Technical Note

Uplift Performance of Anchor Plates Embedded in Cement-Stabilized Backfill

Nilo Cesar Consoli[1]; Cesar Alberto Ruver[2]; and Fernando Schnaid[3]

Abstract: A series of pullout tests is presented in this paper and is used to identify the kinematics of failure and the uplift response of circular anchor plates embedded in sand-cement stabilized layers at distinct normalized embedment depths (H/D), where H is the thickness of the treated layer and D is the diameter of the anchor plates. Experimental results show that the uplift capacity of anchor plates embedded in sand backfill layers increases considerably after mixing 3% cement with the backfill material. Distinct failure mechanisms observed for anchor plates embedded in both sand and cement-stabilized backfills are shown to be a function of H/D. The addition of cement to the sand backfill leads to an increase in uplift capacity of 9 times for an H/D ratio of 1.0 and of 13 times for an H/D ratio of 2.0. For sand backfill with $H/D = 1.0$, the failure surface had a truncated cone shape with a vertical inclination of 22°, whereas for H/D of 1.5 and 2.0, radial cracking was observed, and final failure surfaces had inclinations of 26 and 30°, respectively. Pullout of anchor plates in cement-stabilized backfills at H/D ratios ranging from 1.0 to 2.0 exhibit two distinct characteristics: (a) a linear elastic deformation response at small pullout displacements and (b) a later stage where radial fracturing of the stabilized backfill leads to hardening just prior to failure. Radial cracks starting at the top of the layer near the center of the anchor plates start to propagate only at about 90% of the final uplift failure load, irrespective of H/D. **DOI:** 10.1061/(ASCE)GT.1943-5606.0000785. *© 2013 American Society of Civil Engineers.*

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Introduction

Foundation systems for electricity transmission lattice tower structures are required to resist both uplift and compressive loading when subjected to permanent and transient load conditions. Permanent loads are caused by angle and anchor loading in the towers; angle loading takes place when there is a change in direction of the transmission line at a particular tower, whereas anchor loading is produced by different cable tensions and construction loads on the first and last tower in a row of towers. Transient loading produced by wind forces is usually the dominant design loading and may produce sudden mechanical failure of the line. As a result, according to the geometric characteristics of the line and the tower, the design load is given by the superposition of the compression and tension vertical loads combined with mutually perpendicular horizontal loads acting transversely and along the transmission line (Pacheco et al. 2008). The present paper focuses on permanent vertical loading as a first stage of a research effort conceived to optimize the design of shallow spread footings constructed using reinforced concrete or pressed plates. These foundations often require piles or ground anchors to provide the required uplift stiffness and capacity when loose or unstable soils exist near the surface.

A few field studies of spread footings bearing on cement-treated layers, all of them concentrating on compressive loadings (Stefanoff et al. 1983; Consoli et al. 2003, 2009a), have shown a noteworthy increase in the bearing capacity of foundations. Looking at the use of soil-improvement techniques, this paper examines the potential of an alternative solution for increasing uplift capacity of shallow foundations involving the stabilization of soil with cement and its subsequent use as backfill at distinct H/D.

The work on tensioned foundations was firstly addressed by Balla (1961). However, a number of studies followed around the world such as at University of Grenoble (Biarez and Barraud 1968), Nova Scotia Technical College (Meyerhof and Adams 1968), University of Sydney and University of Western Ontario (Rowe and Davis 1982a, b), University of Wales (Murray and Geddes 1987), and University of Western Australia (Lehane et al. 2008; Rattley et al. 2008), among many others. This paper attempts to extend these early contributions by introducing the results of a comprehensive testing program that is being carried out at the experimental site of the Federal University of Rio Grande do Sul (UFRGS) in southern Brazil. Three layers of different thicknesses of compacted sand and cement-stabilized sand were constructed. Shallow circular anchor plates were embedded in the sand layer, as well as in cement-stabilized backfill layers, and were tested. The main purposes of the research are to investigate the following:

- The effectiveness of using cementitious materials for increasing the uplift capacity of anchor plates embedded in cement-stabilized backfill layers of distinct thickness, and
- The kinematics of failure of circular anchor plates embedded in cement-stabilized backfill layers (when compared with an uncemented sand layer), considering distinct normalized embedment depths ($H/D = 1.0$, 1.5, and 2.0, where H is the thickness of the treated layer and D is the diameter of the anchor plate), when subjected to vertical pullout.

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Backfill Characteristics

The project comprises the pullout of circular anchor plates embedded in uncemented sand and cement-stabilized sand backfills. Before the compaction of the sand and cement-stabilized backfill layers, a 1.0-m-thick layer of the local soil was removed throughout the testing site. After removal, six improved soil areas, each 1.5×1.5 m in plan, were constructed, three in sand and three in sand-cement. The sand and sand-cement test areas consisted of 300-, 450-, and 600-mm-thick layers built using a vibratory plate to reach a dry unit weight of $15.8\ \mathrm{kN/m^3}$ (see Fig. 1). The sand-cement mixtures were allowed to cure for 7 days before testing, whereas the uncemented sand layers did not need any curing period.

Proper trench backfill and compaction are critical success factors for load tests. To allow comparison of the achieved field compaction with the laboratory reference values, field density, moisture content, and unconfined compression tests (UCTs) were carried out systematically. Field bulk density was control by ensuring compatibility between the sand volume and weight placed in the compaction pit, moisture content was measured in the laboratory from field samples, and UCT was carried out according to ASTM D2166 (ASTM 2006). Although the moisture content of a soil mass is not significantly altered by the compaction process, the degree of compaction achieved for a given compaction effort is dependent upon the moisture content of the soil being compacted. Overall, the backfill control indicated a homogenous mass and compliance with laboratory test reference data in both sand and cement-stabilized sand.

Sand

The sand used is classified as nonplastic, uniform fine sand (SP) according to the Unified Soil Classification System; the specific gravity of solids is 2.62, and the grain-size distribution is 100% fine sand (0.075 mm < diameter < 0.42 mm) with $D_{10} = 0.09$ mm, $D_{30} = 0.14$ mm, $D_{50} = 0.16$ mm, and $D_{60} = 0.19$ mm; the uniformity and curvature coefficients are 2.1 and 1.2, respectively; the minimum and maximum void ratios are 0.60 and 0.90, respectively. The stress-strain-volumetric response of sand specimens (molded to a moisture content of 10% and a dry unit weight of $15.8\ \mathrm{kN/m^3}$) in saturated drained triaxial tests at effective confining pressures ranging from 20 to 200 kPa is presented in Fig. 2(a). The peak friction angle (ϕ') for the sand specimens was 39.2° and peak cohesion intercept (c') about zero, showing a frictional response. The initial shear modulus (G_0) is a function of mean effective stress and is represented by an average value of 20 MPa.

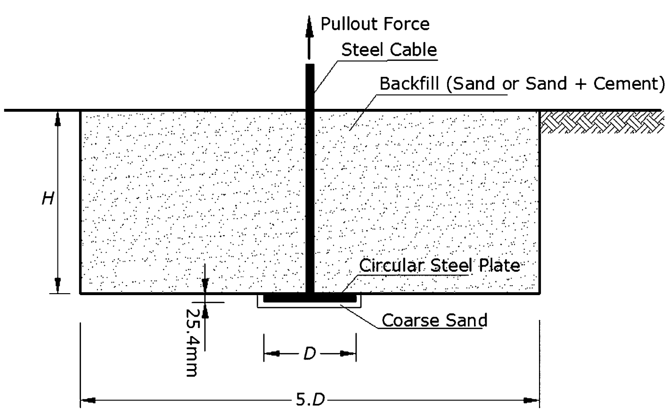

Fig. 1. Uplift test layout

Cement-Stabilized Sand

The cement-stabilized backfill was prepared in a rotating drum mixer, by mixing air-dried sand, Portland cement (3% by weight of dry sand), and water (10% moisture content).

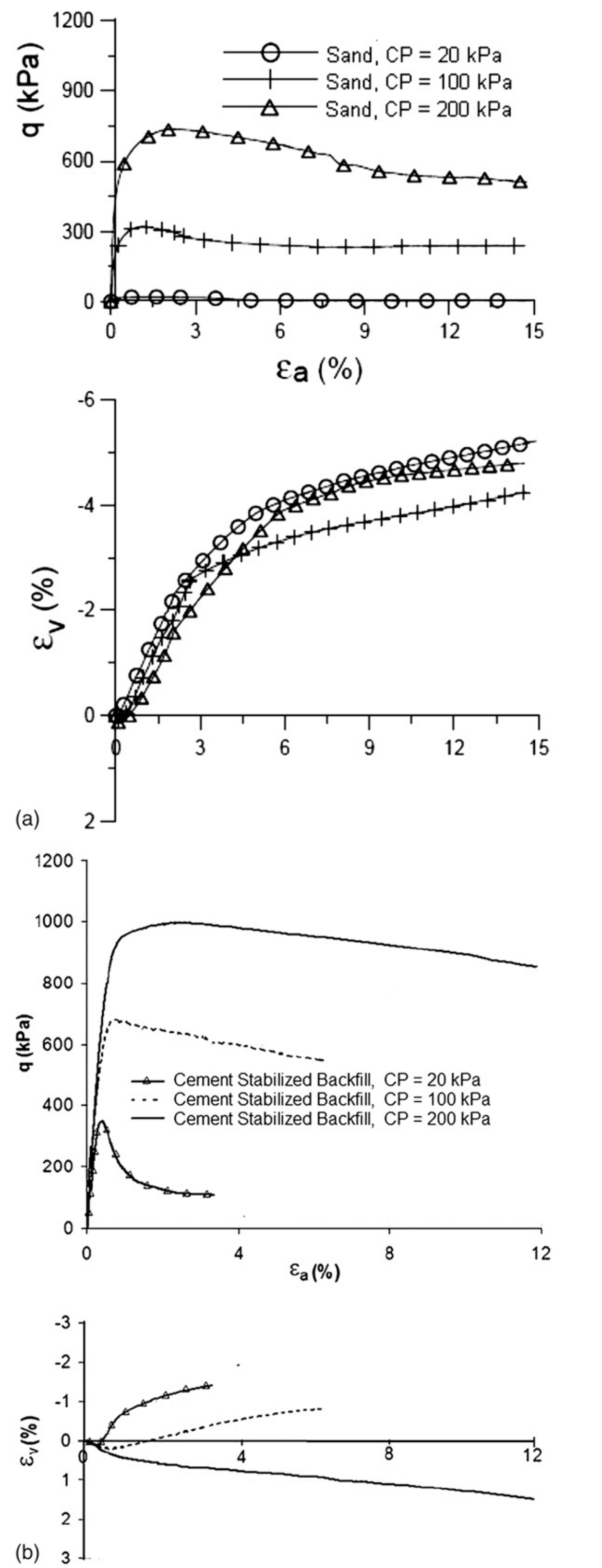

Fig. 2. Stress-strain volumetric response in drained triaxial tests for (a) sand specimens and (b) cement-stabilized backfill specimens

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Layers of this mixture were built over the residual soil in consecutive sublayers, each with 150-mm maximum thickness, using a vibratory plate to reach a dry unit weight of $15.8\ \mathrm{kN/m^3}$ at 10% moisture content. These layers were allowed to cure for 7 days before being pulled out with circular anchor plates of 0.3-m diameter. Conventional UCTs on specimens retrieved from this layer after 7 days of curing were carried out and compared with UCT results of specimens molded in the laboratory by Consoli et al. (2009b, 2010). The results for unconfined compressive strength (UCS) of about 320 kPa perfectly match field and laboratory UCT results, proving that cement-stabilized backfill field mixing was successful. The stress-strain-volumetric response on cement-stabilized backfill specimens in saturated drained triaxial tests at effective confining pressures ranging from 20 to 400 kPa is presented in Fig. 2(b), yielding a peak cohesion intercept (c') of 110 kPa and a peak friction angle (ϕ') of 28° for the cement-stabilized sand specimens. The cement-stabilized backfill mixture has less dependency on the normal stress, which is reflected in the peak friction angles (ϕ') of 28° for the cement-stabilized sand specimens and 39.2° for the sand specimens. The initial shear modulus (G_0) of the cement-stabilized backfill is about 200 MPa.

Field-Testing Program

The field-testing program was carried out at the experimental site described previously. Anchor plate pullout tests were conducted using a rigid circular steel plate 300 mm in diameter and 25.4-mm thick. The setup used for carrying out the anchor plate load tests was in accordance with ASTM D1194 (ASTM 1998). The load was applied through a system comprising a hydraulic jack, a reaction beam, a loading platform, and a calibrated load cell. Three dial gauges with resolution of 0.01 mm and 50 mm travel were used for settlement measurements. Measurements of displacements were made at the surface directly on the top of the sand/cement-stabilized sand at three points (near the central rod of the anchor plate), separated 120° from each other. The gauges were fixed to a reference beam and supported on external rods. The load was applied in equal increments of not more than one-tenth of the estimated ultimate uplift capacity. For each pullout load increment, measurement of settlement was made at the following fixed times: zero, 30 s, 1 min, 2 min, 4 min, 8 min, 15 min, 30 min, 60 min, and 120 min. In accordance with Brazilian standard ABNT NBR-12131 (Associação Brasileira de Normas Técnicas 1991) and ASTM D1194 (ASTM 1998), each increment was maintained for a minimum of 30 min until the following criterion was reached:

$$L_n - L_{n-1} \leq 0.05 \cdot (L_n - L_1) \tag{1}$$

where L_n = average dial gauge reading at a specified time interval t; L_{n-1} = average dial gauge reading immediately previous to L_n; and L_1 is the first reading of the stage of loading taken just after stage loading application.

Test Results and Analysis

Load-Displacement Response in the Anchor Plate Pullout Tests

Experimental results of 0.3-m steel circular anchor plates embedded in uncemented sand are summarized in Fig. 3, in a plot that relates the applied uplift load to displacements at the top of the layer for three different embedment depths corresponding to 0.30, 0.45, and 0.60 m. Tests loaded to failure showed that increasing H/D values produce an increase in uplift peak capacity of the anchor plates, with pullout loads of 2.4 kN for $H/D = 1.0$, 5.0 kN for $H/D = 1.5$, and 6.8 kN for $H/D = 2.0$. Similarly to tests on sand backfill, results of uplift load in cement-stabilized sand mixtures (3% by weight of dry sand) are presented in Fig. 4, for three different embedment depths corresponding to 0.30, 0.45, and 0.60 m. The test results have also shown an increase in the uplift peak capacity of anchor plates with increasing normalized embedment depths from 22.3 kN for $H/D = 1.0$, to 44.3 kN for $H/D = 1.5$, and to 87.3 kN for $H/D = 2.0$. An interesting aspect to be noticed in Fig. 4 is the loading cycle carried out on cement-stabilized backfill with $H/D = 1.0$. During the application of the first load-unloading cycle, which reached more than 90% of the failure load reached during the second loading, the load-displacement behavior showed a stiff and elastic response with no observed plastic displacement.

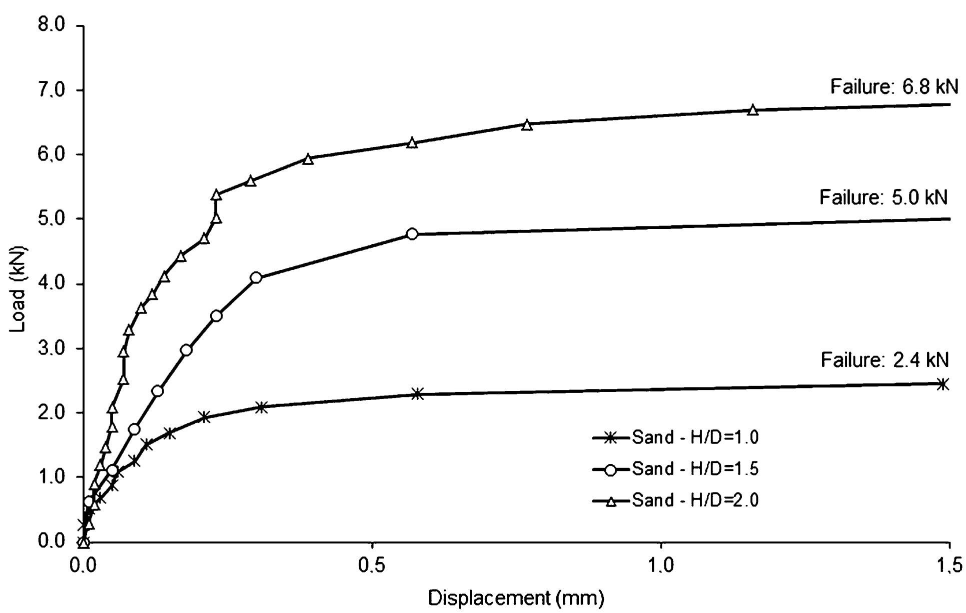

Fig. 3. Load-displacement curves of pullout tests on sand layers of distinct normalized embedment depths ($H/D = 1.0, 1.5,$ and 2.0)

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The variation of failure loads with H/D is shown in Fig. 5 in which it is possible to observe that the uplift peak capacity does not increase linearly with H/D. For the sand backfill, the curve has a concave shape, whereas for the cement-stabilized backfill, the curve shows a convex shape. For $H/D = 1.0$, the uplift capacity is increased by about 9 times as a result of the insertion of 3% cement; for $H/D = 2.0$, the increase in uplift capacity is 13 times greater than that of sand backfill at the same normalized embedment depth. Clearly, the increase of uplift capacity attributable to soil improvement with small amounts of cement has considerable application in engineering practice.

A similar study carried out in a centrifuge by Rattley et al. (2008) shows that the addition of 3% cement to the sand backfill (resulting in UCS of about 87 kPa) leads to an increase in uplift capacity of about 3 times for an H/D ratio of 1.5. In the current study, the same addition of cement (3%) to the sand backfill (resulting in UCS of about 320 kPa) and the same H/D ratio of 1.5 yield an increase in uplift capacity of 9 times. It is worth noticing that the uplift capacity measured in the field is 3.0 times the value measured in the centrifuge by Rattley et al. (2008) for the same cement content and H/D ratio. This increase is proportional to the variation in UCS, which in the present study is about 3.5 times that obtained in the centrifuge study.

Regarding displacement-to-diameter ratios (δ/D) at uplift limit loads, values calculated from Figs. 3 and 4 are 0.16 and 0.05%, respectively, for sand and cement-stabilized backfill layers for H/D

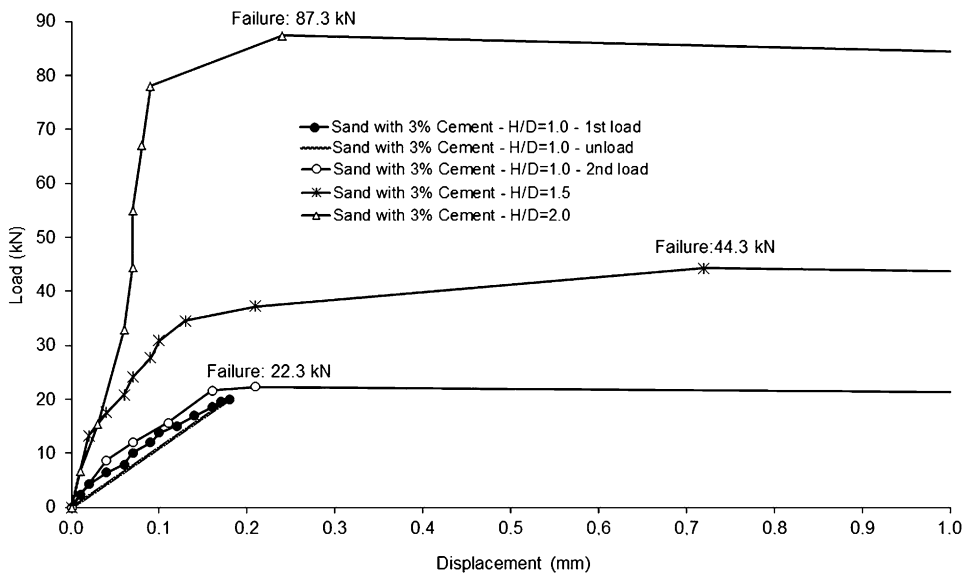

Fig. 4. Load-displacement curves of pullout tests on sand-cement layers of distinct normalized embedment depths ($H/D = 1.0, 1.5$, and 2.0)

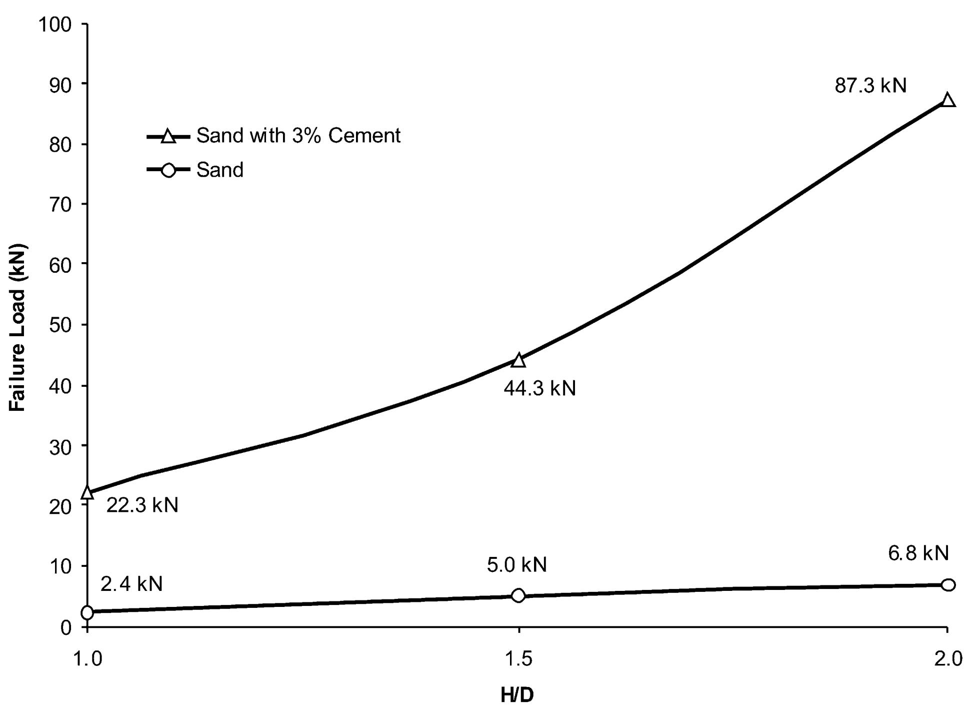

Fig. 5. Variation of uplift load with H/D for sand and sand-cement layers

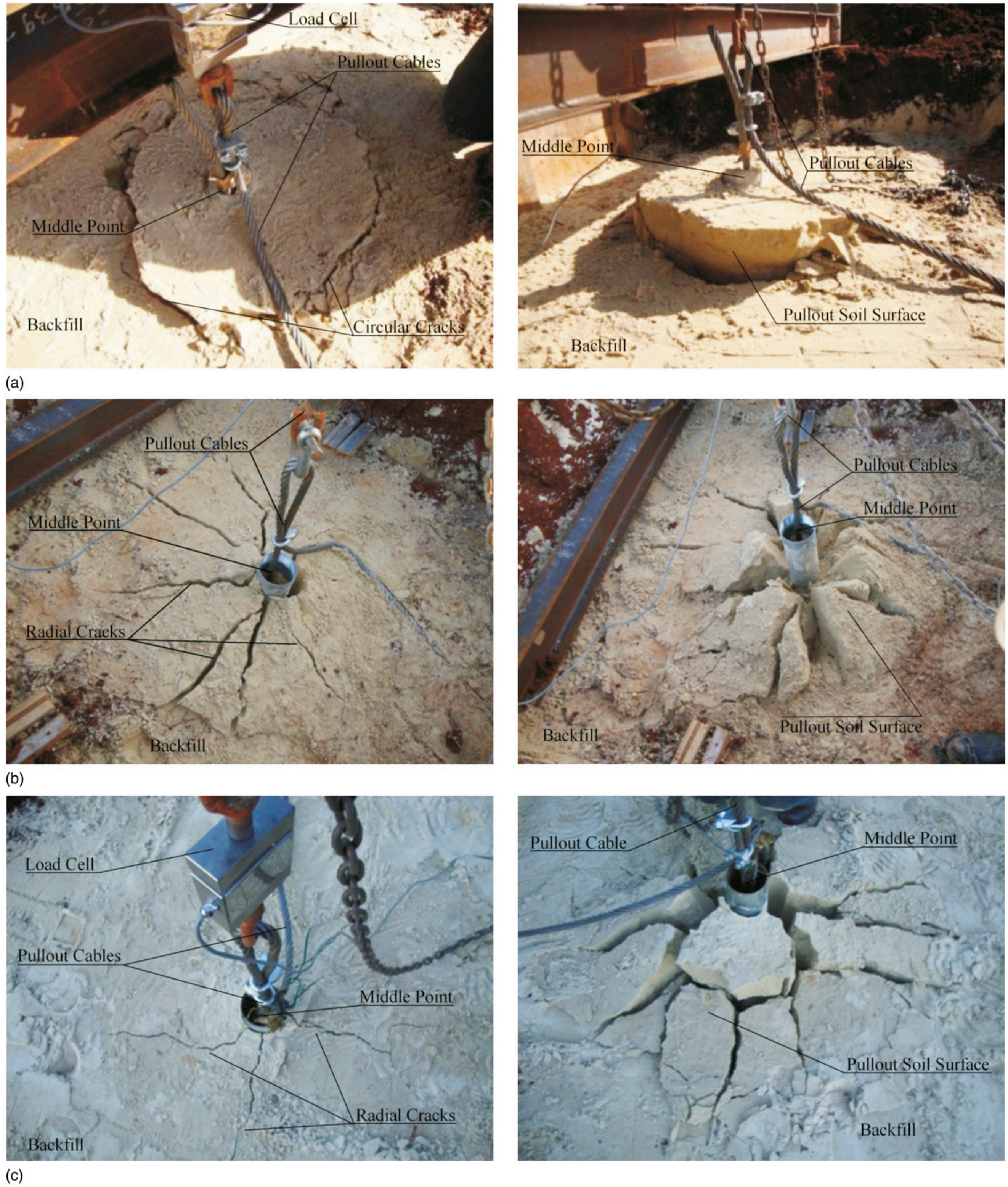

Fig. 6. Photos of the pullout failure mechanisms in sand layers considering anchor plates with distinct normalized embedment depth (a) $H/D = 1.0$, (b) $H/D = 1.5$, and (c) $H/D = 2.0$

values of up to 2.0. At working loads, the uplift displacement-to-diameter ratios would be about a third of the limit loads, reaching values as small as 0.05 and 0.015% for sand and cement-stabilized backfills. Berardi and Lancellotta (1991) and Consoli et al. (2009a) analyzed the behavior of shallow foundations submitted to compressive loading, respectively, on granular soils and cement-stabilized soils and found that displacement-to-diameter ratios at compressive working loads were generally on the order of 1%. A possible reason for foundations submitted to tensile loading presenting displacements that are smaller than those with the same compressive load is that shear strains under uplift loading are more pronounced than volumetric strains in contributing to displacements. This finding is quite

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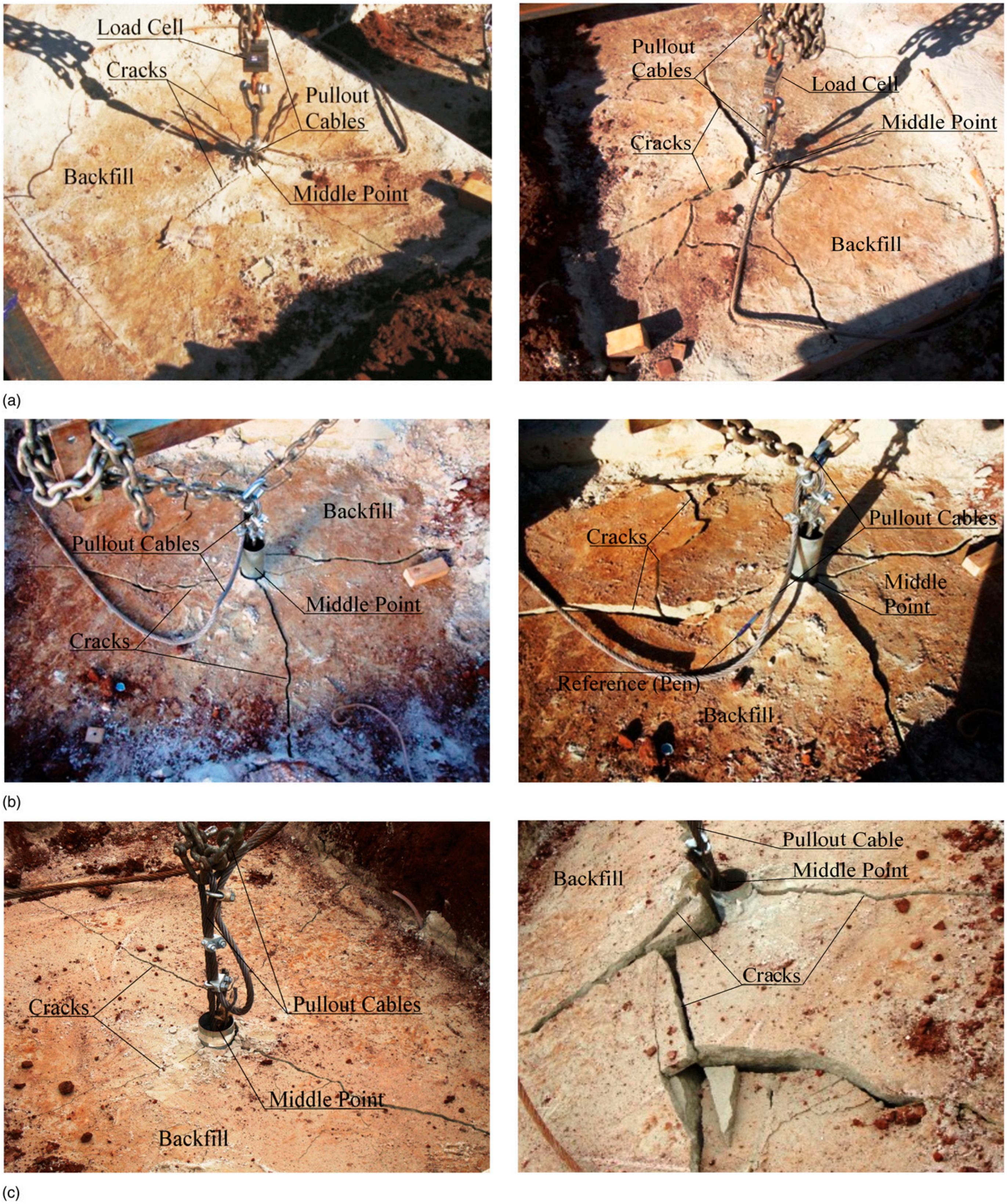

Fig. 7. Photos of the pullout failure mechanisms in sand-cement layers considering anchor plates with distinct normalized embedment depth (a) $H/D = 1.0$, (b) $H/D = 1.5$, and (c) $H/D = 2.0$

important in the design of anchor plates embedded in cement-stabilized backfills submitted to uplift loads.

Failure Mechanism

The pullout failure mechanism has been investigated by a detailed observation of displacements and crack propagation around the anchor plates, as well as by exhuming the top layer after the completion of tests. (That is, anchor plates were exhumed, and the failure patterns above and around the anchor plates were examined.) Vertical boreholes were excavated above the anchor plates after testing. The failure surfaces were shown to be approximately straight lines that started close to the outer edge of the embedded anchor plates and reached the surface with a constant slope of the failure surface. Fig. 6 shows examples of mechanisms developed in sand backfill layers considering anchor plates at three distinct normalized embedment depths: $H/D = 1.0$, 1.5, and 2.0. Distinct failure mechanisms are observed for different H/D values. For $H/D = 1.0$ [Fig. 6(a)], the failure surface had a truncated cone shape with an angle with the vertical of 21.8°. For normalized embedment depths of 1.5 [Fig. 6(b)] and 2.0 [Fig. 6(c)], radial cracking was observed, and final failure surfaces had angles with the vertical increasing to 26 and 30°, respectively, for H/D of 1.5 and 2.0.

Fig. 7 presents photos of pullout failure mechanisms in cement-stabilized backfill layers at three distinct H/D ratios: 1.0, 1.5, and 2.0. At the end of the pullout testing, cracks developed on the top of the treated layers. Cracks were radial, propagating on the top of the layer from the center of the anchor plates toward the edges, at an applied load of about 90% of the final uplift failure load. Radial cracking possibly occurs for both uncemented and cement-stabilized backfill when tensile strength is reached just before failure (i.e., before reaching ultimate shear strength).

Conclusions

The outcomes from this work can be summarized as follows:

- The uplift capacity increased drastically because of the insertion of cement in the backfill for all studied H/D. Considering circular anchor plates of 0.3-m diameter and H/D of 1.0, 1.5, and 2.0, the uplift peak capacity of the anchor plates subjected to pullout changed from 2.4, 5.0, and 6.8 kN to 22.3, 44.3, and 87.3 kN, respectively, when the sand backfill was substituted by cement-stabilized backfill.
- Distinct pullout failure mechanisms were seen in sand backfill layers with anchor plates at three distinct H/D, namely, 1.0, 1.5, and 2.0. For $H/D = 1.0$, the failure surface had a truncated cone shape with an angle from the vertical of about 21.8°. For H/D of 1.5 and 2.0, radial cracking was observed, and final failure surfaces had angles with the vertical increasing to 26 and 30°.
- During pullout testing in cement-stabilized backfill layers, propagation of cracks was observed on the top of the treated layers at the final loading stage of about 90% of the uplift failure load. Before the propagation of cracks, the load-displacement behavior showed a stiff and elastic response with no observed plastic displacement, which suggests that continuum mechanics can be applied to the solution of bearing-capacity problems.

Acknowledgments

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Notation

The following symbols are used in this paper:

c' = effective peak cohesive intercept;
D = anchor plate diameter;
G_0 = initial shear modulus;
H = thickness of backfill layer;
H/D = normalized embedment depth;
L_1 = first dial gauge reading of the stage of loading;
L_n = average dial gauge reading at specified time interval t;
L_{n-1} = immediately previous average dial gauge reading to L_n; and
ϕ' = effective peak friction angle.

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