02 May 2013, 4:00 pm - 6:00 pm

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ABSTRACT

Earth retaining structures usually need careful monitoring after construction in order to detect any signs of distress. In cases where failure is likely to occur, appropriate remedial techniques need to adopted, backed by a detailed analysis.

This paper presents a case study on the rehabilitation of a retaining wall that was constructed for a bypass road project. The structure showed clear signs of distress immediately after completion and hence could not be opened for traffic. Preliminary finite element analysis of the wall showed values of factor of safety that are lesser than permissible values. The values of factor of safety obtained from limit equilibrium analyses based on overturning, sliding and bearing pressure were also inadequate. Soil nailing with grouted nails has been suggested as a remedial measure for this case. The results of the finite element analysis of the wall reinforced with grouted nails are presented in this paper. Results show that the soil nailing technique is effective in the rehabilitation of the wall.

INTRODUCTION

It is often the case for retaining walls constructed for bridges that negligence of certain prevalent site conditions results in an inadequate design, which more often than not leads to failure. One such case is presented in this paper wherein a remedial measure backed by detailed numerical analysis was sought by the client. The retaining walls considered here were constructed for a bridge which was part of a bypass road project. The signs of distress and impending failure were quite evident immediately after completion and hence it could not be opened for traffic. Figure 1 shows the section of the embankment with top width 12 m, and wall height (backfill) 12.75 m. The unsupported height is 9.75 m. The retaining walls have been constructed symmetrically as shown in Fig 1. A detailed limit equilibrium analysis gave unsatisfactory safety factors. Finite Element modeling has been employed to get a clearer picture in this paper. All FEM analysis was done using the general purpose soil mechanics finite element code PLAXIS.

Soil Nailing has been suggested as the remedial measure for this wall and thus numerical analysis was carried out for the retaining wall using nails of appropriate length and equivalent material properties. Numerous case studies available in literature demonstrate the capability and versatility of soil nailing as a viable reinforcing technique [Durgunoğlu et al. 2007].The performance of soil nail walls mainly depends on the complex mutual interaction between the soil, the reinforcements (nails) and the facing [Singh and Sivakumar Babu 2010]. There are various other parameters such as construction sequence, installation method and distribution of

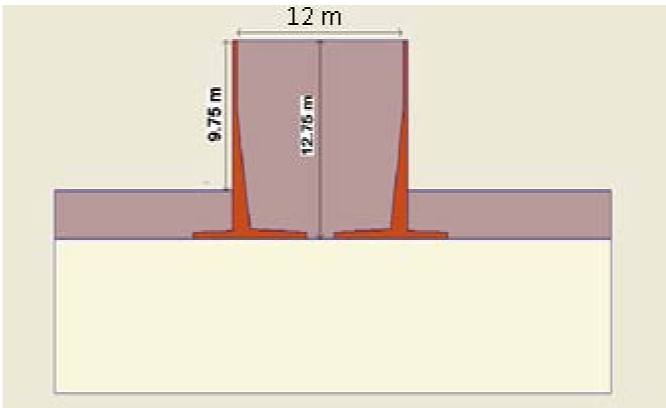


Fig. 1. Embankment Section with 9.75 m unsupported height and 12 m top width

load along the nails that need to be accounted for, which conventional limit equilibrium techniques fail to address [Lima et al. 2003, Sivakumar Babu and Singh 2009, Singh and Sivakumar Babu 2010]. Many studies, both experimental and numerical have also been conducted on the pull-out resistance of nails which yielded logical results such as an increase in pull-out resistance with increasing overburden pressure and satisfactory validation of numerical models to simulate pull-out resistance [Ann et al. 2004, Pradhan et al. 2006, Zhou 2008, Seo et al. 2012]. Briaud and Lim (1997) provided useful guidelines about the appropriate placement of boundaries in simulations to ensure the minimization of their effect on nail performance. Literature also provides ample instances of PLAXIS being used for the study of structures reinforced with soil nails [Shiu et al. 2006; Fan and Luo 2008, Sivakumar Babu and Singh 2009, Singh and Sivakumar Babu 2010].

The important guidelines from the aforementioned studies include the use of plane strain models and using plate elements to model the nails. The Hardening Soil (HS) model is commonly used for these cases to model the soil, but in case the input parameters are not available or the expected lateral displacements are small, the Mohr-Coulomb (MC) model can be utilized. Also, an overall fineness set to "very fine" may be used provided the computing machine is capable of handling such simulations without significantly affecting the speed of calculation. It has also been reported in literature that the soil-nail interaction co-efficient has been found to be much greater than unity form field pull-out tests [Wang and Richwein 2002]. However, in this study analysis has been carried both with and without interface elements.

An equivalent modulus (E_{eq}) shall be used for the grouted nails, given by the following equation:

$$E_{eq} = E_N \left(\frac{A_N}{A}\right) + E_G \left(\frac{A_G}{A}\right) \quad (1)$$

Where,

E_N = Young's Modulus of nail (kN/m^2)

E_G = Young's Modulus of grout concrete (kN/m^2)

A_N = Cross-sectional area of nail (m^2)

A = Total cross-sectional area (m^2)

A_G = Cross-sectional area of grouted part = A - A_N (m^2)

The important input parameters for the plate elements are axial stiffness (EA) and Bending Stiffness (EI) per meter length (plane strain). These parameters can be obtained as follows:

$$EA = \frac{E_{eq}}{S_H} \left(\frac{\pi D^2}{4}\right) \quad (2)$$

$$EI = \frac{E_{eq}}{S_H} \left(\frac{\pi D^4}{64}\right) \quad (3)$$

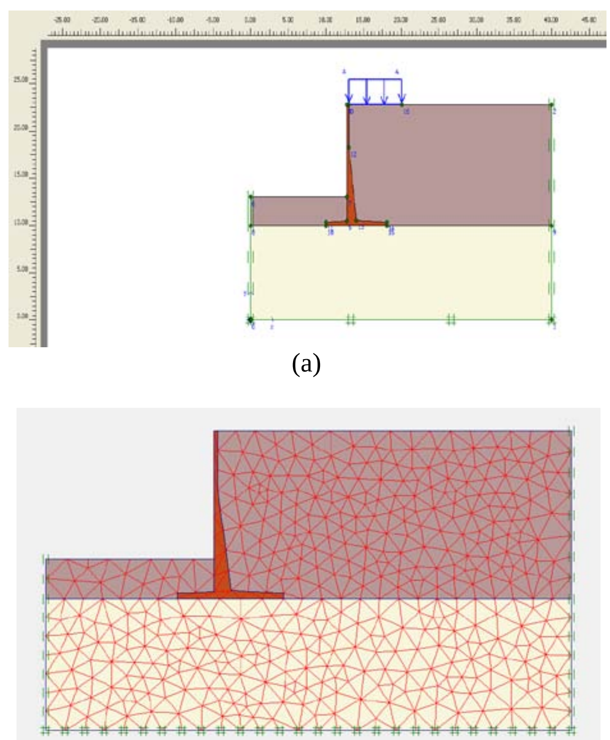
Where D is the diameter of the bore hole and S_H is the horizontal spacing.

CONVENTIONAL ANALYSIS

Limit Equilibrium analysis was first performed for this wall with checks for overturning, sliding and bearing failure. The factor of safety against overturning and bearing failure were found to be 3.33 and 2.31, respectively, but the factor of safety against sliding was 1.33, which is less than the permissible value of 1.5. Horizontal soil nails of length 9 m with spacing of 1.5 m x 1.5 m (horizontal x vertical) have been proposed as a remedial measure for this distressed retaining wall. The factors of safety for the reinforced case against overturning was computed as 5.78 and the minimum factor of safety against sliding (considering the trial wedge with minimum safety factor) was 1.66, which are satisfactory values.

MODELING WITH PLAXIS AND RESULTS

A plane strain model was employed and 15 noded triangular elements were used for discretisation (Fig. 2). The varying



(a)

(b)

Fig. 2. (a) PLAXIS model with half the geometry (one retaining wall).
(b) Finite Element Mesh for unreinforced case

ground water conditions have been approximated by a horizontal Phreatic Level 0.5 m above the ground surface. Due to its symmetrical nature, only half of the geometry was modeled. A surcharge load of 20 kPa was considered and standard boundary conditions were applied. The properties used in PLAXIS for the Foundation Soil, Backfill Soil and Concrete (retaining wall) are shown in Table 1, Table 2 and Table 3, respectively. Both the soil layers were modeled as Mohr-Coulomb materials and concrete was modeled as a Linear Elastic material.

Table 1. Properties of backfill soil

Parameter	**Name**	**Value**
Material Model	Model	Mohr - Coulomb
Type of Material Behavior	Type	Drained
Dry Unit Weight	γ_{unsat}	18.0 kN/m^3
Saturated Unit Weight	γ_{sat}	20.0 kN/m^3
Horizontal Permeability	k_x	1.0 m/day
Vertical Permeability	k_y	1.0 m/day
Young's Modulus	E_{ref}	$1x10^5$ kN/m^2
Poisson's Ratio	ν	0.25
Cohesion	c_{ref}	10 kN/m^2
Friction Angle	Φ	30°

Table 2. Properties of foundation soil

Parameter	**Name**	**Value**
Material Model	Model	Mohr - Coulomb
Type of Material Behavior	Type	Drained
Dry Unit Weight	γ_{unsat}	16.0 kN/m^3
Saturated Unit Weight	γ_{sat}	18.0 kN/m^3
Horizontal Permeability	k_x	1.0 m/day
Vertical Permeability	k_y	1.0 m/day
Young's Modulus	E_{ref}	$2x10^5$ kN/m^2
Poisson's Ratio	ν	0.25
Cohesion	c_{ref}	15 kN/m^2
Friction Angle	Φ	30°

The soil body failed as shown in the deformed mesh in Fig 3. Since the soil body collapses, the factor of safety was estimated from the percentage of the applied load (∑Mstage) at which failure takes place. This factor of safety was found to be 0.73. Both overturning and sliding failure mechanisms were observed and the inadequacies of design, especially with respect to the water table at such low depths can be cited as the main causes of failure.

A plot of the displacements for the failed unreinforced case is shown in Fig. 4 along with the proposed nails. As evident from the failure pattern above, the proposed nail length of 9 m is sufficient to mobilize shear resistance since it is embedded both in the active and the passive zones. Figure 5 shows the model with the horizontal soil nails incorporated. For a bore diameter of 150 mm and nail diameter of 20 mm and taking moduli of steel and grout concrete as 200 GPa and 20 GPa, respectively, the value of the equivalent modulus for the grouted nail was calculated using eq. (1) and was found to be 25.19 GPa.

Table 3. Properties of M25 concrete

Parameter	**Name**	**Value**
Material Model	Model	Linear Elastic
Type of Material Behavior	Type	Non-Porous
Dry Unit Weight	γ_{unsat}	25.0 kN/m^3
Young's Modulus	E_{ref}	$2.5x10^7$ kN/m^2
Poisson's Ratio	ν	0.15

Using eq. (2) and eq. (3), the value of EA was found to be 295,597 kN/m and EI was found to be 417.37 kNm^2/m. These values take into account the horizontal spacing of 1.5 m.

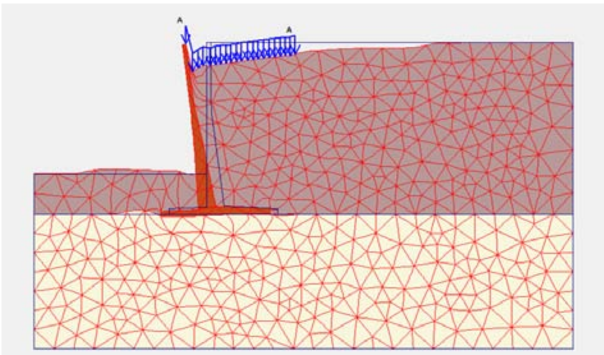


Fig. 3. Deformed mesh at failure for unreinforced case

These values of EA and EI were assigned to the plate elements representing the soil nails and the analysis carried out resulted in the deformed mesh and the failure pattern are shown in Fig 6. The retaining wall performed much better with these reinforcements and the maximum displacement along the wall was found to be 6 mm.

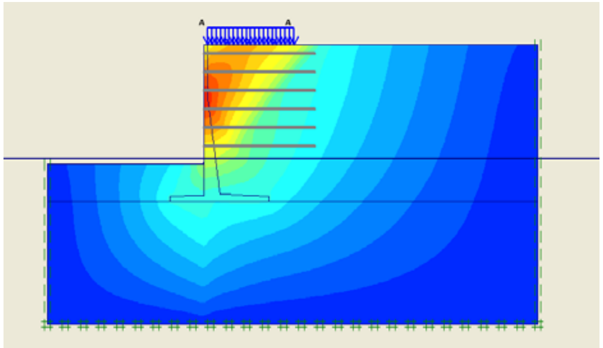
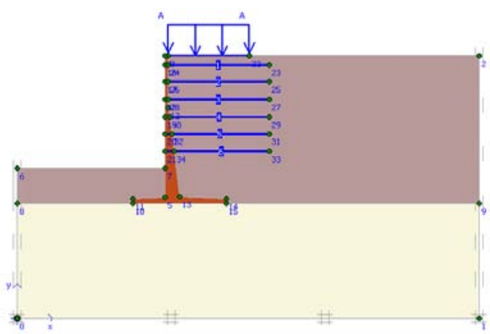
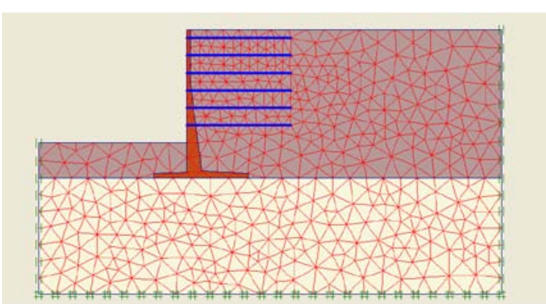


Fig. 4. Failure pattern for the unreinforced case showing nails of proposed length

The PLAXIS code has an in-built tool for safety factor calculation which employs a φ-c reduction technique, i.e., the values of friction angle and cohesion are reduced by a certain factor and the analysis is done for that state of the parameters. The critical value of this reduction factor for which the body collapses returned in the calculations program as the factor of safety. The factor of safety for this case was found to be 1.73. It is to be noted that this factor of safety accounts for all the possible failure mechanisms (overturning, sliding, etc).

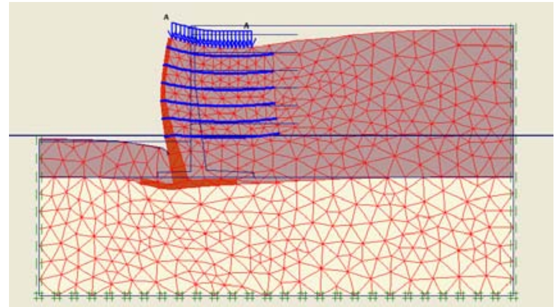


(a)

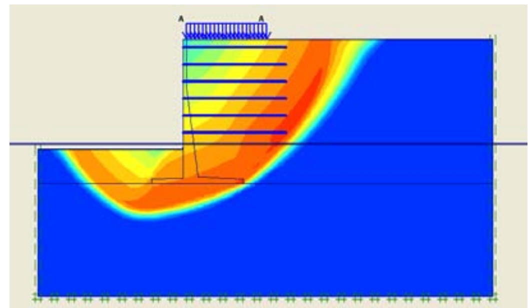


(b)

Fig. 5. (a) PLAXIS model with grouted nails. (b) Finite Element mesh



(a)



(b)

Fig. 6. (a) Deformed with grouted nails. (b) Failure pattern

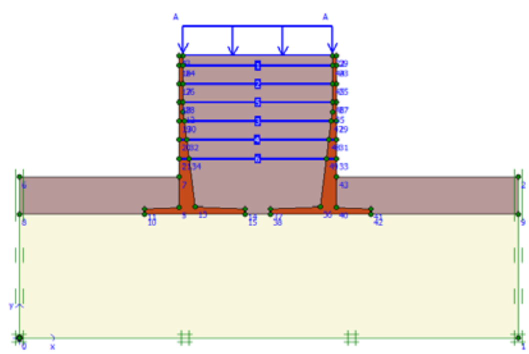


Fig. 7. Model considering complete geometry and nails connecting the two walls

The same analysis was repeated with interface elements for each nail with an interface shear strength reduction factor of 0.8, which resulted in a similar factor of safety of 1.73 and a slightly higher value of maximum displacement of 7 mm, which is still well within the permissible limits.In order to complete the analysis, the case with both the walls was also considered, as shown in Fig 7. In this case 12 m long nails were considered which connected the two walls. The analysis for this case resulted in a much higher factor of safety of 2.57. Thus the results of the analysis for half the geometry will be considered for implementation, which are satisfactory. The arrangement shown in Fig 7 is easier to implement on the field since only single nails are to be driven from one wall to the other as opposed to arranging the nails in a staggered manner.

CONCLUSIONS

A forensic analysis was performed on a distressed retaining wall using both limit equilibrium and finite element methods with soil nailing as the adopted rehabilitation measure. A factor of safety against sliding less than the permissible limit was obtained from limit equilibrium analysis, however, the very low factor of safety obtained from the FEM analysis for the unreinforced case was a much better agreement with the fact that clear signs of distress were noticeable in the field. This showcases the superiority of FEM packages when compared to conventional techniques. The PLAXIS results for the wall reinforced with grouted nails show that the performance of the wall is much better with the nails, with adequate factors of safety and very low displacement values. Alternate analyses were also carried out considering the entire geometry and also incorporating soil-nail interface elements. The performance of the wall was found satisfactory in all cases and thus proposed design of the grouted nails can be implemented in the field without any issues.

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