Volume 1.)

Four parameters (logarithmic bulk modulus, Poisson's Ratio, elastic tensile limit and void ratio) needed be defined to model the volumetric and shear behavior of a porous elastic material. The following properties were selected for the clay at NRC/IRC; logarithmic bulk modulus $K=0.026$,

Poisson's ratio $\nu=0.3$, elastic tensile limit=2 kPa and void ratio $e=1$. However, natural frequencies extracted from the model were again closely spaced and low. This meant that the model still predicted modal responses which were primarily associated with soil rather than bar behavior. To examine the higher modal frequencies produced by the porous element, a frequency shift "S" (a cut-off frequency) was introduced into the output request for modal properties.

A cut-off frequency (frequency shift) can be defined on the data line of the (*FREQUENCY) option in ABAQUS input file so that the closest modes to that frequency will be extracted first.

Different cut-off frequencies for the various soil elements were tested. However, a 500 Hz cut-off frequency was found to give the most descent results i.e. the first printed frequency was 535 Hz with the rest at intervals of about 270 Hz. It should be noted that infinitesimal sliding at the contact surface was used to obtain the above stated results.

The extracted frequencies above 500 Hz appeared to be associated with the response of the steel bar, although they were affected by the type of connection which linked the steel and soil nodes.

As a result, a very "weak" connection linking the steel and the soil was sought so that the response of the nail would be mostly associated with the steel bar. Gap elements appeared to provide the means to achieve the goal.

5.5.1 Gap Elements

Gap elements allow for contact between nodes on two surfaces. They have infinite compressive axial stiffness but zero tensile axial stiffness. These elements form a layer of negligible thickness along the interface, which can be designed to model the real contact between the steel bar and the soil. Three types of Gap elements were available in ABAQUS; GAPUNI, GAPCYL and GAPSPHER. A unidirectional gap element (GAPUNI) was used to model the connection

between the steel and the soil. This element is designed in ABAQUS by specifying the two nodes which form the Gap and by providing geometric data which describes the initial state and, if necessary the direction of the Gap (Fig. 5-8).

Figure 5-7: Structure of Gap Element

The basic parameters needed to define a GAPUNI element are:

1. -Initial clearance, d : The soil was in contact with the steel bar. Therefore, the initial clearance was set to zero and the Gap was said to be closed. The Gap is said to be open when a positive value is assigned to the initial clearance. Assigning a negative clearance makes the Gap overclosed.
2. -Global X-direction cosine of the contact direction (1 in our case)
3. -Global Y-direction cosine of the contact direction (0 in our case)
4. -Global Z-direction cosine of the contact direction (0 in our case)
5. -Cross sectional area of the Gap element: The cross-sectional area of a Gap element was not crucial since there was no interest in calculating the contact stress transformed throughout the

element. In fact, Gap elements have unit area by default; therefore, the calculated contact stress is actually the contact force.

Upon extracting the natural frequencies from the Gap-element model, it was clear that the frequencies were primarily associated with the response of the steel bar. The first frequency above 500 Hz was about 750 Hz with the higher modes following at 750 Hz intervals. Changing the material properties of the soil or the diameter or length of the soil layer had almost no effect on the extracted natural frequencies above 500 Hz. These natural frequencies can therefore be considered to correspond principally with the dynamic response of the steel bar. The soil did not participate as it can not readily transfer the higher frequencies associated with these modes.

Gap elements represent the link to weakly connect the soil to the steel. For low modal frequencies, the steel and the soil respond together but as the modal frequency rises the soil can not keep up with the steel response. Gap elements thus provide the means for the two components to separate dynamically.

Another approach, which can be used to model the interaction between the soil and the steel, is the Surface Element approach. This approach may lead to more reliable model as it handles the frictional forces between the steel and the soil in more comprehensive way.

5.5.2 Boundary Conditions

Steel Bar: To get the axial response of the steel bar, all nodes along the axis of symmetry were fixed in the X direction (transverse).

Soil Layer: Soil nodes along the exterior boundary parallel to the steel bar were fixed in both X and Y directions. Soil nodes along the exterior boundary beneath the steel bar were fixed in the Y direction to prevent rigid body motion of the entire model in the Y direction.

5.6 Soil Nail A1

Soil Nail A1 is a composite in-ground soil nail consisting of a 25-mm diameter, 3.66 m long steel bar surrounded by a 150-mm diameter concrete cover (Fig. 5-8).

Figure 5-8: Layout of Soil Nail A1

The input file for Soil Nail A1 is given in Appendix D. The model for Soil Nail A1 was constructed by combining the surface options of Soil Nail S1 and Soil Nail A. Contact at the soil-steel and soil-concrete interfaces was modeled using Gap elements, whereas contact at the concrete-steel interface was fashioned as tied using the surface interaction approach. Unfortunately, the model has not been verified or calibrated as only a few experiments have been conducted on the outdoor soil nail to date.

Chapter 6 Numerically-Determined Nail Responses

6.1 Laboratory Soil Nails

6.1.1 Soil Nail D

Figure 6-1 shows the response spectrum of Soil Nail D to an actual impact produced by the small instrumented hammer equipped with a steel head. The response was calculated for the node on the Y-axis at the struck end of the steel bar. The model contained 400 steel elements with defined properties of 206 GPa for modulus of elasticity, 0.3 for Poisson's Ratio and 7.85 for specific gravity. The modulus had been adjusted until a reasonable match was obtained between the numerical and experimental natural frequencies. The time history of the actual force was inserted into ABAQUS in 3.91×10^{-5} ms increments (determined by the frequency range of the analyzer) and the response at the end of the steel bar calculated using the first 22 natural frequencies. Damping ratios for the modes were estimated at 1 % for the fundamental and 0.5 % for the remainder.

It can be seen from the figure that the frequency spacing for the first four modes averaged about 640 Hz. This corresponds to an expected wave velocity of about 5160 m/s for the 4.03-m long steel bar. The figure also shows that modal acceleration responses decrease monotonically on either side of the fourth mode (2550 Hz) suggesting that this mode had a high participation factor.

Figure 6-1: Calculated Response of Soil Nail D to Impact Induced by Small Instrumented Hammer using Steel Head

6.1.2 Soil Nail A

Figure 6-2 shows the response spectrum of Soil Nail A to an actual impact produced by the medium instrumented hammer with a plastic head. The response was calculated for the node on the Y-axis at the impacted end of the steel bar. For improved accuracy, 800 elements were used in the model along the Y-axis (longitudinal direction). As previously mentioned, the mechanical properties of the concrete cover needed be adjusted to account for the presence of transverse cracks in the “grouted” laboratory nails. A dramatic reduction of the modulus of elasticity, from 18 GPa to 1.8 GPa, appeared to give the best match between the numerical and experimental natural frequencies.

The time history of the force was entered into ABAQUS in 1.95×10^{-4} ms increments and the response at the end of the steel bar calculated using the first 22 natural frequencies. However, it would have been sufficient to calculate the response using only the first 10 natural frequencies, as the impact contained sufficient energy only to about 2 kHz. As for the other mechanical

properties of the concrete, a specific gravity of 2.4 and a Poisson's Ratio of 0.25 were assigned to the cementitious cover. Damping ratios for the modes were estimated at 2 % for the first mode and 1 % for the remainder.

Figure 6-2: Calculated Response of Soil Nail A to Impact Induced by Medium Instrumented Hammer using Stiff Plastic Head

It can be seen from the figure, that the frequency spacing of the resonant peaks ranged from 165-220 Hz with the modal acceleration responses decreasing monotonically from the first mode. A steady reduction in frequency spacing suggests that the phase velocity is decreasing with increasing resonant frequency. This observation was verified in Chapter 7.

6.1.3 Soil Nail B

Figure 6-3 shows the response spectrum for Soil Nail B to an actual impact produced by the medium instrumented hammer equipped with a stiff plastic head. The response was once again calculated for the node on the Y-axis at the impacted end of the steel bar. The FEM was

constructed with 800 elements along the Y-axis. The modulus of elasticity of the concrete was also significantly reduced to account for transverse cracks in the cementitious cover.

Five noticeable modal peaks, up to 750 Hz, can be seen in the figure. Above 750 Hz, the force appears not to have contained enough energy to excite the higher modes (Fig. 6-4). However, modes after the first peak seem to pair up perhaps due to the 0.5-m gap in the cover of Soil Nail B. With this in mind, maybe only three modal peaks need be considered in estimating the length of the nail, with only the first peak in each pair being selected for the calculation. Note also that the frequency spacing between peaks in each pair decreased with increasing resonant frequency. This response was also observed in the experimental data presented in Chapter 7.

Figure 6-3: Calculated Response of Soil Nail B to Impact Induced by Medium Instrumented Hammer using Stiff Plastic Head

Figure 6-4: Fourier Spectrum of the Force used in ABAQUS to calculate the Response of Soil Nail B

6.1.4 Soil Nail C

Figure 6-5 shows the frequency response for Soil Nail C to an actual impact produced by the medium instrumented hammer equipped with a stiff plastic head. The response was obtained for the node on the Y-axis at the struck end of the bar. The FEM for Soil Nail C was constructed in the same manner as the other laboratory nails in terms of mechanical properties of the steel bar and concrete cover and the number of elements in the longitudinal direction.

Several resonances can be identified with frequency spacing ranging from 190-230 Hz.

Similar to Soil Nail A, the modal acceleration responses decrease monotonically after the first mode suggesting that this mode had the highest participation factor in the longitudinal direction.

Figure 6-5: Calculated Response of Soil Nail C to Impact Induced by Medium Instrumented Hammer using Stiff Plastic Head

The average frequency spacing could be used to estimate the length of the nail by assuming a wave velocity commensurate with the actual condition of the concrete cover. In this case, the slight difference in phase velocities between the modes would be ignored.

6.2 In-ground soil Nails

6.2.1 Soil Nail S1

Figure 6-6 shows the response spectrum at the struck end of Soil Nail S1 to an actual impact produced by the medium instrumented hammer equipped with a steel head. The impact produced a broadband force containing frequency components to about 8 kHz (Fig. 6-7). The model was constructed with 400 steel elements along the longitudinal direction. The same mechanical properties for the steel bar that were used for the Soil Nail D were inserted into the model for Soil Nail S1. The ground was modeled by a porous soil material. Ground elements were weakly

connected to the steel bar by gap elements. Changing the soil properties had almost no effect on the frequencies of the higher modes (above 500 Hz) in the response spectrum.

The frequency spacing of the higher modes remained constant at about 750 Hz, which corresponded to the length of the steel bar for a wave velocity in steel of about 5160 m/sec. Therefore, a reasonable estimation of the length could be achieved for a simple in-ground nail using the average frequency spacing of the higher modes.

Figure 6-6: Calculated Response of Soil Nail S1 to Impact Induced by Medium Instrumented Hammer with Steel Head

Figure 6-7: Fourier Spectrum of the Force used in ABAQUS to calculate the Response of Soil Nail S1

Chapter 7 Verification of Wave Velocities in Composite

Laboratory Soil Nails

7.1 Verification Techniques

To verify that the modal (phase) velocities of the longitudinal wave induced in the laboratory soil nails were frequency-dependent, two analysis techniques were used with experimentally generated waveforms, cross-correlation and cross-spectral density. Numerical verification was also done to see whether the FE model produced the same results.

Cross-correlation and cross-spectral density are considered as methods of relating measurement data observed at one point in a system to data obtained at some other point within the same system (*Bruel & Kjaer*). The cross-correlation function is the inverse Fourier transform of the cross spectrum.

7.2 Cross-Correlation Technique

The cross-correlation technique is used to measure similarities between two non-identical waveforms. If the same signal is presented in both waveforms, it will be reinforced in the cross-correlation function, while any uncorrelated noise will be reduced.

7.2.1 The experimental procedures

The cross-correlation technique was applied to the laboratory nails using the following procedure.

A narrowband excitation containing the desired modal frequency was generated at one end of the soil nail using a small dynamic shaker. The time required for the wave to propagate from one end

of the nail to the other was determined by applying the cross-correlation function to the signal captured by accelerometers mounted at both ends of the nail. However, before conducting the test, the modal frequencies of the nail were reconfirmed using steady state excitations from the shaker.

To determine the resonant frequencies, a sine sweep ranging from 100 Hz to 1 kHz was generated by the 2-channel frequency analyzer and fed into the small shaker which was attached to one end of the soil nail. An accelerometer was mounted at the other end to capture the response at the far end of the nail (Fig. 7-1).

Figure 7-1: Shaker Attached to One End of a Laboratory Soil Nail

At the conclusion of the sweep, the modal peaks (resonances) were selected from the frequency response function (FRF) derived from the accelerometer embedded within the shaker. Using these resonant frequencies, bursts containing a single resonant frequency were fed from the analyzer into the shaker, which was attached to one end of Soil Nail A. The number of cycles contained in each burst and the frequency bandwidth of the analyzer varied depending on the selected resonant frequency. For the higher resonant frequencies, up to 10 cycles and a bandwidth of 20 kHz were

required to obtain the desired time resolution (Δt between the points in the time domain) in the cross-correlation function. The accelerometer signal at the shaker end was correlated with the captured signal from the opposite end to obtain the cross-correlation function. From the cross-correlation function, the time delay between the two accelerometer signals was obtained. By repeating the procedure, wave velocities were calculated for the lowest group of resonant frequencies, by dividing the length of the nail by the time delays.

7.2.2 Soil Nail A

Figure 7-2 shows the frequency response function for Soil Nail A derived from the sine sweep test. From this figure, five resonant frequencies (245, 430, 583, 770 and 950 Hz) were selected for the cross-correlation procedure.

Figure 7-2: Resonant Frequencies of Soil Nail A Obtained from Sine Sweep Test

Figure 7-3 shows the time delay of the signal captured at both ends of Soil Nail A for the resonant frequency at 245 Hz. Table 7-1 shows the time delay and the corresponding wave velocity for

each resonant frequency below 1 kHz. Data for the fourth resonant frequency is shaded to indicate a derived wave velocity which exceeds even that of steel.

Figure 7-3: Cross-Correlation Function Obtained for the 245 Hz Resonant Frequency of Soil Nail

A

Table 7-1: Time delays and wave velocities for the lowest resonant frequency of Soil Nail A

Frequency [Hz]	Time delay [Sec]	Velocity [m/sec]
245	0.0021114	1895
430	0.0012121	3300
583	0.002106	1900
770	0.0007215	5544
950	0.0033345	1200

It can be seen from the table that a large range in velocity was obtained for the lowest resonant frequencies of Nail A. The expected decrease in velocity with increasing resonant frequency

(based on wavelengths derived from the FE analysis) did not materialize. An examination of the shaker output to the nail revealed a possible source for the bizarre results.

The shaker could not output a suitable 5-cycle burst containing mainly a single frequency. If the FFT of the shaker-generated force for the 245 Hz resonant frequency is examined, it can be seen that significant sub-harmonics of the resonant frequency were being generated by the shaker due to its inherent characteristics, (Fig. 7-4). The inclusion of significant low-frequency sub-harmonics can readily influence the measured delay time (for all but the first resonant frequency) especially if the sub-harmonics travel at faster velocities than selected resonant frequency. As a result, a more reliable technique was needed to examine the perceived frequency dependency of the phase velocity.

Figure 7-4: Spectrum of Burst Shaker Force at 245 Hz for Soil Nail A

7.3 Cross-Spectral Density Technique:

As previously noted, the cross-spectral density function is the Fourier Transform of the cross-correlation function. It is a complex function containing both imaginary and real parts, which can also be displayed as the magnitude and the phase between frequency components in two simultaneously measured signals (Fig. 7-5).

Figure 7-5: Phase between Signals from Accelerometers Located at Opposite Ends of Soil Nail A
(Sine Sweep Test)

From the phase relationship, the time of travel and thus the (phase) velocity of each of the modal components within the longitudinal stress wave can be determined using Equation 7-1.

$$C = \frac{360 \cdot f \cdot l}{\Phi}$$

Equation 7-1

where: f = frequency [Hz]

L = distance between accelerometer locations on the soil nail [m]

Φ = Phase shift [degree]

7.3.1 Experimental Procedure

The cross-spectral technique was conducted using the same placement of instrumentation as that assembled to perform the cross-correlation technique. A sine sweep containing the desired modal frequencies was generated by the analyzer and fed into the shaker. Nail response was captured at two locations using accelerometers mounted at opposite ends of the nail. The phase between the two accelerometer signals was obtained from the cross spectrum of the two waveform (Fig. 7-5). Table 7-2 shows the phase between the two accelerometer locations and the corresponding wave velocity calculated for each resonant frequency.

Table 7-2: Wave Velocity Calculated for Each Resonant Frequency Using Phase between Responses Measured at Opposite Ends of Soil Nail A

Frequency [Hz]	Phase Shift [Degree]	Velocity [m/sec]
245	176	1860
430	365.91	1570
583	538	1450
770	882	1165
950	1088.6	1165

It can be seen from the table that the lower resonant frequencies travelled faster than the higher resonant frequencies. It would appear that the phase velocity within Soil Nail A is frequency-dependent. Figure 7-6 plots the velocity variation with resonant frequency.

Figure 7-6: Variation of Phase Velocity with Frequency in Soil Nail A

7.3.2 Soil Nail B

The experimental procedure was repeated on Soil Nail B. Figure 7-7 shows the frequency response function for the nail from which the resonant frequencies were obtained.

Figure 7-7: Resonant Frequencies of Soil Nail B Obtained from Sine Sweep Test

Using the cross-spectral technique and plotting the phase between accelerometers mounted at opposite ends of the nail (Fig.7-8), the wave velocity for each resonant frequency was calculated using Equation 7-1.

Figure 7-8: Phase between signals from accelerometers located at opposite ends of Soil Nail B
(Sine Sweep Test)

Table 7-3 shows the phase between the two accelerometer signals and the resulting wave velocity calculated for each resonant frequency.

Table 7-3: Wave Velocity Calculated for Each Resonant Frequency Using Phase between
Responses Measured at Opposite Ends of Soil Nail B

Frequency [Hz]	Phase [Degree]	Velocity [m/sec]
220	180	1633
390	214	2434
613	706	1160
795	1172	906

Figure 7-9 plots the velocity variation with resonant frequency for Soil Nail B.

Figure 7-9: Variation of Phase Velocity with Frequency in Soil Nail B

7.4 Numerical Verification

Numerically produced mode shapes for the lowest resonant frequencies are shown in Figures 7-10 to 7-13 of Soil Nail “A”. Wavelengths for each mode can be readily determined from the figures since the total length of the nail is known (4.030 m).

Having obtained the wavelength for each mode, the wave velocity can be calculated from the well-known expression:

$$c = \lambda * f \quad \text{Equation 7-2}$$

Figure 7-10: Numerically Obtained Mode Shape for First Mode of Soil Nail A

Figure 7-11: Numerically Obtained Mode Shape for Second Mode of Soil Nail A

Figure 7-12: Numerically Obtained Mode Shape for Third Mode of Soil Nail A

Figure 7-13: Numerically Obtained Mode Shape for Fourth Mode of Soil Nail A

Table 7-4 and Figure 7-14 show how the wave velocity decreased as the modal frequency increased.

Table 7-4: Wavelengths and Wave Velocities for the Lowest Resonant Frequencies of Soil Nail A

Mode #	Wave Length λ (m)	Frequency (Hz)	Wave Velocity (m/sec)
1	8	225	1800
2	4	445	1780
3	8/3	645	1720
4	2	840	1680
5	8/5	1005	1608

A conclusion can be drawn from this table that the phase velocity for the first five modal frequencies decreases as the frequency increases.

Figure 7-14: Variation of Phase Velocity with Modal Frequency in Soil Nail A

Chapter 8 Comparison of Experimental and Numerical Results

8.1 Laboratory Soil Nails

8.1.1 Soil Nail D

Figure 8-1 shows the response spectra obtained experimentally and calculated numerically for a small hammer impact to the end of the steel bar of Soil Nail D.

Figure 8-1: Comparison of Experimental and Numerical Response Spectra of Soil Nail D

It can be seen from the figure that the two response spectra are identical with respect to resonances and frequency spacings. However, there is one striking difference between the two and that is amplitude. Resonant amplitudes for the response spectrum obtained experimentally are considerably larger than those obtained numerically. The most obvious reason for the difference

may have to do with the modal damping ratios assigned to the finite element model (1% for the first mode and 0.5% for the others) which appear from the comparison to be far too high for a simple steel bar.

8.1.2 Soil Nail A

Figure 8-2 shows response spectra for Soil Nail A obtained experimentally and calculated numerically. The two responses were produced by the medium instrumented hammer equipped with a stiff plastic head striking the end of the steel bar. Overall, the two spectra are as much similar as they are different. On the positive side, it can be seen that the resonances in both spectra occurred at about the same frequencies although the match could be improved by a slight increase in the modulus of elasticity for the concrete cover. The spectra also support the view of decreasing phase velocity as the spacing between peaks is narrowing with increasing resonant frequency. However, the peaks in the experimental spectrum are much wider than the numerical suggesting that the modal damping ratios for this nail are much higher than those assumed in the model (2% for the first mode and 1% for the others).

Another noticeable difference exists around 0 Hz. The experimental spectrum contains a peak at 0 Hz as a result of the support provided to the nail in the laboratory. Soil Nail A was only restrained in the axial direction by the horizontal resistance provided by two soft rubber strips resting on the laboratory floor slab. However, a soft spring was attached to one end of the steel bar in the FEM, which created a low-frequency resonance which did not respond to the impact.

Figure 8-2: Comparison of Experimental and Numerical Response Spectra of Soil Nail A

8.1.3 Soil Nail B

Figure 8-3 shows experimental and numerical response spectra for Soil Nail B. The two responses were produced by the medium instrumented hammer with a stiff plastic head striking the end of the steel bar. It can be seen that the first three resonant responses calculated by the FEM match resonances obtained experimentally. However, the experimental spectrum contains a significant second mode which is not present in the numerical model. Perhaps the second and third peaks in the experimental spectrum actually represent only one mode, the second.

With respect to the amplitude of the peaks, those in the experimental spectrum are lower for the first mode and higher for the second and third than those in the numerical spectrum suggesting that the amount of damping present in Soil Nail B is higher for the first mode and lower for the higher modes than those assigned in the finite element model.

Figure 8-3: Comparison of Experimental and Numerical Response Spectra of Soil Nail B

8.1.4 Soil Nail C

Figure 8-4 shows experimental and numerical response spectra for Soil Nail C. The two responses were produced by the medium instrumented hammer with a stiff plastic head striking the end of the steel bar. It is clear that resonances in the two spectra below 1 kHz occurred at about the same frequencies. Above 1 kHz, numerical frequencies and spacing need to be increased to compare better with the experimental properties. Increasing the modulus of elasticity of the concrete cover would improve the comparison above 1 kHz at the expense of worsening the fit below 1 kHz. The shape of the resonant peaks also indicates that the damping ratios assumed for the FEM were too low and should be approximately doubled to improve the fit.

Figure 8-4: Comparison of Experimental and Numerical Response Spectra of Soil Nail C

8.2 In-Ground Soil Nails

8.2.1 Soil Nail S1

Figure 8-5 shows the numerically obtained spectrum of Soil Nail S1 superimposed on the experimental spectrum. The two responses were produced by the small instrumented hammer with a steel head striking the end of the steel bar. It is easy to see how identical the two spectra are.

Figure 8-5: Comparison of Experimental and Numerical Response Spectra of Soil Nail S1

The only difference between the two is the amplitude of the resonant responses above 2 kHz. The experimental amplitudes are considerably larger than the numerical, which suggests that the amount of modal damping assumed in the FEM for the higher modes is about 2 to 4 times too high.

8.3 Efficacy of IR Technique

Simple Soil Nails

For simple soil nails comprising only one material (steel) such as Soil Nail D and S1, the length of laboratory and in-ground nails could be determined using the constant spacing between resonant frequencies. The constant frequency spacing meant that the modal components in the induced waves travelled at the same velocity, namely the wave velocity in steel.

Composite Soil Nails

Soil Nail A

Due to the large number of transverse cracks present in the concrete cover of Soil Nail A, modal components in the induced stress waves travelled along the nail with varying velocities, which were considerably less than the velocity in good condition concrete. Therefore, knowing the phase velocity of each of the modal components is a must to estimate the length of this nail.

Soil Nail B

The existence of the gap and the transverse cracks made it extremely difficult to estimate the length of the nail using the IR technique as the modal components in the induced stress waves travelled at different wave velocities. The variable frequency spacing was indicative of the varying wave velocities within the nail.

Soil Nail C

Although the concrete cover of the nail possessed transverse cracks similar to those in Soil Nails A and B, modal components in the induced stress waves travelled at about the same velocity. However, the velocity was still less than that of good condition concrete. As a result, the stress wave velocity can be estimated using the Standard Test Method for Pulse Velocity Through Concrete (ASTM C 597-97). Using this velocity the length of this nail can be determined with reasonable accuracy.

Table 8-1 summaries the results obtained on the laboratory and in-ground nails using the IR technique.

Table 8-1: Summary of Results Obtained from IR Technique

Soil Nail	Cover Condition	IR Ability	Accuracy	Ease of Use	Reason
D	No Cover	Yes	High	Very Easy	Wave velocity in steel is known
A	Transverse Cracks	No	Low	Difficult	Phase Velocities must be determined
B	Discontinuity with Transverse Cracks	No	Low	Extremely Difficult	Phase Velocities must be determined
C	Transverse Cracks	Yes	Medium	Easy	Wave Velocity can be readily determined
S1	No Cover	Yes	High	Very Easy	Wave velocity in steel is known

In conclusion, obtaining the phase velocities in composite nails is extremely difficult in the lab, let alone in the field. Therefore, using the impulse-response technique as a stand-alone technique to determine the length of in-situ composite nails may be inappropriate especially for nails with deteriorated grout covers. Nevertheless, using the IR technique along with a finite element modal as a tool to better understand the response of a composite nail can give a reasonable estimate for the length of the nail.

A practical field approach would be the following:

- a) Apply the IR technique to obtain the response spectrum of a recently installed soil nail.
- b) Run the finite element model with the same mechanical properties and configurations as indicated for the soil nail in the drawings and obtain the response spectrum numerically.
- c) Try to match the numerical spectrum with the experimental by varying the length of the nail.
- d) If a match cannot be obtained for a reasonable range of nail length, determine the pulse velocity of the concrete cover using the ultrasonic pulse velocity method (ASTM C 597-97)
- e) Redo step c

The above approach will be applicable only if the grout cover is in good condition.

Chapter 9 Conclusions & Recommendations

9.1 Conclusions

1. The mechanical properties of the concrete cover in effect controlled the properties of the induced longitudinal waves in the three composite laboratory soil nails at NRC/IRC. Cracks in the concrete cover of these nails significantly affected the axial dynamic properties of the nails.
2. Induced waves in composite soil nails with cracked concrete covers may contain modal components possessing different phase velocities. For Soil Nail A, the phase velocity of the lowest four modes decreased as the modal frequency increased. The decrease in frequency spacing of the lower modes was indicative of the variability of phase velocity and its decrease with increasing modal frequency. In keeping with the poor condition of the concrete covers, wave velocities in the three composite nails were below 2000 m/sec, considerably lower than that for typical concrete.
3. The medium instrumented hammer equipped with the stiff plastic head produced impacts best suited for determining the dynamic properties of the short (about 4-m long) composite laboratory nails. The impacts contained sufficient energy to excite most modes below 2 kHz. On the other hand, the small or medium instrumented hammer equipped with the steel head produced impacts best suited for determining the dynamic properties of the simple laboratory and in-ground nails. The impacts contained sufficient energy to excite all modes to 10 kHz.
4. The finite element models constructed for the laboratory and in-ground nails using ABAQUS produced modal properties and dynamic responses, which compared favorably with those obtained experimentally. The models were built using CAX4 axisymmetric elements for nail and soil components, tied contact at nail-concrete interfaces and Gap elements at the nail-soil

interface. Nodes were constrained along the axis of symmetry in the lateral direction so as to derive only the axial response of the nail. Typical material properties were selected for steel and soil elements. The modulus of elasticity of concrete elements in composite laboratory nails was considerably reduced to a level well below normal values to reflect the cracked status of the concrete cover. Response calculation also suggested that modal damping ratios for the lowest modes of the composite nails were generally above 1 % of critical.

5. A favorable estimate of nail length can be made for short composite nails using the frequencies of the first few modes. However, establishing a suitable wave velocity in nails with deteriorated concrete covers is the key for obtaining an accurate estimate of nail length.

9.2 Recommendations

The following recommendations pertain to the on-site execution of the impulse-response technique:

1. **Accelerometer Attachment:** The accelerometer must be firmly connected to the nail so as not to slip or move when the nail is impacted. A small steel prism screwed to the side of the steel rod gave the best results.
2. **Impact Delivery:** The hammer should impact the steel bar perpendicular to the nail surface i.e. the impact should be in the axial direction, because only the axial response of the nail is of interest. Impacting the concrete cover is not recommended as repeated impacts can damage the cover and thus substantially alter the frequency content of the induced stress wave.
3. **Frequency Range & Hammer Type:** A frequency range of 10 kHz for the data recorder/analyzer is adequate for simple “not grouted” soil nails. A small or medium instrumented hammer with a steel tip is, therefore, sufficient to excite desired modes to about 10 kHz. For grouted laboratory soil nails, a frequency range of 2 kHz will suffice. A medium hammer with a stiff plastic tip will be capable of exciting desired modes to about 2 kHz.
4. **Numerical Analysis & Finite Element Model:** Using the Gap element approach to model the weak connection between the simple nail and the soil gave results, which matched the experimental. However, this approach did not directly take the frictional forces between the steel bar and the soil into consideration. Therefore, a more direct approach, say using Surface Elements, may need to be investigated.

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Appendices

A) Fast Fourier Transform (FFT)

It is an algorithm for transferring signal information from the time to the frequency domain by digitizing the time record into N equally spaced samples. Usually N is a power of 2 to simplify the numerical process. The FFT transfers all the signal information to $N/2$ equally spaced frequencies (or lines) in the frequency domain (Fig. A- 1).

Figure A- 1

Although the FFT contains only half as many data points as the original time signal, there is no loss of information as each line in the frequency domain contains two pieces of information; magnitude and phase.

The lowest frequency line (other than zero Hertz) in the FFT spectrum is based on the length of the time record; it is the reciprocal of the time record. Now that we know the spacing between these two lines (zero line and lowest frequency line) and thus we now know the spacing between every line. The spacing between two lines is the reciprocal of the time record.

Now we can calculate the frequency range of the FFT. In other words, we can work out the highest frequency we can measure:

$$f_{\max} = (N/2) * (1 / \text{time record})$$

Now, to adjust the frequency range of our measurement, we must vary $f_{\max}$. The number of time samples N is fixed by the implementation of the FFT algorithm (1024). Therefore we must vary the period of the time record to vary $f_{\max}$. To do so we must vary the sample rate so we always have N samples in our variable time record. To cover high frequency we must sample faster (Fig. A- 2). In practice for instance, if the frequency range of interest is 10000, the sampling frequency should be at least $2.56 * 10000$.

Figure A- 2

The FFT spectrum shows the distribution of signal energy over the various frequencies.

The resolution in the spectrum (the frequency difference between adjacent discrete points) is equal to the sampling frequency divided by the number of points in the waveform record.

B) Cross-Correlation technique

The Cross-Correlation technique is used to measure the similarities between two non-identical waveforms. If the same signal is presented in both waveforms, it will be reinforced in the Cross-Correlation function, while any uncorrelated noise will be reduced.

The cross-Correlation function is given by the relationship:

$$\psi_{xy}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T f_x(t) f_y(t+\tau) dt \quad \text{Equation B- 1}$$

Where:

$f_x(t)$ is the magnitude of a signal observed at a point X at an arbitrary instant of time, t, and $f_y(t+\tau)$ is the magnitude of a signal observed at a point y at a time τ later. By varying τ a complete function of time delays is obtained.

C) Cross-Spectral Density technique:

Basically, the Cross-Spectral Density function (Power Spectrum) is the Fourier Transform of the Cross-Correlation function. It is a complex function contains both imaginary and real part which can be readily seen in both magnitude and phase measurements. It is given by the relationship:

$$W_{xy}(f) = \int_{-\infty}^{\infty} \psi_{xy}(\tau) e^{-i2\pi f\tau} d\tau$$

Equation C- 1

To represent the real part of the cross-spectral density function a function termed the co-spectrum, $C_{xy}(f)$, is used. Similarly, the imaginary part of the cross-spectral density function is represented by the quad-spectrum, $Q_{xy}(f)$.

D) Input Files:

INPUT FILE No. 1 for Soil Nail D

*HEADING

STEEL ROD

AXISYMMETRIC ELEMENTS FOR THE STEEL ROD

THE SYMMETRY AXIS IS Y AXIS

UNITS IN m, kg, sec, N

RESPONSE ANALYSIS

*****MODEL DEFINITION*****

DEFINING AXIAL NODES FOR STEEL ROD**

*****SEC-1*****

*NODE, NSET=AXIAL-NODES-1

1, 0, 4030E-3

17, 0, 3860E-3

*NGEN, NSET=AXIAL-NODES-1

1, 17, 1

*****SEC-2*****

*NODE, NSET=AXIAL-NODES-2

387, 0, 155E-3

*NGEN, NSET=AXIAL-NODES-2

17, 387, 1

*****SEC-3*****

*NODE, NSET=AXIAL-NODES-3

401, 0, 0

*NGEN, NSET=AXIAL-NODES-3

387, 401, 1

*NSET, NSET=AXIAL-NODES

AXIAL-NODES-1, AXIAL-NODES-2, AXIAL-NODES-3

*****DEFINING BOUNDARY NODES FOR THE STEEL ROD*****

*****SEC-1*****

*NODE, NSET=BOUNDARY-NODES-1

500, 14.25E-3, 4030E-3

516, 14.25E-3, 3860E-3

*NGEN, NSET=BOUNDARY-NODES-1

500, 516, 1

*****SEC-2*****

*NODE, NSET=BOUNDARY-NODES-2

886, 14.25E-3, 155E-3

*NGEN, NSET=BOUNDARY-NODES-2

516, 886, 1

*****SEC-3*****

*NODE, NSET=BOUNDARY-NODES-3

900, 14.25E-3, 0

*NGEN, NSET=BOUNDARY-NODES-3

886, 900, 1

*NSET, NSET=BOUNDARY-NODES

BOUNDARY-NODES-1, BOUNDARY-NODES-2, BOUNDARY-NODES-3

*****DEFINING ELEMENTS FOR THE STEEL ROD*****

*****SEC-1*****

*ELEMENT, ELSET=STEEL-1, TYPE=CAX4

1, 1, 2, 501, 500

*ELGEN, ELSET=STEEL-1

1, 16, 1, 1

*****SEC-2*****

*ELEMENT, ELSET=STEEL-2, TYPE=CAX4

17, 17, 18, 517, 516

*ELGEN, ELSET=STEEL-2

17, 370, 1, 1

*****SEC-3*****

*ELEMENT, ELSET=STEEL-3, TYPE=CAX4

387, 387, 388, 887, 886

*ELGEN, ELSET=STEEL-3

387, 14, 1, 1

*ELSET, ELSET=STEEL

STEEL-1, STEEL-2, STEEL-3

*SOLID SECTION, ELSET=STEEL, MATERIAL=STEEL

*****MATERIAL DEFINITION*****

*****FOR STEEL ROD*****

*MATERIAL, NAME=STEEL

*ELASTIC

206.E9, 0.3

*DENSITY

7850

*****DEFINING A SPRING*****

*ELEMENT, TYPE=SPRING1, ELSET=SPRING

50000, 401

*SPRING, ELSET=SPRING

2

200

*****BOUNDARY CONDITIONS*****

*BOUNDARY

AXIAL-NODES, 1

*****Defining Impulse*****

*AMPLITUDE, NAME=IMPULSE, DEFINITION=EQUALLY SPACED, FIXED

INTERVAL=3.91E-5,

INPUT=Impact.dat2, VALUE=ABSOLUTE, BEGIN=0

*NSET, NSET=NODE1

1, 401

*****HISTORY DEFINITION*****

*STEP

*FREQUENCY, EIGENSOLVER=LANCZOS

22

*NODE FILE

U

*FILE FORMAT, ASCII

*END STEP

*STEP

*MODAL DYNAMIC

3.91E-5, 0.0400384

*MODAL DAMPING, MODAL=DIRECT

1, , 0.005

2, 22, 0.001

*CLOAD, AMPLITUDE=IMPULSE

1, 2, 1

*NODE FILE, NSET=NODE1

A

*END STEP

.....

Input file No. 2 for Soil Nail A

*HEADING

SPEC-A-

AXISYMMETRIC ELEMENTS FOR THE STEEL ROD AND THE CONCRETE

THE SYMMETRY AXIS IS Y AXIS

UNITS IN m, kg, sec, N

RESPONSE ANALYSIS

****DEFINING AXIAL NODES FOR STEEL ROD*****

*****SEC-1*****

*NODE, NSET=AXIAL-NODES-1

1, 0, 4030E-3

17, 0, 3860E-3

*NGEN, NSET=AXIAL-NODES-1

1, 17, 1

*****SEC-2*****

*NODE, NSET=AXIAL-NODES-2

387, 0, 155E-3

*NGEN, NSET=AXIAL-NODES-2

17, 387, 1

*****SEC-3*****

*NODE, NSET=AXIAL-NODES-3

401, 0, 0

*NGEN, NSET=AXIAL-NODES-3

387, 401, 1

*NSET, NSET=AXIAL-NODES

AXIAL-NODES-1, AXIAL-NODES-2, AXIAL-NODES-3

*****DEFINING BOUNDARY NODES FOR THE STEEL ROD*****

*****SEC-1*****

*NODE, NSET=BOUNDARY-NODES-1

500, 14.25E-3, 4030E-3

516, 14.25E-3, 3860E-3

*NGEN, NSET=BOUNDARY-NODES-1

500, 516, 1

*****SEC-2*****

*NODE, NSET=BOUNDARY-NODES-2

886, 14.25E-3, 155E-3

*NGEN, NSET=BOUNDARY-NODES-2

516, 886, 1

*****SEC-3*****

*NODE, NSET=BOUNDARY-NODES-3

900, 14.25E-3, 0

*NGEN, NSET=BOUNDARY-NODES-3

886, 900, 1

*NSET, NSET=BOUNDARY-NODES

BOUNDARY-NODES-1, BOUNDARY-NODES-2, BOUNDARY-NODES-3

*****DEFINING ELEMENTS FOR THE STEEL ROD*****

*****SEC-1*****

*ELEMENT, ELSET=STEEL-1, TYPE=CAX4

1, 1, 2, 501, 500

```

*ELGEN, ELSET=STEEL-1

1, 16, 1, 1

*****SEC-2*****

*ELEMENT, ELSET=STEEL-2, TYPE=CAX4

17, 17, 18, 517, 516

*ELGEN, ELSET=STEEL-2

17, 370, 1, 1

*****SEC-3*****

*ELEMENT, ELSET=STEEL-3, TYPE=CAX4

387, 387, 388, 887, 886

*ELGEN, ELSET=STEEL-3

387, 14, 1, 1

*****

*ELSET, ELSET=STEEL

STEEL-1, STEEL-2, STEEL-3

*****

*****DEFINING NODES FOR CONCRETE*****

*****RIGHT SIDE*****

*****INNER CONCRETE*****

*NODE, NSET=RIC

1000, 14.25E-3, 3860E-3

1370, 14.25E-3, 155E-3

*NGEN, NSET=RIC

1000, 1370, 1, 1

*****OUTTER CONCRETE*****

*NODE, NSET=ROC

```

1500, 85.757E-3, 3860E-3

1870, 85.757E-3, 155E-3

*NGEN, NSET=ROC

1500, 1870, 1, 1

*****DEFINING ELEMENTS FOR CONCRETE*****

*****RIGHT SIDE*****

*ELEMENT, ELSET=CONCRETE, TYPE=CAx4

1000, 1000, 1001, 1501, 1500

*ELGEN, ELSET=CONCRETE

1000, 370, 1, 1

*SOLID SECTION, ELSET=STEEL, MATERIAL=STEEL

*SOLID SECTION, ELSET=CONCRETE, MATERIAL=CONCRETE

*****MATERIAL DEFINITION*****

*****FOR STEEL ROD*****

*MATERIAL, NAME=STEEL

*ELASTIC

206.E9, 0.3

*DENSITY

7850

*****FOR CONCRETE*****

*MATERIAL, NAME=CONCRETE

*ELASTIC

18.E9, 0.25

*DENSITY

2400

*****DEFINING A SPRING*****

*ELEMENT, TYPE=SPRING1, ELSET=SPRING

50000, 401

*SPRING, ELSET=SPRING

2

200

*****BOUNDARY CONDITIONS*****

*BOUNDARY

AXIAL-NODES, 1

*****DEFINING SURFACES*****

*SURFACE, NAME=OSR

STEEL-2, S3

*SURFACE, NAME=IC

CONCRETE, S1

*****DEFINING CONTACT*****

*SURFACE INTERACTION, NAME=OSR-IC

89.54E-3

*FRICTION

0.3

*CONTACT PAIR, INTERACTION=OSR-IC, TIED, ADJUST=0

IC, OSR

*****Defining Impulse*****

*AMPLITUDE, NAME=IMPULSE, DEFINITION=EQUALLY SPACED, FIXED

INTERVAL=3.91E-5,

INPUT=Impact.dat2, VALUE=ABSOLUTE, BEGIN=0

*NSET, NSET=NODE1

1, 401

*****HISTORY DEFINITION*****

*STEP

*FREQUENCY, EIGENSOLVER=LANCZOS

22

*NODE FILE

U

*FILE FORMAT, ASCII

*END STEP

*STEP

*MODAL DYNAMIC

3.91E-5, 0.0400384

*MODAL DAMPING, MODAL=DIRECT

1, , 0.01

2, 22, 0.005

*CLOAD, AMPLITUDE=IMPULSE

1, 2, -1

*NODE FILE, NSET=NODE1

A

*END STEP

.....

Input file 3 for Soil Nail S

*HEADING

SPEC-S-

AXISYMMETRIC ELEMENTS FOR THE STEEL ROD AND THE SOIL

THE SYMMETRY AXIS IS Y AXIS

UNITS IN m, kg, sec, N

DEFINING AXIAL NODES FOR STEEL ROD

*****SEC-1*****

*NODE, NSET=AXIAL-NODES-1

1, 0, 3440E-3

12, 0, 3315E-3

*NGEN, NSET=AXIAL-NODES-1

1, 12, 1

*****SEC-2*****

```

*NODE, NSET=AXIAL-NODES-2

345, 0, 0

*NGEN, NSET=AXIAL-NODES-2

12, 345, 1

*NSET, NSET=AXIAL-NODES

AXIAL-NODES-1, AXIAL-NODES-2

*****

*****DEFINING BOUNDARY NODES FOR THE STEEL ROD*****

*****SEC-1*****

*NODE, NSET=BOUNDARY-NODES-1

500, 12.5E-3, 3440E-3

511, 12.5E-3, 3315E-3

*NGEN, NSET=BOUNDARY-NODES-1

500, 511, 1

*****SEC-2*****

*NODE, NSET=BOUNDARY-NODES-2

844, 12.5E-3, 0E-3

*NGEN, NSET=BOUNDARY-NODES-2

511, 844, 1

*****

*****DEFINING ELEMENTS FOR THE STEEL ROD*****

*****SEC-1*****

*ELEMENT, ELSET=STEEL-1, TYPE=CAX4

1, 1, 2, 501, 500

*ELGEN, ELSET=STEEL-1

1, 12, 1, 1

```

```

*****SEC-2*****
*ELEMENT, ELSET=STEEL-2, TYPE=CAX4
12, 12, 13, 512, 511
*ELGEN, ELSET=STEEL-2
12, 332, 1, 1
*****
*ELSET, ELSET=STEEL
STEEL-1, STEEL-2
*****
*****DEFINING NODES FOR SOIL*****
*****RIGHT SIDE*****
*****FIRST COLOMN*****
*NODE, NSET=RIS1
900, 12.5E-3, 3315E-3
1254, 12.5E-3, -100E-3
*NGEN, NSET=RIS1
900, 1254, 1
*****SECOND COLOMN*****
*NODE, NSET=RIS2
1300, 37.5E-3, 3315E-3
1654, 37.5E-3, -100E-3
*NGEN, NSET=RIS2
1300, 1654, 1
*****THIRD COLOMN*****
*NODE, NSET=RIS3
1700, 62.5E-3, 3315E-3

```

2054, 62.5E-3, -100E-3

*NGEN, NSET=RIS3

1700, 2054, 1

*****FOURTH COLOMN*****

*NODE, NSET=RIS4

2100, 87.5E-3, 3315E-3

2454, 87.5E-3, -100E-3

*NGEN, NSET=RIS4

2100, 2454, 1

*****FIFTH COLOMN*****

*NODE, NSET=RIS5

2500, 112.5E-3, 3315E-3

2854, 112.5E-3, -100E-3

*NGEN, NSET=RIS5

2500, 2854, 1

*****DEFINING NODES FORSOIL UNDERNEATH THE STEEL ROD****

*****AXIAL NODES*****

*NODE, NSET=AUNSOIL

350, 0E-3, 0E-3

360, 0E-3, -100E-3

*NGEN, NSET=AUNSOIL

350, 360, 1

*****LATERAL NODES ARE DUBLICATED WITH RIS1***

*NSET, NSET=SOILNODES

RIS1, RIS2, RIS3, RIS4, RIS5, AUNSOIL

*NSET, NSET=BOTTOMNODES

360, 1254, 1654, 2054, 2454, 2854

*****DEFINING ELEMENTS FOR UNDERNEATH SOIL*****

*ELEMENT, ELSET=SOIL, TYPE=CAX4

350, 350, 351, 1245, 1244

*ELGEN, ELSET=SOIL

350, 10, 1, 1

*****DEFINING ELEMENTS FOR LATERALSOIL*****

*****FIRST COLUMN*****

*ELEMENT, ELSET=SOIL, TYPE=CAx4

900, 900, 901, 1301, 1300

*ELGEN, ELSET=SOIL

900,354, 1, 1

*****SECOND COLUMN*****

*ELEMENT, ELSET=SOIL, TYPE=CAx4

1300, 1300, 1301, 1701, 1700

*ELGEN, ELSET=SOIL

1300,354, 1, 1

*****THIRD COLUMN*****

*ELEMENT, ELSET=SOIL, TYPE=CAx4

1700, 1700, 1701, 2101, 2100

*ELGEN, ELSET=SOIL

1700,354, 1, 1

*****FOURTH COLUMN*****

```

*ELEMENT, ELSET=SOIL, TYPE=CAx4

2100, 2100, 2101, 2501, 2500

*ELGEN, ELSET=SOIL

2100,354, 1, 1

*****

*SOLID SECTION, ELSET=STEEL, MATERIAL=STEEL

*SOLID SECTION, ELSET=SOIL, MATERIAL=SOIL

*****

*****MATERIAL DEFINITION*****

*****FOR STEEL ROD*****

*MATERIAL, NAME=STEEL

*ELASTIC

206.E9, 0.3

*DENSITY

7850

*****FOR SOIL*****

*MATERIAL, NAME=SOIL

*POROUS ELASTIC, SHEAR=POISSON

0.026, 0.3, 2E3

*DENSITY

1700

*INITIAL CONDITIONS, TYPE=RATIO

SOILNODES, 1

*****

*****BOUNDARY CONDITIONS*****

*****

```



```

*BOUNDARY

AXIAL-NODES, 1

RIS5, 2

BOTTOMNODES, 1

*****

*ELEMENT, TYPE=GAPUNI, ELSET=AGAP

5000, 511, 900

*ELGEN, ELSET=AGAP

5000, 345, 1, 1

*GAP, ELSET=AGAP

0, 1, 0, 0, 1

*****

*AMPLITUDE, NAME=IMPULSE, DEFINITION=EQUALLY SPACED, FIXED

INTERVAL=3.91E-5,

INPUT=Impact.dat2, VALUE=RELATIVE, BEGIN=0

*NSET, NSET=NODE1

1, 345, 505

*****

*****HISTORY DEFINITION*****

*****

*STEP

*FREQUENCY, EIGENSOLVER=LANCZOS

22, 500

*NODE FILE

U

*FILE FORMAT, ASCII

```

*END STEP

*STEP

*MODAL DYNAMIC

3.91E-5, 0.0400384

*SELECT EIGENMODES, GENERATE

1, 22, 1

*MODAL DAMPING, MODAL=DIRECT

1, , 0.01

2, 22, 0.005

*CLOAD, AMPLITUDE=IMPULSE

1, 2, -1

*NODE FILE, NSET=NODE1

A

*END STEP

Input File for Soil Nail B

*HEADING

SPEC-B-

AXISYMMETRIC ELEMENTS FOR THE STEEL ROD AND THE CONCRETE

THE SYMMETRY AXIS IS Y AXIS

800 ELEMENTS ALONG THE AXIS OF SYMMETRY

UNITS IN m, kg, sec, N

RESPONSE ANALYSIS

```

*****

***DEFINING AXIAL NODES FOR STEEL ROD*****

*****      LINE -1-      *****

*****SEC-1*****

*NODE, NSET=AXIAL-NODES-1

1, 0, 4030E-3

33, 0, 3865E-3

*NGEN, NSET=AXIAL-NODES-1

1, 33, 1

*****SEC-2*****

*NODE, NSET=AXIAL-NODES-2

353, 0, 2260E-3

*NGEN, NSET=AXIAL-NODES-2

33, 353, 1

*****SEC-3*****

*NODE, NSET=AXIAL-NODES-3

453, 0, 1760E-3

*NGEN, NSET=AXIAL-NODES-3

353, 453, 1

*****SEC-4*****

*NODE, NSET=AXIAL-NODES-4

773, 0, 155E-3

*NGEN, NSET=AXIAL-NODES-4

453, 773, 1

*****SEC-5*****

*NODE, NSET=AXIAL-NODES-5

```

```

801, 0, 0

*NGEN, NSET=AXIAL-NODES-5

773, 801, 1

*NSET, NSET=AXIAL-NODES

AXIAL-NODES-1, AXIAL-NODES-2, AXIAL-NODES-3, AXIAL-NODES-4, AXIAL-
NODES-5

*****

***** LINE -2- *****

*****SEC-1*****

*NODE, NSET=LINE-2

810, 7.125E-3, 4030E-3

842, 7.125E-3, 3865E-3

*NGEN, NSET=LINE-2

810, 842, 1

*****SEC-2*****

*NODE, NSET=LINE-2

1162, 7.125E-3, 2260E-3

*NGEN, NSET=LINE-2

842, 1162, 1

*****SEC-3*****

*NODE, NSET=LINE-2

1262, 7.125E-3, 1760E-3

*NGEN, NSET=LINE-2

1162, 1262, 1

*****SEC-4*****

*NODE, NSET=LINE-2

```

1582, 7.125E-3, 155E-3

*NGEN, NSET=LINE-2

1262, 1582, 1

*****SEC-5*****

*NODE, NSET=LINE-2

1610, 7.125E-3, 0

*NGEN, NSET=LINE-2

1582, 1610, 1

***** LINE -3- *****

*****SEC-1*****

*NODE, NSET=LINE-3

1620, 14.25E-3, 4030E-3

1652, 14.25E-3, 3865E-3

*NGEN, NSET=LINE-3

1620, 1652, 1

*****SEC-2*****

*NODE, NSET=LINE-3

1972, 14.25E-3, 2260E-3

*NGEN, NSET=LINE-3

1652, 1972, 1

*****SEC-3*****

*NODE, NSET=LINE-3

2072, 14.25E-3, 1760E-3

*NGEN, NSET=LINE-3

1972, 2072, 1

```

*****SEC-4*****

*NODE, NSET=LINE-3

2392, 14.25E-3, 155E-3

*NGEN, NSET=LINE-3

2072, 2392, 1

*****SEC-5*****

*NODE, NSET=LINE-3

2420, 14.25E-3, 0

*NGEN, NSET=LINE-3

2392, 2420, 1

*****

*****DEFINING ELEMENTS FOR THE STEEL ROD*****

***** COLUMN -1- *****

*****SEC-1*****

*ELEMENT, ELSET=STEEL-1, TYPE=CAX4

1, 1, 2, 811, 810

*ELGEN, ELSET=STEEL-1

1, 32, 1, 1

*****SEC-2*****

*ELEMENT, ELSET=STEEL-1, TYPE=CAX4

33, 33, 34, 843, 842

*ELGEN, ELSET=STEEL-1

33, 320, 1, 1

*****SEC-3*****

*ELEMENT, ELSET=STEEL-1, TYPE=CAX4

353, 353, 354, 1163, 1162

```

```

*ELGEN, ELSET=STEEL-1

353, 100, 1, 1

*****SEC-4*****

*ELEMENT, ELSET=STEEL-1, TYPE=CAX4

453, 453, 454, 1263, 1262

*ELGEN, ELSET=STEEL-1

453, 320, 1, 1

*****SEC-5*****

*ELEMENT, ELSET=STEEL-1, TYPE=CAX4

773, 773, 774, 1583, 1582

*ELGEN, ELSET=STEEL-1

773, 28, 1, 1

***** COLUMN -2- *****

*****SEC-1*****

*ELEMENT, ELSET=STEEL-2, TYPE=CAX4

810, 810, 811, 1621, 1620

*ELGEN, ELSET=STEEL-2

810, 32, 1, 1

*****SEC-2*****

*ELEMENT, ELSET=STEEL-2, TYPE=CAX4

842, 842, 843, 1653, 1652

*ELGEN, ELSET=STEEL-2

842, 320, 1, 1

*****SEC-3*****

*ELEMENT, ELSET=STEEL-2, TYPE=CAX4

1162, 1162, 1163, 1973, 1972

```

```

*ELGEN, ELSET=STEEL-2

1162, 100, 1, 1

*****SEC-4*****

*ELEMENT, ELSET=STEEL-2, TYPE=CAX4

1262, 1262, 1263, 2073, 2072

*ELGEN, ELSET=STEEL-2

1262, 320, 1, 1

*****SEC-5*****

*ELEMENT, ELSET=STEEL-2, TYPE=CAX4

1582, 1582, 1583, 2393, 2392

*ELGEN, ELSET=STEEL-2

1582, 28, 1, 1

*****

*ELSET, ELSET=STEEL

STEEL-1, STEEL-2

*****

*****DEFINING NODES FOR CONCRETE*****

*****

*****      RIGHT SIDE      *****

*****      FIRST LINE      *****

*****      SEC -1-      *****

*NODE, NSET=CLINE-1

2500, 14.25E-3, 3865E-3

2820, 14.25E-3, 2260E-3

*NGEN, NSET=CLINE-1

2500, 2820, 1

```


***** SEC -2- *****

*NODE, NSET=CLINE-1

2830, 14.25E-3, 1760E-3

3150, 14.25E-3, 155E-3

*NGEN, NSET=CLINE-1

2830, 3150, 1

***** SECOND LINE *****

***** SEC -1- *****

*NODE, NSET=CLINE-2

3200, 32.127E-3, 3865E-3

3520, 32.127E-3, 2260E-3

*NGEN, NSET=CLINE-2

3200, 3520, 1

***** SEC -2- *****

*NODE, NSET=CLINE-2

3530, 32.127E-3, 1760E-3

3850, 32.127E-3, 155E-3

*NGEN, NSET=CLINE-2

3530, 3850, 1

***** THIRD LINE *****

***** SEC -1- *****

*NODE, NSET=CLINE-3

3860, 50.004E-3, 3865E-3

4180, 50.004E-3, 2260E-3

*NGEN, NSET=CLINE-3

3860, 4180, 1

***** SEC -2- *****

*NODE, NSET=CLINE-3

4190, 50.004E-3, 1760E-3

4510, 50.004E-3, 155E-3

*NGEN, NSET=CLINE-3

4190, 4510, 1

***** FOURTH LINE *****

***** SEC -1- *****

*NODE, NSET=CLINE-4

4520, 67.881E-3, 3865E-3

4840, 67.881E-3, 2260E-3

*NGEN, NSET=CLINE-4

4520, 4840, 1

***** SEC -2- *****

*NODE, NSET=CLINE-4

4850, 67.881E-3, 1760E-3

5170, 67.881E-3, 155E-3

*NGEN, NSET=CLINE-4

4850, 5170, 1

***** FIFTH LINE *****

***** SEC -1- *****

*NODE, NSET=CLINE-5

5180, 85.758E-3, 3865E-3

5500, 85.758E-3, 2260E-3

*NGEN, NSET=CLINE-5

5180, 5500, 1

***** SEC -2- *****

*NODE, NSET=CLINE-5

5510, 85.758E-3, 1760E-3

5830, 85.758E-3, 155E-3

*NGEN, NSET=CLINE-5

5510, 5830, 1

***** DEFINING ELEMENTS FOR CONCRETE *****

***** COLUMN -1- *****

*ELEMENT, ELSET=CONCRETE-1, TYPE=CAX4

2500, 2500, 2501, 3201, 3200

2830, 2830, 2831, 3531, 3530

*ELGEN, ELSET=CONCRETE-1

2500, 320, 1, 1

2830, 320, 1, 1

***** COLUMN -2- *****

*ELEMENT, ELSET=CONCRETE, TYPE=CAX4

3200, 3200, 3201, 3861, 3860

3530, 3530, 3531, 4191, 4190

*ELGEN, ELSET=CONCRETE

3200, 320, 1, 1

3530, 320, 1, 1

***** COLUMN -3- *****

*ELEMENT, ELSET=CONCRETE, TYPE=CAX4

3860, 3860, 3861, 4521, 4520

4190, 4190, 4191, 4851, 4850

```

*ELGEN, ELSET=CONCRETE

3860, 320, 1, 1

4190, 320, 1, 1

*****          COLUMN -4-          *****

*ELEMENT, ELSET=CONCRETE, TYPE=CAX4

4520, 4520, 4521, 5181, 5180

4850, 4850, 4851, 5511, 5510

*ELGEN, ELSET=CONCRETE

4520, 320, 1, 1

4850, 320, 1, 1

*****

*ELSET, ELSET=CONCRETE

CONCRETE-1, CONCRETE

*****

*SOLID SECTION, ELSET=STEEL, MATERIAL=STEEL

*SOLID SECTION, ELSET=CONCRETE, MATERIAL=CONCRETE

*****

*****MATERIAL DEFINITION*****

*****FOR STEEL ROD*****

*MATERIAL, NAME=STEEL

*ELASTIC

206.E9, 0.3

*DENSITY

7850

*****FOR CONCRETE*****

*MATERIAL, NAME=CONCRETE

```

*ELASTIC

0.6E9, 0.25

*DENSITY

2400

*****DEFINING A SPRING*****

*ELEMENT, TYPE=SPRING1, ELSET=SPRING

50000, 801

*SPRING, ELSET=SPRING

2

200

*****BOUNDARY CONDITIONS*****

*BOUNDARY

AXIAL-NODES, 1

*****DEFINING SURFACES*****

*SURFACE, NAME=OSR

STEEL-2, S3

*SURFACE, NAME=IC

CONCRETE-1, S1

*****DEFINING CONTACT*****

```

*****

*SURFACE INTERACTION, NAME=OSR-IC

89.54E-3

*FRICTION

0.3

*CONTACT PAIR, INTERACTION=OSR-IC, TIED, ADJUST=0

IC, OSR

*****

*****Defining Impulse*****

*AMPLITUDE, NAME=IMPULSE, DEFINITION=EQUALLY SPACED, FIXED

INTERVAL=1.95E-4,

INPUT=Impact.dat2, VALUE=RELATIVE, BEGIN=0

*NSET, NSET=NODE1

1, 801, 1650

*****

*****HISTORY DEFINITION*****

*****

*STEP

*FREQUENCY, EIGENSOLVER=LANCZOS

22

*NODE FILE, NSET=AXIAL-NODES

U

*FILE FORMAT, ASCII

*END STEP

*****

*STEP

```

*MODAL DYNAMIC

1.95E-4, 2.00E-1

*SELECT EIGENMODES, GENERATE

1, 22, 1

*MODAL DAMPING, MODAL=DIRECT

1, , 0.02

2, 22, 0.01

*CLOAD, AMPLITUDE=IMPULSE

1, 2, -1

*NODE FILE, NSET=NODE1

A

*END STEP

.....

Input File for Soil Nail C

*HEADING

SPEC-C-

AXISYMMETRIC ELEMENTS FOR THE STEEL ROD AND THE CONCRETE

800 ELEMENTS ALONG THE AXIS OF SYMMETRY

THE SYMMETRY AXIS MUST BE Y AXIS

UNITS IN m, kg, sec, N

RESPONSE ANALYSIS

****DEFINING AXIAL NODES FOR STEEL ROD*****

```

***** LINE -1- *****

*****SEC-1*****

*NODE, NSET=AXIAL-NODES-1

1, 0, 4030E-3

33, 0, 3860E-3

*NGEN, NSET=AXIAL-NODES-1

1, 33, 1

*****SEC-2*****

*NODE, NSET=AXIAL-NODES-2

773, 0, 155E-3

*NGEN, NSET=AXIAL-NODES-2

33, 773, 1

***** SEC -3-*****

***** THIS SECTION BEONGS TO THE CONCRETE *****

*NODE, NSET=AXIAL-NODES-3

801, 0, 0E-3

*NGEN, NSET=AXIAL-NODES-3

773, 801, 1

*****

*NSET, NSET=AXIAL-NODES

AXIAL-NODES-1, AXIAL-NODES-2, AXIAL-NODES-3

*****

***** LINE -2- *****

*****SEC-1*****

*NODE, NSET=LINE-2

810, 7.125E-3, 4030E-3

```


842, 7.125E-3, 3860E-3

*NGEN, NSET=LINE-2

810, 842, 1

*****SEC-2*****

*NODE, NSET=LINE-2

1582, 7.125E-3, 155E-3

*NGEN, NSET=LINE-2

842, 1582, 1

***** SEC -3_*****

***** THIS SECTION BEONGS TO THE CONCRETE *****

*NODE, NSET=LINE-2

1610, 7.125E-3, 0E-3

*NGEN, NSET=LINE-2

1582, 1610, 1

***** LINE -3- *****

*****SEC-1*****

*NODE, NSET=LINE-3

1620, 14.25E-3, 4030E-3

1652, 14.25E-3, 3860E-3

*NGEN, NSET=LINE-3

1620, 1652, 1

*****SEC-2*****

*NODE, NSET=LINE-3

2392, 14.25E-3, 155E-3

*NGEN, NSET=LINE-3

1652, 2392, 1

***** SEC -3-*****

***** THIS SECTION BEONGS TO THE CONCRETE *****

*NODE, NSET=LINE-3

2420, 14.25E-3, 0E-3

*NGEN, NSET=LINE-3

2392, 2420, 1

***** DEFINING ELEMENTS FOR THE STEEL ROD *****

***** FIRST COLUMN *****

***** SEC -1- *****

*ELEMENT, ELSET=STEEL, TYPE=CAX4

1, 1, 2, 811, 810

*ELGEN, ELSET=STEEL

1, 32, 1, 1

***** SEC -2- *****

*ELEMENT, ELSET=STEEL, TYPE=CAX4

33, 33, 34, 843, 842

*ELGEN, ELSET=STEEL

33, 740, 1, 1

***** SECOND COLUMN *****

***** SEC -1- *****

*ELEMENT, ELSET=STEEL, TYPE=CAX4

810, 810, 811, 1621, 1620

*ELGEN, ELSET=STEEL

810, 32, 1, 1

```

***** SEC -2- *****

*ELEMENT, ELSET=STEEL-1, TYPE=CAX4

842, 842, 843, 1653, 1652

*ELGEN, ELSET=STEEL-1

842, 740, 1, 1

*****

*ELSET, ELSET=STEEL

STEEL-1, STEEL

*****

*****DEFINING ELEMENTS FOR CONCRETE UNDER THE STEEL*****

***** FIRST COLUMN *****

*ELEMENT, ELSET=CONCRETE, TYPE=CAX4

773, 773, 774, 1583, 1582

*ELGEN, ELSET=CONCRETE

773, 28, 1, 1

***** SECOND COLUMN *****

*ELEMENT, ELSET=CONCRETE-1, TYPE=CAX4

1582, 1582, 1583, 2393, 2392

*ELGEN, ELSET=CONCRETE-1

1582, 28, 1, 1

*****

*ELSET, ELSET=CONCRETE

CONCRETE-1, CONCRETE

*****

***** DEFINING NODES FOR LATERAL CONCRETE *****

***** LINE -1- *****

```

*NODE, NSET=CLINE-1

2500, 14.25E-3, 3860E-3

3268, 14.25E-3, 0E-3

*NGEN, NSET=CLINE-1

2500, 3268, 1

***** LINE -2- *****

*NODE, NSET=CLINE-2

3270, 32.127E-3, 3860E-3

4038, 32.127E-3, 0E-3

*NGEN, NSET=CLINE-2

3270, 4038, 1

***** LINE -3- *****

*NODE, NSET=CLINE-3

4040, 50.004E-3, 3860E-3

4808, 50.004E-3, 0E-3

*NGEN, NSET=CLINE-3

4040, 4808, 1

***** LINE -4- *****

*NODE, NSET=CLINE-4

4810, 67.881E-3, 3860E-3

5578, 67.881E-3, 0E-3

*NGEN, NSET=CLINE-4

4810, 5578, 1

***** LINE -5- *****

*NODE, NSET=CLINE-5

5580, 85.758E-3, 3860E-3

6348, 85.758E-3, 0E-3

*NGEN, NSET=CLINE-5

5580, 6348, 1

*****DEFINING ELEMENTS FOR CONCRETE*****

***** FIRST COLUMN *****

*ELEMENT, ELSET=CONCRETE-2, TYPE=CAX4

2500, 2500, 2501, 3271, 3270

*ELGEN, ELSET=CONCRETE-2

2500, 768, 1, 1

***** SECOND COLUMN *****

*ELEMENT, ELSET=CONCRETE, TYPE=CAX4

3270, 3270, 3271, 4041, 4040

*ELGEN, ELSET=CONCRETE

3270, 768, 1, 1

***** THIRD COLUMN *****

*ELEMENT, ELSET=CONCRETE, TYPE=CAX4

4040, 4040, 4041, 4811, 4810

*ELGEN, ELSET=CONCRETE

4040, 768, 1, 1

***** FOURTH COLUMN *****

*ELEMENT, ELSET=CONCRETE, TYPE=CAX4

4810, 4810, 4811, 5581, 5580

*ELGEN, ELSET=CONCRETE

4810, 768, 1, 1

```

*ELSET, ELSET=CONCRETE

CONCRETE-1, CONCRETE-2, CONCRETE

*****

*SOLID SECTION, ELSET=STEEL, MATERIAL=STEEL

*SOLID SECTION, ELSET=CONCRETE, MATERIAL=CONCRETE

*****

*****MATERIAL DEFINITION*****

*****FOR STEEL ROD*****

*MATERIAL, NAME=STEEL

*ELASTIC

206.E9, 0.3

*DENSITY

7850

*****FOR CONCRETE*****

*MATERIAL, NAME=CONCRETE

*ELASTIC

1.8E9, 0.25

*DENSITY

2400

*****

*****DEFINING A SPRING*****

*****

*ELEMENT, TYPE=SPRING1, ELSET=SPRING

50000, 801

*SPRING, ELSET=SPRING

2

```

200

```
*****
*****BOUNDARY CONDITIONS*****
*****
*BOUNDARY
AXIAL-NODES, 1
*****
*****DEFINING SURFACES*****
*****
*SURFACE, NAME=OSR
STEEL-1, S3
CONCRETE-1, S3
*SURFACE, NAME=IC
CONCRETE-2, S1
*****
*****DEFINING CONTACT*****
*****
*SURFACE INTERACTION, NAME=OSR-IC
89.54E-3
*FRICTION
0.3
*CONTACT PAIR, INTERACTION=OSR-IC, TIED, ADJUST=0
IC, OSR
*****
*****Defining Impulse*****
```

```

*AMPLITUDE, NAME=IMPULSE, DEFINITION=EQUALLY SPACED, FIXED
INTERVAL=1.95E-4,
INPUT=Impact.dat2, VALUE=RELATIVE, BEGIN=0
*NSET, NSET=NODE1
1, 801, 1650
*****
*****HISTORY DEFINITION*****
*****
*STEP
*FREQUENCY, EIGENSOLVER=LANCZOS
50
*NODE FILE, NSET=AXIAL-NODES
U
*FILE FORMAT, ASCII
*END STEP
*****
*STEP
*MODAL DYNAMIC
1.95E-4, 2.00E-1
*SELECT EIGENMODES, GENERATE
1, 22, 1
*MODAL DAMPING, MODAL=DIRECT
1, , 0.02
2, 22, 0.01
*CLOAD, AMPLITUDE=IMPULSE
1, 2, -1

```


*NODE FILE, NSET=NODE1

A

*END STEP

.....

Input File for Soil Nail S1

*HEADING

SPEC-S1-

AXISYMMETRIC ELEMENTS FOR THE STEEL ROD AND THE SOIL

THE SYMMETRY AXIS IS Y AXIS

UNITS IN m, kg, sec, N

DEFINING AXIAL NODES FOR STEEL ROD**

*****SEC-1*****

*NODE, NSET=AXIAL-NODES-1

1, 0, 3440E-3

12, 0, 3315E-3

*NGEN, NSET=AXIAL-NODES-1

1, 12, 1

*****SEC-2*****

*NODE, NSET=AXIAL-NODES-2

345, 0, 0

*NGEN, NSET=AXIAL-NODES-2

12, 345, 1

*NSET, NSET=AXIAL-NODES

AXIAL-NODES-1, AXIAL-NODES-2

*****DEFINING BOUNDARY NODES FOR THE STEEL ROD*****

*****SEC-1*****

*NODE, NSET=BOUNDARY-NODES-1

500, 12.5E-3, 3440E-3

511, 12.5E-3, 3315E-3

*NGEN, NSET=BOUNDARY-NODES-1

500, 511, 1

*****SEC-2*****

*NODE, NSET=BOUNDARY-NODES-2

844, 12.5E-3, 0E-3

*NGEN, NSET=BOUNDARY-NODES-2

511, 844, 1

*****DEFINING ELEMENTS FOR THE STEEL ROD*****

*****SEC-1*****

*ELEMENT, ELSET=STEEL-1, TYPE=CAX4

1, 1, 2, 501, 500

*ELGEN, ELSET=STEEL-1

1, 12, 1, 1

*****SEC-2*****

*ELEMENT, ELSET=STEEL-2, TYPE=CAX4

12, 12, 13, 512, 511

*ELGEN, ELSET=STEEL-2

12, 332, 1, 1

*ELSET, ELSET=STEEL

STEEL-1, STEEL-2

*****DEFINING NODES FOR SOIL*****

*****RIGHT SIDE*****

*****FIRST COLOMN*****

*NODE, NSET=RIS1

900, 12.5E-3, 3315E-3

1254, 12.5E-3, -100E-3

*NGEN, NSET=RIS1

900, 1254, 1

*****SECOND COLOMN*****

*NODE, NSET=RIS2

1300, 37.5E-3, 3315E-3

1654, 37.5E-3, -100E-3

*NGEN, NSET=RIS2

1300, 1654, 1

*****THIRD COLOMN*****

*NODE, NSET=RIS3

1700, 62.5E-3, 3315E-3

2054, 62.5E-3, -100E-3

*NGEN, NSET=RIS3

1700, 2054, 1

*****FOURTH COLOMN*****

```

*NODE, NSET=RIS4

2100, 87.5E-3, 3315E-3

2454, 87.5E-3, -100E-3

*NGEN, NSET=RIS4

2100, 2454, 1

*****FIFTH COLUMN*****

*NODE, NSET=RIS5

2500, 112.5E-3, 3315E-3

2854, 112.5E-3, -100E-3

*NGEN, NSET=RIS5

2500, 2854, 1

*****

*****DEFINING NODES FOR SOIL UNDERNEATH THE STEEL ROD****

*****AXIAL NODES*****

*NODE, NSET=AUNSOIL

350, 0E-3, 0E-3

360, 0E-3, -100E-3

*NGEN, NSET=AUNSOIL

350, 360, 1

*****LATERAL NODES ARE DUBLICATED WITH RIS1***

*NSET, NSET=SOILNODES

RIS1, RIS2, RIS3, RIS4, RIS5, AUNSOIL

*NSET, NSET=BOTTOMNODES

360, 1254, 1654, 2054, 2454, 2854

*****

*****DEFINING ELEMENTS FOR UNDERNEATH SOIL*****

```

```

*****

*ELEMENT, ELSET=SOIL, TYPE=CAX4

350, 350, 351, 1245, 1244

*ELGEN, ELSET=SOIL

350, 10, 1, 1

*****DEFINING ELEMENTS FOR IATERALSOIL*****

*****FIRST COLOMN*****

*ELEMENT, ELSET=SOIL, TYPE=CAx4

900, 900, 901, 1301, 1300

*ELGEN, ELSET=SOIL

900,354, 1, 1

*****SECOND COLOMN*****

*ELEMENT, ELSET=SOIL, TYPE=CAx4

1300, 1300, 1301, 1701, 1700

*ELGEN, ELSET=SOIL

1300,354, 1, 1

*****THIRD COLOMN*****

*ELEMENT, ELSET=SOIL, TYPE=CAx4

1700, 1700, 1701, 2101, 2100

*ELGEN, ELSET=SOIL

1700,354, 1, 1

*****FOURTH COLOMN*****

*ELEMENT, ELSET=SOIL, TYPE=CAx4

2100, 2100, 2101, 2501, 2500

*ELGEN, ELSET=SOIL

2100,354, 1, 1

```

```

*****

*SOLID SECTION, ELSET=STEEL, MATERIAL=STEEL

*SOLID SECTION, ELSET=SOIL, MATERIAL=SOIL

*****

*****MATERIAL DEFINITION*****

*****FOR STEEL ROD*****

*MATERIAL, NAME=STEEL

*ELASTIC

206.E9, 0.3

*DENSITY

7850

*****FOR SOIL*****

*MATERIAL, NAME=SOIL

*POROUS ELASTIC, SHEAR=POISSON

0.026, 0.3, 2E3

*DENSITY

1700

*INITIAL CONDITIONS, TYPE=RATIO

SOILNODES, 1

*****

*****BOUNDARY CONDITIONS*****

*****

*BOUNDARY

AXIAL-NODES, 1

RIS5, 2

BOTTOMNODES, 1

```

```

*****

*ELEMENT, TYPE=GAPUNI, ELSET=AGAP

5000, 511, 900

*ELGEN, ELSET=AGAP

5000, 345, 1, 1

*GAP, ELSET=AGAP

0, 1, 0, 0, 1

*****

*AMPLITUDE, NAME=IMPULSE, DEFINITION=EQUALLY SPACED, FIXED

INTERVAL=3.91E-5,

INPUT=Impact.dat2, VALUE=RELATIVE, BEGIN=0

*NSET, NSET=NODE1

1, 345, 505

*****

*****HISTORY DEFINITION*****

*****

*STEP

*FREQUENCY, EIGENSOLVER=LANCZOS

22, 500

*NODE FILE

U

*FILE FORMAT, ASCII

*END STEP

*****

*STEP

*MODAL DYNAMIC

```

```

3.91E-5, 0.0400384

*SELECT EIGENMODES, GENERATE

1, 22, 1

*MODAL DAMPING, MODAL=DIRECT

1, , 0.01

2, 22, 0.005

*CLOAD, AMPLITUDE=IMPULSE

1, 2, -1

*NODE FILE, NSET=NODE1

A

*END STEP

.....

```

Input File for Soil Nail A1

```

*HEADING

SPEC-A1-

AXISYMMETRIC ELEMENTS FOR THE STEEL ROD, CONCRETE AND THE SOIL

THE SYMMETRY AXIS IS Y AXIS

UNITS IN m, kg, sec, N

*****

****DEFINING AXIAL NODES FOR STEEL ROD*****

```



```

***** FIRST LINE *****

***** SECTION -1- *****

*NODE, NSET=AXIAL-NODES

1, 0, 3660E-3

26, 0, 3495E-3

*NGEN, NSET=AXIAL-NODES

1, 26, 1

***** SECTION -2- *****

*NODE, NSET=AXIAL-NODES

60, 0, 3265E-3

*NGEN, NSET=AXIAL-NODES

26, 60, 1

***** SECTION -3- *****

*NODE, NSET=AXIAL-NODES

551, 0, 0

*NGEN, NSET=AXIAL-NODES

60, 551, 1

***** SECOND LINE *****

***** SECTION -1- *****

*NODE, NSET=SLINE-2

560, 6.25E-3, 3660E-3

585, 6.25E-3, 3495E-3

*NGEN, NSET=SLINE-2

560, 585, 1

***** SECTION -2- *****

*NODE, NSET=SLINE-2

```

619, 6.25E-3, 3265E-3

*NGEN, NSET=SLINE-2

585, 619, 1

***** SECTION -3- *****

*NODE, NSET=SLINE-2

1110, 6.25E-3, 0

*NGEN, NSET=SLINE-2

619, 1110, 1

***** THIRD LINE *****

***** SECTION -1- *****

*NODE, NSET=SLINE-3

1120, 12.5E-3, 3660E-3

1145, 12.5E-3, 3495E-3

*NGEN, NSET=SLINE-3

1120, 1145, 1

***** SECTION -2- *****

*NODE, NSET=SLINE-3

1179, 12.5E-3, 3265E-3

*NGEN, NSET=SLINE-3

1145, 1179, 1

***** SECTION -3- *****

*NODE, NSET=SLINE-3

1670, 12.5E-3, 0

*NGEN, NSET=SLINE-3

1179, 1670, 1

```

*****  DEFINING ELEMENTS FOR THE STEEL ROD  *****

***** FIRST COLUMN *****

***** FIRST BLOCK *****

*ELEMENT, ELSET=STEEL-1, TYPE=CAX4

1, 1, 2, 561, 560

*ELGEN, ELSET=STEEL-1

1, 25, 1, 1

***** SECOND BLOCK *****

*ELEMENT, ELSET=STEEL-1, TYPE=CAX4

26, 26, 27, 586, 585

*ELGEN, ELSET=STEEL-1

26, 34, 1, 1

***** THIRD BLOCK *****

*ELEMENT, ELSET=STEEL-1, TYPE=CAX4

60, 60, 61, 620, 619

*ELGEN, ELSET=STEEL-1

60, 491, 1, 1

***** SECOND COLUMN *****

***** FIRST BLOCK *****

*ELEMENT, ELSET=STEEL-2, TYPE=CAX4

560, 560, 561, 1121, 1120

*ELGEN, ELSET=STEEL-2

560, 25, 1, 1

***** SECOND BLOCK *****

*ELEMENT, ELSET=STEEL-3, TYPE=CAX4

585, 585, 586, 1146, 1145

```

```

*ELGEN, ELSET=STEEL-3

585, 34, 1, 1

*****          THIRD BLOCK          *****

*ELEMENT, ELSET=STEEL-4, TYPE=CAX4

619, 619, 620, 1180, 1179

*ELGEN, ELSET=STEEL-4

619, 491, 1, 1

*****

*ELSET, ELSET=STEEL

STEEL-1, STEEL-2, STEEL-3, STEEL-4

*****

*****          DEFINING NODES FOR GROUT          *****

*****          FIRST LINE          *****

*NODE, NSET=LINE1

1900, 12.5E-3, 3265E-3

2391, 12.5E-3, 0

*NGEN, NSET=LINE1

1900, 2391, 1

*****          SECOND LINE          *****

*NODE, NSET=LINE2

2400, 30.377E-3, 3265E-3

2891, 30.377E-3, 0

*NGEN, NSET=LINE2

2400, 2891, 1

*****          THIRD LINE          *****

*NODE, NSET=LINE3

```

2900, 48.254E-3, 3265E-3

3391, 48.254E-3, 0

*NGEN, NSET=LINE3

2900, 3391, 1

***** FOURTH LINE *****

*NODE, NSET=LINE4

3400, 66.131E-3, 3265E-3

3891, 66.131E-3, 0

*NGEN, NSET=LINE4

3400, 3891, 1

***** FIFTH LINE *****

*NODE, NSET=LINE5

3900, 84.008E-3, 3265E-3

4391, 84.008E-3, 0

*NGEN, NSET=LINE5

3900, 4391, 1

***** DEFINING ELEMENTS FOR THE GROUT *****

***** FIRST COLUMN *****

*ELEMENT, ELSET=GROUT1, TYPE=CAX4

1900, 1900, 1901, 2401, 2400

*ELGEN, ELSET=GROUT1

1900, 491, 1, 1

***** SECOND COLUMN *****

*ELEMENT, ELSET=GROUT2, TYPE=CAX4

2400, 2400, 2401, 2901, 2900

```

*ELGEN, ELSET=GROUT2

2400, 491, 1, 1

*****      THIRD COLUMN      *****

*ELEMENT, ELSET=GROUT3, TYPE=CAX4

2900, 2900, 2901, 3401, 3400

*ELGEN, ELSET=GROUT3

2900, 491, 1, 1

*****      FOURTH COLUMN      *****

*ELEMENT, ELSET=GROUT4, TYPE=CAX4

3400, 3400, 3401, 3901, 3900

*ELGEN, ELSET=GROUT4

3400, 491, 1, 1

*****

*ELSET, ELSET=GROUT

GROUT1, GROUT2, GROUT3, GROUT4

*****

*****      DEFINING NODES FOR SOIL      *****

*****      LINE -1-      *****

*****      SEC -1-      *****

*NODE, NSET=LINE-1

5000, 12.5E-3, 3495E-3

5034, 12.5E-3, 3265E-3

*NGEN, NSET=LINE-1

5000, 5034, 1

*****      SEC -3-      *****

*NODE, NSET=LINE-1

```

```

5035, 12.5E-3, 0

5100, 12.5E-3, -200E-3

*NGEN, NSET=LINE-1

5035, 5100, 1

***** LINE -2- *****

***** SEC -1- *****

*NODE, NSET=LINE-2

5200, 28.425E-3, 3495E-3

5234, 28.425E-3, 3265E-3

*NGEN, NSET=LINE-2

5200, 5234, 1

***** SEC -3- *****

*NODE, NSET=LINE-2

5235, 28.425E-3, 0E-3

5300, 28.425E-3, -200E-3

*NGEN, NSET=LINE-2

5235, 5300, 1

***** LINE -3- *****

***** SEC -1- *****

*NODE, NSET=LINE-3

5400, 44.35E-3, 3495E-3

5434, 44.35E-3, 3265E-3

*NGEN, NSET=LINE-3

5400, 5434, 1

***** SEC -3- *****

*NODE, NSET=LINE-3

```

5435, 44.35E-3, 0E-3

5500, 44.35E-3, -200E-3

*NGEN, NSET=LINE-3

5435, 5500, 1

***** LINE -4- *****

***** SEC -1- *****

*NODE, NSET=LINE-4

5600, 60.275E-3, 3495E-3

5634, 60.275E-3, 3265E-3

*NGEN, NSET=LINE-4

5600, 5634, 1

***** SEC -3- *****

*NODE, NSET=LINE-4

5635, 60.275E-3, 0E-3

5700, 60.275E-3, -200E-3

*NGEN, NSET=LINE-4

5635, 5700, 1

***** LINE -5- *****

***** SEC -1- *****

*NODE, NSET=LINE-5

5800, 76.2E-3, 3495E-3

5834, 76.2E-3, 3265E-3

*NGEN, NSET=LINE-5

5800, 5834, 1

***** SEC -2- *****

*NODE, NSET=LINE-5

6325, 76.2E-3, 0E-3

*NGEN, NSET=LINE-5

5834, 6325, 1

***** SEC -3- *****

*NODE, NSET=LINE-5

6390, 76.2E-3, -200E-3

*NGEN, NSET=LINE-5

6325, 6390, 1

***** LINE -6- *****

***** SEC -1- *****

*NODE, NSET=LINE-6

6400, 92.125E-3, 3495E-3

6434, 92.125E-3, 3265E-3

*NGEN, NSET=LINE-6

6400, 6434, 1

***** SEC -2- *****

*NODE, NSET=LINE-6

6925, 92.125E-3, 0E-3

*NGEN, NSET=LINE-6

6434, 6925, 1

***** SEC -3- *****

*NODE, NSET=LINE-6

6990, 92.125E-3, -200E-3

*NGEN, NSET=LINE-6

6925, 6990, 1

***** LINE -7- *****

***** SEC -1- *****

*NODE, NSET=LINE-7

7000, 108.05E-3, 3495E-3

7034, 108.05E-3, 3265E-3

*NGEN, NSET=LINE-7

7000, 7034, 1

***** SEC -2- *****

*NODE, NSET=LINE-7

7525, 108.05E-3, 0E-3

*NGEN, NSET=LINE-7

7034, 7525, 1

***** SEC -3- *****

*NODE, NSET=LINE-7

7590, 108.05E-3, -200E-3

*NGEN, NSET=LINE-7

7525, 7590, 1

*NSET, NSET=SOILNODES

LINE-1, LINE-2, LINE-3, LINE-4, LINE-5, LINE-6, LINE-7

***** DEFINING ELEMENTS FOR THE SOIL *****

***** COLUMN -1- *****

***** SEC -1- *****

*ELEMENT, ELSET=SOIL1, TYPE=CAX4

5000, 5000, 5001, 5201, 5200

*ELGEN, ELSET=SOIL1

5000, 34, 1, 1

***** SEC -3- *****

*ELEMENT, ELSET=SOIL2, TYPE=CAX4

5035, 5035, 5036, 5236, 5235

*ELGEN, ELSET=SOIL2

5035, 65, 1, 1

***** COLUMN -2- *****

***** SEC -1- *****

*ELEMENT, ELSET=SOIL, TYPE=CAX4

5200, 5200, 5201, 5401, 5400

*ELGEN, ELSET=SOIL

5200, 34, 1, 1

***** SEC -3- *****

*ELEMENT, ELSET=SOIL, TYPE=CAX4

5235, 5235, 5236, 5436, 5435

*ELGEN, ELSET=SOIL

5235, 65, 1, 1

***** COLUMN -3- *****

***** SEC -1- *****

*ELEMENT, ELSET=SOIL, TYPE=CAX4

5400, 5400, 5401, 5601, 5600

*ELGEN, ELSET=SOIL

5400, 34, 1, 1

***** SEC -3- *****

*ELEMENT, ELSET=SOIL, TYPE=CAX4

5435, 5435, 5436, 5636, 5635

```

*ELGEN, ELSET=SOIL

5435, 65, 1, 1

*****          COLUMN -4- *****

*****          SEC -1- *****

*ELEMENT, ELSET=SOIL, TYPE=CAX4

5600, 5600, 5601, 5801, 5800

*ELGEN, ELSET=SOIL

5600, 34, 1, 1

*****          SEC -3- *****

*ELEMENT, ELSET=SOIL, TYPE=CAX4

5635, 5635, 5636, 6326, 6325

*ELGEN, ELSET=SOIL

5635, 65, 1, 1

*****          COLUMN -5- *****

*****          SEC -1- *****

*ELEMENT, ELSET=SOIL, TYPE=CAX4

5800, 5800, 5801, 6401, 6400

*ELGEN, ELSET=SOIL

5800, 34, 1, 1

*****          SEC -2- *****

*ELEMENT, ELSET=SOIL, TYPE=CAX4

5834, 5834, 5835, 6435, 6434

*ELGEN, ELSET=SOIL

5834, 491, 1, 1

*****          SEC -3- *****

*ELEMENT, ELSET=SOIL, TYPE=CAX4

```

6325, 6325, 6326, 6926, 6925

*ELGEN, ELSET=SOIL

6325, 65, 1, 1

***** COLUMN -6- *****

***** SEC -1- *****

*ELEMENT, ELSET=SOIL, TYPE=CAX4

6400, 6400, 6401, 7001, 7000

*ELGEN, ELSET=SOIL

6400, 34, 1, 1

***** SEC -2- *****

*ELEMENT, ELSET=SOIL, TYPE=CAX4

6434, 6434, 6435, 7035, 7034

*ELGEN, ELSET=SOIL

6434, 491, 1, 1

***** SEC -3- *****

*ELEMENT, ELSET=SOIL, TYPE=CAX4

6925, 6925, 6926, 7526, 7525

*ELGEN, ELSET=SOIL

6925, 65, 1, 1

*ELSET, ELSET=SOIL

SOIL1, SOIL2

*SOLID SECTION, ELSET=STEEL, MATERIAL=STEEL

*SOLID SECTION, ELSET=GROUT, MATERIAL=GROUT

*SOLID SECTION, ELSET=SOIL, MATERIAL=SOIL

```

*****

*****MATERIAL DEFINITION*****

*****FOR STEEL ROD*****

*MATERIAL, NAME=STEEL

*ELASTIC

206.E9, 0.3

*DENSITY

7850

*****FOR GROUT*****

*MATERIAL, NAME=GROUT

*ELASTIC

43E9, 0.3

*DENSITY

2400

*****FOR SOIL*****

*MATERIAL, NAME=SOIL

*POROUS ELASTIC, SHEAR=POISSON

0.026, 0.3, 2E3

*DENSITY

1700

*INITIAL CONDITIONS, TYPE=RATIO

SOILNODES, 1

*****BOUNDARY CONDITIONS*****

*****

*BOUNDARY

AXIAL-NODES, 1

```

***** DEFINING SURFACES *****

***** FOR STEEL *****

*SURFACE, NAME=OSR

STEEL-4, S3

***** FOR GROUT *****

*SURFACE, NAME=IG

GROUT1, S1

***** DEFINING CONTACT *****

*CONTACT PAIR, INTERACTION=OSR-IG, TIED, ADJUST=0

IG, OSR

*SURFACE INTERACTION, NAME=OSR-IG

***** DEFINING GAP ELEMENTS *****

***** STEEL & SOIL *****

*ELEMENT, TYPE=GAPUNI, ELSET=AGAP1

10000, 1145, 5000

*ELGEN, ELSET=AGAP1

10000, 34, 1, 1

*GAP, ELSET=AGAP1

0, 1, 0, 0, 1

***** GROUT & SOIL *****

*ELEMENT, TYPE=GAPUNI, ELSET=AGAP2

20000, 3900, 5834

*ELGEN, ELSET=AGAP2

20000, 491, 1, 1

*GAP, ELSET=AGAP2

0, 1, 0, 0, 1

*****Defining Impulse*****

*AMPLITUDE, NAME=IMPULSE, DEFINITION=EQUALLY SPACED, FIXED

INTERVAL=3.91E-5,

INPUT=Impact.dat2, VALUE=RELATIVE, BEGIN=0

*NSET, NSET=NODE1

1, 551, 1140

*****HISTORY DEFINITION*****

*STEP

*FREQUENCY, EIGENSOLVER=LANCZOS

22, 1300

*NODE FILE, NSET=AXIAL-NODES

U

*FILE FORMAT, ASCII

*END STEP

*STEP

*MODAL DYNAMIC

3.91E-5, 4.00E-2

*SELECT EIGENMODES, GENERATE

1, 22, 1

*MODAL DAMPING, MODAL=DIRECT

1, , 0.01

2, 22, 0.005

*CLOAD, AMPLITUDE=IMPULSE

1, 2, -1

*NODE FILE, NSET=NODE1

A

```
*NODE PRINT, NSET=NODE1
```

A

*END STEP

[illegible]