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Prediction of the Safety Factor for the Slope of Two Cohesive Layers

Dr.Husain Ali Abdul - Husain
University of Kufa – College of Engineering – Civil Department
Email:husain_ali1975@yahoo.com

ABSTRACT

Analysis of slope stability focus, on determining the value of the safety factor (F_s) which is mean the ratio between the shear strength of the soil to the developed shear stress on a certain slip surface. Engineers are interested with the minimum value of F_S which is obtained by analyzing some trials of slip surface. In the present work, slope of two cohesive layers of the same unit weight is studying. About (100) different problems are analyzed using the package (Slide 6.0). These problems takes into account the impact of some factors on the minimum value of F_S. These factors are: the ratio between the cohesion of the top layer to that of the second one (c_{u1}/c_{u2}) which is denoted by (C_r), the ratio between the height of the top layer to that of the slope (H_1/H) which is denoted by (H_r) and the angle of the slope (B). The results of the analysis are normalized as a stability number (N_s).A regression analysis then conducted to these problems using well known package (STATISTICA). The accuracy of the suggested model is tested by R^2. The value of R^2 of model to predict stability number is about 0.982.

حساب معامل الأمان لمنحدر مكون من طبقتين متماسكتين

الخلاصة

ان الأسس الحصيرية المدعمة بالركائز تسمح بزيادة التحمل و تقليل الهطول وبشكل اقتصادي بالمقارنة مع مجاميع الأسس التقليدية. ونتيجة التطور الحاصل في التراكيب المستخدمة للأسس الحصيرية المدعمة بالركائز, أجريت هذه الدراسة النمذجية أخذين بنظر الاعتبار عوامل وظروف مختلفة. تسلط الدراسة الحالية الضوء على النسبة المئوية للتحمل ما بين الركيزة والأساس. تم التحقق من نتائج النمذجة الحالية المستحصل عليها باستخدام برنامج (PLAXIS 3D Foundation V 1.1) من خلال مقارنتها مع عمل مختبري يعالج نفس المشكلة وبنفس الترتيب وتم حل النموذج مع اضافة حالتين هما 8 و 16 ركيزة مع الأساس و لطبقات تربة مختلفة. وبالإضافة إلى ذلك، تم إجراء مقارنة اخرى بين النتائج الحالية مع دراسة نظرية باستخدام برنامج (ANSYS). تهدف البرامج التي

تعتمد طريقة العناصر المحددة من خلال برنامج (PLAXIS) الى تقييم تأثيرسلوك علاقة الحمل-الهطول للأسس الحصيرية المدعمة بالركائز. كما درس تأثير المسافة بين الركائز على هذه العلاقة. وجدت النسبة المؤية لقابلية تحمل الركائز الى الحمل الكلي في النموذج النظري لحالة ستة عشر ركيزة مع الاساس هي بحدود 42 %. وتبين من الدراسة أن مقدار مساهمة الركائز في قابلية التحمل الكلية تقل بزيادة المسافة بين الركائز. وقد وجد في حالة ركيزيتين مع الأساس الحصيري تقل قابلية التحمل بمقدار 23 % مع زيادة المسافة بين الركائز من ثلاثة أضعاف الى عشرة أضعاف قطر الركيزة.

INTRODUCTION

A ground surface that stands at an angle with the horizontal is called an unrestrained slope. Slopes are either exist in the field due to natural causes which are called natural slopes or man made slopes like the sides of cuttings, the slopes of embankments and earth dams. The slopes whether natural or artificial may be infinite or finite based on their extent. Cruden and Varnes (1996) stated five categories of slope failure. These categories are; fall, topple, slide, spread and flow [2]. This paper relates to the analysis of the slope fails by sliding.

In the slide failure mode, the gravitational force will tend to move a part of the soil of the slope downward as illustrated in Figure (1).

The failure of the slope can occur (the soil mass slide downward) when this force is large enough. In most clear words the driving force exceeds the resistance developed from shear strength of the soil along the failure (sliding) surface.

In many cases, civil engineers are expected to make calculations to check the safety of slopes. This check involves determining and comparing the shear stress developed along the most-likely rupture surface to the shear strength of the soil. This process is called slope stability analysis [2].

There are many important factors, in addition to the gravitational force, that cause instability of a slope and lead to failure, such as: force due to seepage water, erosion of the surface of slope due to flowing water, sudden lowering of water adjacent to a slope and force due to earthquake [5].

The aim of the present work is to obtain a correlation used to predict the safety factor of the slope of two cohesive soils based on slope geometry and soil strength.
Regression analysis is used to obtain the mentioned correlation. The required data are generated using computer program Slide 6.0 to analyze about (100) cases.

SLOPE STABILITY ANALYSIS

The results of slope failure can be often catastrophic involving the loss of considerable property and many lives.
However, slope stability is an extremely important consideration especially in the design and construction of earth dams and embankments. Hence, the evaluating of slope stability is an important, interesting and challenging aspect of civil engineers [3].

The task of engineer charge with a slope stability analysis is to determine the safety factor which is defined as:

$$F_s = \frac{t_f}{t_d} \quad \ldots (1)$$

The average shear stress developed along the potential failure surface can express in a similar manner of the soil strength (Mohr-Coulomb failure criteria). So, it consists of two components cohesion and friction. Hence, the safety factor can write as:

$$F_s = \frac{c + s\,.\tan f}{c_d + s\,.\tan f_d} \quad \ldots (2)$$

New aspect of the safety factor that are safety factor with respect to cohesion, Fc, and safety factor with respect to friction, F_ϕ, defined as:

$$F_c = \frac{c}{c_d} \quad \ldots (3\text{-a})$$

$$F_f = \frac{\tan f}{\tan f_d} \quad \ldots (3\text{-b})$$

When Fc becomes equal to F_ϕ, it gives the safety factor with respect to strength. It can write as:

$$F_s = F_c = F_f \quad \ldots (4)$$

The general shape of the potential failure surface is necessary to carry out the process of stability analysis. There is considerable evidence that the slope failures usually occur on curved surface. Culmann (1875) approximated the potential failure surface to a plane surface. After extensive investigation of slope failures in the 1920s, a Swedish geotechnical commission recommended that the actual sliding surface may be approximated to a circularly cylindrical [2].

Since that time, most methods of slope stability have been made by assuming that the curve of the potential sliding surface is an arc of a circle. There are many modes of sliding surface occurrence. These modes are demonstrated in Figure (2).

Stability analysis of slopes may be conducted using various procedures. In general, there are two classes of these procedures:

1. Mass procedure, where the mass of the soil above the surface of failure is taken as a unit.

2. Slices procedure, where the soil above the surface of failure is divided into a number of vertical parallel slices.

In the present work, the computer program Slide 6.0 is used to analyze slopes. This program is analyzed using method of slices. The advantage of this method is that the non-homogeneity of the soil is considered in the analysis. The non-homogeneity in the main problem of the work.

Stability analysis using the method of slices can be explained by referring to Figure (3). The arc AC represents trial failure surface. The soil above the failure surface is divided into vertical slices and stability of each slice is separately calculated. As an approximate assumption, the resultant of Pn and Tn is equal in magnitude to that of Pn+1 and Tn+1, and also their line of action coincide.

For equilibrium of the trial wedge ABC, the moment of driving force about (O) equals the moment of the resisting force about (O), or:

$$\sum_{n=1}^{p} W_n . r . \sin a_n = \sum_{n=1}^{p} \frac{1}{F_s}\left[c + \frac{W_n . \cos a_n}{\Delta L_n} \tan f\right](\Delta L_n).r \quad \ldots (5)$$

or,

$$F_s = \frac{\sum_{n=1}^{p}\left[c.(\Delta L_n) + W_n . \cos a_n \tan f\right]}{\sum_{n=1}^{p} W_n . \sin a_n} \quad \ldots (6)$$

This method is generally referred to as the ordinary method.

Bishop (1955) proposed a more refined solution to the ordinary method of slices. The effect of forces on the sides of each slice are accoutered. By using $m_{an} = \cos a_n + \frac{\tan f . \sin a_n}{F_s}$, safety factor can expressed as:

$$F_s = \frac{\sum_{n=1}^{p}\left[c.b_n + W_n . \tan f\right] . \frac{1}{m_{an}}}{\sum_{n=1}^{p} W_n . \sin a_n} \quad \ldots (7)$$

The Centre of the most critical surface (circle) can be found only by trial and error. A number of failure surfaces are to be analyzed and the minimum safety factor finally obtained.

The Centre of each trial circle is plotted and the value of the corresponding factor of safety marked near it. After analyzing a number of such trial circles, contours of the factor of safety may be drawn [6].

COMPUTER PROGRAM

1. General Overview

In the present work, a computer program Slide 6.0 is used to generate the required data to perform regression analysis. The analysis of any slope stability problem in this program consists of two major steps as illustrated in Figure (4):

In the first step, the problem is modeled. The geometry of the slope (angle and height of the slope) and soil properties are entered. Also, the method of analysis and slip surface and convergence options are selected.

In the second step, the results of the analysis are presented. The results contain the global minimum safety factor and the contours of safety factors. These contours are based on minimum calculated safety factor at each grid point.

2. Verification of the Program

To reassured from the accuracy of the program results and to select the method used throughout the work, three problems are analyzed using program. The results of the program (using three common method for the case of zero pore water pressure) are compared with that of hand calculations by Taylor chart stated in the references. Table (1) shows the results of the verification. It can be noted that the use of Bishop's method is more reliable because it have the minimum absolute error compared with the other two methods. In the purpose of determining the optimum number of slices used in the analysis, a stability problem with different number of slices is analyzed. Table (2) shows the results of these analyses. The magnitude of safety factor is still constant after 12 slices. Hence, Bishop's method of analysis with (12) slices is used throughout the present work.

PARAMETRIC STUDY

The stability of slope is affected by some parameters. Some of these parameters are encountered in this work like; slope angle, strength of soils, height ratio (H_r) and strength ratio (C_r) as defined in Figure (5).

These variation of the parameters is demonstrated in Table (3). The results of the analysis of each problem is expressed as a stability number. The stability number used in this work is as:

$$N_s = \frac{(1+C_r)}{g.H.F_s} c_{u2} \qquad \dots (8)$$

Figures (6) to (8) illustrate the variation of N_s with H_r, β and C_r respectively. It can be seen that the increasing in H_r and β will increase the value of N_s. While, the value of N_s decreases with the increasing of C_r value.

As known from equation (8), the increasing of N_s means decreasing in the safety factor and visa versa.

A set of different situations are analyzed. The total number of problem is (100) cases. The results of these problems are plotted in Figure (9).

Regression analysis of these data, then performed using well known program STATISTICA. The following correlation is suggested to predict N_s based on H_r, C_r, β, H and c_{u2}:

$$N_s = C_1.(\cos b)^{C2} + C_3.\ln(C_4.C_r) + C_5.e^{C_6.H_r} + C_7(\sin b).\left(\frac{H_r}{C_r}\right)^{C_8} \quad \dots (9)$$

C_1	0.288534	C_5	0.157872
C_2	-0.222732	C_6	-0.07234
C_3	0.076754	C_7	0.107602
C_4	0.114717	C_8	1.473629

The predicted values of the stability number (N_s) from the suggested formula are plotted against the calculated values using computer program are illustrated in Figure (10). The accuracy of the suggested formula to simulate the analysis using Slid 6.0 is tested by computing the coefficient of the correlation (R^2) which is (0.982). This value of R^2 indicates that the use of the suggested formula will give a good results.

DISCUSSIONS AND CONCLUSIONS

Duncan stated that depending on the type of slope and the mount of time and effort which can appropriately be devoted to risk investigation and analysis, a number of different procedures may be used for investigation and design of slopes. Three frequently used procedures, which represent increasing levels of complexity and cost, are the following:

- § Use field observation and experience alone with no test borings, laboratory tests or slope stability calculations.
- § Use of slope stability calculation by means of charts in combination with field observation and minimum number of test borings and laboratory tests.
- § Use of detailed slope stability calculations in combination with a thorough program of site investigation and laboratory tests.

The available charts are for the cases of soil with one layer only. When the slope consists of more than one layer the average values of the strength are used [4].

A certain problem is analyzed by Slide 6.0 with the average soil strength gives Fs = 1.797. While, the safety factors of the same problem using the suggested correlation (equation (9)) and analysis using the computer program are 1.98 and 1.985 respectively.

When the two layers have different unite weight, the weighted average value can be used without significant error in the computed value of the safety factor. So, the present work considered that the two layers of the slope have the same unit weight.

The following points can be concluded based on the results of the present work:

1. The use of Bishop's method is more accurate than the use of ordinary and Janbu methods with no water pressure.
2. The suggested correlation (equation (9)) can be used to predict the stability number with a reliable results.
3. The simplicity of using equation (9) will facilitate the analysis of slope according to the second procedure as stated by Duncan (1987).
4. Use of the suggested correlation (equation (9)) gives more reliable results than the analysis using average soil strength.

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LIST OF SYMBOLS

B	*width of a slice*
C	*Cohesion*
c_d	*Developed cohesion*
C_r	*strength ratio*
c_u	*Undrained cohesion*
F_c	*factor of safety with respect to cohesion*
F_s	*factor of safety with respect to strength*
F_f	*factor of safety with respect to friction*
H	*Height*
H_r	*height ratio*
N_s	*stability number*
P	*horizontal force on the sides of a slice*
r	*radius of trial failure circle*
T	*Tangential force on the sides of a slice*
W	*weight*
a	*angle*
b	*slope angle with respect to horizontal*
g	*unit weight*
DL	*length of a slice at its base* $\left(\approx \frac{b}{\cos a}\right)$
σ	*Normal stress*
τ_d	*developed shear stress* $\left(= c_d + s \tan f_d\right)$
τ_f	*shear strength* $\left(= c + s \tan f\right)$
f	*angle of internal friction*
f_d	*developed angle of internal friction*

Table (1) Results of verification of the computer program.

Problem No.	**Reference No.**	**Slope geometry**		**Soil properties**			**Safety factor**				**Absolute error (%)**		
		H (m)	b **(deg.)**	g **(kN/m^3)**	**c (kN/m^2)**	`f **(deg.)**	**HS**	**Slide 6.0**					
								O	**B**	**J**	**O**	**B**	**J**
1	1	10	26.5	20	5	30	1.40	1.18	1.40	1.23	16	0	12
2	1	8	26.5	18	30	0	1.47	1.41	1.41	1.37	4.1	4.1	6.8
3	2	12	30	16	20	20	1.73	1.61	1.70	1.57	6.9	1.7	9.2

*HS: hand calculations;**O: ordinary method, B: Bishop's method, J: Janbu's method.

Table (2) Results of selection of optimum slices number.

No. of Slices	6	8	10	12	14	16	18	20	22
Fs	1.63	1.62	1.62	1.61	1.61	1.61	1.61	1.61	1.61

Table (3) Values of the parameters used in the regression analysis.

Parameter	Used values
β (deg.)	15, 30, 45, 60 and 75
Hr (H1/H)	0, 0.25, 0.5, 0.75 and 1.0
Cr (cu1/ cu2)	0.2, 0.4, 0,6, 0.8 and 1.0

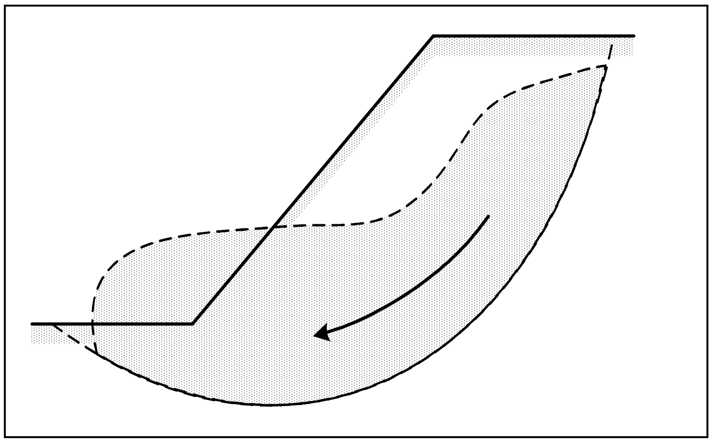

Figure (1) Piled raft foundation [1].

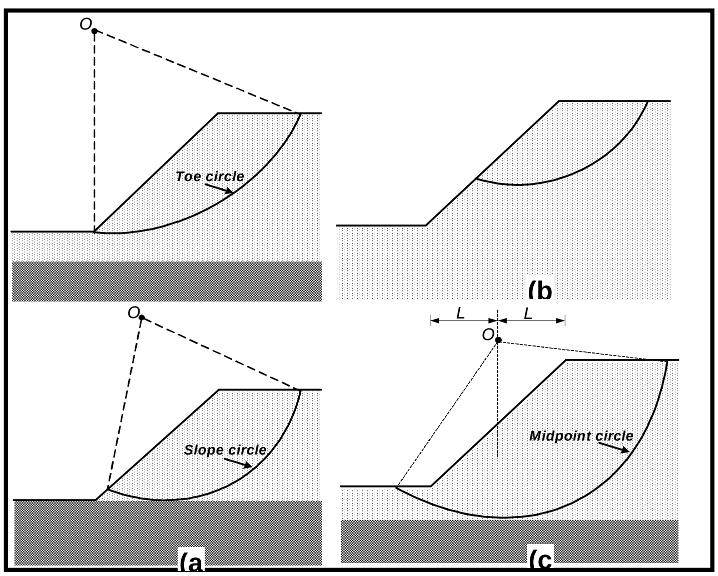

Figure (2) Mode of failure of finite slopes (a) slope failure, (b) shallow slope failure, and (c) base failure.

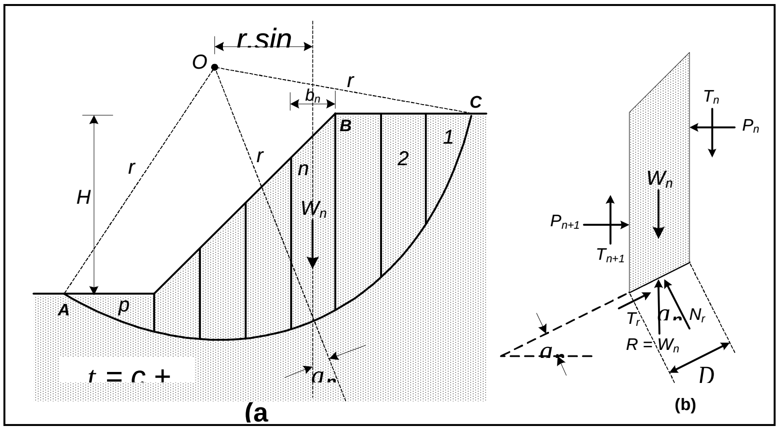

Figure (3) Stability analysis by slices method (a) trial failure

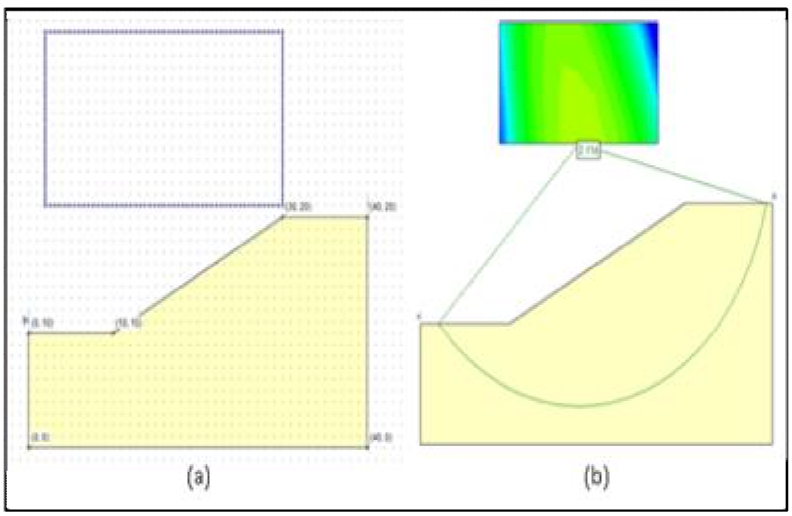

Figure (4) stability problem in computer program slide 6.0 (a) Modeling of the problem (b) result of the analysis.

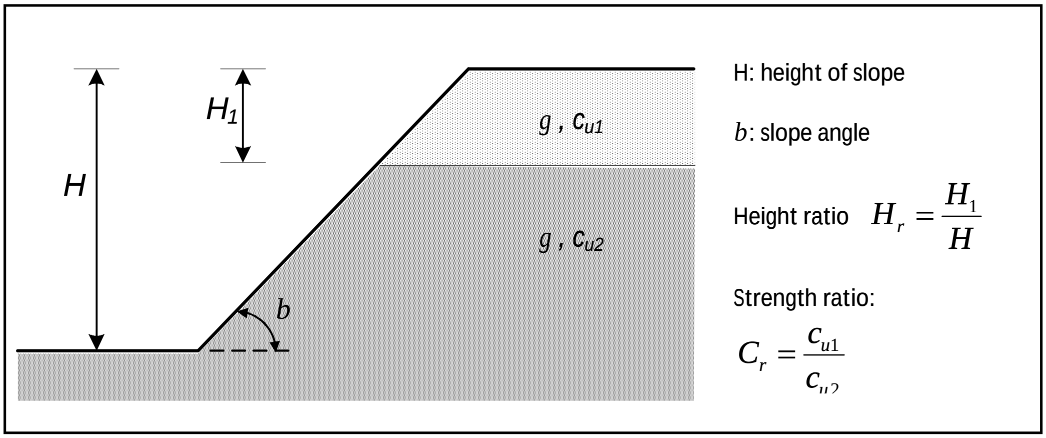

Figure (5) Definitions of the parameters used in the present work.

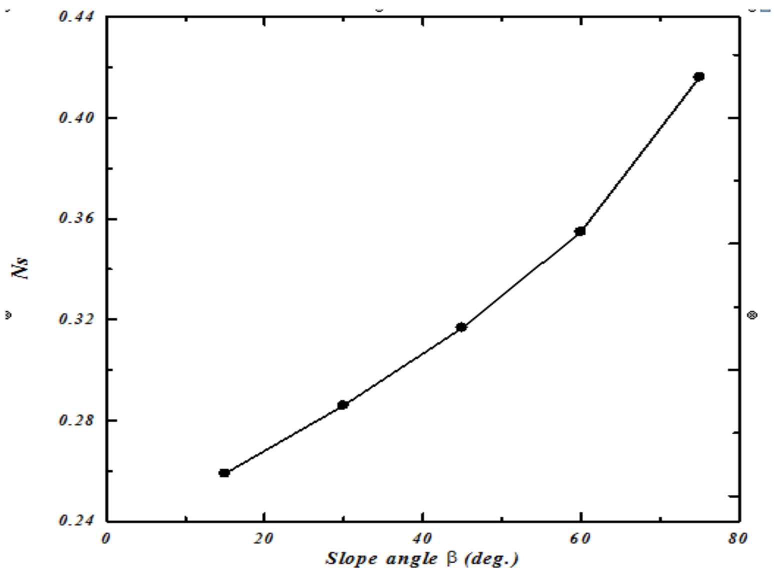

Figure (6) Variation of N_s with slope angle (b).

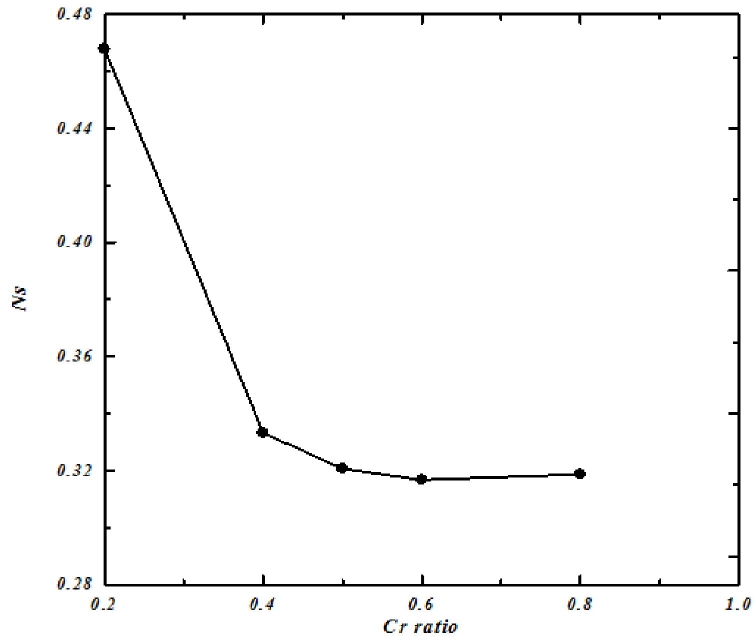

Figure (7) Variation of N_s with C_r ratio.

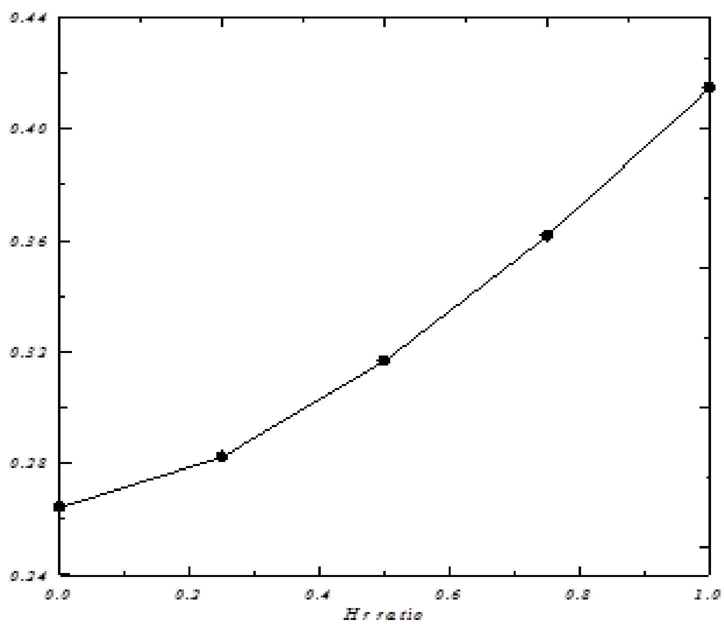

Figure (8) Variation of N_s with H_r ratio.

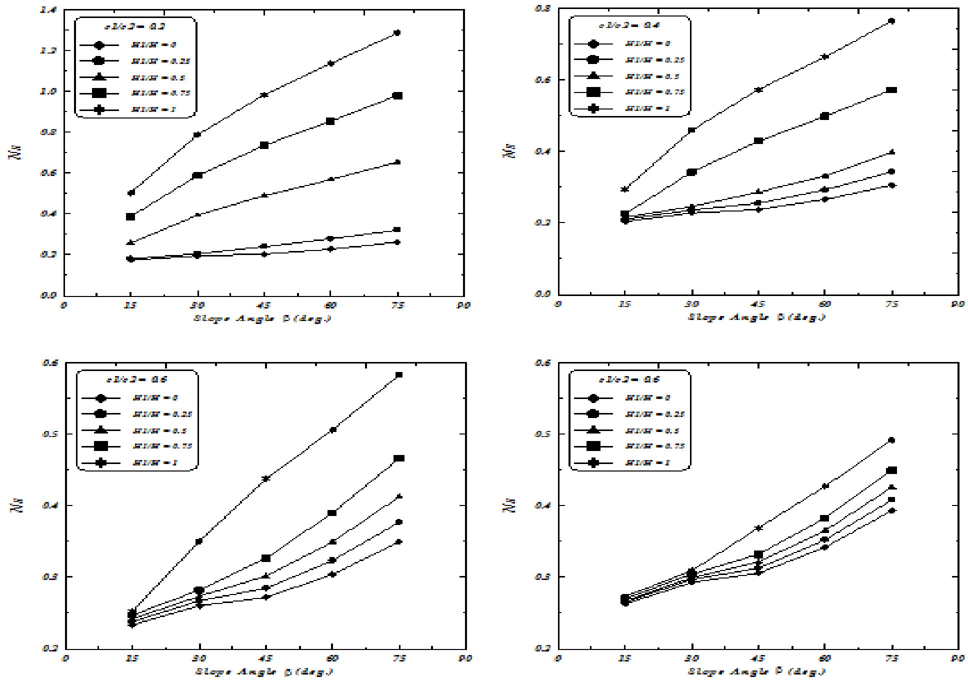

Figure (9) Variation of N_s with slope angle (*b*) for different C_r and H_r ratios.

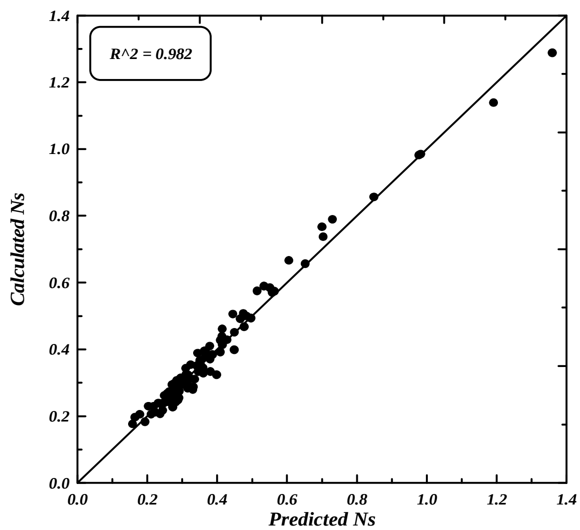

Figure (10) Predicted values of N_s by Slide 6.0 and calculated Values of N_s by equation (9).