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Pullout resistance of granular anchors in clay for undrained condition ☆

B.C. O'Kelly[a,*], R.B.J. Brinkgreve[b,c], V. Sivakumar[d]

[a]Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Dublin, Ireland
[b]Geo-Engineering Section, Delft University of Technology, CN Delft, The Netherlands
[c]Research and Projects, Plaxis bv, Computerlaan 14, 2628 XK Delft, The Netherlands
[d]Geotechnical Engineering SPACE, Queen's University Belfast, Belfast, UK
*Corresponding author. Tel.: +353 1896 2387; fax: +353 1677 3072.

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Abstract

Granular anchors (GAs) can resist pullout/uplift forces, compression forces and also provide ground improvement. Under pullout loading, a centrally located tendon transmits the applied surface load to the base of the granular column via a base plate attachment, which compresses the column causing significant dilation of the granular material to occur, thereby forming the anchor. This paper describes a program of field testing and numerical modelling of the pullout resistance of GA installations in overconsolidated clay for the undrained (short term) condition. Pertinent modes of failure are identified for different column length to diameter (L/D) ratios. The applied pullout load is resisted in shaft capacity for short GAs or in end-bulging of the granular column for long GAs. In other words, the failure mode is dependent on the column L/D ratio. A novel modification in which the conventional flat base-plate is replaced by a suction cup was shown to significantly improve the undrained ultimate pullout capacity of short GAs.

Keywords: Bulging capacity; Failure; Granular anchor; Uplift; Ultimate capacity

1. Introduction

Granular anchors are a relatively new and promising foundation solution, particularly suited for lightly loaded structures. In addition to the improvement provided to the surrounding ground, granular anchors can resist both pullout/uplift forces and compression forces. Hence they have been adopted, for instance, to prevent foundation uplift caused by flooding (Liu et al., 2006) or to resist foundation heave in expansive clays (Phanikumar et al., 2004, 2008; Sharma et al., 2004; Srirama Rao et al., 2007). Another recent development is the jet mixing anchor pile, a supporting technology particularly suited for foundation pit engineering in soft clay. The ultimate capacity and load–deformation relationship of such piles have been investigated by Xu et al. (2014) using uplift field tests and numerical analyses.

The focus of the present study is to investigate the ultimate capacity and load–deformation relationship of granular anchor (GA) foundations under uplift loading. The GA consists of three main components (Fig. 1): a horizontal base plate, a central vertical tendon (metallic rod or stretched cable) and densified granular material introduced into the borehole to form a granular column. Under an applied uplift force (P), the

E-mail addresses: bokelly@tcd.ie (B.C. O'Kelly), r.b.j.brinkgreve@tudelft.nl (R.B.J. Brinkgreve), v.sivakumar@qub.ac.uk (V. Sivakumar).
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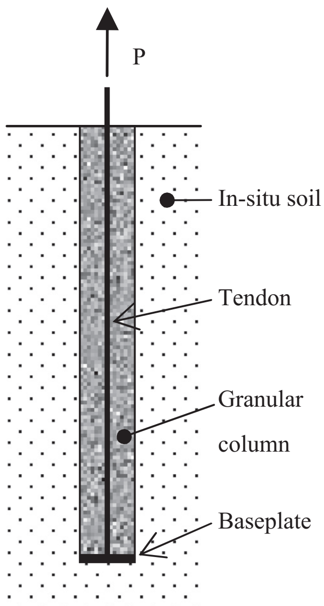

Fig. 1. Schematic of granular anchor.

tendon transmits the load to the column base via the base plate attachment. The resulting upward pressure over the column base compresses the laterally confined granular column against the sidewall of the soil bore, thereby mobilizing an anchor resistance.

Unlike a conventional concrete anchor cast in-situ, pullout loading can be applied to the GA immediately after its installation. Significant yielding occurs under pullout loading. For short GAs, this is also accompanied by significant ground heave. In contrast, conventional concrete anchors generally fail by sudden pullout on mobilizing the full shaft capacity, assuming the anchor itself remains structurally sound. The granular column also acts as an effective drainage system to prevent excessive buildup of porewater pressure from occurring (Sivakumar et al., 2013).

The success of the GA technique for real applications requires a method to reasonably predict the load–displacement behavior for pullout loading. Various methods of analyses that consider different failure modes, including the vertical slip surface model (friction cylinder method) and block type failures (e.g. inverted cone, circular arc, or in the case of deep anchors, truncated cone), exist for the determination of the ultimate pullout capacity of strip/plate anchors embedded in uniform deposits of sand/clay (Meyerhof and Adams, 1968; Ilamparuthi et al., 2002; Merifield et al., 2001; Merifield and Sloan, 2006; Khatri and Kumar, 2009, Rangari et al., 2013). Recently, Miyata and Bathurst (2012a, b) investigated the tensile reinforcement load/pullout capacity of steel strips used in reinforced soil walls in Japan. However, the failure modes for GAs are more complex compared with these scenarios; i.e. strip/plate anchors embedded in uniform deposits of sand/clay. This arises on account of the distinctly different response of the densified gravel material (used to construct the granular column) compared with that of the surrounding native material. For the GA, the applied pullout loading at the ground surface is transferred directly to the tendon base-plate assembly and resisted by the granular column. The dilatency of the granular material is a significant factor controlling the GA's pullout capacity. Recent experimental studies by O'Kelly et al. (2013) and Sivakumar et al. (2013), among others, indicate that the applied pullout load is resisted in shaft capacity for short GAs or in localized bulging near the column base for long GAs. In other words, the failure mode depends on the column length to diameter (L/D) ratio.

The motivations for the experimental and numerical studies presented in this paper were to: (a) investigate the operation of GAs, particularly the development of the pullout load–displacement response for the undrained (short term) condition; (b) confirm the postulated modes of failure in shaft capacity or in end bulging and their dependence on the column L/D ratio and ground conditions/properties; (c) develop appropriate methods of analyses for the determination of the ultimate pullout capacity. The research programme involved performing 8 instrumented GA field tests which were subsequently modeled using finite element software. A novel modification of the GA arrangement to improve its undrained ultimate pullout capacity was also modeled numerically.

2. Experimental programme

2.1. Ground conditions

Full-scale field trials were performed on 8 GAs installed in the upper Brown Dublin Boulder Clay (BrDBC) layer of the Dublin Boulder Clay (DBC) deposit; an intact lodgement till. This is the primary superficial deposit within the greater Dublin region, Ireland. The DBC deposit is heavily overconsolidated (it was deposited under ice sheets more than 1 km in thickness), with reported overconsolidation ratios of 15–30. The DBC material is significantly stiffer and stronger than other well-characterized tills (e.g. ~6–8 times stiffer than typical London Clay and ~5 times stiffer than typical Cowden till from the east coast of the UK), at least for the lower strain range (Long and Menkiti, 2007; O'Kelly, 2014). Further details on the geotechnical properties and behavior of the DBC deposit have been reported by Farrell et al. (1995) and Long and Menkiti (2007). The results of interface shear tests on a novel geogrid in DBC backfill material have also been reported by O'Kelly and Naughton (2008).

The BrDBC material is characterized as stiff to very stiff, slightly sandy slightly gravelly silt/clay of low plasticity, with typical liquid limit and plastic limit values of 29% and 16%, respectively (Long and Menkiti, 2007), and a high bulk unit weight of 22 kN/m^3 (Kovacevic et al., 2008). Borehole logs for the test site indicated that the near saturated BrDBC stratum at this location was ~1.8 m in depth, with a relatively high stone content (i.e. particle size > 20 mm) of typically 5–15% over this depth. A very clayey/silty gravel layer was encountered in some of the boreholes at a depth of ~0.8 m below ground surface level (bgl). The standing groundwater table at the site was located at between 1.8 and 2.0 m bgl.

Fig. 2 shows strength against depth data determined for the test area using a 20 t cone penetration test (CPT) rig and