Investigating the Influence of Groundwater Level Variation on Performance of Soil Nailed Slopes

Meletetsega Gashaw and A. Murali Krishna

Abstract The use of soil-nailing is one of the methods adopted for the stabilization of slopes and supporting the deep excavations. Many design guidelines and manuals suggested the suitable and favorable conditions for the application of soil-nailing techniques, among which groundwater level is the main concern. But most of the studies failed to show how this groundwater level and its fluctuation in the slope will affect the serviceability and ultimate limit state criteria which include the deflection, the axial forces developed in the nails, the distribution of tensile force along the nails and safety factors as a whole. Hence, in the present study, the influence of the variation of groundwater level on the behavior of soil nailed slopes using a finite element modeling software 'RS2-Rocscience' is studied. For this study, a homogenous unstable slope for three different soils with different strength and hydraulic properties are analyzed and soil nail support systems are designed as per the FHWA soil nail design manual. Then, the variations of slope deformation developed axial forces and factor of safety for the variation of the groundwater level are presented. The results of numerical modeling show that the increase in the groundwater table will decrease the critical factor of safety and increase the horizontal deformation and the peak axial force on the nails. Further in case of unsaturated soils, due to the presence of the groundwater the top nails are all under compression (negative axial force) and the increase in stability is offered by the lower nails only.

Keywords Soil nail · Slope stabilization · Groundwater variation · RS2-Rocscience · Slope stability

1 Introduction

Soil-nailing is a technique that involves reinforcing and strengthening of unstable slopes and deep excavations by installing closely spaced steel bars, termed as soil nails. The construction method proceeds from top to bottom. This technique has

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several advantages, over other stabilization techniques, such as cost, ease of construction, time of construction, construction flexibility, environmental/esthetic considerations, requirement of limited access area etc. [1, 2]. The reinforcing action of soil nails develops through the development of tensile force in passive reinforcement as the result of lateral deformation of the structure as construction goes from top to down [2–5].

Shaw-Shong [6], Tan and Chow [8] discussed the design requirements, available manuals for design and other important considerations that should be considered while designing the soil nails. The manuals widely referred in designing the soil-nailing strengthening work are: (a) BS8006:1995 Code of practice for Strengthened/reinforcement soils and other fills, (b) Federal Highway Administration (FHWA) Manual for Design & Construction Monitoring of Soil Nail Walls, and (c) BS8081:1989 Code of practice for Ground Anchorage [6, 8]. These different design manuals specified the favorable and suitable ground conditions for the application of soil nails. Among these conditions, the soil type and the groundwater conditions are the main concerns. Many studies have been conducted to study how the soil type affects the nail performance. But studies related to groundwater effect on the performance of soil nails and these structures are very rare. Byrne et al. [1] and Lazarte et al. [4] recommended locating the nails above the groundwater level and if it exists in case, it should not affect the face of excavation, the bond between the ground and the soil nails. The groundwater level inside the slope mass will vary for various changes in hydrological conditions. The aim of this study is therefore to investigate the influence of groundwater variation on the general performance of slopes stabilized with soil nails including the axial forces developed in the nails, the critical factor of safety, the displacement and the variation in suction inside the slope mass.

1.1 Problem Statement

Three different soils (Soil-A, Soil-B & Soil-C) representing a homogenous c-ϕ' soils with different mechanical and hydraulic properties are adopted in the study. The slope geometry and soil properties adopted for the study are listed in (Fig. 1, Tables 1 and 2) respectively. Initially the slope is analyzed assuming the dry condition (the groundwater is at infinite depth from the slope) for the three soil types. Then the groundwater level starts to rise from the base of the slope to the toe of the slope which is located at 10 m from the base of the slope. Five different locations of groundwater table were considered. The 'Z' term in (Fig. 1) represents the depth of the groundwater level at a particular location. The five cases considered are: (a) $Z = 0$ m, (b) $Z = 2$ m, (c) $Z = 4$ m, (d) $Z = 6$ m, (e) $Z = 8$ m and (f) $Z = 10$ m. Then the slope is designed for its dry condition state using soil nails to improve the safety factor thereby stabilizing it using Byrne et al. [1] and Lazarte et al. [3, 4] soil nail design guidelines. Finally, with the set of assumptions with regard to in-situ conditions, the reinforced slope is numerically simulated using two-dimensional finite element
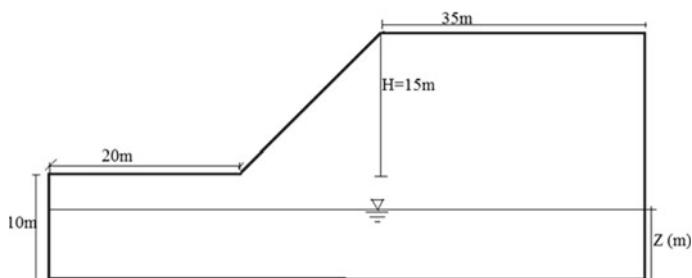
Fig. 1 Geometry of slope

Table 1 Mechanical properties soils

Soil type	γ (kN/μ^3)	c'(kPa)	ϕ' (°)	ϕb(°)	E(MPa)	Υ
Soil-A	18	8	25	25	100	0.3
Soil-B	20	10	30	30	50	0.33
Soil-C	20	20	20	20	75	0.35

Table 2 Hydraulic properties of soils

Soil type	α (m^{-1})	n	θ_r	Θ_s	k_s (m/s)
Soil-A	7.087	0.005	0.049	0.304	$1.8292e^{-05}$
Soil-B	1.6	1.37	0.034	0.46	$2.39e^{-06}$
Soil-C	0.5	1.09	0.070	0.36	$5.5e^{-08}$

based computational tool RS2 Phase 2 V.9 (Rocscience2018) software for different groundwater levels and results are discussed in detail. The modeling approach used for this study was first verified by validating a model proposed by Zolqadr et al. [9].

Slope stability analysis is performed by strength reduction method followed by transient seepage analysis using coupled solid-fluid interaction analysis. In a coupled analysis, the changes in pore pressure and the effective stresses affect the deformation but not the pore pressure. A fully drained condition which defines a condition of zero excess pore pressure is considered. After seepage analysis has been done, the results of the pore pressure distribution including negative pore water pressure known as matric suction in the unsaturated zone above the water table are used to determine the stability of the slope through the strength reduction method.

2   Numerical Model

2.1   Validation of Model

Numerical model is developed using finite element method base numerical package RS2 (Rock and soil 2-dimensional) used for soil and rock applications. One of the major features of RS2 is a finite element slope stability analysis using shear strength reduction (SSR) method which automatically determines the most critical failure mode and the corresponding safety factor. To verify the results of the numerical model, a soil nailed wall constructed to support underground excavation [9] was modeled in RS2 and the horizontal deformation of the model is compared with reported data. Properties used for the validation model are presented in (Tables 3 and 4).

The modeling approach consists of simulating soil behavior by Mohr-coulomb model which exhibits linear-elastic and perfectly plastic soil behavior; applying fully grouted tie back bolts (with 100% bond length) for modeling soil nails; applying liners of standard beam as elastic material for modeling of temporary facings (shotcrete); using denser mesh in the vicinity of soil nails; and no interface element to model both soil-facing and soil-nailing interaction. The values of modulus of elasticity for

Table 3 Input parameters for Seattle wall [9]

Soil layer	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Thickness (m)	4	3.6	3.6	3.6	3.6
c(kPa)	9.6	9.6	9.6	9.6	9.6
$\phi(°)$	40	40	40	40	40
γ(kN/m^3)	21.6	21.6	21.6	21.6	21.6
E(MPa)	40.7	95.7	143.5	358.8	923.4
υ	0.34	0.32	0.29	0.234	0.2

Table 4 Input parameters used for soil nails and shotcrete

Bolt type	Tieback
Bolt diameter (mm)	50
Bolt modulus, (kPa)	4,222,698.95
Bond shear stiffness, kN/m/m	3000
Bond strength (kN/m)	1000
Borehole diameter (mm)	150
Liner type	Standard beam
Young's modulus, E(kPa)	1,628,878.28
Poisson's ratio	0.18
Thickness (m)	0.1
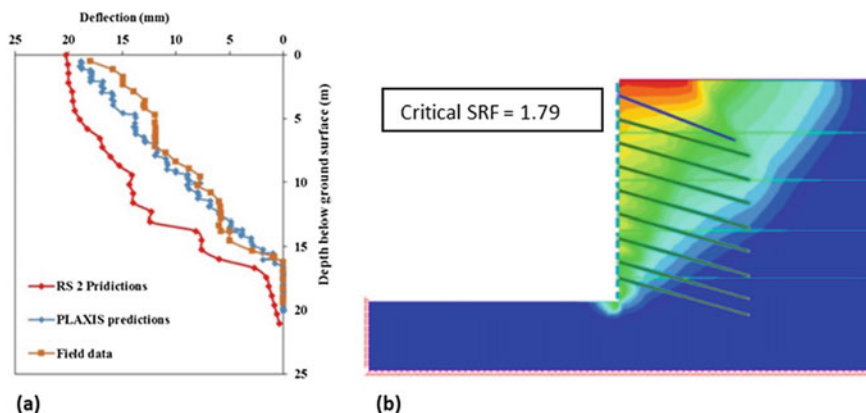
Fig. 2 **a** Comparisons of horizontal deformations, **b** numerical model of Seattle wall

both shotcrete element and tieback were calculated from the axial stiffness (EA in kN/m) values given from Zolqadr et al. [9].

The reported final horizontal deformation at the end of construction from Zolqadr et al. [9] was 18 mm from field inclinometer measurements and 19.7 mm from PLAXIS FEM predictions. The RS2 deformation prediction of the same model was found to be 20.22 mm at the end of construction. Comparing the three results, it shows that the numerical predicted horizontal displacement by RS2 is acceptable (Fig. 2).

2.2 *Analysis of Unreinforced Slope*

Numerical model of homogenous slope has been prepared to study the effect of groundwater rise in unreinforced slope for the three different soils through a finite element model using RS2 Phase-2 (Rocscience, 2018) software using coupled analysis followed by strength reduction analysis. A uniform mesh type with 1500 six nodded triangular elements is used for both slope stability and groundwater analysis. The bottom boundaries were assigned fixed boundary condition and left and right sides of slope were assigned roller boundary conditions to allow movement in the vertical direction for stability analysis. And for seepage analysis, each level of groundwater is defined as a total head boundary at the left and right side of the model. The boundaries above the groundwater table are defined as a nodal flow rate with seepage face condition. The face of slope is assigned undefined flow rate and the bottom boundary is assigned a nodal flow rate except for the conditions when the groundwater table is at the base of the slope as shown in (Fig. 3).

Figure 4 illustrates the pore pressure profile variation with the change in the groundwater table. It is observed that with the rise in the groundwater table the pore pressure changes from zero which was the case when groundwater table was fixed

Fig. 3 Numerical model of
seepage analysis
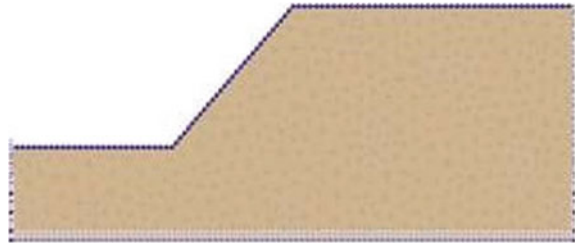
Fig. 4 Porewater pressure
variation with increase in
groundwater level
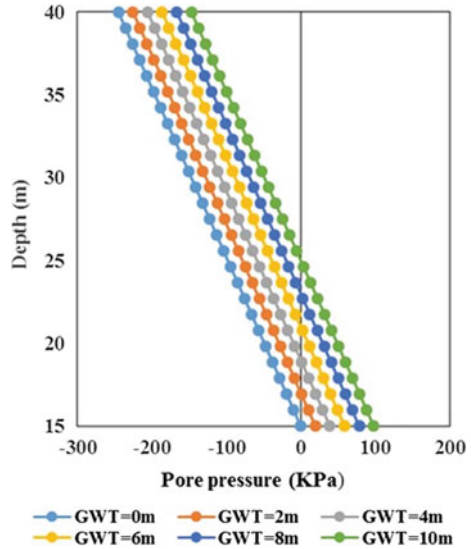
at the base of the slope to 98.1 kPa when the water reaches the toe of the slope at the same time the negative pore pressure which is known as matric suction is decreasing with the increase in the groundwater table. Matric suction changes from 245.24 kPa when groundwater table was fixed at the base of the slope to 147.15 kPa when water table reaches the toe of the slope. The decrease in the suction results in decrease of effective stresses which is the cause of reduction of strength of soil.

Figure 5a depicts the change in critical factor of safety with the rise in the groundwater level. Due to the inherent suction, the factor of safety of the soils are very high at higher suction levels compared to the ideal dry condition which is difficult to find in real case. But with the rise in the groundwater table, the safety factor reduces for all soils considered in the study. But depending on the strength and unsaturated properties of the soils the stability of soils varies. For example, for Soil-A, the factor of safety of the slope changes from 2.46 to 1.34, for Soil-B from 2.89 to 1.58 and for Soil-C from 2.1 to 1.33 when the groundwater rises from the base of slope (0 m) to toe of the slope (10 m). Soil-B is more stable than Soil-A and Soil-C. This shows
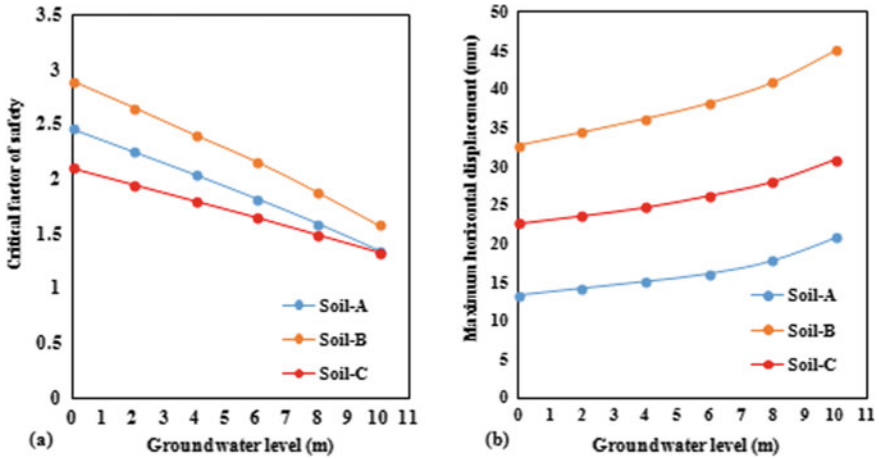
Fig. 5 **a** Variation of critical factor of safety of unreinforced slope with groundwater increase, **b** variation of maximum horizontal deformation of unreinforced slope with groundwater increase

that the strength parameters together with the unsaturated shear strength parameter will result different response of the slope subjected to similar seepage condition.

Figure 5b depicts the maximum horizontal deformations at different groundwater levels. Since the deformations are the results of the changes in the pore pressure and effective stress, the decrease in effective stresses and increase in pore pressure will result in more deformation. The maximum horizontal deformation increases from 13.3 mm to 20.8 mm, 32.7 mm to 45.1 mm and 22.6 mm to 30.9 mm for Soil-A, Soil-B and Soil-C respectively when the groundwater increases from the base to toe of slope. The values of horizontal deformations also show that deformations in finite element analysis are directly influenced by deformation properties of soils (E and υ).

2.3   Design of Reinforced Slope

The design of the soil nail support for the three soil types system is carried out based on the [1, 3] soil nail design manual. The allowable stress/load design method and the simplified wedge failure method of design [7] are used. For soils the design of soil nails is done for the dry condition where the groundwater is neglected. The design parameters used and the outputs of the design for all soils considered in the study are presented in Tables 5, 6, 7 and 8.

Table 5 General material properties and performance requirements used for design

Parameter	Value
Height of the slope (m)	15
Slope of backfill, $\beta(°)$	0
Face batter, $\alpha(°)$	45
Nail installation method	Rotary drilled
Nail distribution at wall face	Uniform
Grade of steel	Fe-420
Modulus of elasticity of nail EN, GPa	200
Nail spacing, S_V and S_H (m)	1 × 1
Nail inclination from the horizontal i, (°)	15
Drill hole diameter, D_{DH}, mm	150
Compressive strength of grout, f_{ck}, MPa	30
Ultimate bond strength, q_u, kPa	150
Modulus of elasticity of grout, E_g, GPa	30
FS for global stability, F_{SG}	1.35
FS for pullout, FS_P	2.0
FS for tensile strength, FS_T	1.8
FS for flexural failure, FS_{FF}	1.35
FS for punching shear, FS_{FP}	1.35

Table 6 Summary of design for nails

Design parameter	Soil-A	Soil-B	Soil-C
Length L, m	14	14	15
Diameter D, mm	32	32	32
Max. axial force T_{max}, kN	105.93	97	142.18
Axial force at the head, kN	63.56	58	85.31
Pullout capacity Q_U, kN/m	70.65	70.65	70.65
Max. tensile load capacity R_T, kN	337.78	337.784	337.784
FOS against pullout, FS_P	9.28	10.18	7.4
FOS against tensile strength, FS_T	3.2	3.5	2.4

Table 7 Summary of design for facing

Type	Temporary shotcrete		
Thickness, h, mm	200		
Reinforcement	102 × 102-MW26 × MW26		
Other reinforcement	Waller bars 2 × 10 mm (2×#10)		
Bearing plate grade	Fe-420		
Bearing plate dimension	225 mm × 225 mm × 25 mm		
Flexural capacity R_{FF}, kN	260.56	260.56	260.56
Punching shear capacity R_{FP}, kN	440.60	440.60	440.60
FS against flexural failure, FS_{FF}	4.1	4.5	3.05
FS against punching shear, FS_{FP}	6.9	7.6	5.16

Table 8 Factor of safety of unreinforced and reinforced slope for dry condition

Soil type	FOS of unreinforced slope	FOS of reinforced slope
Soil-A	0.89	1.9
Soil-B	1.02	2.37
Soil-C	1.01	1.74

Table 9 Soil nail and facing properties used in numerical modeling

Nail properties	
Bolt type	Tieback
Bolt diameter, (mm)	32
Bolt modulus, *E* (GPa)	200
Tensile capacity (kN)	300
Bond shear stiffness (kN/m/m)	20,000
Bond strength (kN/m)	150
Facing properties	
Liner type	Standard beam
Young's modulus (kPa)	3×10^7
Poisson's ratio	0.25
Thickness (m)	0.2

2.4 Analysis of Reinforced Slope

Using the same numerical modeling approach in the case of unreinforced slope the reinforced slopes are modeled in RS2. The soil nails are modeled as tieback bolts with 100% bond length and the facing are modeled as standard beam of elastic material. The input parameters used for the soil nails and facing are shown in Table 9.

Figure 6a depicts the variation of critical factor of safety of the reinforced slope with groundwater table increase. As in the case of unreinforced slope, the factor of safety reduces with groundwater rise. The factor of safety of reinforced slope changes from 2.63 to 1.55 for Soil-A, 3.14 to 1.94 for Soil-B and 2.33 to 1.54 for Soil-C when the groundwater keeps increasing from base of the slope to toe of the slope. The changes in horizontal deformation of reinforced slope are also shown in (Fig. 6b). The maximum horizontal deformation changes from 12.5 mm to 17.9 mm for Soil-A, from 29.1 mm to 37 mm for Soil-B and from 20.4 mm to 26.5 mm or Soil-C.

For soil nails to develop their reinforcing action, the axial tension force that is developed in the nails as the result of the interaction between soil and soil nail as the ground deforms is required. Figure 7 depicts the changes in the peak axial loads with increase in the groundwater table. Since the displacement of the slope is increasing with groundwater rise, the axial force that develops on the nails increases because the nail forces are mobilized when there is enough displacement. Therefore, the peak axial load that develops at the lower nails is increasing.
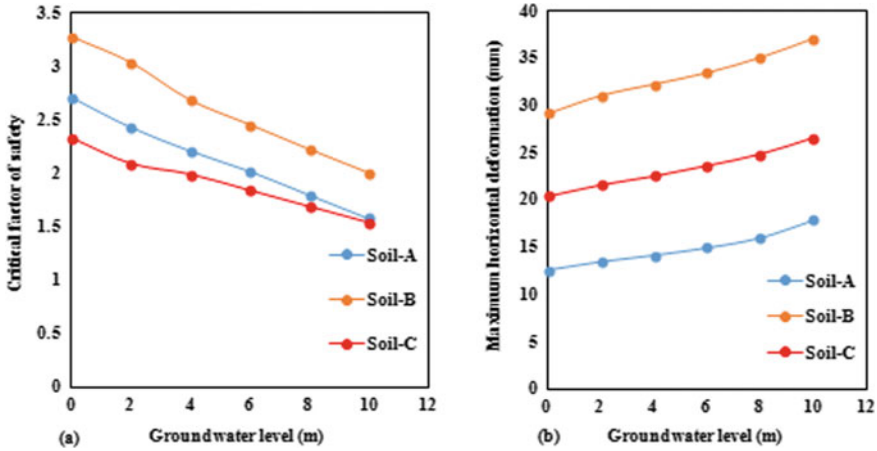
Fig. 6 a Variation of critical factor of safety of reinforced slope with groundwater increase, **b** variation of maximum horizontal deformation of reinforced slope with groundwater increase

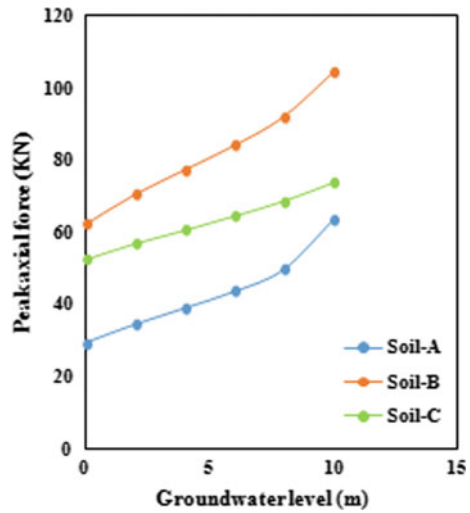**Fig. 7** Variation of peak axial force with groundwater increase


Figure 8 shows the axial force distribution along the bottom nail for different groundwater levels. It is clearly seen that the axial force along the nails increases with groundwater rise. But it was also observed that due to the presence of the groundwater the top nails in the unsaturated zone are all under compression (negative axial force) and the increase in stability is offered by the lower nails only. The top nails are not providing any resistance since the axial forces are not mobilized in the nails unlike the dry case where groundwater is neglected. In this case, it can be observed that in the case of unsaturated soils relatively large displacements are required to mobilize
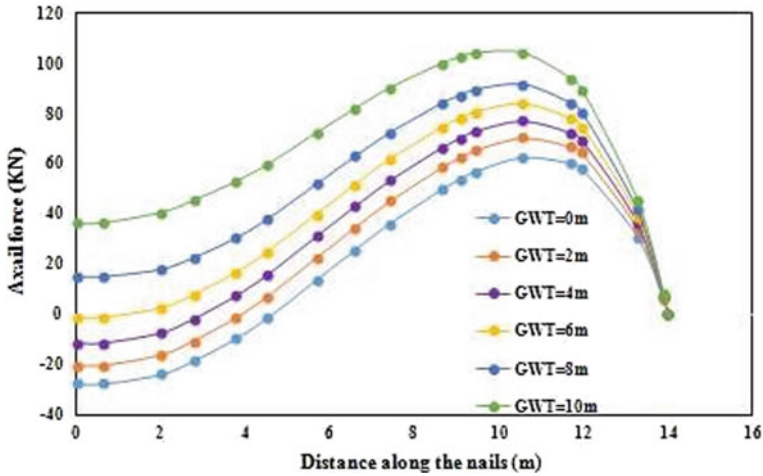
Fig. 8 Axial force variation with groundwater changes along the nail length for the bottom nail (Soil-B)

the nail forces. If the more axial force develops on the nails, then only there will be increase in the stability of the slope. This observation is seen in (Fig. 9).

3   Conclusions

Three different homogenous soils with different mechanical and hydraulic properties were modeled to study the effects of groundwater variations in soil nailed slopes. From the results, it can be concluded that with the increase in the groundwater table the factor of safety reduces, and the deformations increase as the result of reduction in suction for both reinforced and unreinforced slopes. In the case of reinforced slopes, the peak axial force that develops in the bottom nails also increases with rise in the groundwater as the result of large deformations. The results also show how the performance of the nails in mobilizing their axial force is affected by the presence of seepage compared to the dry soil conditions. The axial forces that are the main sources of stability for soil nailed structures are not mobilized as required in the case of the presence of groundwater flow. For the axial forces in the nails and basic reinforcement mechanism of nails to develop a relatively lager displacements are required in case of unsaturated soils. But this again has to be checked from serviceability criteria where the deformations should lay within the acceptable ranges.
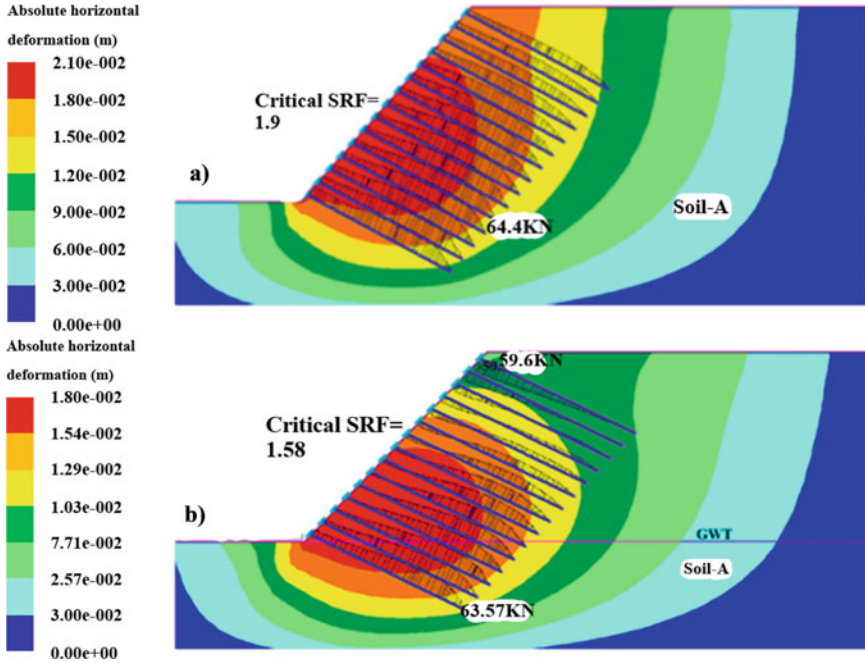
Fig. 9 Axial force distribution along the nails for Soil-A **a** Under dry condition, **b** groundwater at 10 m

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