STATIC STABILITY AND SEEPAGE ANALYSIS BORINQUEN DAMS AT PANAMA CANAL

Sujan Kulkarni
Sr. Manager (Technical), Geo Dynamics, Vadodara – 390 023.
Sujan@geodynamics.net
Ramon Martinez
Resident Design Engineer, URS Holdings, Inc. (Panama)
ramon.martinez@urs.com

ABSTRACT: The Panama Canal Authority (ACP) is constructing four earth and rockfill dams as part of the Pacific Access Channel (PAC) which will connect the Gaillard Cut section of the Panama Canal to the new Pacific Post-Panamax Locks. For such a monumental project, having international importance, detailed engineering was required. Also, the location of the project is such that expert geotechnical engineering was required. The geology at the dam site is very complex and the region is also known to be seismically active.

In order to address all these issues, detailed seepage and stability analysis was performed at various sections of the dams. The main objective was to confirm the static stability of the proposed dams, evaluate issues associated with seepage through the dam and foundation, and calculate yield accelerations for use in dynamic analysis of the dams.

Slope stability and seepage evaluations were performed for various construction and operating stages including end of dam foundation excavation, end dam construction, long term seepage, rapid drawdown and Pseudo-static analysis. Geo-Slope (SEEP/W and SLOPE/W) and UTEXAS4 software were used for the analyses. Analyses were performed at various cross-sections which were selected based on geology, dam height, presence of fault, etc.

Using SEEP/W, seepage quantities were estimated and the potential for piping and internal erosion of the embankment and foundation material was evaluated. The results of slope stability analysis including rapid drawdown indicated that the calculated factors of safety exceed the minimum acceptable values for all analyzed stages.

1. INTRODUCTION

ACP is currently constructing four earth and rockfill dams as a part of Panama Canal Expansion Project. The general project layout is presented in Figure 1. The project area is known for its complex geology and seismic activity. Hence, the project was full of challenges especially from a geotechnical engineering standpoint. Since the planning phase of the dams, it was imperative that issues related to stability and seepage were addressed using state of the art engineering practices. The paper addresses such evaluations performed for one of the major embankments viz. Dam 1E, the longest one.

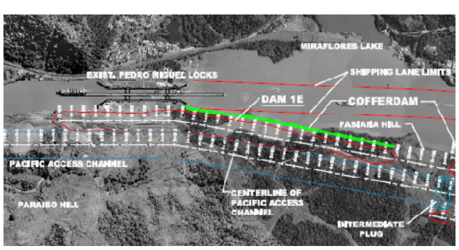


Fig. 1 General Layout of PAC and Dams

2. TYPICAL EMBANKMENT DETAILS

The proposed Dam 1E is approximately 2.4km long and extends from near the northern gates of the Pedro Miguel Lock to the northern slope of Fabiana Hill. The design consists of a zoned earth and rockfill embankment section with crest elevation of 32m and crest width of 30m. Inboard slope was planned at 3:1 (H:V) and the outboard slope was 3:1 from crest to elevation 16 and 2:1 from elevation 16 to foundation surface as shown in Figure 2.

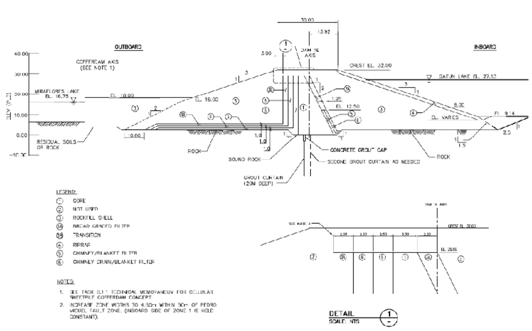


Fig. 2 Typical Section of Dam 1E

A layer of riprap was planned for erosion protection of the inboard slope. Also a two row (20m deep) grout curtain was considered in the design for seepage control through the foundation.

3. ANALYSIS APPROACH AND MATERIAL PARAMETERS

3.1 Analysis Approach

Slope stability and seepage evaluations were performed for several construction and operating stages. The analyzed construction stages included: end of dam foundation excavation, end of dam construction, recovery of water table outboard of the dam following dam construction, etc. The operating stages included: long term steady state seepage, rapid drawdown, and pseudo-static seismic analysis for long term operating conditions.

Seepage and static stability analyses were performed using SEEP/W and SLOPE/W program (Geo-Slope) respectively. For seepage analyses, rockfill and riprap zones were not considered in the model due to their relatively high permeabilities. In order to develop a more accurate phreatic surface across the dam core and to avoid over estimating flow quantities into unsaturated zones above phreatic surface, some materials were modeled using saturated-unsaturated conditions. As specified in the geotechnical interpretation reports, permeability anisotropy was incorporated in the model. The grout curtain was also incorporated in the model.

The slope stability analysis was performed using Spencer method of slices. Many trial slip surfaces were analyzed to find the one which provides the lowest factor of safety. Slip surfaces included circular, piece wise linear or combination of curved and linear segments. Also an anisotropic function was utilized to model variations of the material cohesion and friction angle with respect to the base inclination angle along a given slip surface.

Pseudo-static seismic stability analyses were performed using UTEXAS4 to estimate yield acceleration values to input into seismic deformation analysis. The analysis was performed by applying a horizontal body force to each slice to simulate the earthquake loading.

3.2 Material Parameters

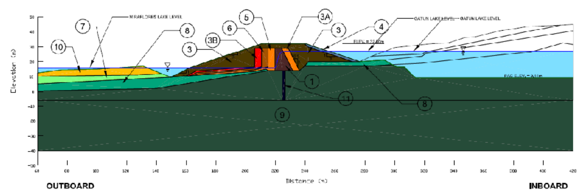
A Mohr-Coulomb model was used to characterize material shear strength. The rockfill and riprap strength was modeled using a variable friction angle function. Unconsolidated-undrained shear strength was used for the dam core for stability evaluation during construction stages. For rapid drawdown and pseudo-static analyses, total and effective strength envelopes were used for the dam core to develop the strength parameters for the multi-stage computations.

Shear strength parameters, permeability and unit weight values for foundation and embankment materials are summarized in attached Tables 1a and 1b, respectively.

4. DESCRIPTION OF ANALYSIS AND RESULTS

4.1 Selection of Dam Sections

In order to identify the most critical sections for analysis purposes, a number of cross-sections were cut along the dam alignment. Four cross-sections were selected for analyses based on the following considerations: geology, dam height, presence of Pedro Miguel Fault, presence of highly weathered rock and/or bedrock units slopping towards Miraflores Lake. The selected cross-sections incorporate subsurface conditions developed from available boring information, including surfaces for the top of residual soil, weathered rock, and sound rock. A typical model developed for the analyses is presented as Figure 3.



MATERIAL		SATURATED UNIT WEIGHT	TOTAL STRESS PARAMETERS		EFFECTIVE STRESS PARAMETERS		UNDRAINED STRENGTH	HORIZONTAL PERMEABILITY	k_y/k_x
No.	Description	kN/m³	c kPa	φ deg	c' kPa	φ' deg	s_u kPa	k_x (cm/s)	
1	Core	17.0	25	13	20	26	60	1.0 E-06	0.1
3	Rockfill Shell	21.6	-	-	0	Note 1	-	1.0	1
3B	Transition	20.4	-	-	0	40	-	1.0	1
4	Rip Rap	21.6	-	-	0	Note 1	-	1.0	1
5, 3A	Chimney/Blanket Filter	20.4	-	-	0	40	-	1.0 E-02	1
6	Chimney Drain/Blanket Filter	20.4	-	-	0	40	-	3.0	1
7	La Boca Fm. Residual Soil	17.6	-	-	10	21	60	6.0 E-04	1
8	Weathered Tuff	21.6	-	-	100	25	-	3.1 E-04	1
9	Sound Tuff	21.6	-	-	100	25	-	3.1 E-04(2)	1
10	Existing Fill	17.7	-	-	20	24	45	6.0 E-03	1
11	Grout Curtain(3)	-	-	-	-	-	-	1.0 E-05	1

Fig. 3 Static Stability and Seepage Analysis – Typical Model

4.2 Analysis Results

A series of steady-state seepage analyses were performed with SEEP/W at selected cross sections to establish the location of the phreatic surface and to estimate seepage quantities. Results of the SEEP/W seepage modeling for long term conditions for a typical section are presented in Figure 4.

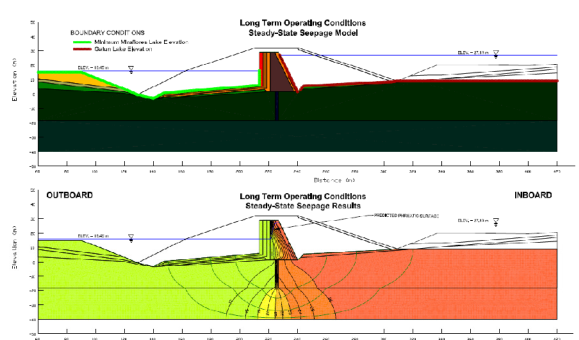


Fig. 4 Long Term Steady State Seepage Analysis

Based on the seepage analyses it was estimated that the total seepage quantity would be about 430 gallons per minute (gpm). For assessment of the potential for piping and internal erosion, hydraulic gradients were evaluated along the interface of the blanket drain system and along the foundation materials. The model calculated a relatively small maximum gradient of about 0.35 for the four sections evaluated.

Static slope stability of the dam was evaluated for critical construction and operating conditions ranging from end of foundation excavation to long term, steady state seepage conditions. The results are summarized in Table 2. A typical analyses is presented as Figure 5.

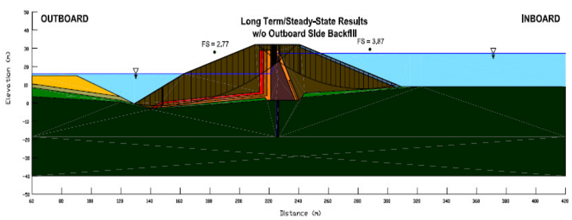


Fig. 5 Long Term Steady State Static Stability Analysis

Yield acceleration coefficients obtained with UTEXAS4 pseudo static analysis for evaluated 4 sections. Table 3 summarizes the range in yield acceleration coefficients k_y, which was used for dynamic analysis of the dam.

5. CONCLUSIONS

The results of the SEEP/W analyses indicated relatively small seepage quantities through and beneath the dam. The seepage quantity was estimated to be around 430gpm during long term steady-state conditions. The results also indicated that the dam section is adequate to control piping and internal erosion of the embankment and foundation materials.

The results of slope stability analyses indicated that the calculated safety factors exceed minimum acceptable values for all stages of dam construction and long term, operating conditions. It was concluded that the excavation slopes should not be steeper than 2.5:1 to avoid slope instability during foundation excavation. The calculated safety factor for rapid drawdown condition also met the minimum required value.

Yield acceleration coefficients were obtained with UTEXAS4 pseudo static analysis for the four sections evaluated. The yield acceleration coefficients k_y were used for dynamic analysis of the dam.

REFERENCES

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Table-1 Material Properties

(a) Foundation Materials

Material	Unit Weight kg/m³		Unconsol. Undrained Strength	Total Stress Parameters		Effective Stress Parameters		Permeability	
	Moist	Saturated	c kPa	c kPa	φ deg	c' kPa	φ' deg	Horizontal Permeability k_h (cm/sec)	k_h/k_v
Pedro Miguel Dam - Select Fill	1,810	1,810	45	17	12.5	25	23	1.6×10^{-4}	10
Pedro Miguel Dam - Rock/Waste Fill	1,810	1,810	45	17	12.5	25	23	2.1×10^{-2}	1
Upper Pre-1907 Fill	1,830	1,830	45	17	12.5	25	23	4.7×10^{-5}	10
Basalt Pre-1907 Fill	1,830	1,830	45	17	12.5	25	23	1.5×10^{-2}	1
General Fill	1,700	1,800	45	-	-	20	24	6.0×10^{-3}	1
Residual Soil	1,790	1,790	60	-	-	10	21	8×10^{-8} (note 2)	1
Pedro Miguel Agglomerate	2,350	2,350	-	-	-	300	47	0 - 20 m below found. 3.1×10^{-4} (note 3)	1
La Boca Sandstone and Siltstone	2,200	2,200	-	-	-	200	32		1
La Boca Tuff	2,200	2,200	-	-	-	100	25	> 20 m below found. 7.3×10^{-5} (note 3)	1

(b) Embankment Materials

Material	Unit Weight kg/m³		Total Stress Parameters		Effective Stress Parameters		Second Stage Strengths (2)		Unconsol. Undrained Strength	Permeability	
	Moist	Saturated	c kPa	φ deg	c' kPa	φ' deg	d kPa	ψ deg	s_u kPa	Horizontal Permeability, k_h (cm/sec)	k_h/k_v
Core	1,600	1,730	25	13	20	26	28	15	60	1×10^{-6}	10
Rockfill/Riprap	1,900	2,200	-	-	0	See note 3	-	-	-	1	1
Transition	2,000	2,080	-	-	0	40	-	-	-	1	1
Filter	2,000	2,080	-	-	0	40	-	-	-	1×10^{-2} (note 4)	1
Drain	2,000	2,080	-	-	0	40	-	-	-	3 (note 5)	1
Earthfill	2,100	2,160	15	19	20	32	18	22	-	1×10^{-5}	10

Table-2 Summary of Static Stability Analyses Results

Station (1)	End of Foundation Excavation (2) (min. F.S. = 1.3)		End of Dam Construction (min. F.S. = 1.3)		Post Dam Construction Outboard Water Rebound (min. F.S. = 1.3)		Long term, Steady Seepage (min. F.S. = 1.5)	Rapid Drawdown (min. F.S. = 1.3) Inboard Slope		MFSP (3,4) (min. F.S. = 1.4)
	Inboard Slope	Outboard Slope	Inboard Slope	Outboard Slope	Inboard Slope	Outboard Slope	Outboard Slope (4)	Before Drawdown	After (5) Drawdown	Outboard Slope
0 + 820	1.78	1.49	3.95	3.51	3.72	3.06	3.09	3.79	> 1.3	> 1.4
1 + 620	2.14	1.86	4.08	3.12	4.02	2.76	2.77	3.87	> 1.3	> 1.4
2 + 120	3.85	2.60	5.24	3.48	5.11 (3.31) (6)	3.28	3.26	5.32 (4.33) (6)	> 1.3	> 1.4
2 + 560	1.94	3.50	4.65	4.20	4.85 (3.14) (6)	3.88	3.71	4.97 (4.31) (6)	> 1.3	> 1.4

Notes:

(1) Stations referenced to Dams 1E-2E baseline.
(2) Based on excavation slope of 2.5:1; assumes dewatering will draw the groundwater table below the slope.
(3) MFSP = Maximum Flood Surcharge Pool.
(4) Analysis of the outboard slope under operating conditions assumed no backfilling outboard of the dam.
(5) Conditions not critical due to the small magnitude of drawdown/flooding and high safety factors for the long term steady-state seepage condition.
(6) Number in parenthesis corresponds to a global slip surface impacting the PAC cut slope.

Table-3 Yield Acceleration Coefficient k_y

Station	Range in k_y	
	Outboard Slope	Inboard Slope
0+820	0.44 – 0.63	0.36 – 0.59
1+620	0.37 – 0.62	0.35 – 0.55
2+120	0.54 - 0.65	0.46 - 0.69
2+560	0.62	0.50 - 0.51