

## **Upgrading and Reconstruction of a Collapsed Man-Made Lake Embankment Founded on Salty Soil**

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### **Abstract**

Failure of the embankment of a man-made lake has caused a disaster and initiated a full-scale study to upgrade and reconstruct the embankments. An extensive field geotechnical study was conducted along the embankments to investigate the cause of the embankment failure and look into the measures and precautions to be taken into consideration while designing the new embankment. This study included executing 29 boreholes and static cone penetration tests. The field study showed the presence of a high percentage of salts mainly sodium and chloride in the surface layers. Washing the present salts with time might have been one of factors that caused the embankment failure. The areas nearby the lake were surveyed to find the suitable borrow bits to be used in the upgrade of the embankments. An extensive laboratory study was conducted on the samples collected from the different borrow bits. The results showed that the local suitable construction materials are not sufficient to construct a homogenous embankment. Therefore, it was decided to construct a zoned embankment.

The embankment consisted of an impermeable core, three transitional layers, a filter, and protected shoulders. The surface salty layer under the base of the embankment was replaced with a compacted silty clayey sand layer with a minimum thickness of 2.0 m. A cutoff was created by extending down the core to an impermeable silty clay layer. Additional seepage control measure was considered by forming a cutoff drain at a distance from the downstream slope. The purpose of the cutoff drain is to avoid creating a hydraulic gradient at the toe of the downstream slope, which may cause internal and external erosion at the downstream section of the embankment. A numerical study of the embankment was conducted. This study included a seepage study, slope stability study, and a stress-strain study.

**Keywords:** Earth Embankment, Embankment Failure, Man-Made Lake, Finite Element

### **Introduction**

Earthfill embankments have several advantages over other embankment types. One of the main advantages is the adaptability to foundations that might not be suitable for other embankment types (Jansen et al., 1988). The safety of any embankment depends on many factors such as the appropriate embankment foundations, stability of its side slopes, seepage control, and erosion control. Although the foundation is not actually designed, certain provisions for treatment are made in designs to assure that the essential requirements will be met (U.S.D.I., 1970).

The drainage system of one of the Egyptian governrates that lies west of the Nile River depends mainly on two drainage lakes. The lake under consideration in this study has an area over 330000 square meters. In the year 2000, a reach with a length of about 200 m of the lake embankment collapsed and caused a disaster for the human beings, agricultural lands, and cattle. This disaster called for an immediate full-scale study to determine the cause of the failure and suggest the best way to upgrade and reconstruct the lake embankment. The upgrade of the embankment was necessary to increase the lake area to about 900000 square meters. The full-scale study started with a filed trip aiming at examining the failed embankment. Then, it was followed by an extensive field geotechnical study along the embankment to investigate the cause of the failure and look into the measures and precautions to be taken into consideration while designing the new embankment. Then a survey of the area around the lake was done to investigate the suitability of the available construction materials to the construction of the new embankment. Based on the survey of the local material, a cross section of the embankment was introduced and a numerical analysis is conducted to evaluate the safety and suitability of the suggested cross section under working condition.

### **Field Investigations**

Examining the failed embankment showed the presence of an intercepting drain at the downstream toe of the embankment. Improperly designed toe drain can cause trouble for embankments (Dewey, 1993). It was noticed that internal erosion started at the toe drain and could have been one of the factors that lead to the failure. It was also found that the embankment site was originally a salt bed and that the embankment was constructed directly on the ground without any treatment. The geotechnical field study consisted of 29 boreholes along the lake embankment. The spacing between the boreholes was about 120 m. The depth of the boreholes ranged between 14.25 m and 20.0 m. Standard Penetration tests were done in the sandy soil layers. Another 29 locations were bored for the Static Cone Penetration tests along the lake embankment. The readings were taken every 0.5 m down to a depth of 10 m for each hole. Undisturbed and disturbed samples were extracted from the boreholes. Figure 1 shows a sketch of the locations of the boreholes along the lake embankment.

From the boreholes, the soil deposit starting from the embankment surface consisted of a non-compacted sandy clayey silt layer at the surface with a thickness of 1 m to 5 m. Then follows a layer of silty clay with an extremely high percentage of slats, especially Sodium Chloride salts, at a depth that ranges between 1 m to 2 m and extends down to 5.0 m. Then follows a deep layer of silty clay that extends to the end of most of the boreholes. According to Atterberg limits, this layer is classified as clay with medium to high plasticity. In some boreholes, there are lenses of silty sand with some clay at different depths. It was noticed that the percentage of salts in all the layers was high. From the readings of the static cone penetration tests, it was noticed that the smallest readings were at the silty clay layer with an extremely high percentage of salts, that is the ground surface of the old salt bed.

### Laboratory Testing

A laboratory-testing program was conducted on the soil samples. It was directed to determining Atterberg limits, grain size distribution, free swell ratio, shear strength, and chemical properties of the soil samples. The results showed that the silty clay layer has a liquid limit that ranges between 42% and 64%, a plasticity index between 19% and 40%, and a free swell ratio between 20% and 45%. The total soluble salts reached as high as 37.50%. The concentration of Sodium Chloride salts reached up to 32%.

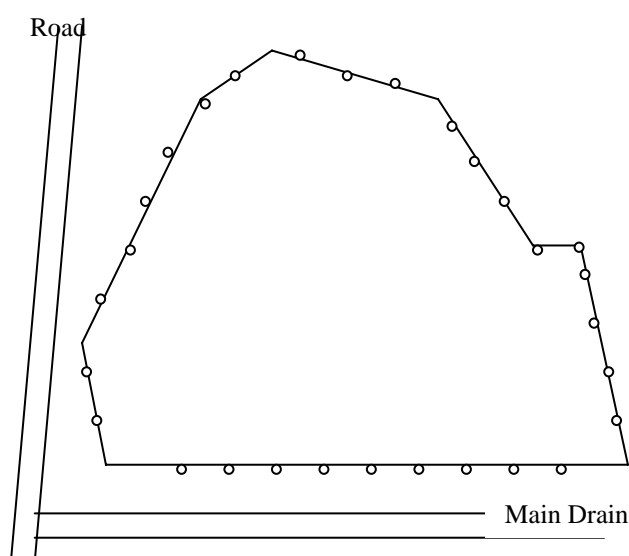


Figure 1. Sketch of the drainage lake embankment and the locations of the boreholes along it.

One of the objectives of the laboratory-testing program was to investigate the effect of the high percentage of salts on the behavior of the soil. Therefore, direct shear tests were conducted on undisturbed samples after submerging them in water for one day and then for ten days. It was noticed that submerging the samples for ten days reduced the shear strength of the samples by 15% to 20% of the shear strength after submerging for one day. Thus, it was concluded that washing the salt assisted in reducing the shear strength of the embankment soil and instigating the failure.

### Survey of Local Construction Material

Design of earthfill embankments must be optimized by using the local materials (Jansen et al., 1988). Consequently, the area around the site of the drainage lake was surveyed. Ten sites were selected and samples of different soil types were collected to be tested. The available soil types were sand with some silt, silty gravelly sand, silty sandy clay, and silty clayey sand. Tests such as Atterberg limits, free swell, sieve analysis,

hydrometer, and chemical analysis were conducted. Based on the test results, the different soil types were evaluated and it was decided to construct a zoned embankment. The embankment will consist of an impermeable core, filter, and shoulders. The silty sandy clay available at one of the surveyed sites was chosen to construct the core because of the high percentage of fines, low swelling potential, and low amount of soluble salts. The sand with some silt was chosen to construct the shoulders and the silty gravelly sand to construct the filter layers around the impermeable core. All the chosen soils have a low amount of soluble salts.

### Embankment Cross Section

The suggested cross section of the embankment is shown in Figure 2. The height of the embankment is 6.0 m and the maximum depth of water in the drainage lake is 5.0 m. The total depth of the salty layer at the surface must be completely replaced with the silty sandy clay soil, with a minimum depth of 2.0 m. The impermeable core has a width of 3.0 m at the top and 5.0 at the bottom. To minimize the amount of water seeping through the embankment, the core is extended down through a trench to penetrate the silty clay layer for a depth of at least 1.0 m and a width of 1.5 m. A filter and three transitional layers, each is 75 cm thick, protects the core at the upstream and downstream sides. The first layer near the core is a mix of 80% of the core soil with a 20% of the filter soil. The second layer is a mix of 30% of the core soil with a 70% of the filter soil. The third layer is a mix of 10% of the core soil with a 90% of the filter soil. Then follows the shoulders, 15 cm thick filter of sand and gravel, and a 30 cm thick external protection layer of gravel.

Since improperly designed toe drain can cause trouble for embankments (Dewey, 1993), an intercepting open drain, to relieve pore water pressure and collect any seeping water, is made at a distance of about 45 m downstream the embankment to avoid any piping that would lead to internal erosion at the downstream toe of the embankment. The filter around the core is extended for 7.0 m upstream the embankment and until the intercepting drain downstream the embankment.

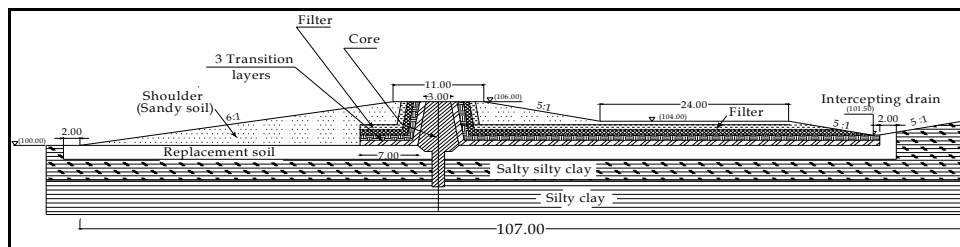


Figure 2. Details of the suggested cross section of the new embankment.

### The Analysis of the Embankment

Since it allows for the study of earthfill embankment under a wide range of conditions, numerical analysis of embankments and dams has become a common lesson learned from several failures (James et al., 1988). Thus, a numerical analysis was carried out to study the suitability and behavior of the suggested embankment cross section. The

finite element method was utilized and Figure 3 shows the finite element mesh. The study included slope stability analysis, seepage analysis, and stress-strain analysis.

### Seepage analysis

The seepage analysis was used to estimate the amount of water seeping through and underneath the core of the embankment and collected in the intercepting drain. The amount of seeping water in the intercepting drain was estimated at about  $1.2 \text{ m}^3/\text{day}/\text{m}$ . This amount is considerably small and could be collected and pumped into the drainage lake. Figure 4 shows the flow lines and equipotential lines in the case of maximum water level in the drainage lake

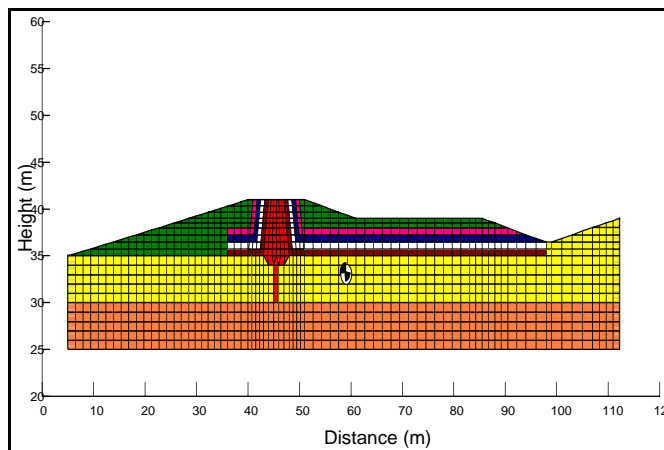


Figure 3. Finite element mesh of the embankment suggested cross section.

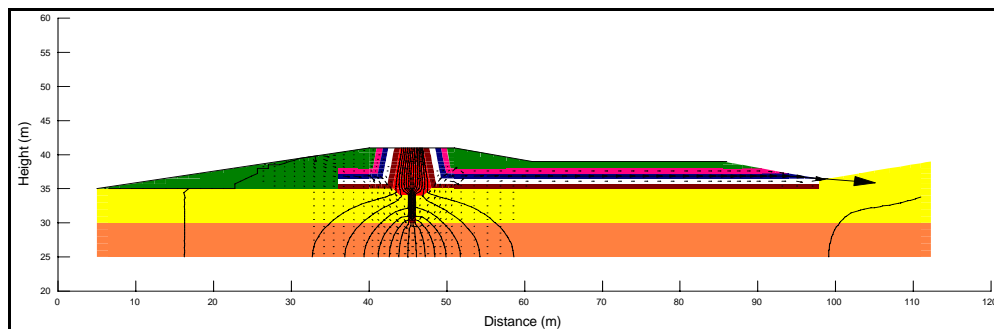


Figure 4. Flow and equipotential lines through and underneath the embankment.

### Slope Stability Analysis

The slope stability analysis used several methods to determine the minimum factor of safety of the embankment slopes. The methods used are Bishop's, Janbu's, and Spencer's method. A live load of  $10 \text{ kN}/\text{m}^2$  was used on the top of the embankment. The strength used for the clayey soil was reduced to consider for the long-term effect of salt washing on the shear strength of the soil. The safe slope of the upstream side was found to

be 6 (horizontal) : 1 (vertical) and 5 (horizontal) : 1 (vertical) for the downstream slope. It was noticed that the critical circles are local circles. The minimum factor of safety for the upstream slope is 1.6 and for the downstream slope is 1.82. Figures 5, 6 show the critical circles and their factor of safety in the upstream and downstream sides consequently.

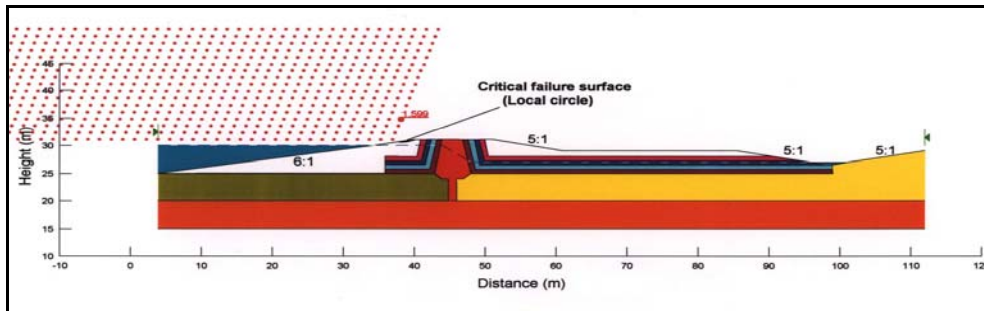


Figure 5. Critical circle and its factor of safety of the upstream slope.

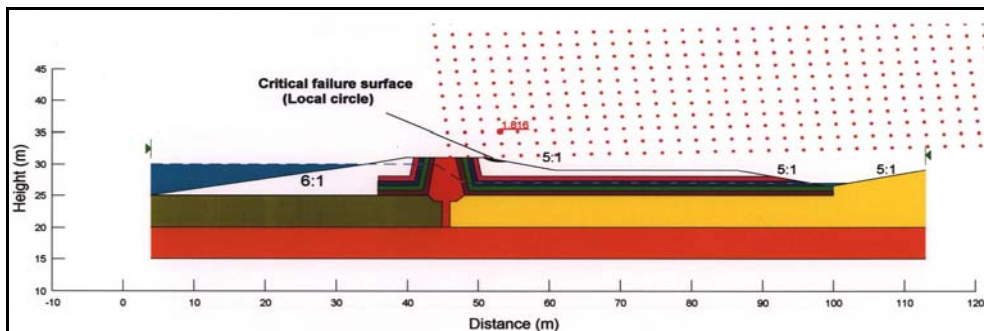


Figure 6. Critical circle and its factor of safety of the downstream slope.

### Stress-strain analysis

The stresses and strains in the embankment and the foundation were studied using the finite element method. The construction sequence was taken into consideration by dividing the embankment into several layers. The stresses and strains resulting from the application of each layer are calculated and then the following layer is applied.

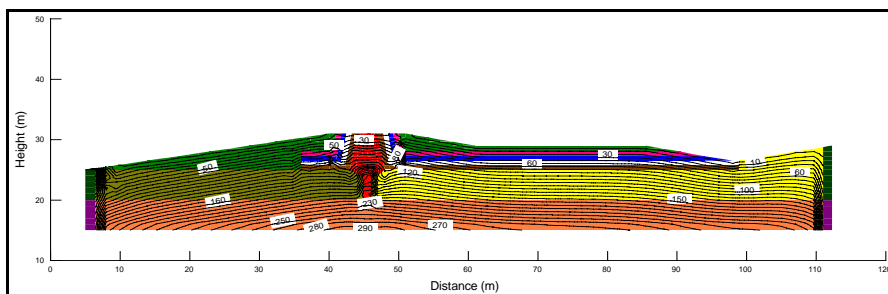


Figure 7. Contour lines of the total vertical stresses in the embankment.

Figure 7 shows the contour lines of the total vertical stresses in the embankment and underneath it. It shows that the maximum total vertical stress in the embankment is at the contact plane between the bottom of the impermeable core and the replacement layer, that is at a depth of about 1.5 m below the original ground surface, with a value that range between 11 kN/m<sup>2</sup> and 18 kN/m<sup>2</sup>. The total vertical stress reaches 23 kN/m<sup>2</sup> at the bottom of the cutoff trench, that is at a depth of about 6.5 m below the original ground surface. Then, the total vertical stress keeps increasing with the depth until it reaches the value of 29.5 kN/m<sup>2</sup> at a depth of about 11.5 m below the centerline of the embankment, that is the bottom of the model. These values are all less than the maximum strength of the soil.

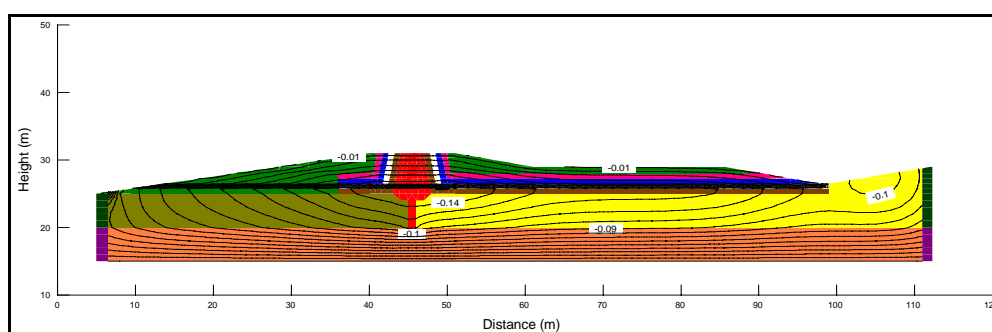


Figure 8. Contour lines of the vertical displacements in the embankment.

Figure 8 shows the contour lines of the vertical displacements in the embankment and underneath it. It shows that the maximum accumulative vertical displacement is 14 cm below the core near the downstream side. The value of the vertical displacement decreases with either going up or down from the bottom of the core until it reaches 1 cm at the top of the embankment and at the bottom of the model.

### Conclusions

The failure of a drainage lake embankment was investigated. The foundation of the failed embankment was not suitable since it contained an extremely high amount of salts. Washing the salt with time reduced the strength of the foundation soil. The presence of an intercepting drain at the downstream toe of the failed embankment was not proper since it helped on washing the salt and eroding the soil at the toe.

A new embankment was designed and analyzed. Several recommendations for the construction of the new embankment were made but the most important ones were the removal and replacement of the salty layer at the top of the ground surface and constructing the intercepting drain about 45 m away from the downstream toe to avoid any destabilizing erosion to the embankment downstream slope. Other recommendations included extending the core down to penetrate completely the silty clay layer with an extremely high percentage of salts and 1 m into the deep silty clay layer. This was to reduce the pressure head at the downstream toe, reduce the amount of seeping water and consequently minimize the effect of washing the salt in the salty silty clay layer. To protect the core and relieve the pore water pressure, it was also recommended to extend the filter and the

transitional layers for a length of 7 m in the upstream and till the intercepting drain in the downstream side.

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## تطوير وإعادة بناء جسر تراي منهار مؤسس على تربة ملحية

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معهد بحوث الموارد المائية - المركز القومي لبحوث المياه - القناطر الخيرية - مصر

يتعرض هذا البحث لمشكلة إهمار جسور بحيرة صناعية بالوادي الجديد والتي أدت إلي العديد من المشكلات البيئية والاجتماعية في المناطق السكانية المحيطة. وقد أجريت دراسة حيوتكنيكية شاملة للجسر المنهار لدراسة أسباب إهماره. وقد أوضحت الدراسة الميدانية وجود نسبة عالية من الأملاح، كلوريد الصوديوم بصفة أساسية، في الطبقات القريبة من سطح الأرض، ومع مرور الزمن أدى غسيل الأملاح الموجودة ضمن عوامل أخرى إلي إهمار الجسر. وقد أوضحت الدراسة الجيولوجية ونتائج الاختبارات العملية للمنطقة المحيطة بالبحيرة أن المواد الإنشائية المحلية الملائمة غير كافية لإنشاء جسر متجانس. ومن ثم فقد رؤي إنشاء جسر غير متجانس. الجسر يتكون من نواه (كور) غير منفذة، ثلاث طبقات انتقالية، فلتر وأكتاف لها طبقات حماية. وقد استبدلت الطبقة السطحية المالحة تحت قاعدة الجسر بطبقة رمل طيني طميي مدموكة بسمك لا يقل عن 2.00 متراً. وقد أجريت دراسة تحليلية عديدة للجسر لدراسة سلوك القطاع المقترح تحت ظروف التشغيل المختلفة. وقد استبدلت الطبقة السطحية المالحة تحت قاعدة الجسر بطبقة رمل طيني طميي مدموكة بسمك لا يقل عن 2.00 متراً. وقد أجريت دراسة تحليلية عديدة للجسر لدراسة سلوك القطاع المقترح تحت ظروف التشغيل المختلفة.

الكلمات المفتاحية: جسور ترايية- بحيرة صناعية-تحليل عددي- إهمارات جسور.