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Full Length Article

Pullout of soil nail with circular discs: A three-dimensional finite element analysis

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ABSTRACT

An internal failure mode for a soil-nailed system consists of failure at nail heads, slope facing, nail strength, along grout–soil interface and pullout failure. A better understanding of pullout of soil nail thus becomes important to assess the stability of a soil-nailed system. In the present study, an investigation into the pullout behaviour of soil nail with circular discs along the shaft has been carried out by a three-dimensional finite element analysis using Abaqus/Explicit routine. A total of 67 simulations have been performed to accurately predict the pullout behaviour of soil nail. The soil nail under study has circular discs along its shaft varying in numbers from 1 to 4. The pullout of this soil nail in a pullout test box has been simulated with a constant overburden pressure of 20 kPa acting on the nail. The pullout load–displacement characteristics, stresses around soil nail and failure mechanism during pullout are studied. Variations of dimensionless factors such as normalised pullout load factor and bearing capacity factor have been obtained with different combinations of parameters in terms of relative disc spacing ratio, anchorage length ratio, embedment ratio, diameter ratio and displacement ratio. From the results of analyses, it is found that nail with more circular discs requires higher pullout load. There are critical relative disc spacing ratio and diameter ratio which significantly affect the pullout behaviour of nail.

1. Introduction

The overall shear strength of an existing slope or a future slope/cut can be increased by installing closely spaced inclusions termed as 'soil nails'. These soil nails intersect the failure surface of slope and provide reinforcement to the soil-nailed system. Since the soil is weak in tension, tensile strength of these nails is mobilised during slope failure. The internal stability of a soil-nailed system can be assessed by a simple two-zone model (Schlosser, 1982). The potential failure surface divides soil mass into two zones, i.e. active and passive. The soil nail acts as a tie which fastens the active to the passive zone. The front active zone has a tendency to detach itself from the remaining soil mass and cause pullout of soil nails. Thus, a soil nail is subjected to tensile forces during slope failure. Stresses are also mobilised during shearing at the intersection of slip surface with soil nails (Juran, 1985; Bridle and Davies, 1997). However, Geoguide 7 (GEO, 2008) put emphasis on external and internal failure modes of a soil-nailed system. The internal failure modes are related to failure surface within the soil-nailed ground. Along with failure at nail heads, slope facing, nail strength, and along grout–soil interface, pullout failure is also primarily an internal failure mode. When the nail length in the passive zone is insufficient, it renders a poor pullout resistance per unit length of soil nail. This leads to an occurrence of failure at the grout–soil interface.

Many researchers have carried out experimental as well as analytical studies to comprehend the pullout behaviour of soil nails (Heymann et al., 1992; Milligan and Tei, 1998; Luo et al., 2000; Pradhan et al., 2006; Yin and Su, 2006). Past studies also reflect on the fact that pullout of soil nails depends on various factors such as installation method, overburden stress, grouting pressure, roughness of nail surface, soil dilation, degree of saturation and soil-nail bending (Zhou, 2008). From a large-scale field study, Lum (2007) observed that pullout of soil nails causes cracking in the grout column formed during nail installation. This cracking reduces the composite stiffness but increases the axial strain. This increase in axial strain leads to higher pullout capacity of nails. The overburden pressure is found to increase the normal stress around the nail shaft. The increase in normal stress is found to increase the apparent coefficient of friction between nail and soil interface that

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causes an increase in nail pullout resistance. However, Luo et al. (2000) developed an analytical model to theoretically predict that the actual normal stress acting around a soil nail during pullout is higher than the overburden pressure due to soil dilation. As a result, a higher coefficient of friction than the true soil internal friction is mobilised during soil-nail pullout. To understand the effect of surface roughness on pullout capacity of soil nail, Hong et al. (2003) conducted model tests on the pullout of single and double nails in sand. A large number of variations in parameters regarding surface roughness, nail length to diameter ratio, overburden pressure and group efficiency were also observed. It was concluded that the apparent coefficient of friction at soil-nail interface varies with change in the surface roughness of nail.

Numerical modelling of soil nail pullout has also captured the interest of past researchers (Kao, 2004; Akiş, 2009; Zhou et al., 2009) to further enhance or validate pullout testing. The effect of overburden and soil dilation on pullout capacity of soil nail is modelled using a three-dimensional (3D) finite element analysis by Su et al. (2010) with a conclusion that pullout resistance of soil nail is dependent on constrained dilatancy of soil-nail interface to surrounding soil rather than overburden stress. The accuracy of simulated soil nail pullout by finite element modelling was also validated by Zhou et al. (2011). With the advancement in soil nailing technique, researchers like Tokhi et al. (2016) developed a screw-type soil nail to overcome the installation complexities of soil disturbance and produced spoils identified with conventional grout soil nails. It was observed from experimental and numerical analyses of screw nail that it holds the advantage of easy installation by providing torque with better pullout resistance as compared to conventional soil nails.

The soil nails mounted with parallel circular discs can be driven into ground by pushing and rotation technique. To initiate the horizontal penetration of nail into ground, this type of nail needs to be pushed into ground which splits the soil and displaces it to the sides by a distance equal to the radius of the shaft. This initial soil displacement allows the circular discs to be positioned into soil with small penetration. As the nail is pushed further accompanied by torque at its head, the soil is cut and displaced to the sides. The volume of soil displaced is equal to the volume of circular discs which is similar to a helical plate with small pitch (Perko, 2000). The average distance required to displace the soil for circular disc insertion is approximately equal to half the thickness of the disc (Perko, 2000). Since the thickness of discs in the present study is small, it can easily cut through loose soil and the minimal soil displacements can also be expected. Consequently, soil-nail contact can be reestablished in relatively less time. As the first disc cuts and displaces the soil, it paves way for the following discs to be located at desired locations. Moreover, these soil nails with circular discs can also be used by burying them in advance during reinstating a failed slope or a loose fill slope.

HKIE (2003) reported that to reinstate a failed loose fill slope, the top 3 m of the slope should be excavated and recompacted so as to increase its stability. In such cases, soil nails with circular discs can be placed at desired levels during reconstruction of such slopes after excavation, which will not only reduce compaction efforts but also increase the stability of loose fill slope with much better efficiency than compaction. Some other real application examples of these soil nails can be in cases of newly built embankments, where these nails can be installed easily and effectively owing to weak soil conditions as staged construction of embankment progresses.

Moreover, some researchers have analytically studied helical micropiles (Papadopoulou et al., 2014), multi-plate helical anchors (Merifield, 2011) and helical soil nails (Rawat and Gupta, 2017) by considering helix as circular or conical shape, but have mainly adopted axisymmetric condition, considering that uniform stress–strains are developed during soil nail pullout behaviour. With this constraint of available literature on soil nail with circular discs in 3D finite element analyses condition, the introduction focused on such soil nails which can be approximated with the nail in the present study.

Based on the literature review, the present work focuses on understanding the pullout behaviour of a soil nail with circular discs along the nail shaft. The 3D finite element analysis of this soil nail is carried out by numerical modelling in Abaqus/Explicit v6.13. Variations in peak pullout capacity (P) with soil nail displacement (u), number of circular discs along the nail shaft ($N = 0, 1, 2, 3$ and 4) and diameter of circular discs (D_c) have been investigated. The optimisation of pullout response is done by considering relative disc spacing ratio (s/D_c = 1, 1.5, 2, 2.5, 3, 3.5 and 4). Variations in relative diameter ratio (D_c/d_s = 1, 2, 3 and 4), anchorage length ratio (L/D_c), embedment ratio (H/D) and displacement ratio (u/L) are also incorporated to observe the effect on soil nail pullout capacity. The normalised pullout capacity is determined by using a dimensionless factor (P/P_0) and circular disc contribution to soil nail pullout is studied by a bearing capacity factor (N_q). The results obtained from finite element analysis are validated and found in good agreement with testing and numerical results obtained from literature.

2. Problem definition

A soil nail may be positioned at different angles with horizontal inside the soil mass. In the present analysis, soil nail with circular disc is oriented at 0° with horizontal for all cases under study. The soil nail consists of a circular shaft having diameter (d_s) of 15 mm. The number of circular discs along the shaft varies from 1 to 4, i.e. $N = 1, 2, 3$ and 4. The circular discs have a diameter (D_c) which is considered on the basis of a relative diameter ratio (D_c/d_s). The D_c/d_s ratios used are 1, 2, 3 and 4, resulting in D_c variation of d_s, $2d_s$, $3d_s$ and $4d_s$. The circular discs are evenly spaced along the nail shaft at a specified spacing (s). Different spacings of circular discs are adopted based on a relative spacing ratio (s/D_c) taken as 1, 1.5, 2, 2.5, 3, 3.5 and 4. The variation of s/D_c has been studied for $N = 2, 3$ and 4. With the change in number of circular discs along soil nail shaft, variation in soil nail shaft length beyond the first disc to nail head (L) is used to define anchorage length ratio as L/D_c. The depth of embedment of soil nail from the top surface of pullout box (H) is 500 mm for all parametric variations. An overburden pressure of 20 kPa adopted from Tokhi et al. (2016) is considered to be acting on the surface of pullout box. The general layout of the problem definition to be analysed is given in Fig. 1.

A conventional soil nail consists of shaft embedded in grout column so that during nail pullout, the apparent friction at grout–soil interface is mobilised. It can be visualised that in conventional soil nail, shaft friction contributes significantly to resisting the pullout force. The shear stresses are generated at soil-nail interface around the perimeter of soil nail shaft throughout its anchorage length. These shear stresses are transferred as tensile forces to soil nail. Hence it can be inferred that grout column diameter and length of soil nail behind the potential slip surface govern the pullout of conventional soil nails. Thus, pullout capacity (P) of soil nail as given in FHWA (2003) can be calculated by

$$P = \pi q D_{\mathrm{DH}} L \tag{1}$$

where q is the mobilised shear stress acting along the perimeter of soil-nail interface, and D_{DH} is the diameter of drill hole for grouting.

The shear stress acting along the perimeter is a function of normal stress around the soil nail and the interface friction. Since soil is a weaker material in comparison to nail embedded in grout column, it can be said that during pullout, soil will tend to fail before the grout column. This makes the soil–soil interface friction more critical than soil-grout interface friction. Hence the mobilised interface friction is treated as equal to tanϕ, where ϕ is the angle of internal friction of soil. Thus, Eq. (1) can also take a form of