Soil Stability Analysis in Irrigation Canals: A Case Study

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ABSTRACT

Long term stability of side slopes in large irrigation canals is very vital to avoid soil sloughing under diverse operational conditions during the canal life cycle. A 30.5 km long main irrigation canal currently under construction in Gambella Alwero Rice Project (GARP) in Ethiopia is part of an irrigation water supply scheme to render regulated water to 10,000 ha downstream rice fields. During feasibility studies a 1.5H:1V (horizontal to vertical) side slope was proposed for the canal. However, a comprehensive geotechnical studies at later stage revealed that the proposed side slope may not seem safe and a flatter side slope may deem necessary. This change would add substantial burden to the project budget if not properly substantiated and justified. The geotechnical investigation also suggested that the main canal must be furnished with 15 to 25 cm thick under filter cushion overlaid by a layer of HDPE geo-membrane and a 7 cm thick concrete lining.

As in case of any other irrigation canals, the GARP main canal may undergo diverse future operational conditions during the course of its life cycle. The most critical condition is expected to occur during drawdown condition when under an unforeseeable circumstance the ponded water in canal recedes rapidly leaving the residual pore water pressure in the side embankments invoking canal failure. This unsound behavior may be even accelerated due to additional surcharge loads imposed by the live load of heavy vehicles, the weight of both filter cushion and concrete lining. A slope stability analysis was conducted using SLOPE/W model to assess the consistency of selected 1.5H to 1V side slope versus a tentative flatter 2H to 1V one. The analysis revealed that 2H:1V side slope would provide a more reliable factor of safety leading to minimized risk of failure ensuring stability under all future operational conditions such as end of construction, rapid drawdown and steady state seepage. This paper seeks to summarize the results of stability analyses, which led to a safer design mitigating the future likely failure.

KEYWORDS: Stability Analysis, Soil Stability, HDPE Geomembrane, Irrigation Canal, Concrete Lining.

INTRODUCTION

Large scale irrigation schemes require huge investment for constructing big conveyance canals. Stability of side slopes in such large canals is very vital to prevent any soil sloughing under diverse future operational conditions. A 30.5 km long main irrigation canal currently under construction in

Gambella Alwero Rice Project (GARP) in Ethiopia is part of an irrigation water supply scheme to provide regulated water to 10,000 ha downstream rice fields. The water is released from Abobo Dam located 20 km upstream from project area. The initial project concept during feasibility studies envisioned a side slope of 1.5H:1V (horizontal to vertical) for the main canal. During detailed design phase, a comprehensive geotechnical investigation was conducted to define the physical and engineering properties of soil along the main canal. Observations in fourteen rotary drilled boreholes and extensive laboratory tests on samples taken along the main canal suggested that a flatter side slope may be more reliable over the reaches between km 0+00 to 9+500 and km 16+000 to 21+000. This change could add substantial burden to the project budget if not properly justified and substantiated. The geotechnical investigation also suggested that the main canal should also be furnished by 15 to 25 cm thick under filter cushion overlaid by a layer of HDPE geo-membrane and a 7 cm thick concrete lining (Anon., 2010a).

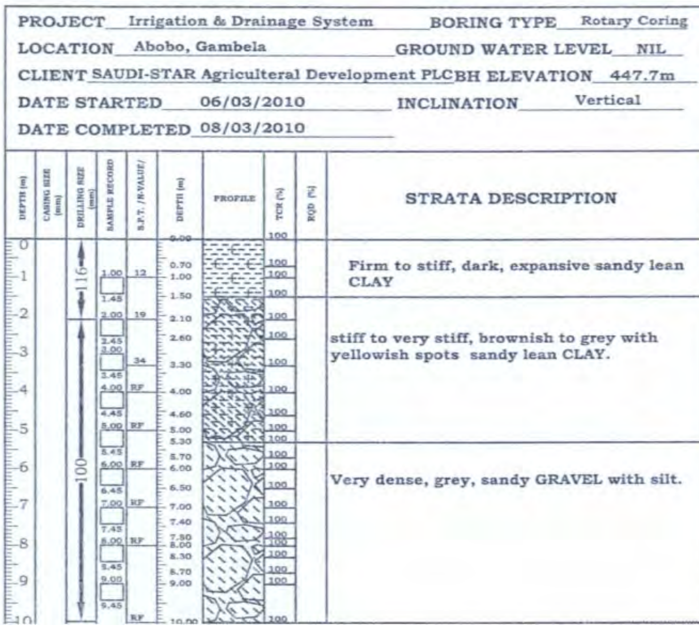
Construction of main canal has, in fact, been envisaged as part of a significant effort to conserve water resources and reduce future canal maintenance and operational costs. Even though, the canal may still undergo diverse unfavorable operational conditions during its entire life cycle. The canal should withstand empty canal state at the end of construction period. It should also remain functional if steady seepage from canal happens or even a rapid drawdown due to sudden break down under unknown circumstances occurs. The most critical condition for operation of the proposed canal is expected to occur when the canal water recedes rapidly (sudden crack) leaving likely residual pore water pressure in the side embankments invoking massive canal failure. This unsound behavior could be even accelerated due to additional surcharge loads imposed by the live load of heavy vehicles, the weight of both filter cushion and concrete lining. A slope stability analysis was conducted using SLOPE/W Janbu and Ordinary method to determine a suitable side slope. The analysis helped to define a safer side slope minimizing the risks under all future operational conditions (Anon., 2010b). This paper will summarize the results of stability analyses performed for main canal, which led to a safer design mitigating the likely future failure.

SOIL CHARACTERISTICS

The geotechnical investigation for main canal consisted of subsurface exploration via sixteen rotary drilled boreholes dug to a depth ranging from 7 to 25 m accompanied by standard penetration tests (SPT) at verious depths (Anon., 2010b). This investigation was launched in order to establish subsurface geology and hydrogeology along the main canal. The result of site investigation classifies the soil as sandy lean clay to clayey sand using the ASTM D2487 Classification system. Table 1 presents a typical soil profile up to a depth of 10 m below surface and Fig. 1 illustrates the plot of grain size distribution for the same soil.

The water table along the main canal is located at more than 25 m below ground surface. The direct shear tests conducted on the soil samples indicated the internal angle of friction for drained samples ranging between ϕ = 25-32° and cohesion changing between c = 5-10 kPa. The said values for undrained samples were 15° and 50 kPa, respectively.

Table 1: Soil Characteristics


PROJECT Irrigation & Drainage System BORING TYPE Rotary Coring
LOCATION Abobo, Gambela GROUND WATER LEVEL NIL
CLIENT SAUDI-STAR Agriculteral Development PLC BH ELEVATION 447.7m
DATE STARTED 06/03/2010 INCLINATION Vertical
DATE COMPLETED 08/03/2010

DEPTH (m)	CASING SIZE (mm)	DRILLING SIZE (mm)	SAMPLE RECORD	S.P.T. (N-VALUE)	DEPTH (m)	PROFILE	TCR (%)	RQD (%)	STRATA DESCRIPTION
0–1.50		116		12	0.00–1.50		100		Firm to stiff, dark, expansive sandy lean CLAY
1.50–5.30		100		19, 34, RF	1.50–5.30		100		stiff to very stiff, brownish to grey with yellowish spots sandy lean CLAY.
5.30–10.00		100		RF	5.30–10.00		100		Very dense, grey, sandy GRAVEL with silt.

Drained		Undrained	
Angle of Internal Friction	Cohesion C kPa	Angle of Internal Friction	Cohesion C kPa
25-32 degrees	5-10	15 degrees	50

Figure 1: Grain size analysis

The SPT test results showed ascending values ranging from 12 to 83 blows per 30 cm as per increasing soil depth. This indicates that the shearing strength of ground is moderately high at the surface and further increases with depth (Anon., 2010b). The static lateral earth pressure coefficients for active (Ka), passive (Kp) and at rest (Ko) conditions using angle of internal friction as 30 degrees are as follows:

Ka = 0.33

Kp = 3.0

Ko = 0.5

The lateral earth pressure was increased due to additional residual earth pressures to be induced by the effect of compaction as per provisions of NAVFAC (Anon., 1986).

Canal side slope determination

In certain stretches, the main canal is being constructed in up to 4 meters compacted fills. The canal cross section takes trapezoidal shape with an inner side slope 1.5H:1V (horizontal to vertical). The determination of side slope configurations was incepted during the feasibility stage (Anon., 2010a). However, further geotechnical investigation at later stage raised speculation about stability of such proposed slope taking into account that 1.5H:1V side slope could reduce the project execution cost. Raising concerns about the stability of side slopes has occurred in other projects too (Iglesia, et al., 2011); however, in GARP the following stability concerns were matter of interest:

- Laboratory test results collected from direct shear test of drained samples indicated a soil friction angle value as low as 25°.
- Soil layering proved to be heterogeneous in character horizontally and vertically along the main canal.
- There is a good chance of potential effects of rainfall on stability of the slope.
- Existence of relatively low SPT blow counts at shallow depths indicates presence of areas of lower shear strength.

Therefore, in order to mitigate such potential risks, a 2H:1V side slope was also introduced for study and comparison purpose.

Side slope stability analysis

The primary aim of slope analysis is to compare the stability of selected 1.5H:1V side slope versus the proposed flatter 2H to 1V one. The slope stability analysis of embankment and foundation soil was conducted using the SLOPE/W component of GeoStudio software (Geo-Slope, 2004). SLOPE/W employs the limit-equilibrium solution scheme based on Morgenstern-Price method of slices. As demonstrated in Fig. 2, the software utilizes slices forces as well as moments to compute the factor of safety against failure. SLOPE/W solves two factor of safety equations; one equation satisfies force equilibrium and the other satisfies the moment equilibrium.

A factor of safety is defined as that factor by which the shear strength of the soil must be reduced in order to bring the mass of the soil into a state of limiting equilibrium along a selected slip surface. A general definition of the factor of safety (FS) as expressed in eqs. 1 and 2 results from comparing the down slope shear stress (τ) with the shear strength (τ_f) of the soil along an assumed or known rupture surface:

$$FS = \frac{TotalDrivingForce}{Total\,ResistingForce} = \frac{ShearStrength}{ShearStress} \quad \text{eq. 1}$$

$$FS = \frac{\tau_f}{\tau} \quad \text{eq. 2}$$

In order to estimate the factor of safety (FS) for a slope in terms of effective, the pore water pressure must be known. This is frequently the greatest source of inaccuracy in slope stability work, since the determination of the most critical conditions of pore water pressure for various stages of life of canal is complex and costly. However, to overcome this limitation, the three following dominant sets of conditions were used in the analysis to satisfy the main canal future operational conditions:

- End of construction
- Rapid drawdown
- Steady seepage

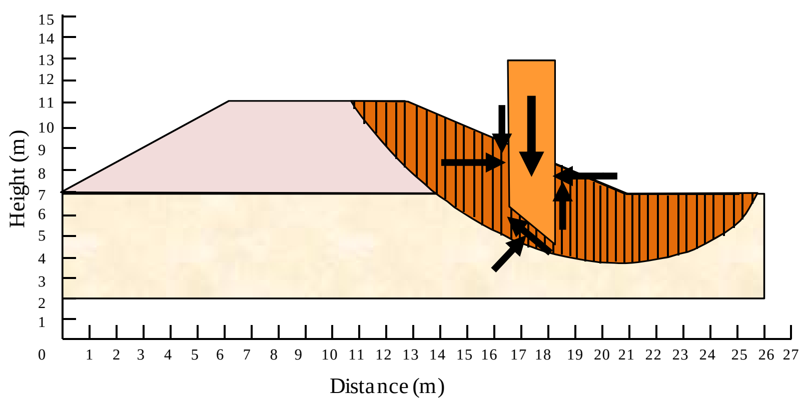


Figure 2: Slice discretization and distribution of slice forces in a sliding canal slope

For an effective stress analysis, the shear strength is defined as (Anon. 2012):

$$s = c' + (\sigma_n - \mu)\tan\phi' \quad \text{eq. 3}$$

where:

s = shear strength

c' = effective cohesion

ϕ' = effective angle of internal friction

σ_n = total normal stress

μ = pore water pressure

The Limit Equilibrium Solution Scheme in the software uses the following equations of statics in solving for the factor of safety (Anon., 2012):

- The summation of forces in a vertical direction for each slice is used to compute the normal force at the base of the slice, *N*.

- The summation of forces in a horizontal direction for each slice is used to compute the interslice normal force, *E*. This equation is applied in an integration manner from left to right across the sliding mass.

- The summation of moments about a common point for all slices. The equation can be rearranged and solved for the moment equilibrium factor of safety, F_m, as expressed in equation 4.

$$F_m = \frac{\sum \left(c'\beta R + \left(N - \mu\beta\right) R \tan\phi'\right)}{\sum Wx - \sum Nf + \sum kWe \pm \sum Dd \pm \sum Aa} \qquad \text{eq. 4}$$

- The summation of forces in a horizontal direction for all slices, giving rise to a force equilibrium factor of safety, F_f, as expressed in equation 5.

$$F_f = \frac{\sum \left(c'\beta \cos\alpha + \left(N - \mu\beta\right) \tan\phi' \cos\alpha\right)}{\sum N \sin\alpha + \sum kW - \sum D \cos\omega \pm \sum A} \qquad \text{eq. 5}$$

where:

W = the total weight of a slice of width b and height h
N = the total normal force on the base of the slice
x = the horizontal distance from the centerline of each slice to the center of rotation
D = an external point load
kW = the horizontal seismic load applied through the centroid of each slice
R = the radius for a circular slip surface or the moment arm associated of shear force
f = the perpendicular offset of the normal force from the center of rotation or moments
d = the perpendicular distance from a point load to the center of rotation or moments
h = the vertical distance from the center of the base of each slice to the uppermost line
a = the perpendicular distance from the resultant external water force & center of rotation
A = the resultant external water forces
ω = the angle of the point load from the horizontal
α = the angle between the tangent to the center of the base of each slice and the horizontal

As per seismic hazard map of project site, the area falls in zero zone; therefore, slope stability was evaluated in no seismic condition only.

DISCUSSION

Amongst various canal operational conditions, the rapid drawdown case has been recognized as one of the most severe loading conditions that the main canal can be subjected to. The effect of this inundation on the side slopes, both prior to and subsequent to drawdown, is the essence of the rapid drawdown loading condition. Although, the rapid drawdown loading condition could be employed using two different methods: (i) the total stress method, and (ii) the effective stress method but, for the main canal analysis the effective stress method is utilized because we want to consider the long term (drained) loading conditions. In fact, the effective stress method can be applied to both long term (drained) and short term (un-drained) loading (Kerkes, and Fasset, 2006). However, the difficulty in applying the effective stress method to the short term case is in defining the pore pressures that exist for the particular loading condition. In any case, it appears that the most crucial case for main canal might be expected in long term (drained) circumstances. Besides, analysis for end of construction period will take in to account any short term hazard for canal. Therefore, the stability analysis was mainly concentrated on drained situations.

The stability analysis with SLOPE\W involves passing a slip surface through the earth mass and dividing the inscribed portion into vertical slices. The limit equilibrium formulation within the software assumes that the factor of safety of cohesive component of strength and the frictional component of strength are equal for all layers of soils involved. This formulation also assigns the same factor of safety to all slices (Krahn, 2004). To conduct an analysis, various solution techniques could be employed. The solution techniques differ in manner of interslice static forces and relationship between the interslice shear and normal forces. Given the main canal overall condition, Janbu and Ordinary method of analysis were seemed fit for the analysis. The Janbu method in principle utilizes interslice normal forces and moment equilibrium; however, Ordinary method satisfies only moment equilibrium. The software by default utilizes the half-sine function for Morgenstern-Price method which in turn employs user-specified interslice function. The half-sine function tends to concentrate the interslice shear forces towards the middle of the sliding mass and diminishes the interslice shear in the crest and toe areas (Krahn, 2004).

Since the most crucial anticipated failure might occur in high compacted fills, therefore, stability analysis was conducted using a layer of compacted fill over natural soil. The properties of aforesaid soils are presented in Table 2 (Anon., 2010a). An additional surcharge of 14.5 kPa load was also adopted to simulate the traffic load on the embankment.

Table 2: Summary of soil properties used for drained side slope analysis

Description	**Unit Weight** (kN/m^3)	**Cohesion** (kPa)	**Phi** (Degree)
Fill Embankment	19	10	25
Natural Soil	19	10	25

After loading the SLOPE/W with other inputs as tabulated in Table 3, the model was first run for side slope 1.5H:1V for three dominant canal operational conditions. For all runs the piezemetric lines with Ru and zero seismic coefficient was adopted. Figure 3 shows distribution of slices and the pertinent minimum factor of safety value.

Table 3: The summary of analysis setting for SLOPE\W

Description	Analysis Setting
Method	• Limit equilibrium • Ordinar, Janbu • Side Function: Half-sine function
PWP	• Piezometric lines with Ru
Slip Surface	• Entry and exit
FOS Distribution	• Constant
Advanced	• Number of slices: 30 • Factor of safety tolerance: 0.01 • Minimum slip surface thickness: 0.1 • Maximum number of iteration: 2000 • Convergence tolerance: 1e-007 • Number of points on slip surface: 8 to 16 • No. of complete passes per point insertion: 1

The model then was run for different sets of canal operational conditions using side slope 2H:1V. Figure 4 demonstrates and compares the results in graphical fashion.

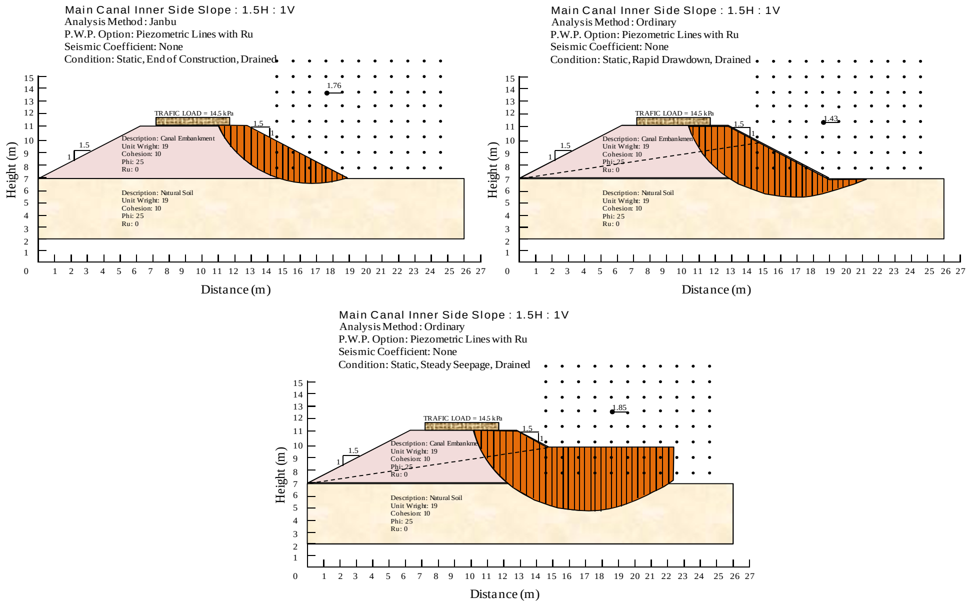


Figure 3: Stability analysis for inner side slope 1.5H:1V

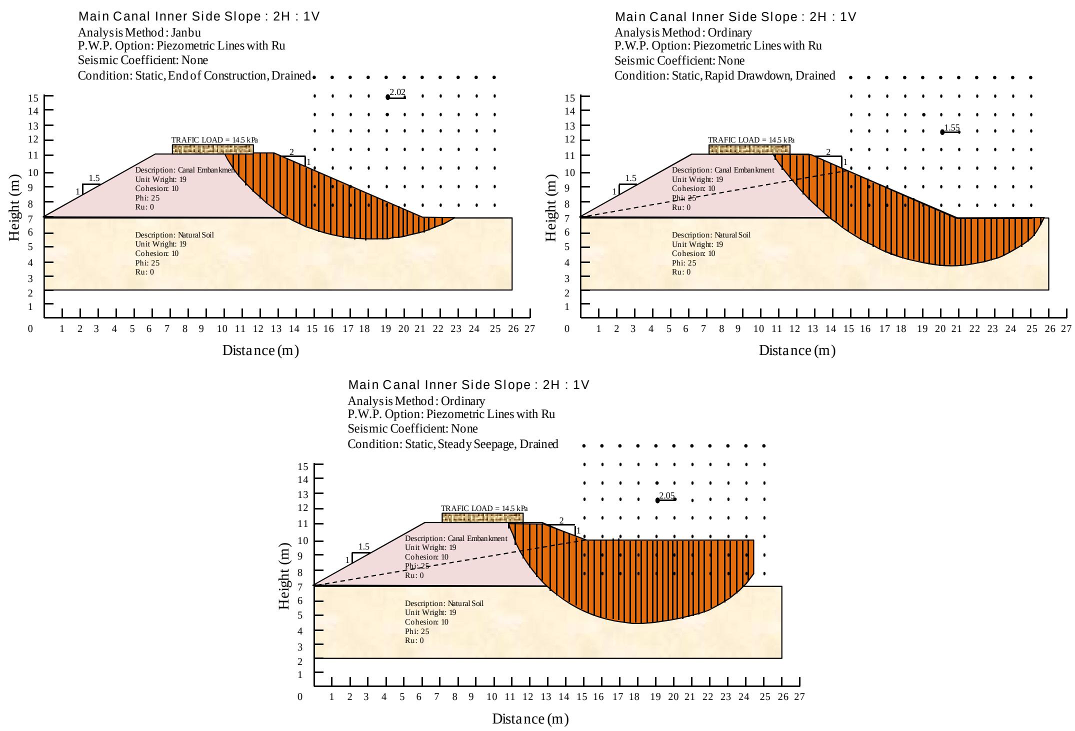


Figure 4: Stability analysis for inner side slope 2H:1V

The summary of calculated factor of safety for each side slopes are presented in Table 4.

Table 4: The summary of slope stability analysis

Condition	Inner Side Slope	
	1.5H:1V	**2H:1V**
End of Construction	1.76	2.02
Rapid Drawdown	1.43	1.55
Steady Seepage	1.85	2.05

Figure 5 shows the free body diagram of a typical soil slice and Fig. 6 illustrates distribution and peak shear resistance along the canal cross section.

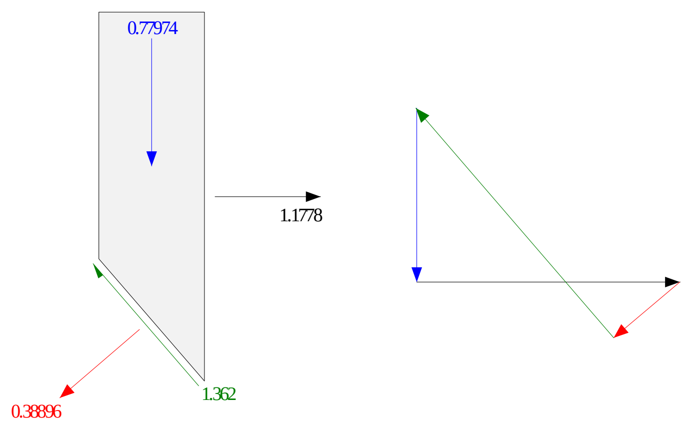


Figure 5: A free body diagram resulted from Janbu method analysis

The result of analysis show that for 1.5H:1V side slope, the lowest factor of safety, 1.43, is designated for rapid drawdown condition. Whereas for 2H:1V side slope under the same prevailing condition the factor of safety is elevated to 1.55 which is above the 1.5 acceptable limit. The rapid drawdown condition is, in fact, a realistic simulation of a likely future operational situation when for any unforeseeable reason the ponded water in the main canal recedes rapidly, leaving residual pore pressure in the embankment invoking massive canal failure. Upon close scrutiny of available results, the conventional side slope 1.5H:1V proves risky and unreliable; hence constructing side slope of 2H:1V deems safer not only for rapid drawdown condition but also in all other future operational situations such as end of construction and steady seepage.

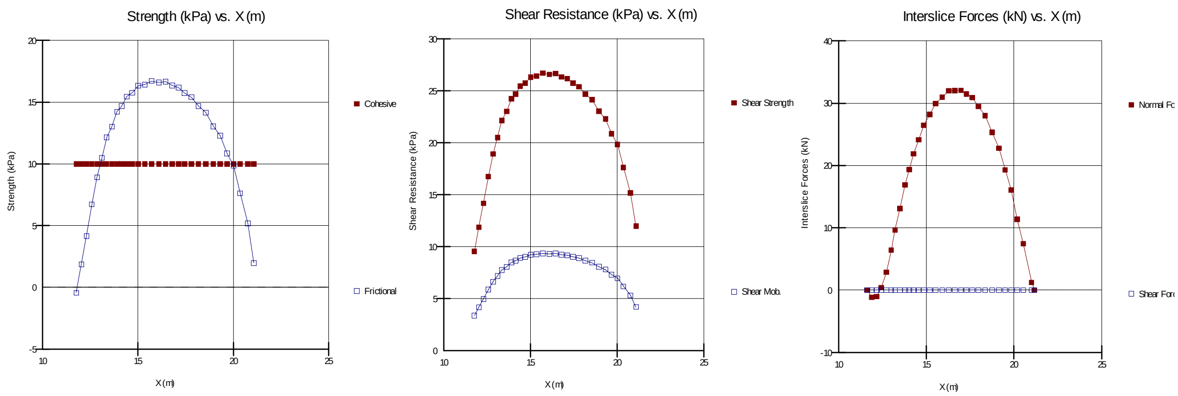


Figure 6: Strength and forces along the canal cross section for Janbu analysis

Canal bed preparation

There are a number of factors which affect stability of canal including property of soil, quality of equipment used, skill of manpower, adequacy of testing laboratory and the weather condition. Canal bed preparation is effectively performed using a wide range of variables changing from one meter of land to the next. Therefore, there is no guarantee in the consistency of the system. The creation or rather smoothing of the surface of soil layer as precondition for laying the geomembrane poses the greatest difficulties for both personnel and machines. In order to obtain the intimate contact between the soil layer and the covering geomembrane, the soil surface must be smooth and free of foreign matter, gravel or other sharp objects. Accordingly, construction of main canal required extensive clearing, grubbing, excavation, pre-wetting, compacting, trimming, placing concrete and constructing contraction joints.

Even for a well-compacted embankment, secondary compression and shear strain can cause slight settlements after completion. Normally this is only of significance in high embankments, and can amount to between 0.1 and 0.2 percent of fill height in three to four years or between 0.3 and 0.6 percent in 15 to 20 years. The larger values are for fine-grained plastic soils (Anon., 2005). However, to prepare a solid and stable canal bed in this project, all suitable soils hauled from approved borrow areas were properly moistened and compacted to at least 95% proctor optimum value. The soil was deposited in layers of 20 cm maximum and, as Fig. 7 illustrates, the compaction was achieved using vibrating sheep foot rollers. The canal cross section was excavated through the compacted soil and was latter accurately trimmed using long boom excavator.

Figure 7: Canal compaction using vibrating sheep foot roller machine

Geo-membrane installation

The geomembrane under liner provides water barrier to main canal, and the concrete cover protects the geomembrane from mechanical damage and weathering. Due to susceptibility to stress cracking, geomembrane was used only as a simple barrier, not as a load bearing member of the lining system. As demonstrated in Fig. 8, the canal cross section was well compacted and trimmed to stabilize the base for a successful geomembrane installation where differential settlement could ruin and the lining. Properly installed geomembrane generally provides exceptionally low permeability rate as well as a long lifetime well beyond the ordinary life cycle of an irrigation canal (Peggs, 2005; Rollin, 2004).

Figure 8: Canal bed preparation and trimming

For the GARP main canal, as demonstrated in Fig. 9, a textured 1.5 mm High Density Polyethylen (HDPE) liner was laid over a 25 cm thick filter cushion material along the length of main canal. The geo-membrane has the following average tensile properties (Anon., 2011):

- Yield strength, 22 kN/m
- Break strength, 16 kN/m
- Yield elongation, 12%
- Tear resistance of 187 N
- Break elongation, 100%

The Geomembrane rolls were stacked on a flat and trimmed surface. The 7 m wide Geomembrane panels were unrolled across the canal (crosswise) from one side of canal towards the other and were temporarily fixed to avoid slipping down the slope. Excess membrane was left at the foot of the embankment for overlap connection with adjoining panel to enable weld joining. Welding the panels was done utilizing a method of hot air fusion, which provides a fully fused, water tight weld. Individual fabricated panels are overlapped using a 1m interlocking overlap, backfilled, overlaid with filter cushion and lined with 7 cm concrete layer.

Figure 9: Geo-membrane installation in main canal

Construction of canal concrete lining

The geomembrane under liner is supposed to provide strong water barrier, and the concrete cover protects the geomembrane from likely unforeseen mechanical damage and weathering. About 40,000 cubic meters of concrete will be used for lining the 30.5 kilometers long main canal. The geotechnical investigation suggested that the main canal should be furnished by 25 cm thick under filter cushion (Anon., 2010a). Under drainage in the lined canal is necessary to avoid building of pore water pressure behind the lining under drawdown condition. A typical detail of filter cushion and the under drainage is shown in Fig. 10.

In average 40 crew members are engaged in order to place average 50 linear meter of concrete in a single eight-hour daily shift. The concrete lining was to be done in two passes. According to Fig. 11 illustrates, the concrete is cast on one side of canal first (half of cross section) using concrete transit trucks loaded with fresh concrete shipped from nearby batching plant. Adjustment for depth on side slopes and bed is done using a cross ward rolling drum. The surface finishing, as demonstrated in Fig. 12, is performed manually utilizing a moving steel frame supporting 10 labors sitting along each side of frame. The concrete lining process is complemented by spraying curing compound to prevent undesirable development of cracks due to likely dry out.

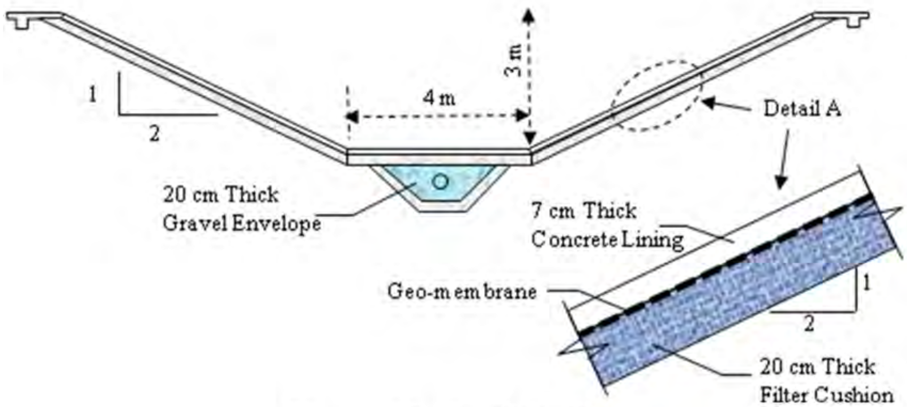


Figure 10: Canal details

Figure 11: Casting concrete on canal side slope

Since the canal is still under construction, the process of geomembrane installation and concrete lining has shown itself to be very satisfactory. However, after completion of main canal, the operating crew will monitor the performance of the canal.

Figure 12: Finishing process for concrete Lining

CONCLUSION

The slope analysis of concrete lined canal proved to be a thoughtful and meticulous scrutiny of prevailing future operational conditions. The soil stability analysis shed clarifying light on the decision-making process. The results show that for 1.5H:1V side slope, the lowest factor of safety, 1.43, is calculated for rapid drawdown condition. Whereas for 2H:1V side slope under the same prevailing condition the factor of safety is elevated to 1.55 which is above the 1.5 acceptable limit. The rapid drawdown condition is, in fact, a realistic simulation of a likely future situation when for any unforeseeable reason the ponded water in main canal recedes rapidly, leaving residual pore pressure in the embankment invoking massive canal failure. Upon close scrutiny of the available results, the conventional side slope 1.5H:1V proves risky and unreliable; hence constructing side slope 2H:1V deems safer not only for rapid drawdown condition but also in all other future operational situations such as end of construction and steady seepage.

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