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Coupled Effect of Soil Nail/Slope Systems

쏘일네일-사면의 상호작용 효과

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요 지

본 연구에서는 쏘일네일로 보강된 사면을 한계평형 해석법과 2차원 유한차분 해석을 수행하여 그 결과를 비교·분석하였다. 특히, 유한차분법을 이용한 FLAC 2D를 바탕으로 하는 커플링 해석에 주안점을 두었으며, FLAC을 이용하여 전단강도감소기법에 따른 보강사면의 안전율을 계산하기 위해 FLAC의 내장언어인 FISH를 이용하여 작성하였다. 커플링 해석에서 쏘일네일에 의한 안정화된 사면을 해석하기 위해 쏘일네일 거동과 사면안정을 동시에 고려하였다. 따라서 본 연구에서는 이 두 방법을 적용하여 쏘일네일의 사면내 설치위치, 설치각도, 설치간격 등에 따라 각각의 활동파괴면 및 안전율을 비교·분석하였으며 강도정수 감소법을 적용한 해석기법의 적용성과 타당성 분석을 수행하였다.

Abstract

In this paper, a numerical comparison of predictions by limit equilibrium analysis and finite difference analysis is presented for slope/soil-nail system. Special attention is given to the coupled analysis based on the explicit-finite-difference code, FLAC 2D. To this end, an internal routine (FISH) was developed to calculate a factor of safety for a soil nail slope according to shear strength reduction method. The case of coupled analyses was performed for soil nails in slope in which the soil nails response and slope stability are considered simultaneously. In this study, by using these methods, the failure surfaces and factors of safety were compared and analyzed in several cases, such as toe, middle and top of the slope, respectively. Furthermore, the coupled method based on shear strength reduction method was verified by the comparison with other analysis results.

Keywords : Factor of safety Coupled/ uncoupled analysis, Limit equilibrium analysis, Shear strength reduction, Soil nail-slope system

1. Introduction

The fundamental concept of soil nailing consists of placing in the ground passive inclusions, closely spaced, to restrain displacement and limit decompression during and after excavation. The design of soil-nail retaining structures is currently based on limit equilibrium approaches (Stocker et al., 1979; Shen et al., 1981; Schlosser, 1982). This methods have been developed to evaluate the global stability of the soil nailed mass and/or the

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surrounding ground, taking into account the shearing, tension, or pull-out resistance of the inclusions crossing the potential failure surface.

The type of method has been used to investigate the soil nail/slope system, which is analyzed as a continuous elastic or elasto-plastic medium using either finite-element or finite-difference formulations. This method provides coupled solutions in which the nail response and slope stability are considered simultaneously and thus, the critical surface invariably changes due to the addition of nails.

For slopes, the factor of safety *F* is traditionally defined as the ratio of the actual soil shear strength to the minimum shear strength required to prevent failure (Bishop, 1955). As Duncan (1996) points out, *F* is the factor by which the soil shear strength must be divided to bring the slope to the verge of failure. Since it is defined as a shear strength reduction factor, an obvious way of computing *F* with a finite element or finite difference program is simply to reduce the soil shear strength until collapse occurs. The resulting factor of safety is the ratio of the soil's actual shear strength to the reduced shear strength at failure. This shear strength reduction technique was used as early as 1975 by Zienkiewicz et al., and has since been applied by Matsui et al. (1992), Ugai et al. (1995), Cai & Ugai (2000) and You et al. (2000), etc.

The shear strength reduction technique is used in this study. It has a number of advantages over the method of slices for slope stability analysis. Most importantly, the critical failure surface can be found automatically. Application of the technique has been limited in the past due to a long computational run-time. However with the increasing speed of the desktop computer, the technique is becoming a reasonable alternative to the method of slices, and is being used increasingly in engineering practice.

In this study, factors of safety obtained with the shear strength reduction technique were investigated for the soil nail on the stability of the homogeneous slope. The case of an uncoupled analysis using limit equilibrium analysis and subsequently the response of coupled analysis based on the shear strength reduction method were performed to illustrate the changes of critical surface invariably due to addition of nails on the soil nail-slope stability problem.

2. Reinforced Slope Stability Analysis

2.1 Limit Equilibrium Method (LEM)

The reinforcing effect of soil nail was simplified as an axial tension that acted at the base of the slice where the slip surface intersects the soil nail. Based on the concept of Bishop's simplified method, this approach is conventionally used to calculate the safety factor of slopes reinforced with soil nails. Bishop's simplified method takes the equilibrium of forces in the vertical direction for each slice to calculate the normal force at the base of the slice, and gives the safety factor by taking the equilibrium of moments about the centre of the slip circle for all slices. If the axial tension is directly used to calculate the normal force at the base of the slice where the slip surface intersects the soil nail, the axial tension is implicitly decomposed into two components: one in the vertical direction and the other tangential to the base of the slice to calculate the resisting moment of the axial tension about the center of the slip circle, as shown in Fig. 1.

This method can be explained below:

The equilibrium of forces in the vertical direction gives

$$N\cos\alpha + S_m\sin\alpha = W + T\sin\theta \qquad (1)$$

The shear strength along the base of a slice is given by

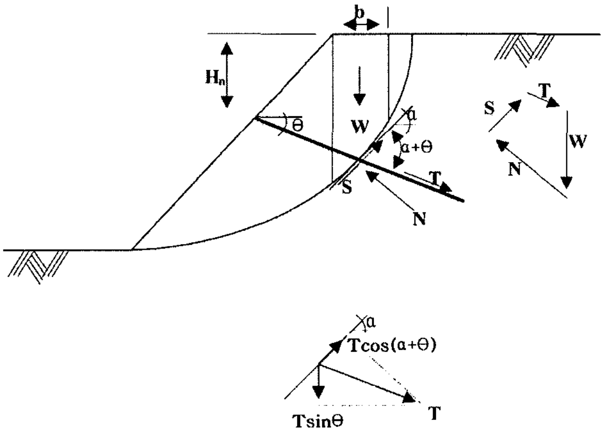


Fig. 1. Safety factor of slopes with nails

$$S_m = \frac{1}{F_s m_\alpha}(cb + N \tan \alpha) \quad (2)$$

The shear force can be solved from Equations (1) and (2)

$$S_m = \frac{1}{F_s m_\alpha}[cb + (W + T\sin\theta)\tan\alpha] \quad (3)$$

where, $m_\alpha = \cos\alpha(1 + \tan\alpha\frac{\tan ø}{F}) = \cos\alpha + \sin\alpha \tan ø_m$

The equilibrium of the resisting moment and the driving moment gives

$$\sum[W\sin\alpha - T\cos(\alpha+\theta)] = \sum\frac{1}{Fm_\alpha}[cb + (W + T\sin\theta)\tan\phi] \quad (4)$$

Thus the safety factor is given by

$$F = \frac{\sum[cb + W\tan\phi + (T\sin\theta\tan\phi)]/m_\alpha}{\sum[W\sin\alpha - T\cos(\alpha+\theta)]} \quad (5)$$

Rearranging Equations (5), the safety factor can be expressed as

$$F = \frac{\sum[cb + W\tan\phi]/m_\alpha + \sum T_e}{\sum W\sin\alpha} \quad (6)$$

Where, T_e is an additional shearing resistance on the slip surface (Cai et al., 2003), and is tangential to the base of the slice where the slip surface intersects the anchor.

$$T_e = \frac{FT}{1 + \tan\alpha\tan\phi_m}[\cos(\alpha+\theta) + \sin(\alpha+\theta)\tan\theta_m] \quad (7)$$

2.2 Shear Strength Reduction Method (SSRM)

To calculate the factor of safety of a slope defined in the shear strength reduction technique, a series of stability analyses are performed with the reduced shear strength parameters c^{trial} and ϕ^{trial} defined as follows (Fig. 2).

$$c^{trial} = \frac{1}{F^{trial}}c \quad (8)$$

$$\phi^{trial} = \arctan\left(\frac{1}{F^{trial}}\tan\phi\right) \quad (9)$$

where c, ϕ are real shear strength parameters and F^{trial} is a trial factor of safety. Usually, initial F^{trial} is set to be sufficiently small so as to guarantee the system to be stable. Then the value of F^{trial} is increased by F^{inc} values until the slope fails. After slope fails, the F^{start} is replaced by the previous F^{low} and F^{inc} is reduced by 1/5. Then the same procedure is repeated until the F^{inc} is less than user-specified tolerance (ε).

Fig. 3 shows the flowchart of the routine to calculate a factor of safety. This iterative procedure is based on the incremental search method. This final value of F^{low}, by definition, is identical to the one in limit equilibrium analysis. It should be noted, however, that in the finite

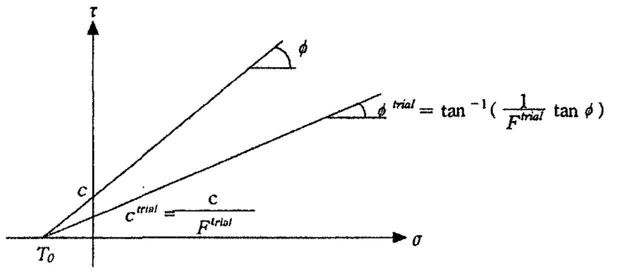


Fig. 2. A relationship between the actual strength and a strength reduced by a trial factor of safety

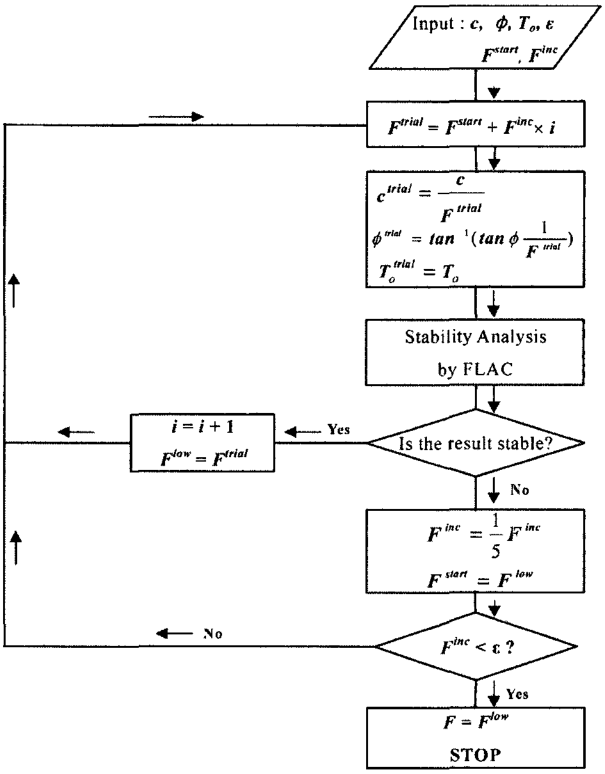


Fig. 3. Flowchart of the calculation routine for safety factor

element and finite difference methods, local equilibrium is satisfied everywhere, whereas in the limit equilibrium analysis, only global equilibrium for the sliding mass is considered in the analysis.

3. Model Slope

The response of a slope/nail system is analyzed by using a two-dimensional explicit-finite difference approach. The mesh consists of solid elements and is assumed to be resting on a rigid layer, and the vertical boundaries at the left- and right-hand sides are assumed to be on rollers to allow movement of soil layers.

The soil nail element is assumed to remain elastic through the analysis, while the surrounding soil is idealized as a Mohr-Coulomb elasto-plastic material. This model was selected from among the soil models in the library of FLAC 2D, the commercial explicit finite-difference package used for this work. Factors of safety are computed based on a shear strength reduction technique using an internal routine (Fish) of FLAC 2D.

The convergence criterion for FLAC is the ratio defined to be the maximum unbalanced force magnitude for all the gridpoints in the model divided by the average applied force magnitude for all the gridpoints. If a model is in equilibrium, this ratio should be close to zero. For this study, a simulation is considered to converge to equilibrium when the ratio becomes less than 10^{-5}.

An idealized slope with a height of 10 m and a gradient of 1V:1.5H and a ground thickness of 10 m is analyzed with a two-dimensional finite different mesh, as shown in Fig. 4. The material parameters used in the analysis is described in Table 1.

The uncoupled analysis is carried out using SLOPE/W based on the limit equilibrium method. When the slope is not reinforced with nails, the shear strength reduction techniques and the Bishop's simplified method gave safety factors of 1.13 and 1.14, respectively. Here, a slope failure that the surface of sliding intersects the slope at its toe is considered. Based on this, it is obvious that the failure mechanism, indicated by the nodal velocities in the shear strength reduction techniques, agrees well with the failure surface given by the Bishop's simplified method, as shown in Fig. 5.

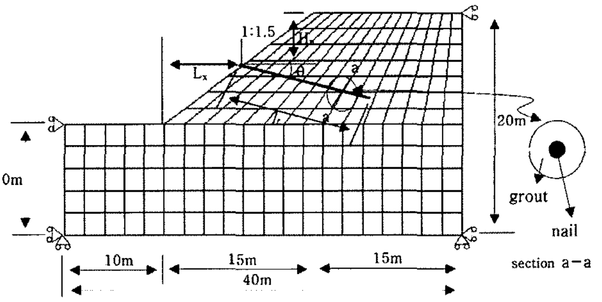


Fig. 4. Model slopes and Finite meshes

Table 1. Material Properties and Geometries

Soil Condition	Unit Weight (kN/m^3)		20.0
	Plastic (Mohr−Coulomb)	Cohesion (kPa)	10
		Friction angle (°)	20°
		Dilation angle (°)	0
	Elastic	Young's modulus (kPa)	2.0×10^5
		Poisson's ratio	0.25
Nail	Young's modulus (kPa)		2.0×10^8
	Diameter of nail (mm)		25.4
	Length of nail (m)		11 ~ 14
	Installation angle (°)		5 ~ 45
	Diameter of boring hole (mm)		100
	Yield stress (kg/cm^2)		4000
Grout	Young's modulus (kPa)		$2.2\times10_7$
	Poisson's ratio		0.2
	Compressive strength (kPa)		2.1×10^4
	Vertical stiffness (kN/m/m)		8.4×10^2
	Shear stiffness (kN/m)		2.2×10^6

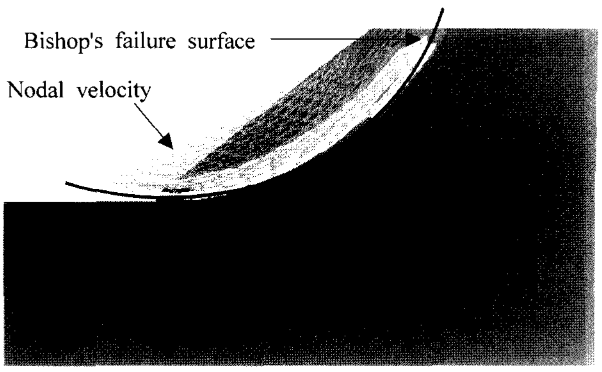


Fig. 5. Comparative results between FLAC2D and Bishop's simplified method

4. Results and Discussions

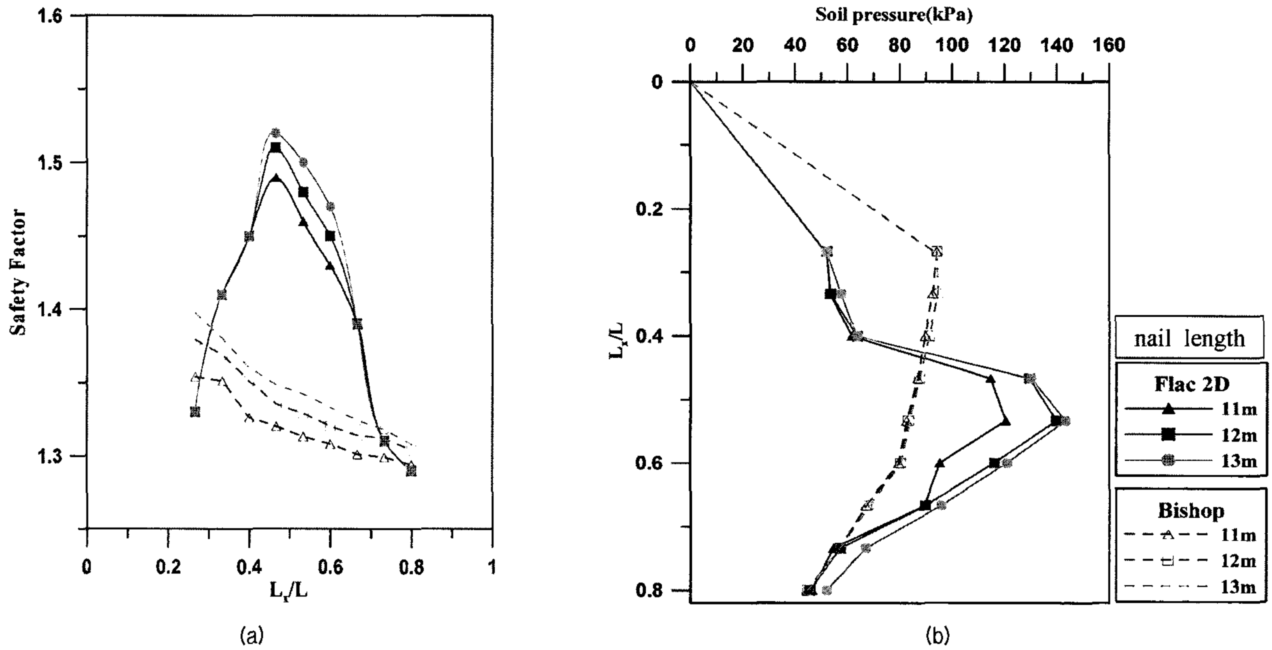
4.1 Effect of Soil Nail Positions

Fig. 6 (a) shows the safety factor as a function of the relative position of the soil nails on the slope. Here, the nail positions in the slope are shown with a dimensionless ratio of the horizontal distance between the slope toe and the nail position, L_x, to the horizontal distance between the slope toe and slope shoulder, L. The FLAC results, obtained with the shear strength reduction technique, show that the improvement of the safety factor of the slopes reinforced with nails is the largest when the nails are installed in the middle of the slopes. However, limit equilibrium method based on Bishop's simplified method shows that the nails should be placed slightly closer to the toe of the slope for the largest safety factor. In addition, the safety factors of the slopes analyzed by SSRM are larger than those by LEM. The reason for this is that when the nails are placed in the middle portion of the slopes, the shear strength of the soil-nail interface is sufficiently mobilized by the fact that the pressure acting on the nails is larger than that on the nails in the upper portions of the slopes, as shown in Fig. 6 (b).

4.2 Effect of Soil Nail Length

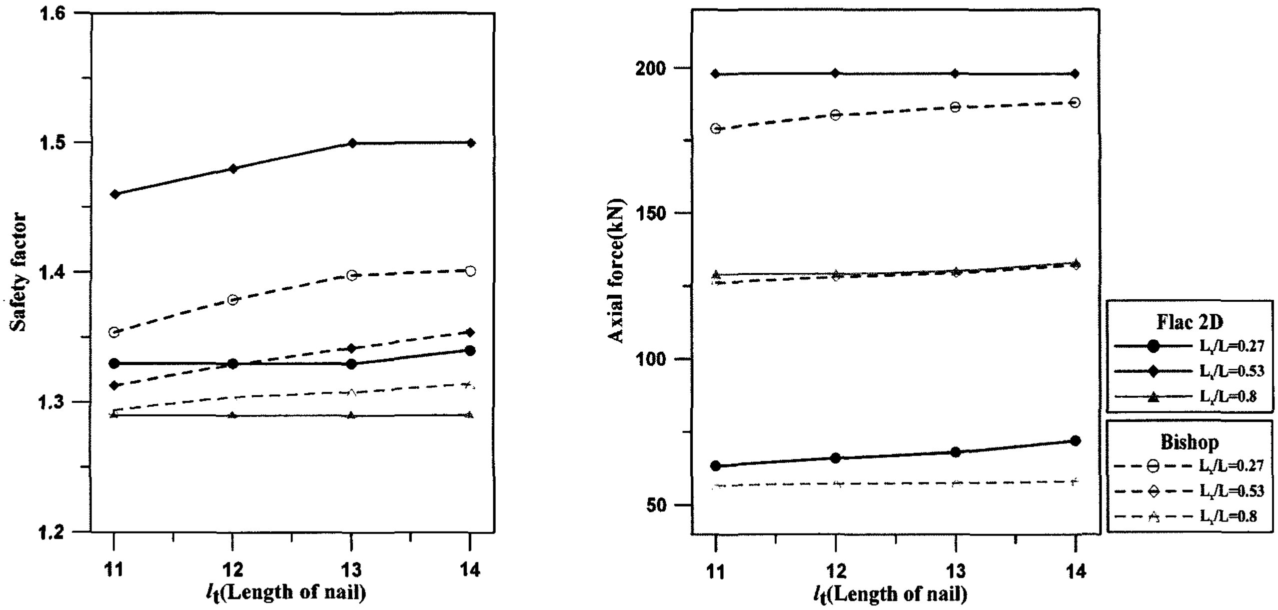
Fig. 7 (a) shows the influence of the nail length on the safety factor. The rate of increase in the safety factor of LEM increases with increasing the nail length. However, the SSRM results show that the safety factor only increases with increasing the nail length when the nails are installed in the middle portion of the slopes. In the slope toe and shoulder, it makes no difference in the safety factor with nail length in SSRM.

It is known that the distribution of maximum tensile force with nail length is shown in Fig. 7 (b). The maximum tension occurs at the slope toe (Lx/L=0.27) for the LEM, but at the middle portion of the slope (Lx/L=0.53)



(a) (b)

Fig. 6. Effect of nail positions on safety factor and soil pressure at failure surface



(a) (b)

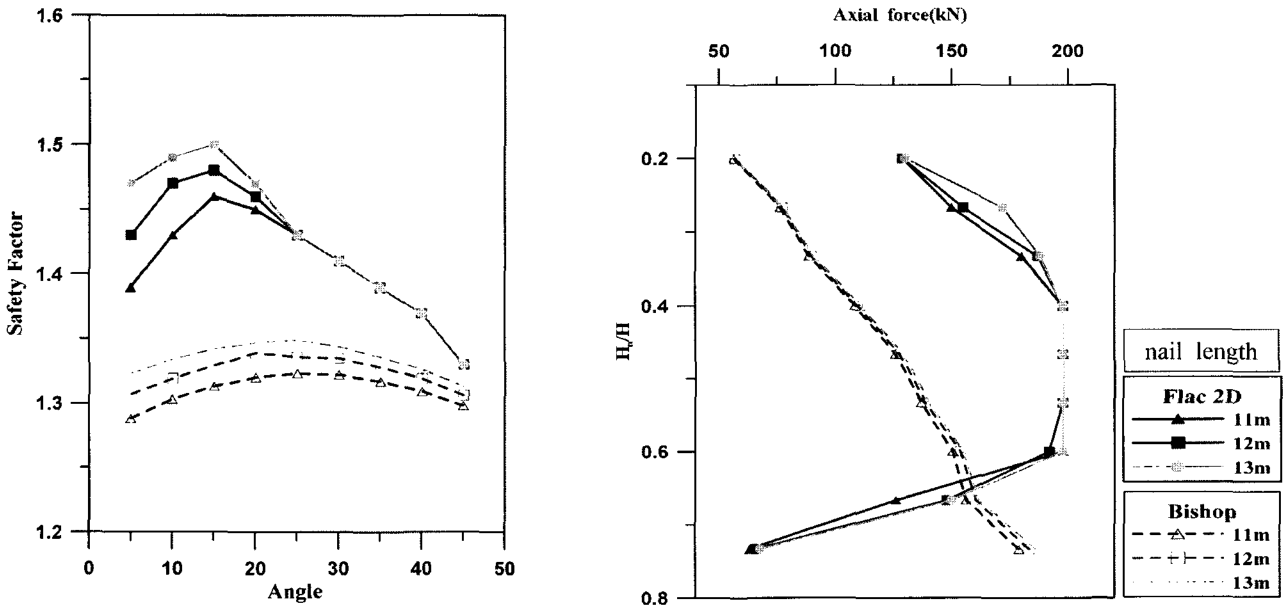
Fig. 7. Effectof nail length on safety factor and axial force

for the SSRM. This clearly shows that the reinforcing effect of nails is more advantageous when the nails are installed in the middle of the slope.

4.3 Effect of Nail Installation Angle

Fig. 8 (a) shows the influence of the nail installation angle on the safety factor. There is an optimal range of the angle from 20 to 30 degree in LEM, from 5 to 20 degree in SSRM, respectively. In general, there was an optimum range of installation angle is from 5 to 15 degree for the safety factor of the slope (Schlosser, 1991).

The numerical results, obtained with SSRM, show these tendencies and little effect of safety factors with nail length for the optimum installation angle. This can be indicated by SSRM results and the safety factor is rather



(a) (b)

Fig. 8. Effect of nail installation angle on safety factor and axial force

insensitive to the nail length near the optimum installation angle.

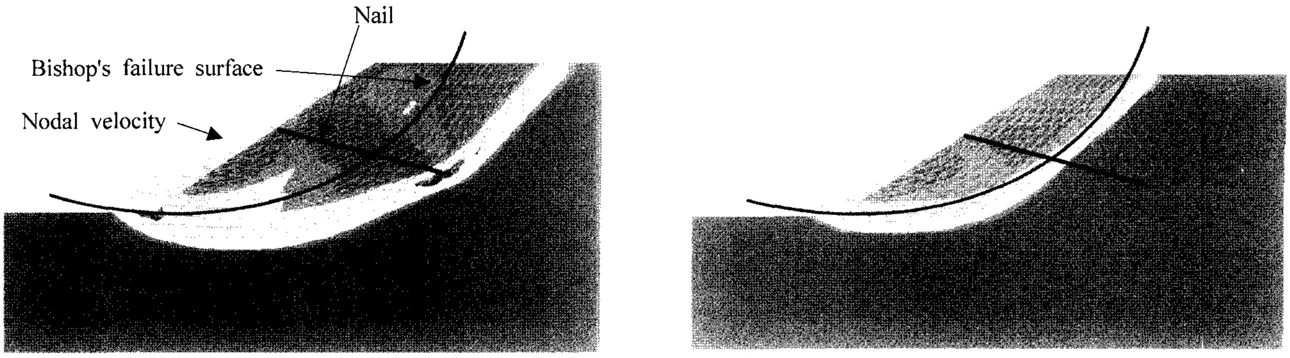
To clarify the difference between the safety factor of LEM and SSRM, the axial tensile force distribution in the angle of 15 degree was shown in Fig. 8 (b). As expected, the distribution of axial tension increases with increasing nail length for LEM, but is almost the same with a various nail length for SSRM.

This can be explained by the fact that the install angle is more influential than the nail length for the axial force.

Fig. 9 shows the failure surface considering a nail length with an optimum angle. The failure surface, obtained by SSRM, is affected by nail length and installation angle for the SSRM, but LEM results show little change of failure surface with nail length and angle.

4.4 Effect of Nail Spacings and Installation Cases

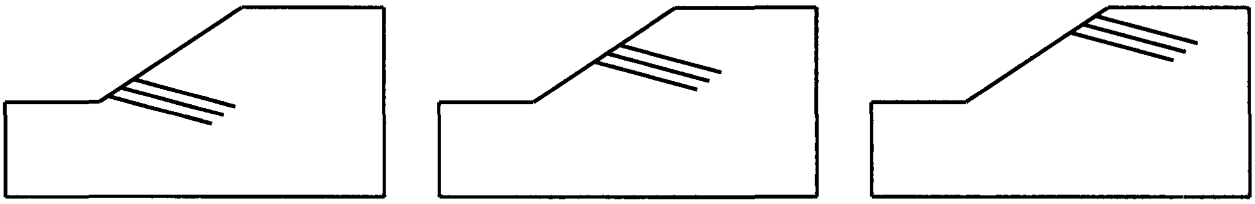
To study the effect of the nail spacing, three different cases of numerical analyses were considered, as shown



(a) L_x=8 m. lt=11 m, θ=15°

(b) L_x=8 m. lt=13 m, θ=15°

Fig. 9. Comparative results between FLAC2D and Bishop's method on optimum angle

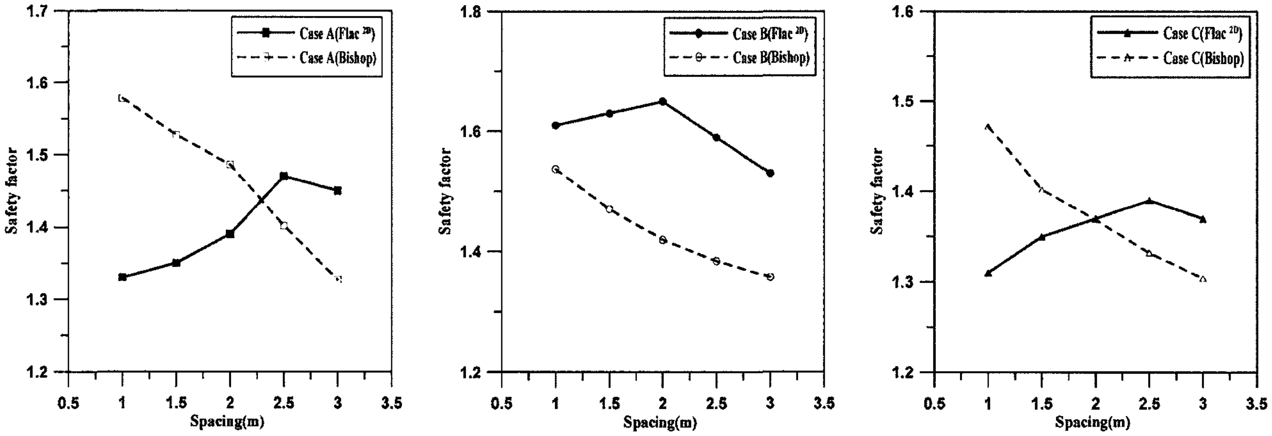


(a) Case A

(b) Case B

(c) Case C

Fig. 10. Installation cases of nails



(a) Case A

(b) Case B

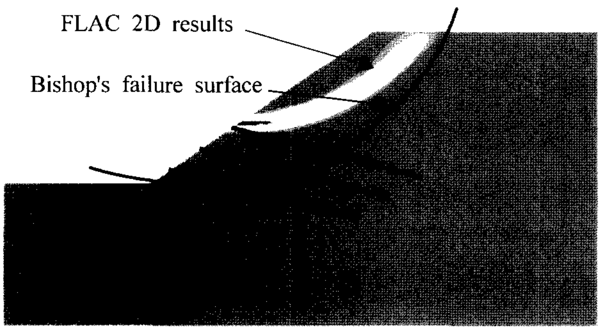
(c) Case C

Fig. 11. Effect of nail spacings with different cases

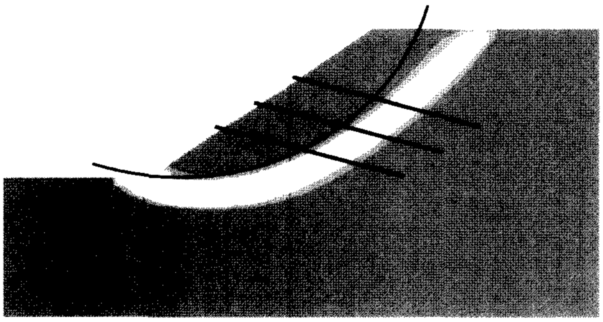
in Fig. 10. The spacing of nails used in analysis is about 1~3 m.

Fig. 11 shows the effect in the safety factor both on nail spacings and installation cases. For the cases A and C, the safety factor decreases with increasing the nail spacing in LEM analysis, on the contrary, the safety factor, obtained by SSRM increases. For the case B, the safety factors of slopes analyzed by SSRM are larger than those by LEM, as pile spacing decreases.

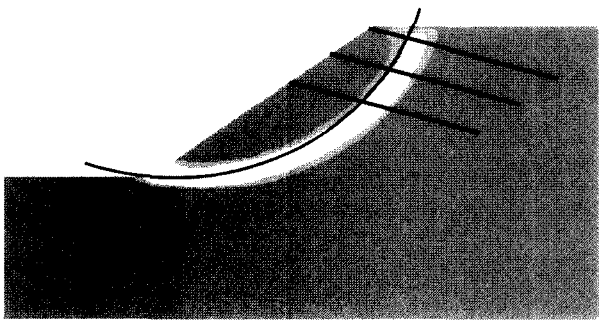
This is probably due to the fact that as nail spacing increases, the shear strength of soil is decreased between nail to nail in the LEM. In the SSRM, the nails will be moved in the middle portion of slopes, as nail spacing increases (case A, C), and so this is the same as the results of the reinforcing effect of the middle of slope (see Fig. 6).



(a) Case A, S_v=2 m



(b) Case B, S_v=2.5 m



(c) Case C, S_v=3 m

Fig. 12. Comparative results between SSRM and LEM

It is also shown that the case B is more advantage than case A and C for the reinforcing effect of slope stability.

Fig. 12 shows the various failure surfaces considering the soil-nail interaction. This clearly demonstrated that the coupled effect exists between nails and soils so that the failure surface can change due to the nail position and spacing. However LEM analysis is no change of failure surface. Thus, the depth of failure surface implies that LEM cannot indicate the true failure mechanism for the slope reinforced with soil nails. It is noted, therefore, that the uncoupled analysis, which can only consider a fixed failure surface, should be limited in its application.

5. Conclusions

In this study, a coupled analysis of slopes stabilized with a soil nail has been presented and discussed based on an analytical study and a numerical study. The numerical results are compared with those obtained by the limit equilibrium method for slope stability analysis. A limited study of numerical analysis was carried out to examine nail/slope coupling effect on relative nail position, different nail spacing and install angle.

From the findings of this study, the following conclusions are drawn

(1) The prediction in the safety factor in slopes is more conservative for an uncoupled analysis than for a coupled analysis. However, the uncoupled analysis underestimates the safety factor of the nail/slope system.

(2) A SSRM has been identified between nails and soil, so that the failure surface invariably changes due to the nail-soil interaction. It is noted, therefore, that the LEM, which can only consider a fixed failure surface, should be limited in its application.

(3) The numerical results show that the pressure acting on the nails is the largest when the soil nails are placed in the middle portion of a slope. Therefore,

the soil nails should be installed in the middle of a slope, when the stability of a slope is required to be improved optimally.

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