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A new experimental device for determining reinforcement mechanisms in soil nails

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ABSTRACT: The paper describes the development of a new experimental device to determine the reinforcement mechanisms mobilized in soil nails used to reinforce existing ground. Unlike previous laboratory efforts to measure these mechanisms, which typically measured group behavior of relatively closely spaced inclusions, the new device measures the behavior of a single nail in a soil specimen. Measurements are made to determine the tensile force and bending stress mobilized in the inclusion as well as the overall shearing stress versus deformation behavior of the reinforced soil mass. The paper argues that the testing of a single element is more representative of the *in situ* conditions. Results from initial tests using the device are presented and plans for future testing described.

1 INTRODUCTION

The use of passive inclusions, such as soil nails, for *in situ* soil reinforcement is gaining wider acceptance in the United States. This increasing use is prompted in part by designers and owners looking for economical methods to stabilize cut slopes and excavations, particularly along highways, and to remediate existing slopes that have undergone significant deformations. As practitioners increasingly consider soil nails as a design option, however, there is a growing need for a design method that is accessible. The method should not be proprietary or overly difficult to implement and should be proven through field and laboratory tests.

A necessary step in quantifying soil nail effects on soil mass behavior is conducting basic studies under controlled conditions. These studies should model, as closely as possible, the physical and kinematic conditions present in the nailed soil mass. If the tests are on laboratory models, they should account for dimensional scaling, soil conditions and applied stress-strain conditions.

This paper describes a new experimental device designed to determine the reinforcement mechanisms mobilized in soil nails for excavation support, and to determine soil nailing's effect on soil stress-strain-strength behavior. The results from the proposed testing program will be used to develop a design method that spans across different soil types and has a relatively simple formulation.

2 BACKGROUND

2.1 *Nail reinforcement mechanisms*

There are two mechanisms of nail-soil interaction which contribute to improved soil mass stability (Fig. 1). The first is friction between the soil and the nail leading to tension in the nail. This tension in turn is transferred to the wall facing and increases the stability of the potential failure block. The second interaction mechanism is passive earth pressure on the nail, leading to soil bending and shear stress development. In theory, the importance of each mechanism depends on the deformation of the nail and soil, the nail's stiffness in extension and bending, and soil type. As a measure of the soil nail's stiffness, the transfer length, l_o, is used, defined as

$$l_o = \sqrt[4]{\frac{4EI}{k_s D}} \quad (2.1)$$

with

E,I,D=the nail modulus, moment of inertia and diameter, respectively

k_s=soil reaction modulus

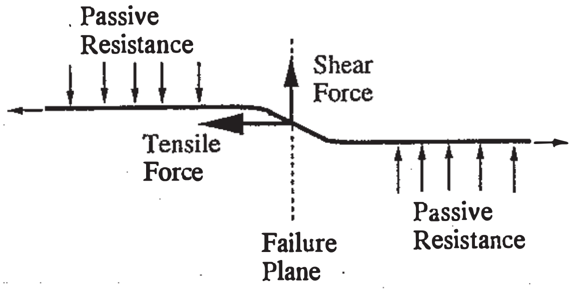

Fig. 1. Nail reinforcement mechanisms

Based on elastic theory, when the actual length of the nail, L, is greater than or equal to $3l_0$, the nail can be considered as flexible and the friction/tension mechanism is assumed to predominate. In this case, the nail's pullout capacity and interaction with the wall facing are important since they provide the tensile reactions. When L falls below $3l_0$, the passive earth pressure mechanism is predicted to become important; this mechanism relies on bending/shear of the nail.

The analysis of passive inclusions is based on their similarity to laterally loaded piles. The loading placed on soil nails, as finite soil mass deformation occurs in the potential slip zone, is analogous to laterally loaded pile groups. Assuming the nails are in a regular grid pattern, laterally loaded pile group theory treats two loading geometries which are analogous to the soil nail situation. Figure 2a shows *side-by-side* loading when the lateral load is normal to the line of piles of diameter b at center-to-center spacing s. *In-line* loading (Fig. 2b) occurs when the loading is parallel to the pile line. Experimental studies (Cox et al. 1985) have shown that laterally loaded piles in a line group act independent of one another (i.e., have a pile group efficiency of unity) when the s/b ratio is 3 or greater for side-by-side loading, and 5 or greater for in-line loading. When applied to soil nails, these data mean that as long as soil nail row and column spacings exceed these s/b ratios (3 along the wall's length between columns and 5 down its height between rows), laterally loaded pile group tests show that the nails will act independently. Even if the nail group efficiency is greater than one, conservative estimates of nail reinforcement will result from treating them as independent. For perspective, these s/b ratios imply that for a typical soil nailed wall using 2.5 cm (1 in.) diameter nails with, say, a 15.2 cm (6 in.) diameter grout zone, the nail columns would be spaced at least 45 cm (18 in.) on center and the rows would be spaced 75 cm (30 in.) on center. These spacing minima are almost always exceeded in soil nailed walls.

Thus, based on the foregoing reasoning, a nail's reinforcement influence is primarily independent of surrounding inclusions if the these minimum spacing ratios are maintained. Laboratory testing of soil nail reinforcement mechanisms can therefore be based on element-level testing, i.e., testing the effect of a single nail in a soil element with sufficiently large dimensions to avoid boundary-soil nail interaction.

2.2 *Current design methods*

A number of design methods for soil nailed walls have been developed. FHWA (1991) provides an overview of the most common procedures. However, despite these developments, Keeley (1993) notes that a primary research need is the "evaluation of current design computer codes to

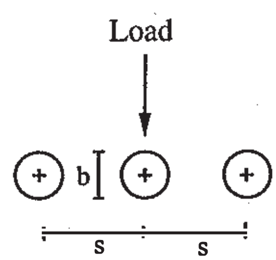

Fig. 2a. Side-by-side loading of nails

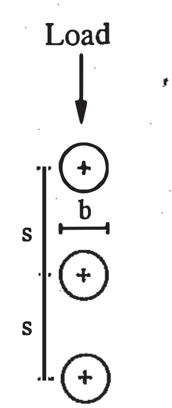

Fig. 2b. In-line loading of nails

establish points of commonality and difference, and to validate those methods suitable for soil nail wall design." In conjunction with this, future design method development should be consistent with observed field behavior and be analytically sound. Data from controlled laboratory tests should clearly show the effect of nails on measured soil behavior. Further, the design method should be available to the public (not proprietary) and relatively simple to implement.

3 THE NEW TESTING DEVICE: SETARIS

3.1 *Description of the basic device*

A new testing device was designed and constructed at Northeastern University (NU) to perform tests on nail reinforced soil specimens. The SETARIS (Single Element Testing Apparatus for Reinforcing Inclusions in Soil) device is a specialized direct shear box in which the applied normal stress is parallel to the direction of applied shearing (cf. a conventional direct shear device in which applied normal and shear stresses are perpendicular). Ultimately, the goal of the research is to examine the reinforcement's effect on specimens of natural clay.

Figure 3 shows the lengthwise (or side view) elevation cross-section through the device when a reinforced soil specimen has been loaded into it. It is configured to model the nail-soil interaction at the potential failure surface in a nailed soil mass. The soil specimen is 25.4 cm (10 in.) high, 61.6 cm (24.3 in.) long, and based on the perspective of Fig. 3, 20.3 cm (8 in.) deep. These dimensions were selected to eliminate the boundary effects on a 1.3 cm (0.5 in.) diameter reinforcing nail inside a 2.5 cm (1 in.) diameter grout zone. The in-line loading direction requires 5 nail diameters above and below the nail, a condition satisfied by the 25.4 cm height. The side-by-side loading direction requires 3 nail diameters on either side laterally, which the 20.3 cm

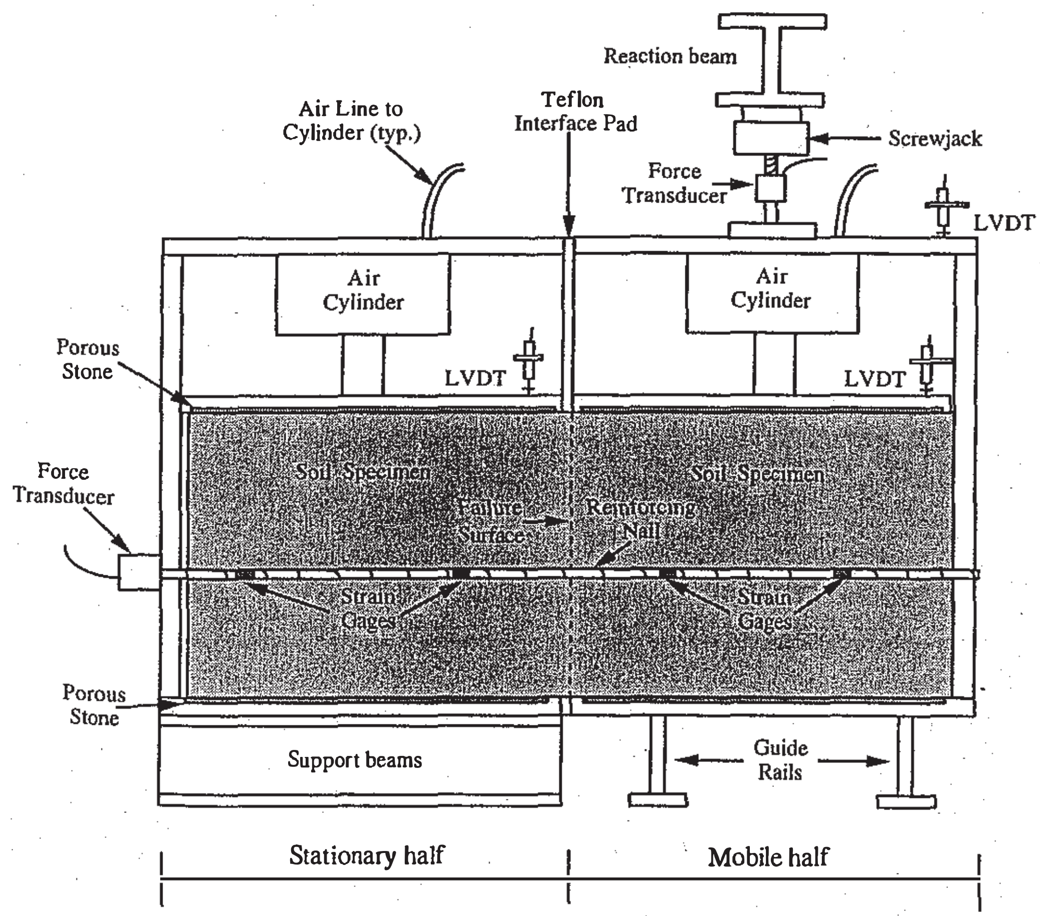

Fig. 3. Lengthwise cross-section of SETARIS device

depth satisfies. Finally, the 61.6 cm length of the nail is for flexible behavior as determined by Eq. 2.1.

The soil nail is a 1.3 cm (0.5 in) diameter piece of reinforcing steel inserted in the soil specimen after the entire specimen has been placed in the box. This is done by drilling through the specimen via holes in each end platen and inserting the model nail. Grouting procedures are still being developed.

Referring to Fig. 3, two pneumatic cylinders, one for each side of the split shear box, apply a uniform normal stress to the specimen's top surface via top platens, each attached to its pneumatic cylinder. The top platens have flush mounted porous plates for specimen drainage; two porous plates identical to those on top are flush mounted on the bottom of the box.

After the normal stress (which represents the overburden stress on the soil element) is applied, a shearing force is independently applied, causing one half of the box to mobilize (labeled "mobile half" in Fig. 3) in the vertical direction. Figure 4 shows an end view cross-section of the mobile half of the device. A variable speed motor turns a wormgear screwjack which drives the loading shaft downward at constant rate of shear deformation. A 0.64 cm (0.25 in.) thick strip of Teflon is attached to the end walls of the stationary half of the box. When the two box halves are together, the Teflon strips form an interface seal that causes insignificant friction between the two box halves. Because of the new device's unique design, normal (or overburden) stress is controlled separately from the applied shear force; as is the case *in situ*, shear failure can be imposed on the reinforced soil mass under constant overburden stress.

3.2 *Instrumentation and data acquisition*

Figure 3 shows the primary measurement instrumentation to be used with the SETARIS device. The nail (as modeled in the device by the 1.3 cm diameter reinforcing steel bar) has four strain gages mounted along its length to determine the amount of bending and shear stress being mobilized during shear. A force transducer is connected via a moment break to the end of the nail (which is fixed on the end of the mobile half end wall with a pin connection) to measure axial nail tension. Another force transducer built into the shear force loading shaft measures the total load to support the box and to drive its downward movement (net force is total force measured in the loading shaft less mobile half weight). Two linear variable displacement

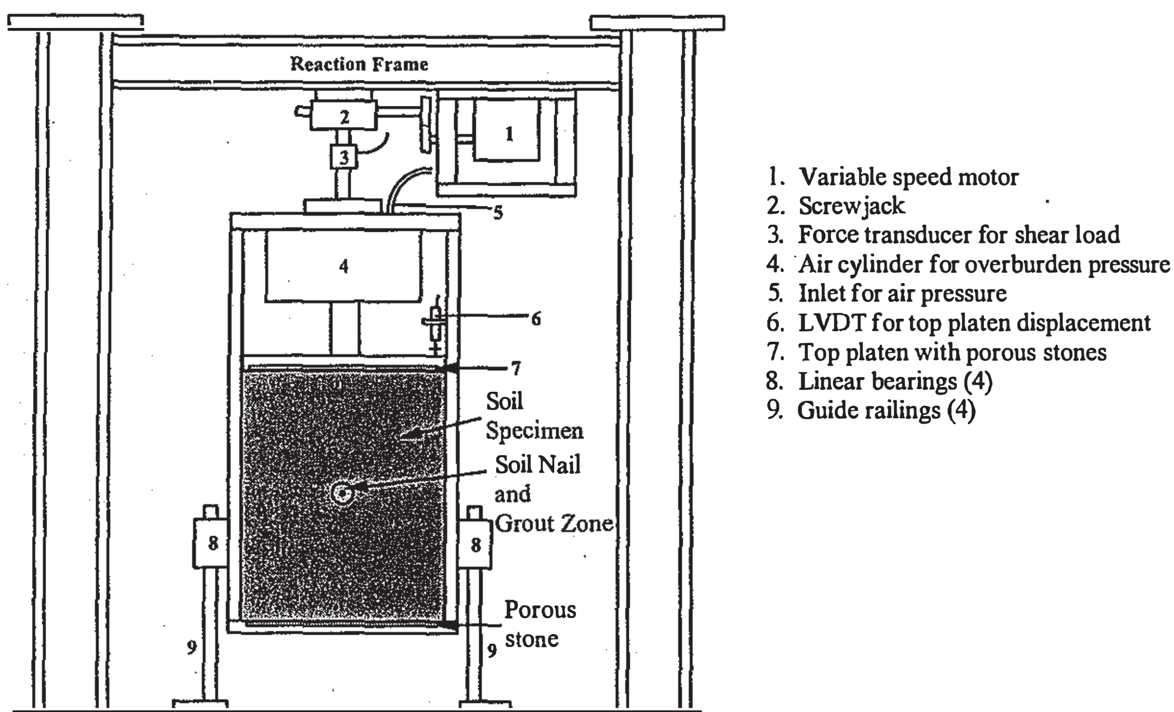

Fig. 4. Cross-section of the mobile half

transducers (LVDT) measure the top platen displacements (one for each half of the box). A third LVDT measures mobile half displacement during shear.

All measurements are logged at selected time intervals onto a PC hard disk using a high resolution data acquisition interface board and control software that was written by the authors.

3.3 *Advantages of the new device*

The advantages of the new device over previous shear boxes used to test soil inclusions are:

- Applied normal and shear forces are in the same direction, better modeling a significant portion of the failure zone in the field.
- The device will test natural versus compacted soils, including cohesive soils consolidated prior to shear.
- The applied normal (overburden) stress can be varied to assess nail reinforcement mechanisms at different depths in the soil mass.
- The single element approach will isolate the reinforcement effects of a single nail which is consistent with laterally loaded pile theory.

3.4 *Preliminary test results*

To date, the new device has been proof-tested using dry, standard 20-30 Ottawa sand (ASTM C778) without reinforcement. The results have been compared to existing data on Ottawa sand (e.g., Holtz and Kovacs 1981) as well as to conventional direct shear tests performed at NU. Figure 5 shows the Mohr circles (before and after shear) and the Mohr-Coulomb failure criterion for the new device. Test specimens in both the new SETARIS device and the direct shear device were surcharged with a vertical stress, σ_v, and the computed void ratio at this stress was 0.5. In Fig. 5, the Mohr circle labeled "preshear" is for K_o conditions in the SETARIS device, where ϕ=32° as obtained from the direct shear device. During shear, σ_v remains constant, the imposed failure plane is vertical, and τ_{meas} is computed from the force transducer (see Fig. 3). At failure, the Mohr circle marked "failure" in Fig. 5 results and the friction angle ϕ must satisfy the equation

$$\tan\phi = \frac{\tau_{meas}}{\sigma_v - 2\tau_{meas}\tan\phi} \qquad (3.1)$$

for ϕ values less than 35°. In the preliminary tests, the SETARIS device yielded τ_{meas} = 27 kPa and an overburden of σ_v = 77 kPa, corresponding to about ϕ=32° from Eq. 3.1. This agrees well with the ϕ values obtained from the direct shear tests.

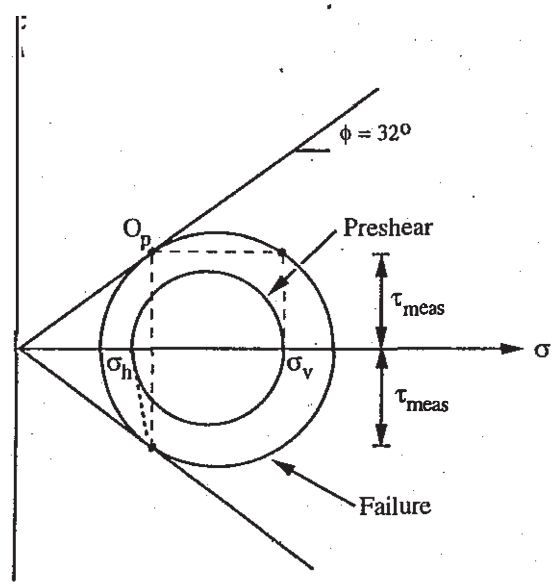

Fig. 5. Proposed Mohr circle for SETARIS device

4 SUMMARY AND FUTURE TESTING

The paper has described a new testing device for determining soil nail reinforcement mechanisms. The new SETARIS device is a specialized direct shear box based on an element testing approach which assumes that soil nails act independently to influence soil mechanical behavior. Preliminary tests on Ottawa sand without reinforcement indicate that the new device yields reasonable values of friction angle, ϕ, compared to the conventional direct shear device. In the future, tests will be performed on specimens of reinforced Ottawa sand, natural unreinforced clay and finally, reinforced clay. The new device is intended to provide much needed, basic information about the effect of soil nails on the stress-strain-strength properties of a reinforced soil mass. The results can eventually be used to develop better design approaches for soil nail walls.

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