Cases of Slope Failure of Irrigation And Drainage Channels In Egypt and Their Rehabilitation

Sherif M. Elkholy[1]

Abstract

Side slope failures of Irrigation and drainage water channels may cause major disasters with devastating losses of both human life and property, especially in the case where such water channels are higher in level than urban areas along with a complete failure of the embankment. Additional live loads, seepage forces, erosion, and/or gravitational forces may instigate complete or partial slope failure of irrigation and drainage channels. The present article looks at some case studies of slope failure trying to identify the causes of failure and consequently recommending the suitable technique of rehabilitation in the case of partially collapsed slope or reconstruction in the case of a complete failure. The reasons behind the slope failures of the studied channels were mainly piping (migration of soil particle or internal erosion) in salt affected or dispersive soil, seepage forces in sandy or clayey soil, poor quality of the embankment soil mass as in the case of soft clay or loose sand, overtopping and consequently erosion caused by excessive use of irrigation water or using surface irrigation at areas close to the embankment, high velocity of the flow in the channel, and/or mechanical dredging which distorts the channel cross section. There is no single or general way of rehabilitation for slope failures because of the uniqueness of the characteristics and circumstances of each site. Therefore, each site has to be studied separately and in details to find out the best way to deal with it.

Keywords : Piping, Rehabilitation, Seepage, Slope Failures.

Introduction

Stable earth slopes, both natural and man-made, are of great importance as demonstrated by the consequences of slope failures given in the Cedergren (1977). Slope failures may be attributed to many reasons such as, seepage, piping, and/or excessive settlement (Burgi and Karaki, 1971, Rhee and Bezuijen, 1992, Govindaraju, 1998, and Budhu and Gobin, 1996). Studies on the failure mechanisms of the banks of Ohio River (Hagerty and Spoor, 1989) and the Illinois water way (Spoor and Hagerty,1989) identified piping and seepage as causes of widespread failures in their banks. Other investigators emphasized on the importance of the emerging seepage in failure of alluvial Monogahela River (Hamel, 1988) and the Mississippi River (Nakato and Anderson, 1998). Hagerty and Parola (2001) concluded in their study that the riprap revetments even those protected by filters might fail as a result of excessive seepage. Furthermore, leaching of salts in soil with high salt concentration leads to internal erosion and successive failure of side slope and embankment (El-Ashaal et al., 2003 and Heza et al., 2003). Embankments constructed on soft clay foundation typically have a potential failure mode in the form of an approximately circular slip surface that extends into the soft foundation. Failure, if it occurs, will follow the path along which the factor of safety is the minimum (Low, 1989).

El-Ashaal, Hikal, and Abdel-Motaleb (2000) demonstrated the rehabilitation and upgrading of a cracked zoned fill dike. They indicated that the rehabilitation works were divided into two stages. The first one was to carry out urgent protection measure by providing a stabilizing mass of graded sandstone to support the dike back slope and the second one was to execute a permanent protection measure by providing a stabilizing prism of loamy sand as an extension for the berm at the upstream dike slope. Stability of the embankment slopes may be achieved using riprap revetment and such revetment can be protected against seepage using filters (Hagerty and Parola, 2001). Biotechnical stabilization of slopes was also used as a measure for slope protection (Gry and Sotir, 1992). Using drains is considered as one of the most effective methods for improving the stability of slopes when an unfavorable

[1]Associate Professor, Engineering College, Qassim University, AlQassim, KSA
Corresponding author: [1]Selkholy@qec.edu.sa

ground-water condition is the main cause of instability (Cedergren, 1977, Zaruba and Mencl, 1982, and Resnick and Znidarcic, 1990)

Using piles to stabilize slopes has been used successfully for many years. DeBeer and Wallays (1970) reported the use of bored piles reinforced with steel beams in the stabilization of a slope. Poulous and Davis (1980) pointed out that large diameter piles (1.0 to 1.5m) were used to stabilize active landslide areas in the United States. In Japan, steel-pipe piles with 30-cm diameter were also used to stabilize landslides. Chow (1996) and Hassiotis et al. (1997) presented the design of slopes reinforced with a single row of piles. El-Ashaal, Abdel-Motaleb, and Haggag (2000) used reinforced concrete piles to stabilize the embankment of a major canal made of uncompacted marine deposits and founded over soft clay. Despite the frequent use of piles to stabilize slopes, there has not been a standard method for the design of such piles.

Stark et al. (2008) presented a case study where PVC geomembrane was successfully used to mitigate a failure in water ponds.

In the present study, five case studies of slope failures are presented. For each case, the geotechnical investigation, causes of failure, and the suitable technique of rehabilitation are demonstrated. Those case studies were chosen to cover a wide range of soil nature, seepage flow conditions, boundary conditions, and site restrictions enforcing certain limitations on the rehabilitation technique. It will be shown that there is no straightforward solution for the rehabilitation of the failed slope. The main lessons inferred from the case studies and the conclusions are mentioned.

Area of study

The current study presents five case studies as examples of the irrigation and drainage channels in Egypt. They are located at the northern, eastern, and southern parts of Egypt. The selected cases include several open channels that are part of the irrigation and drainage channels which are part of the Egyptian irrigation/drainage system. Some of these channels lie in the old agriculture lands in the southern part of the irrigation system in western part of the River Nile while the others lie in the eastern part of Egypt which transfers the water to the new reclaimed areas in Sinai. The studied channels include agricultural drains and canals which are used for both irrigation and drinking purposes.

Materials and methods

The studied cases cover a wide variety of soil characteristics and groundwater and flow conditions. An extensive site investigation program for each location was carried out. It included drilling boreholes, 15 20 m in depth, to extract soil samples. The investigations included conducting some field tests, Standard Penetration Tests (SPT) and Seismic Cone Penetrometer Test (SCPT). While an extensive laboratory testing program was also conducted to determine the natural, mechanical, and chemical properties of the different soil deposits. Samples of surface as well as ground water were also collected in order to determine their nature, properties, and their effect on the stability of channels side slopes. The determined properties of soil and water are used in the investigation of the stability of the studied cases. The field and lab testing program varies from one case study to the other and their details will be discussed in the following sections for each case separately. The conducted studies and testing programs ran during the period of 2001-2003.

The stability of the channels side slopes are investigated using the computer program package called “GEO-SLOPE Office” was used for the seepage and the slope stability analysis of the problem. This package is based on the finite element method. The program package consists of several programs. Each one of them is meant to study a different type of problem. For example, the program SEEP/W is used to perform seepage analysis, SLOPE/W to perform slope stability analysis, and SIGMA/W to perform stress and deformation analyses. The pore water pressure inside these slopes and the effect of seepage forces were taken into consideration by using SEEP/W.

A. Background and Soil Investigation of Case Study 1

In this case, a reach of the left embankment of a major canal in the eastern part of Egypt is studied. The height of the embankment is 5.50 m and the water depth is about 2.50 m. The problem started in 1997 when a main road was being constructed on the left embankment. Part of the construction process was to reshape the embankment side slope to its original slope 2 (horizontal):1 (vertical) and then put riprap to protect it. Then, a 100.0 m reach of the side slope failed with the riprap. The local authority made a replacement for a shallow depth of the soil and replaced the riprap. Unfortunately, the road suffered a large settlement and a deeper replacement was made again. But the road settled again causing lateral displacement for the riprap cracks along the road. At this time, the local authorities looked for technical assistance. Consequently, a complete geotechnical study was conducted including three boreholes; two of them with a depth of 15.0 m and the third with a depth of 19.5 m. Disturbed and undisturbed samples were extracted and SPT were conducted. Three holes on the left embankment with a depth of 10.0 m and six holes on the slope and inside the water with a depth ranging between 3.8 and 5.0 m were executed to perform SCPT. Since the natural soil of the left embankment was replaced for a significant depth, the original strength of the soil was investigated by conducting SPT and SCPT along the right embankment. Three holes on the right embankment were executed to conduct SPT and four holes on the right side slope and inside the water to conduct SCPT.

The boreholes on the left embankment showed that the soil deposit consisted of two layers. The first layer is a loose gravelly sand soil with clay traces with a thickness ranging between 3.00 m and 4.65 m. This layer was mixed with the gravelly sand replacement soil. The SPT count in this layer ranges from 2 to 7 blows, which means that the replacement soil was very loose and not compacted. The second layer is highly plastic silty clay with strength medium to stiff. The silty clay layer extended to the end of the boreholes. On the right embankment, the SPT count in the surface loose layer ranges from 1 to 15 blows, which means that the natural soil is also very loose to medium dense. Talking to the people living close to the studied area, they mentioned that a bomb hit this reach of the canal during 1973 war, which might explain the very loose nature of the surface soil.

B. Background and Soil Investigation of Case Study 2

This case study represents an irrigation channel having a bed width of 10.0 m, a maximum water depth of 2.75 m, and a side slope of 3:1. The channel cross-section was lined by gabions of gravel. As reported by the owner, the channel side slopes were stable until a parallel drain was constructed. The drain bed width is 5.0 m and the maximum water is 0.25 m. Once the drain was constructed the instability problem was clear. Slope failures of the drain, collapse of the embankment surface, and collapse of the gabions on the canal side slopes were observed.

In order to investigate the cause of the problem, it was necessary to identify the stratification of the soil profile in the site and determine the soil physical and engineering properties. Therefore, an extensive soil investigation was carried out including drilling 54 boreholes along both sides of the canal path to extract soil samples at different levels. One open pit was excavated to collect undisturbed soil samples to determine their natural, chemical, and engineering properties. Samples of ground water as well as surface water in the site (from the canal, the drain, and the open pit) were also collected to determine their nature and find their effect on the soil. Furthermore, comprehensive laboratory test program was conducted. Using the results of the field and laboratory tests, the soil profile along the canal path consisted mainly of layers of medium dense sand, clayey silt, and soft clay with shells as shown in Figure 1. Chemical analysis of the different soil types, ground water, and surface water of the canal and the drain showed high salt concentration.

C. Background and Soil Investigation of Case Study 3

In this case, a drain in northern part of Egypt with a bed width that ranges from 2.0 m to 5.0 m. The drain bed level is (-4.55), berm level is (0.00), and the embankment level is (2.00) m. The ground level is (1.20) m. All levels are referenced to mean sea level. The problem in this case was noticed by the increasing amount of sand collected in front of the suction basin of the pump station. Therefore, two sand traps were constructed to collect the sand but this solution did not solve the problem. Then, consecutive failures of the drain embankment were obvious and the flowing water in the drain washed out each collapsed mass.

To identify the problem, an extensive site investigation program was carried out including 60 boreholes with a depth of 15.0 m and SPT tests along both sides of the drain path. The results of the site investigation and laboratory tests

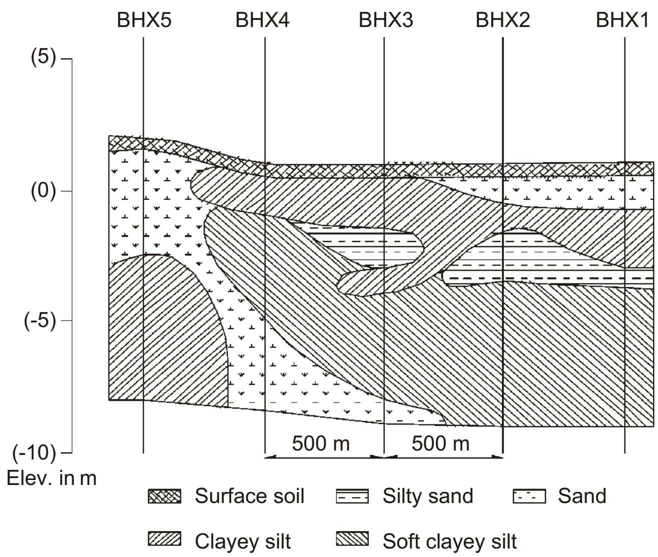

Figure 1 : Soil profile of case 2

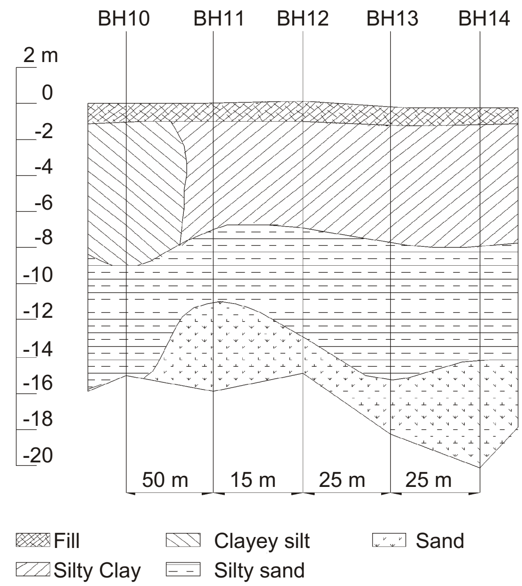

Figure 2 : Soil profile of case 4

Showed that the soil profile consists mainly of layers of poorly graded fine to medium sand intermitted by layers of clayey silty sand. There were also lenses of silty clay or clayey silt. The SPT results varied significantly along the drain path with corrected values from 3 to 50.

D. Background and Soil Investigation of Case Study 4

The canal considered in this case is a major element of the irrigation system of southern Egypt. It has a bed width of 22.0 m and side slopes of 3:2. The designed cross section of the canal has no berm and the embankment height is about 6.0 m. After the winter closure period (a period during which the discharge from the high dam is at its lowest level because of the lowest water demands), several failures along the canal path of lengths between 120.0 m and 380.0 m were observed at the internal side slope of the canal which resulted in reducing the canal cross section at some areas and endangering the heavy traffic on the canal embankment. During the field investigation, Deep cracks, parallel to the canal, were noticed at the left embankment and a drain parallel to the canal was observed at a distance not more than 50.0 m.

A complete geotechnical study of the site was carried out including drilling 20 boreholes with a depth between 15.0 m to 20.0 m and disturbed and undisturbed samples were collected. Furthermore, field and laboratory tests in order to determine the physical and engineering properties of the soil deposits in the site were carried out. The results of the field and laboratory tests showed that the soil stratification in the site consists of a surface soil layer with a thickness of 1.0 m followed by about 7.0 m of medium stiff silty clay with traces of lime. Then, a layer of silty fine sand with a thickness of about 7.0 m exists, followed by a fine sand layer with a thickness of about 5.0 m. Figure 2 shows the soil profile of case 4.

E. Background and Soil Investigation of Case Study 5

A major drain in the northeastern part of Egypt has suffered a slope failure through a reach of about 400.0 m. The height of the embankment is 6.0 m over the bed of the drain with a berm at 4.90 m above the bed and side slopes 2:1. To explore the nature of the soil deposits at the site, four boreholes with a depth of 15.00 m to extract disturbed samples only since the soil deposits at the site were very soft to extract undisturbed samples. Two holes for field vane shear tests were drilled to determine the strength of the soft soil layers.

The boreholes showed that the soil deposit consisted mainly of two layers. The first one is highly plastic soft silty clay layer that extends to a depth ranging from 6.5 m to 8.0 m. The second one is poorly graded sand that extends to the end of the borehole. A lens of peat with a thickness ranging from 0.35 m to 0.60 m existed at a depth 3.00 m. Figure 3 shows the soil profile of this case. The value of the cohesion of the soft silty clay layer resulting from the field vane shear test ranged from 0.11 kg/cm^2 to 0.29 kg/cm^2 and its liquid limit ranged from 50% to 107%.

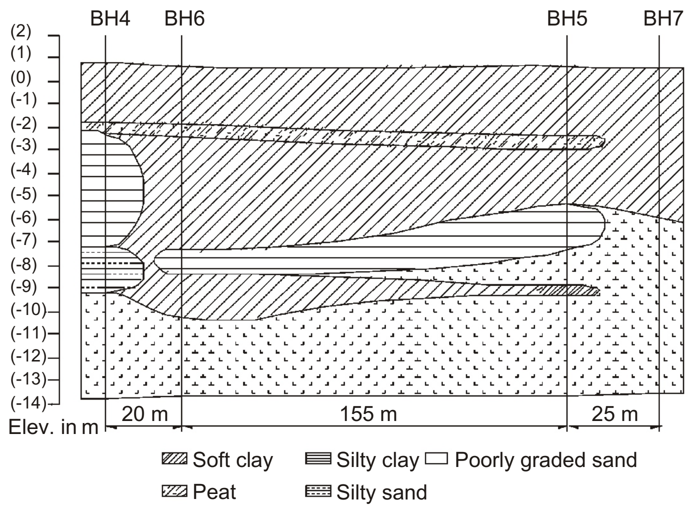

Figure 3 : Soil profile of case 5

Investigating possible causes of slope failure

After completing the site investigation, the natural, physical, mechanical, and/or chemical properties of the soil deposits in each site were identified. Then, the site conditions were examined and a slope stability study was conducted trying to identify the causes of the failures in each case. The Geo-Slope software package was utilized to investigate the stability of the side slopes of the channels. The effect of the seepage forces was taken into consideration using the SEEP/W module and the resulted output were integrated into the SLOPE/W module to investigate the probable causes of failure and the proposed method of mitigation. The critical factor of safety of the failed slopes at different locations was calculated with and without the effect of seepage forces to determine their effect on the slope stability.

A. Causes of Slope Failure of Case Study 1

In this case, when examining the site history and condition, it was found that a main road was constructed on the left embankment of the canal to allow heavy traffic loads to pass along it. The construction process included completing the embankment width and reshaping the side slope to its original slope 2:1 and then put riprap to protect it. It was also known that a bomb hit the site during 1973 war. Consequently, the site investigation was directed to investigate the presence of a camouflets which is an underground cavity formed by the explosion of a bomb without the formation of a crater (British Standards Institution, 1957). Not finding any cavity, a slope stability study of the left embankment was conducted. An equivalent load of a 60-ton lorry and the case of sudden draw down of the water level in the canal were considered. The critical factor of safety was almost 1.0 and the sliding circle lied inside the loose surface soil layer. This value of the factor of safety is low and explains the repeated failure of the left embankment and the riprap on the side slopes. When using a slope of 2.5:1 and the properties of dense soil in the stability analysis, the critical factor of safety became 1.48, which is accepted according to the Egyptian code. Hence, it was concluded that the explosion at the site caused the top sandy soil to loosen along the failing 100.0 m reach. Then, after constructing the main road, the loose nature of the top soil layer could not stand the new heavy traffic loads causing the repeated slope failures. Figure 4 shows the slope failure of the embankment.

Figure 4 : Slope failure of case 1

Figure 5 : Salt leaching and slope failure of case 2

B. Causes of Slope Failure of Case Study 2

Stability analysis of the slopes of the channel and drain was carried out to identify the main cause of the slope failure. This study was carried out under different boundary conditions such as with and without seepage effect, with and without sudden draw down of the water level in the channel, and with and without live load on the embankment. In all cases, the factor of safety achieved the requirements of the Egyptian code of practice. Therefore, the existing slope failure cannot be attributed to any of the above-mentioned conditions. Looking at the laboratory test results, it was noted that the chemical analysis of the soil samples showed the presence of a high percentage of dissolved salts.

Hence, the attention was drawn to the results of the chemical analysis of the soil and the water and it was concluded that the failure occurred because of the leaching effect of the high salt concentration within the soil particles and consequently initiating the piping phenomenon (internal erosion). Figure 5 shows salt traces due to leaching at the drain side slopes. The developed seepage forces started the fine particles washing (migration) and that in turn reduced the stability of the drain side slopes and consequently causing the slope failure of the drain. Furthermore, the continuing process of internal erosion created cavities within the soil mass between the canal and drain causing collapse of parts of the embankment surface and parts of the gabions on the canal side slopes. Field observations supported the above-mentioned conclusion of the cause of failure.

C. Causes of Slope Failure of Case Study 3

Examining the drain cross-sections, field observations, the site investigation data, and the laboratory test results, two major characteristics of this site were noticed. The first one is that the soil is poorly graded fine to medium sand as revealed from the grain size distribution of the soil samples. The poorly graded sand is hard to be compacted efficiently and as well known, the maximum stable slope angle for dry sand, under no external loads, is its angle of internal friction (Budhu and Gobin, 1996). If seepage or surface erosion is permitted through the sand mass of such drain, it will collapse ending up with a flatter slope. The second major characteristic of the site is that the water table in the neighboring agricultural land is quite higher than the water level in the drain with a difference that ranges from 1.40 m to 2.40 m. Such a difference caused high seepage forces on the drain side slopes. This in turn caused the sliding of the slope mass into the drain at different locations along the drain path as indicated in Figure 6. The failures were worse in the locations closer to the pump station because of the severity of the bed erosion and the higher values of the hydraulic exit gradient on the side slopes. Then, the failing mass was washed out by the flowing water causing the sedimentation of the soil particles inside the suction basin of the pump station.

A slope stability analysis was carried out using a computer program. In the beginning, the stability of the slopes on the dry condition was examined and the factor of safety was 1.1, which shows that the slope does not satisfy the requirements of the Egyptian code of practice. Then, additional runs were carried out with seepage forces and live loads and the factor of safety was 0.96. The failure of such case can be attributed to two main causes, the first one is the instability of the slope due to the gravitational effect and the seepage forces, which cause the fine particles to migrate causing internal erosion. The second one is due to the high velocity of the flowing water that causes surface erosion either form the side slopes and/or the bed of the drain especially near the suction basin of the pump station.

Figure 6 : Slope failure of case 3

Figure 7 : Slope failure of case 4

D. Causes of Slope Failure of Case Study 4

Figure 7 shows the failure of the canal side slopes. A slope stability analysis was carried out to determine the probable causes of failure. Noting that the failures occurred after the winter closure, a sudden draw down of the water level was considered in the analysis. Also, the case where the seepage line is from the existing drain to the canal was studied. In both cases, equivalent loads of 60-ton lorry have been taken into consideration since heavy traffic loads were allowed on the road on the canal embankment. The factor of safety of the normal working conditions (without heavy traffic loads and sudden draw down) is 1.50, which is safe according to the Egyptian code of practice. While the minimum factor of safety was 0.70 in the case of sudden draw down and heavy traffic loads. Therefore, it was concluded that the sudden draw down combined with the heavier traffic loads caused the slope failure of the canal.

E. Causes of Slope Failure of Case Study 5

Examining the results of the site investigation especially the field vane shear tests and the laboratory tests, it was clear that the cause of failure was the very weak nature of the soil deposits at the site especially the peat lenses in addition to the seepage from the neighboring agricultural land to the drain. Slope stability analysis of the drain cross section was conducted. The seepage from the neighboring agricultural lands was considered. The slip surface was forced to pass through the peat lens since it is much weaker than the surrounding soil deposits. The critical factor of safety was 0.69, which is quite lower than the requirements of the Egyptian code of practice.

Rehabilitation of the failed slope

Rehabilitation of a failed slope is a complex process because of the restrictions enforced on the type of solution. These restrictions may be due to scarcity of suitable replacement soil, the necessity to keep the channel and/or the road on its embankment functioning, and/or the impossibility of changing the dimensions of the cross section. Therefore, there is no fixed solution for the failures of water channels. In other words, there no fixed criteria for a good solution. A good solution is the one that surely satisfies the safety of the embankment and also takes the imposed restrictions into account.

A. Rehabilitation of Case Study 1

In this case, the slope stability study showed that the side slope 2:1 is not suitable and that changing it to 2.5:1 and compacting the soil mass of the slope would satisfy the requirements of the Egyptian code of practice. However, the restriction imposed in this case is the impossibility of changing the side slopes in this reach. Therefore, it was suggested to use a supporting system for the embankment as an alternative solution. This supporting system consisted of reinforced concrete piles with a diameter of 60 cm and a center-to-center space of 1.50 m. The factor of safety of the stabilized embankment was 1.96 and the sliding circle was a base circle. It was recommended to use partial displacement piles, to improve the density of the loose layer, with a depth of 15.0 m and the length of the stabilized reach extended for 20.0 m from both sides of the failing reach of the embankment. A reinforced concrete beam with a width of 70 cm and a depth of 60 cm was used to connect the piles together. Then, the slopes should be dressed to the original slope 2:1 and the riprap replaced with a thickness of 40.0 cm. The details of the rehabilitation technique are shown in Figure 8.

B. Rehabilitation of Case Study 2

Since the problem in this case is mainly due to the seepage that causes salt leaching and consequently cavities, the rehabilitation aimed mainly at controlling the seepage line from the canal to the drain to reduce the values of the exit gradient and protect the soil mass against piping. This goal can be achieved using cutoff wall technique. Several schemes were attempted by changing the number of cutoffs, their positions, and their depths to reach the optimum cutoff solution. The amount of water seeping from the canal to the drain, as well as the values of the critical exit gradient were obtained for each case and the results were compared with the case of no cutoff. The case of inverse seepage from the drain to the canal was also studied to account for the canal maintenance at which the water level drops to almost zero. Based on the results, a system of two cutoff walls was suggested. The first cutoff is at the canal left berm with a depth of 6.0 m and the second one is at the drain right embankment with a depth of 14.0 m. Fig. 9 shows the general layout of the problem area and the suggested solution. Figure 10 shows the details of the protection filter to safeguard the soil mass against fine particle migration to minimize the internal erosion.

C. Rehabilitation of Case Study 3

It was indicated when talking about the causes of this problem that the basic problems in this drain are the loose nature of the original soil and the big difference between the level of the water table in the agricultural lands and the water level in the drain. Therefore, the rehabilitation of this drain depends mainly on satisfying two requirements. The first one is to lay the original soil on a flat slope that will be stable under the working conditions of the drain i.e. with water flowing through the embankment under 2.40 m of hydraulic head. The second one is to put a filter on the original soil to stop the washing out of the fine particles of the original soil.

Hence, to satisfy the first requirement the original soil was laid on a side slope 4:1. The factor of safety for this case is 1.47, which satisfies the requirement of the Egyptian code of practice. Then, a soil filter made of three transition layers was laid to prevent the fine particles from being washed out and to reshape the cross section to its original side slope 2:1. The factor of stability of this case is 1.29, which is less than the requirements of the Egyptian code of practice. Therefore, the side slopes were altered to 2.5:1 with an intermediate berm at level (-1.50). The factor of safety for this cross section is 1.74, which is acceptable according to the Egyptian code. Figure 11 shows the details and dimensions of the suggested cross section.

D. Rehabilitation of Case Study 4

It was stated in the discussion of the causes of failure of this channel that the sudden draw down in the water level combined with the heavier traffic loads caused the slope failure of the canal. Sudden draw down have two negative effects on the stability of the side slope. The first is the destabilizing seepage forces associated with it and the possibility of washing out the finer particles from the original soil. Because of that, the solution depended on flattening the slope of the original soil and then using a filter on it to protect the fine particles. In this case, the slope of the original soil was made 4:1 and then a two-layer filter was laid. Then a gravelly sand soil was used to reshape the canal side slopes to the original one i.e. 3:2 and finally riprap was used with a thickness of 50 cm to protect it. The factor of safety for rehabilitated cross section is 1.52. The details of the suggested cross section are shown in Figure 12. It was recommended that the solution would be executed on alternate sections; each one is 20.0 m long.

E. Rehabilitation of Case Study 5

The drain cross section was stabilized using earth reinforcement technique. The soil was reinforced using geogrid layers at a spacing of 0.60 m and a length of 9.0 m starting from the bed until the berm level. The peak strength of the geogrid is 30.0 KN/m and the yield point elongation is 10%. A single layer of geotextile was laid 0.30 m below the bed level starting from the drain centerline and extending under the embankment width. Silty sand soil was used to replace the natural soil of the site and was compacted accordingly on layers with a thickness of 0.30 m. Figure 13 shows the details of the solution.

Discussion

Irrigation and drainage channels are the backbone of the development in Egypt. Therefore, keeping them efficiently functioning for the longest possible period should be a target for the designer. It is easier and economical to achieve this target during the first construction than during a later rehabilitation. Therefore, this target should be considered during the design, construction, and operation stage of the channel. With the rapid expansion in Egypt, the government was forced to expand beyond the Nile delta. The soil in the new expansion areas is much different than the delta. Therefore, extensive geotechnical studies for those areas including careful site investigation and stability analysis must be carried out.

Many failures have been observed when slope 2:1 is used with fine loose sand. The angle of the channel slope in such case is 26.6º while the friction angle of such soil is about 30º. Therefore, the factor of safety of the slope in the dry condition and without any live loads is 1.15, which is less than the requirements of the Egyptian code of practice. To achieve those requirements, dense sand with an angle of internal friction not less than 37º is needed. However, when having live loads and seepage conditions, 37º is not enough. Hence, when the available local construction material is fine to medium loose sand and importing suitable construction materials is very expensive, slopes ranging from 4:1 to 3:1 should be considered according to the working conditions of the channel.

The designer should look ahead beyond the working conditions of the first operation of the channel. The possibility of having a ground water table higher than the water level in the channel and hence causing seepage forces should be checked carefully especially when designing a drain. In this case, a flatter slope may be needed along with a filter to prevent washing out of the fines of the embankment soil. Furthermore, the future possibility of constructing a road with heavy traffic loads should be examined.

Modern techniques and technology should be considered and implemented; e.g. earth reinforcement, gabions, geotextile, slurry cutoff, flexible, etc... These techniques can deal with exceptional conditions; e.g. limited available area for needed flatter slopes, high cost of importing soil for needed graded filter, etc…

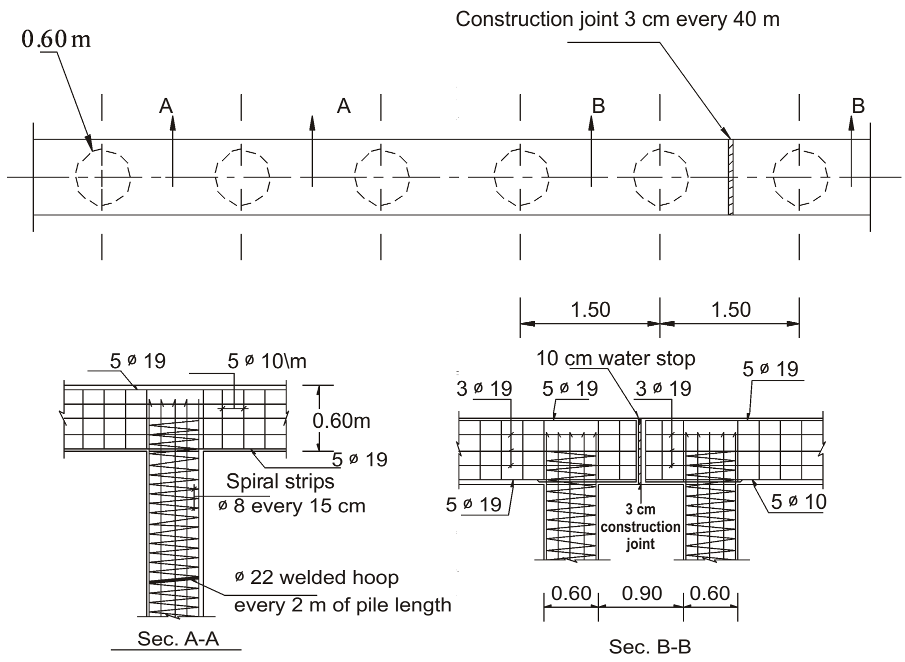

Figure 8 : Rehabilitation technique of case 1.

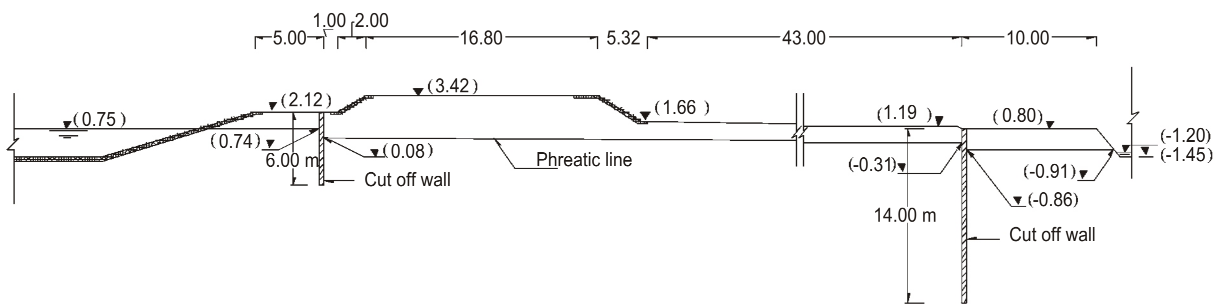

Figure 9 : The general layout of the problem area and the rehabilitation of case 2.

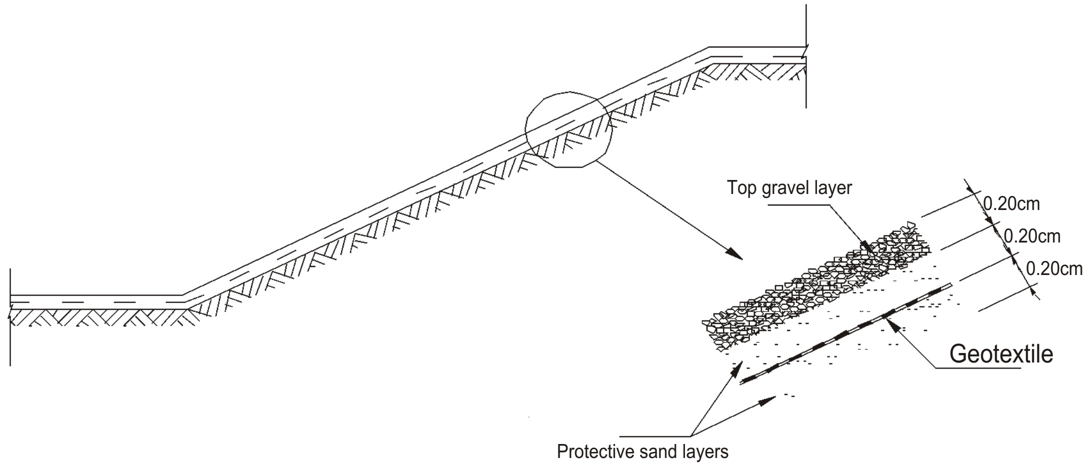

Figure 10 : Protective filter against piping in case 2.

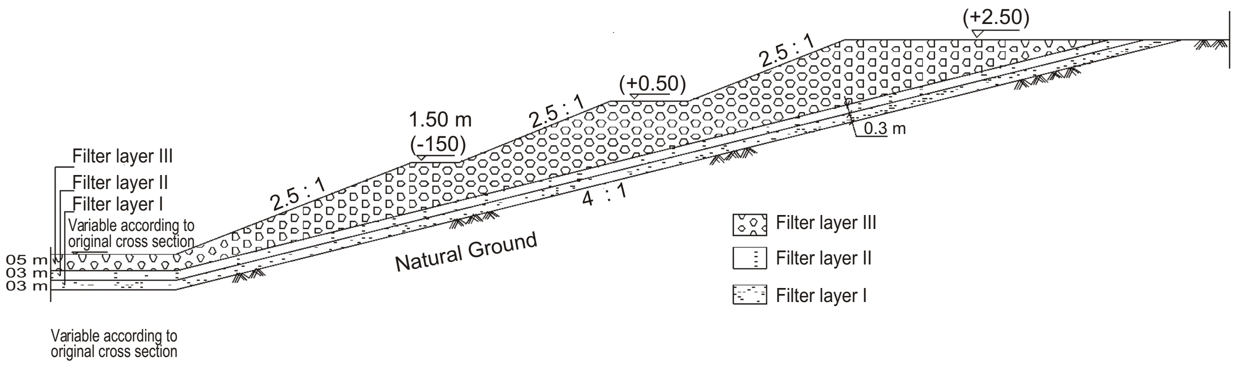

Figure 11 : The details and dimensions of the rehabilitated cross section of case 3

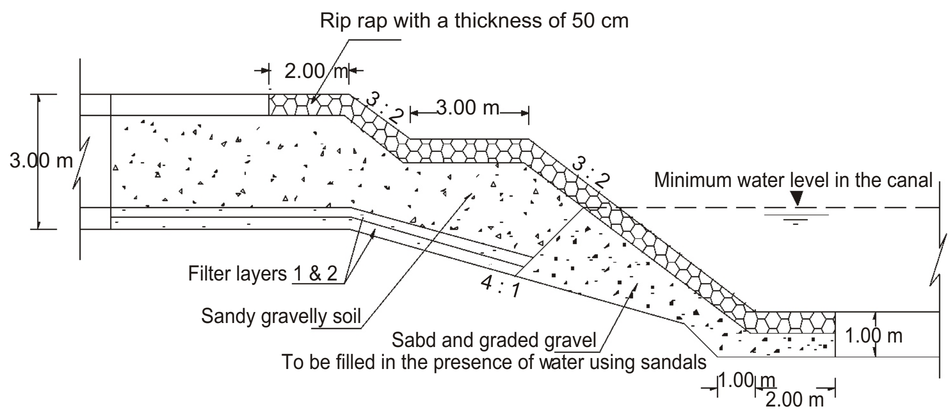

Figure 12 : The details of the rehabilitated cross section of case 4

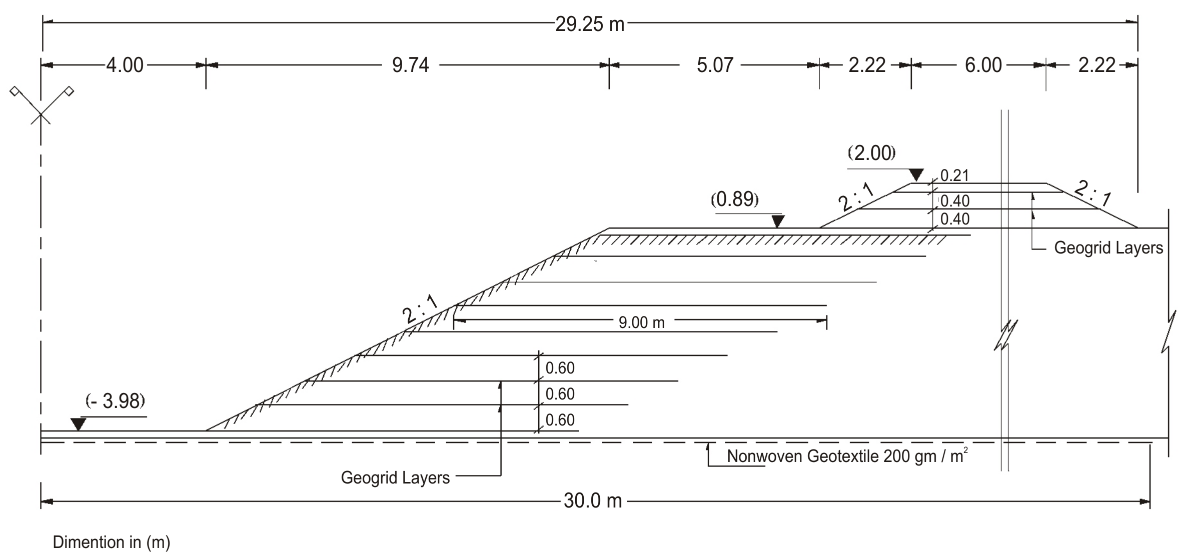

Figure 13 : The details of the rehabilitated cross-section of case 5.

Conculusions

Based on the field investigation, laboratory test results, seepage analysis, and stability analysis of five slope failure cases in Egypt, the following conclusions can be drawn:

1- Common causes of failure of water channels in Egypt include:

Careless geotechnical investigation of the construction site especially when dealing with the newly developed areas outside the Nile delta.

Paying no attention to the various possible working conditions especially those causing seepage either from a channel to another or from the neighboring cultivated land to the channel.

Overlooking the future expected conditions especially the possibility of having a road on the embankment with heavy traffic.

Expecting the soil to behave as a man made material with standard properties wherever it is found; e.g. expansive soil is mainly clayey soil, however it behaves completely different from the clayey soil of the Nile delta.

2- Using side slope 2:1 in cohesionless soil, i.e. sandy soil, in Egypt is disastrous and is a common cause of numerous slope failures.

3- No single or general way of rehabilitation of channels suffering from slope failures because of the uniqueness of the working conditions and characteristics of each site. Therefore, each site has to be studied carefully to find out the best way to deal with it.

4- Rapid draw down of the water level in the channels during the winter closure must be considered when studying the stability of slopes since it was proved to stand behind some dangerous failures.

5- The presence of a high percent of salt may lead to internal erosion due to leaching and thus causing failure.

6- Adopting the modern technology is a must for more efficient water channels.

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References

[1] British Standards Institution (1957), “British Standards Code of Practice, CP2001, Site Investigation” pp. 26.

[2] Budhu, M., Gobin, R. (1996), “Slope Instability From Ground-Water Seepage”, Journal of Hydraulic Engineering, ASCE, Vol. 122, No. 7, July, pp. 415-417.

[3] Burgi, P.H., Karaki, A. (1971), “Seepage Effect on Channel Bank Stability”, Journal of the Irrigation and drainage division, ASCE, Vol. 97, IR 1, March, pp. 59-72.

[4] Cedergren, H.R. (1977), “Seepage, Drainage, and Flow net”, Second edition, A Wiley-Interscience Publication, John Wily and Sons.

[5] Chow, Y.K. (1996), “Analysis of piles Used for Slope Stabilization”, International Journal for Numerical and Analytical Methods in Geomechanics, Vol. 20, pp. 635-646.

[6] DeBeer, E.E., Wallays, M. (1970), "Stabilization of a Slope in Schist by Means of Bored Piles Reinforced with Steel Beams", Proceedings of 2nd International Congress on Rock Mechanics, Vol. 03, pp. 361-369

[7] El-Ashaal, A.A., Abdel-Motaleb, A.A., and ElKholy, S.M. (2003), "Upgrading and Reconstruction of a Collapsed Embankment Founded on Salty Soil", Dam Maintenance and Rehabilitation, Lianos et al. (eds), pp. 763- 768

[8] El-Ashaal, A., Abdel-Motaleb, A., and Haggag, H. (2000), "Stabilizing Embankments Made of and Founded Over Weak Soil Using Piles: A Case History", Proceedings of the Fourth International Engineering Conference, Cairo University, Cairo, Egypt, pp. 415-426

[9] El-Ashaal, A.A., Hikal, A.H., and Abdel-Motaleb, A.A. (2000), , "Rehabilitation and Upgrading of a Zoned Fill Dike", Soil Mechanics and Foundation, Journal of the Egyptian Geotechnical Society, Vol. 11, Part 2, December, pp. 97-116

[10] Govindaraju, R. S. (1998), "Effect of Erosion Parameters for Soil Slopes with Stability Varying Properties" Journal of Irrigation and Drainage Engineering, ASCE, Vol. 124, No. 2, March/April, pp. 81-88

[11] Gry, D.H., Sotir, R.B. (1992), "Biotechnical Stabilization of High Way Cut Slope" Journal of Geotechnical Engineering, ASCE, Vol. 118, No. 9, September, pp. 1395-1409

[12] Hagerty, D.J., Parola, A.C. (2001), "Seepage Effect in Some Riprap Revetments", Journal of Hydraulic Engineering, ASCE, Vol. 127, No. 7, July, pp. 556-566

[13] Hagerty, D.J. and Spoor, M.F. (1989), "Alluvial Streambank Erosion- a 10-Year Study" Proc., In., Symp. Sed. Trans. Modl., ASCE, New York, pp. 594-599

[14] Hamel, J.V. (1988), "Geotechnical Failure Mechanisms in Alluvial Banks" Mechanics of Alluvial Channels, Water Resources Publications, Littleton, Colo., pp. 369-386

[15] Hassiotis, S., Chameau, J.L., and Gunaratne, M. (1997), "Design Method for Stabilization of Slopes with Piles", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 123, No. 4, pp. 314-323

[16] Heza, Y.B.M., ElKholy, S., and ElAshaal, A. (2003), , "Seepage from Irrigation Canal in Dispersive Soil and its Mitigation", Engineering Research Journal, University of Helwan, Faculty of Eng. & Tech., Materia, Cairo, Volume 88, August, pp. C97-c109

[17] Low, B.K. (1989), "Stability of Embankments of Soft Ground", Journal of Geotechnical Engineering, ASCE, Vol. 115, No. 2, February, pp. 211-227.

[18] Nakato, T., Anderson, J. (1998), "Field Survey of Bank-Erosion Sites Along Upper Mississippi River Reach Between St.Paul, Minnesota and Cairo, Illinois", IIHR Tech. Rep. No. 399, Iowa Institute of Hydraulic Research, Iwoa City, Iowa.

[19] Poulous, H.G., Davis, E.H. (1980), “Pile Foundations Analysis and Design”, John Wiley & Sons, New York, pp. 597.

[20] Resnick, G.S., Znidarcic, D. (1990), “Centrifugal Modeling of Drains for Slope Stabiliztion”, Journal of Geotechnical Engineering, ASCE, Vol. 116, No. 11, November, pp. 1607-1624.

[21] Rhee, C.V., Bezujijen,A. (1992), “Influence of Seepage on Stability of Sandy Slope”, Journal of Geotechnical Engineering, ASCE, Vol. 118, No. 08, pp. 1236-1240

[22] Globa R. S. , S L Barbour S. L. (2001), “A case history of shallow sloughing within cut slopes of an irrigation canal in salt-rich clayey colluviums”, Canadian Geotechnical Journal, 38(4): pp. 665-677

[23] Spoor, M.f., Hagerty, D.J. (1989), “Bank Failure and Erosion on the Illinois Waterway”, Proc. In. Symp. Sed. Trans. Modl., ASCE, New York, pp. 600-605

[24] Stark T.D. , Newman E.J. , Aust R.L. (2008), “Back-Analysis of a PVC Geomembrane-Lined Pond Failure”, Geosynthetics International, 15(4), pp 258-268

[25] Zaruba, Q., Mencl, V. (1982), “Landslides and Their Control”, Second edition, Elsevier Scientific Publishing Company, New York, pp. 208-217