Lateral Earth Pressure Analysis of Soil-Nailed Walls under Static Conditions using Finite Difference Method

Alimohammad Sheikhbahaei
Dept. of Civil Eng., Isfahan University of Technology, Isfahan, Iran
Amir M. Halabian, S. Hamid Hashemolhosseini
Dept. of Civil Eng., Dept. of Mining Eng. – Isfahan University of Technology, Isfahan, Iran

ABSTRACT
Soil Nailing is a popular helpful method to reinforce slopes and embankments. Using this method for improving slope stabilities has been widely increasing. Soil nailing construction commonly includes three basic aspects: excavation, nail installation and face stabilization. The present paper has studied distribution of lateral earth pressure behind wall facing and focuses on parameters affecting soil-nail wall behaviour. Therefore, a three-dimensional finite difference model has been developed in order to investigate the soil-nailed wall behaviour. The soil behaviour has been predicted using an Elastic-Perfectly-Plastic accompanied with Mohr-Coulomb failure criterion. The numerical model has modelled soil medium along with nail inclusions and shotcrete facing. The interaction behaviour between different components of the structure has been incorporated appropriately. Effects of different factors such as nail inclination angle, nail length, slope inclination, nail layout on wall surface, soil density and soil strength properties are examined.

RÉSUMÉ
Le clouement de sol est une technique tout à fait efficace pour renforcer des pentes et des remblais de sol. Suivre cette méthode s'était de plus en plus levé pour améliorer la stabilité de pente. Le sol clouant la construction inclut généralement trois aspects de base : excavation, installation d'ongle et stabilisation de visage. Les ongles sont insérés dans le sol par le forage ou le jointoiement et sont habituellement arrangés dans des directions horizontales et verticales. Dans la recherche actuelle les paramètres affectant le comportement de mur de sol-ongle sont étudiés. Par conséquent, un modèle tridimensionnel de différence finie a été développé afin d'étudier le comportement de structure. Le comportement de sol a été prévu par un élastoplastique utilisant le critère d'échec de Mohr-Coulomb. Le modèle simule le milieu de sol, les inclusions d'ongle et également le comportement d'interaction de revêtement de béton projeté suivre la méthode de différence finie. Une étude complète a été entreprise pour examiner des effets de différents facteurs tels que l'inclination d'ongle, longueur d'ongle, modèle de longueur, la pente, arrangement de barres d'ongle sur l'exécution de la structure.

1 INTRODUCTION

In recent years, soil nailing as a method to reinforce soil structures has gained a lot of popularity. This method is commonly used to reinforce slopes and embankment in both temporary and permanent applications. The method of construction usually involves three basic aspects including: excavation of soil mass, nail installation and application of shotcrete to stabilize facing. The reinforcement used to stabilize the soil structure are typically nail bars made of steel which may be inserted as either solid or cable elements. Another essential component of soil-nailed walls is grout which significantly influences wall performance. Grout can be pumped shortly after the nail bar is placed in the pre-drilled hole. Nail bars are connected to the surface of the excavation using a facing system. Soil nailing has many similarities to common reinforced soil walls and gravity walls but it has many discrepancies compared to those walls. Despite disparities during construction procedures, soil-nailed wall present different behavior concerning stress distribution. As the soil-nailed wall construction proceeds, it causes stress relief during this process unlike common gravity walls which results in a stress increase on the nails. It should be noted that mechanism which stress develops along reinforcement is generally different to those like geosythetic reinforced walls. This is because nail features act differently to common strip reinforcements. Thus the failure mechanisms are associated to a number of factors like properties of nails, the arrangement of nails in construction, construction procedure, etc.

The global stability of a soil-nailed wall is concerned with the overall stability of the reinforced soil mass. For this failure mode the retained mass will go beyond the resistance provided along the slip surface and the resistance supplied by intersected nails. This global stability is evaluated through many different approaches mostly based on Limit Equilibrium analysis. Using two dimensional limit equilibrium principles, the potentially sliding soil mass is considered as a rigid block. Afterward, the stability factor of safety is calculated through establishing global force and moment equilibrium. Therefore different types of failure surfaces like planar, bi-linear, parabolic, log spiral and circular can be presumed in order to analyze the global stability of soil-nailed walls. In addition to the general failure mechanisms, these walls expose more potential failure modes which may include breakage of nails, nail bending and shear failure with plastic hinges in nails, nail-soil pullout failure, nail tensile failure, bar-grout failure, etc.

Even though conventional limit equilibrium methods present some information about internal and global stability of soil nailed wall, they include some deficiencies. For instance ground settlements in deep excavations that have been observed in the field may bear serious consequences to safety of other building near the area (Zhang et al. 1993). Since traditional methods of design cannot anticipate general behavior of soil-nailed wall and its deflections, then it's much more crucial to monitor the behavior of the structure and observe its deflections. The numerical methods therefore have been employed to obtain better predictions about behavior of soil-nailed walls including soil deformations.

Some researchers have studied the behavior of soil-nailed walls using numerical procedures; most have applied a two dimensional (2-D) finite element method for analysis of the soil-nailed wall. Many of these studies focus on 2-D plain strain analysis of soil-nailed walls which cannot adequately simulate soil-nail interaction mechanism. In addition, some features of soil which has gone under excavation are not reflected properly in the soil constitutive law. Albeit theses analyses present more satisfactory perception from behavior of soil-nailed walls, they include lots of shortcomings due to a number of factors. As a result it can be concluded that 3-D numerical analysis is certainly more reliable and the final results are much more satisfactory to understand soil-nailed wall behavior and perform a refined analysis of these walls.

Smith et al. (1993) have proposed a 3-D finite element method model for the analyses of soil-nailed walls. Results obtained from the analyses indicated that at the failure moment the locus of maximum tensile forces and also maximum shear forces developed in nails was approximately conformed to the actual failure surface.

Smith and Su (1997) modeled a soil-nailed wall curved in plan using a 3-D finite element method for construction, service and ultimate loading conditions. The information obtained from those analyses contributes to deeper understanding of the behavior of soil-nailed walls. It was ascertained that soil nailing technology significantly improves the stability of a wall during excavation and under service loading. They found out that while a surcharge load is placed in the local area behind the wall head the horizontal displacement will come to rise. The peak vertical settlements occurred in front of the surcharge position when the structure was almost near collapse. The locus of maximum tensile forces was close to the actual failure surface and the maximum tensile force observed in the fourth nail along wall height.

Zhang et al. (1999) investigated the behavior of 3-D soil nailed walls in order to bring a satisfactory estimation of wall deformation. Results concluded that horizontal displacements of wall facing decreased with increasing depth of wall (i.e. increasing distance from surface into the ground). As the excavation depth increases the horizontal displacements increase. The maximum vertical settlements will occur near the top of the wall and its magnitude varies in correspondence with wall facing horizontal displacement variations. Finally results of FEM analysis was compared to those obtained in field observations and it was concluded that FEM analysis is an appropriate method to investigate behavior of these structures

Additionally, further investigations conducted by researchers like, Thompson et al. (1990), Unterreiner, P. et al (1997), Yaung et al. (2000) have considered the behavior of soil-nailed walls under static conditions using numerical methods.

2 PROBLEM DEFINITION

In the present research a 3-D numerical model has been developed using finite difference formulation and the performance of soil-nailed walls under static conditions have been considered. Attention was focused to specify influence of important parameters on performance of soil-nailed wall to have a better understanding of wall behavior. In order to simulate the model, the *FLAC3D* computational program has been used. Having better perception of wall deformation the Mohr-Coulomb failure criterion was employed to describe stress-strain behavior of the soil. 1-D cable elements for representing nail bars were used and it's been assumed that these elements are resistant to tension and present no resistance to bending. 2-D liner elements were used to represent wall shotcrete made facing. It should be noted that according to the program's pre-defined assumptions, the interaction mechanisms between different elements have been taken into account automatically depending on soil-element interaction parameters. Some parametric studies were conducted to understand different factors contributing to the distribution of lateral earth pressure behind the wall facing.

3 NUMERICAL SIMULATION

As mentioned above, a 3-D finite difference model (FDM) has been developed to examine the behavior of soil-nailed walls. Due to the repetitive arrangement of nails along the length of the excavation, only a slice of the soil mass between the vertical plane crossing nail centerlines and another vertical plane at the midpoint of the adjacent nails was examined. The geometry and mesh configuration used for study is shown in Figure 1.

The finite difference mesh is made up of quadrilateral continuum elements representing the soil medium. Each zone created in the model is automatically discretized into sets of tetrahedral elements by the code which, by default, prescribes two overlays for all zones in the model.

Boundary conditions are located so that they have negligible effects on the structure response. The side faces are restrained by rollers and the bottom of the model is assumed to be fixed. It should be noted that for the corner region far away from the excavation top a somewhat larger mesh has been used, but for the region near to excavation face a fine mesh is utilized. The construction process includes 5 stages of soil mass excavation, borehole drilling, nail placement and shotcrete application (Figure 2).

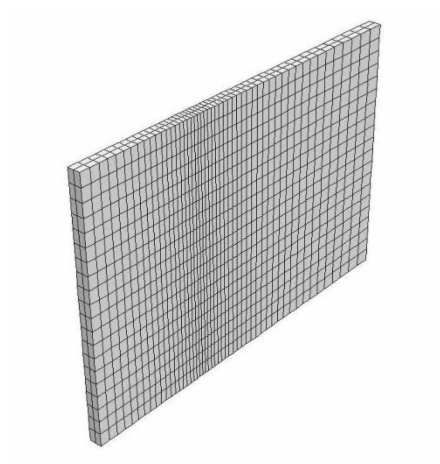

Figure 1. Mesh configuration used for soil-nailed wall

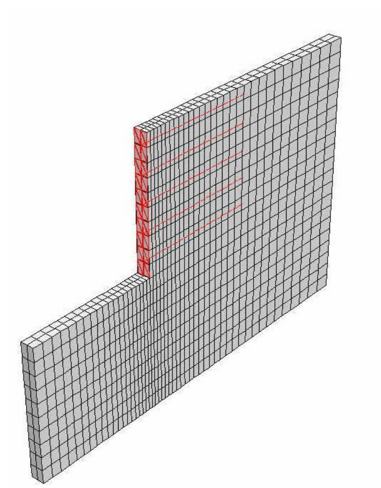

Figure 2. Soil-nailed wall after last stage of construction

The data needed to estimate soil strength properties was collected from pressure meter tests and tri-axial test. These data are presented in Table 1.

Table 1. Characteristics of Soil, nails and shotcrete facing

Soil Properties	Soil	Nail	Facing
Elastic Modulus (MPa)	50	$2x10^5$	$25x10^3$
Poisson Ratio	0.3	0.3	0.2
Cohesion (kPa)	5	-	-
Friction Angle (^{o})	28	-	-
F_y[1] (MPa)	-	460	-
τ_{ult}[2] (kPa)	-	60	-
γ (kN/m^3)	19	78	24

[1]tensile yield strength

[2]ultimate shear stress between nail and soil

The nail bars are modeled using 1D cable elements which are resistant to tension but show no resistance to bending. A nail bar is made of several CableSEL structural elements in *FLAC3D*; each cable structural element is defined by its geometry, material and grout properties and is assumed to be a straight segment of uniform cross-sectional and material properties lying between two nodal points (*FLAC3D*'s Manual 1996). Cable elements usually behave as an elastic material which can yield in both tension and compression but cannot show any resistance to bending. Cables are commonly grouted such that force develops along its length in response to relative motion between the cable and the grid (*FLAC3D*'s Manual 1996). Basically there are three necessary aspects during simulation of nail bars as cable elements; first the axial behavior of the cable itself; secondly the shear behavior of the grout annulus and third the normal behavior of the grout interface. Then in order to take into account axial behavior of nail bars a one-dimensional constitutive model will be adequate for describing it. Thus the axial stiffness known as K is determined based upon nail bar cross-sectional area A, its Young's Modulus E, and its length L ("Eq. 1"). Figure 3 shows a tensile and compressive yield strength F_t, F_c that can be assigned to a cable element so that cable forces cannot develop that are greater than these limits. Without specifying these limits, a cable will undergo infinite strength for loading in that direction.

$$K = \frac{AE}{L} \quad [1]$$

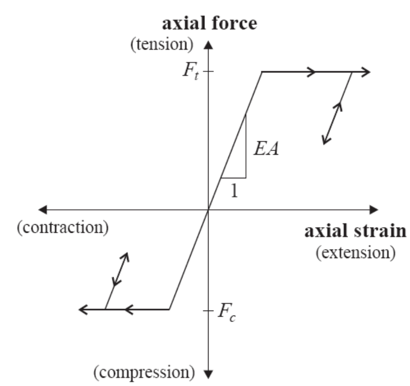

Figure 3. – Cable material behavior (*FLAC3D*'s Manual 1996)

The most general method to determine the properties for fully bonded soil-nail behavior is to conduct pull-out tests on small segments of grouted nail in the field. Typically it has been assumed that segments with 50 cm length are grouted into boreholes. The end of these segments are pulled with a jack mounted at the surface and attached to the cable via a barrel and wedge-type anchor. The force applied to the nail is plotted against deformation of the nail. Consequently, the grout shear stiffness is obtained through calculating the slope of this curve. Therefore according to pull-out test results grout shear stiffness assumed to be as shown in "Eq. 2".

$$E_g = 7 \times 10^3 \frac{kN}{m}/m \qquad [2]$$

Other necessary parameters for nails and facing are summarized in Table 1.

In general, grout for soil nails is commonly a neat cement mortar that fills the annular space between nail bar and surrounding ground and functions to transfer induced stresses developed in soil mass to nail bars. Soil-nail interface shear is naturally cohesive and frictional. To simulate this behavior of grout along the nails, a spring-slider system is applied along the nodal point of the cable. Spring elements represent the shear behavior of the grout, while slider elements function so that the cohesive behavior between the soil and nail is simulated (*FLAC3D*'s Manual, 1996). The idealized mechanism for soil-nail interaction is illustrated in Figure 4. It should be noted that there are two available methods to model the nail end in *FLAC3D.* In the present research, fixing the nail end type is incorporated so that there is compatibility between the soil and nail displacements at the node where the cable element and liner elements have coincided together.

Similar to the nail bars, the wall facing is another crucial component of the soil-nailed wall that has been modeled using liner elements. A liner element is made of several LinerSEL elements which can bear both tensile and compressive stresses in the normal direction to their plane. Taking into account the interaction mechanism, a spring-slider system is incorporated in the tangent direction to the soil liner interface plane. A liner spring with limited tensile strength placed in normal direction is included in order to simulate the interaction between soil and liner elements properly.

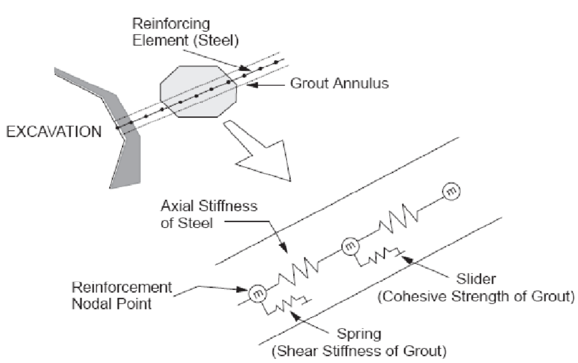

Figure 4. Mechanical scheme of interaction mechanism between soil-nail (FLAC3D's Manual 1996)

4 SOIL CONSTITUTIVE BEHAVIOR

Having a better prediction of soil behavior under static conditions, an Elastic-Perfectly-Plastic stress-strain behavior was assumed to govern soil constitutive law. Therefore the material obeyed the Mohr-Coulomb yield criterion.

5 GOVERNING EQUATIONS AND SOLUTION

As described previously, *FLAC3D* was employed as an explicit FDM tool to analyze soil-nailed walls. Mechanics of each continuum can be derived from main principles, i.e. definition of strain and motion laws along the use of constitutive equations defining the material as an idealized system. The equation of motion and equilibrium governed on an unbounded medium is expressed as below ("Eq. 3"):

$$\sigma_{i,j} + \rho b_i = \rho \frac{dv_i}{dt} \qquad [3]$$

Where ρ is the mass per unit volume of the medium, b_i is the body force per unit mass, and dv_i/dt is the material derivative of the velocity. In the FDM, these governing equations represent the motion of an elementary volume of the medium subjected to the forces. In case of static equilibrium of the medium, the acceleration dv_i/dt is zero, and "Eq. 3" reduces to the partial differential equations of equilibrium ("Eq. 4")

$$\sigma_{i,j} + \rho b_i = 0 \qquad [4]$$

Constitutive laws usually come in form of following equation ("Eq. 5"):

$$\left[\breve{\sigma}\right]_{ij} = H_{ij}(\sigma_{ij}, \xi_{ij}, \kappa) \qquad [5]$$

which $\left[\breve{\sigma}\right]_{ij}$ is the co-rotational stress-rate tensor. H_{ij} is the given function related to Mohr-Coulomb yield criterion, and κ is a parameter that takes into account the history of loading and ξ_{ij} is a strain rate tensor.

Figure 5 displays the computation cycle incorporated in *FLAC3D* based upon finite difference formulation. The code uses an explicit "time-marching" finite difference solution scheme. For each timestep the calculation sequence can be summarized as below:

- New strain rates are derived from nodal velocities
- Constitutive equations are used to calculate new stresses from the strain rates and stresses at the previous time.
- The equations of motion are invoked in order to derive new nodal velocities and displacements from stresses and forces.

The sequence is repeated at every timestep, and the maximum unbalanced (out-of-balance) force in the model is monitored. This force will either approach zero indicating that system has reached equilibrium conditions or it will approach a constant (i.e. non-zero value) implying that a portion of the entire model is a steady-state (plastic) flow of material. This trend is the explicit calculation approach and each complete cycle in this trend is recognized as a timestep (*FLAC3D*'s Manual 1996).

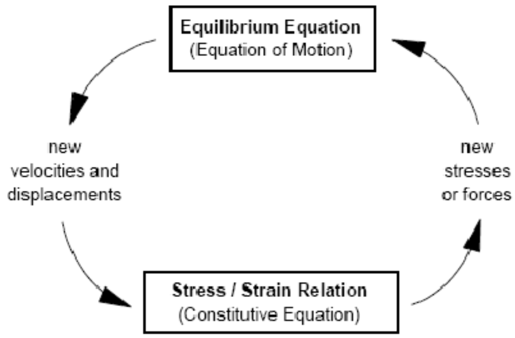

Figure 5. Basic explicit calculation cycle (*FLAC3D*'s Manual, 1996)

For a static or steady state solution, the rate of kinetic energy in the model should reach a negligible value. This purpose is achieved through damping the equations of motion. At the end of the static solution process, the model will be either at an equilibrium state or at steady flow state which a part (or somewhat all) of the model is failed (i.e. unstable) under the applied loading conditions. To determine whether or not the model undergoes instability or encounters the equilibrium, the maximum nodal force vector referred to as unbalanced force is used as the convergence parameter.

Figure 6 demonstrates maximum unbalanced force for soil-nailed wall model during solution steps and it can be seen that the maximum unbalanced force has approached zero indicating equilibrium conditions

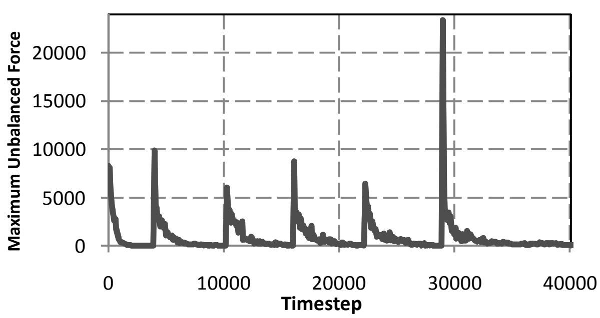

Figure 6. Maximum unbalanced force development process in model during timestepping (static solution)

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6 ANALYSES RESULTS

The analysis of the soil-nailed wall was carried out during timesteps which simulated actual wall stages of construction. The construction process was modeled by the successive excavation of soil followed by placement of nails bars and then applying shotcrete. In *FLAC3D* these sequences were established using the feature "null model". This feature subtracts a specified area from the model, thereby simulating the excavation process of a soil-nailed wall (i.e. removing soil mass), placement of nail bars and application of shotcrete. It should be noted that initial state of equilibrium has to be established before any stage proceeds. Afterward, as each excavation ends, the equilibrium conditions (according to the maximum unbalanced force) will be examined in order to ensure whether or not the model meets equilibrium conditions to resume the next stage.

For the present study, the nail inclination and length are selected as the essential parameters affecting the static behavior of the soil-nailed walls. In the parametric studies it has been assumed that excavation depth is 9 m and horizontal spacing of nail bars is 0.9 m. The wall is constructed in 5 stages where each stage has a 1.8 m depth. In this study, the distribution of lateral earth pressure behind wall facing is considered. Therefore, the results of the analyses for different stages of construction have been obtained and compared with the results of conventional empirical methods proposed by Peck, R. 1984. According to Peck's method, the distribution of lateral earth pressure for soil having $\gamma H > 4C$ will be trapezoidal and its magnitude is estimated around $0.3\gamma H$. Considering results of the analyses (Figure 7), it can be concluded that the empirical methods provide conservative estimation of lateral earth distribution behind wall facing. A comprehensive parametric study has been conducted to investigate the effects of different parameters on the distribution of lateral earth pressure behind the wall facing.

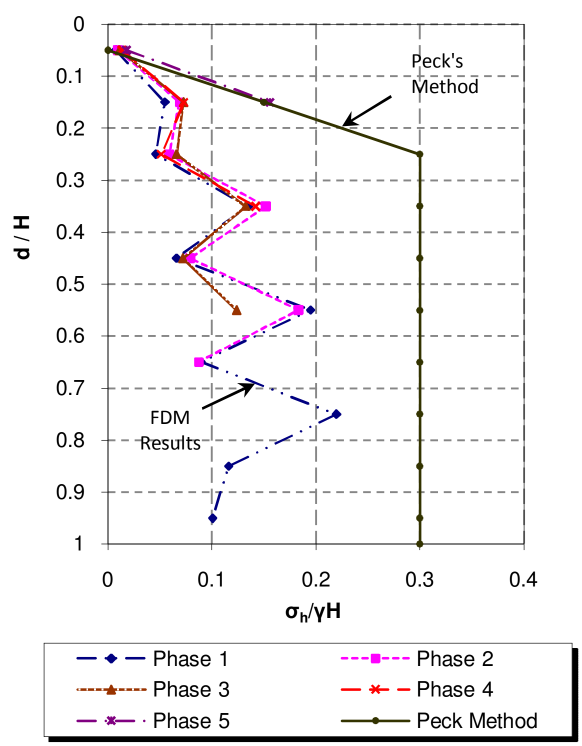

Figure 7. Lateral earth pressure distribution behind wall facing at different stages of wall construction compared with Peck's method.

6.1 Effect of Nail Inclination

The effect of different nail inclination angles on the performance of the structure has been considered. As illustrated in Figure 8, it can be inferred that as the nail inclination angle increases the lateral earth pressure will diminish. However the lessening effect of nail inclination angle on earth lateral pressure will not remain persistent. After a specific value of nail inclination angle varying roughly in the range of 15° to 20° it can be observed that the increase in nail inclination angle will result in a slight increase of lateral earth pressure behind wall facing. As long as the nail inclination angle transcends 25°, it should be considered as a destabilizing parameter for soil-nailed wall.

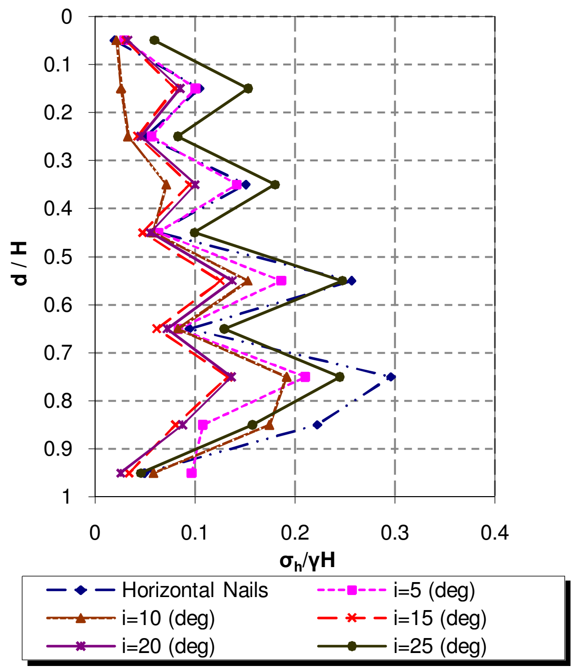

Figure 8. Effect of nail inclination angle on lateral earth pressure distribution behind wall facing

6.2 Effect of Nail Length

The effect of nail length on the distribution of lateral earth pressures behind the wall facing is illustrated in Figure 9. It is evident that lengthening the nails to about 9 m will result in a decrease in the lateral earth pressure behind wall facing, whereas for those walls with nail lengths over 9 m the rate of lateral earth pressure behind wall facing is not considerable.

6.3 Effect of Soil Strength Properties

Of important factors influencing soil-nailed wall performance are soil strength properties. These parameters have affected the distribution of lateral earth pressures behind wall facing. As shown in Figure 10, it was noted that increasing soil cohesion results in improving soil shear strength and therefore reduces the lateral earth pressures behind the wall facing. Additionally, according to Figure 11 it can be concluded that increasing the internal friction angle of the soil will provide a diminished distribution of lateral earth pressure behind the wall facing.

6.4 Effect of Soil Density

It was observed that increasing soil density will result in slight increase in lateral earth pressure behind wall facing. Therefore it can be concluded that soil density variations will not much affect on distribution of lateral earth pressure behind wall facing (Figure 12).

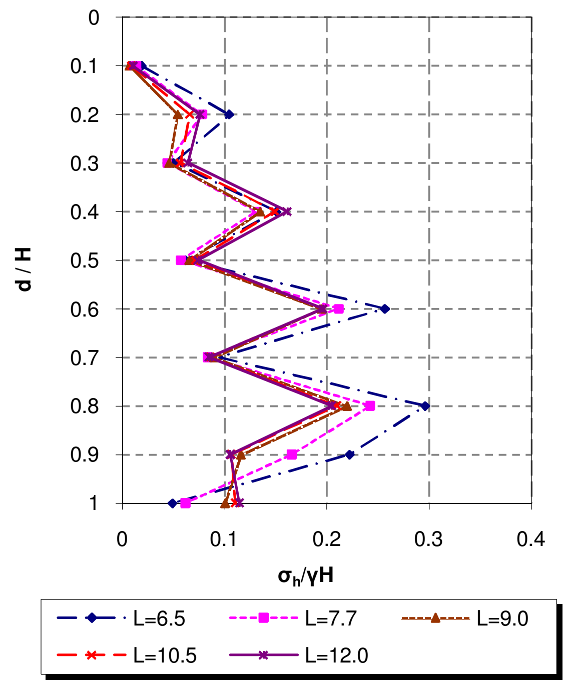

Figure 9. Effect of nail length on lateral earth pressure distribution behind wall facing

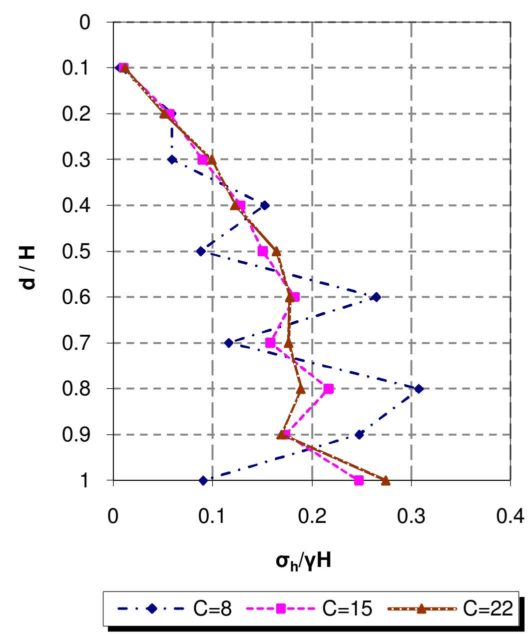

Figure 10. Effect of soil strength properties (Cohesion) on Lateral earth pressure distribution behind wall facing

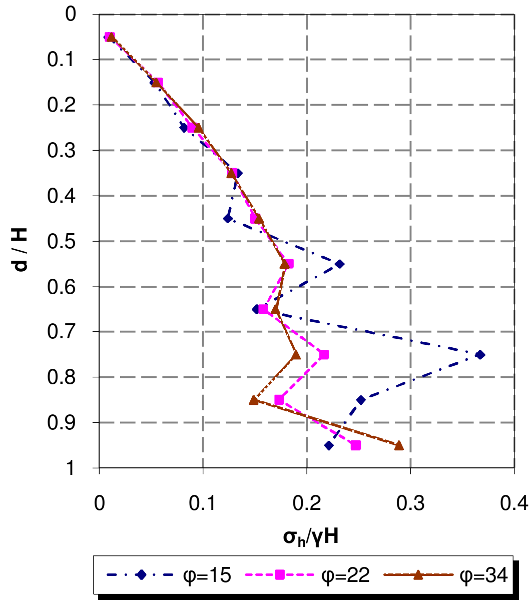

Figure 11. Effect of soil strength properties (Internal friction angle) on Lateral earth pressure distribution behind wall facing

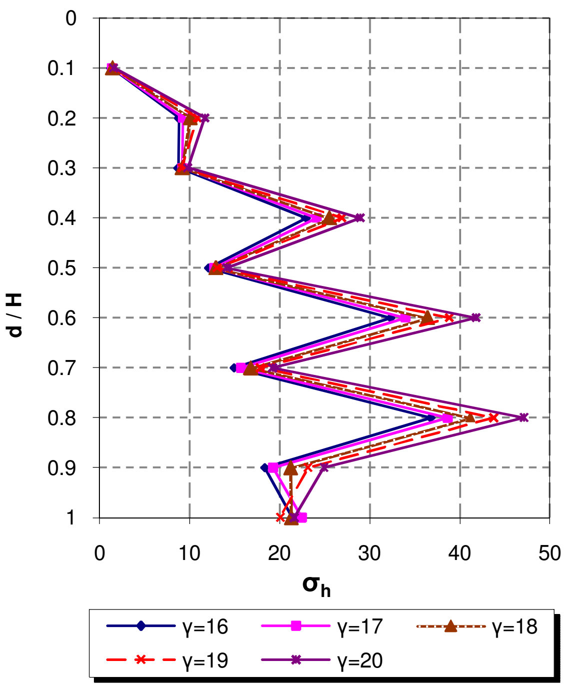

Figure 12. Effect of soil density on Lateral earth pressure distribution behind wall facing

6.5 Effect of Nail Length Pattern

Three different length patterns were considered during the analyses (Figure 13). The short nails are 6.5 m length and long nails are 9 m length.

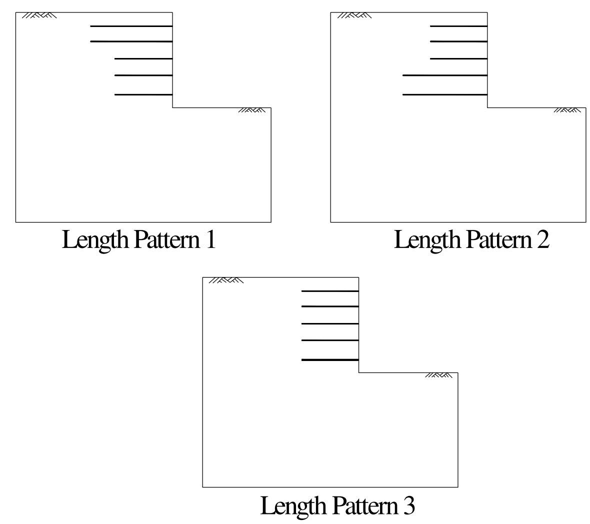

Figure 13. Different nail length patterns used for analyses

Using different nail length patterns influenced the soil-nailed wall performance. According to the results, it is worth noting that using dissimilar pattern of nails along wall facing will resulted in a reduction of lateral earth pressure behind the facing (Figure 14).

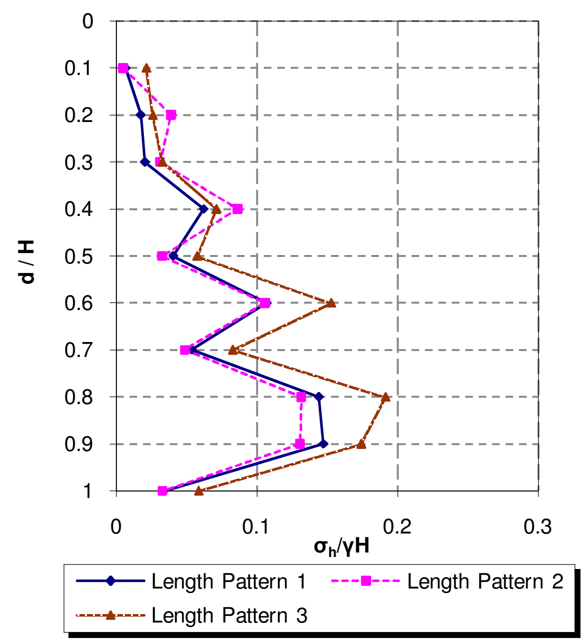

Figure 14. Effect of soil density on Lateral earth pressure distribution behind wall facing

7 CONCLUSIONS

Lateral earth pressure analyses of a 9 m high soil-nailed wall using finite difference method were conducted in the present paper. The soil medium was simulated using quadrilateral continuum elements along with CableSEL and LinerSEL elements to simulate nail bars and shotcrete facing. The interaction behavior among different components of structure was simulated carefully in order to return an accurate response of the structure. Conducting a comprehensive parametric study, the results of the analyses highlight the influence of different parameters on the performance of soil-nailed walls. The preceding finite difference analyses of soil nailed walls provide information concerning distribution of lateral earth pressure behind wall facing. Pertaining to the results of the analyses, it was observed that using empirical methods for estimating lateral earth pressure leads to conservative predictions of lateral earth pressure distributions behind the facing. Further, research implies that using nails with an inclination angle varying in the range of 0° to 15° along the wall height results in a reduction of lateral earth pressures. However, inclined nails with higher angles of inclination result in increased lateral earth pressures behind the facing. Lengthening the nails up to 9 m will result in a lateral earth pressure reduction, while using longer nails will not have much effect on the lateral earth pressure distribution. Moreover, the lateral earth pressures behind the wall facing decreased as the soil strength properties such as soil cohesion and internal friction angle enhanced, whereas the results show that the soil density has not much affected the lateral earth pressure distribution despite a slight increase in enhancing soil density. Using different nail length patterns along wall height influenced the performance of the soil-nailed wall so that by employing decreasing or increasing length patterns along the wall height will affect the lateral earth pressures behind the wall facing.

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REFERENCES

FLAC3D's Manual 1996, Itasca Consulting group, Inc., Minneapolis, Minnesota, USA.

Ho, D. K. H. and Smith, I. M., 1993, Modeling of Soil Nailing Construction by 3-Dimensional Finite Element Analysis, *Retaining Structures*, Thomas Telford, London, pp. 515- 528.

Peck, R.B. and Terzaghi, K.,1967& 1984, *Soil Mechanics in Engineering Practice,* John Wiley and Sons, Inc., New York, N. Y., USA.

Smith IM, Su N. 1997, Three-dimensional FE analysis of a nailed soil wall curved in plan. *International Journal for Numerical and Analytical Methods in Geomechanics*; 21:583±97.

Thompson, S. R. and Miller, I. R., 1990, Design, Construction and Performance of a Soil Nailed Wall in Seattle, Washington, Design and Performance of Earth Retaining Structures, *Geotechnical Special Publication*, No. 25, ASCE , pp. 629- 643.

Unterreiner, P., Benhamida, B. and Schlosser, F., 1997, Finite Element Modeling of the Construction of a Full-Scale Experimental Soil- Nailed Wall. French National Research Project CLOUTERRE, *Ground Improvement*, Vol. 1, No. 1.

Yuang, M, Z. and Drumm, E. C., 2000, Numerical Analysis of the Load Transfer and Deformation in a Soil Nailed Slope, *Numerical Methods in Geotechnical Engineering*, pp. 102- 115.

Zhang, M. and Song, E., Chen, Z., 1999, Ground movement analysis of soil nailing construction by three-dimensional (3-D) Finite element modeling (FEM), *Computers and Geotechnics* 25:191±204.