EFFECT OF SEEPAGE FORCES ON NILE RIVER BANK STABILITY

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ABSTRACT

This reduction of the suspended sediment concentration after the construction of the High Aswan Dam has increased the ability of the flowing water to erode banks and reduce their stability. Bank erosion causes a major loss of agricultural lands. Many factors affect Nile River bank erosion such as soil characteristics, bank height and slope, navigation waves, river bends, river contractions, and spur dike effects and other factors. A very important factor that affects the bank stability and it is not considered by traditional methods of slope stability analysis is the seepage forces through banks due to the differences in Nile River and subsurface water levels. The purpose of this paper is to study and to analyze the effect of seeping water from Nile banks to the river or on their stability. Most stability methods take the effect of seepage forces as the differences in own weight of different submerged slices. However, the seeping water causes some more additional forces and should be considered in river bank stability analysis. This paper includes the usage of some actual study cases and measurements to analyze and estimate the effect of seepage forces on the bank stability. Finally, some conclusions are pointed out to be included in the design analysis.

Key words: Nile River Banks, Slope Stability, Seepage Forces, Safety Factor

BANK EROSION

Nile River banks are subjected to erosion as a result of many factors and combinations of factors. The eroded banks have caused many problems and difficulties. Some of these problems are economical problems since the bank erosion involves a loss of very expensive agricultural lands, some other problems are technical because of the eroded soil particles may settled in some areas causing navigational and water pump intake problems. Since the construction of the High Aswan Dam, the flows downstream the dam have become more controlled and the suspended sediment concentration have been reduced significantly. This reduction of the suspended sediment concentration has increased the ability of the flowing water to erode banks and reduce their stability. Nile Research Institute is performing an annual monitoring of eroded banks to design and apply the suitable bank protection for these sites.

River Bank Erosion Factors

Many factors affect Nile River bank erosion. Some of these factors are related to external loads and forces acting on the banks and some other factors are internal factors related to their resistance to erosion and failure. Some of the external factors can be mentioned as follows:
1- Navigation waves.
2- River bends.
3- River contractions.
4- Spur dike effects.
5- Suspended sediment concentrations.
6- Nile River and subsurface water levels.
7- Human interventions.

It can be noticed that all the previously mentioned factors are related to forces exerted by flowing water on the banks causing an erosion or slope instability for the banks.

Some other factors are related to the resistance of banks to erosion and slope instability and can be summarized as follows:
1- Bank height
2- Bank slope.
3- Soil characteristics.

BANK EROSION ANALYSIS AND BANK PROTECTION

The bank erosion analysis and consequently, the bank protection design, include some standard analyses and procedures to fulfill the following criteria:

1- The bank slope should be sufficiently stable with a minimum factor of safety of at least 1.5, Egyptian Soil Mechanics Code [1].
2- The design of a bank protection, if any, should be the most economical design.
3- The interference with the river should be the minimum smooth interference.

STABILITY ANALYSIS

Stability analysis has to be performed to determine the safety margins for the analyzed bank. The outputs of this analysis are described by the terms: safety factors. In general, the factor of safety is determined from the following equation:

$$Factor\ of\ Safety\,(F.S.) = \frac{Shear\ Strength}{Shear\ Stress} \qquad (1)$$

However, Equation (1) is a very general equation and it requires some assumptions and simplification to be applicable and the different major types for stability analysis are
1) Methods of analyzing shear stresses and shear strength.
2) Methods of analyzing driving and resisting forces.

The methods of analyzing shear stress and strength are usually used for major structures such as earth dams. They determine stresses and strains for the entire slope and predict deformations and local failures using the finite elements analysis; on the other hand, they require more sampling and testing programs in addition to more computer and analysis work.

The methods for analysis of forces are used for ordinary structures since they are more practical in testing program costs. Some examples of these methods are the theory of elasticity method of analysis and limit equilibrium methods. Lowe [2] concluded that the use of limit equilibrium methods is sufficient for the practicing engineer.

Limit Equilibrium Methods

Limit equilibrium methods are the most common methods of slope stability analysis in practice, Deschamps & Leonards [3]. The basis of these methods is to transfer a stable slip surface to one at limiting equilibrium by reducing the shear strength along the potential slip surface by some factor of safety. The factor of safety is assumed to be constant along the slip surface and for more precise analysis, the differences in the factor of safety along the slip surface should be considered in the analysis. The forces acting on one slice of a certain slip surface are shown on Figure (1). For the slip surface shown on the Figure (1), the number of slices is (n) and for these (n) slices the number of unknowns and equations are shown on Table (1).

Table (1) Number of unknowns and equation for a certain slip surface.

Force	No. of unknowns	Equation	No. of equations
E	n-1	Sum of horizontal forces	N
S	n-1	Sum of vertical forces	N
Y	n-1	Sum of moments	N
Yp	N	T and P forces relations	N
P	N		
T	N		
F.S.	1		
Sum	6n-2		4n

From Table (1), it is obvious that the number of equilibrium equations is smaller than the number of unknowns for slope stability analysis, some assumptions have to be made to make the problem determinate. Different two dimensional slope stability analysis methods are using different assumptions for the orientation and the location of side forces such as Ordinary Method of Slices, Modified Bishop Method, Janbu Method, Morgentsern & Price Method, and Spencer method. For the proposed analysis, the Modified Bishop Method was used. It has to be mentioned that, for the proposed analysis the stability analysis is performed using all the available data and information such as:

1- Geometry information determined from hydrographic and land survey.
2- Soil layer information determined from the drilled bore holes, extracted samples, field testing and the performed laboratory soil testing.
3- Water level information determined from Nile water levels for surface water and observation wells for ground water levels.

SEEPAGE FLOW

Seepage flow is given by Darcy equation:

$$v = k\, i = -k \frac{dh'}{ds} \qquad (2)$$

Where

v = Discharge velocity,
k = Coefficient of permeability,
i = Hydraulic gradient.

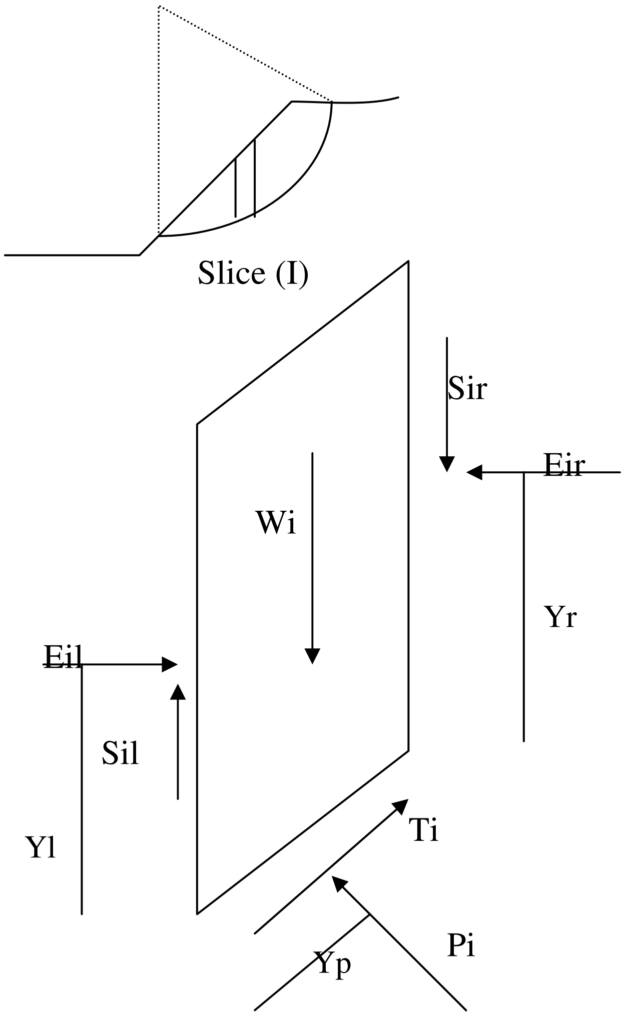

Figure 1. Forces acting on a slice (i) of a certain slip surface.

Two Dimensional Steady State Saturated Flow

The stochastic equation for two dimensional steady state saturated flow is, Smith & Freeze [4]:

$$\frac{\partial}{\partial x}\left[K_x \frac{\partial h'}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_y \frac{\partial h'}{\partial y}\right]=0 \qquad (3)$$

Where:

K_x is the coefficient of permeability in x-direction,

K_y is the coefficient of permeability in y-direction, h' is the hydraulic head.

Seepage Forces

The seepage forces resulting from seeping water through a soil mass on a certain element are estimated by the following equation:

$$F_{seepage} = i \; x \; A \; x \; \gamma_w \qquad (4)$$

Where:

$F_{seepage}$	is the seepage force,
i	is the hydraulic gradient through this element,
A	is the area of the element subjected to these forces,
γ_w	is the water unit weight.

THE PROPOSED ANALYSIS

The proposed analysis is performed to study the effect of seepage forces on the stability of Nile River banks. As mentioned before most of the available traditional slope stability analysis concepts consider the effect of subsurface water on slope stability by considering only the effect of changing the unit weight and effective stresses. During this research, the effect of seepage forces is incorporated in the traditional slope stability analysis to study their effect. A computer program, based on Modified Bishop Concept for slope stability analysis coupled with the effect of seepage forces, was developed by the author to perform the analysis. Two Nile River eroded bank sites were selected for this analysis.

Selected Sites

Two study cases were selected for this analysis. Table (2) shows the names of these sites. In addition to site name, the table shows the site number, which is a code given by Nile Research Institute, the site governorate, site location from EL-Roda, Site length (m), number of surveyed cross section and number of drilled boreholes.

Table (2) Study cases used for the analysis.

No.	Site	Governorate	Km (from El-Roda)	Length (m)	No of cross sections	No. of Bore holes
191	El-Nosirat	Sohag	531.80-532.40	600	10	3
194	Nazlet El-Feliew	Assiut	404.65-405.25	600	8	3

Developed Concept

Figures 2 and 3 show an illustration for the acting forces on a certain slip surface. The section shows on these figures is section (9) of Site 191 (El-Nosirat). For the first figure (Figure 2) the forces acting on a slice of the minimum slip surface are shown as described on figure (1), while Figure (3) shows the seepage forces acting on this slip surface for the mass below the subsurface water surface and subjected to hydraulic gradient. For the Modified Bishop Concept, the relationship of T, P, and W forces are given by the following equations:

$$T_i \sin(\alpha_i) + P_i \cos(\alpha_i) - W_i = 0. \tag{5}$$

$$T_i = \frac{c_i\, l_i + (P_i - U_i\, l_i)\tan(\phi_i)}{F} \tag{6}$$

Where:

P_i is the force normal to the base of the slice,
T_i is the force tangential to the base of the slice,
W_i is the weight of the slice,
C_i is the cohesion along the base of the slice,
L_i is the length of the base of the slice,
U_i is the pore water pressure,
F is the factor of safety,
Φ_i is the angle of internal friction,
α_i is the slope of the base of the slice.

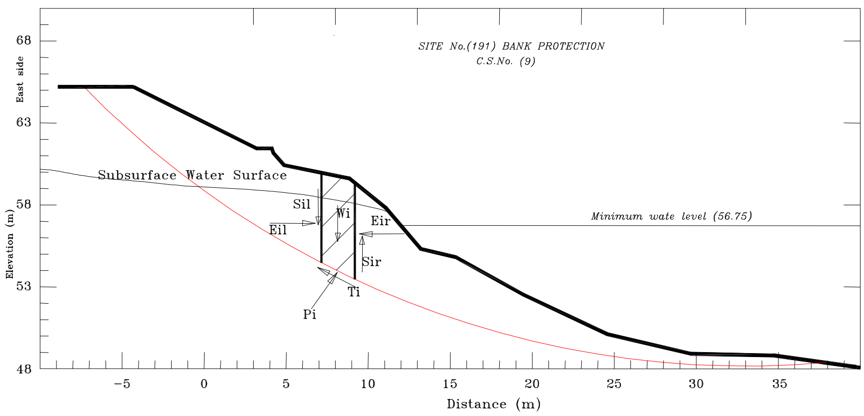

Figure 2. Forces acting on a certain slice for c.s.(9)-site 191.

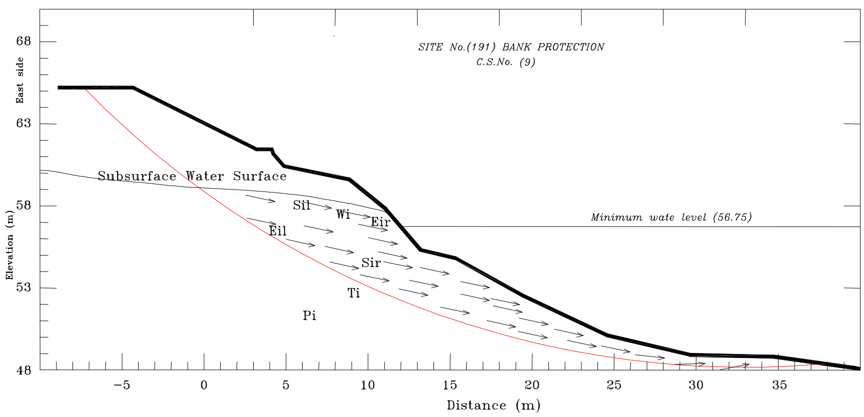

Figure 3. Seepage Forces acting on c.s.(9)-site 191.

The Used Equation

The required equation is obtained by taking the moments around the center of the slip circle for all slices to solve for the factor of safety. The resulted equation for factor of safety is as follows:

$$F = \frac{\sum_{i=1}^{n} [C_i l_i \cos(\alpha_i) + (W_i - U_i l_i \cos(\alpha_i)) \tan(\phi_i)] \, m_\alpha * R}{\sum_{i=1}^{n} W_i \sin(\alpha_i) * R + FSP_i * RSP_i} \quad (7)$$

$$m_\alpha = \frac{\sec(\alpha_i)}{(1. + \frac{\tan(\phi_i)\tan(\alpha_i)}{F})} \quad (8)$$

Where:

R is the radius of the slip surface,

FSP_i is the seepage force,

RSP_i is the normal distance from the center of the slip surface to the seepage force

Factor of Safety Computations

The previously mentioned equations are solved using the developed computer program. This program has a searching routine to determine the minimum factor of safety slip surface based on trial and error concept.

RESEARCH RESULTS

The developed concept was applied to the two selected sites for all cross sections. The resulted safety factors without the effect of seepage forces (traditional approach) were computed and the resulted safety factors including the effect of seepage forces (developed approach) were also computed and compared with the traditional safety factors. Table (3) shows the analysis results for site 191, while Table (4) shows the analysis results for site 194. Each table shows both the safety factors with and without including the effect of seepage forces and the resulted percentage due to the inclusion of seepage forces. The average percentage for the first site cross sections was found to be 88.76 % while the average percentage for the second site cross sections was found to be 90.56 %.

Table (3) Site 191 (El-Nosirat) results of the analysis.

Cross Section No.	Safety Factors without Seepage Forces Effect.	Safety Factors with Seepage Forces Effect.	Percentage of Safety Factors
1	1.12	0.91	81.32
2	1.07	0.98	91.75
3	1.09	1.07	98.27
4	1.13	0.97	85.82
5	1.35	1.13	83.64
6	1.21	0.97	80.10
7	1.22	1.21	98.83
8	1.24	1.02	82.12
9	1.10	1.04	95.16
10	1.01	0.91	90.58
Average			88.76 %
Minimum			80.10 %
Maximum			98.83 %
Standard Deviation			7.10 %

Table (3) Site 194 (Nazlet El-Feliew) results of the analysis.

Cross Section No.	Safety Factors without Seepage Forces Effect.	Safety Factors with Seepage Forces Effect.	Percentage of Safety Factors
1	1.19	1.14	95.58
2	1.04	0.88	84.43
3	1.51	1.51	99.82
4	1.07	0.68	63.54
5	1.28	1.26	97.90
6	1.24	1.23	99.12
7	1.49	1.33	89.40
8	1.52	1.44	94.70
Average			90.56 %
Minimum			63.54 %
Maximum			99.82 %
Standard Deviation			12.10 %

CONCLUSIONS

A computer program was developed during this analysis to study the effect of seepage forces on slope stability safety factors.

The developed approach was applied to two Nile River banks sites, Site 191 (El-Nosirat) and Site 194 (Nazlet El-Feliew).

The results of this analysis show there a significant reduction of the safety factors due to the inclusion of the seepage forces in the safety factors computations.

For the first site, Site 191 (El-Nosirat), the safety factor percentage are ranged from 80.10 % to 98.83% with an average of 88.76 % and a standard deviation of 7.10 %.

For the second site, Site 194 (Nazlet El-Feliew), the safety factor percentage are ranged from 63.54 % to 99.82% with an average of 90.56 % and a standard deviation of 12.10 %.

More studies and study cases are required to obtain more general conclusion about the effect of seepage forces on stability analysis.

The results of this analysis necessitate the inclusion of seepage forces in any Nile River bank stability analysis.

REFERENCES

1. Egyptian Soil Mechanics Code, Building and Construction Research Center, Cairo Egypt, Section (8), PP. 103, 2001.
2. Lowe, J., Stability Analysis of Embankment. ASCE, Vol. 93, part SM4, PP. 1-34.
3. Deschamps, R., and Leonards, G., A Study of Slope Stability Analysis. Stability and Performance of Slopes and Embankments-II, ASCE Special Publication, Vol. 31, part 1, PP. 267-291.
4. Smith, L., and Freeze, R., Stochastic Analysis of Steady State Groundwater Flow in a Bounded Domain Two-Dimensional Simulations, Water Resources Research, Vol. 15, part 6, PP. 1543-1559.