Micropiles founded in rock. Development and evolution of bond stresses under repeated loading
Micropilotes en roca. Desarrollo y evolución de la adherencia bajo cargas repetidas

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Abstract
Four vibrating wire strain gages were installed along a micropile founded in rock. The micropile was subject to cyclic load increments and repeated loading. The results of the test and the analyses performed provided a useful insight into the mechanism of load transfer to the rock during loading. Bond strength values were calculated based on the test data. It was observed that, although the peak strength of the grout-rock interface was mobilized, debonding of the micropile was not observed. The results obtained also illustrate the effect of repeated loading on the response of micropiles in rock, and outline the potential limitations of the interpretation of elastic length values from tests on non-instrumented micropiles.

Resumen
Cuatro sensores de deformación unitaria fueron instalados a lo largo de un micropilote empotrado en roca. El micropilote fue sometido a incrementos de carga cíclicos y a repeticiones de carga. Los resultados de la prueba y de los análisis realizados proveen una visión única del mecanismo de transferencia de carga del micropilote a la roca. La adherenciaa lo largo del pilote fué calculada en base a los resultados de la prueba. A pesar de que se movilizó la resistencia pico del contacto entre el micropilote y la roca, no se observó una pérdida significativa de su resistencia. Los resultados obtenidos ilustran asimismo el efecto de las cargas repetidas sobre el comportamiento de micropilotes en roca y resaltan las limitaciones existentes en la interpretación de la longitud elástica de micropilotes de prueba no instrumentados.

1 INTRODUCTION

The basic understanding of the performance of micropiles has evolved rapidly over the past 20 years. A large portion of our present knowledge has been obtained from traditional friction piles and caissons, as well as ground anchors. This is particularly true in the cases of micropiles socketed into (i.e. founded in) hard rock. Littlejohn and Bruce (1977) presented a compilation of data on rock anchors that forms the basis of much of this understanding. Bruce et al. (1993) developed the idea of the elastic ratio, and showed that cyclic loading of a micropile and the measurement of the ensuing elastic deflections can be used to gain an understanding of the length of the pile that is being stressed, and the magnitude and distribution of the load transferred to the ground. Cavey et al. (2000) presented the results of a series of cyclic, load-reversal load tests on micropiles in soils. They reported that cyclic loading induced a significant reduction in the micropile capacity, as interpreted using the method developed by Davisson (1972).

Still, there are some questions regarding the response of micropiles that have not been fully answered. Specifically, for micropiles bonded into rock, there are few data on the development of grout-rock bond stresses during loading. There are also few data on the potential for reduction of micropile capacity caused by debonding or by post-peak reduction of the bond strength (i.e. softening) of the grout-rock interface throughout repeated load cycles. This may be an important issue for design of micropiles subject to cyclic loading from machinery, and for micropiles installed in seismic areas.

2 THE TEST MICROPILE

The test pile was a Case 1, Type A micropile (Federal Highway Administration 2000), which consisted of a seven-inch (177.8-mm) outside diameter casing inserted into a predrilled, 8.625-inch (219-mm) diameter hole. The hole was drilled approximately 23.4 ft (7.13 m) below grade using a down hole hammer mounted on an electric, track-mounted rig with a rotary percussive drill head. Rock was encountered at a depth of approximately 10 ft (3.04 m); therefore, the drilled hole penetrated approximately 13.4 ft (4.08 m) into rock. Figure 1 summarizes the characteristics of the micropile.

Neat cement grout was used to fill the hole using a tremie tube. Limited pressure was used to complete the grout return to the surface around the outside of the casing. The grout was prepared in a high-speed colloidal mixer to a water:cement ratio of 0.5 by weight. The average specific gravity of the grout was 1.85 as measured during batching, and the compressive strength was greater than 4 ksi (2.8 kg/mm^2) at 28 days.

Four Geonor vibrating wire strain gauges were installed to monitor the strains along the micropile. Each gauge was attached to a one-inch (25.4-mm) diameter steel pipe via a 0.5-inch (12.5-mm) sister bar. The distribution of the gauges along the micropile is illustrated in Figure 1.

3 CHARACTERISTICS OF THE DIABASE ROCK

The test site lies within the Culpepper Basin, a geologic feature that extends from southwestern Virginia to western Maryland, formed during the Triassic. The Culpepper Basin is characterized by a shallow bedrock surface consisting of nearly horizontal, interbedded layers of sedimentary rocks and localized igneous intrusions. These intrusions consist of massive diabase, and they ultimately weather into high plasticity clays and elastic silts.

At the test pile location, the diabase presented a recovery of 89 to 100 percent, and an RQD of 46 to 84 percent, as measured from rock cores collected during the exploration. The unconfined compressive strength of the fresh diabase rock in this area typically ranges between 10 and 20 ksi (7 and 14 Kg/mm^2). However, strength values may be significantly lower in the more fractured and weathered rock that exists closer to the surface.

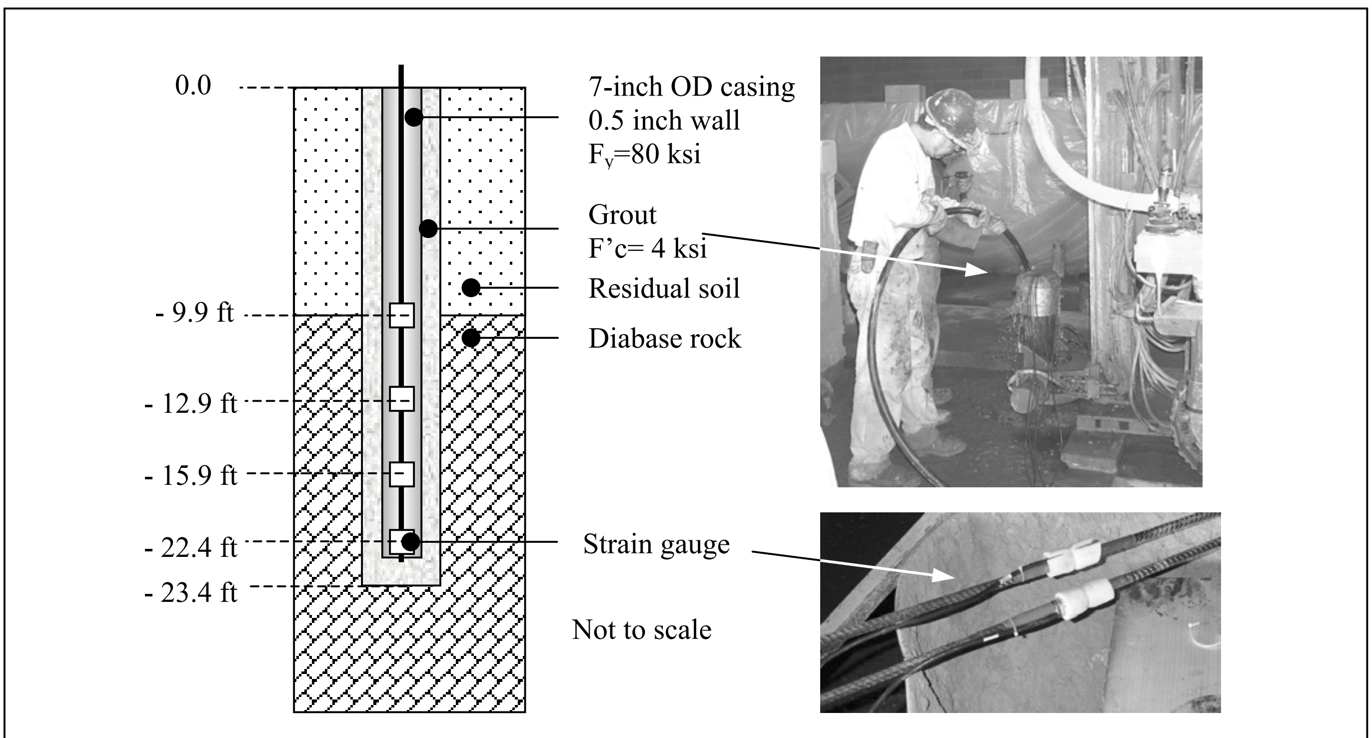

Figure 1. Micropile configuration

4 LOAD TESTING

The load test was performed in two stages. The first stage was conducted as part of the project requirements in general accordance with ASTM D1143 except cyclic load increments were applied. The pile was loaded to a maximum of 640 kip (290 metric tons). The results of the first stage of the test are presented in Figure 2. The second stage was performed exclusively as a research effort and consisted of seven 300-kip load repetitions.

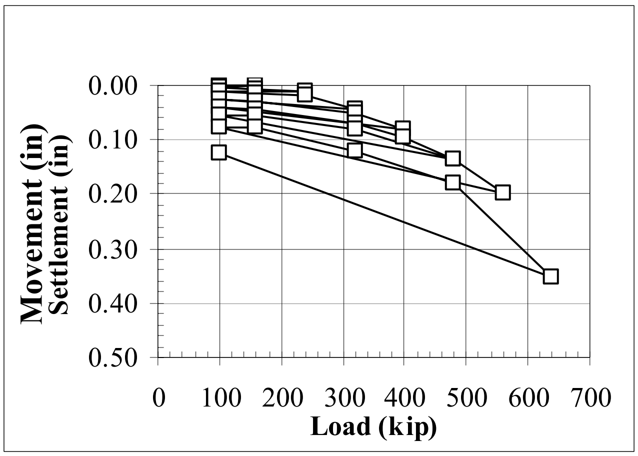

Figure 2. Load test results

5 AXIAL LOAD DISSIPATION

Strain data collected during the test were used to estimate the axial load at each gauge location. The elastic modulus values used were 29,000 ksi (20,407 kg/mm^2) for the steel and 3,500 ksi (2,465 Kg/mm^2) for the grout. Figure 3 shows the axial load values along the pile under the maximum load of each loading cycle in the first stage of the test. The axial load values between strain gauge locations have been interpolated linearly. It can be seen that, for applied loads of 240 kip (109 metric tons) or less, most of the load was shed by skin friction or adhesion along the first 10 feet of the pile. For loads greater than 240 kip, however, axial loads increased significantly along the rock socket of the micropile.

6 MOBILIZED BOND STRESSES ALONG MICROPILE

Three micropile segments were differentiated based on the data presented in Figure 3. Segment

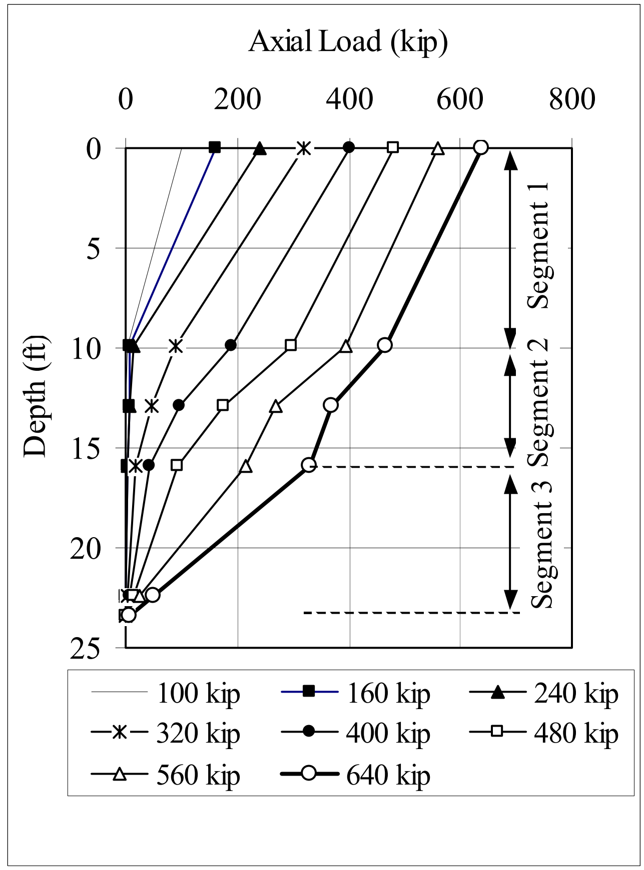

Figure 3. Dissipation of axial load along the pile

1 is contained within the upper 10 ft of residual soil. Segment 2 is contained within the upper 6 ft of weathered diabase. Segment 3 corresponds to the lower 7.3 ft (2.22 m) of diabase and includes the tip of the micropile.

The average mobilized bond stress along each segment was calculated as the load shed along the segment divided by the surface area of the segment. The strain gauge data were integrated along the micropile in order to estimate the total elastic compression of the pile, and the relative settlement at the midpoint of each the segments with respect to the pile tip. Some simplifying assumptions were used to obtain a rough estimate of the relative displacement between each of the segments and the surrounding ground, or grout-ground interface displacement.

The values of mobilized bond stress are plotted against the estimated average segment displacement in Figure 4. It is seen that the ultimate bond strength along Segment 1 was mobilized in the early stages of the test, and reached a peak value of approximately 10 ksf

(0.05 Kg/mm^2). After reaching the peak, the bond strength decreased to a value of approximately 7.5 ksf (0.04 Kg/mm^2).

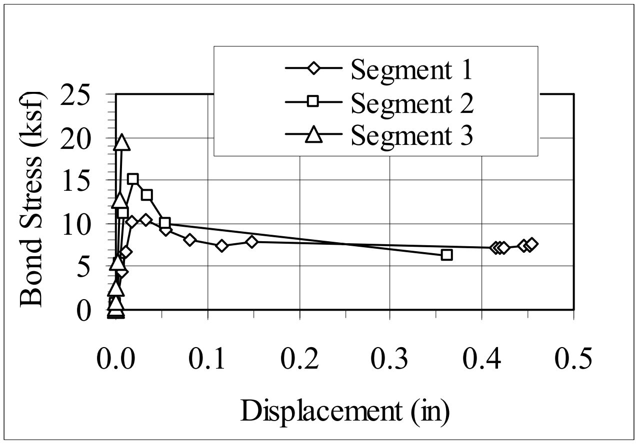

Figure 4. Mobilized bond stresses along micropile

In Segment 2, the peak bond strength was approximately 15 ksf (0.07 Kg/mm^2), and decreased to 10 ksf (0.05 Kg/mm^2). During the second stage of the test, bond strength values decreased below 10 ksf along this segment. In Segment 3, the mobilized bond stresses reached values of 20 ksf (0.1 Kg/mm^2). It does not appear that the ultimate bond strength was mobilized along this segment.

The post-peak reduction of mobilized bond stress, or post-peak softening, has been reported for interfaces between soil or rock and structural materials (Gómez et al. 2000; Kulhawy and Peterson 1979).

7 DEBONDING OF MICROPILE

Commonly, the term debonding refers to a condition where, once tensile or shear stresses at an interface exceed certain limiting value, the interface fails and its tensile or shear strength become insignificant. Debonding as such was not observed during this test. Although post-peak softening took place along Segments 1 and 2, the grout-ground interface retained significant shear strength, which contributed to the overall pile capacity.

8 DEBONDING AND THE ELASTIC RATIO

Two parameters are frequently used for evaluation of the performance of test micropiles. The elastic length, L_e, of a test micropile can be calculated for each loading cycle using the following equation:

$$L_e = \frac{\partial_e \cdot \Sigma EA}{\Delta P} \tag{1}$$

where δ_e is the elastic rebound measured during unloading at each cycle, ΣEA is the combined elastic modulus of the micropile in compression, and ΔP is the magnitude of the load decrement (maximum load in the cycle minus any alignment load).

The value of L_e is related to the length of the portion of the micropile subject to significant axial load; therefore, it is commonly used to estimate average bond stresses acting along a test micropile. It is also used to assess whether an end bearing condition is developing. Given the small cross sectional area of a micropile, development of end bearing may suggest the onset of micropile failure in some cases (Bruce et al. 1993). In addition, increasing values of L_e during repeated loading on micropiles has often been associated with debonding of the micropile-ground interface.

The Elastic Ratio (ER) (Bruce et al. 1993) is defined as the ratio between the elastic deflection of the pile and the applied load (expressed in thousandths of an inch per kip). It must be noted that the parameters L_e and ER are equivalent, and could be used interchangeably.

The calculated values of L_e and ER for the test micropile are represented in Figure 5. It is seen that L_e increased steadily with increasing test load during the first stage of the test. In the previous section, it was shown that debonding of the micropile was not detected during the test. Therefore, it can be concluded that the increase in elastic length is not necessarily a result of physical debonding of the micropile, but may be due to post-peak reduction of the bond strength. It may also correspond to erroneous interpretation of cyclic load tests, where locked-in stresses may develop along the micropile as discussed below.

The foregoing does not imply that debonding along a micropile cannot occur. It is possible that, if the grout-ground interface is strong enough, failure occurs at the interface between the steel casing and the grout. Both cases would likely take place under relatively large loads, and might induce a marked reduction of bond capacity after initial failure.

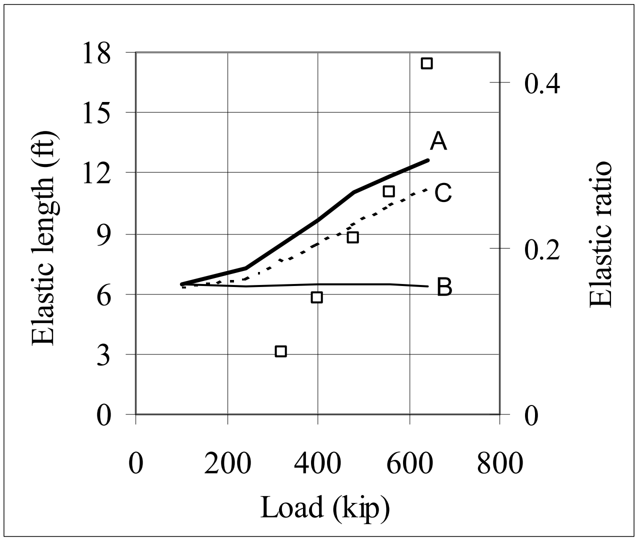

Figure 5. Elastic length and elastic ratio during test

9 NUMERICAL ANALYSES

The spreadsheet MICROPILE-C allows an approximate estimation of the response of a micropile to axial loading. It provides a simplified numerical solution for the problem of a bar loaded axially within a medium. The interface between the bar and the medium is assigned a constitutive model consisting of an initial stiffness, a peak interface shear strength, and a softened interface shear strength.

Three analyses of the test pile were performed. In analysis A, the grout-ground interfaces were modeled to match the behavior illustrated in Figure 4. In analysis B, the interfaces were assumed to have a very large strength and no softening behavior. Analysis C is somewhat an intermediate case, where the grout-ground interfaces are assumed to have the same peak strength as in A, with no softening behavior. For each interface, the corresponding value of initial shear stiffness observed in Figure 4 was assigned in all three analyses.

From the results of the analyses, the elastic length and elastic ratio of the micropile were calculated as described in the previous section, and have been represented together with the test data in Figure 5. It is seen that the elastic length (and elastic ratio) increases with increasing load in cases A and C. The more rapid increase in case A is due to the reduction in bond stresses with increasing load in the upper portion of the micropile, which then yields more load toward the lower portion. In case B, the elastic length only shows a slight increase as the bond stresses can increase indefinitely in the upper portion of the pile. Case B would not match actual conditions in most cases.

The difference between the elastic length value estimated from the analyses and that determined from the test data is explained by the locked-in elastic compression of the test pile during unloading, as discussed below.

10 ELASTIC LENGTH DURING REPEATED LOADING

Figure 6 shows the variation of elastic length and elastic ratio during the second stage of the test. The elastic length remains practically unchanged during the initial load repetitions. After the fourth cycle, the elastic length increases. This increase in elastic length can be attributed to softening of the grout-rock interface with repeated loading along segment 2. No actual debonding of the interface appeared to take place, as determined from the strain data.

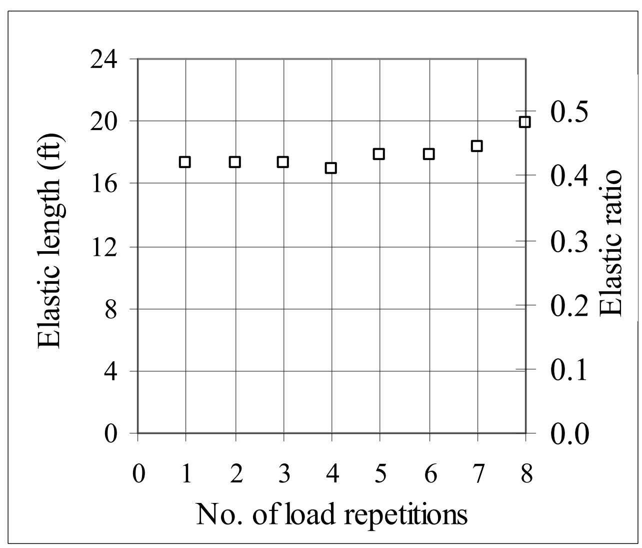

Figure 6. Elastic length and elastic ratio during repeated loading

The increase in elastic length, whether due to debonding or to softening of the grout-ground interface, may be important in micropile applications with strict deflection tolerances and where repeated loading is expected. Therefore, it would be advisable to include several cycles of repeated loading when performing load tests of micropiles for such applications.

11 LOCKED-IN DEFORMATION

Figure 7 provides a comparison between the residual elastic compression of the micropile integrated from strain gauge data, and the measured permanent deflection of the pile upon each unloading. Only data from the first stage of the test are included in the figure. It is seen that a significant portion, up to 50 percent, of the measured permanent deflection upon unloading corresponded to residual elastic compression of the pile, which was caused by locked-in bond stresses at the grout-ground interface.

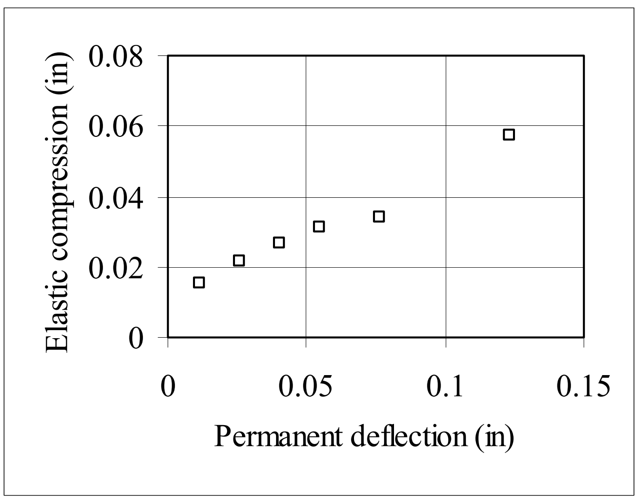

Figure 7. Residual elastic compression upon unloading

Residual elastic compression of the pile is not accounted for when calculating the elastic length or elastic ratio, as it cannot be discerned from the deflection data measured at the head of the pile. This is visualized in Figure 5, where the elastic length calculated from the test data was generally lower than that calculated from the analyses.

12 CONCLUSIONS

From the data and analyses presented in this paper, it may be concluded that, for the micropile under analysis, physical debonding of the grout-ground interface did not occur. However, post-peak reduction of bond strength was observed, which induced a progressive increase in the elastic length, and elastic ratio, of the micropile under increasing loads.

Determination of the elastic length of the micropile is useful for assessing micropile response. However, it may be subject to limitations in cases where significant residual elastic compression exists upon unloading due to locked-in bond stresses along the micropile, and may provide unconservative estimates of bond strength.

The test also highlighted the importance of instrumentation in test piles, as it may provide useful information for design and future research.

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