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Development of Rational Method of Design of Soil Nailing System in Granular Soil

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Abstract. Soil Nailing technique involves installation of driven or grouted nails (steel bars) spaced closely down the slope/excavation in stages to create an insitu coherent gravity structure to increase the shear strength of soil and restrain its movement. Soil nailed wall in granular soils is likely to have rotation about toe and tend to behave as a reinforced earth wall after construction. Hence in the present paper, an attempt is made to design soil nailing system based on classical Rankine's earth pressure theory (1857) coupling with coherent gravity analysis of reinforced earth wall design in selected granular soil possessing required minimum cohesion of 7 kN/m^2 for adopting soil nailing technique. The design data generated for soil nailed wall is compared with the existing Gassler design method (1996). Soil nailed walls designed for soil retention in excavations of heights varying from 4.5m to10m are compared with the Gassler method-based designs. The proposed design methodology yielded L/H ratios of 0.75-1.1 for different heights of soil nail walls in contrast to the L/H ratios of 0.6-0.7 in Gassler's method.

Keywords: Soil nailing; Earth pressure; Reinforced earth; Soil retention, Deep excavation, Driven nail.

1 Introduction

In urban areas, construction of multi storied and high-rise structures with cellar and sub cellar floors is necessitating for soil retention in nearly vertical excavation to ensure the stability of neighboring structures and prevent soil slides from excavated surface into construction area for the safety of working personnel. Also, excavated steep slopes for constructions in hilly areas require soil retention. Soil nailing technique is being extensively used for stabilizing slopes and vertical cuts in deep excavations. Other methods of soil retention namely secant piles, contiguous piles, diaphragm wall are expensive while sheet piles are not readily available and have the limitations on driving of sheet piles in boulder strata. Relatively easier installation of nails makes the technique more advantageous over other reinforcing techniques.

The concept of soil nailing has originated from New Australian tunnel method where metallic rods with anchorages are used to support excavation in rocks during construction of a tunnel. Soil nailing is defined as the technique of reinforcing in situ soil by a regular arrangement of closely spaced metal rods (Gassler et.al 1981, Juran 1987). The major components of a soil nail wall are the in-situ soil, reinforcing elements and facing. The nails are installed down the slope/excavation at regular intervals with an inclination of 10^0-15^0. Different types of nails such as driven, grouted, jet grouted, encapsulated corrosion protection nails, hollow bars (Juran 1987, FHWA) are used based on the site conditions. The nailed wall derives resistance from soil-nail interaction due to ground movement which results in the mobilization of tensile forces in the nailed wall. The potential failure mechanisms such as pull out failure, tension failure, shear, bending and facing failure have been observed in a soil nailed wall. However, the effect of bending and shear strengths is considerably less (< 10% Elias and Juran 1991) on the overall stability of nailed wall. The forces acting on the critical slip surface are to be computed to assess the safety of a soil nail wall. The critical slip surface may be circular or a two wedge surface based on the type of soil i.e. for soils with little cohesion both slip circle and two part wedge are nearly equivalent where as for soils with medium or high cohesion circular slip surface is the least safe failure mechanism (Gassler 1996) .Different graphical and analytical methods are proposed for designing nailed wall based on limit state equilibrium (Gassler method, Davis method, FHWA, BS 8006, HA 68). With the gaining popularity for the soil nailing walls, there is need for development of simplified rational design methods.

The potential failure slip surface of nailed wall falls within the range of 0.3-0.4H at the top (Fig.1) which confirms that it is similar to the failure slip surface of reinforced earth wall, i.e., the tensile force distribution is similar to that of reinforced earth wall (Clouterre 1991, Byrne et.al 1998). Hence in the present study, concept of reinforced earth is adopted in designing soil nailed wall. Soil nailed walls for retaining granular soil of varying heights (4.5m, 6m, 8m and 10m) are designed based on Gassler method and compared with the design details obtained from proposed design methodology under study.

2 Methodology

2.1. Gassler method

Gassler (1996) developed design charts for nailed walls with varying slopes (α) and inclinations of end of nails (ρ) bearing different surcharge loads(q_d) in granular soils using partial safety factors based on Eurocodes. The method considers only reinforcement tensile forces. Pull out resistance is the major stabilizing force for which a partial factor of 1.3 was used in this method.

For a given geometry and soil properties, preliminary design of soil nail wall is carried out using Gassler's charts. Specific nailing density (μ) obtained from these charts is used to determine horizontal spacing using the following equation.

$$\mu = \frac{T}{\gamma . S_{v.S_h}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where,

T= factored pullout force

S_v and S_h are vertical and horizontal spacings respectively.

The design details obtained from charts are verified by considering equilibrium of polygon of forces acting on the critical failure wedge (two wedge slip surface for granular soils). The design is safe if driving forces are less than or equal to resisting forces. The safety of wall against tension and pullout is verified.

2.2. Proposed method for Design of Driven Nails system

It is proposed to consider soil nailed soil similar to reinforced earth wall as soil nailed soil system behaves as coherent gravity system by itself and helps in supporting the neighbouring soil. Hence, it is proposed to use the concept of coherent gravity method used in internal stability of reinforced earth walls for design of nailed soil system. The two-wedge failure surface of coherent gravity method nearly fits the failure surface pattern of soil nailed walls. Soil nailing systems are to be used only if soil has minimum cohesive strength of 7kN/m^2 to ensure stability of soil in excavation surface until facing is formed. The presence of cohesion in soil reduces the tension induced in nails. So, while adopting the coherent gravity method of analysis, Bell's (1915) equation is used for calculation of active earth pressure computation. The details of design coherent gravity structure are described below.

Coherent Gravity structure (AASTHO 1996 and BS-8006-1:2010)

Coherent gravity method derived from the monitored behaviour of various structures is used to verify the internal stability of reinforced earth wall in cohesionless soils. The method considers a two-wedge failure plane in which the maximum tensile force falls within the range of 0.3H at the top (Fig.2). The variation of earth pressure coefficient is shown in Fig. 3. The factors of safety against tension and pull out failures are computed using the following equations.

1. Tension/rupture failure mechanism: The induced tensile force (T) at each reinforcement level is calculated as

$T = K\, \sigma_{vj}\, S_v S_h$ (2)

Factor of safety against tension = T_f/T (3)

where, K= coefficient of earth pressure

σ_{vj} = vertical stress at selected reinforcement level

S_v and S_h are vertical and horizontal spacings respectively.

T_f = Ultimate tensile strength of nail

2. Pull out failure mechanism: Pullout resistance force (F) at each reinforcement level is calculated as

$F = \gamma\ h_j\ \pi d L_e \tan\delta$ (4)

Factor of safety against Pull out = F/T

where,

d=diameter of bar

L_e=length of the nail beyond failure zone

In the present proposed design methodology, the effect of cohesion of soil is considered in determination of induced tensile force in nail as given in Eq. 5

$$T = \left(K\sigma_{vj} - 2c\sqrt{K}\right)S_v.S_h \quad (5)$$

FHWA (2003) recommended minimum factors of safety for design of soil nailed walls for temporary and permanent excavations in static and seismic conditions given in Table 1 are used in the proposed design based on coherent gravity analysis for pull out and tension failures.

Table 1. Minimum Recommended Factors of Safety in Pull out and Tension failures of Nails

Failure mechanism	Temporary walls		Permanent walls	
	Static	Seismic	Static	Seismic
Pull out failure	2.0	1.5	2.0	1.5
Tension failure	1.8	1.35	1.8	1.35

Since the soil nail wall behaves similar to the reinforced earth wall, the design details obtained from Gassler's method are checked for safety against tension and pullout failures using the above equations.

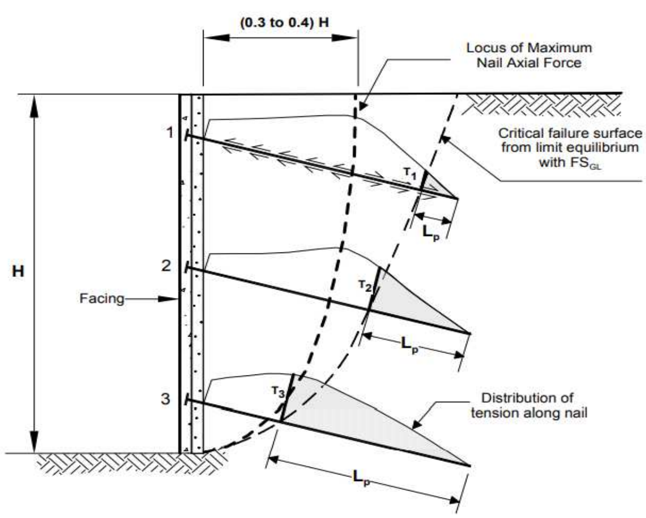

Fig.1 Behaviour of soil nail (FHWA 2003)

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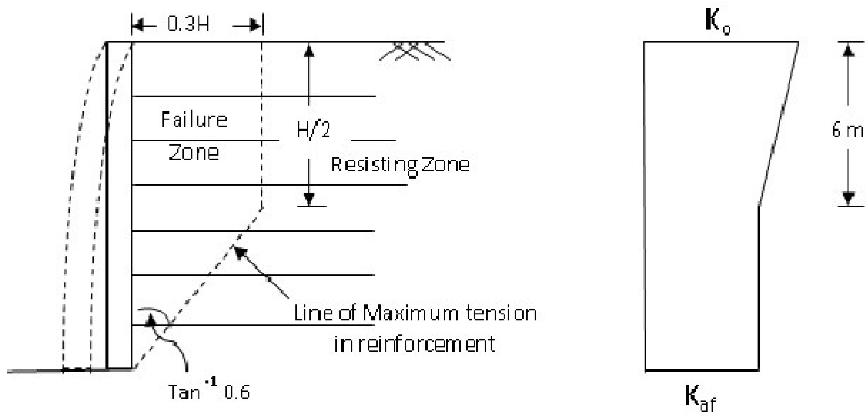

Fig.2. Line of maximum tension in reinforced earth wall

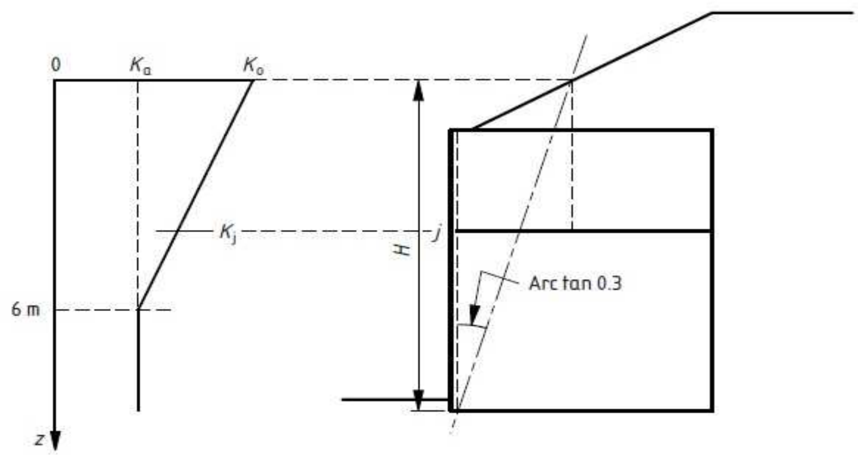

Fig. 3. Variation of earth pressure coefficient along the length of wall in coherent gravity method

3 Design of Soil Nailing Walls

The properties of soil considered for the study are presented in Table 2. Based on gradation and plasticity characteristics, the soil is classified as SM-SC as per IS 1498-1970. Soil nailed walls of heights 4.5m, 6m, 8m and 10m inclined at $10^0$with the vertical by considering the walls as temporary with no surcharge for driven nails inclined at $10^0$with horizontal and adopting L/H ratio of 0.6 are designed for supporting soil in excavations based on Gassler's method and the details are presented in Table 3.The pullout resistance is reduced by a factor of 1.3 and tensile strength is reduced by a factor of 1.15. The two wedge critical slip surface required for design of soil nail walls using Gassler's method is computed either by trial and error method or by using a computer program. In the present study the critical slip surface is obtained from GEO 5 software. For a given geometry and soil profile, nailed wall model is created in GEO5 and the analysis is performed using partial factors of safety given by Euro-code.The induced tensile forces computed by considering equilibrium of critical failure wedge are also reported in Table 3.

Table 2. Engineering properties of soil under study

Property	Value
Specific gravity	2.63
Grain size distribution	
a. Gravel (%)	0
b. Sand (%)	84
e. Fines (%)	16
Plasticity Characteristics	
a. Liquid Limit	23
b. Plastic Limit	18
c. Plasticity Index I_p	5
IS Classification	SM-SC
Compaction Characteristics	
a. Optimum Moisture Content (%)	6.8
b. Maximum Dry Density (kN/m^3)	18.0
Effective Shear Parameters	
a. Cohesion(kN/m^2)	8
b. Angle of Internal Friction	31^0

Table 3. Design details of soil nail walls obtained from Gassler's method

Parameter	Height of wall			
	4.5m	6.0m	8.0m	10m
Length of Nails (m)	2.7	3.6	4.8	6
Inclination of end of nails	0	0	0	0
Grade of steel (Mpa)	415	415	415	415
Diameter of nail (mm)	25	25	25	25
Vertical spacing (m)	0.5	0.5	0.5	0.5
Horizontal spacing (m)	0.5	0.5	0.5	0.5
Factored pull out force (kN/m)	5.72	10.5	19	30
Max. Tensile force(kN)	9.7	25	72	126
Tensile strength (kN)	177	177	177	177
Global factor of safety	1.43	1.35	1.35	1.36

The soil nailed walls designed based on coherent gravity analysis are presented in Table 4. Pull out resistance forces are computed at each reinforcement level for all heights of nailed walls under study and the minimum obtained value factor of safety against pull out is reported.

Table 4. Design details of soil nail walls obtained from Coherent gravity method

Parameter	Height of wall			
	4.5m	6.0m	8.0m	10m
Length of Nails (m)	5.1	5.8	6.7	7.5
Grade of steel (MPa)	415	415	415	415
Diameter of nail (mm)	25	25	25	25
Vertical spacing (m)	0.5	0.5	0.5	0.5
Horizontal spacing (m)	0.5	0.5	0.5	0.5
Factored pull out force (kN/m)	6.54	10.36	16.38	23.34
Max. Tensile force(kN)	203	203	203	203
Tensile strength (kN)	2.0	2.0	2.0	2.0

Gassler design charts are given for L/H=0.6 only. Further, Gassler considered that the soil behind the rectangular wedge only exerts lateral earth pressure and the lateral earth pressure and is computed based on Coulomb'stheory. However, Rankine earth pressure theory is more appropriate in flexible soil nailed wall in granular soil. From Table 4, the proposed design method based on coherent gravity analysis, it is observed that the L/H ratios of soil nailed walls vary between 0.75 to 1.13. It is observed that the L/H ratios of soil nailed walls decrease with increase in height.

4 Conclusions

The following conclusions are drawn from this study,

1. The geometry of nailed walls obtained from Gassler's method fails in mobilizing sufficient pullout resistance as recommended in coherent gravity method. Hence, longer nails are required than those obtained from Gassler's method to maintain minimum recommended factor of safety of 2 against pullout failure.
2. For a given soil, the length of nail obtained from coherent gravity method varies in between 0.75H-1.2H for different heights of soil retention whereas it varies in between 0.6H-0.7.H in conventional design methods.
3. The value of L/H decreases with increase in height of the nailed wall in a given soil. However driven nails are not preferred for supporting permanent structures of greater heights due to lower values of mobilized pullout resistance forces

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