Study on Soil-Nail Pullout Interaction Using a Numerical Analysis

D.W.Jayasekara[1] and N.H.Priyankara[1]
[1]Department of Civil and Environmental Engineering
Faculty of Engineering
University of Ruhuna
Hapugala, Galle
SRI LANKA
E-mail: jayasekaradw@gmail.com

Abstract: *Soil-nailing is one of the most efficient slope stabilizing techniques used in the world today. But due to lack of proven and accepted design methods, the measured pullout force in the field is much higher than the designed pullout force. Hence, numerical analyses were conducted to examine the influence of matric suction, dilation and nail inclination on soil-nail pullout interaction to obtain an economical and conservative design approach. PLAXIS 2D software was used for numerical analysis. The results suggest that the higher dilation angle and matric suction can stabilize the soil-nailed wall by providing higher Factor of Safety (FOS) and lesser facing displacement. The numerical analyses also demonstrate that 15° nail inclination can be recommended for soil-nailing due to increase of FOS.*

Keywords: *pullout force, overdesign, PLAXIS 2D, matric suction, dilation, nail inclination.*

1. INTRODUCTION

Soil-nailing is a construction technique that can be used as a remedial measure to make the slopes, especially cut slopes, more stable and improve safety. It was found that it is the most appropriate method to stabilize slopes in congested areas with minimum working area, low construction period and low cost (Watkins and Powell 1992). The soil-nail is a typical passive inclusion, which builds up the bonding effect with surrounding soil mass to resist the external ground movement. Currently, the most commonly used soil-nail is the cement grouted soil-nail, which is usually the unstressed steel bar grouted in a pre-drill hole of soil mass with cement slurry. The bonding strength of cement grout-soil interface offers the required resistance to maintain the stability of whole structure (Hong 2011).

Many failures have been reported recently in Sri Lanka due to instability of slopes and retaining structures. The cut slope at chainage 42+640 (near Welipenna interchange) and cut slope near 114km post in Kokmaduwa in Southern expressway in Sri Lanka were failed causing huge financial loss to Road Development Authority due to closure of expressway many times. The soil-nailing technique has been successfully applied to stabilize those slopes. As soil-nailing technique has been commonly applied to stabilize cut slopes in Sri Lanka, it is very important to study more about soil-nailing technique in Sri Lankan context.

The behaviour of soil-nailing system depends on the complex interaction between the grouted nail and the soil. The FOS of the soil-nailing system depends on the pullout shear stress mobilized at the grouted nail-soil interface. Numerous assumptions and simplifications are made to produce a quantitative design in which nail properties and spacing are defined. Based on the experiences of design engineers, it is believed that pullout failure is more critical than tensile failure of steel nail (Pradhan et al. 2006; Milligan and Tei 1998). Generally, FOS of at least 1.5 against pullout resistance and FOS of at least 2.0 against tensile failure are used in the soil-nail analysis. Even with these FOS values, based on the field evidences, it was noticed that actual pullout resistance in the field is much higher than the theoretical design values. Even though, nail has not been completely pullout during the field test, pullout resistance in the field is much higher than that of design values. This is a clear indication that the current practice of soil-nailing is an overdesign which costs to the client. Therefore, the objective of this research is to develop an economical and conservative design approach for the soil-nailing system, by investigating the effect of dilation, matric suction and nail inclination on pullout resistance using PLAXIS 2D software.

2. SOIL-NAIL COMPOSITE GROUND

Number of researches on soil-nailing has been conducted in order to investigate the interaction between soil and soil-nail. As it is a very complex interaction, it is really difficult to conclude exactly what are the parameters that affect for the interaction between soil and soil-nail. According to literature review taken from past studies, it is clear that no any research has been conducted in order to verify whether there is a combination among matric suction, nail inclination and dilation effect on pullout resistance by using a numerical analysis.

In order to simulate grouted soil-nail using plate element in PLAXIS 2D software, Equations 1-6 were used.

$$E_{eq} = E_n\left(\frac{A_n}{A}\right) + E_g\left(\frac{A_g}{A}\right) \tag{1}$$

Where E_{eq} is equivalent modulus of elasticity, E_n is modulus of elasticity of nail, $E_g$is modulus of elasticity of grout, A is total cross sectional area of grouted nail (Equation 2), A_n is cross sectional area of soil-nail (Equation 3) and $A_g$is cross sectional area of grout cover.

$$A = 0.25\pi D_{DH}^2 \tag{2}$$

$$A_n = 0.25\pi d^2 \tag{3}$$

Where D_{DH} is diameter of drill hole and d is diameter of soil-nail.

$$A_g = A - A_n \tag{4}$$

Axial and bending stiffness can be determined using Equations 5 and 6.

$$Axial\ stiffness\ EA\left[\frac{kN}{m}\right] = \frac{E_{eq}}{S_h}\left(\frac{\pi D_{DH}^2}{4}\right) \tag{5}$$

$$Bending\ stiffness\ EI\left[\frac{kNm^2}{m}\right] = \frac{E_{eq}}{S_h}\left(\frac{\pi D_{DH}^4}{64}\right) \tag{6}$$

Where S_h is horizontal spacing of soil-nail (Babu and Singh 2009).

3. METHODOLOGY

A slope stabilized using soil-nailing was drawn in PLAXIS 2D software and boundary conditions were applied. Standard fixities option was used, so that a full fixity at base of the geometry and roller conditions at the vertical sides was generated. Plate was used to model the soil-nail and facing and interface was introduced between soil and nail. An overburden pressure of 15 kPa was applied at the top of the slope. Excavations were done as staged construction mode. Figure 1 illustrates the PLAXIS 2D model used for the analysis.

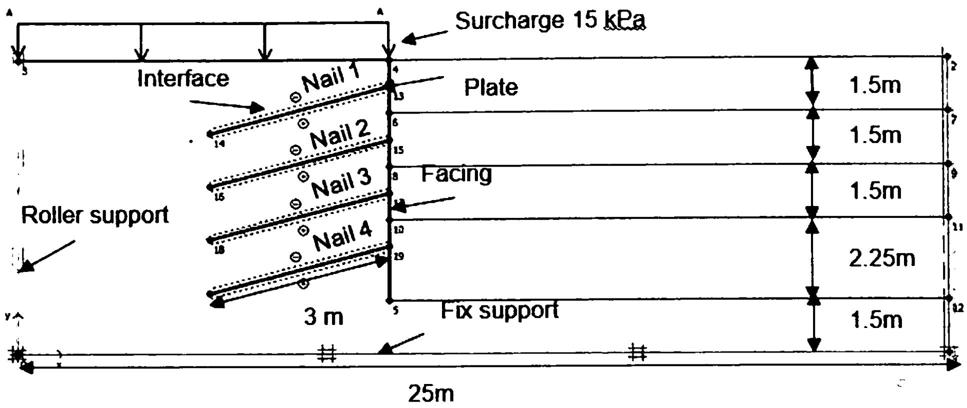

Figure 1 PLAXIS 2D model of the slope

Material properties assigned for soil and soil-nail are presented in Table 1 and Table 2 respectively. As shown in tables, some values were obtained from the laboratory test results where as some typical values were taken from literature. Horizontal spacing between nails was taken as 1.5m.

Table 1 Input parameters of soil in the PLAXIS model

Parameter	Value	Comment
Material model	Mohr - Coulomb	Failure Criteria
Drainage Type	Undrained	Construction stage is considered
Saturated unit weight (γ_{sat})	17.68 kN/m^3	From Proctor Compaction Test
Bulk unit weight (γ)	15.4 kN/m^3	From Proctor Compaction Test
Young's modulus (E)	20 MPa	Isaka and Madushanka (2016)
Friction angle (ϕ)	33^0	From Direct shear test
Dilation angle (ψ)	4^0	From Direct shear test
Cohesion (c')	20 kPa	From Direct shear test
Soil type	MH	From sieve analysis
Poisson's ratio	0.3	Wang and Richwien (2002)
R_{inter}	0.67	To obtain the interface shear strength parameters, R_{inter} was defined as 0.67 theoretically

After assigning materials, a mesh was generated and initial condition was defined in the model (ground water condition). The calculations were performed as staged construction. The phrases used for the model are summarized in Figure 2. In order to find the effect of one parameter on slope stability, all the parameters defined in the model were kept constant and only the relevant parameter was varied. For each and every stage of construction, FOS was found using c-phi reduction calculation option. Resulted FOS variation and displacement of facing variation were analyzed.

Table 2 Input parameters of soil in the PLAXIS model

Parameter	Value	Comment
Soil-nail		
Axial stiffness (EA)	1.734 ×10^5 kN/m	From Equation 5
Bending stiffness (EI)	108.4 kNm^2/m	From Equation 6
Nail – Material Type	Elastic	Elastic behaviour is considered
Facing		
Axial stiffness (EA)	6.3×10^6 kN/m	Barar and Liu 2010
Bending stiffness (EI)	4.882 ×10^4 kNm^2/m	Barar and Liu 2010
Weight (w)	0.67 kN/m/m	Barar and Liu 2010
Void ratio(v)	0.2	Barar and Liu 2010

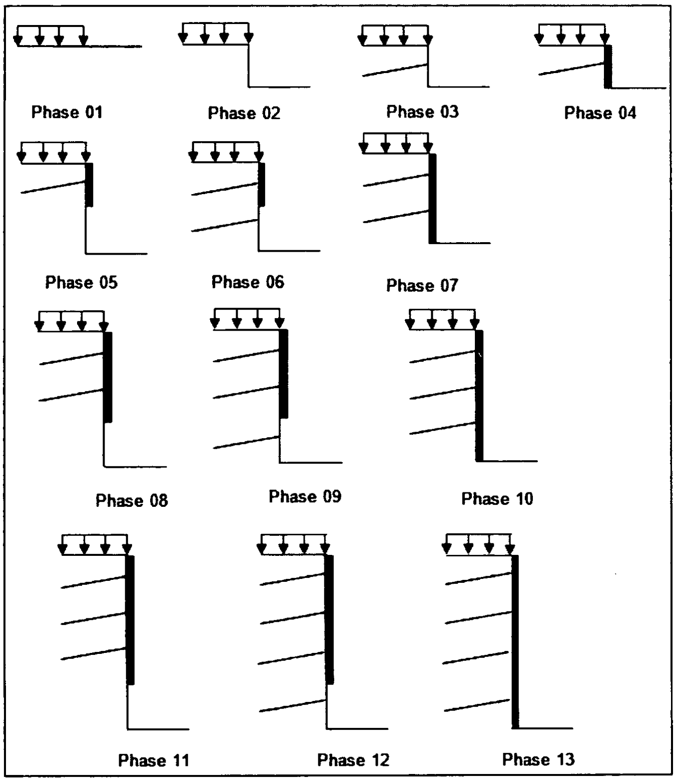

Figure 2 Excavation phases for the model

4. RESULTS AND DISCUSSION

4.1. Effect of Dilation on Pullout Resistance

Effect of dilatancy on slope stability was analyzed by varying dilation angle in the range of 0°-16° (Figure 3). It is clear that FOS increases with dilation angle increment. In addition, the total displacement of the facing decreases with dilation angle increment (Figure 4). The total displacement is highest at the top of the nailed wall.

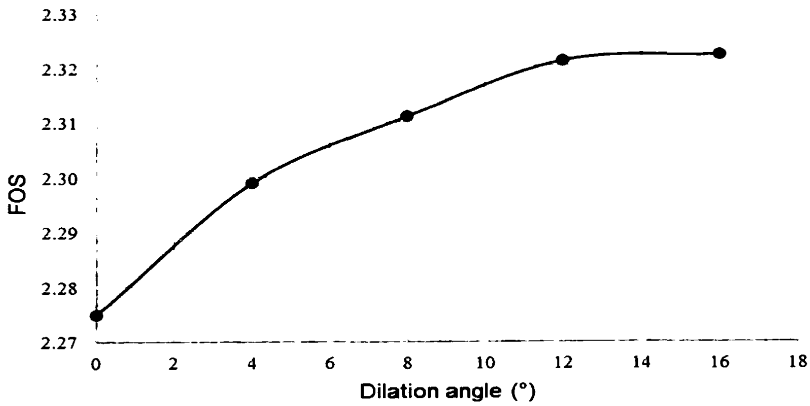

Figure 3 Variation of factor of safety with dilation angle

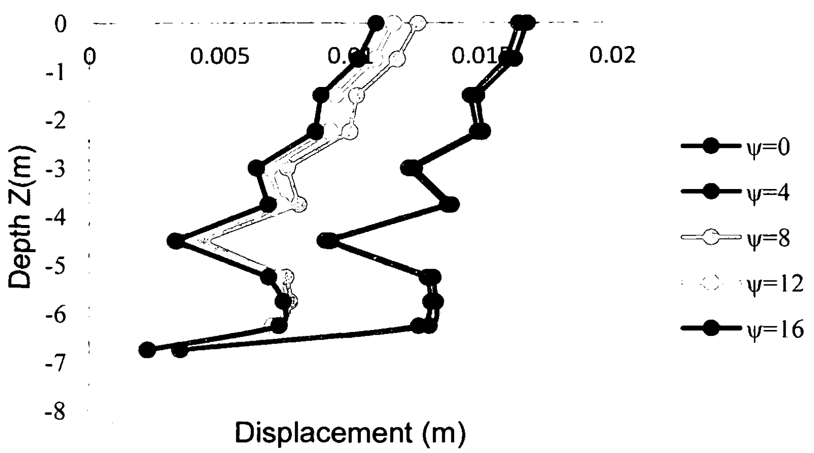

Figure 4 Variation of displacement of facing with depth

4.2. Effect of Nail Inclination on Pullout Resistance

Reinforcement orientation can either increase or decrease the shear strength of soil. When tensile forces are developed in soil-nail, shear strength of reinforced soil increases. When compressive forces are developed in soil-nail, shear strength of reinforced soil decreases. The nail inclination was varied from 0°-55°. Figure 5 shows the soil-nail orientation.

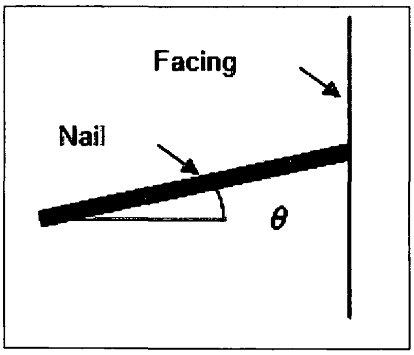

Figure 5 Soil-nail orientation

FOS increases with nail inclination within 0°-15° range while FOS decreases substantially as nail inclination increases beyond 15°, reflecting that the reinforcing action of the nails reduces rapidly with increasing nail inclinations (Figure 6). The reason would be the behaviour of nail alters from tension to compression when nail inclination is beyond 15°. So it is clear that the soil-nails with large inclinations do not provide proper stabilizing effect.

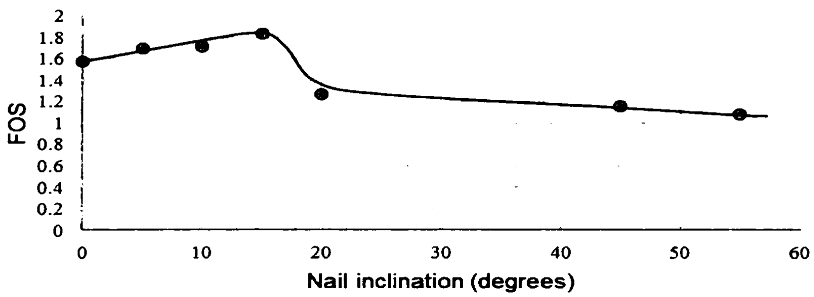

Figure 6 Variation of FOS with nail inclination

Figure 7 compares the distribution of axial force between nail inclinations of 0° and 75°. For θ=0°, tensile forces are mobilized in all the soil-nails while for θ=75°, compression forces are induced in lower row (nail 4) of the nails whereas tension forces are developed in upper three rows (nail 1, 2 and 3). Here, the maximum axial force in a soil-nail is taken to be positive if in tension and negative if in compression.

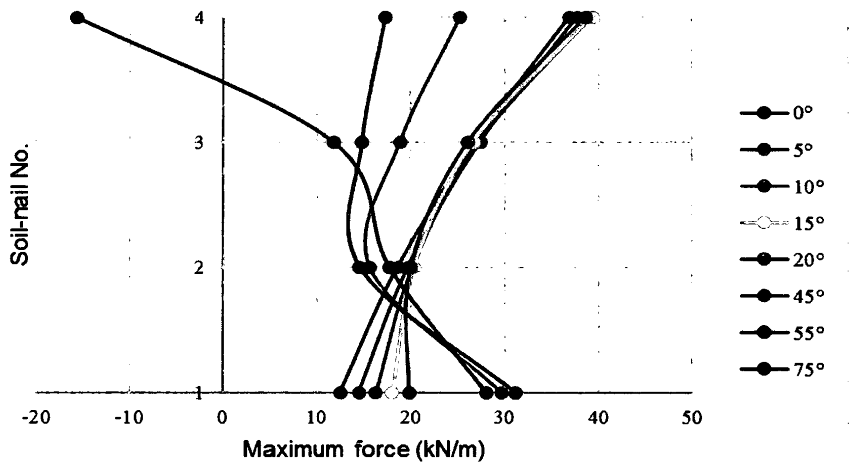

Figure 7 Variation of maximum axial force with depth

Figure 8 shows the variation of total displacement of facing with depth. It is clear that the facing displacement increases with the increase of nail inclination.

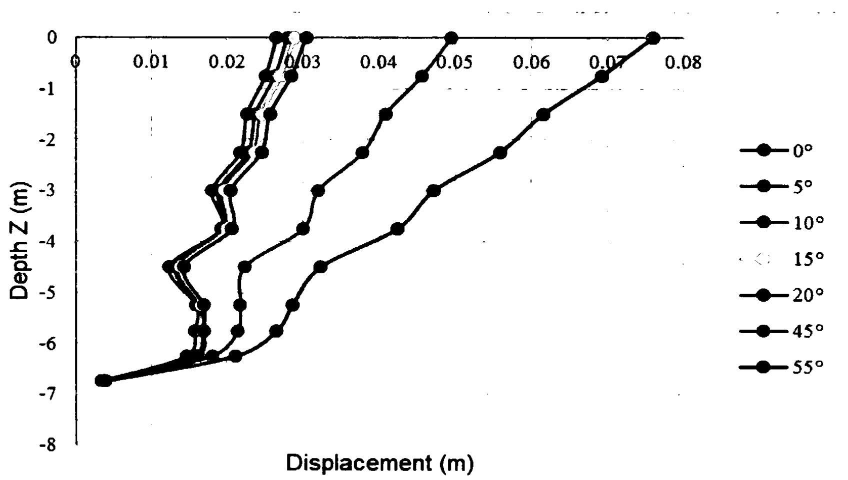

Figure 8 Variation of total displacement of facing with depth

Coastal and Lagoon Environment