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A Risk Assessment Method for Trench Excavations

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Abstract: Many earthwork excavations are being made for pipeline and other utility installation each year. However, frequent slope failures occur in this type of earthwork resulted in many casualties and property losses. These site accidents often occur because contractors consider these excavations as temporary earthwork that would not warrant regular engineering analyses for the slopes. An engineering stability analysis of slopes is considered to be too tedious to conduct. This paper describes a study to provide a quick and easy method to analyze the safety of trenches and excavations which can be used for immediate on-site evaluation. This method uses the direct correlation between the minimum factor of safety and their soil parameters through multiple regressions. However, the use of these equations requires site personnel to have some experience in geotechnical engineering.

Keywords: *excavation, trench, factor of safety, slope stability analysis, regression analysis.*

1. Introduction

Numerous trenches and excavations are made each year in construction, for both permanent and temporary erection of structures, as well as pipeline and utility line installations. These trenches and excavations are neither partially nor fully braced during construction. Many accidents have occurred and resulted in many casualties and loss of properties [1]. The causes of these accidents can be attributed to human negligence, unsafe practices and soil instability. Since most shallow trenches and excavations are usually considered for temporary earthwork on site and do not play a vital role in the overall project schedule, they are frequently done without proper planning and supervision. Often times, the work is done by workers with inadequate training or they fail to comprehend the potential danger that might be involved. Any analyses of stability of soil slope are not deemed necessary by the contractors, who consider them to be tedious and a waste of time. Besides, regulations and guidelines from the Occupational Safety and Health Administration (OSHA) governing trenches and excavations are, by nature, over-simplified [2]. The present study deals with the safety aspects of unbraced trenches and excavations.

2. Background

Excavations, either vertical or sloping, cause soil stability problem in construction. In the trench excavation, because the earth surface is inclined, there is a tendency for the earth mass to move downward along a potential slip surface in order to achieve greater stability. This downward movement of soil mass occurs when the equilibrium is disturbed along a potential slip surface within the excavation. This movement gives rise to sliding failure of the trench excavation. Basically, an unbraced trench slope is supported by the soil's internal shear strength against the driving force which tends to move the soil in the downward direction. A slope failure occurs if the shear stresses caused by the driving forces exceed the internal shear strength of the soil. The investigation of the safety of earth or trench slopes against possible sliding is called slope stability analysis.

In geotechnical engineering, the trench slope is evaluated by determining its factor of safety against sliding failure. The factor of safety is a parameter commonly used by engineers to assess the degree of safety of an earth structure to perform satisfactorily the function for which it was intended. The factor of safety (FS) against sliding failure is generally expressed as

$$FS = \frac{\text{available shear strength}}{\text{shear stress required for equilibrium}} \quad (1)$$

The shear strength of the soil, s at any point along a potential failure surface is governed by the Mohr-Coulomb failure criterion [3] as

$$s = c + \sigma \tan \phi \quad (2)$$

Where

c=cohesion of the soil in units of force per area.
ϕ= angle of friction in degrees
σ= average normal stress on the potential failure surface in units of force per area.

A factor of safety of 1.5 or greater is usually recommended for the design of slopes. However, a factor of safety of 1.0 indicates that the slope is in a state of incipient failure. Significance of factor of safety is defined by Sowers [4], as presented in Table 1.

Table 1.*The Significance of Factor of Safety for Design*

Factor of Safety	Significance
Less than 1	Unsafe or failure
1.0-1.2	Questionable safety
1.3-1.4	Satisfactory for cuts and fills; questionable for dams
Greater than 1.5	Safe for dams

There are numerous methods of analysis of slope currently available to assess the stability of slope. This is due to the various assumptions made in arriving at the respective governing factor of safety equation. These assumptions include the types of failure surface, resultant of the interslice shear forces, and the equilibrium equations they satisfy [5]. These different methods of slope stability analysis may give different factors of safety. However, in this study, the most common method, namely, the Simplified Bishop Method was adopted. This method assumed circular failure surface with zero interslice shear force and has been found to be reasonable and relatively conservative [6]. This method yields similar values of factor of safety with the other method such as the Spencer Method in most of the cases [7].

3. Methodology

The objective of this study is to develop a quick and easy method to analyze the stability of the trench and excavation that can replace the regular and iterative slope stability analysis procedure. In order to accomplish the objective, numerical analyses were first performed to determine the stability of trenches and excavations. There are many factors which are found to influence the factor of safety determined in the slope stability analysis [8]. These factors include:

a. unit weight of soil (ϒ)
b. frictional angle of soil (ϕ)
c. cohesion of soil (c)
d. level of groundwater (H_w)
e. angle of trench slope (β)
f. depth of the trench (H)
g. depth of bedrock or impenetrable firm layer(z)
h. ratio of groundwater level to trench depth (H_w/H)

These eight factors with different combinations are incorporated into the slope stability analyses of trenches performed in this study. In addition to these combinations of variables, slope stability problems are further complicated by further subdivision of six types of conditions encountered described in the next paragraph. Thousands of output of the slope stability analyses are reduced and saved as data files. Subsequently, statistical analyses of the data acquired were used to correlate the results of the slope stability analyses to these various influence factors. Due to the vast amount of data required, all analyses were performed using the computer software.

4. Stability Analyses of Trenches

The software that was used to determine the factors of safety against failure for each slope trench is called STABR, a stability code developed by Lefebvre and later modified by Wong at the University of California [9]. Stability analyses using the circular type of failure surface were performed by Bishop's Simplified Method for each slope. The programme calculates the factor of safety using the auto-search option for the critical failure surface with the minimum factor of safety. In this study, soil layers up to three are considered in the analysis. Figure 1 shows the general slope geometry for the slope stability analyses. Since it is not possible for this study to cover all types of soil conditions due to the natural complexity of the trench materials, it is the purpose of this study to cover the most reasonable ranges of soil properties that will be encountered in actual construction practices. For this reason, six soil conditions were used for the analyses. They are as follow:

a) Soil Condition 1: dry cohesive soil with no water table,
b) Soil Condition 2: dry cohesionless soil with no water table,
c) Soil Condition 3: dry combined soil (mixture of cohesive and cohesionless soil) with no water table,
d) Soil Condition 4: wet cohesive soil with groundwater level within trench depth ,
e) Soil Condition 5: wet cohesionless soil with groundwater level with the trench depth,
f) Soil Condition 6: wet combined soil with groundwater level within the trench depth.

Various ranges of variables or factors were compiled together for the six types of soil conditions so that they are representative of trench stability problems for all practical conditions, as shown in Table 2.

Table 2.*The Applicable Ranges of Soil and Trench Parameters for the Six Soil Conditions*

Soil/Trench Parameters	Applicable range
Depth of Trench (H), (m)	1.5 - 6.0
Depth to Bedrock (D), (m)	0.01H- 1 H
Trench Slope (β), (H:V)	0.01 – 2.0
Cohesion (c), kN/m^2	0.05-120
Friction angle (ϕ), (degree)	0.01 - 40
Groundwater level to trench depth (H_w/H)	0-1.0
Unit weight (ϒ), (kN/m^3)	14 - 21

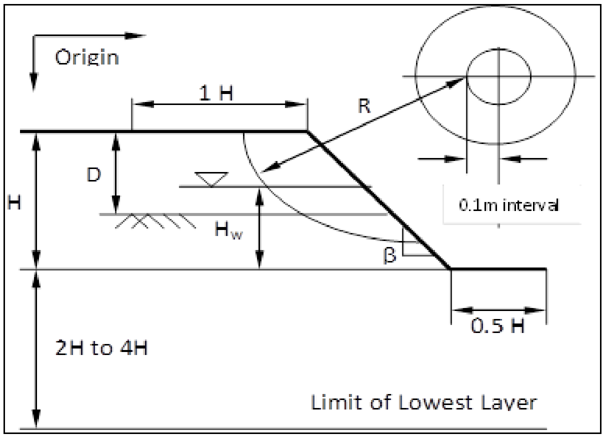

Figure 1.*Slope geometry and other variables for the slope stability analysis*

5. Statistical Analyses

The results in the slope stability analyses were then used as the database for statistical analyses. The statistical analysis software, called ABstat, is used because it can perform the stepwise multiple linear regressions analysis [10]. In this study, the governing factors in slope stability analyses were transformed into logarithmic forms in order to yield better results in the multiple regression analyses. This is due to the wide range of variables encountered and spanned from 0.01 to 0.10; 0.10 to 1.00; 1.00 to 10.0; 10.0 to 100.0 and 100.0 to 1000.0 (5 normal arithmetic scale) on a single axis. Hence, the logarithm of minimum factor of safety was used as the dependent variable while the logarithms of others were used as independent variables, as shown in Table 3. The forward stepwise process was used so that the independent variables in the highest degree of correlation with dependent variable is used in the first step, the next most highly correlated independent variable is added in the second step and so forth. Due to the vast amount of data required, batch procedures are developed in the computer program code to facilitate the computer analyses.

Table 3.*Dependent and Independent Variables Used for the Regression Analyses*

Soil Condition	**Dependent Variable**	**Independent Variable**
Condition 1	log (FS)	log (β), log (H), log (D), log(ϒ), log(c)
Condition 2	log (FS)	log (β), log (H), log (D), log(ϒ), log(tan ϕ)
Condition 3	log (FS)	log (β), log (H), log (D), log(ϒ), log(c), log(tan ϕ)
Condition 4	log (FS)	log (β), log (H), log (D), log(ϒ), log(c), log (W_H)
Condition 5	log (FS)	log (β), log (H), log (D), log(ϒ), log(tan ϕ), log (W_H)
Condition 6	log (FS)	log (β), log (H), log (D), log(ϒ), log(c), log(tan ϕ), log (W_H)

6. Results

Multiple regression analyses are performed using the data acquired from the results of slope stability analyses. For all types of soil conditions except the dry cohesionless soil and wet cohesionless cases, it was found that the distribution of the minimum factors of safety along the depth of slope geometry from the top of the slope to the rock foundation, is a curve that has two distinctive segments with a sharp change in direction at the level of the toe of the slope. Therefore, two equations were derived for each of the soil conditions. As the result, ten equations were derived from the regression analyses to correlate the minimum factor of safety to its various slope geometry and soil parameters. They are listed as follow for each of the 6 soil conditions:

For the dry cohesive soil with depth of rock less than or equal to the depth of trench,

$$FS = \frac{8.5581(c)^{1.0027}(\beta)^{0.1071}}{(D)^{0.8873}(H)^{0.1428}(\gamma)^{1.0474}} \tag{3}$$

For dry cohesive soil with depth of rock greater than the depth of trench,

$$FS = \frac{6.5255(c)\ (\beta)^{0.1098}}{(H)^{0.8371}(D)^{0.1785}(\gamma)} \tag{4}$$

For dry cohesionless soil with depth of rock equal to the depth of trench,

$$FS = \frac{1.0747(\tan\phi)\ (\beta)^{0.9276}}{(D)^{0.0109}(\gamma)^{0.0016}} \tag{5}$$

For dry combined soil with depth of rock less than or equal to the depth of trench,

$$FS = \frac{0.0185(c)^{0.5390}(\beta)^{0.1506}(\gamma)^{0.8767}(\tan\phi)^{0.0868}}{(H)^{0.1535}(D)^{0.6896}} \tag{6}$$

For dry combined soil with depth of rock greater than the depth of trench,

$$FS = \frac{0.0963(c)^{0.5675}(\beta)^{0.1280}(\gamma)^{0.4635}(\tan\phi)^{0.0766}}{(D)^{0.0398}(H)^{0.7578}} \tag{7}$$

For wet cohesive soil with depth of rock less than or equal to the depth of trench:

$$FS = \frac{9.0276(c)^{1.0050}(\beta)^{0.1065}}{(H)^{0.1390}(D)^{0.8890}(\gamma)^{1.0632}} \quad (8)$$

For wet cohesive soil with depth of rock greater than the depth of trench:

$$FS = \frac{7.3036(c)^{1.0037}(\beta)^{0.1226}}{(H)^{0.8449}(D)^{0.1799}(\gamma)^{1.0250}} \quad (9)$$

For wet cohesionless soil with depth of rock equal to the depth of trench:

$$FS = \frac{0.1066(\beta)^{0.7263}(D)^{0.0825}(\tan\phi)^{1.01}(\gamma)^{0.2870}}{(W_H)^{0.1575}} \quad (10)$$

For wet combined soil with depth of rock less than or equal to the depth of trench:

$$FS = \frac{0.0028(c)^{0.5357}(\beta)^{0.1204}(\gamma)^{1.2682}(\tan\phi)^{0.1439}}{(H)^{0.1185}(D)^{0.7409}(W_H)^{0.0262}} \quad (11)$$

For wet combined soil with depth of rock greater than the depth of the trench:

$$FS = \frac{0.0011(c)^{0.4476}(\beta)^{0.1601}(\gamma)^{1.6030}(\tan\phi)^{0.1634}}{(D)^{0.25188}(H)^{0.6103}(W_H)^{0.0306}} \quad (12)$$

In general, the results of the regression analyses revealed that the unit weight of soil (ϒ) does not play a significant role in the calculation of factors of safety in most soil cases. However, it seems to play a major role in defining the minimum factor of safety in the case of combined soil where the depth of rock is greater than the depth of the trench. The magnitude of cohesion (c) and friction angle (ϕ) appear to have a strong influence on the stability of the soil in most cases. Groundwater effect (H_w) does not appear in equations for cohesion soils, thus confirming that it has no influence on the cohesive strength of the soil. It is more difficult to identify the influence of other parameters on the calculation of factors of safety. Table 3 summarizes the results of regression analyses giving the coefficient of correlation (*r*), coefficient of determination (r^2) and standard errors of estimate in the sampling population. The results indicated that in most cases the regression equations can be expected to give excellent approximations to the results of analyses using the Simplified Bishop method.

Table 3.*Coefficient of determination* $(r)^2$ *and standard errors for the equations developed*

	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5	Condition 6
r	a) 0.9956	a) 0.9995	a) 0.9725	a) 0.9955	a) 0.9733	a) 0.9795
	b) 0.9989	b) 0.9995	b) 0.9807	b) 0.9983	b) 0.9733	b) 0.9811
r^2	a) 0.9912	a) 0.9990	a) 0.9459	a) 0.9911	a) 0.9475	a) 0.9594
	b) 0.9979	b) 0.9990	b) 0.9617	b) 0.9967	b) 0.9475	b) 0.9627
Standard Error	a) 0.0417	a) 0.0093	a) 0.0809	a) 0.0417	a) 0.0809	a) 0.0750
	b) 0.0192	b) 0.0093	b) 0.0664	b) 0.0241	b) 0.0809	b) 0.0649
Cases	a) 685	a) 220	a) 2779	a) 1998	a) 355	a) 6949
	b) 1228	b) 220	b) 1302	b) 3396	b) 355	b) 5648

Note: a) for depth of rock less than or equal to the depth of trench b) for depth of rock greater than the depth of trench

7. Conclusion

The problem of safety in trench and excavation is a growing concern in the construction industry. In order to simplify the conventional rigorous methods of slope stability analysis, the factors of safety from the analysis are statistically correlated to its various slope and soil parameters. Multiple linear regression analyses were performed to yield ten regression equations for six types of site conditions encountered in trench operation. The results showed good correlation with the correlation coefficient (r) and determination coefficient (r^2) of more than 95% between the Simplified Bishop method and the regression equations. These equations can be used to determine the minimum factor of safety for a given slope geometry and soil condition. It is designed to provide an alternative approach to the regular, iterative slope stability analysis procedures by a simple and direct correlation between the minimum factor of safety and their soil parameters. The uses of these equations are limited to the factor of safety determined by the Simplified Bishop method and limited to depth of trench of less than 6m.

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