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Dynamic pull-out tests to characterize the earthquake behavior of soil-nailed walls

Clouage des sols: Comportement sous sollicitation sismique de l'interface sol-cloué

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ABSTRACT: Soil-nailed walls are commonly used for their cost-effectiveness and ease of implementation. These structures have demonstrated remarkable seismic resilience, as evidenced by post-earthquake surveys following events like the Loma Prieta earthquake. Researchers have attributed their stability to the dynamic mobilization of friction at the soil-nail interface. However, designing soil-nailed walls to withstand seismic forces often results in increased stiffness, which can affect the transfer of motion to the structures they support. Improving the seismic design of these walls requires a closer examination of the local dynamic behavior at the soil-nail interface, a topic that has received limited attention in the existing literature. To address this gap, the RRO laboratory at Gustave Eiffel University has recently developed an innovative impulsive pullout testing device. This paper introduces the device, which is capable of applying static tension forces and a series of dynamic load pulses at the nail's head, reaching up to 50% of the applied force and operating at specified frequencies ranging from 0.1 to 5 Hz. In addition to traditional tension force and displacement measurements at the nail head, this device incorporates optical fiber technology to monitor micro strains along the entire length of the steel bar with millimeter longitudinal resolution. This new approach enables the comprehensive investigation of the local seismic behavior of the interface, with the goal of proposing an improved design model for soil-nailed walls.

RÉSUMÉ: Les murs en sol cloué sont couramment utilisés pour leur rentabilité et leur facilité de mise en œuvre. Ces ouvrages ont démontré une résilience sismique remarquable, comme en témoignent les enquêtes menées après des événements tels que le séisme de Loma Prieta. Les chercheurs ont attribué leur stabilité à la mobilisation dynamique du frottement à l'interface sol-clou. Cependant, le dimensionnement des murs en sol cloué sous sollicitations sismiques entraîne souvent une rigidité accrue, ce qui peut avoir un impact sur le transfert des mouvements aux structures qu'ils soutiennent. L'amélioration de ce dimensionnement nécessite un examen plus approfondi du comportement dynamique local à l'interface sol-clou, un sujet peu abordé dans la littérature existante. Pour combler cette lacune, le laboratoire RRO de l'Université Gustave Eiffel a récemment développé un nouvel appareil impulsif d'essais d'arrachement innovant. Cet article présente l'appareil, qui est capable d'appliquer des tensions statiques et une série d'impulsions de charge dynamique à la tête du clou, atteignant jusqu'à 50 % de la force appliquée et fonctionnant à des fréquences spécifiées allant de 0,1 à 5 Hz. Cette nouvelle approche permet d'effectuer une étude détaillée du comportement sismique local de l'interface, dans le but de proposer un modèle de dimensionnement amélioré pour les murs en sol cloué.

Keywords: Soil-nailed wall; pull out test; interface; seismic behavior.

1 INTRODUCTION

Soil reinforcement techniques, such as soil-nailed walls, originally introduced in France in 1972-1973 to support a railway platform in Versailles, have gained widespread use due to their ability to enhance soil stability and strength (Schlosser and Unterreiner, 1991). These walls offer several advantages, including lightweight equipment, adaptability to various site conditions, and efficiency in terms of time and cost. The core principle behind soil-nailed walls is the interaction between the soil inclusion and the surrounding soil. The resistance provided by soil nails is a result of the axial tension that develops within the nail due to the deformation of the soil mass around it (Schlosser and Unterreiner, 1991). Additionally, these structures have demonstrated their resilience during powerful ground motion events. A notable example is the 1989 Loma Prieta earthquake, that occurred at magnitude of 7.1 and was considered to be at that time the costliest single natural disaster in the United States' history, causing massive damage in various areas of San Francisco Bay. Nine soil-nailed walls were inspected post-earthquake, and despite their proximity to the earthquake's epicenter, these walls exhibited no signs of distress or deformation, in contrast to other structures that sustained severe damage (Vucetic et al., 1998). Different methods have been employed to study the dynamic behavior of soil-nailed walls. These include centrifuge (Tufenkjian and Vucetic, 2000), 1g shaking table tests (Yazdandoust, 2017;Tabucanon et al., 1995; Xu et al., 2020), and numerical models. However, these studies primarily focus on assessing the global stability of the entire structure and do not account for localized deformations at the soil-nail junction. In contrast, static pull-out tests have proven effective in investigating the interaction and shear strength between the nail and the surrounding soil. These tests have explored various parameters, such as nail length, diameter, stiffness, and interface roughness (Tei and Milligan, 1998). The grouting pressure and saturation of soil influence was also investigated through laboratory pull-out tests (Su, 2006) on CDG (completely graded granite) classified as well graded, clayey gravelly silty sand frequently present at slopes in Hong Kong. Moreover, studies have delved into soil properties, including cohesion, friction angle, moisture content, and particle degradation (Shahraki Ghadimi *et al.*, 2017). Cyclic shear box tests, conducted by (Poulos, 1989) and (Tabucanon et al., 1995), have shed light on the degradation of skin friction in the interface under cyclic loads. Factors like the number of cycles, amplitude of displacements, roughness, and interface stiffness were considered in these studies, which revealed a reduction in shear stresses after a specific number of cycles. Furthermore, research by Zhou *et al.* examined the influence of particle shape in shear cyclic tests, demonstrating that particle breakage near the interface and soil densification contributed to an increased contact area between particles in the interface zone (Zhou *et al.*, 2020), resulting in a gradual increase in the interface friction angle. To further explore dynamic resistance at the interface, rapid pull-out tests were conducted by Tan et al. (2008) using an impulsive hammer with varying nail roughness and diameter. The tests showed that the pre-peak pullout response was stiffer and achieved higher peak pullout values with larger nail diameters, especially for rough-textured nails. Notably, the rate of loading had no effect in the case of smooth nails. However, it's worth noting that dynamic resistance at the interface, particularly for rough-textured nails, remains insufficiently understood. To address this knowledge gap, the GERS-RRO laboratory introduced an innovative dynamic pull-out device and combines it with optical fiber to monitor strain evolution and calibrate measurements. This device aims to provide essential experimental data on the characteristics of the soil-nail interface during dynamic loading, contributing to a deeper understanding of the behavior of soil-nailed walls.

2 THE DYNAMIC PULL-OUT DEVICE

2.1 Description of the device

An innovative equipment was developed to enable the application of dynamic, controlled, and predetermined tensile forces on reinforcement bars within geotechnical structures. This pull-out testing device may apply a dynamic tension force with specified frequency ranging from 0.1 to 5 Hz, corresponding to frequencies typically associated with moderate earthquakes.

The design of the equipment allows for the superimposition of vibrational pulses onto the static loading applied either in incremental steps or as a gradual slope.

The device consists of an actuator connected to a hydraulic circuit, that is controlled through programmable automaton. The device is designed to enable testing both in a laboratory setting and out in the field. For this purpose, the structure consists of components, each weighing less than 30 kilograms.

2.2 Components of the device

The five components of this device are shown in Figure1: a hydraulic pump of 700MPa maximum pressure equipped with an oil radiator, a hydraulic accumulator with a pressure regulator and a pressure gauge (manometer), a high-pressure controlled modulating solenoid valve, a programmable user interface for integrating the programmable logic controller (PLC), and finally, a 600kN hydraulic jack attached to the nail for imposing loading. These elements are designed for robustness, have undergone field testing, and can be transported individually by a single person.

2.3 Mode of operation

The system can operate in both manual and automatic modes. The automatic mode allows for the programming of test cycles by interacting with the programmable logic controller (PLC). The static load can be applied as load increments in traditional incremental loading pull-out tests (steps configuration), or during a linear increase of the tensile force (slope configuration).

The fundamental principle underlying the functionality of this device is to enable the simultaneous imposition of a specific dynamic pulse alongside a static tensile load of a predetermined magnitude. Similarly, in the slope configuration, the linear increase of the tensile load can reach up to 350 kN, with the same duration.

Figure 1. Connection of the device in running order: (1) hydraulic pump, (2) hydraulic accumulator, (3) controlled solenoid valve, (4), programable automate (PLC).

The dynamic pulse generated during loading is defined by two key parameters:

- Period of pulse, which falls within a range of 100ms to 5000ms, corresponding to a frequency range of 0.1 to 5 Hz.
- Amplitude of tension pulse, ranging from 1% to 50% of the static tensile load.

These pulses are superimposed onto the ongoing static loading program. They are centered and their intensity oscillates by +/- the specified amplitude for the specified pulse duration.

3 EXPERIMENTAL TESTING AND ASSESMENT OF THE DEVICE

3.1 Experimental setup

Table 1.Specifications of used bar

Nominal diameter (mm)	**Yield stress (N/mm²)**	**Yield load (kN)**	**Ultimate load (kN)**	**Area (mm²)**	**Weight (Kg/m)**
32 mm	550	405	440	804	6.31

Initial tests were carried out to check and validate the accurate functioning of the apparatus, specifically concerning the generation of pulsed tensile forces applied to a steel bar in a controlled laboratory environment.

To achieve this, a steel bar (with specifications outlined in Table 1) was inserted into a hollow metallic tube, used as a reservoir for the sand to fill in. The tube is 2 m in length, and the internal diameter 150 mm (Figure 2).

The steel nail was centered in the tube with one of the ends securely affixed using a support plate and a nut, and glued with silicon to avoid leakage of the sand. In order to ensure the proper connections at the edges of the tube, and avoid inducing any parasite moments or bending when applying tension in the steel bar, the two edges of the tube were cut parallel with laser geometry control. In order to fill the sand, the tube was placed in a vertical position. Hostun sand HN31 with well-defined properties, such as maximum density of 1.62 g/cm3 (Zeybek, 2017) was used to fill the tube after the bar was installed.

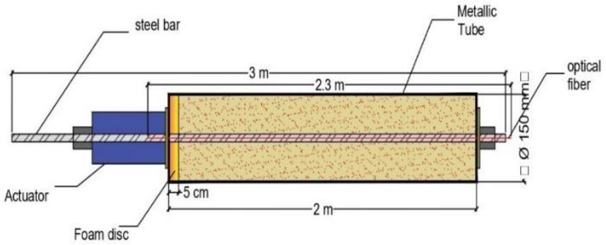

Figure 2. Illustration of the metallic tube used as sand reservoir setup.

With the nail placed prior to sand installation as well as a foam disc (0.95 L) of volume being used to ensure the centering of the bar, and as a stopper of the sand at the top edge of the tube, the total volume to be filled with sand thus is 32.86 liter. At the maximum density of sand, a mass of about 55kg of sand would be required to fill up the tube. The sand was filled along four levels, and a quarter was filled per once. Each insertion was followed by vibration of the metallic tube to ensure maximum density is attained. However, the remaining mass of non-filled sand was measured to 2.4 kg. This has affected the density assumed, and eventually the new value of the sand density in the tube is 1.54 kg\l, corresponding to a relative density of 79.1 %.

3.2 Monitoring and measurements

The nail's head is fitted with a load sensor, enabling direct measurement of applied tensile force, to be checked against the force generated by the dynamic machine. Additionally, the steel bar is equipped with an optical fiber that spans its entire length, in order to measure strain during the loading process. The tests also aimed to ensure accurate calibration of the strain measurements obtained through this optical fiber, through comparing the values to theatrically computed strains. The optical fiber employed, with a length of 2.3 m, is securely affixed within the grooves to the nail's surface. Measurements are taken at an acquisition frequency of 125Hz, with a discretization of 2.6mm between recording points along the fiber.

3.3 Testing procedure

In order to investigate the performance of the interface of soil and nail, both static and dynamic loads were applied. The static tests were designed in two different configurations, using an incremental loading process performed over four stages at specified pressures of 10-100-140-213 bar, and another slope loading up till 213 bar. The employment of the dynamic loading however requires the definition of the properties of the dynamic pulse to be imposed as well as that for the static tension. An incremental loading process same as that used in static tests was also used.

The pulse applied was defined at 5% and 20% amplitude of the loading, with varying the chosen frequency between 2 ,4 and 5Hz. Each increment in loading was sustained for a period of 20 seconds/step, with always having the first step in only static (no pulse applied).

4 RESULTS AND DISCUSSION

The results represented in the following section correspond to dynamic test, pulse applied at 5Hz, with an amplitude of 20% of the static tension load. It is to be noted though that the same loading and strains profile was maintained at other frequencies of 2Hz and 4Hz. The color mapping represented in Figure 3, displays the strains record by the optical fiber through the loading procedure at every position along the nail. The horizontal strips marked in yellow frames the executed dynamic pulses. It can be observed that the dynamic pulse occurs at the same time along every position of the nail, which indicates that the load is being transmitted uniformly through the nail.

In order to verify the measurements of the optic fiber, the strains measured were compared to the strains calculated using Hook's law ($\sigma = E\varepsilon, \varepsilon = \frac{F}{AE}$), where E is modulus of the steel material, ε the strains in axial direction, F the force applied at the head of nail, and A the surface area of the nail cross section, assumed constant. Figure 4 depicts the comparison, highlighting the alignment between the computed strain values and those obtained from the optical fiber measurements at the end point of the fiber located in the actuator (nearest to the position of the load sensor). The following plot allows us to verify the compatibility of the loading sensor and optical fiber.

The values of the strains measured by the fiber are slightly smaller than those computed by Hook's law accounting only for the deformations induced by the tension applied at the head of the nail.

This indicates that the interface between soil and the nail experiences little friction that reduces the impact of the tension caused by the pull-out, and eventually the deformations.

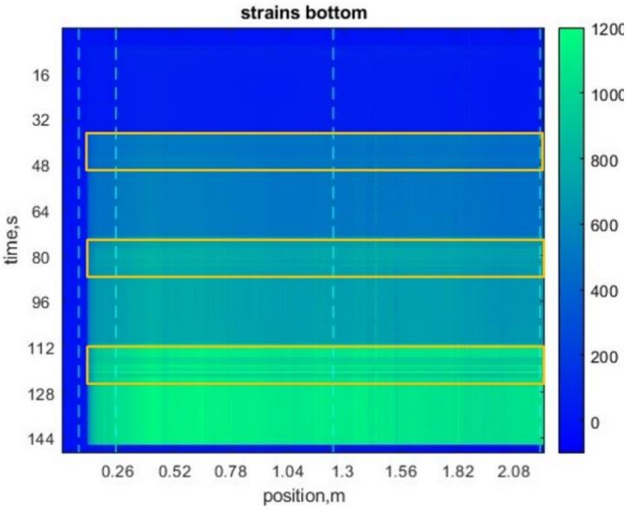

Figure 3. Color mapping representing the strains' distribution, yellow contours marking the positions of the dynamic pulses.

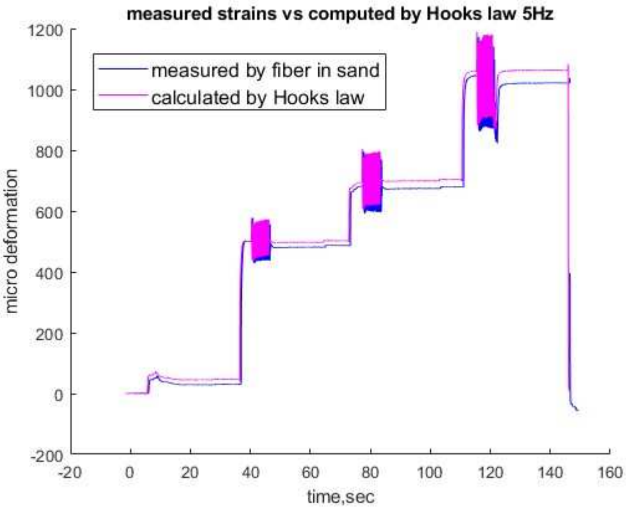

Figure 4. Strains measured by optic fiber vs strains computed by Hook's law, in test at 5HZ.

This is also consistent with the shown in Figure 5 representing the strains experienced along the nail, which has almost a uniform profile. A minimal friction is thus experienced between the soil and inclusion. The fact that the nail was inserted into the sand without being grouted, as well as the low density of confinement achieved (67.87%) is to be considered. Throughout previous studies (mentioned in the introduction), it has been shown that the roughness possessed by the interface has a major effect on the interaction mechanism occurring between the inclusion and the sand, which may be the reason to obtain these values.

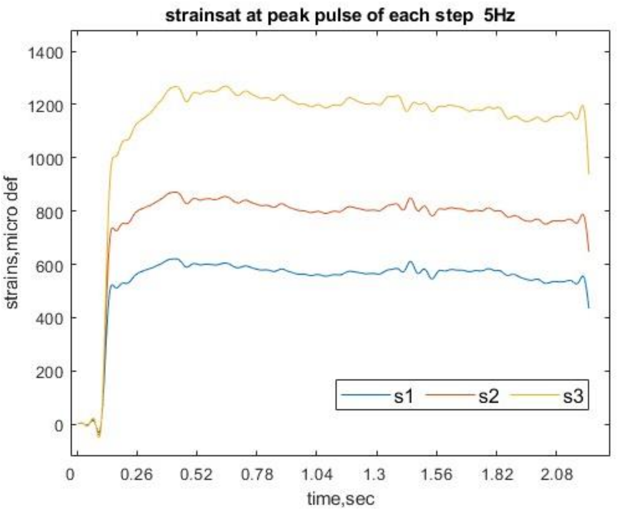

Figure 5. Strains during peak of the dynamic pulse at 5Hz at different steps.

5 CONCLUSIONS

A new impulsive device designed to study dynamic pull-out of nails has been developed and presented in this paper. The performance of this device has been examined through series of tests, with the aid of measurements obtained by optic fiber. The employment of the optic fiber allowed for accessing the strains all over the nail, which are essential to understand the interface behavior.

The tests allowed to assess the new dynamic device's capacity, and validity of the measurements of the optic fiber in case of dynamic pulses present. A consistency between the measurements of the sensors is achieved, as well as a uniform load transmission of the load through the nail. However, the measurements obtained by the optic fiber has shown no friction, eventually almost no interaction at the interface. This is due to the absence of grouting around the nail affecting the interface's roughness. This is to be tackled in the upcoming tests, where proper grouting of the nail will be done.

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