Trinidad Pump-Storage Reservoir Concept

ACP
AUTORIDAD DEL CANAL DE PANAMA

June 2001

Options for Incrementing the Hydrologic Resources

1. Incremented Regulation (Trinidad EBT)
2. Water Saving Locks and Recycling Ponds
3. Incorporation of New Sources (Rio Indio Diversion)

Water usage in the existing basin (in lockages)

20 years (1980 – 1999)

Total: 62 lockages

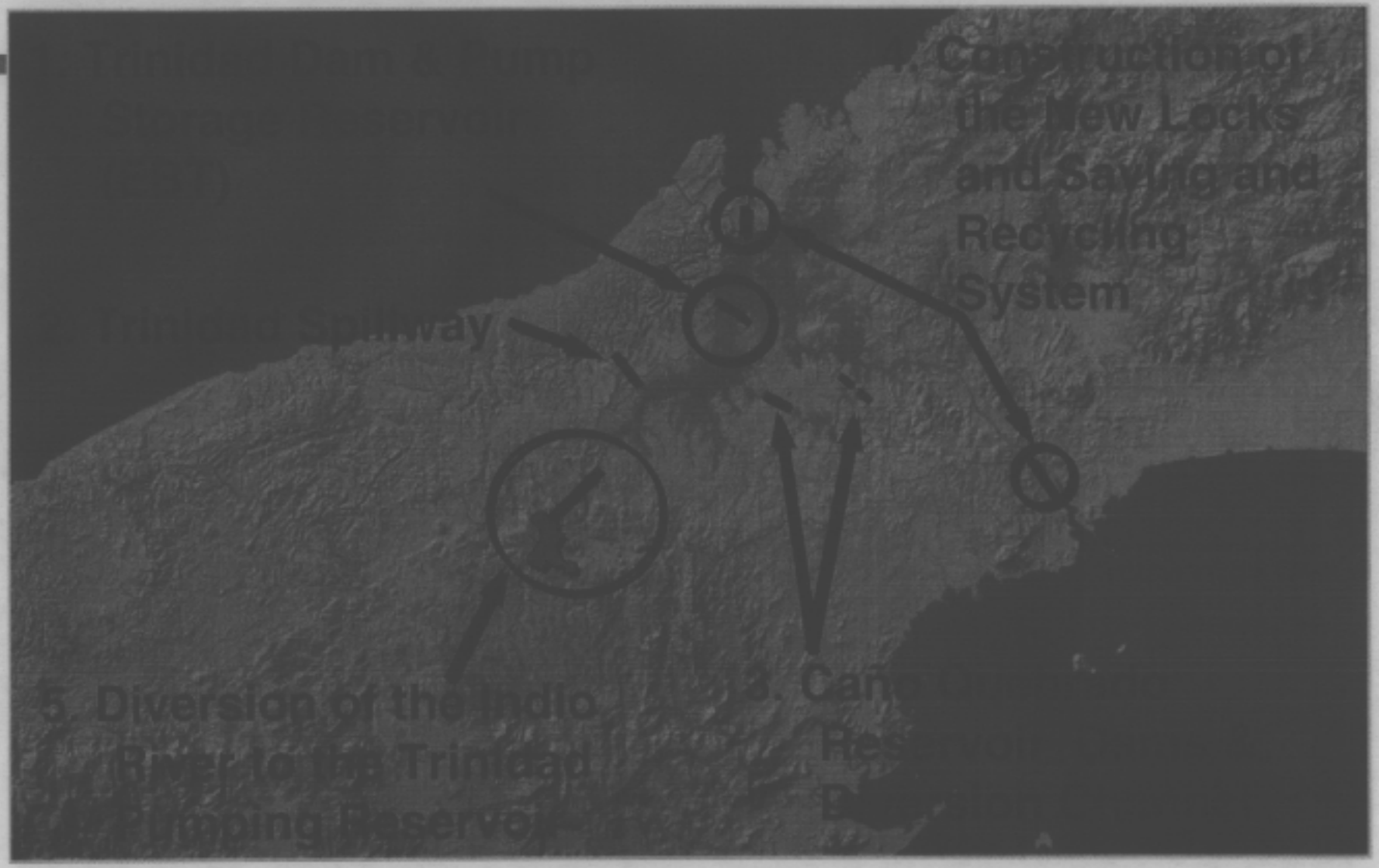
Advantage of Incremented Regulation

Efficient Use of the Infrastructure

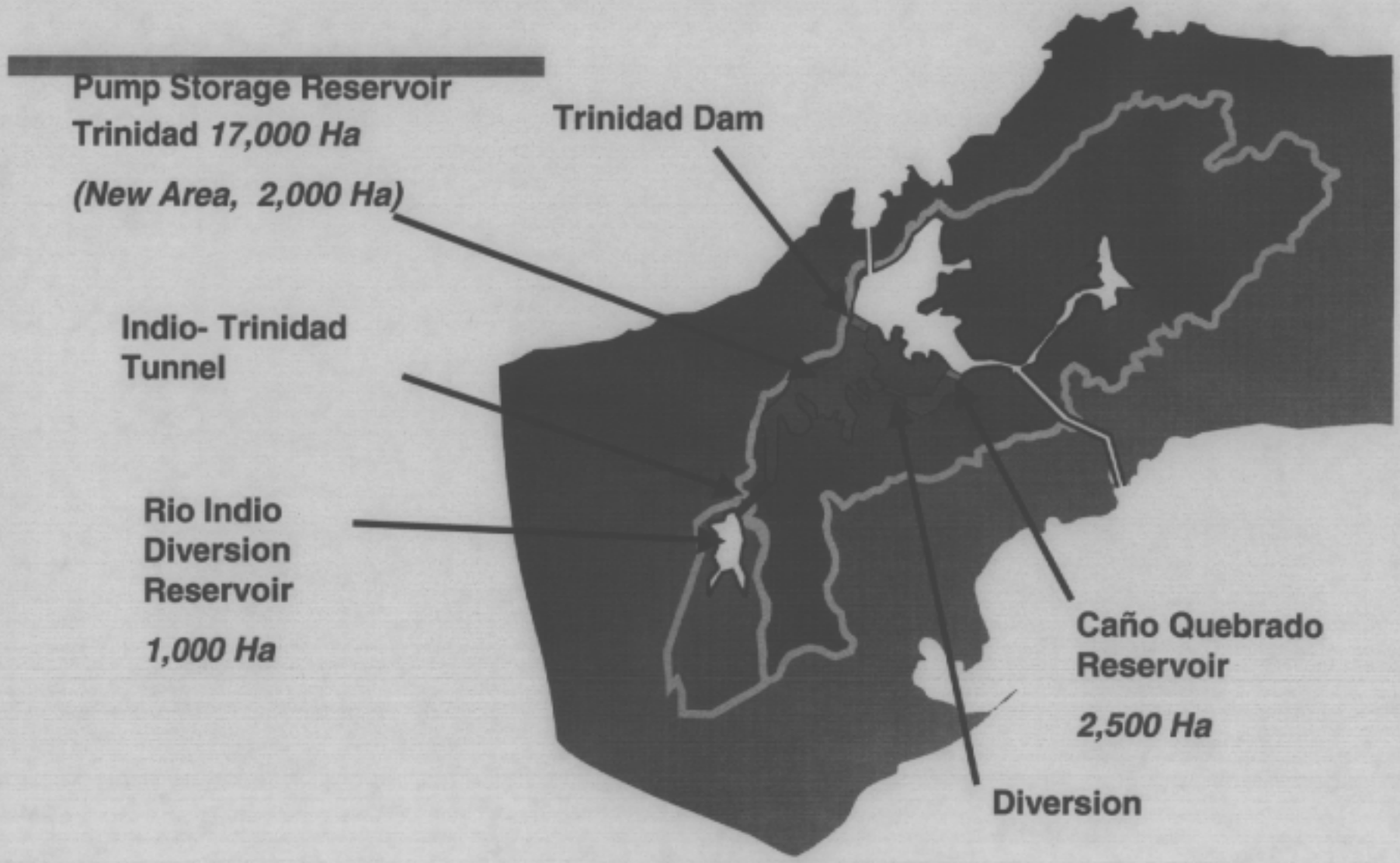
Available Storage in the Watershed (Gatún y Alhajuela)	**1,412 Mm^3**
Average Annual Run off in the Watershed (20 years)	**4,723 Mm^3 (62 Lockages/Day)**

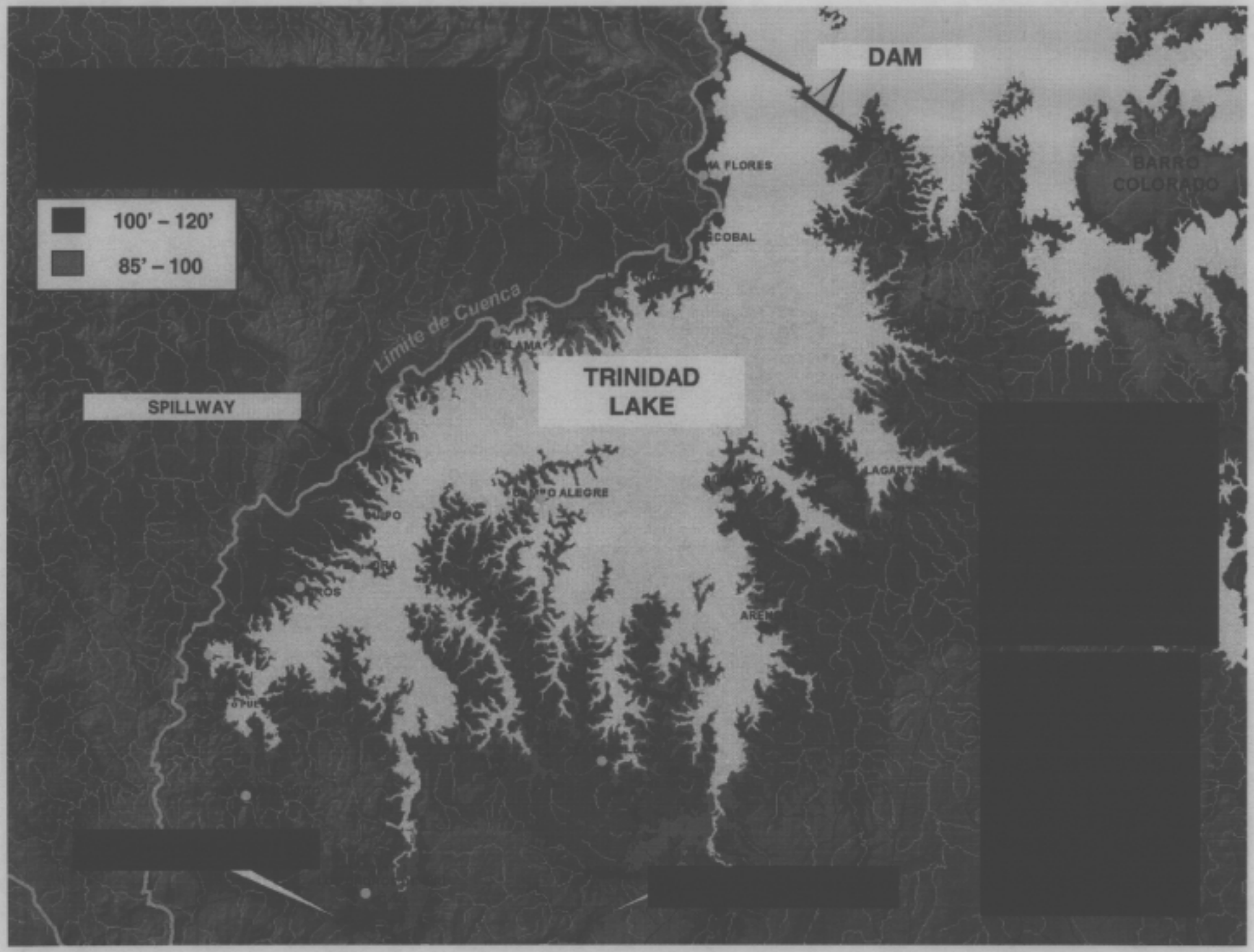
Ratio = 3.3

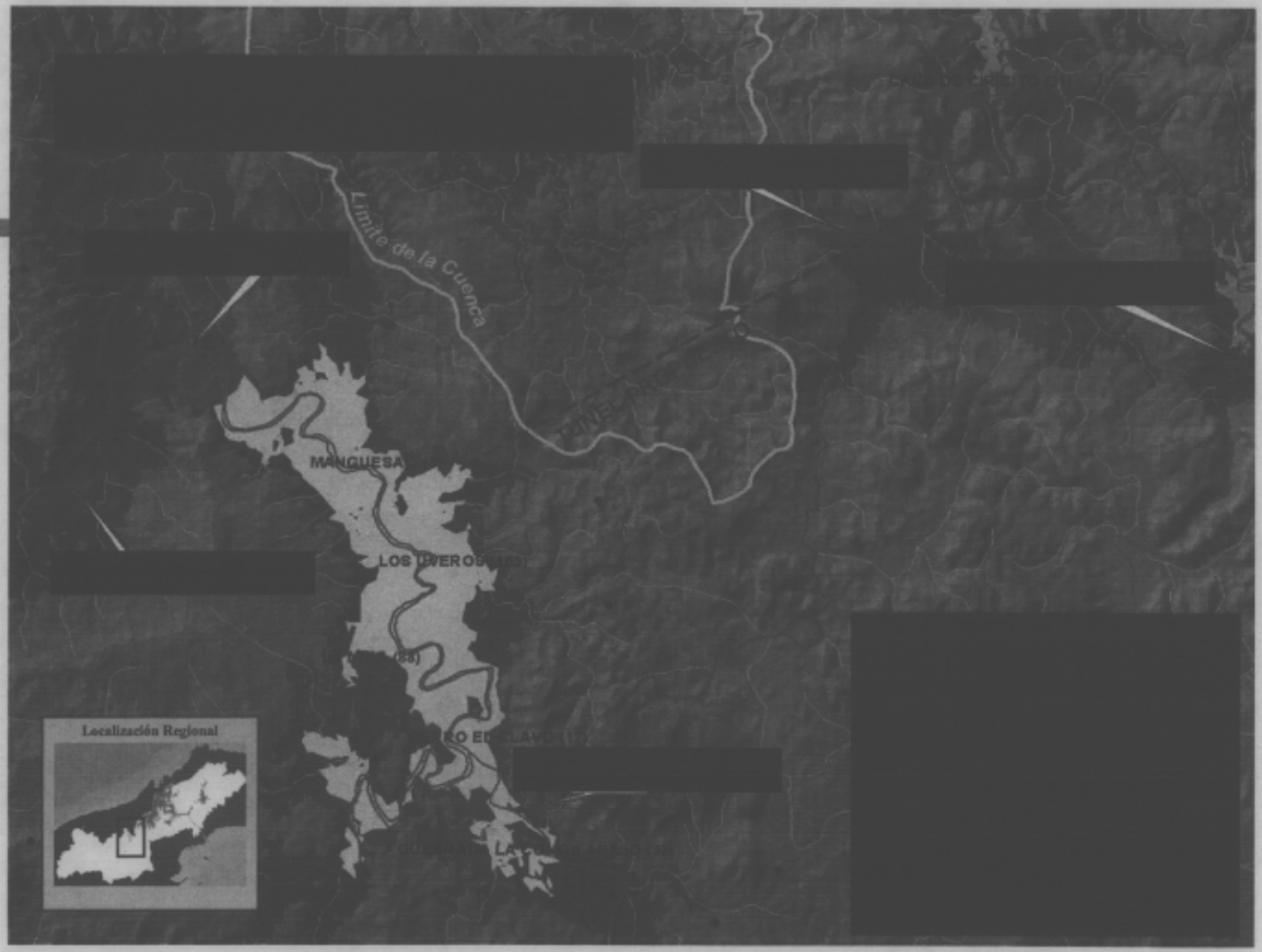
Trinidad Pump-Storage Reservoir & Supplemental Projects

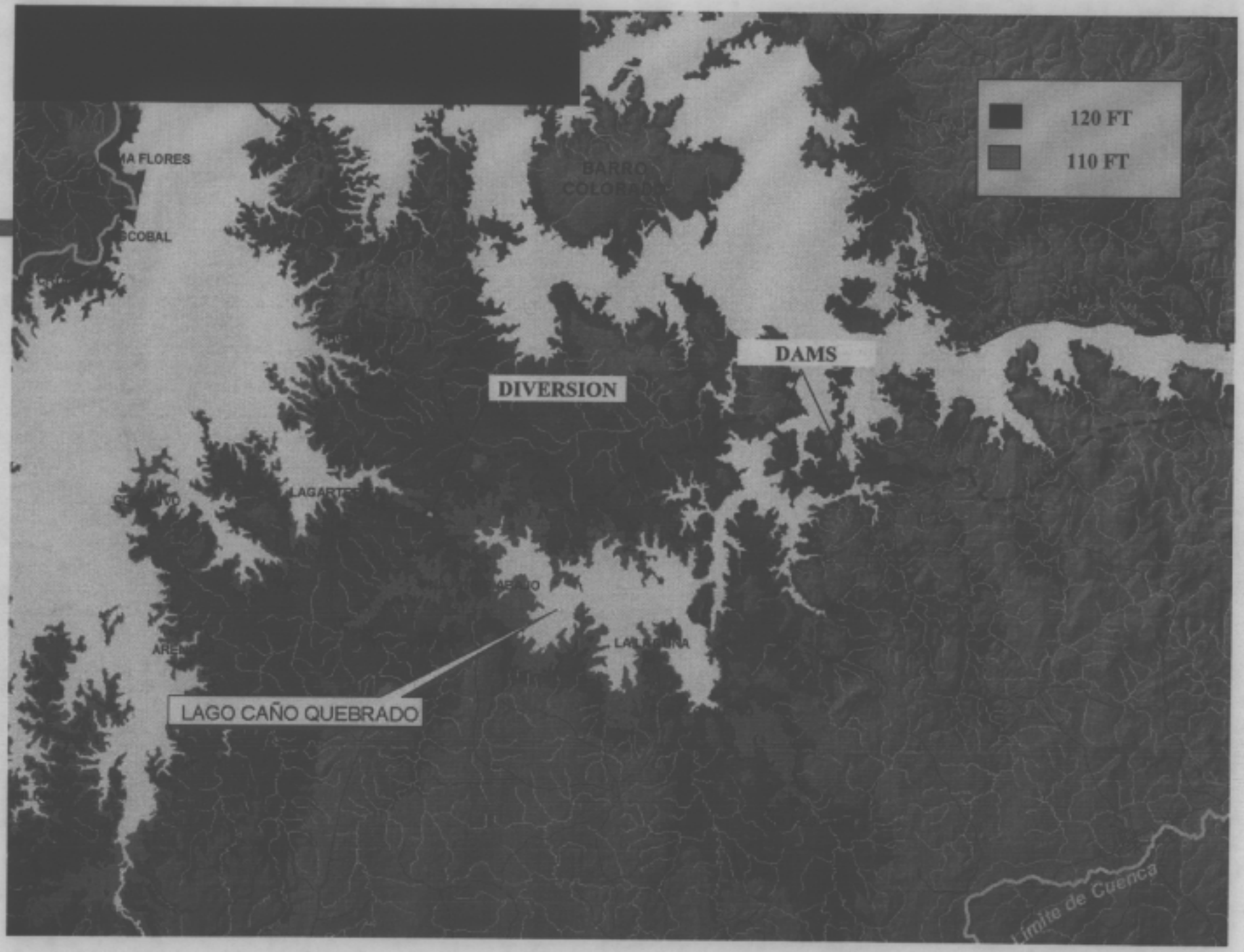


Trinidad Pump-Storage Reservoir & Supplemental Projects

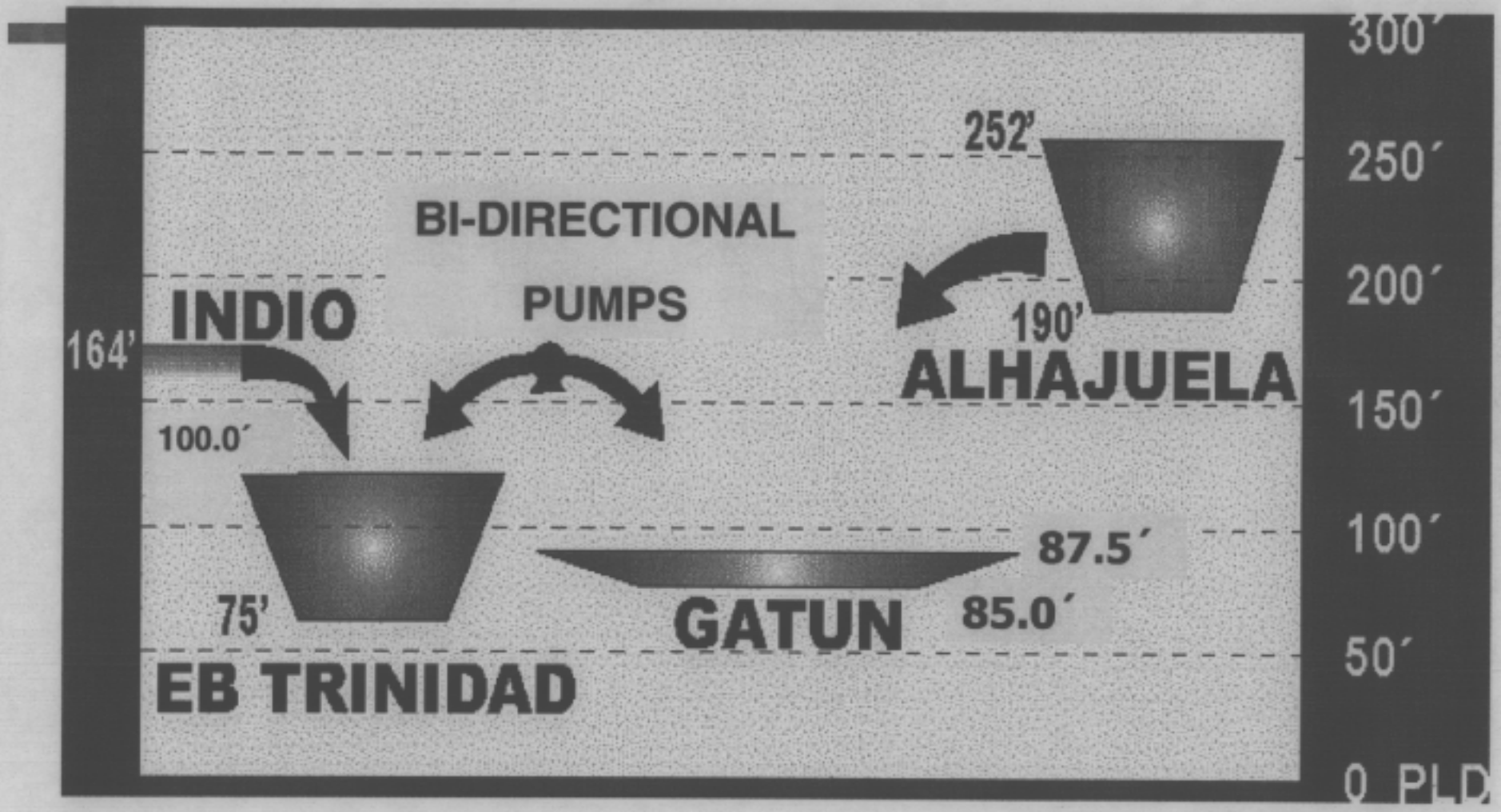



DAM
100' – 120'
85' – 100
Límite de Cuenca
SPILLWAY
TRINIDAD
LAKE
BARRO
COLORADO

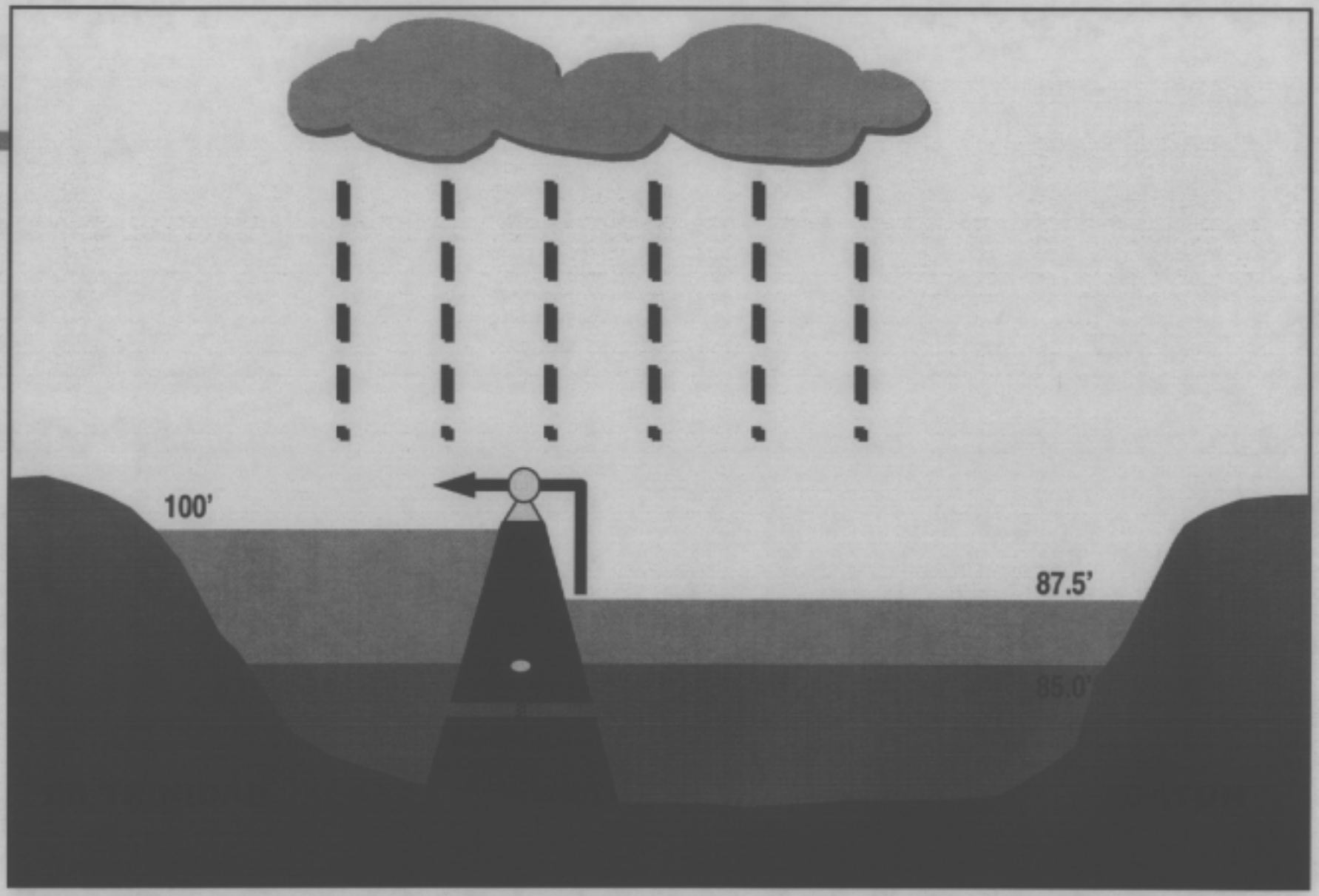

Límite de la Cuenca
MANGUESA
LOS LIVEROS
Localización Regional


120 FT
110 FT
BARRO
COLORADO
DAMS
DIVERSION
LAGARTERO
LAGO CAÑO QUEBRADO
Límite de Cuenca

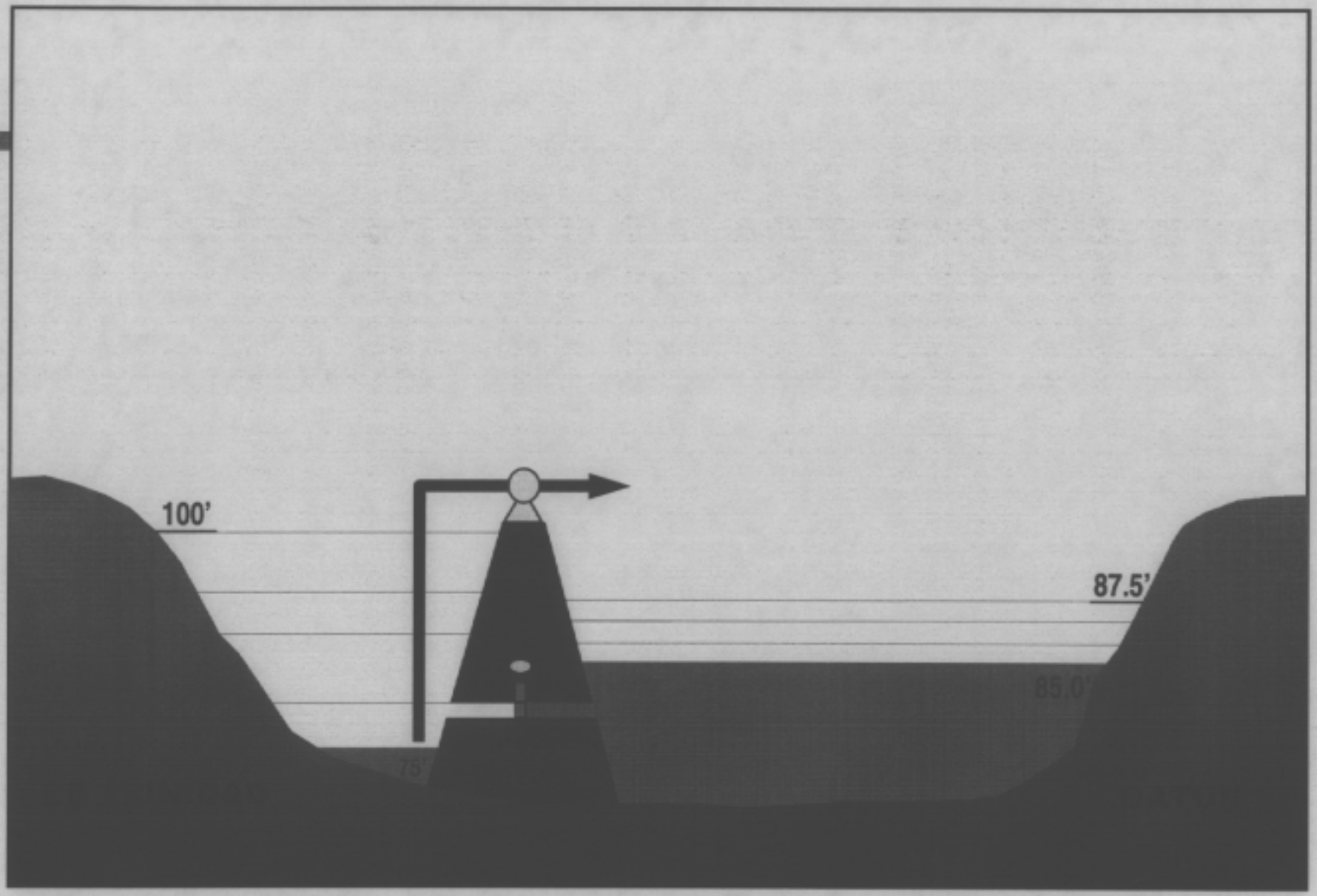
Squematic Profile of System



Operation of the EBT



Operation of the EBT



Location Map

Trinidad Pumping Station and Generation Plant

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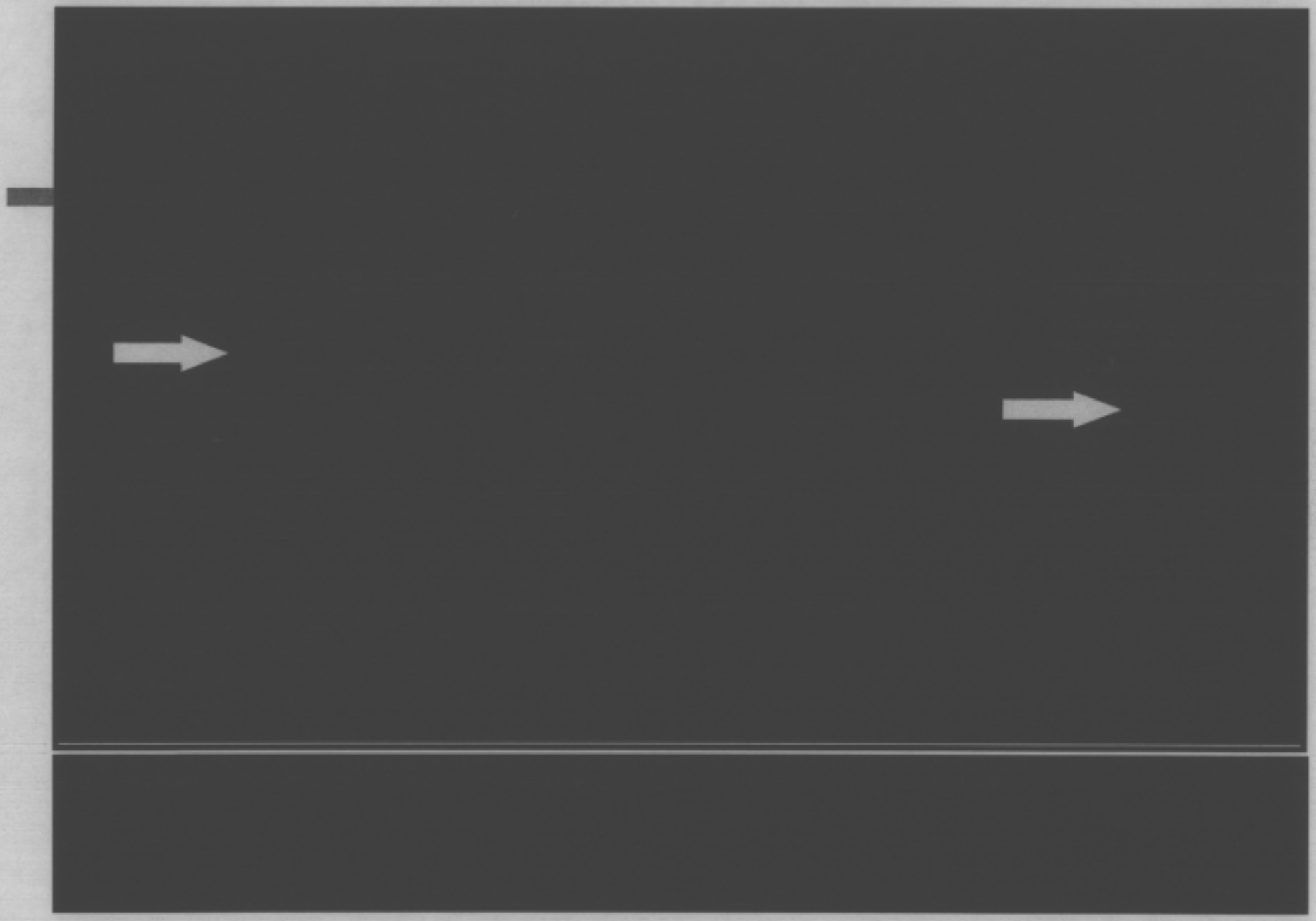
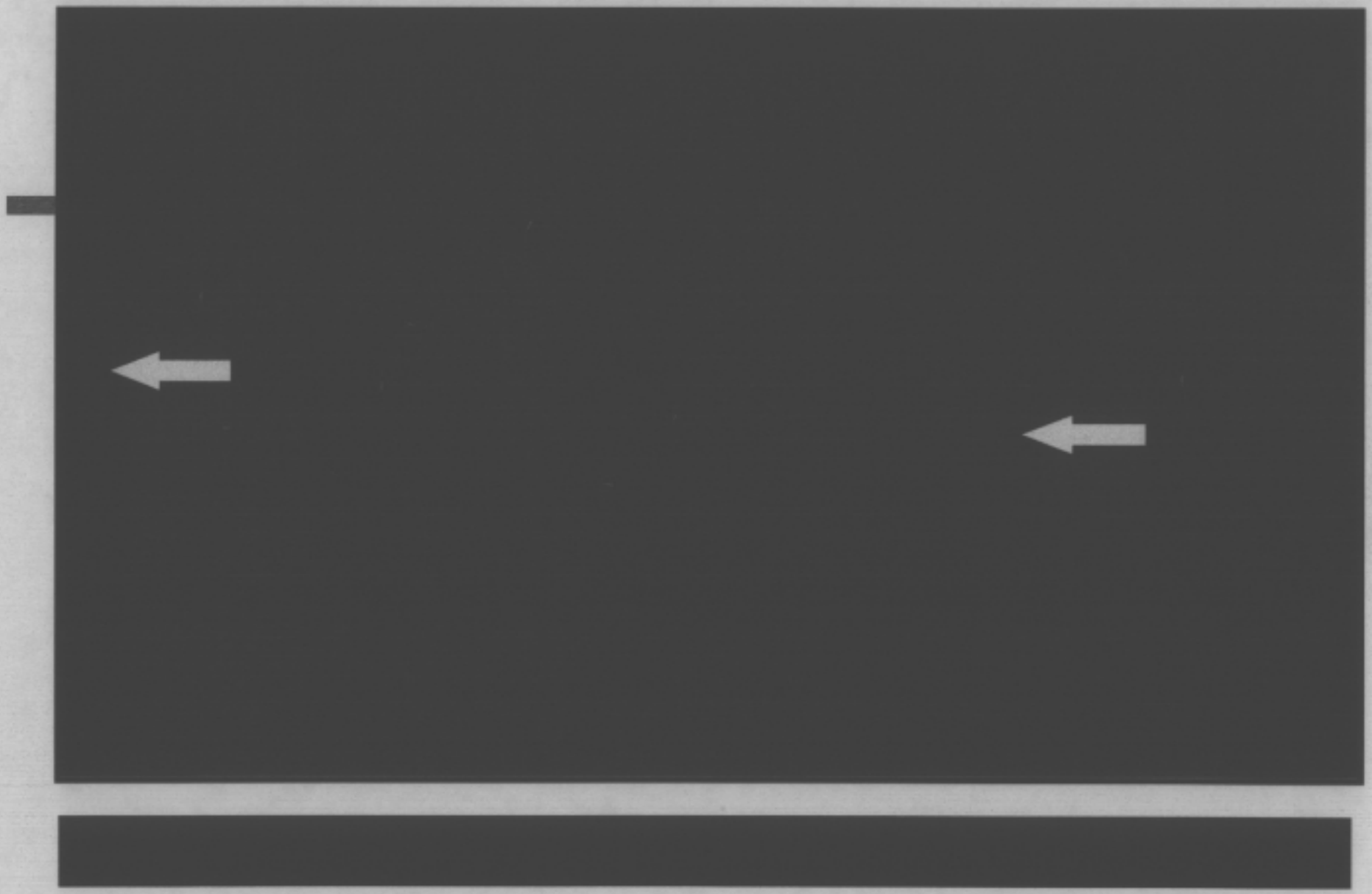
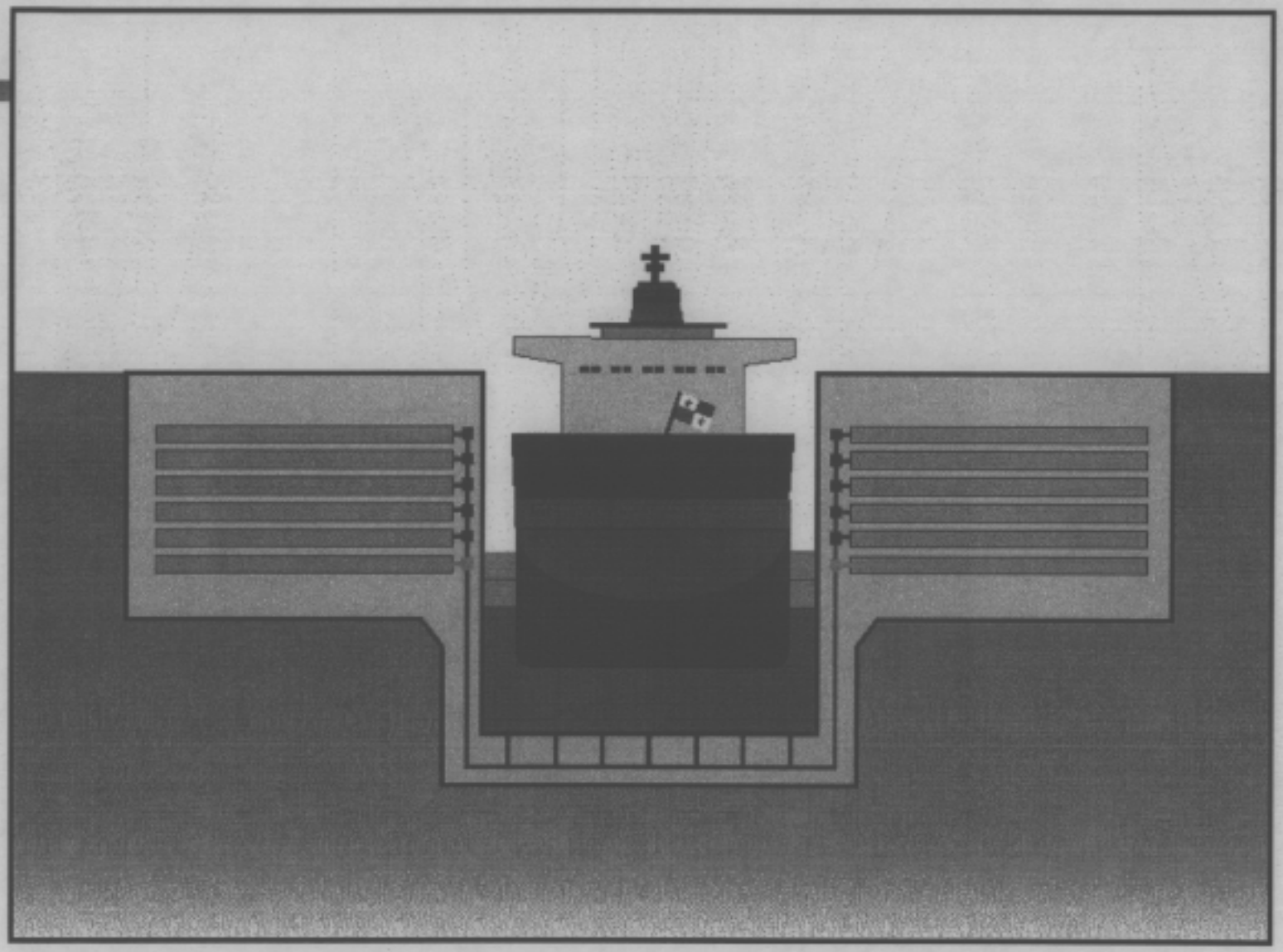


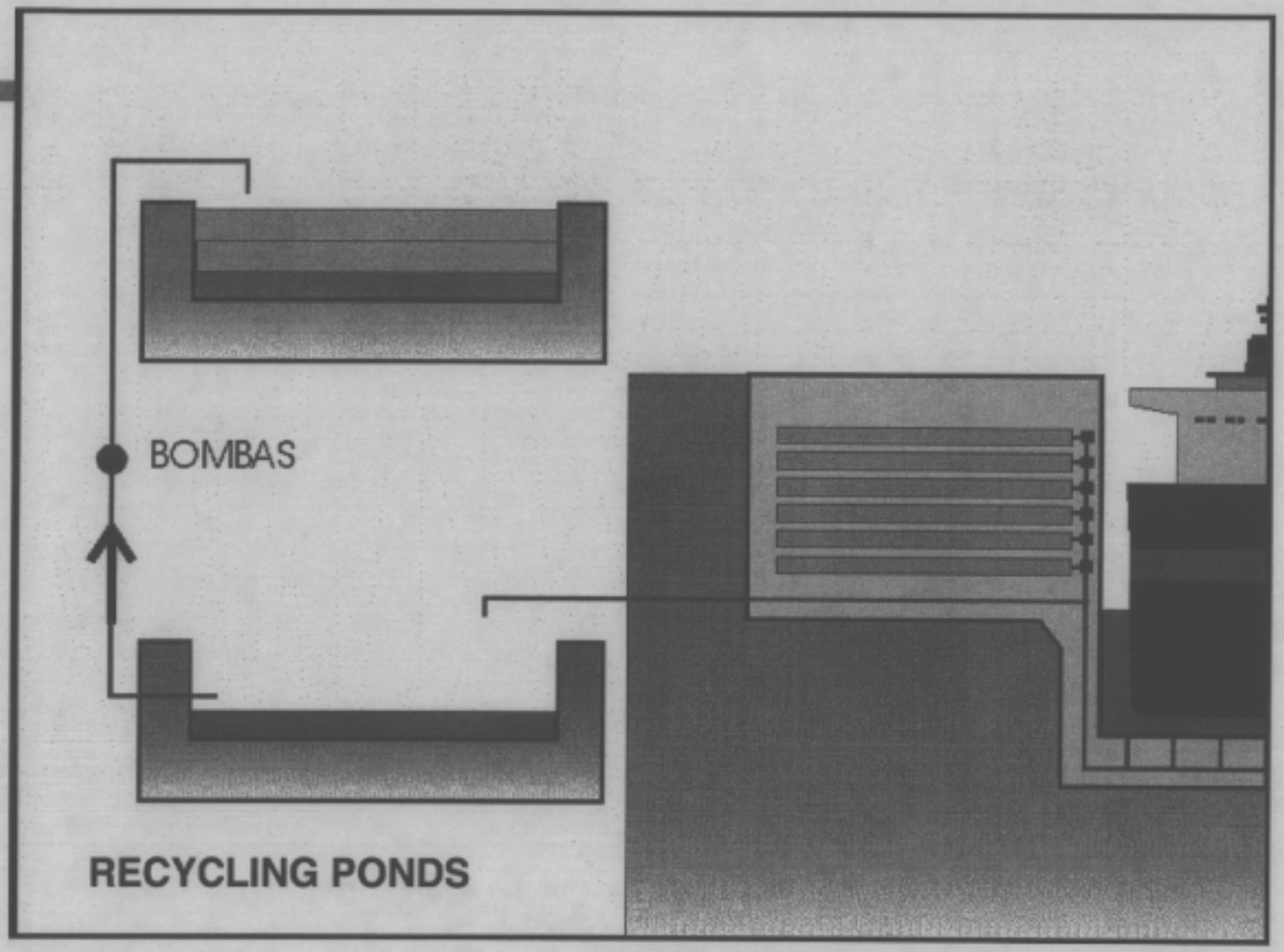


Construction of the New Water Saving Locks and Recycling Ponds

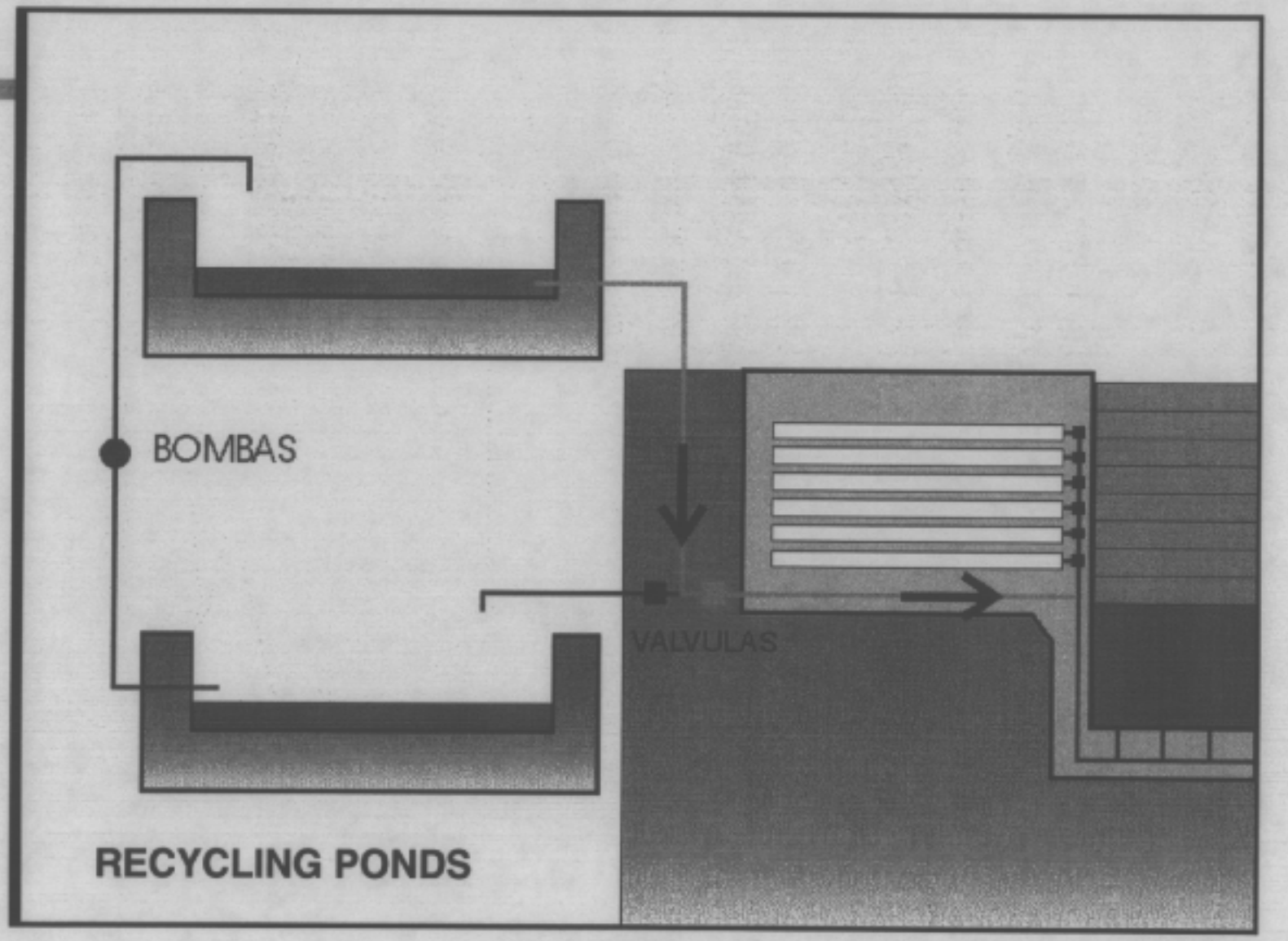
Operation of Saving and Recycling Sistems



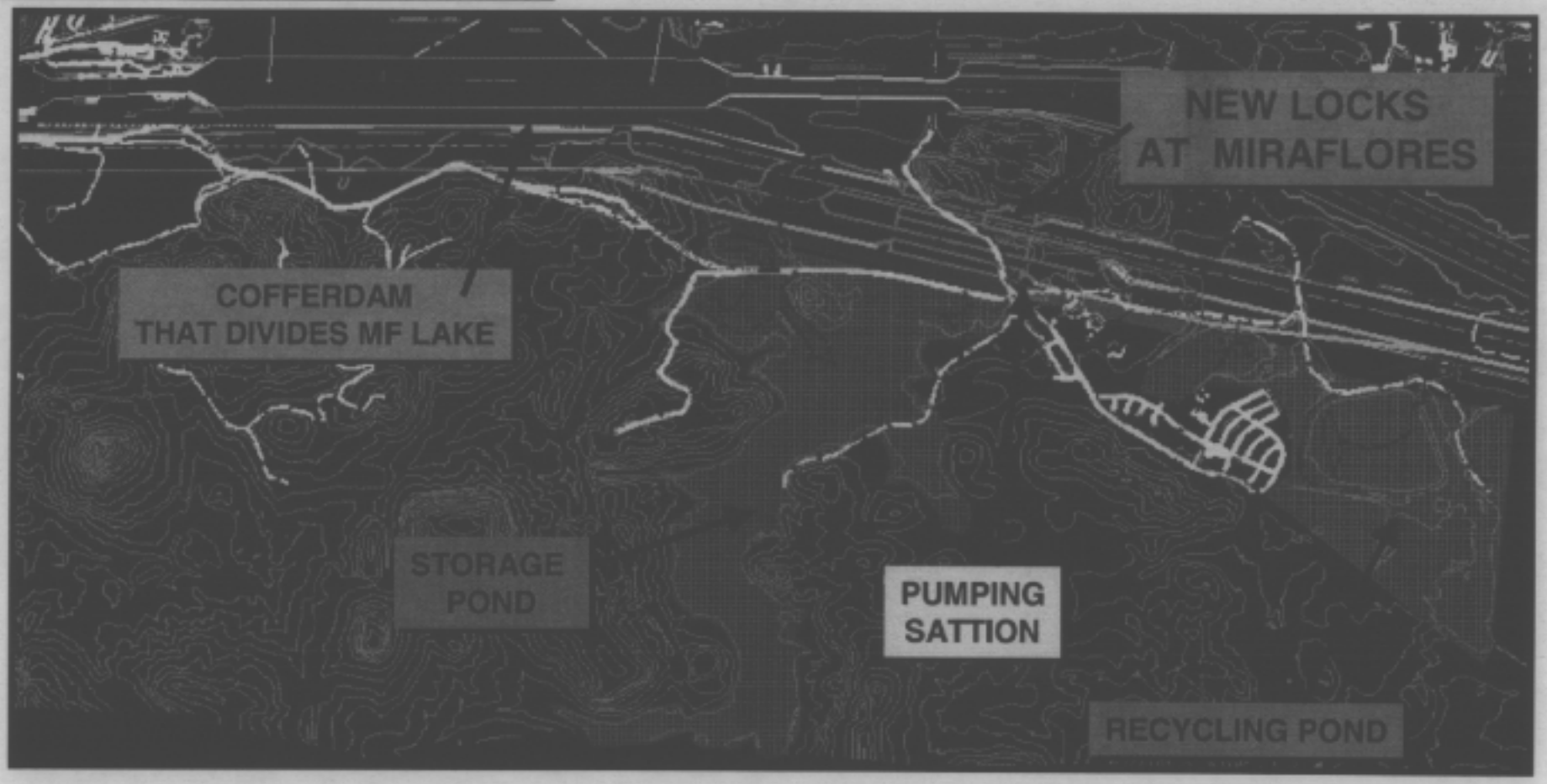
Operation of Saving and Recycling Sistems



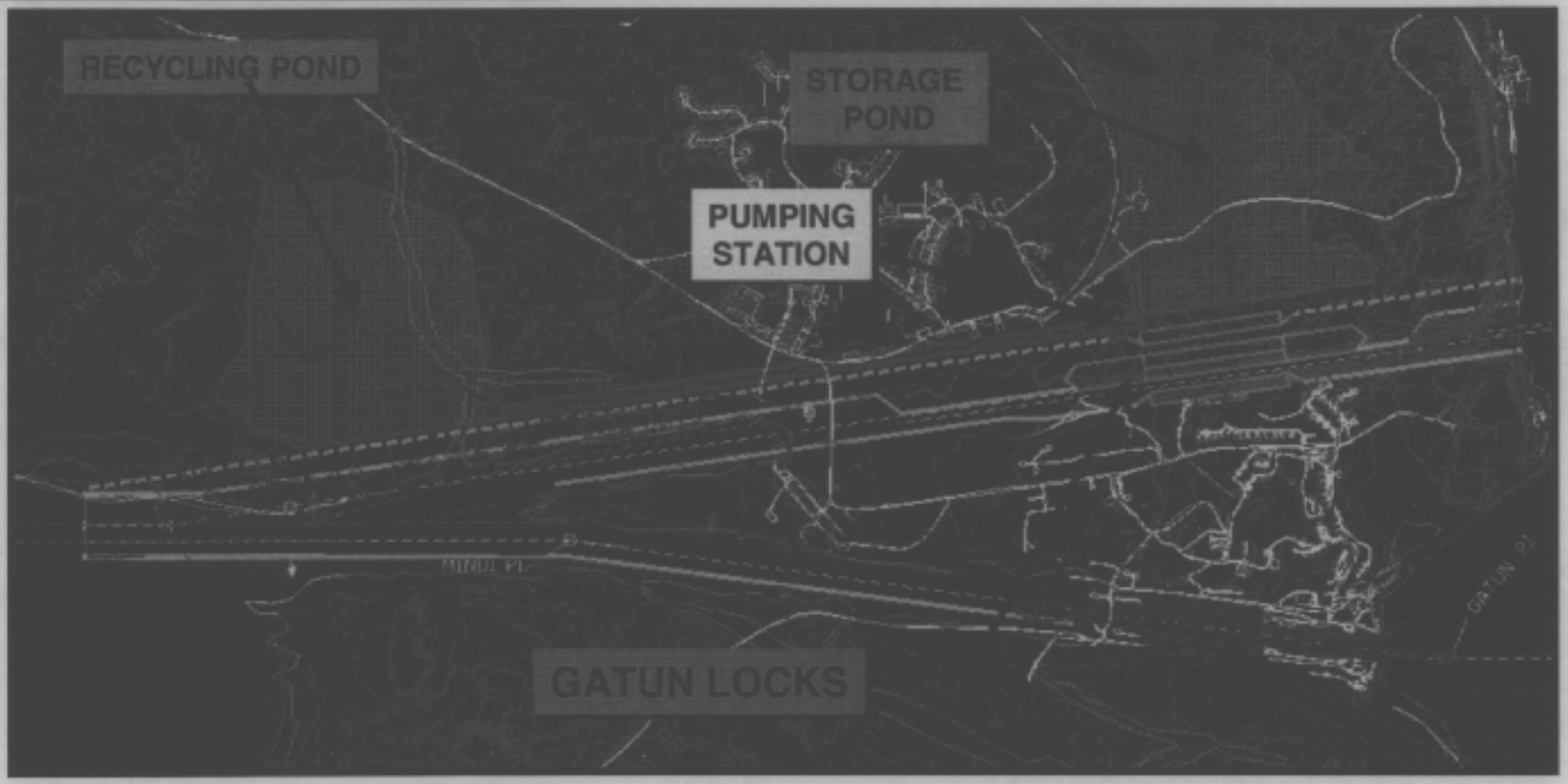
Operation of Saving and Recycling Sistems



Recycling Ponds - Pacific

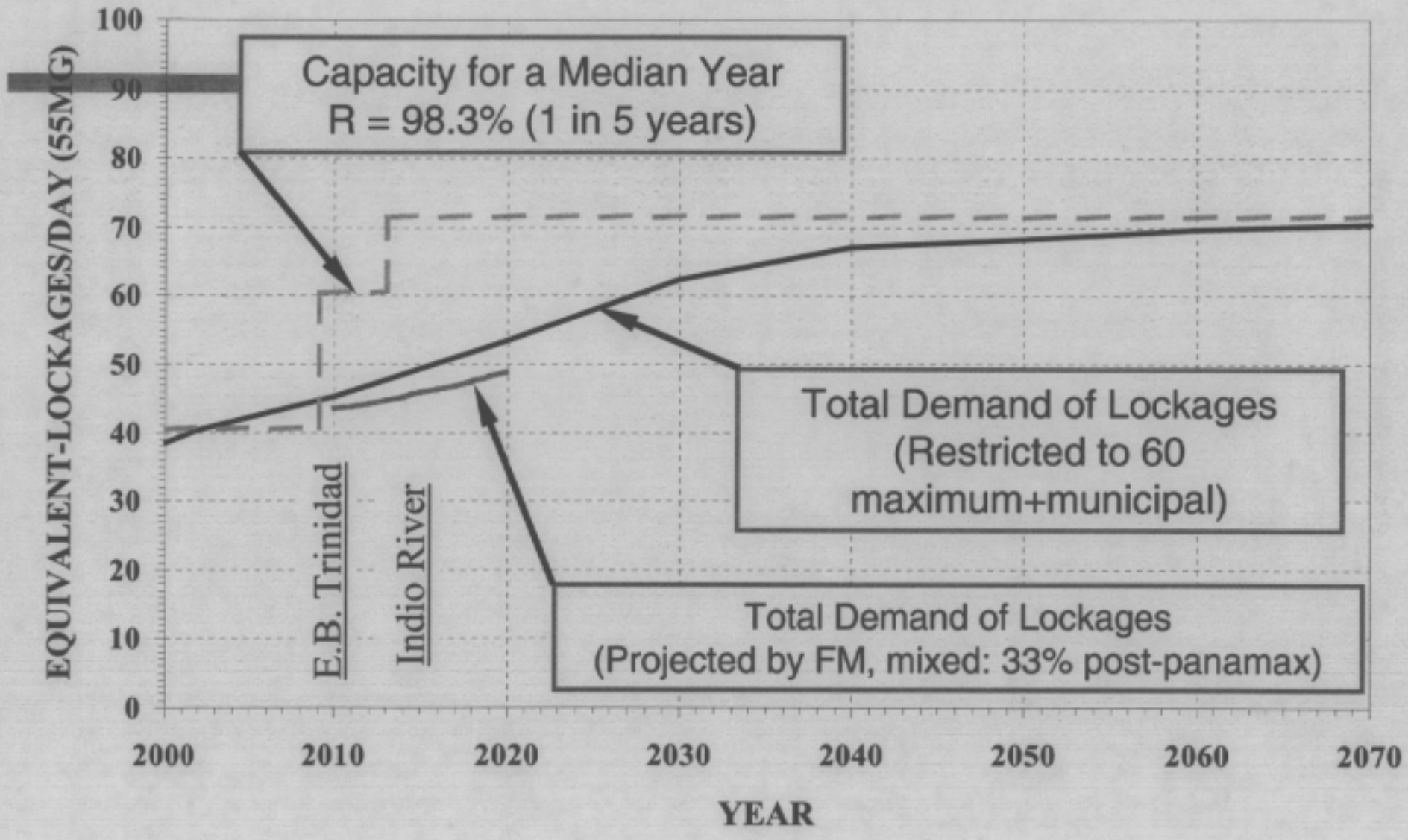


Recycling Ponds - Atlantic

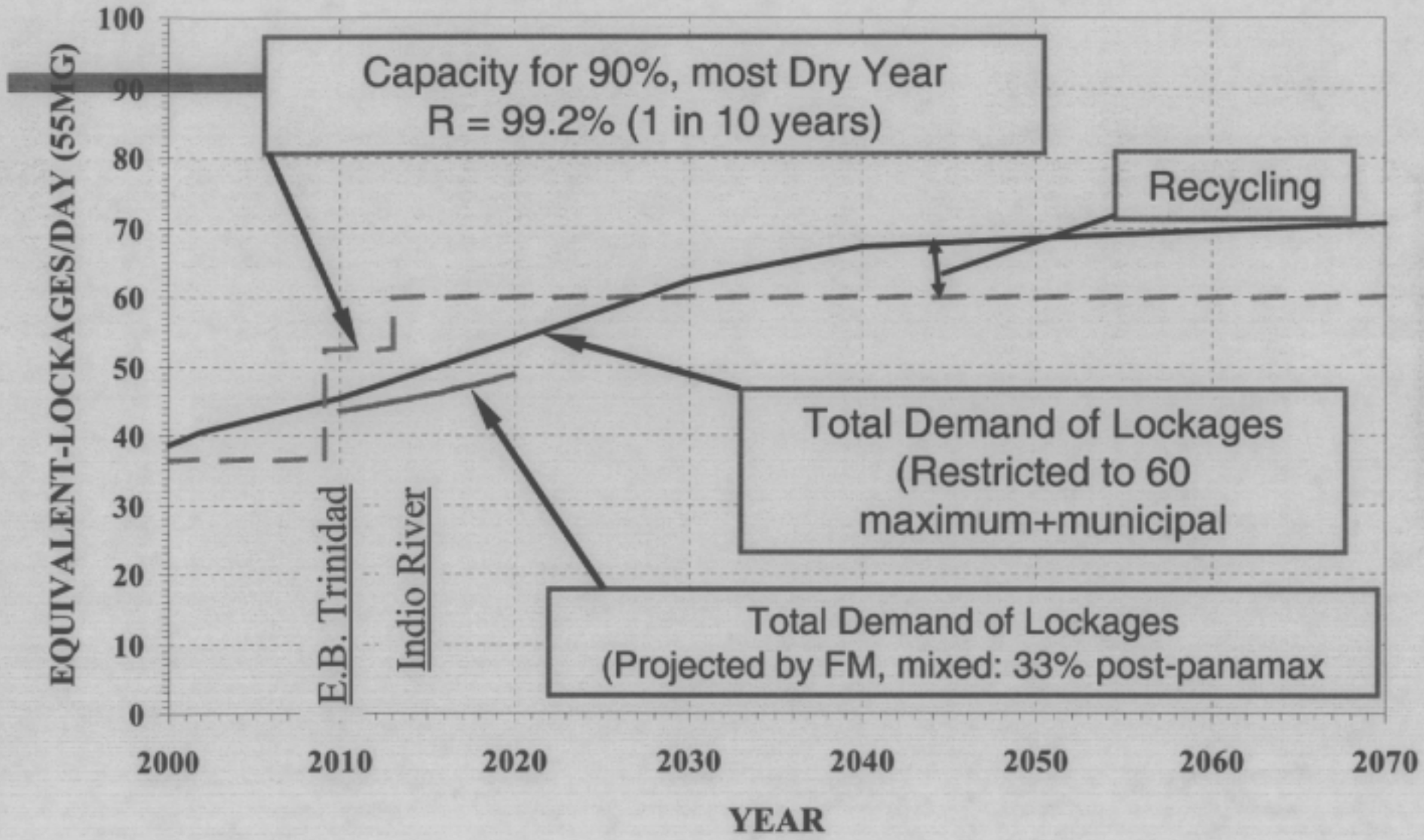


System Capacity vs. Demand

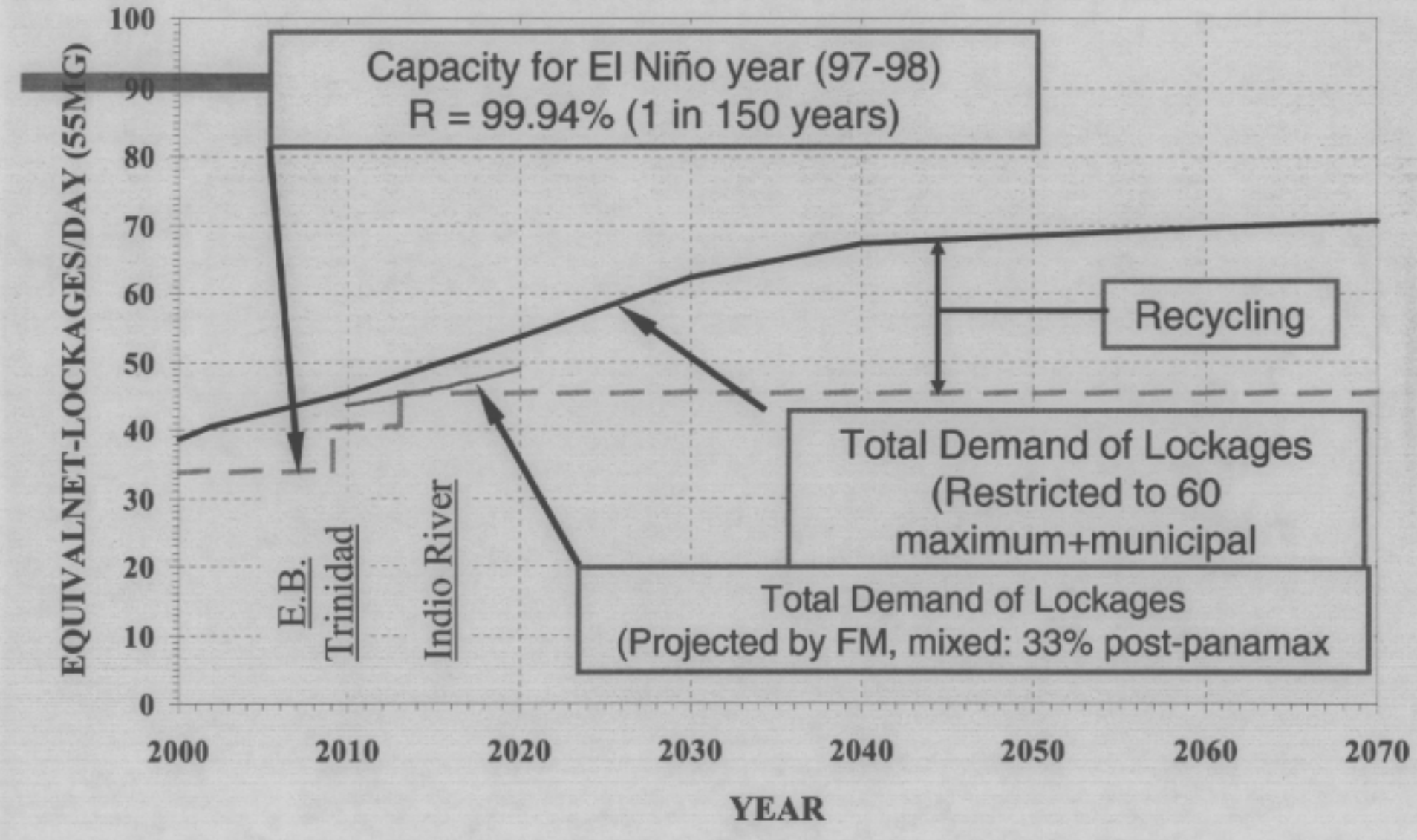
Capacity vs. Demand



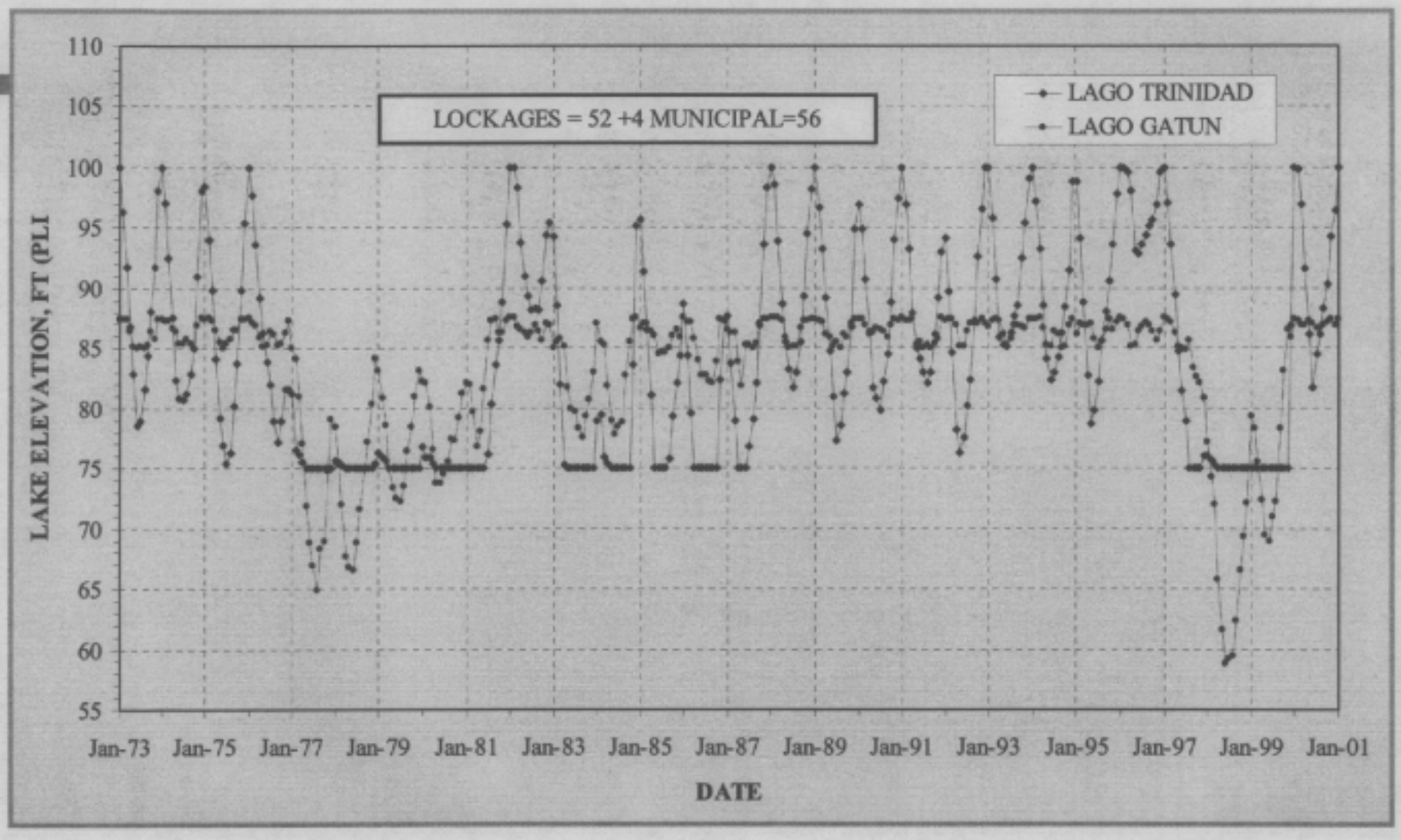
Capacity vs. Demand



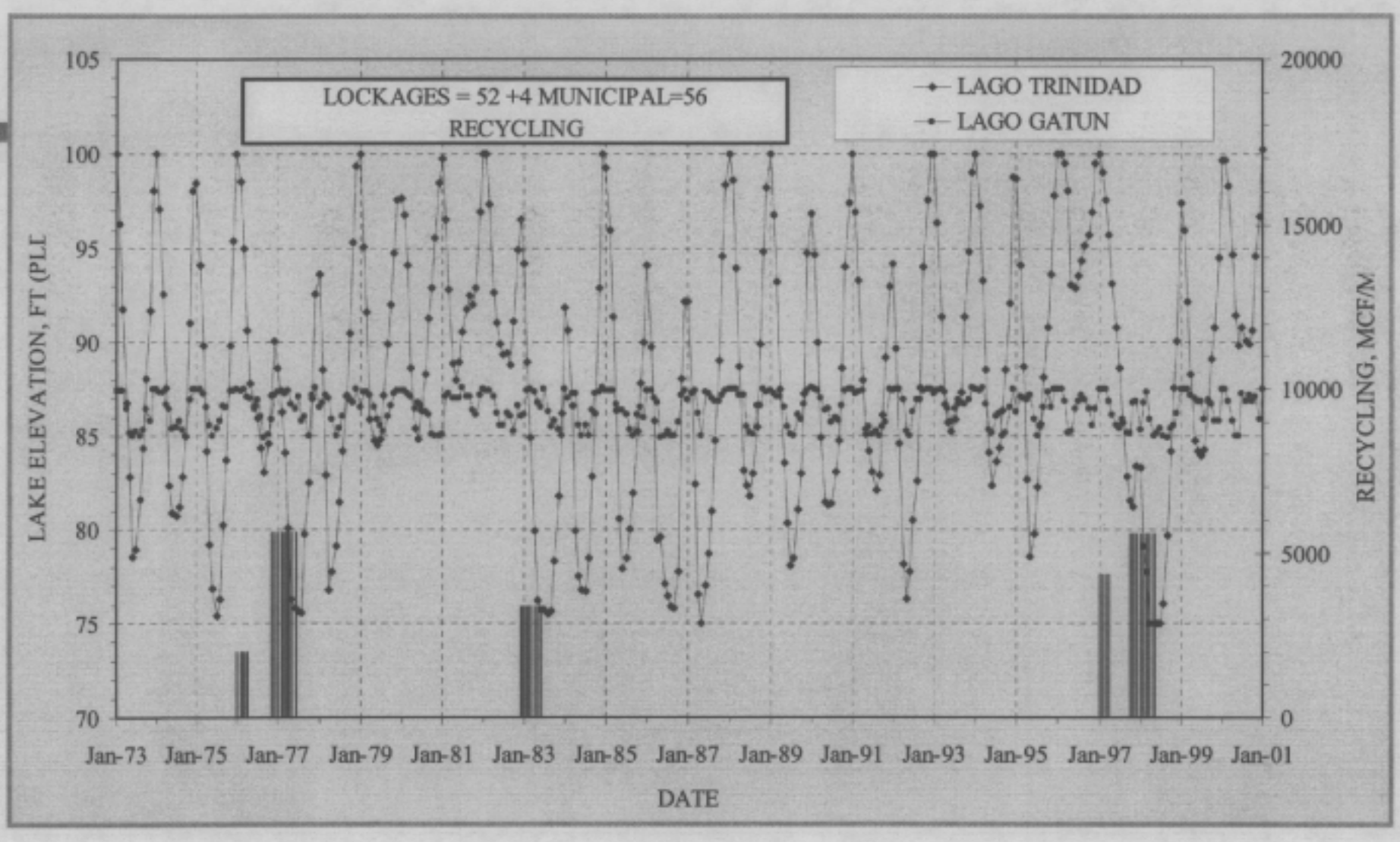
Capacity vs. Demand



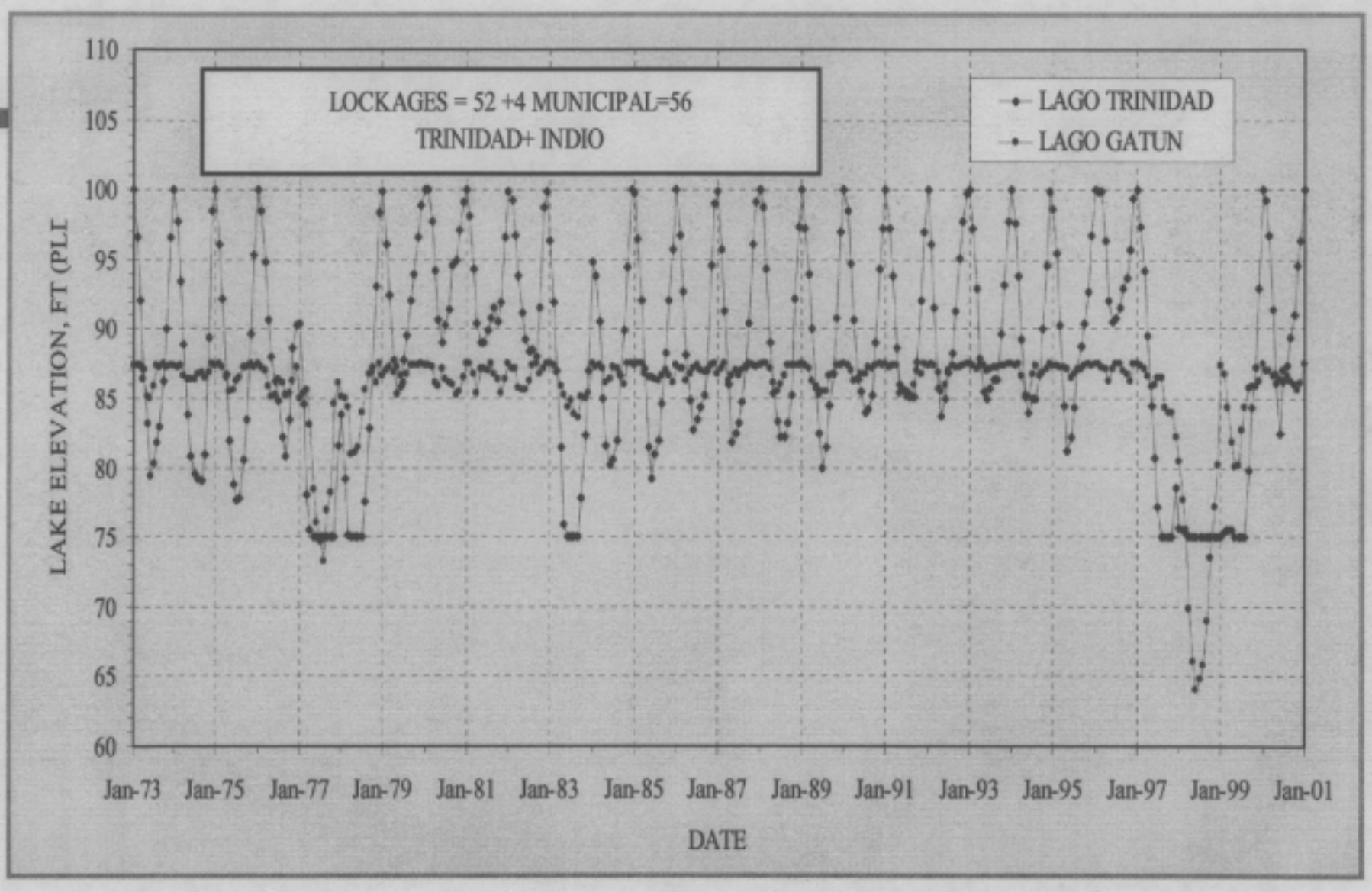
Water Balance (Trinidad EBT)



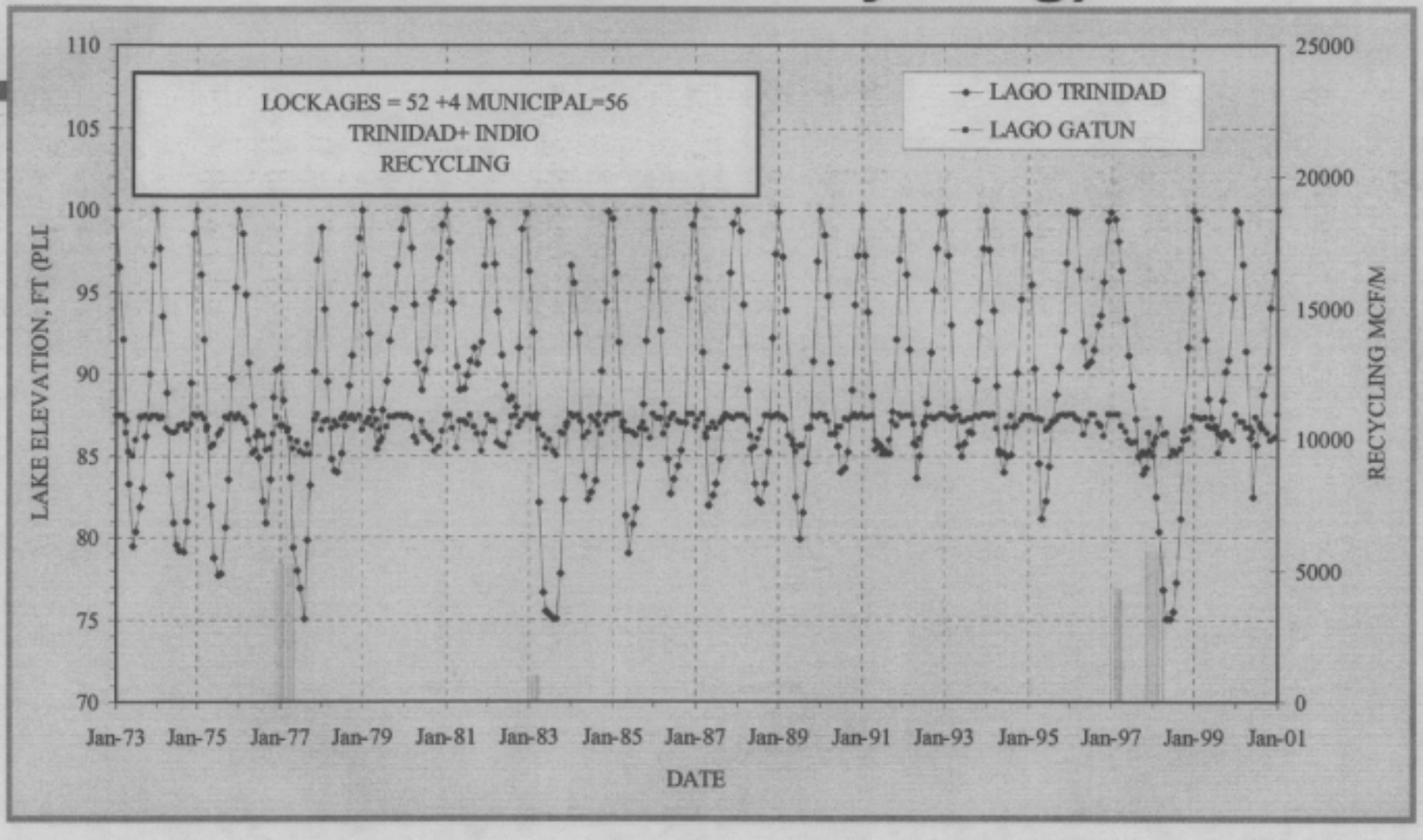
Water Balance (Trinidad EBT+Recycling)



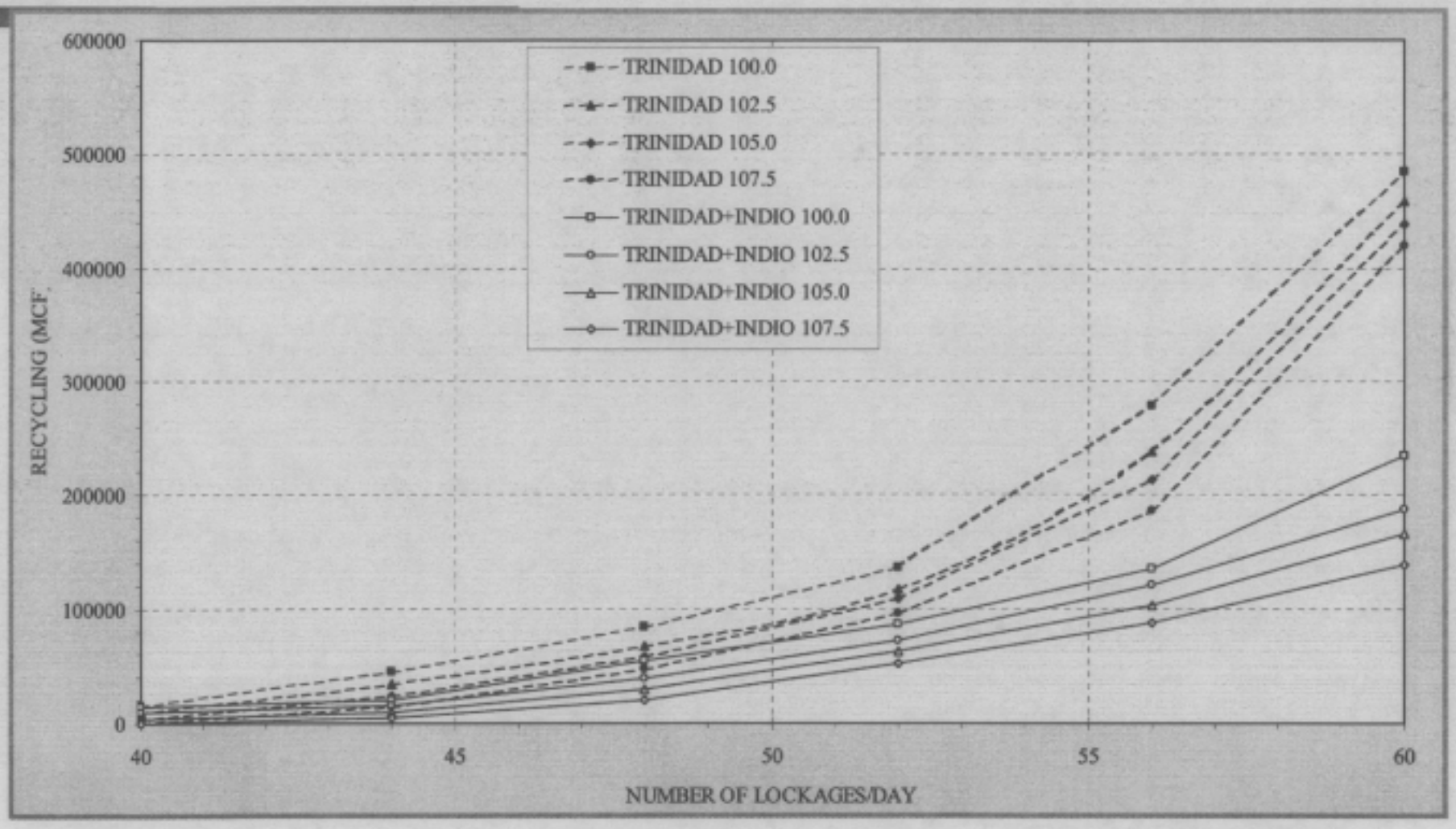
Water Balance (Trinidad EBT+Indio)



Water Balance (Trinidad EBT+Indio+Recycling)



Recycling Requirements vs. Lake Elevation and # of Lockages (1973-2000)



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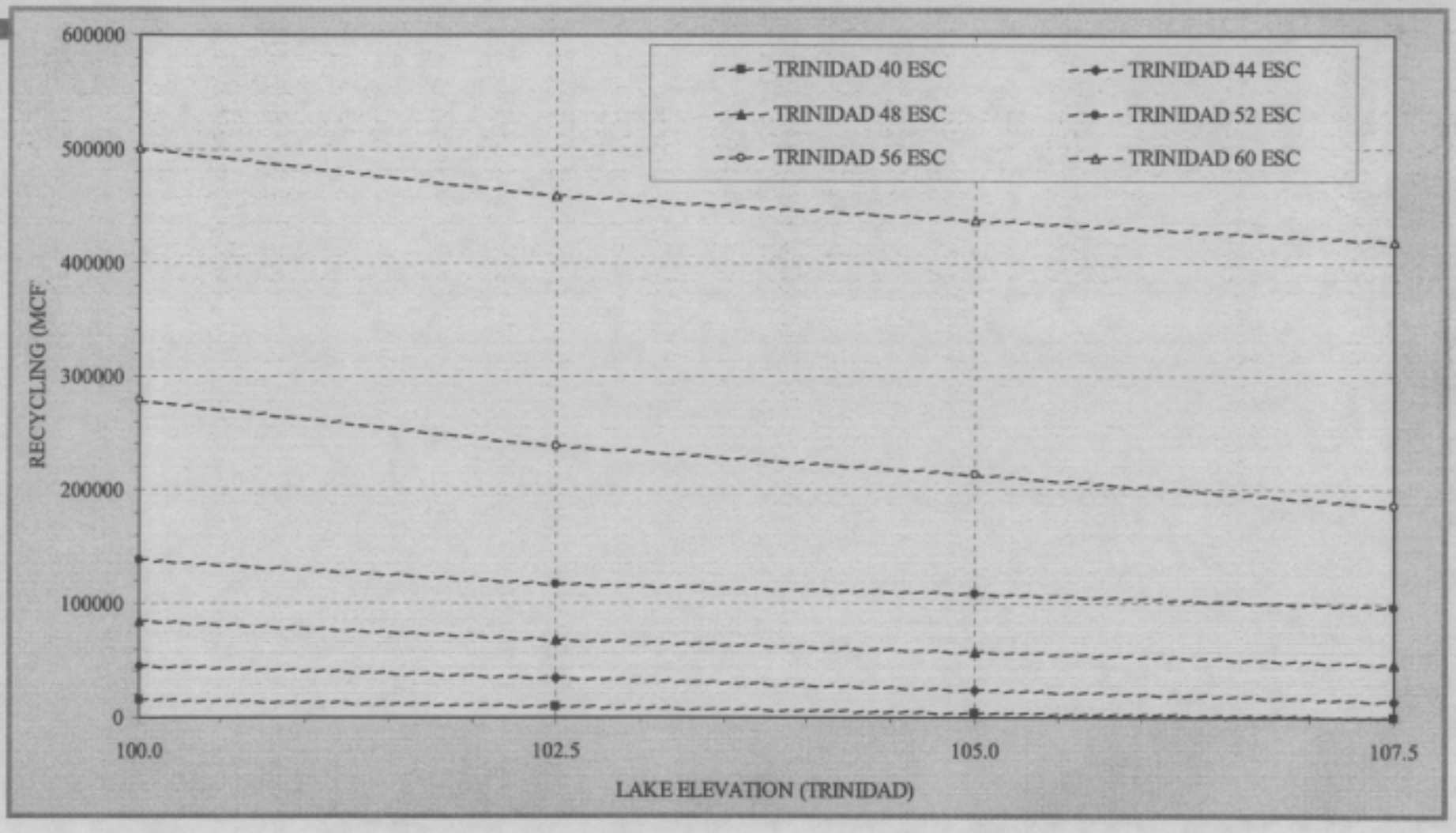

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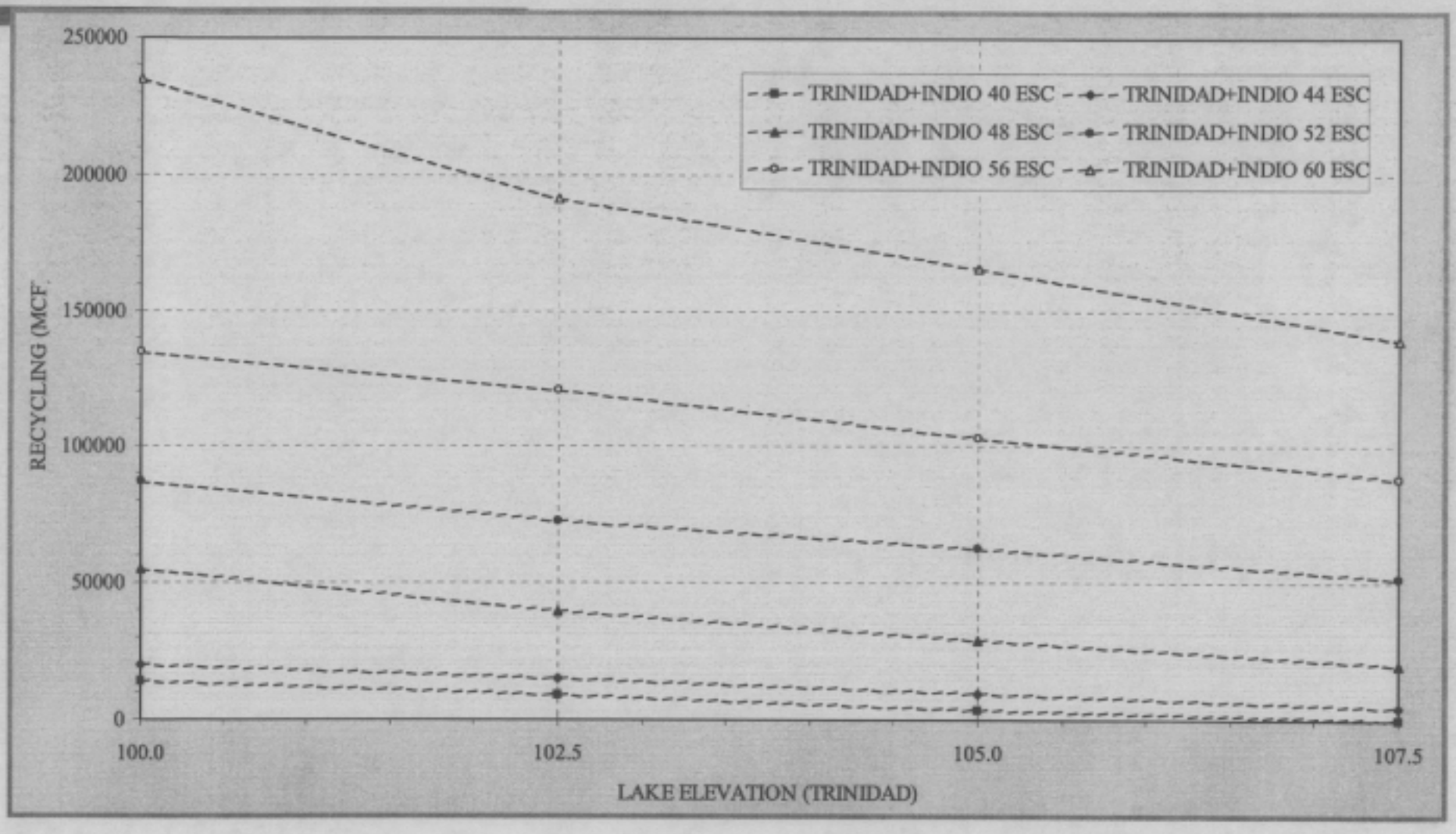
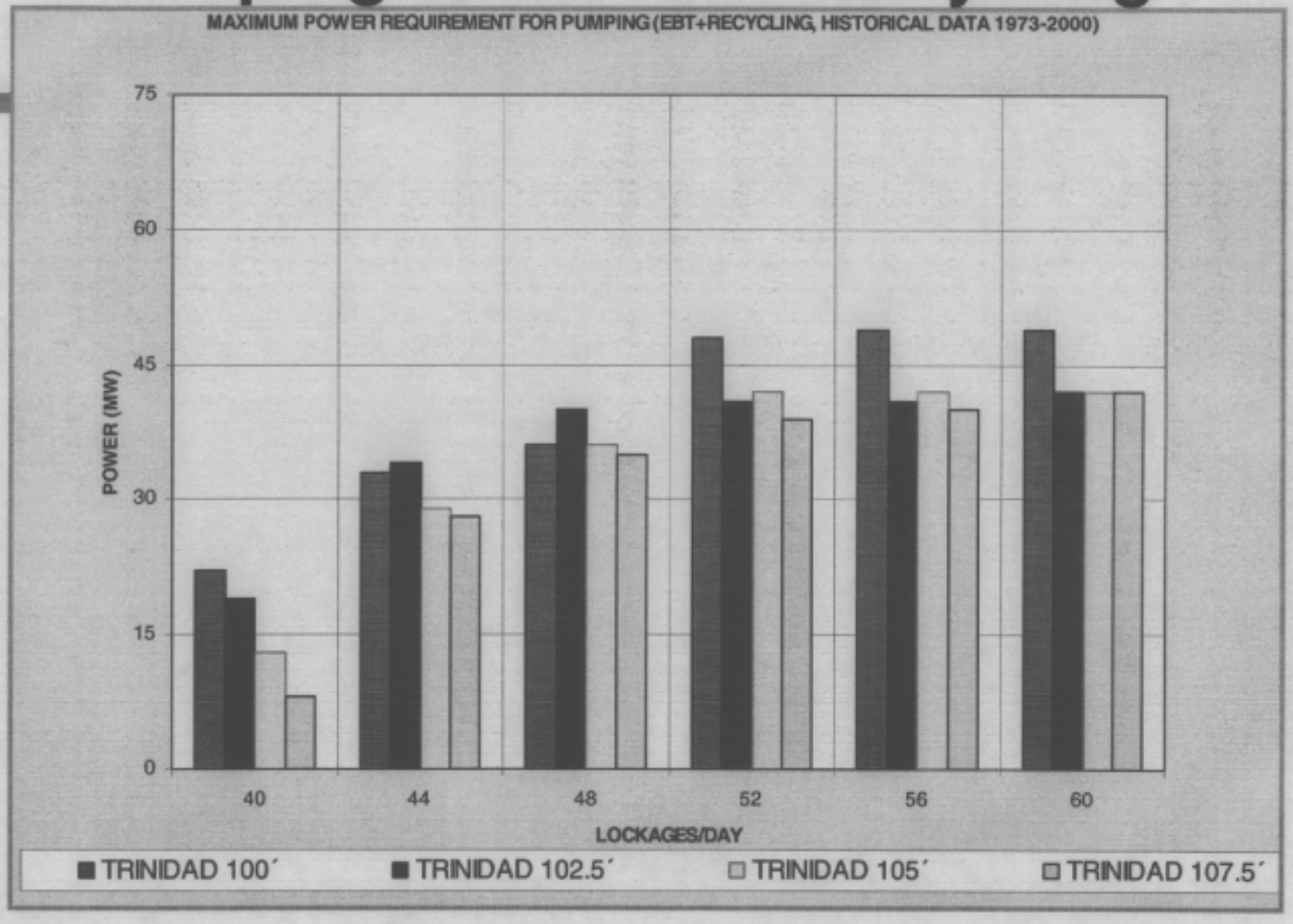
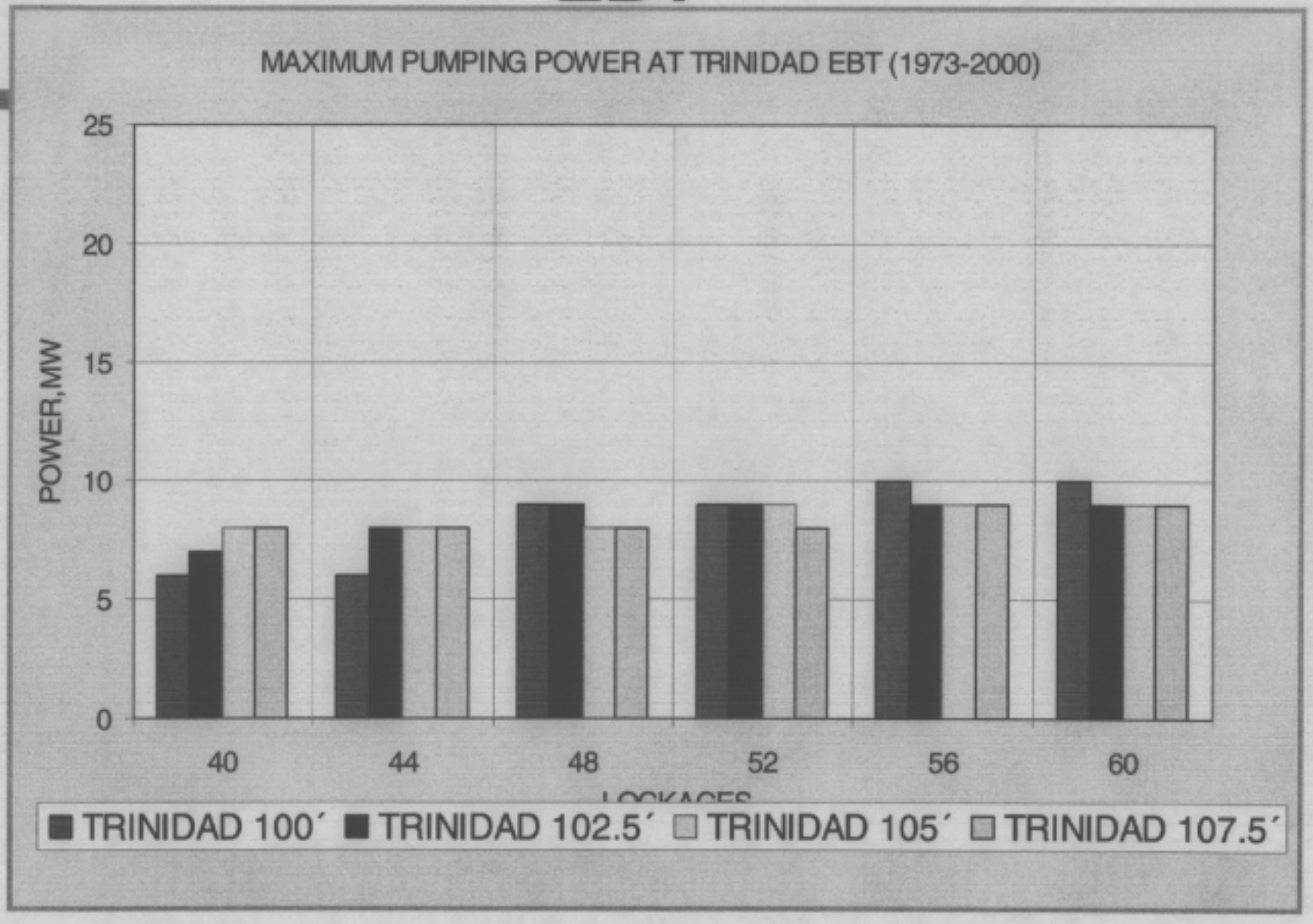


Power & Cost Requirements

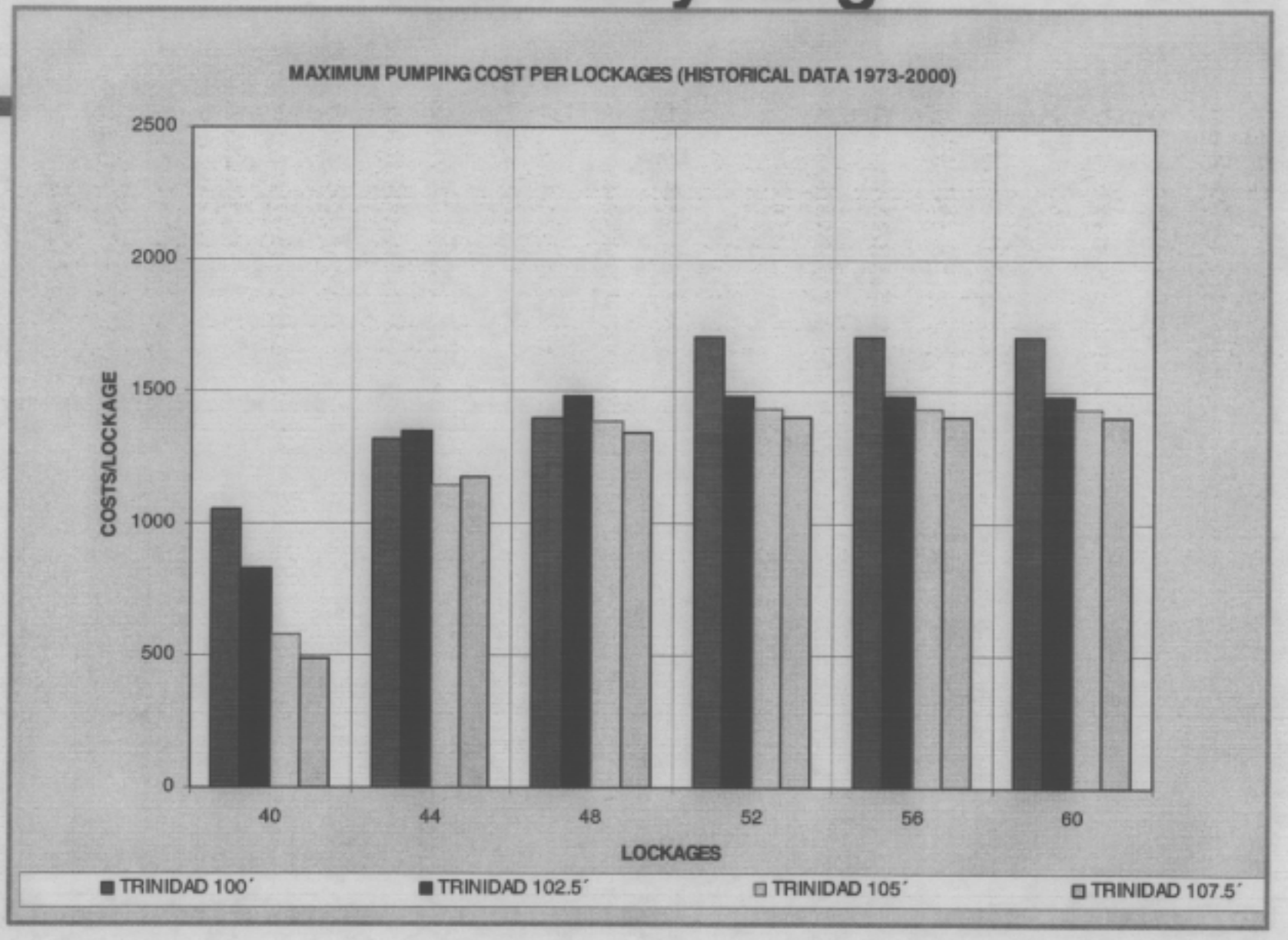
Maximum Power Requirements for Pumping at EBT and Recycling



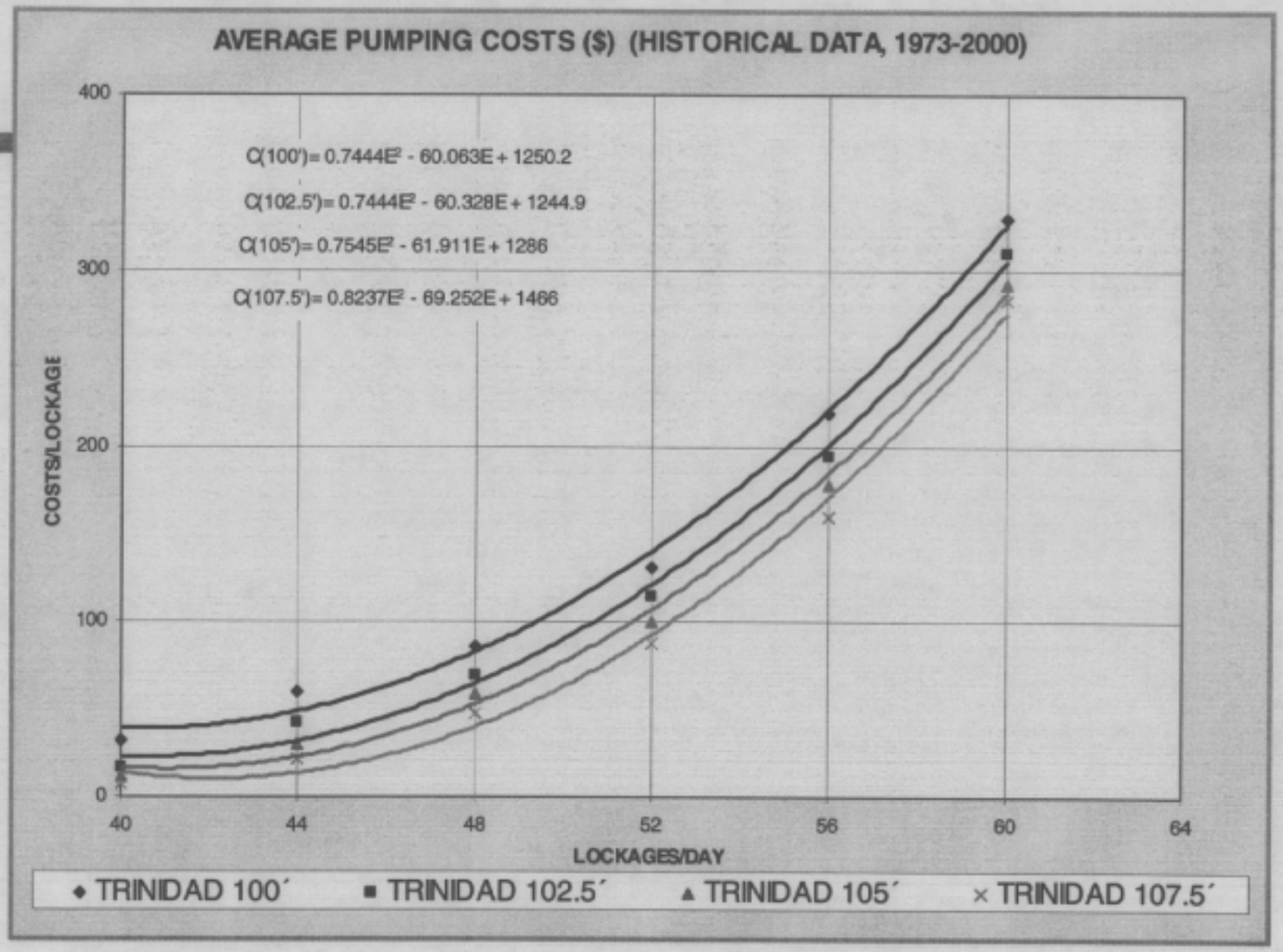
Maximum Pumping Power at Trinidad EBT



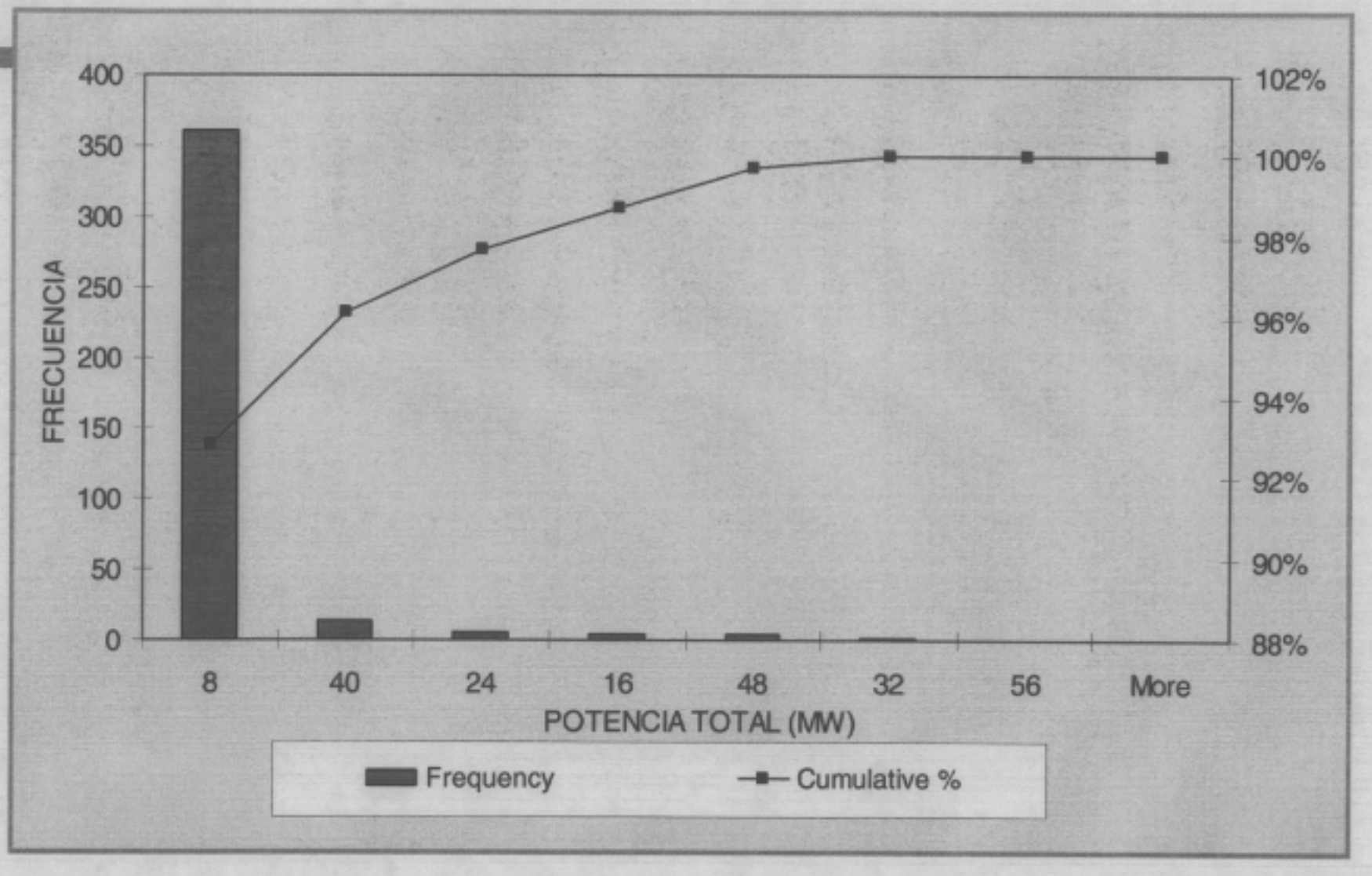
Cost Requirements for Pumping at EBT and Recycling



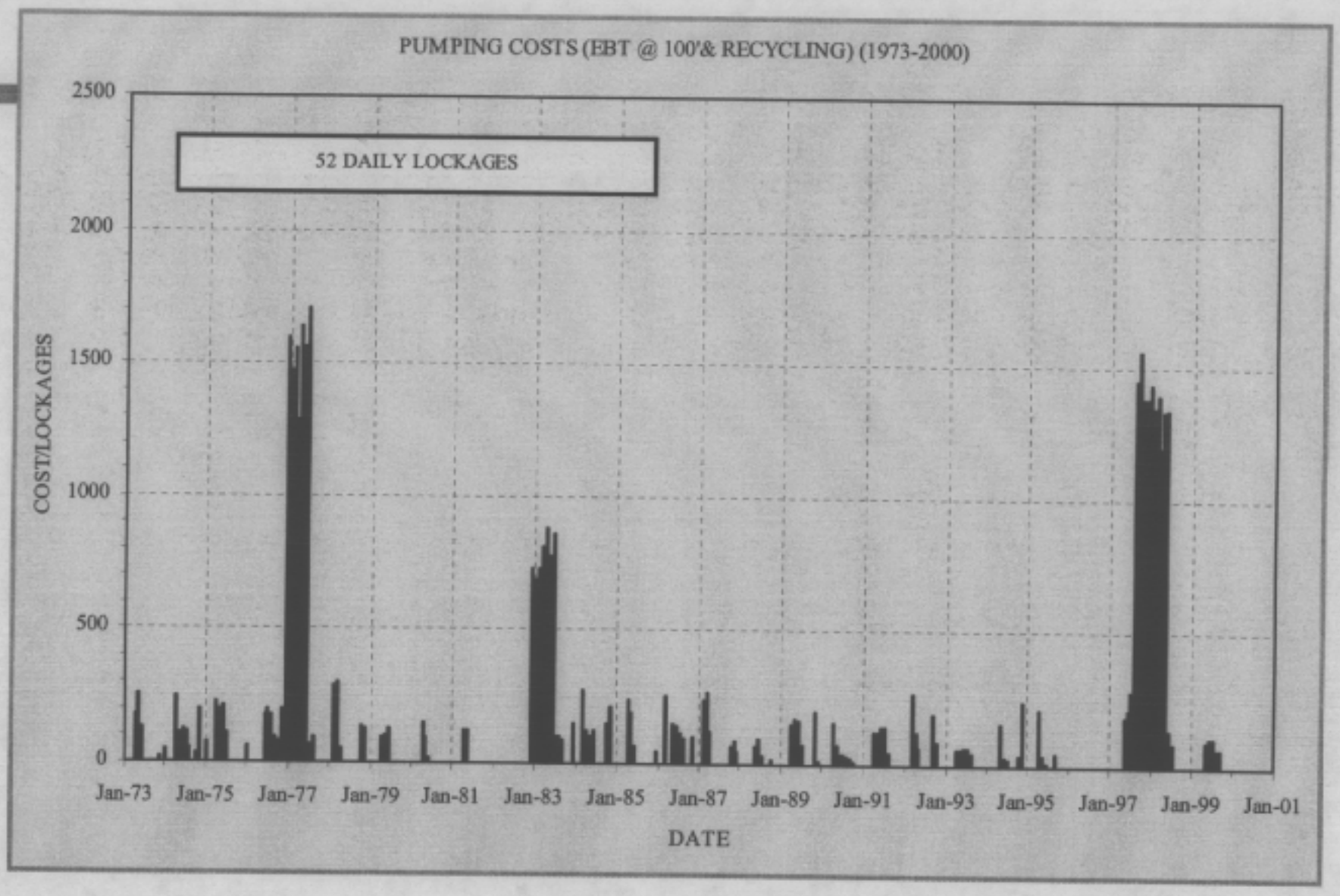
Average Pumping Costs (1973-2000)



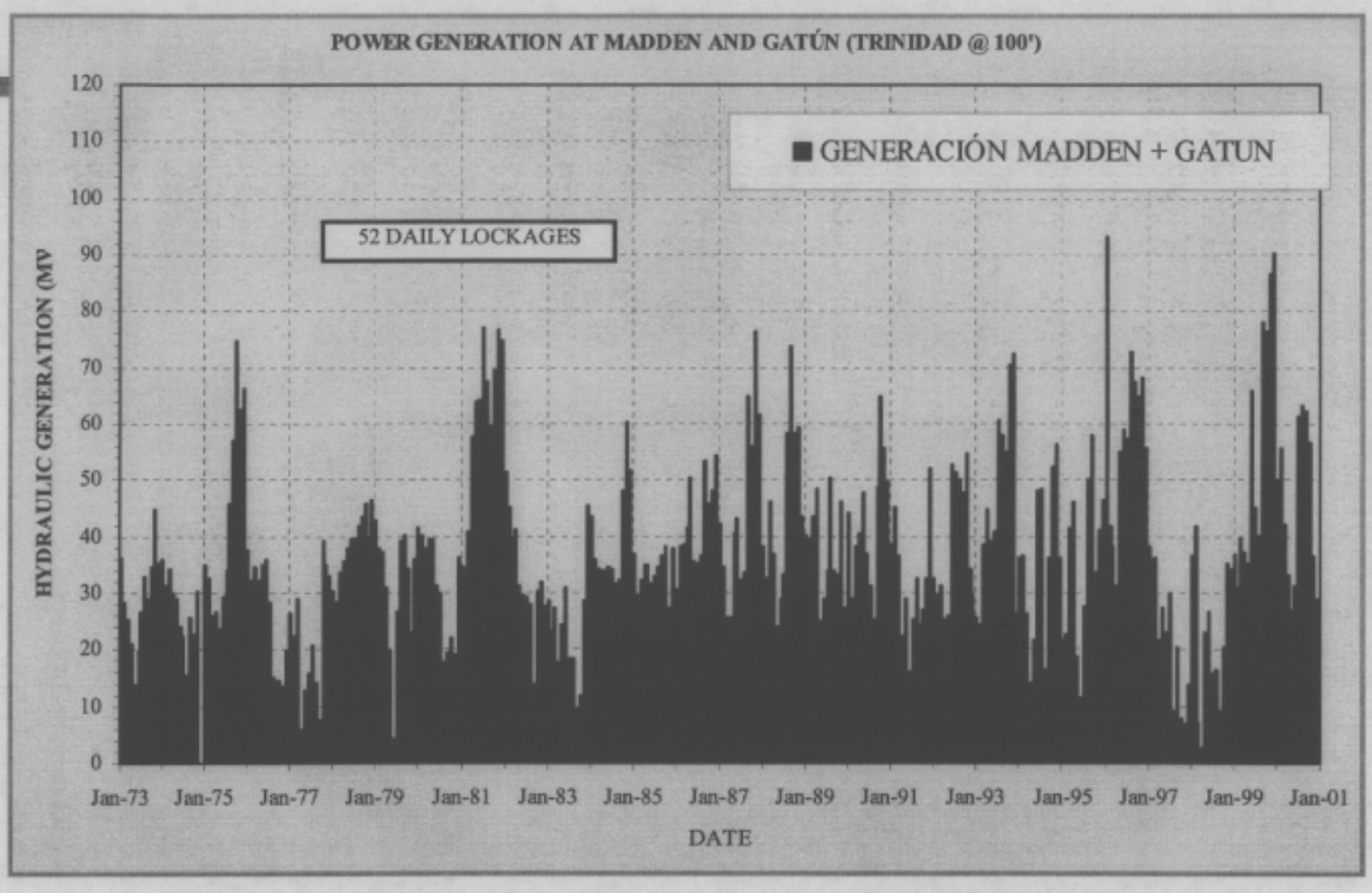
Power Distribution for 52 Lockages (Trinidad @ 100')



Pumping Cost (EBT @ 100')



Power Generation (EBT @ 100')



The Trinidad Pump Storage will enable an integral solution in our existing watershed that is less costly and less problematic than any other solution to the water supply problem

END

The New Trinidad Dam

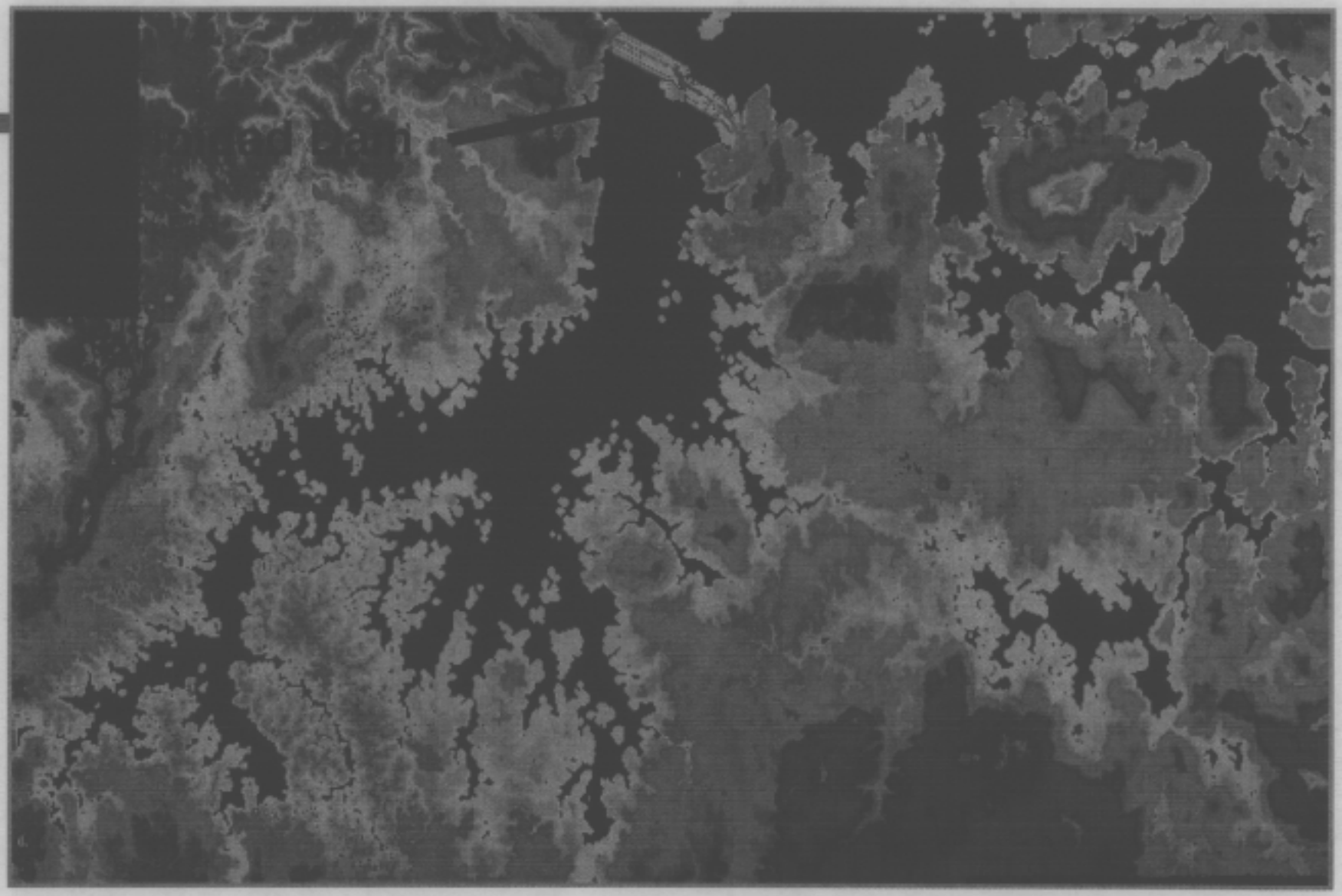
"Start by doing what is necessary, then do what is possible, and suddenly you are doing the impossible."

-- Saint Francis of Assisi

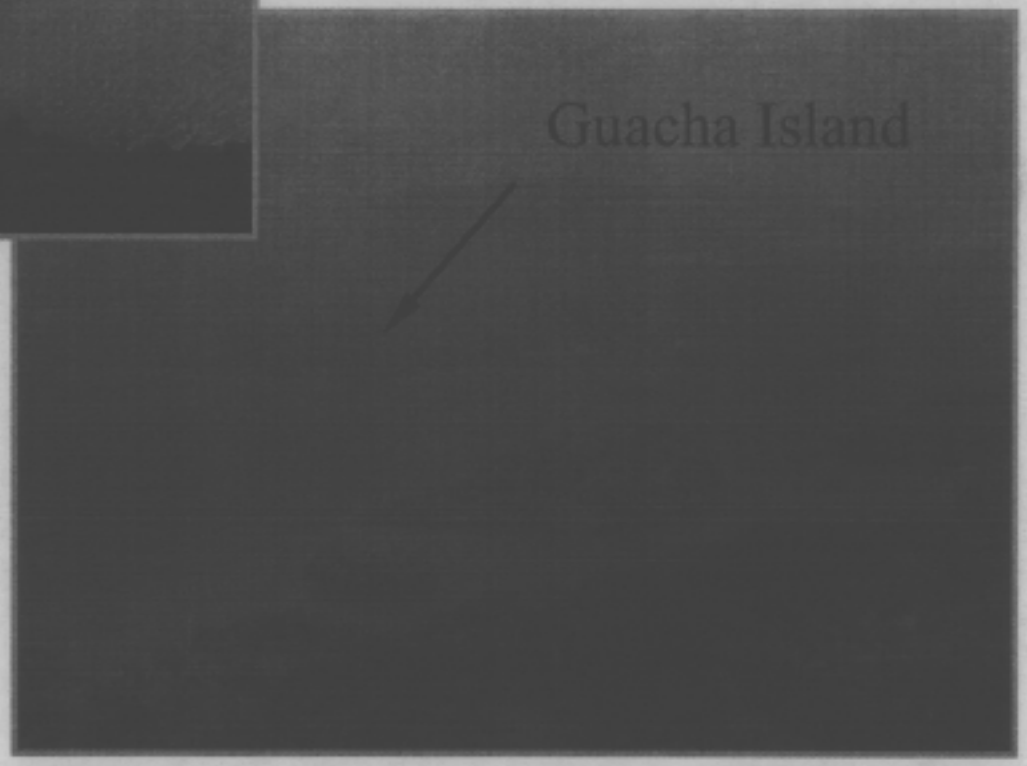
Content

1. Introduction to Trinidad Dam Project
2. General Geology of Trinidad Dam Area
3. Engineering Properties of the Atlantic Muck
4. Analysis and Stability of the Proposed Dam
    1. Settlement and Deformation Analysis
    2. Stability Analysis by Stress and Deformations
    3. Seepage Analysis
    4. Stability Analysis by Limit Equilibrium – Undrained

Location Plan

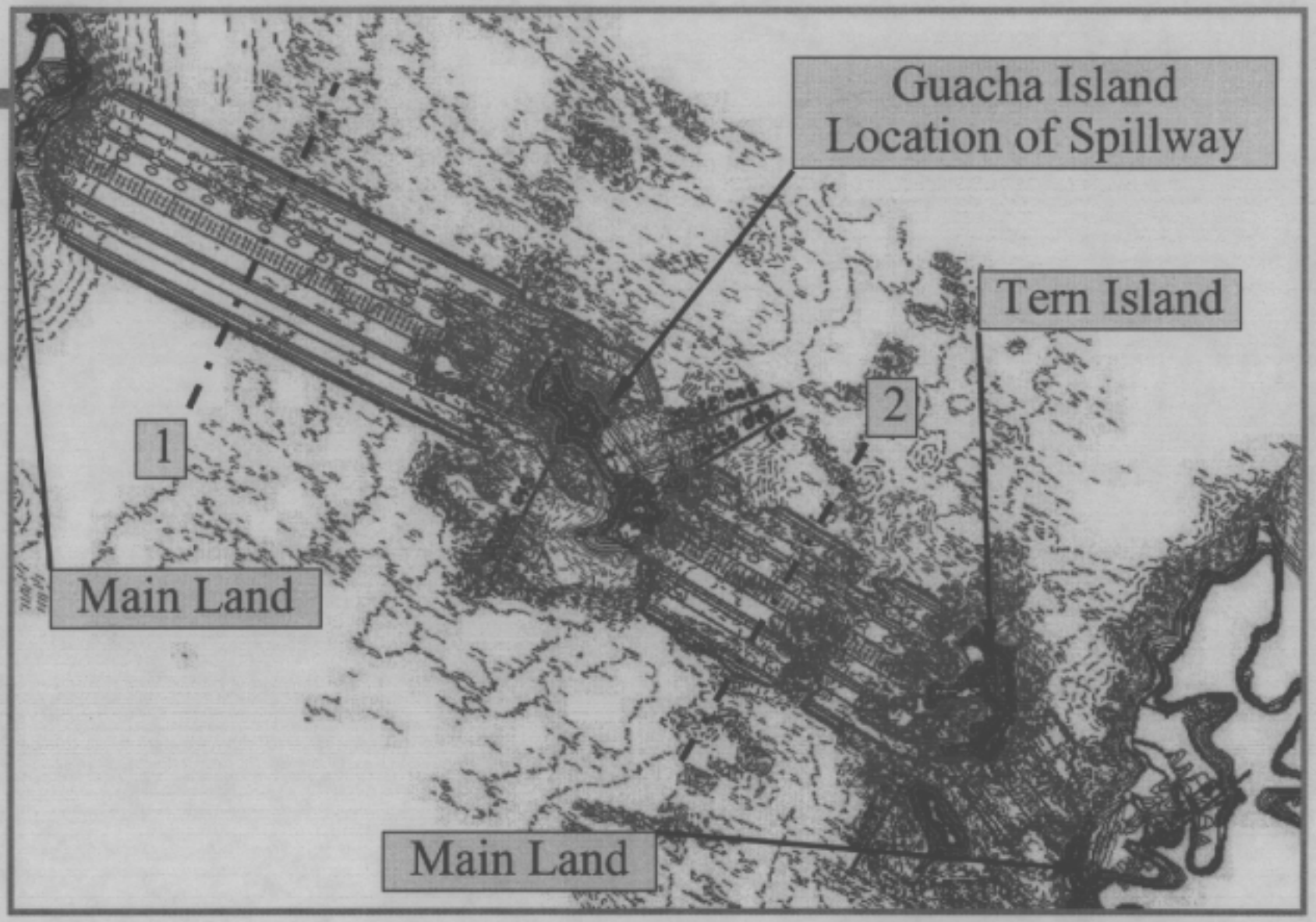


South View

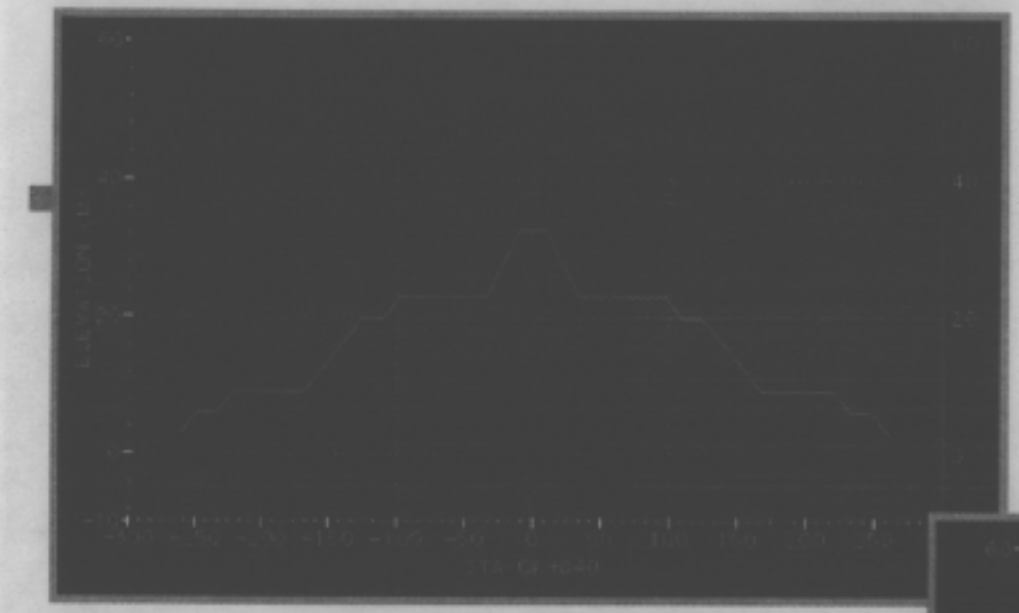


North View

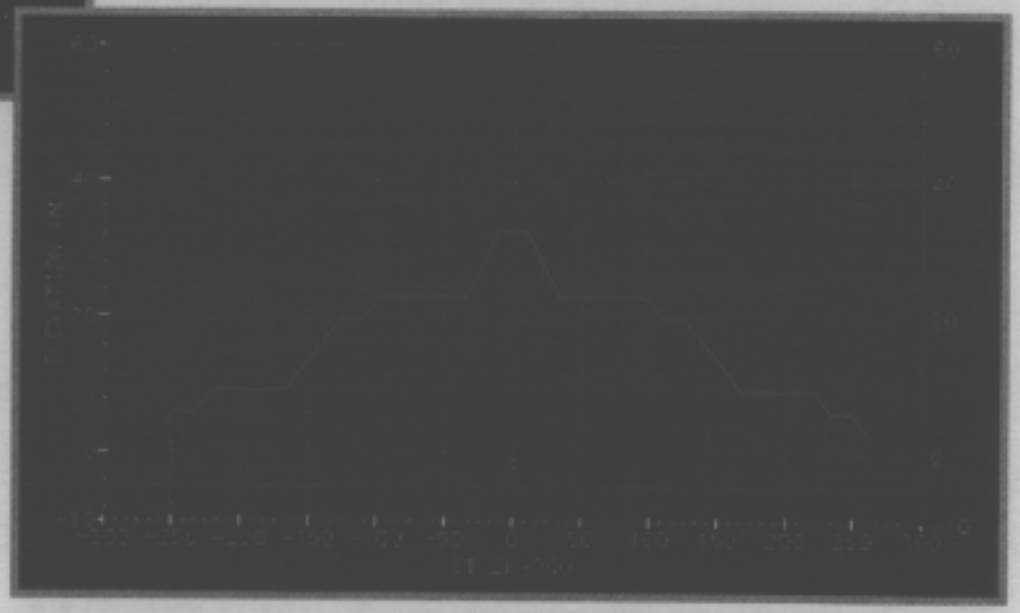
Plan View


Guacha Island
Location of Spillway
Tern Island
2
1
Main Land
Main Land

Sections

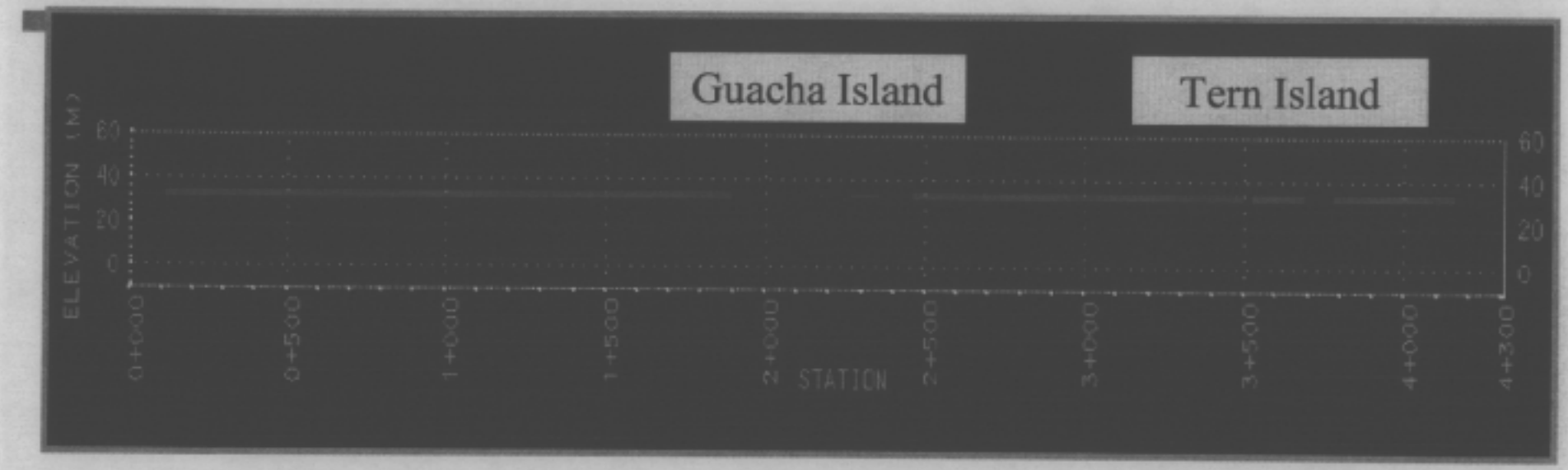


SECTION 1

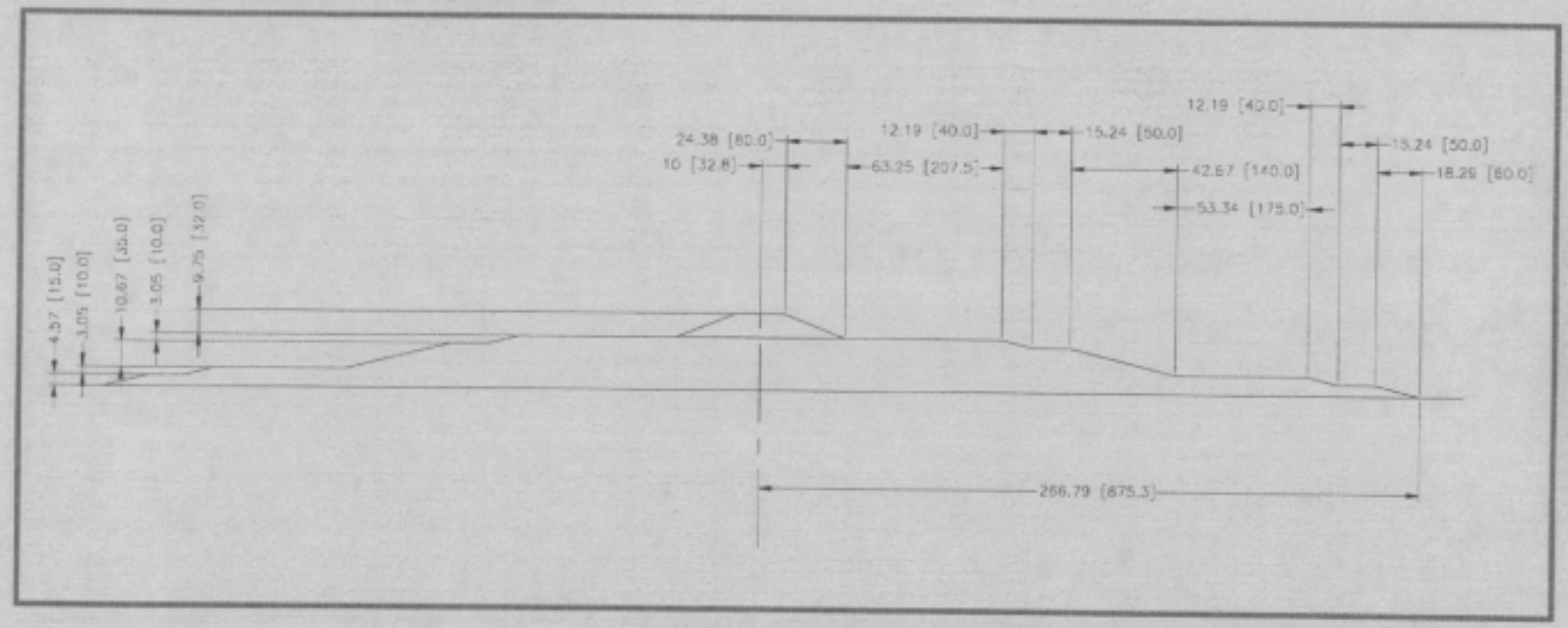


SECTION 2

Profile


ELEVATION (M)
60
40
20
0
0+000
0+500
1+000
1+500
2+000
2+500
3+000
3+500
4+000
4+300
STATION
Guacha Island
Tern Island

Dam Geometry

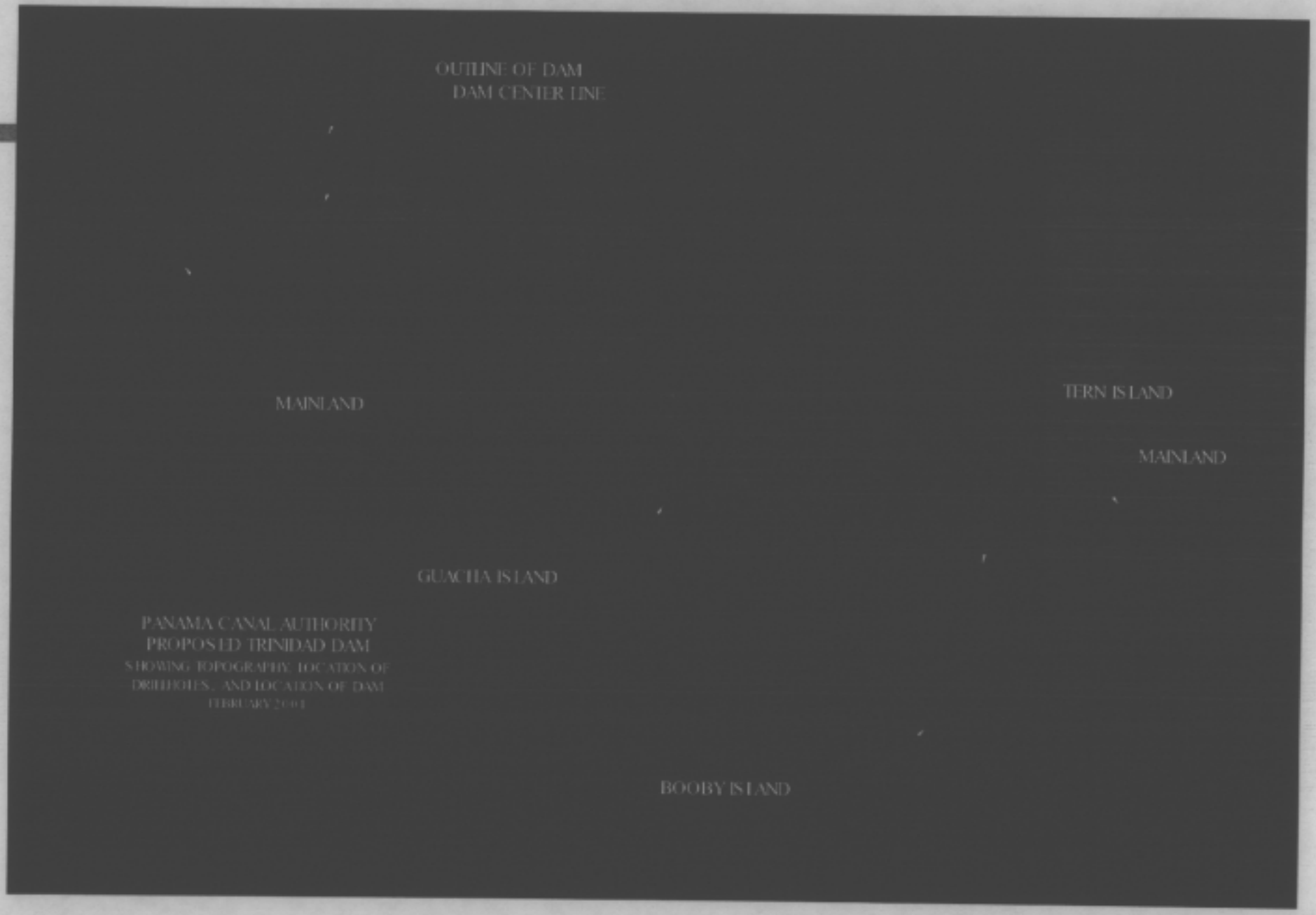


Characteristics

	Trinidad	Gatún
CREST ELEV	107 ft PLD	105 ft PLD
LENGTH	4,100 M	2,500 M
BASE	535 M	700 M
VOLUME	16,000,000 M3	17,500,000 M3

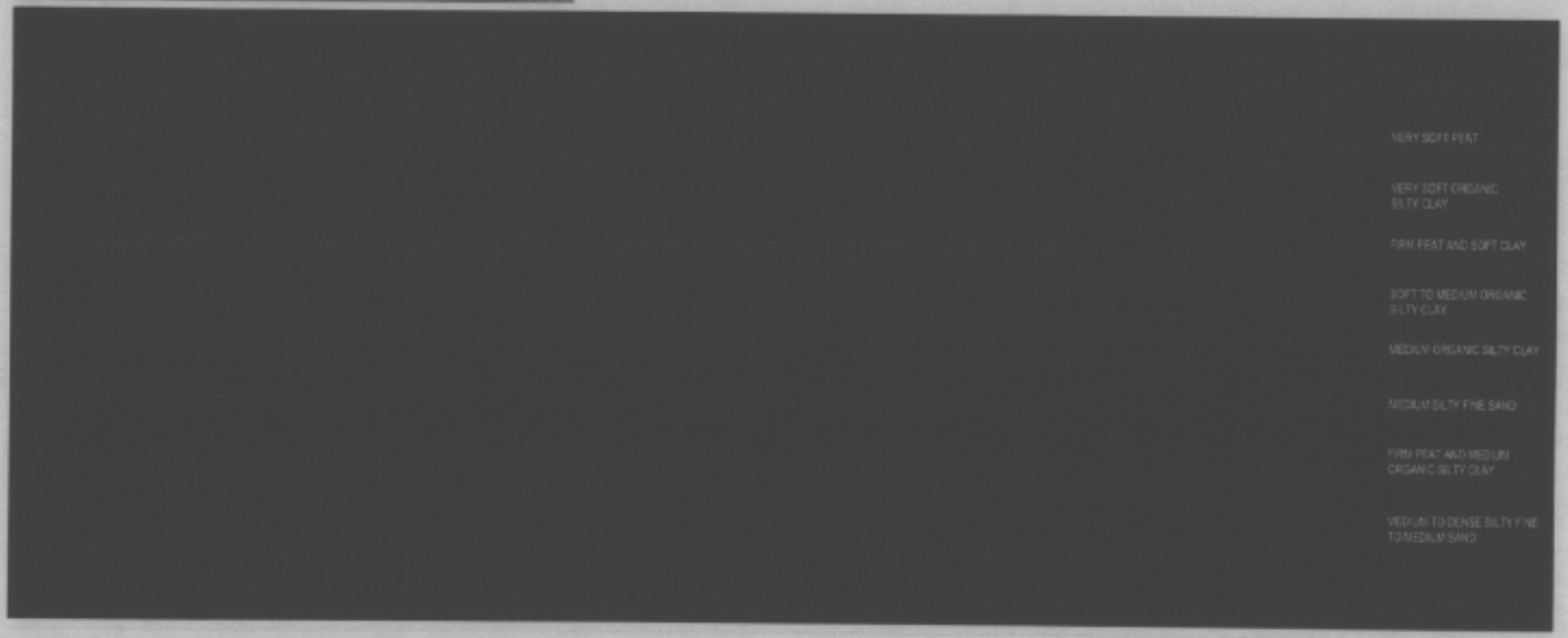
Brief Geological Description

Boring Location Plan



Geological Profile – Punta Mala & Guacha

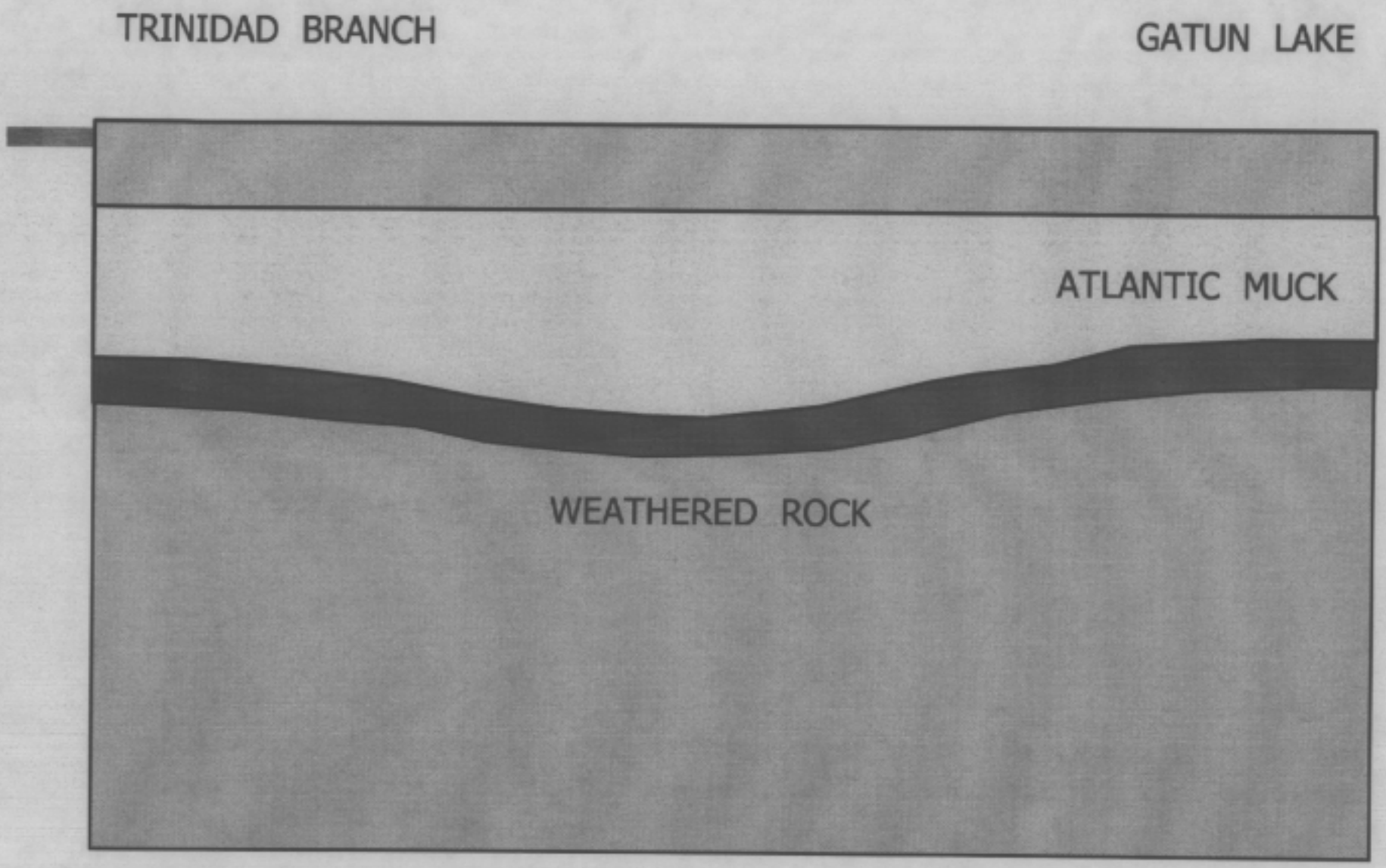
Section for the Analysis

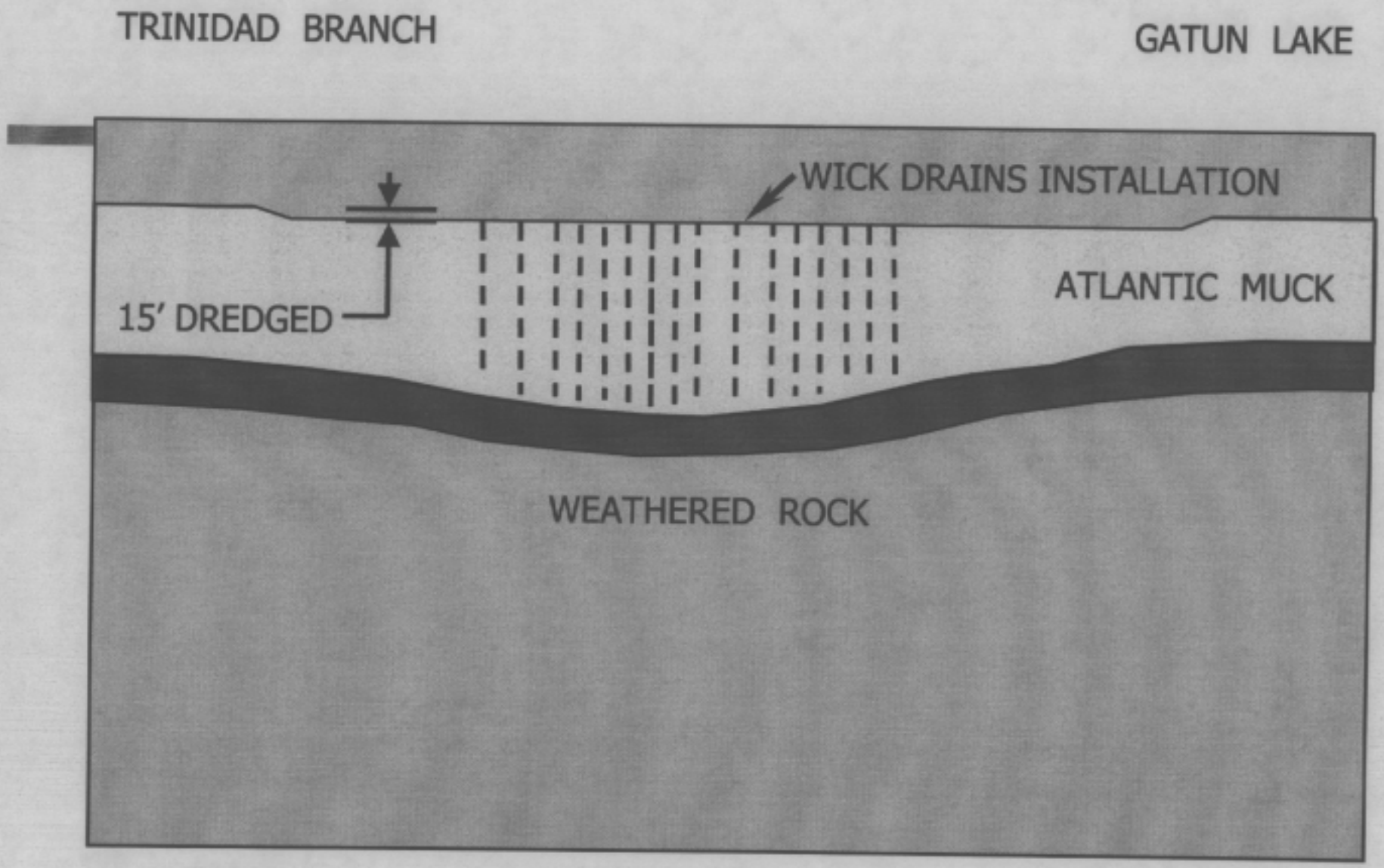


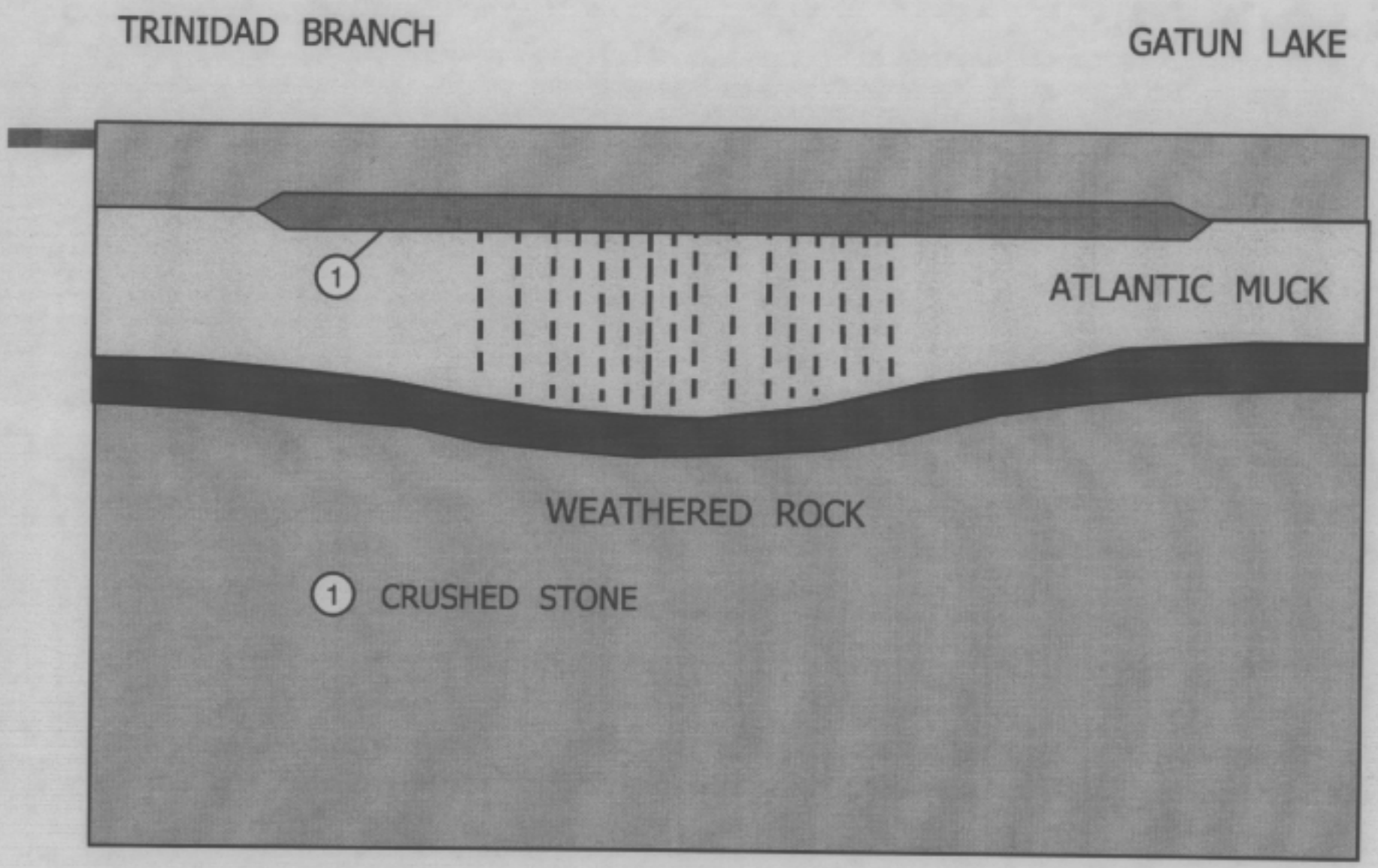
Columnar Stratrigraphy

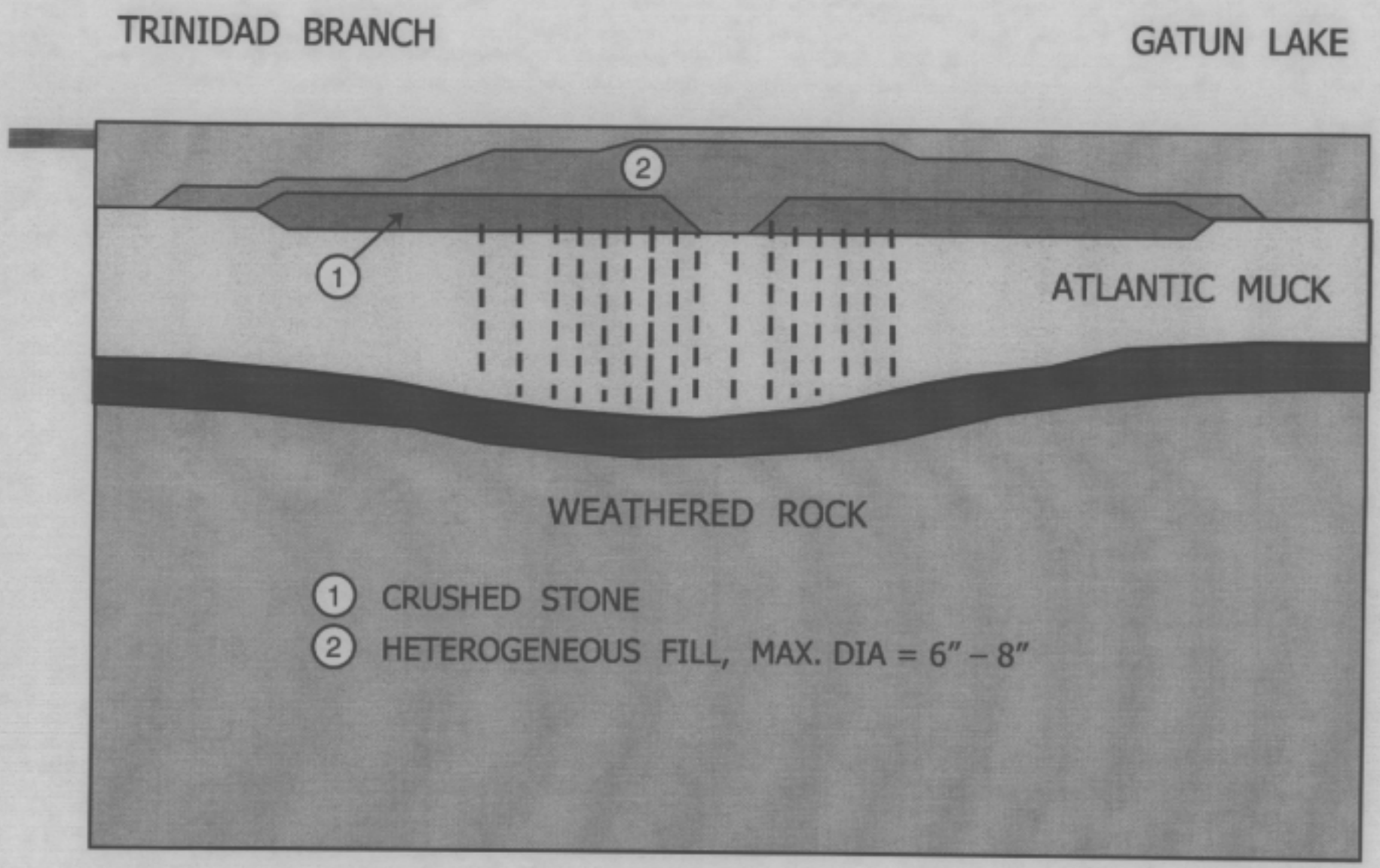
MATERIAL	DEPTH
VERY SOFT PEAT	77.2
VERY SOFT ORGANIC SILTY CLAY	84
FIRM PEAT AND SOFT CLAY	96
SOFT TO MEDIUM ORGANIC SILTY CLAY	108
MEDIUM ORGANIC SILTY CLAY	142
MEDIUM SILTY FINE SAND	201
FIRM PEAT AND MEDIUM ORGANIC SILTY CLAY	210
MEDIUM TO DENSE SILTY FINE TO MEDIUM SAND	223
SILTSTONE	243

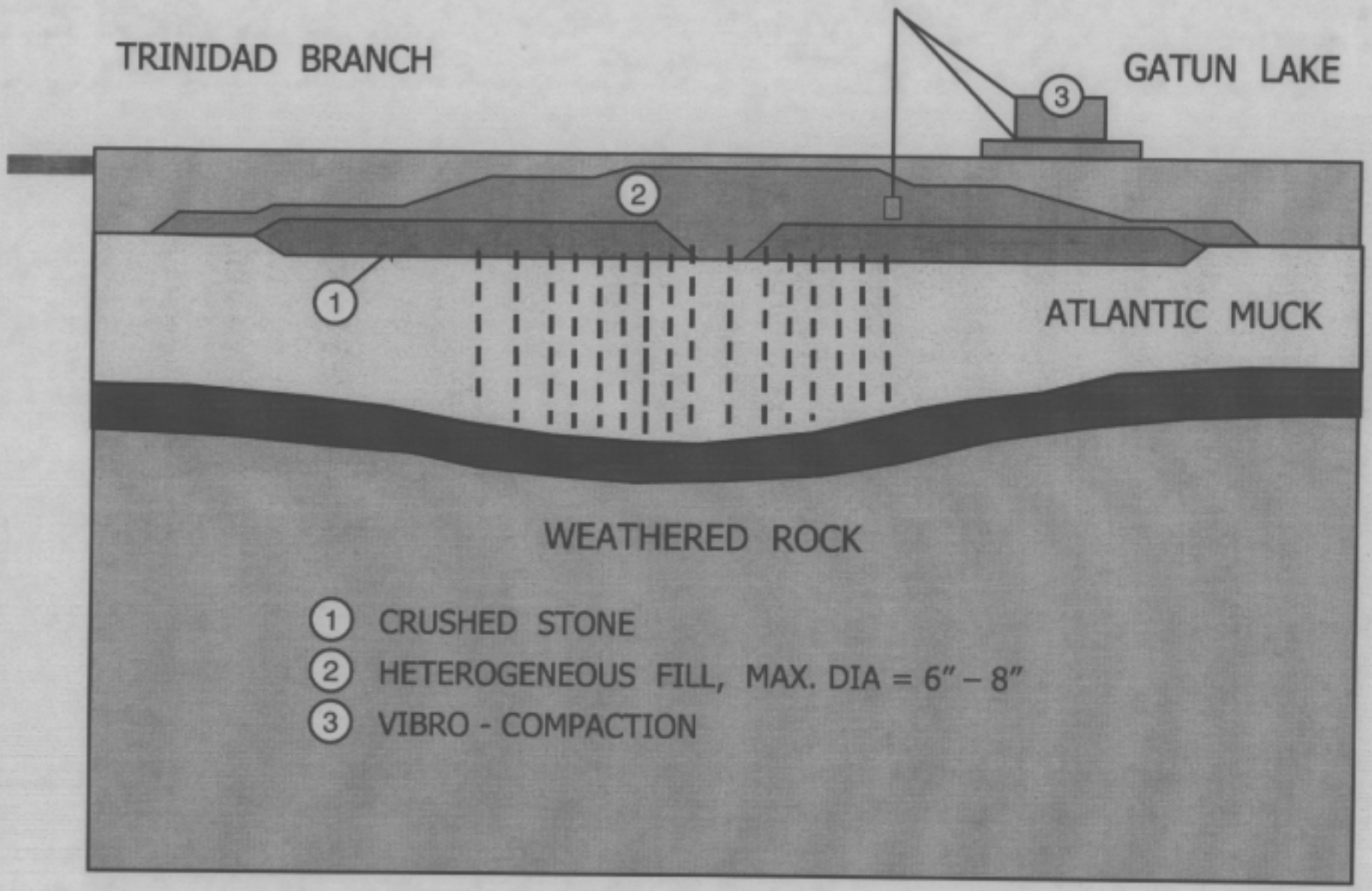
Construction Scheme for Trinidad Dam

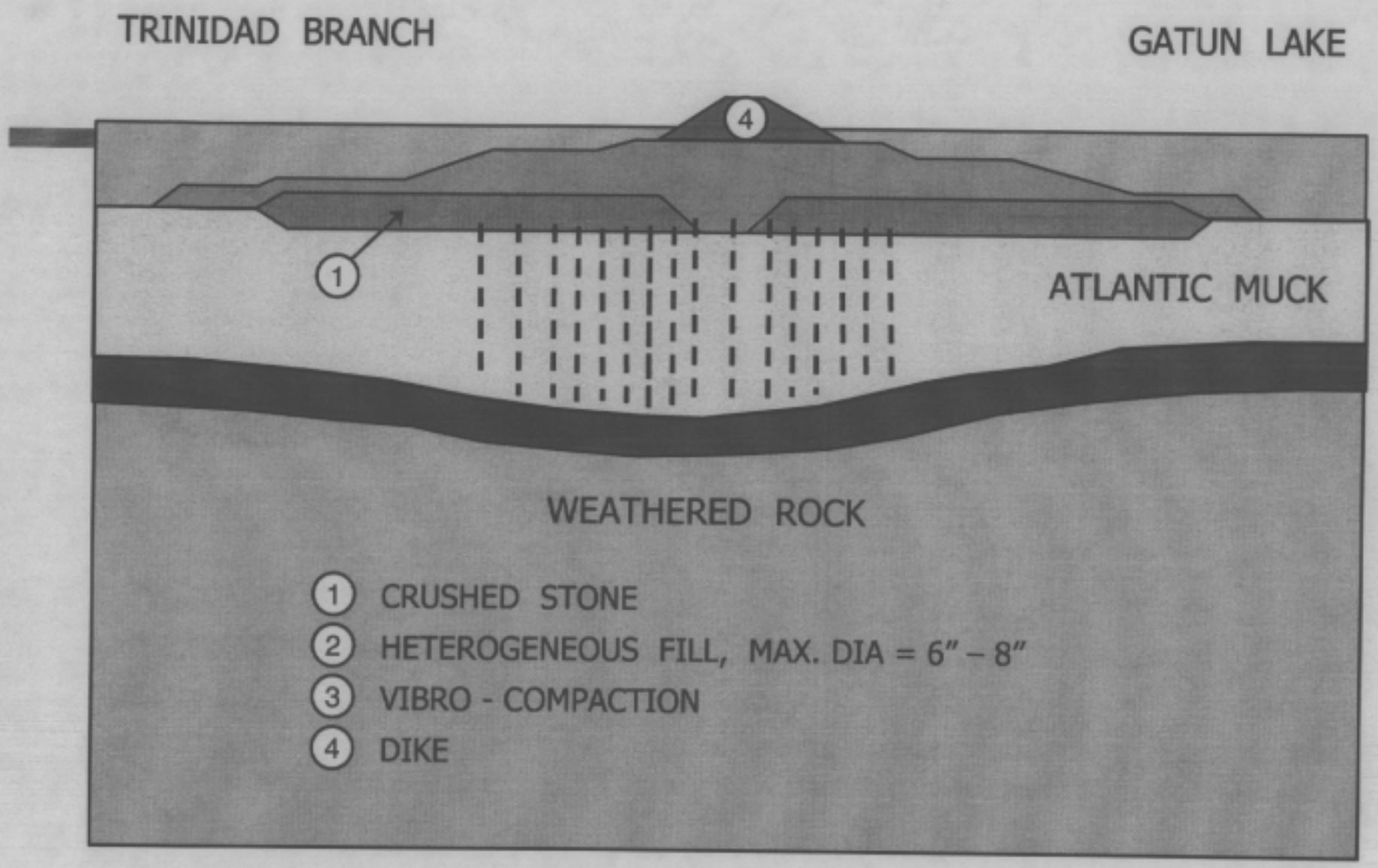

TRINIDAD BRANCH
GATUN LAKE
ATLANTIC MUCK
WEATHERED ROCK

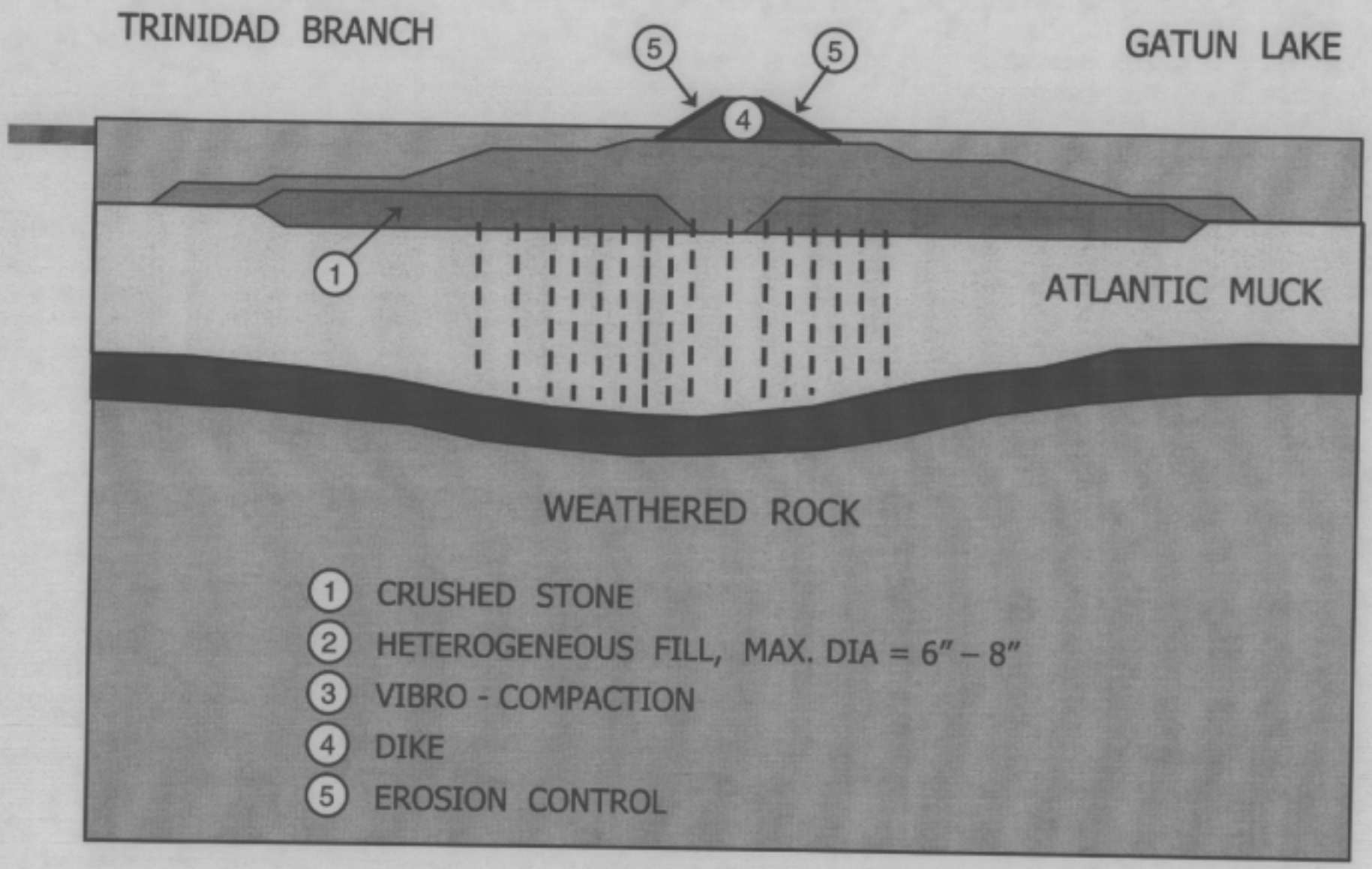

TRINIDAD BRANCH
GATUN LAKE
WICK DRAINS INSTALLATION
15' DREDGED
ATLANTIC MUCK
WEATHERED ROCK

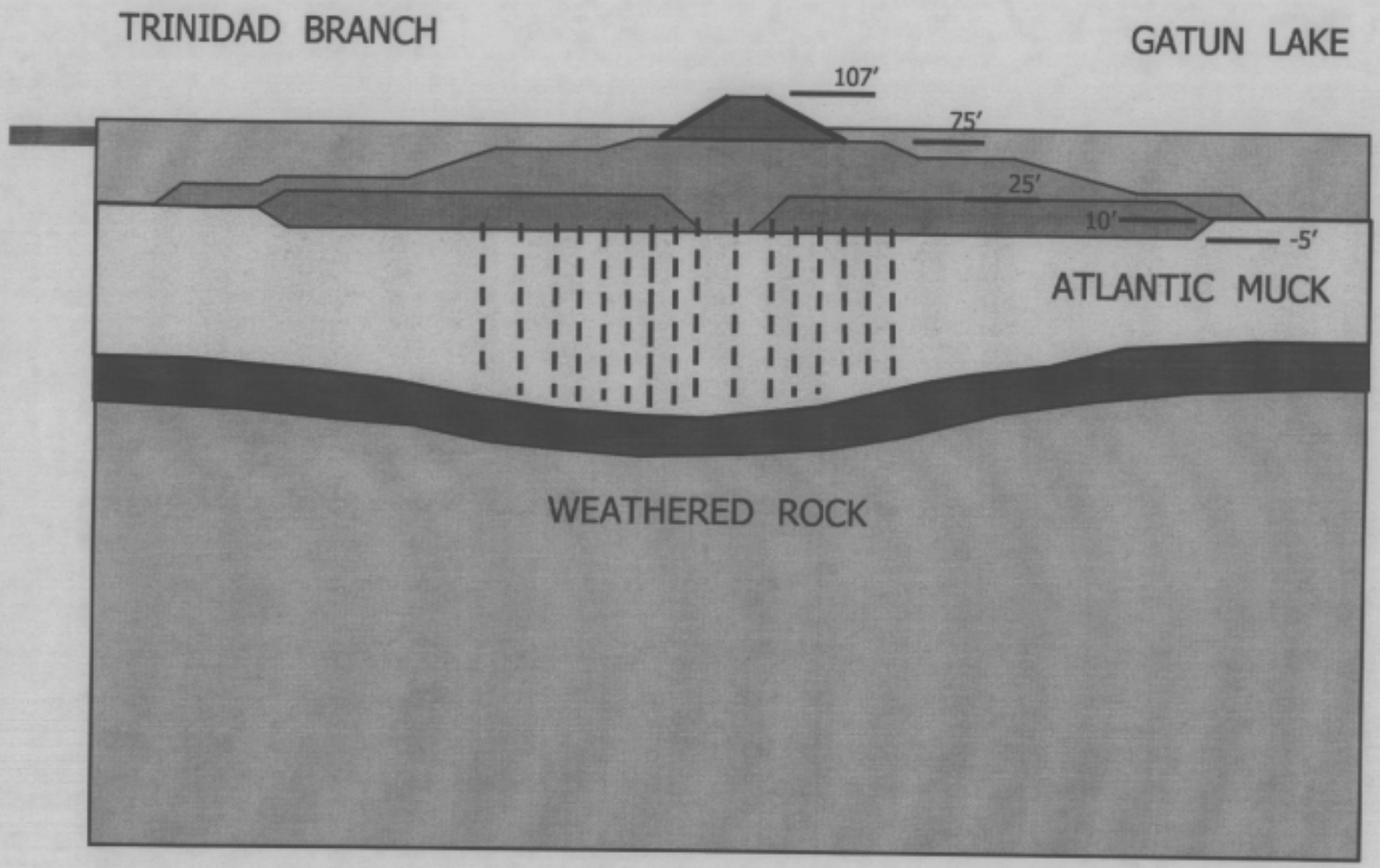

TRINIDAD BRANCH
GATUN LAKE
1
ATLANTIC MUCK
WEATHERED ROCK
1 CRUSHED STONE


TRINIDAD BRANCH
GATUN LAKE
2
1
ATLANTIC MUCK
WEATHERED ROCK
1 CRUSHED STONE
2 HETEROGENEOUS FILL, MAX. DIA = 6" – 8"

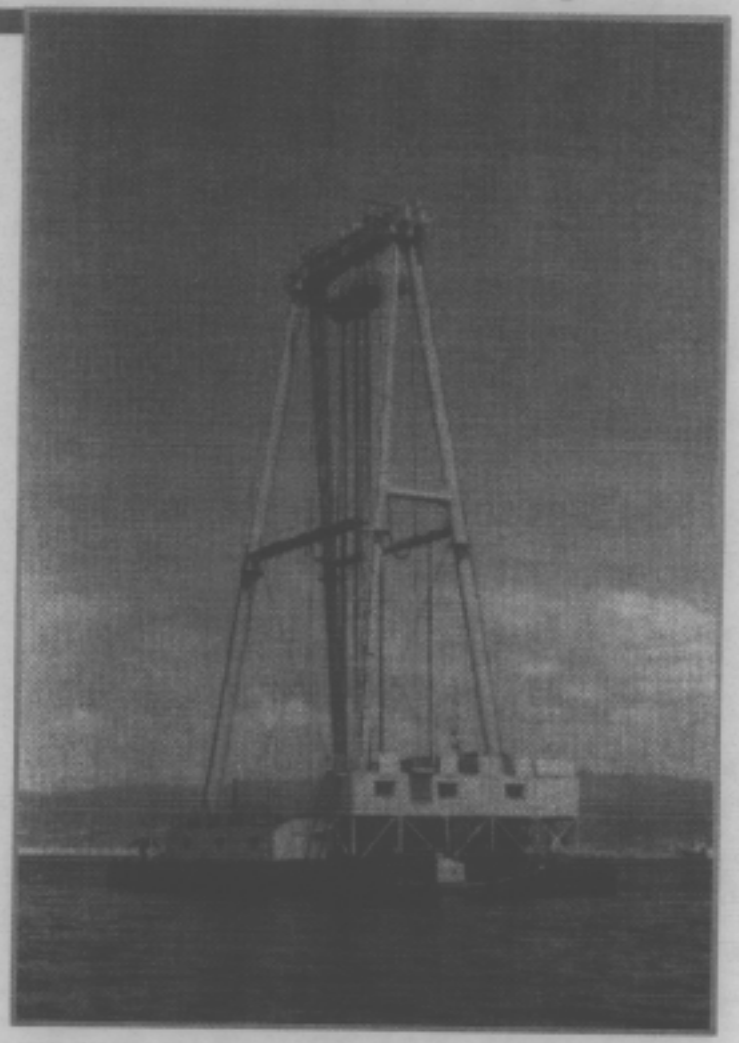

TRINIDAD BRANCH
GATUN LAKE
3
2
1
ATLANTIC MUCK
WEATHERED ROCK
1 CRUSHED STONE
2 HETEROGENEOUS FILL, MAX. DIA = 6" – 8"
3 VIBRO - COMPACTION


TRINIDAD BRANCH
GATUN LAKE
4
1
ATLANTIC MUCK
WEATHERED ROCK
1 CRUSHED STONE
2 HETEROGENEOUS FILL, MAX. DIA = 6" – 8"
3 VIBRO - COMPACTION
4 DIKE


TRINIDAD BRANCH
GATUN LAKE
5
5
4
1
ATLANTIC MUCK
WEATHERED ROCK
1 CRUSHED STONE
2 HETEROGENEOUS FILL, MAX. DIA = 6" – 8"
3 VIBRO - COMPACTION
4 DIKE
5 EROSION CONTROL


TRINIDAD BRANCH
GATUN LAKE
107'
75'
25'
10'
-5'
ATLANTIC MUCK
WEATHERED ROCK

Floating Rig for Installation of Wick Drains from open water



Engineering Properties of the Atlantic Muck

1. Index Properties
2. Stress History and Precompression Stresses
3. Deformation and Compressibility Properties
4. Coefficient of Consolidation and Permeability
5. Shear Strength

ACP

Summary of Index Properties
Atlantic Muck

- Liquid Limit: 12 - 337
- Plastic Limit: 15 – 165
- Plasticity Index: 6 – 194
- Dry Density: 10 – 81 lbs/ft3
- Wet Density 62.4 - 108 lbs/ft3
- Specific Gravity 2.00 – 2.64

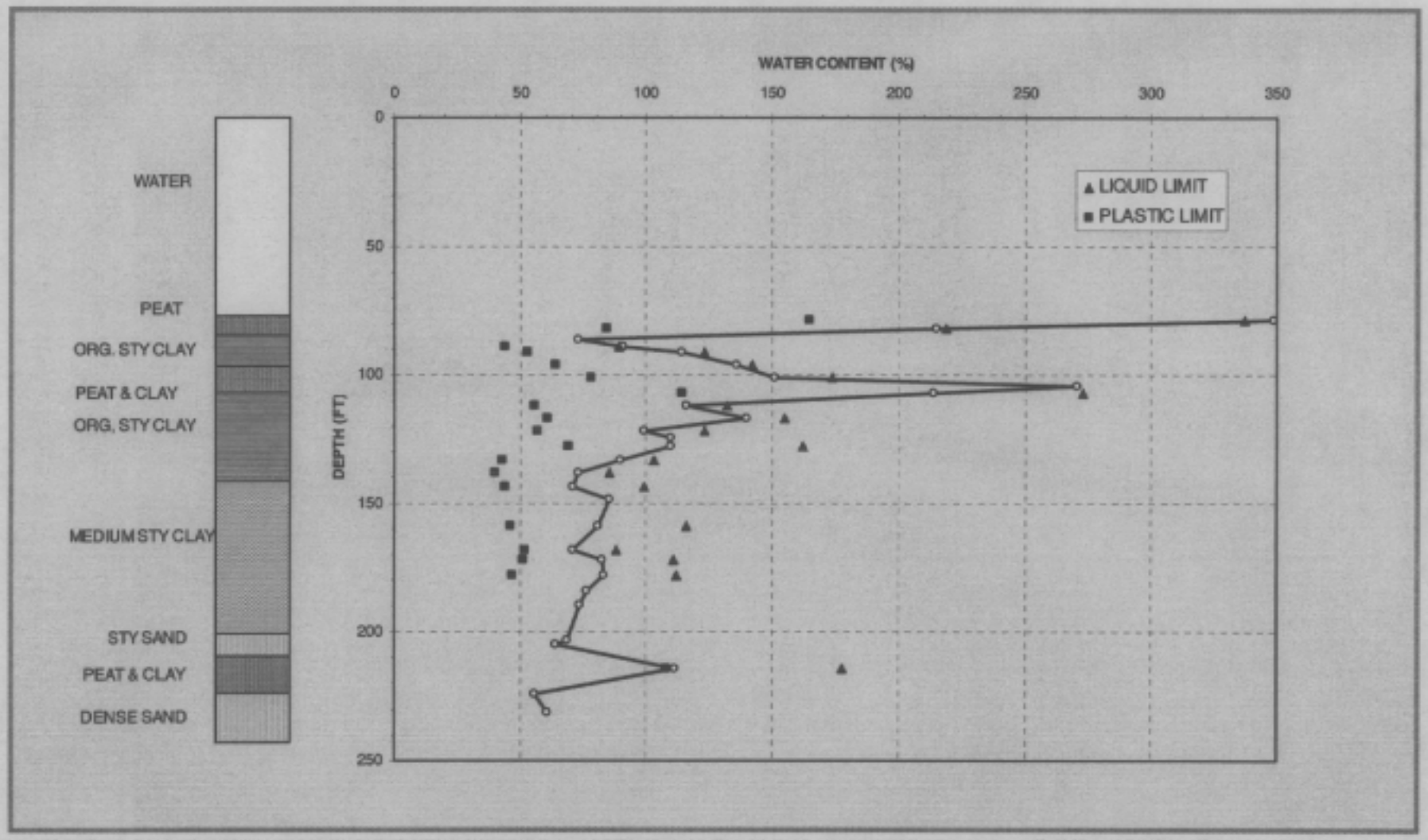
ACP

Index Properties (Trinidad, Borehole A-25)

MATERIAL	DEPTH	SAMPLE	DEPTH	Wn %	LL	LP	IP	IP	γw	γwprom	γd	γdprom
VERY SOFT PEAT	77.2	1	78.5	349.0	337	165	172	153.5	62.4	64.2	10.0	15.0
		2	81.9	215.0	219	84	135		66.0		20.0	
VERY SOFT ORGANIC SILTY CLAY	84	3	86.1	73.2				57.5	94.2	89.3	56.0	48.7
		4	88.6	91.0	89	44	45		93.3		52.0	
		5	91.2	114.5	123	53	70		80.3		38.0	
FIRM PEAT AND SOFT CLAY	96	7	96.2	136.0	142	64	78	111.0	84.2	76.8	19.0	24.5
		9	101.1	151.0	174	78	96		88.4		31.0	
		10	104.2	271.0					64.7		28.0	
		11	106.7	214.0	273	114	159		69.7		20.0	
SOFT TO MEDIUM ORGANIC SILTY CLAY	108	13	111.7	115.9	132	56	76	72.3	82.9	85.7	40.0	45.7
		15	116.9	140.0	155	61	94		79.5		35.0	
		17	121.9	99.0	123	57	66		81.3		42.0	
		18	124.4	110.0					88.1		46.0	
		19	127.9	110.0	162	69	93		85.2		44.0	
		21	133.1	90.0	103	43	60		87.1		55.0	
		23	138.3	73.0	85	40	45		95.6		58.0	
MEDIUM ORGANIC SILTY CLAY	142	25	143.8	71.0	99	44	44	55.0	91.9	93.8	53.0	55.0
		27	148.5	85.5					91.1		50.0	
		31	158.9	80.9	116	46	70		93.4		52.0	
		34	168.4	70.9	88	52	36		95.6		58.0	
		35	171.9	82.6	111	51	60		95.8		57.0	
		51	178.3	83.1	112	47	65		93.9		55.0	
		53	184.3	76.6					93.7		57.0	
		55	189.8	73.7					94.6		58.0	
MEDIUM SILTY FINE SAND	201	59	203.3	68.6					95.5	95.5		63.0
		60	205.3	63.9					95.5		63.0	
FIRM PEAT AND MEDIUM ORGANIC SILTY CLAY	210	63	214.3	111.2	178	108	70	70.0	82.8	82.8	42.0	42.0
MEDIUM TO DENSE SILTY FINE TO MEDIUM SAND	223	67	224.3	55.9					92.5	92.5		62.0
		69	231.5	60.8					92.5		62.0	
SILTSTONE	243											

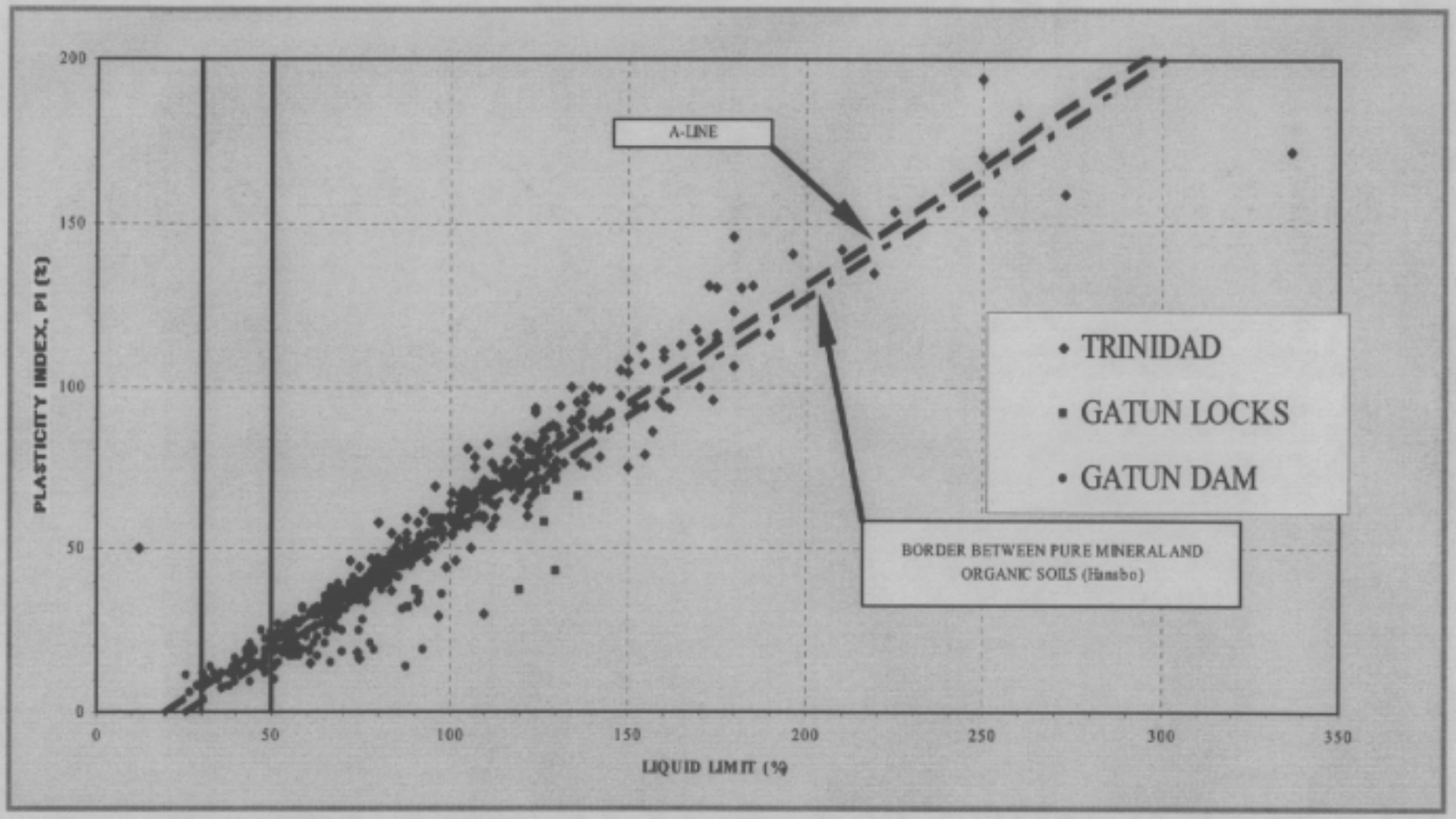
ACP

Atterberg Limits (Trinidad, Borehole A-25)



ACP

Plasticity Chart



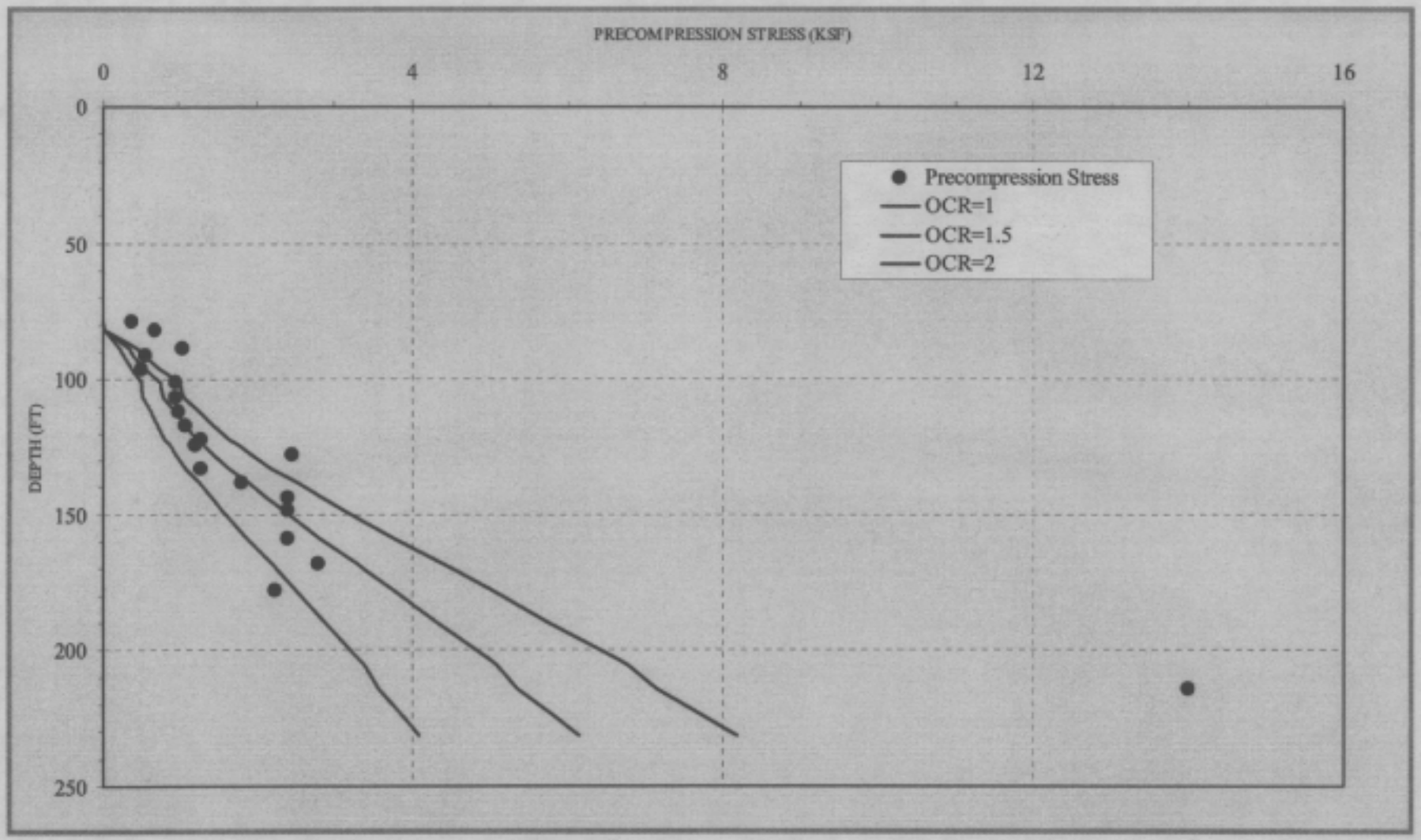
ACP

Stress History and Precompression Stresses

MATERIAL	DEPTH	SAMPLE	DEPTH	σp'	σt	σo' (kips/ft2)	OCR
VERY SOFT PEAT	77.2	1	78.5	0.380	4.8984	0.000	
		2	81.9	0.680	5.1228	0.012	55.556
VERY SOFT ORGANIC SILTY CLAY	84	3	86.1		5.51844	0.146	
		4	88.6	1.040	5.75169	0.223	4.663
		5	91.2	0.560	5.96047	0.270	2.077
FIRM PEAT AND SOFT CLAY	96	7	96.2	0.500	6.38147	0.379	1.321
		9	101.1	0.960	6.81463	0.506	1.897
		10	104.2		7.0152	0.513	
		11	106.7	0.960	7.18945	0.531	1.807
SOFT TO MEDIUM ORGANIC SILTY CLAY	108	13	111.7	1.000	7.60395	0.634	1.578
		15	116.9	1.080	8.01735	0.723	1.494
		17	121.9	1.280	8.42385	0.817	1.566
		18	124.4	1.200	8.6441	0.882	
		19	127.9	2.460	8.9423	0.961	2.559
		21	133.1	1.280	9.39522	1.090	1.175
		23	138.3	1.800	9.89234	1.262	1.426
MEDIUM ORGANIC SILTY CLAY	142	25	143.8	2.400	10.39779	1.425	1.685
		27	148.5	2.400	10.82596	1.560	
		31	158.9	2.400	11.79732	1.882	1.275
		34	168.4	2.800	12.70552	2.197	1.274
		35	171.9		13.04082	2.314	
		51	178.3	2.240	13.64178	2.516	0.890
		53	184.3		14.20398	2.704	
		55	189.8		14.72428	2.881	
MEDIUM SILTY FINE SAND	201	59	203.3		16.01353	3.328	
		60	205.3		16.20453	3.394	
FIRM PEAT AND MEDIUM ORGANIC SILTY CLAY	210	63	214.3	14.000	16.94973	3.577	3.913
MEDIUM TO DENSE SILTY FINE TO MEDIUM SAND	223	67	224.3		17.87473	3.878	
		69	231.5		18.54073	4.095	
SILTSTONE	243						

ACP

Stress History and Precompression Stresses



ACP

Deformation and Compressibility Properties

Definitions

$$1\text{-}\ E_{OED}\,(\text{constrained modulus}) = \frac{1}{m_v} = \frac{(1+e)\sigma_i'}{0.434C_c} = \frac{\sigma_i'}{0.434CR}$$

$$\text{and } E = \frac{(1-2\nu)(1+\nu)}{(1-\nu)} * E_{OED}$$

$$2\text{-}\ Eu = 19.3N^{0.63} * Pa \quad (\text{undrained})\ (N = \text{SPT})$$

$$E = \frac{2*(1+\nu)}{3} * E_u$$

$$3 - E = 5N * Pa \quad (N = \text{SPT})$$

$$4.\ E = E_o\left(\frac{\sigma}{Pa}\right)^{\alpha} \quad (\text{MPa})$$

$$5\text{-}\ Eu = 100Su$$

	E_o	α
Fine Sands	15	0.75
Coarse Sands	25	0.70
Well Graded Sands	20	0.70
Organic Silt & Clay	0.5	1.00
High Plasticity Clay	0.6	1.00
Medium to High Plasticity Silts	3	0.90

ACP

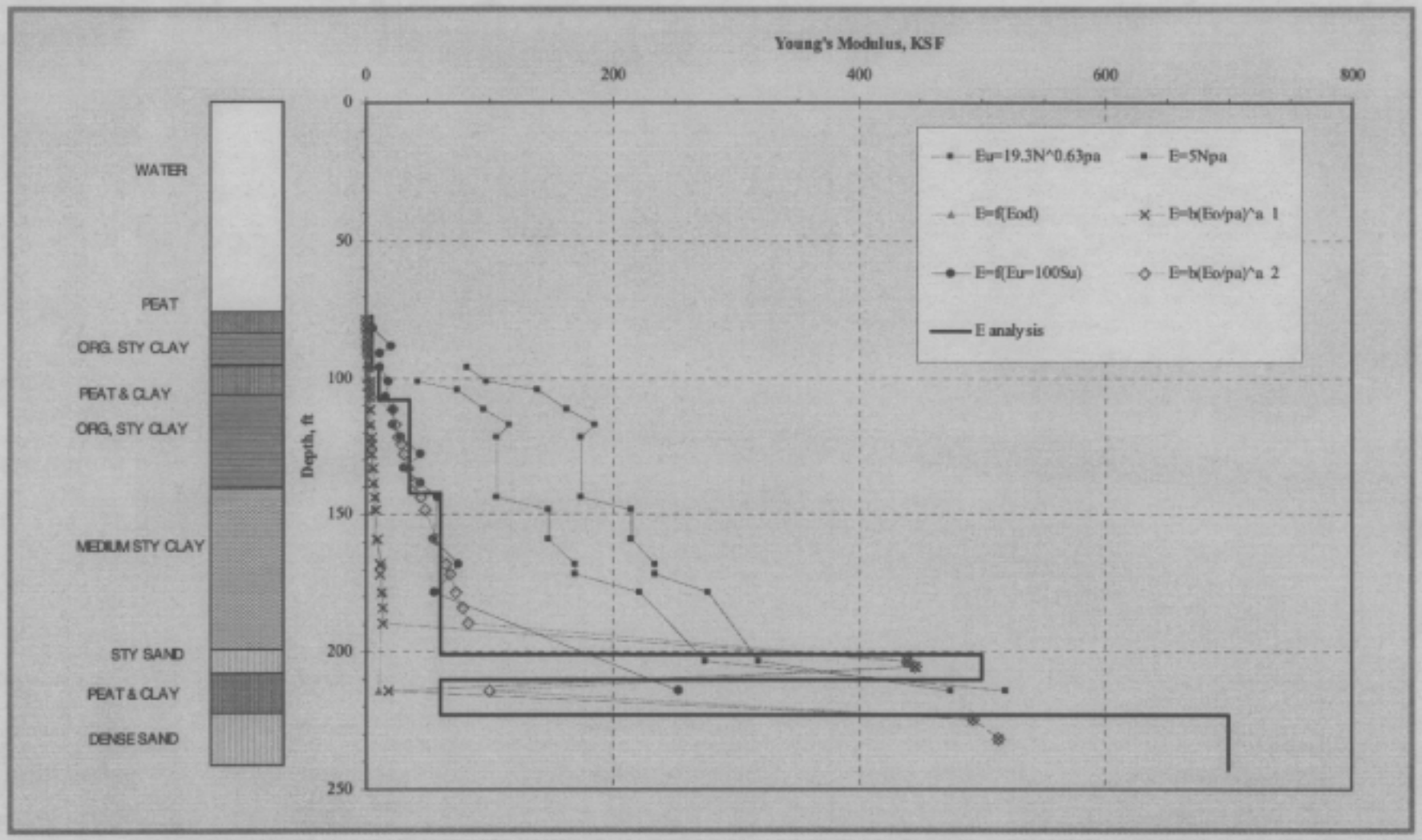
Deformation Modulus, E

MATERIAL	DEPTH	SAMPLE	DEPTH	Blows/foot	Eu=19.3N^0.63pa	E=f(Eu)	E=5Npa	Eod	E=f(Eod)	E=b(Eo/pa)^a 1	E=b(Eo/pa)^a 2	Eu=100Su	E=f(Eu=100Su)	Emax	Emin
VERY SOFT PEAT	77.2	1	78.5					0.00	0.00	0.00	0.00			6.00	0.03
		2	81.9					0.08	0.05	0.07	0.07	6.7	6.0		
VERY SOFT ORGANIC SILTY CLAY	84	3	86.1							0.72	0.79			16.00	1.05
		4	88.6					2.43	1.51	1.10	1.21	22.7	20.5		
		5	91.2	0				2.82	1.76	1.33	1.46	12.8	11.5		
FIRM PEAT AND SOFT CLAY	96	7	96.2	3	81.6	73.5		3.85	2.40	2.24	2.05	12.2	11.0	95.60	2.29
		9	101.1	4	97.8	88.1	42.3	3.07	1.91	2.99	2.75	20.5	18.4		
		10	104.2	7	139.2	125.3	74.1			3.04	2.78				
		11	106.7					4.11	2.56	3.14	2.88	17.7	16.0		
SOFT TO MEDIUM ORGANIC SILTY CLAY	108	13	111.7	9	163.1	146.8	95.3	5.98	3.72	3.1	21.16	23.7	21.3	156.73	4.49
		15	116.9	11	185.1	166.6	116.4	6.92	4.31	3.6	23.82	24.3	21.9		
		17	121.9	10	174.3	156.8	105.8	6.74	4.20	4.0	26.60	31.5	28.4		
		18	124.4					7.52	4.69	4.3	28.47				
		19	127.9					7.33	4.57	4.7	30.78	49.9	44.9		
		21	133.1					8.05	5.02	5.4	34.46	34.2	30.8		
		23	138.3					11.85	7.38	6.2	39.34	49.9	44.9		
MEDIUM ORGANIC SILTY CLAY	142	25	143.8	10	174.3	156.8	105.8	13.20	8.22	7.03	43.86	64.7	58.2	202.79	9.94
		27	148.5	14	215.4	193.9	148.2	9.93	6.19	7.69	47.58				
		31	158.9	14	215.4	193.9	148.2	12.47	7.77	9.28	56.35	60.6	54.5		
		34	168.4	16	234.3	210.9	169.3	21.41	13.34	10.84	64.78	83.8	75.4		
		36	171.9	16	234.3	210.9	169.3			11.41	67.88				
		51	178.3	21	278.1	250.3	222.3	22.78	14.19	12.41	73.17	62.0	55.8		
		53	184.3							13.33	78.07				
		55	189.8							14.21	82.66				
MEDIUM SILTY FINE SAND	201	59	203.3	26	318.2	265.1	275.2			439.70	439.70			442.98	265.15
		60	205.3							446.25	446.25				
FIRM PEAT AND MEDIUM ORGANIC SILTY CLAY	210	63	214.3	49	474.3	426.9	518.6	15.96	9.94	17.64	100.45	282.5	254.3	518.62	9.94
MEDIUM TO DENSE SILTY FINE TO MEDIUM SAND	223	67	224.3							493.23	493.23			503.50	503.50
		69	231.5							513.76	513.76				
SILTSTONE	243														

E in ksf

ACP

E assumed for Analysis



ACP

Compression Index, Cc, Compression Ratio, CR and Cam-Clay λ, κ, Λ

Definitions

$$1-CR = \frac{C_c}{(1+e)} = Compression\ Ratio$$

$$\lambda = \frac{Cc}{2.3} \qquad k = \frac{Cr}{2.3} \qquad \Lambda = \frac{\lambda-\kappa}{\lambda}$$ (Cam-Clay)

$$\lambda^* = \frac{\lambda}{1+e} \qquad k^* = \frac{k}{1+e}$$ (Plaxis)

$$\lambda^* = \frac{C_c}{2.3(1+e)} \qquad k^* \approx 1.3\frac{(1-\nu_{ur})C_r}{(1+\nu_{ur})(1+e)} \approx \frac{C_r}{2.3(1+e)} \approx \frac{1}{3}\,to\,\frac{1}{7}\lambda^*$$

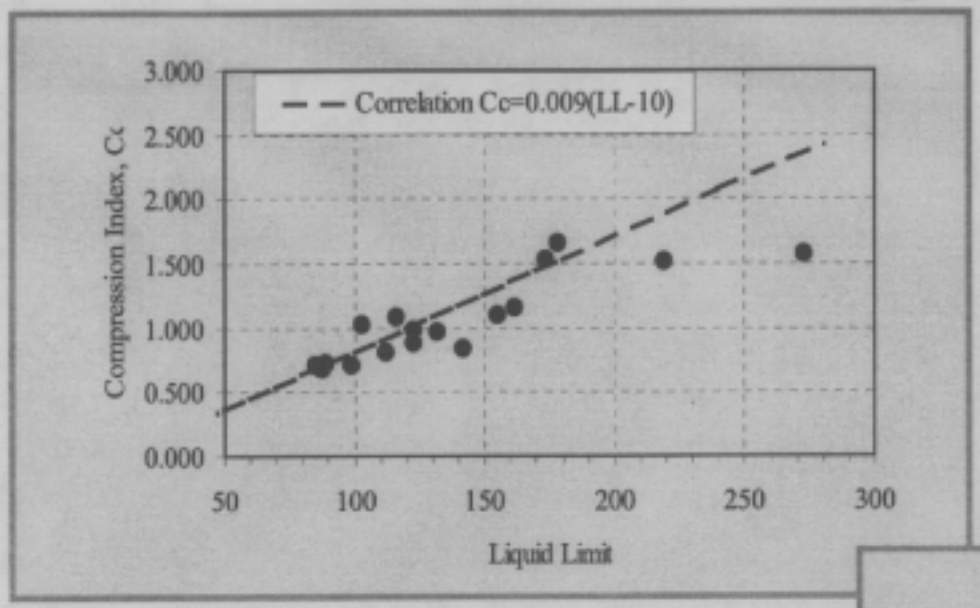
ACP

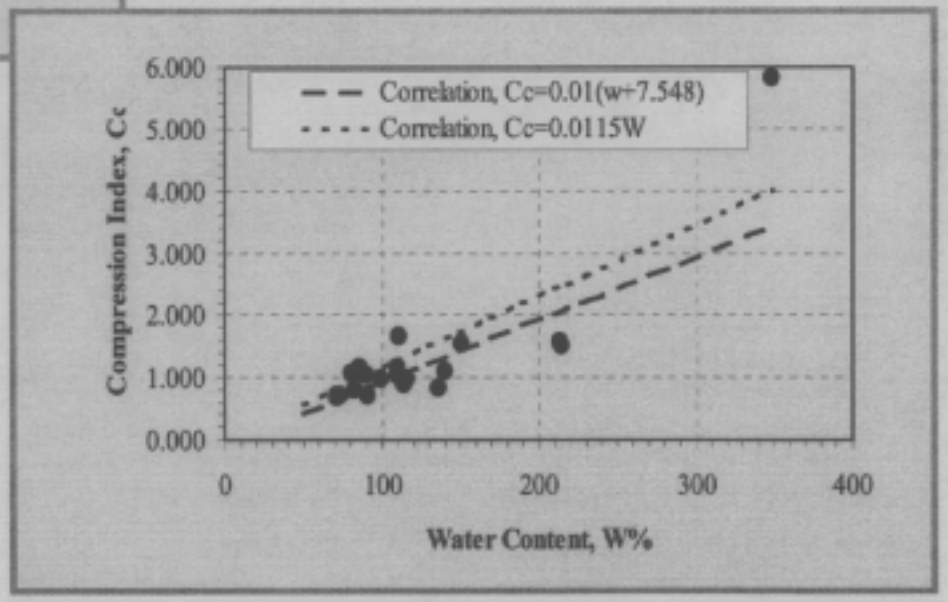
Compression Index, Cc, Compression Ratio, CR and Cam-Clay λ, κ, Λ

MATERIAL	DEPTH	SAMPLE	DEPTH	eo = 1 GS*Wn	eo aver.	CR	CR aver	Cc=CR/(1+e)	Cc Average	λ	k	Λ	λ*	k*	C_α = 0.05Cc	μ*
VERY SOFT PEAT	77.2	1	78.5	5.479	4.427	0.9006	0.624	5.835	3.676	1.5983	0.3197	0.8000	0.2945	0.0589	0.1838	0.0147
		2	81.9	3.376		0.3467		1.517								
VERY SOFT ORGANIC SILTY CLAY	84	3	86.1	1.932	2.453		0.216		0.802	0.3488	0.0696	0.8000	0.1010	0.0202	0.0401	0.0051
		4	88.6	2.402		0.2113		0.719								
		5	91.2	3.023		0.2201		0.885								
FIRM PEAT AND SOFT CLAY	96	7	96.2	2.720	3.860	0.2263	0.301	0.842	1.312	0.5703	0.1141	0.8000	0.1173	0.0235	0.0656	0.0059
		9	101.1	3.020		0.379		1.524								
		10	104.2	5.420												
		11	106.7	4.280		0.2973		1.570								
SOFT TO MEDIUM ORGANIC SILTY CLAY	108	13	111.7	2.967	2.699	0.2439	0.270	0.968	0.995	0.4327	0.0865	0.8000	0.1170	0.0234	0.0496	0.0058
		15	116.9	3.584		0.2401		1.101								
		17	121.9	2.534		0.2791		0.986								
		18	124.4	2.816		0.2696		1.029								
		19	127.9	2.816		0.3016		1.151								
		21	133.1	2.304		0.3114		1.029								
		23	138.3	1.869		0.245		0.703								
MEDIUM ORGANIC SILTY CLAY	142	25	143.8	1.846	2.029	0.2483	0.289	0.707	0.884	0.3846	0.0769	0.8000	0.1270	0.0254	0.0442	0.0063
		27	148.5	2.223		0.3613		1.164								
		31	158.9	2.103		0.3471		1.077								
		34	168.4	1.843		0.2361		0.671								
		35	171.9	2.148												
		51	178.3	2.161		0.254		0.803								
		53	184.3	1.992												
		55	189.8	1.916												
MEDIUM SILTY FINE SAND	201	59	203.3	1.818	1.756											
		60	205.3	1.693												
FIRM PEAT AND MEDIUM ORGANIC SILTY CLAY	210	63	214.3	2.224	2.224	0.5159	0.516	1.663	1.663	0.7232	0.1446	0.8000	0.2243	0.0449	0.0832	0.0112
			223													
MEDIUM TO DENSE SILTY FINE TO MEDIUM SAND	223	67	224.3	1.481	1.546											
		69	231.5	1.611												
SILTSTONE	243															

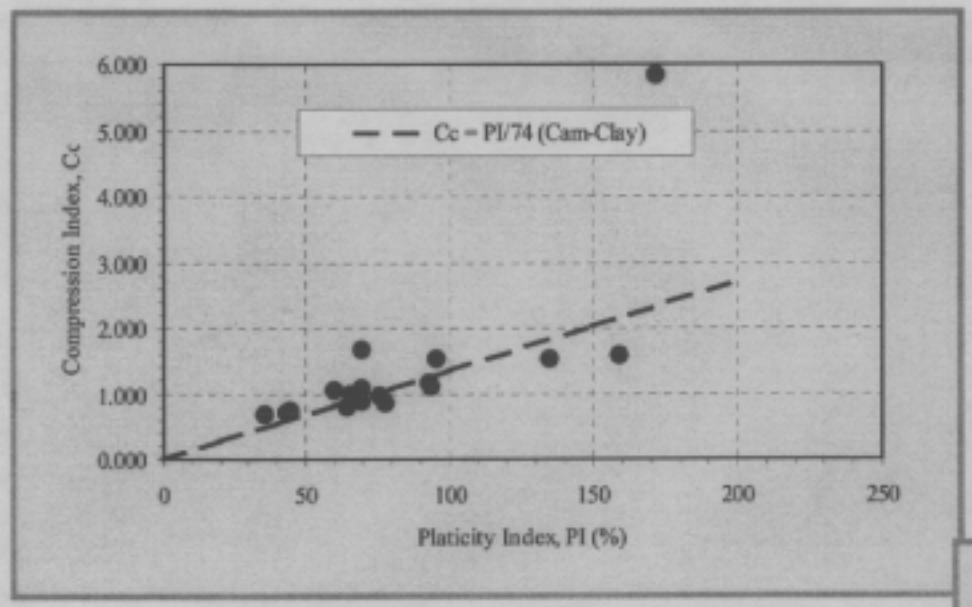
ACP

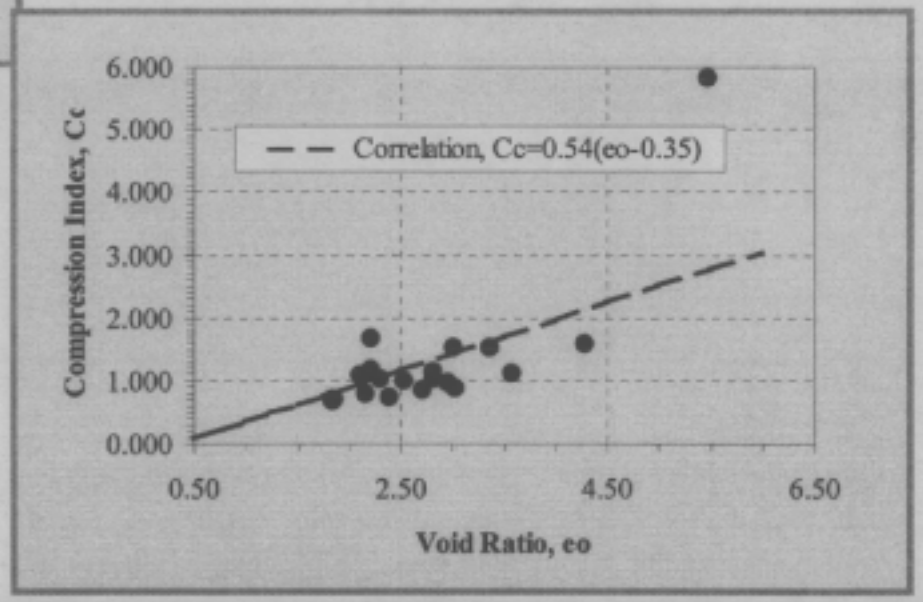
Correlations - Compression Index, Cc





Correlations - Compression Index, Cc





ACP

Coefficient of Consolidation and Permeability

Definitions

$$kv = \frac{0.434 CRC_v \gamma_w}{\sigma_i'} = \frac{0.434 C_c C_v \gamma_w}{(1+e)\sigma_i'} = Permeability$$

$$\text{where: } CR = \frac{C_c}{(1+e)}$$

$$K_{equivalent} = \frac{1}{\sum_{j=1}^{n} \frac{H_j}{H} * \frac{1}{K_j}}$$

$$Cv_{equiv} = \frac{\left[\sum_{i=1}^{n} h_i\right]^2}{\left[\sum_{i=1}^{n} \frac{h_i}{\sqrt{Cv_i}}\right]^2} = Equivalent\ Coefficient\ of\ Consolidation$$

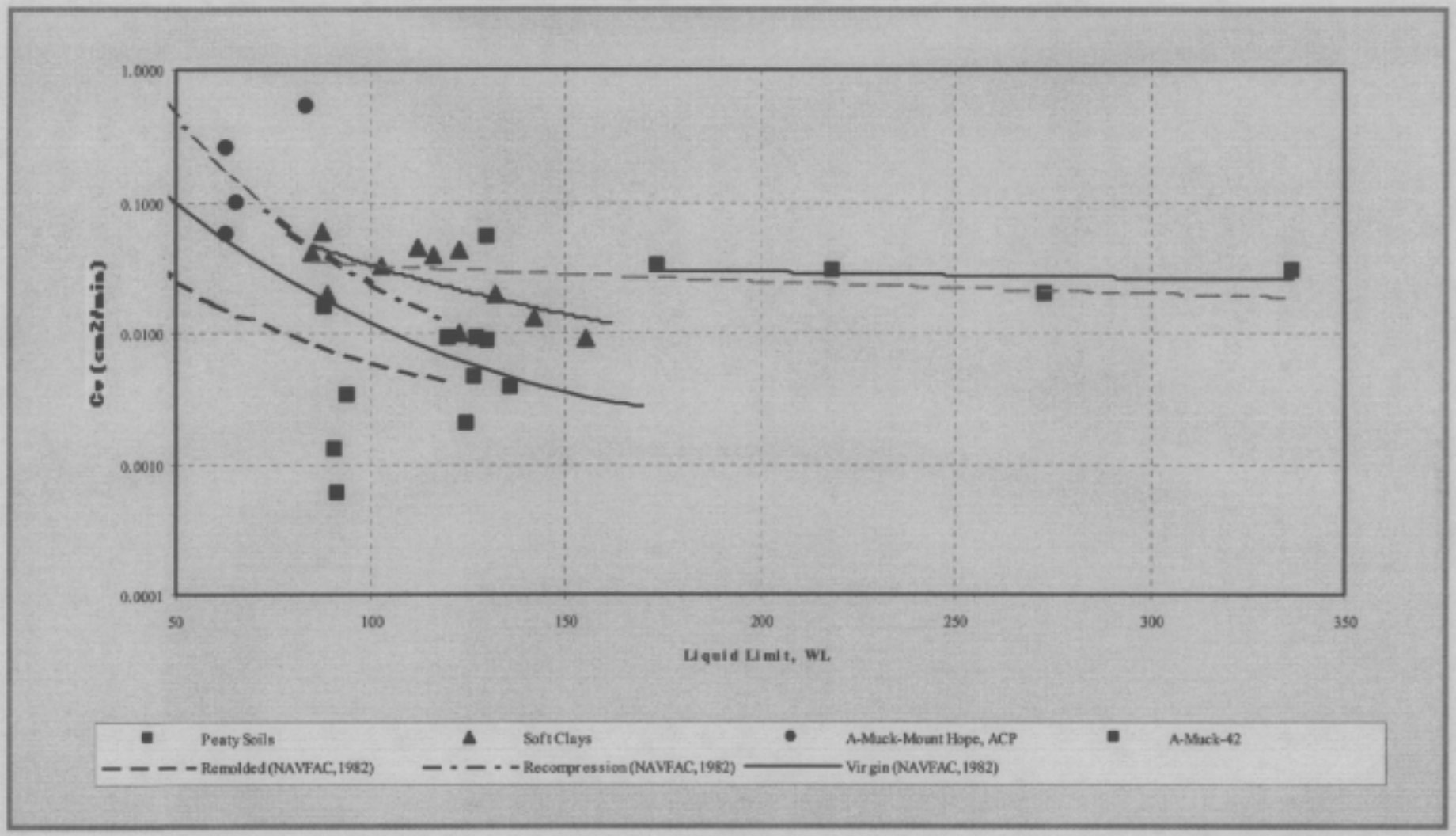
ACP

Coefficient of Consolidation and Permeability

MATERIAL	DEPTH	SAMPLE	DEPTH	CV (cm2/min)	Kv=f(Cv,Cc) (m/s)	Hi/K	Hi	Kv equiv (m/s)	Kv (m/s)	Kh	Kv (ft/dia)	Kh
VERY SOFT PEAT	77.2	1	78.5	0.03	3.0797E-05	4.221E+04	1.3	1.720E-07	1.71967E-07	1.71967E-06	4.875E-02	4.875E-01
		2	81.9	0.03	1.2459E-07	2.729E+07	3.4					
VERY SOFT ORGANIC SILTY CLAY	84	3	86.1					1.677E-09	1.67699E-09	1.67699E-08	4.754E-04	4.754E-03
		4	88.6	0.02	2.8059E-09	8.910E+08	2.5					
		5	91.2	0.01	1.2092E-09	2.150E+09	2.6					
FIRM PEAT AND SOFT CLAY	96	7	96.2	0.013	1.1511E-09	1.738E+08	0.2	2.482E-09	2.4822E-09	2.4822E-08	7.036E-04	7.036E-03
		9	101.1	0.032	3.5508E-09	1.380E+09	4.9					
		10	104.2									
		11	106.7	0.02	1.6577E-09	1.508E+09	2.5					
SOFT TO MEDIUM ORGANIC SILTY CLAY	108	13	111.7	0.02	1.1401E-09	3.245E+09	3.7	9.913E-10	9.91278E-10	9.91278E-09	2.810E-04	2.810E-03
		15	116.9	0.009	4.4293E-10	1.174E+10	5.2					
		17	121.9	0.044	2.2262E-09	2.246E+09	5.0					
		18	124.4	0.033	1.4953E-09	1.672E+09	2.5					
		19	127.9									
		21	133.1	0.033	1.3971E-09	3.722E+09	5.2					
		23	138.3	0.041	1.1789E-09	4.411E+09	5.2					
MEDIUM ORGANIC SILTY CLAY	142	25	143.8					9.571E-10	9.57104E-10	9.57104E-09	2.713E-04	2.713E-03
		27	148.5	0.04	1.373E-09	3.423E+09	4.7					
		31	158.9	0.04	1.0931E-09	9.514E+09	10.4					
		34	168.4	0.06	9.5524E-10	9.945E+09	9.5					
		35	171.9									
		51	178.3	0.045	6.7318E-10	9.507E+09	6.4					
		53	184.3									
		55	189.8									
MEDIUM SILTY FINE SAND	201	59	203.3						1.00E-06	1.000E-05	2.835E-01	2.835E+00
		60	205.3									
FIRM PEAT AND MEDIUM ORGANIC SILTY CLAY	210	63	214.3	0.0303	6.4747E-10			6.475E-10	6.47466E-10	6.475E-09	1.835E-04	1.835E-03
MEDIUM TO DENSE SILTY FINE TO MEDIUM SAND	223	67	224.3						1.00E-06	1.000E-05	2.835E-01	2.835E+00
		69	231.5									
SILTSTONE	243											

ACP

Coefficient of Consolidation Correlations



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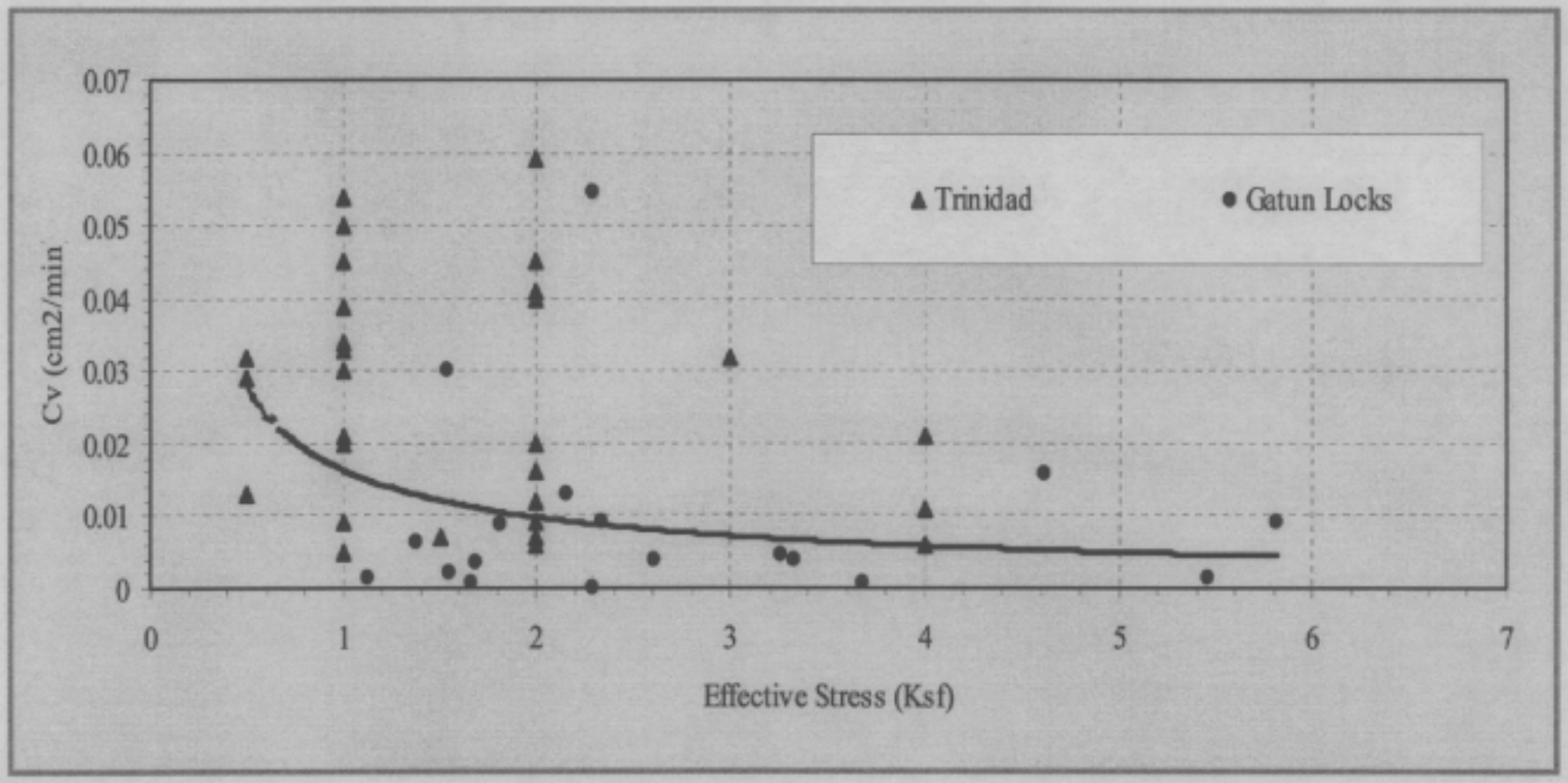
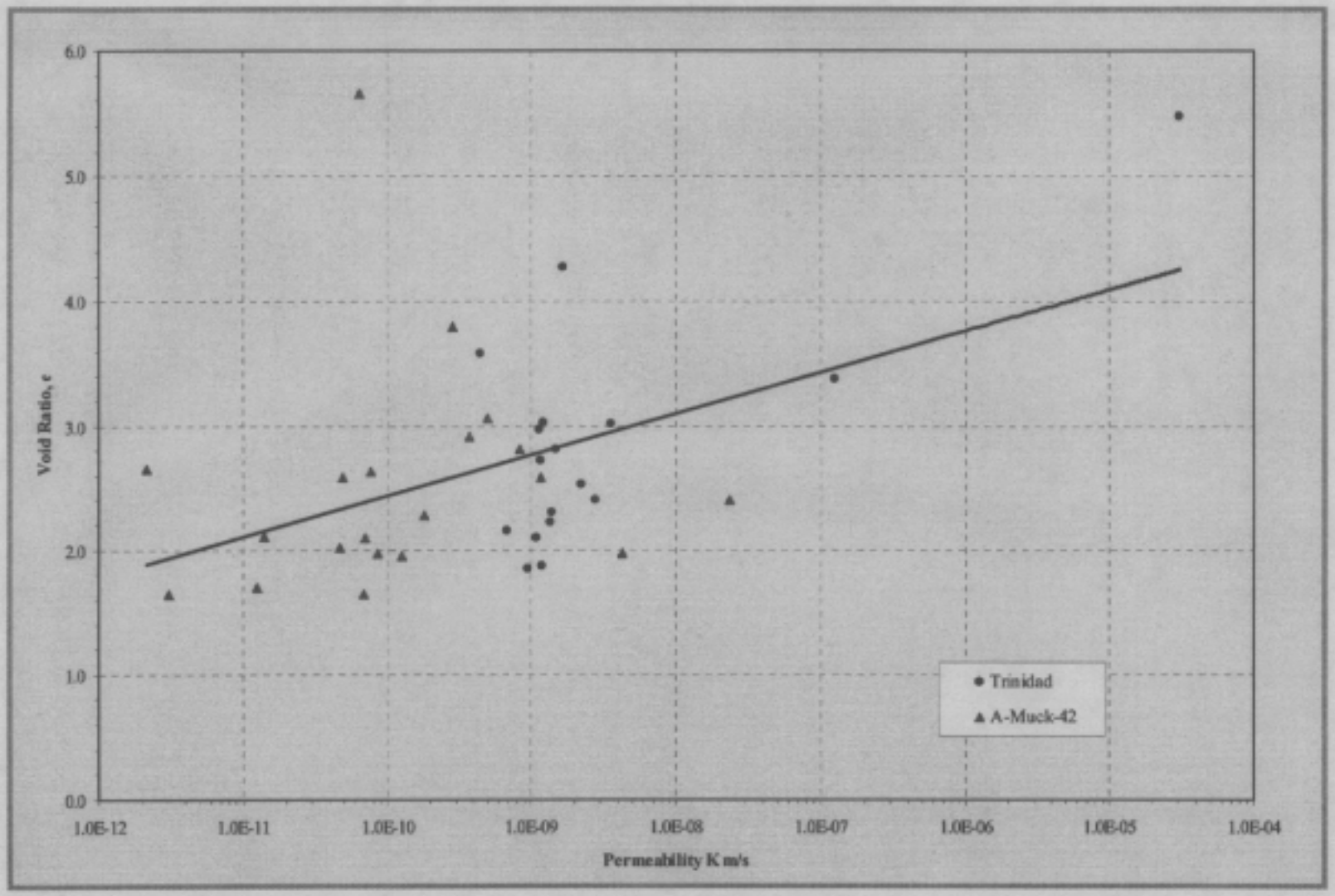
Coefficient of Consolidation vs. Stress



ACP

Permeability vs. Void Ratio



ACP

Cv equivalent

MATERIAL	DEPTH	SAMPLE	DEPTH	DEPTH2	H (FT)	CV (cm2/min)	CV (ft2/min)	H/(Cv)^0.5
VERY SOFT PEAT	77.2	1	78.5	77.2	3	0.03	3.23E-05	5.28E+02
		2	81.9	80.2	5.05	0.03	3.23E-05	8.89E+02
		4	88.6	85.25	4.65	0.02	2.15E-05	1.00E+03
		5	91.2	89.9	3.8	0.01	1.08E-05	1.16E+03
FIRM PEAT AND SOFT CLAY	96	7	96.2	93.7	4.95	0.013	1.40E-05	1.32E+03
		9	101.1	98.65	5.25	0.032	3.44E-05	8.95E+02
		11	106.7	103.9	5.3	0.02	2.15E-05	1.14E+03
SOFT TO MEDIUM ORGANIC SILTY CLAY	108	13	111.7	109.2	5.1	0.02	2.15E-05	1.10E+03
		15	116.9	114.3	5.1	0.009	9.69E-06	1.64E+03
		17	121.9	119.4	3.75	0.044	4.74E-05	5.45E+02
		18	124.4	123.15	5.6	0.033	3.55E-05	9.40E+02
		21	133.1	128.75	6.95	0.033	3.55E-05	1.17E+03
		23	138.3	135.7	7.7	0.041	4.41E-05	1.16E+03
		27	148.5	143.4	10.3	0.04	4.31E-05	1.57E+03
		31	158.9	153.7	9.95	0.04	4.31E-05	1.52E+03
		34	168.4	163.65	9.7	0.06	6.46E-05	1.21E+03
		51	178.3	173.35	27.65	0.045	4.84E-05	3.97E+03
MEDIUM SILTY FINE SAND	201	59	203.3	201				
		60	205.3	210				
FIRM PEAT AND MEDIUM ORGANIC SILTY CLAY	210	63	214.3	210	13	0.0303	3.26146E-05	2276.34
MEDIUM TO DENSE SILTY FINE TO MEDIUM SAND	223	67	224.3	223				
		69	231.5					
SILTSTONE	243				136.8			24026.92
				H^2=	18714.24		(H/(Cv)^0.5)^2	577292806.80
							Cv eq (ft2/min)	3.24E-05
							Cv eq (cm2/min)	0.030
							Cv eq (ft2/year)	17.039

ACP

Field Estimation of the Compression Index and Coefficient of Consolidation

Feb 14, 2001

by Manuel Barrelier
and Fernando Guerra

ACP

Estimates are based on settlement Measurements of the Atlantic Muck at the South Approach Wall of the Gatún Locks

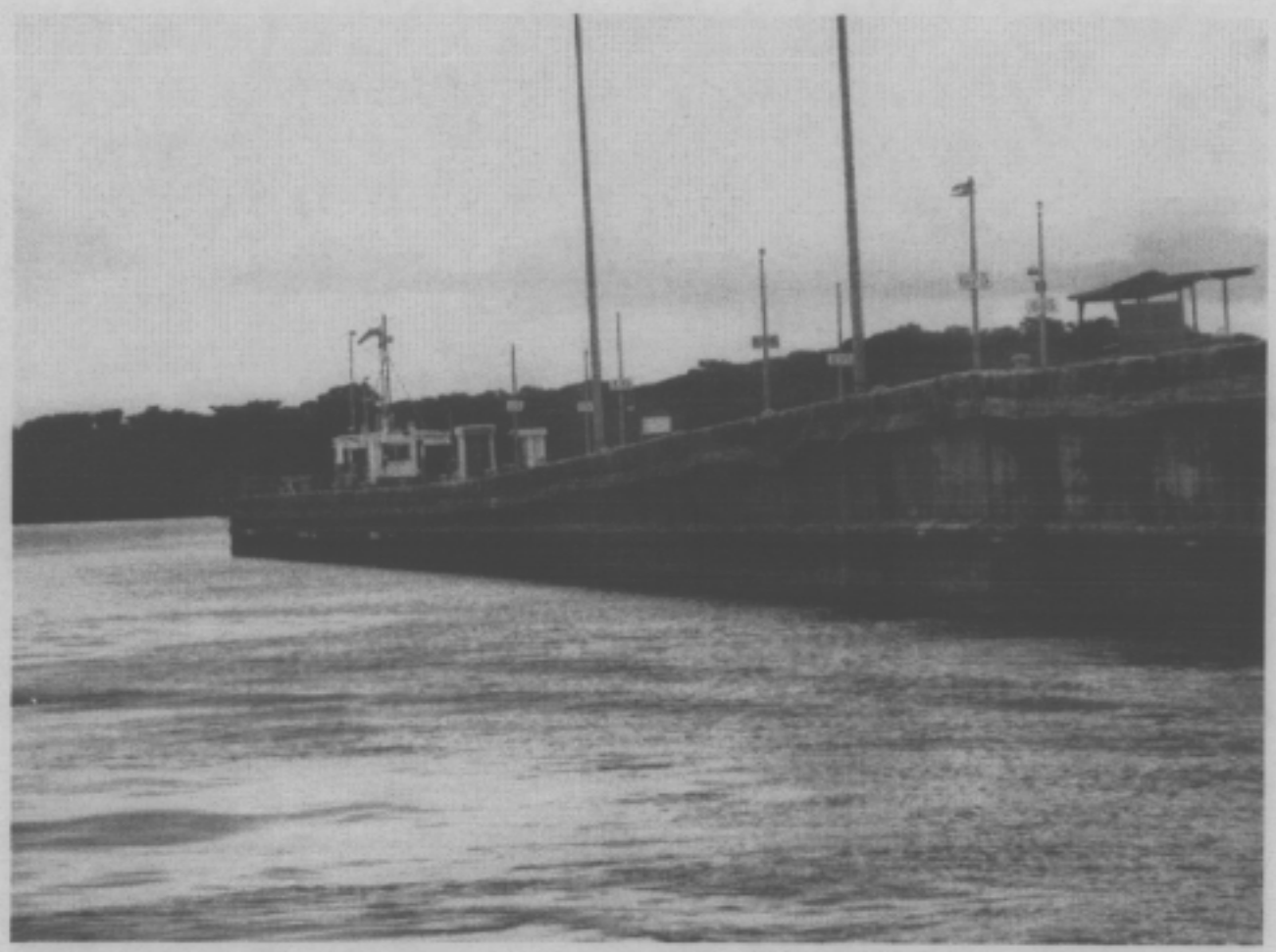
ACP

Available Data

- Geometry
- Center wall structural details
- Measured settlements along the center wall
  - From 1914 to 2000
- Geological information

ACP

South Approach at Gatún Locks



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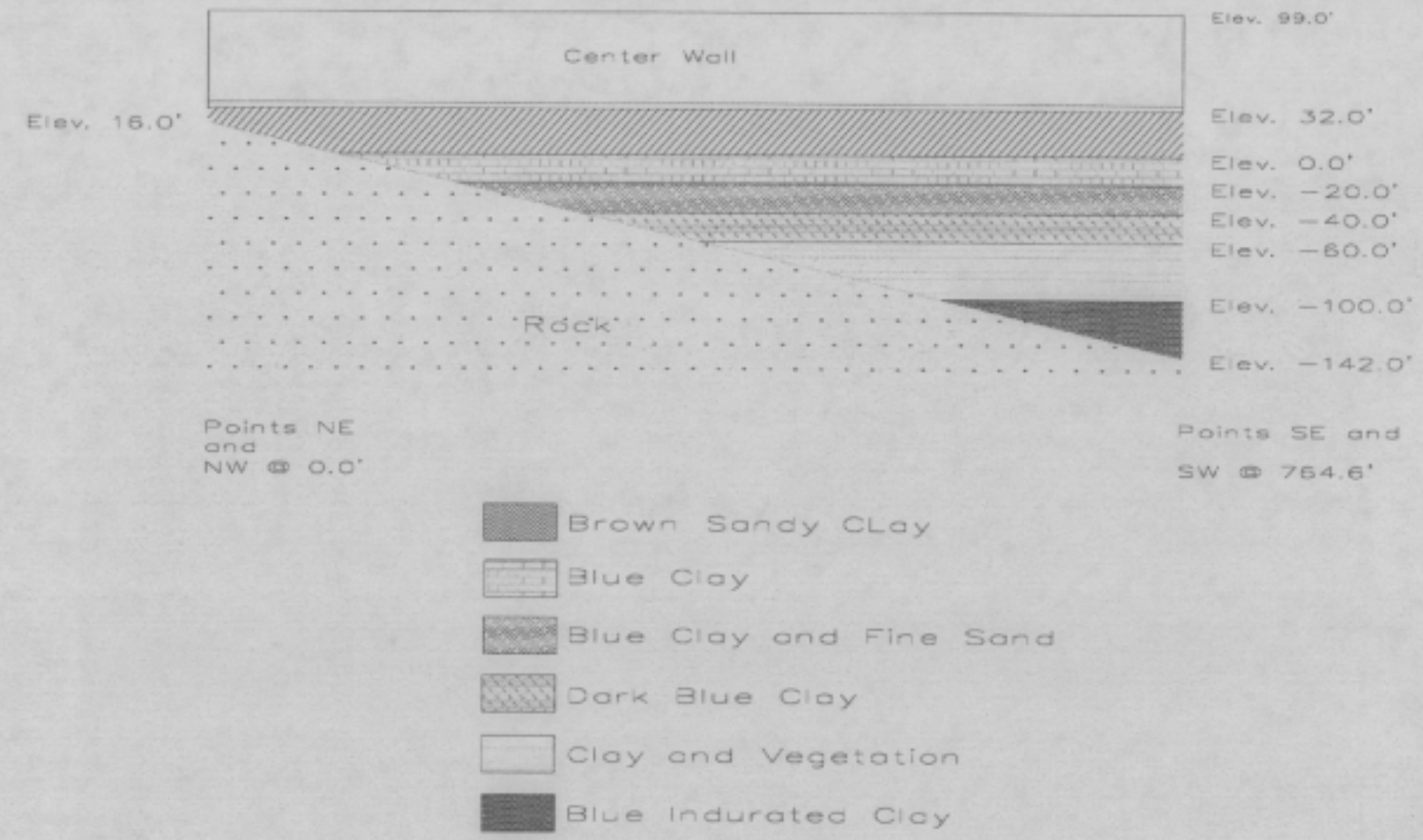
Joint of the South Approach

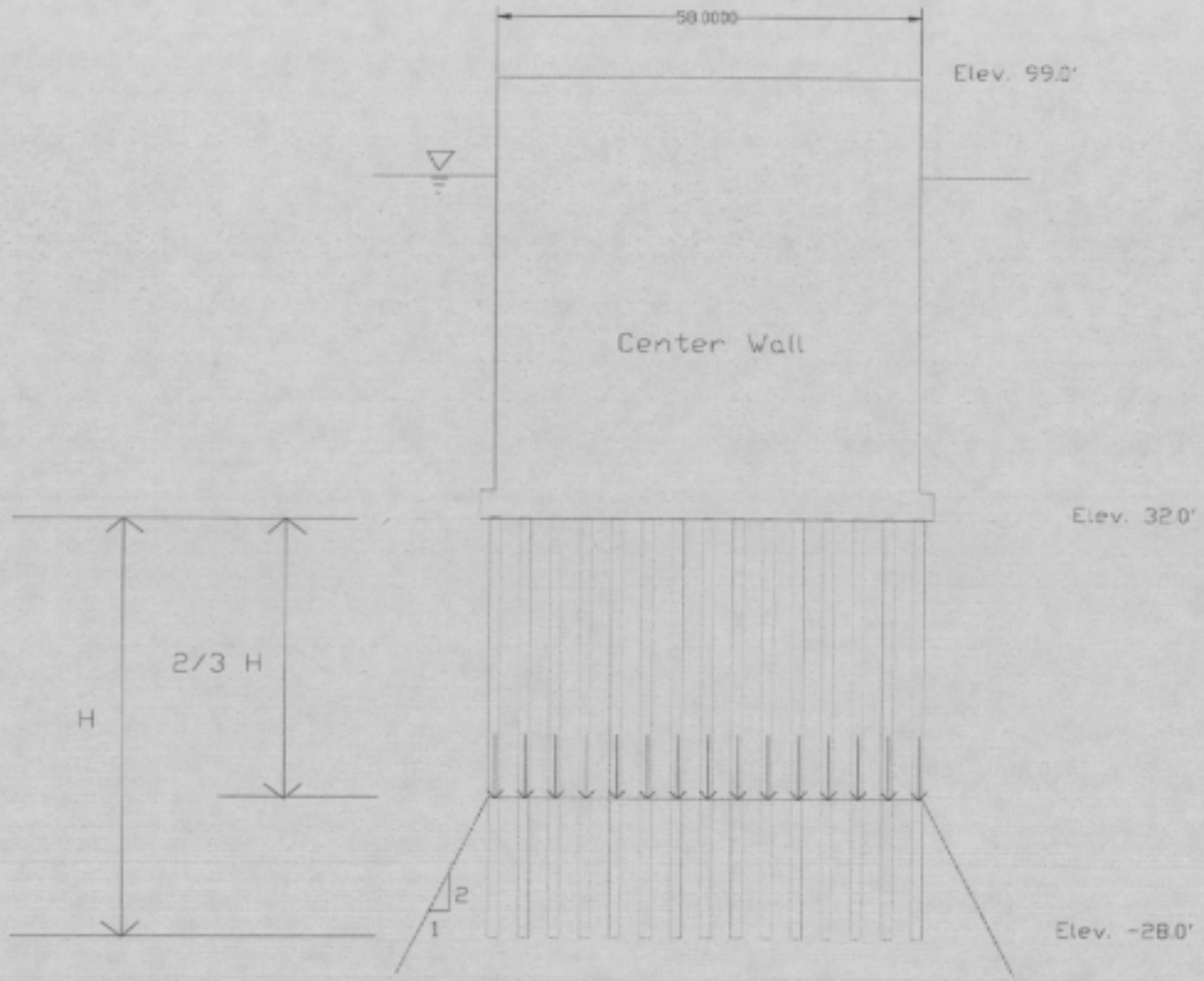
ACP



Gatún Center Wall Profile

ACP

Typical Cross Section



Estimation of C’

Assumptions

- Load transferring from piles to soil is assumed to start at distance equal to 2/3 of Pile lengths from the bottom of center wall
- Total strata thickness is measured from the beginning of the Load transferring up to the rock
- The strata was divided into layers to improve accuracy
- Stresses are computed at layer midpoints

….continue

…continuation

- Contribution to the settlement for each layer:

$$H_i * \text{Log}\,[(\Delta\sigma + \sigma'_o)/\sigma'_o]$$

- C' comes from:

$$C' = \delta / \Sigma\, H_i\, \text{Log}\,[(\Delta\sigma + \sigma'_o)/\sigma'_o]$$

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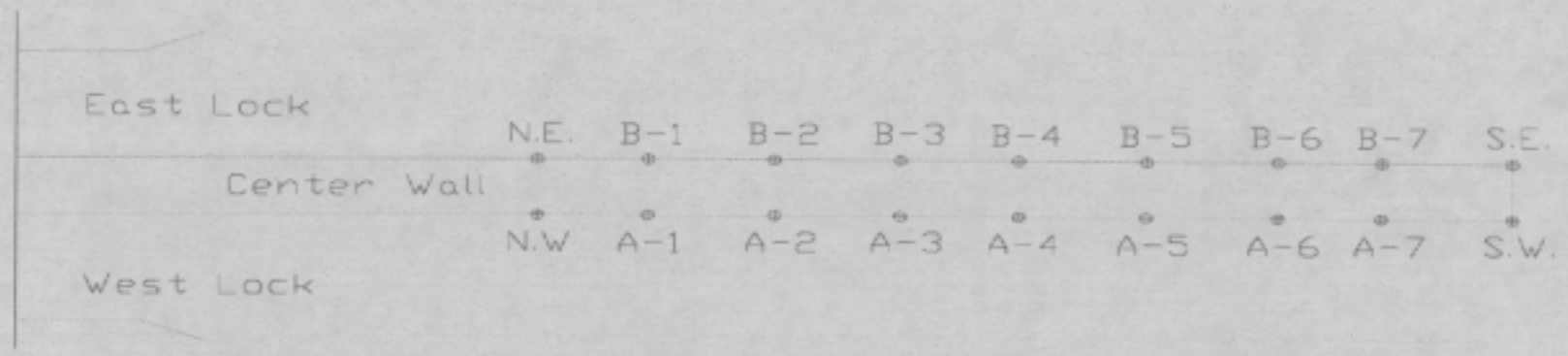
Center Wall Plan and Control Points



ACP

Typical Calculations

(Compression Index) 2/8/01 11:27

W (center wall) =	160 Kips	D piles =	40	ft	Layers
Width =	62 ft	# layers =	10		Vertical = 1
Bot Elev =	32 ft				Horizontal = 1
Rock Elev at NE =	16 ft	Max Rock depth =	142		
		L wall =	764.6	ft	
		Gama Sat =	0.09	K/ft3	
		Gama water =	0.0624	K/ft3	

Location	Max Def ft	Delta X ft	H ft	H -D ft	Layers ft	Hz ft	$\Delta\sigma$ ksf	σ'_o ksf	Hi / Log $(\Delta\sigma+\sigma'_o)/\Delta\sigma$
Point A-5	5.19	477.60	104.70	64.70	6.47	43.23	2.34	1.19	3.05
						49.70	1.97	1.37	2.50
						56.17	1.70	1.55	2.08
						62.64	1.49	1.73	1.75
						69.11	1.33	1.91	1.49
						75.58	1.20	2.09	1.28
						82.05	1.10	2.26	1.11
						88.52	1.01	2.44	0.97
						94.99	0.93	2.62	0.85
						101.46	0.87	2.80	0.76
								C' =	0.33

ACP

Coefficients per point

Point	Location	H	Settlement	Mean Sett	C'	Aver. C'	Notes
Point N.E.	0	16.00	-0.364	-0.459			*
Point N.W.	0	16.00	-0.554				*
Point B-1	86.6	32.08	1.030	0.943			*
Point A-1	86.6	32.08	0.856				*
Point A-2	185.4	50.43	2.716	2.618	0.5848	0.5637	
Point B-2	185.4	50.43	2.520		0.5426		
Point B-3	284.6	68.86	4.440	4.343	0.4397	0.4301	
Point A-3	284.6	68.86	4.246		0.4205		
Point A-4	377.6	86.13	5.246	5.103	0.3919	0.3812	
Point B-4	377.6	86.13	4.960		0.3705		
Point B-5	477.6	104.70	5.470	5.328	0.3457	0.3368	
Point A-5	477.6	104.70	5.186		0.3278		
Point A-6	580.6	123.83	5.306	5.193	0.3014	0.2950	
Point B-6	580.6	123.83	5.080		0.2885		
Point B-7	661.6	138.87	5.300	5.178	0.2838	0.2773	
Point A-7	661.6	138.87	5.056		0.2708		
Point S.E.	764.6	158.00	5.196	5.166	0.2633	0.2618	
Point S.W.	764.6	158.00	5.136		0.2602		

Average = 0.3637

* Points within the Pile area

ACP

Typical Calculations

Cc'
(Compression Index)

2/9/01 11:26

W (center wall) =	160 Kips	D piles =	40		Layers
Width =	62 ft	# layers =	10	Vertical =	2
Bot Elev =	32 ft			Horizontal =	1
Rock Elev at NE =	16 ft	Max Rock depth =	142 ft		
		L wall =	764.6 ft		
		Gama Sat =	0.09 K/ft3		
		Gama water =	0.0624 K/ft3		

Location	Max Def ft	Delta X ft	H ft	H -D ft	Layers ft	Hz ft	Ds ksf	s'o ksf	Hi / Log (Ds+s'o)/Ds
Point A-5	5.19	477.60	104.70	64.70	6.47	43.23	2.45	1.19	3.14
						49.70	2.23	1.37	2.71
						56.17	2.05	1.55	2.36
						62.64	1.89	1.73	2.08
						69.11	1.76	1.91	1.83
						75.58	1.64	2.09	1.63
						82.05	1.54	2.26	1.46
						88.52	1.45	2.44	1.31
						94.99	1.37	2.62	1.18
						101.46	1.30	2.80	1.07
								Cc =	0.28

ACP

Coefficients per point

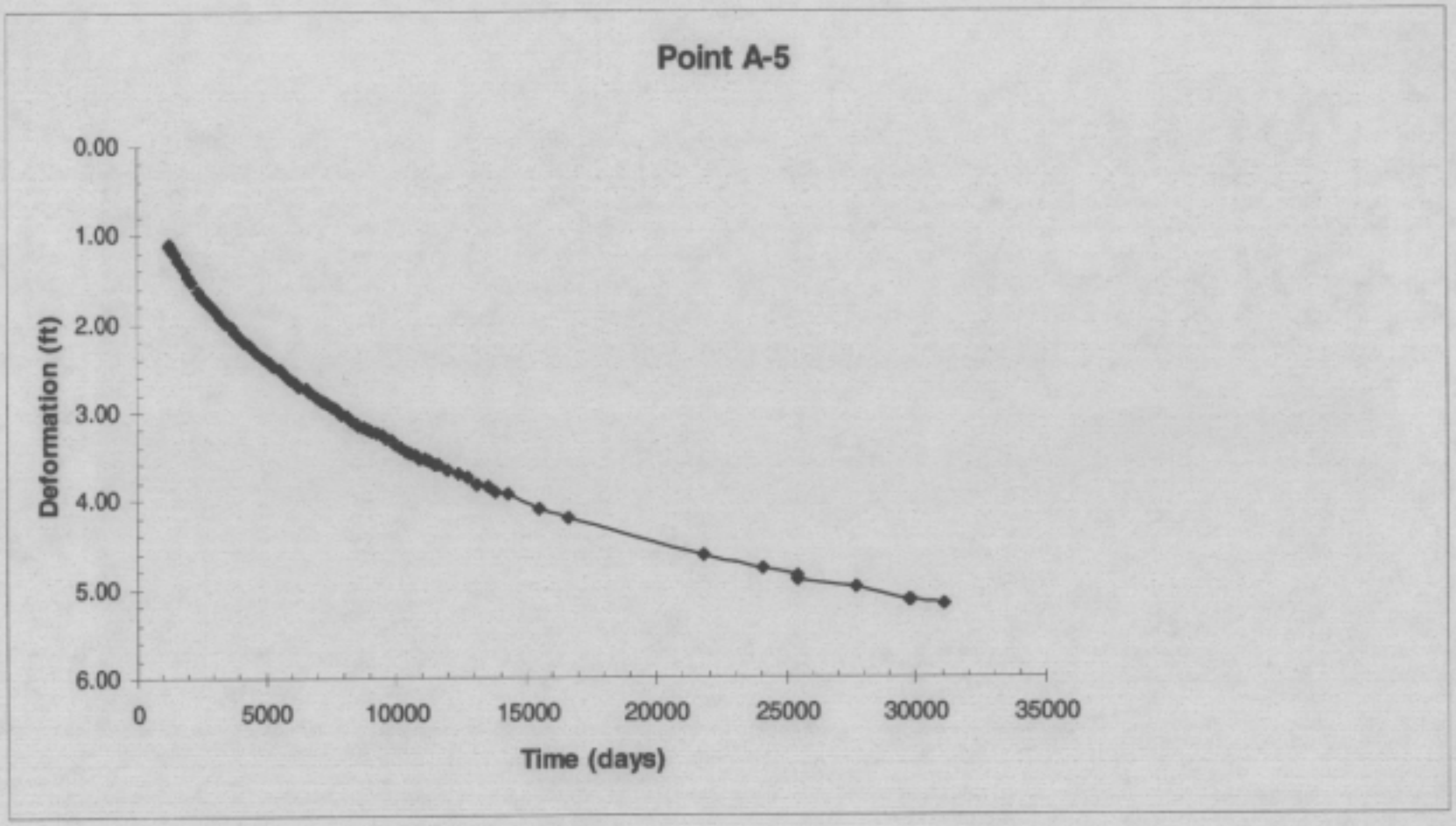
Point	Location	H	Settlement	Mean Sett	Cr	Aver. Cr	Notes
Point N.E.	0	16.00	-0.364	-0.459			*
Point N.W.	0	16.00	-0.554				*
Point B-1	86.6	32.08	1.030	0.943			*
Point A-1	86.6	32.08	0.856				*
Point A-2	185.4	50.43	2.716	2.618	0.5599	0.5397	
Point B-2	185.4	50.43	2.520		0.5195		
Point B-3	284.6	68.86	4.440	4.343	0.3974	0.3887	
Point A-3	284.6	68.86	4.246		0.3800		
Point A-4	377.6	86.13	5.246	5.103	0.3407	0.3314	
Point B-4	377.6	86.13	4.960		0.3222		
Point B-5	477.6	104.70	5.470	5.328	0.2915	0.2839	
Point A-5	477.6	104.70	5.186		0.2763		
Point A-6	580.6	123.83	5.306	5.193	0.2480	0.2427	
Point B-6	580.6	123.83	5.080		0.2375		
Point B-7	661.6	138.87	5.300	5.178	0.2301	0.2248	
Point A-7	661.6	138.87	5.056		0.2195		
Point S.E.	764.6	158.00	5.196	5.166	0.2101	0.2089	
Point S.W.	764.6	158.00	5.136		0.2077		
					Average =	**0.3172**	

* Points within the Pile area

ACP

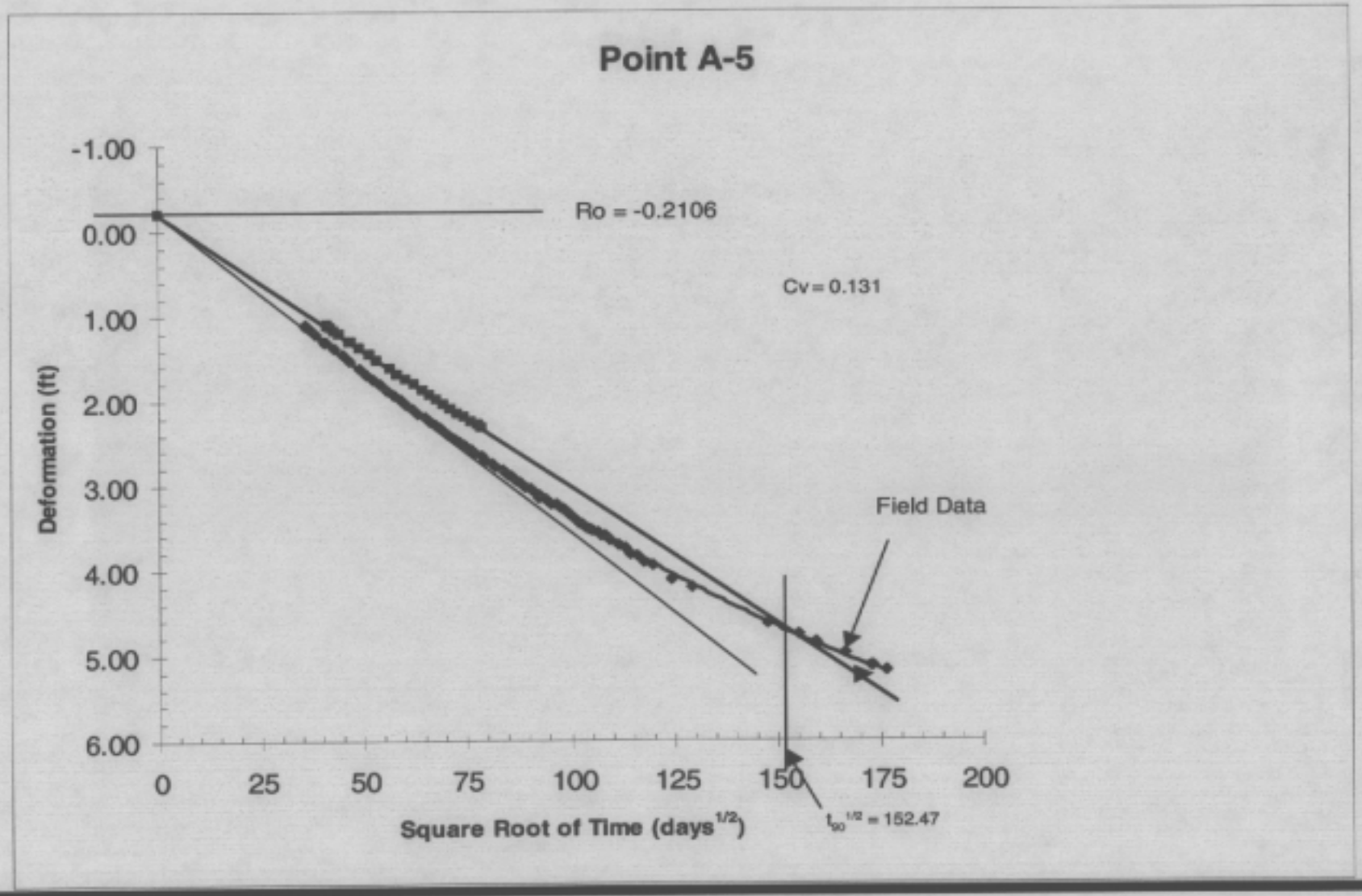
Estimation of Cv

Deformation – vs - Time



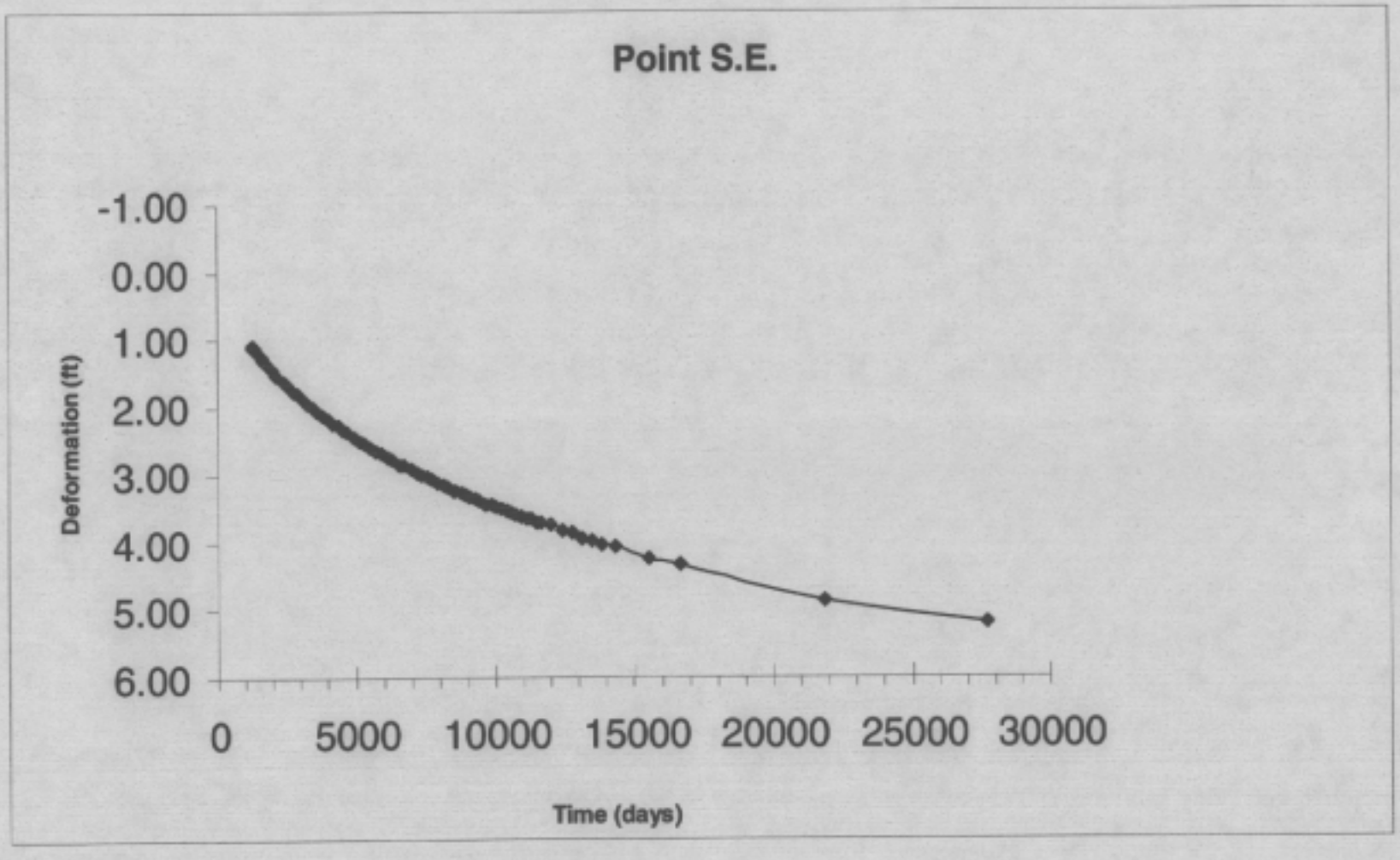
ACP

Determination of the Coefficient of Consolidation by Taylor's Method



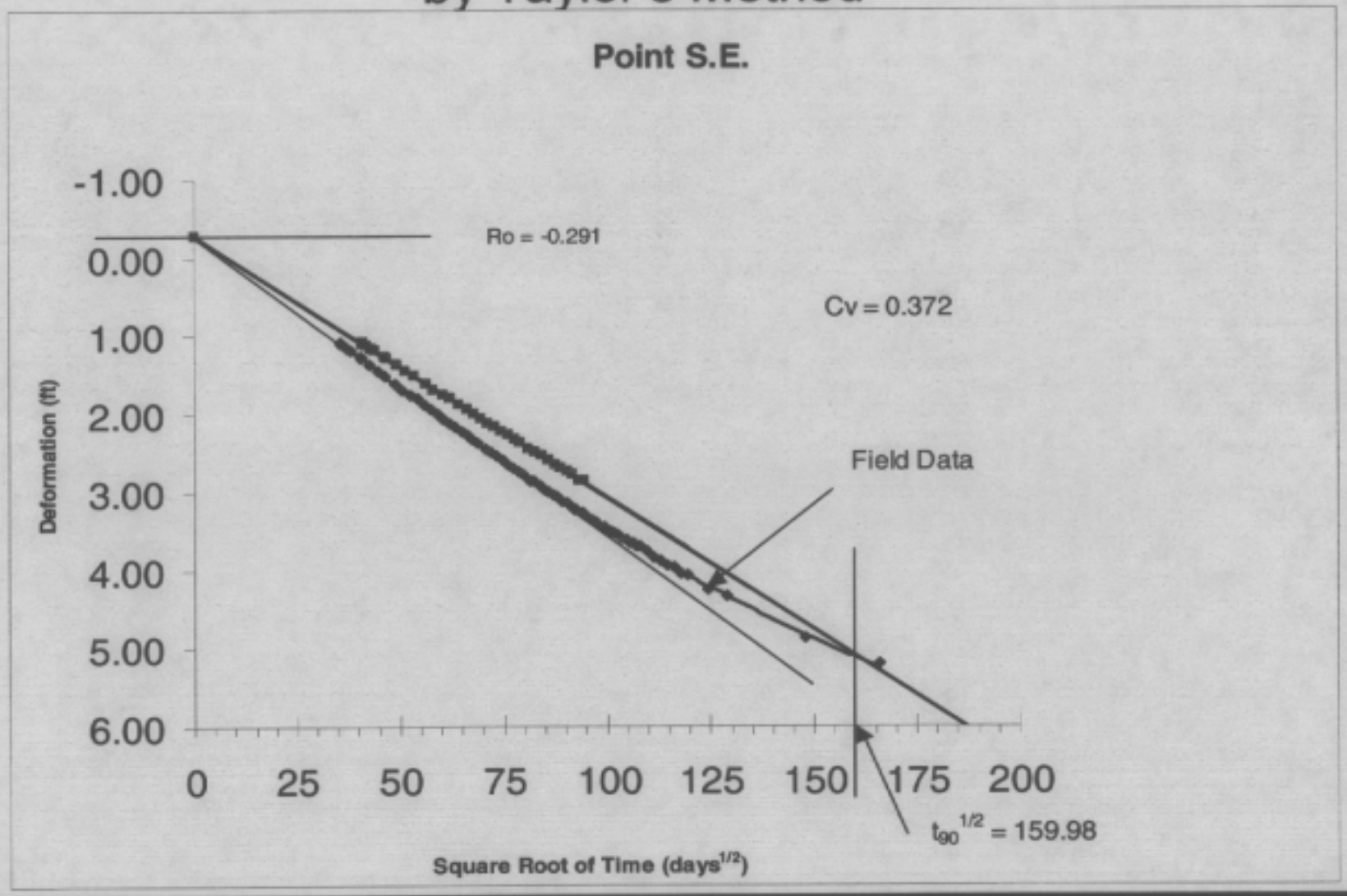
ACP

Deformation – vs - Time



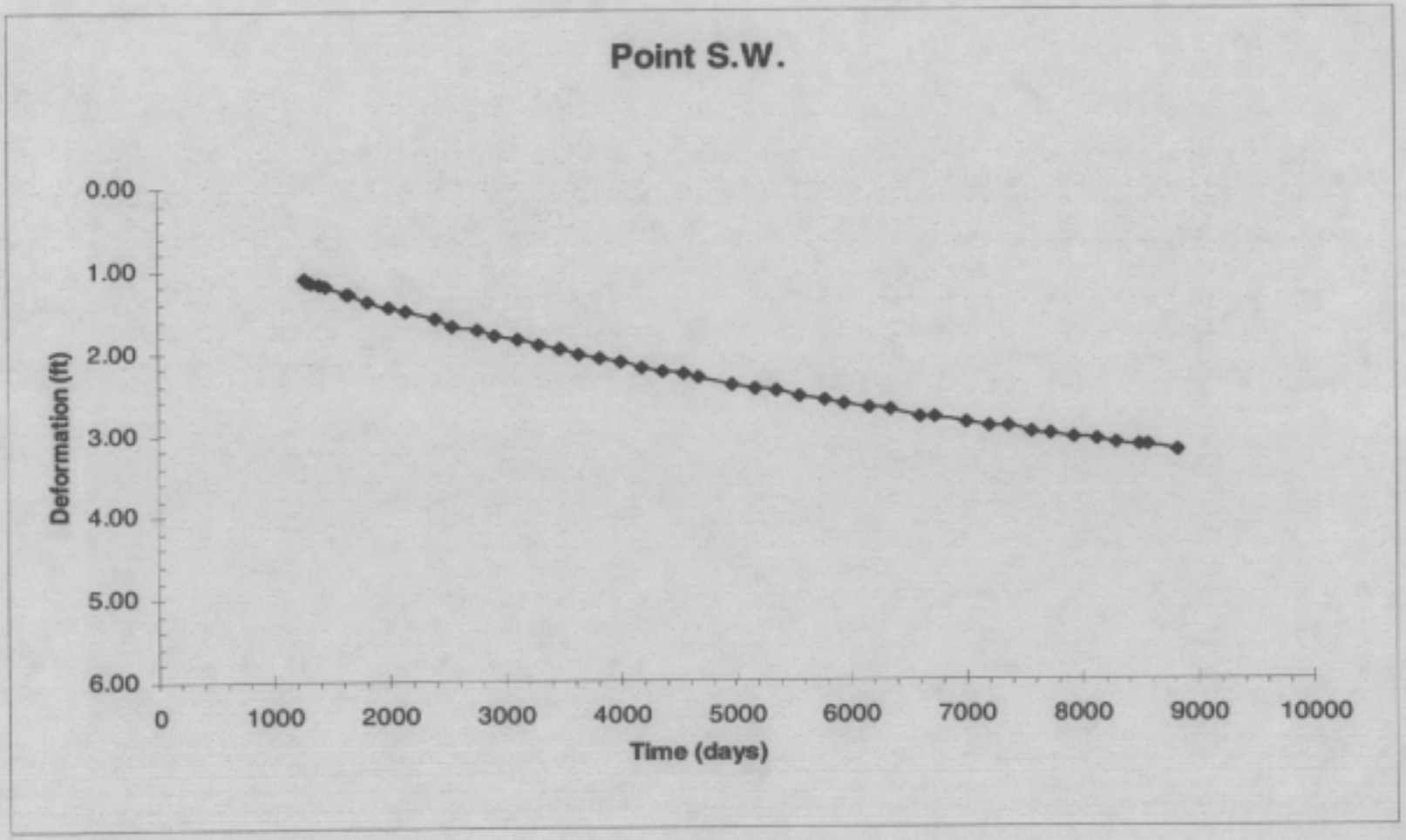
ACP

Determination of the Coefficient of Consolidation by Taylor's Method



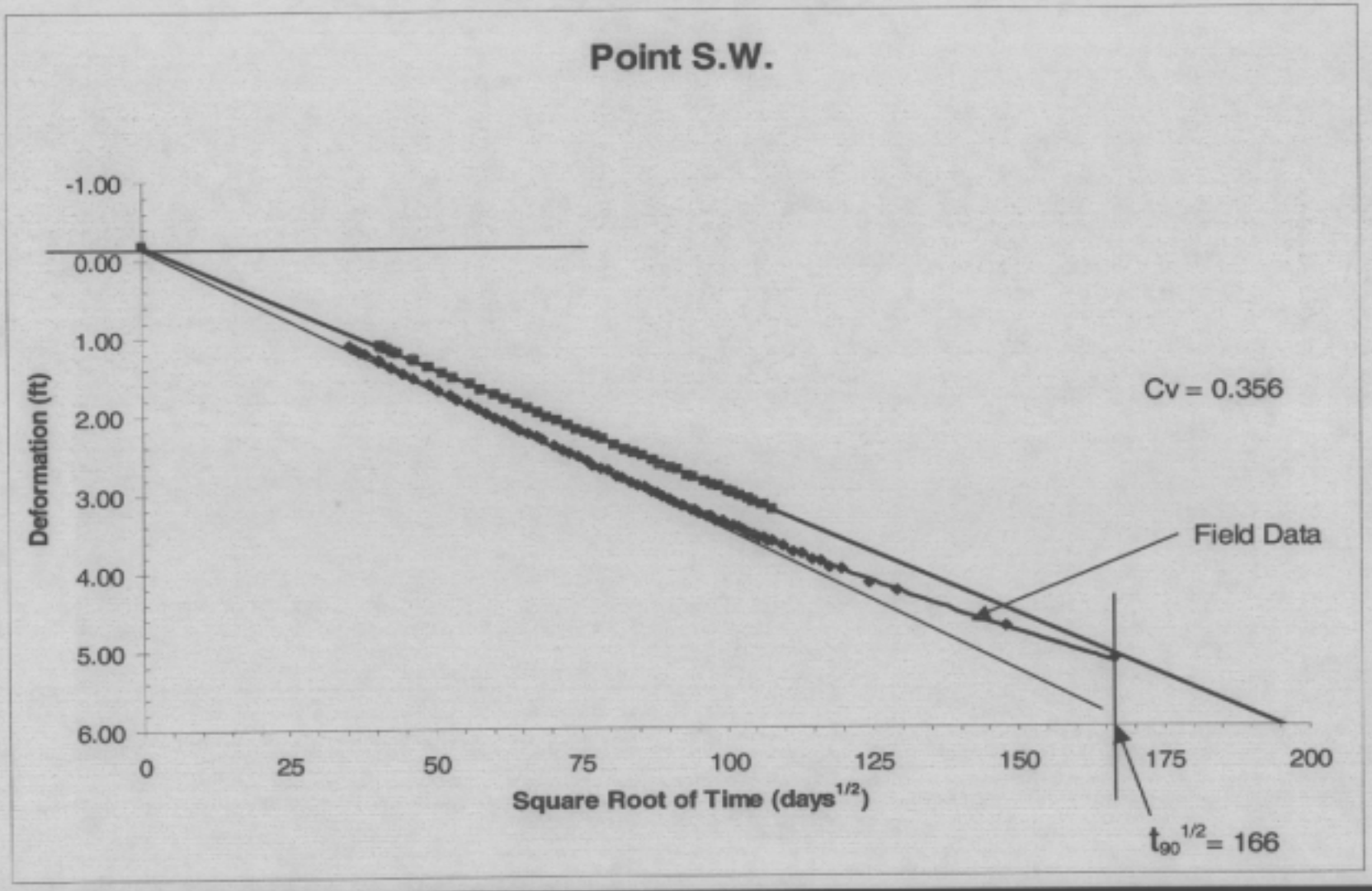
ACP

Deformation – vs - Time



ACP

Determination of the Coefficient of Consolidation by Taylor's Method



ACP

Field Values

Point	T_{90} (cm²/min)	$t_{90(days)}$	H(ft)	C_v
A-5	0.848	23247	74.7	0.131
B-5	0.848	22053	74.7	0.138
A-6	0.848	21893	96.0	0.230
B-6	0.848	26347	96.0	0.191
A-7	0.848	27104	112.7	0.256
B-7	0.848	25409	112.7	0.273
S.E.	0.848	25593	134.0	0.372
S.W.	0.848	27556	134.0	0.356

ACP

Effective Shear Strength Parameters

TRIAXIAL TESTS

Borehole	Shelby No.	Sample	Depth (m)	Moisture Content	Effective Confined Stress (Kpa)	(σ1'-σ3) (Kpa)	σ'3	σ'1	P. P. AT FAILURE	Af	angle ϕ'	C' (kpa)	Liquid Limit	Plastic Limit	PI	Classific.
Mount Hope Multistage-triaxial		1	28.50-29.20	63	121	179	40	290	81	0.5	28	55	69	43	26	MH
		2		63	221	308	110	510	118	0.4						
		3		63	319	438	140	580	168	0.4						
Mount Hope Remolded-Triaxial		1	28.50-29.20	44.4	80	91.2	32	163	27	0.3	33	14	54	34	20	MH
		2		40.3	148	148	64	295	83	0.6						
		3		33.95	290	210	105	409	161	0.8						
MHID-2	2		10.50-11.20	46.0	109.0	141.9	40.9	183.0	68.0	0.5	30	17	48	27	19	SC
	3		13.00-13.7	62.0	148.0	125.0	41.0	167.0	91.0	0.7			46	30		SM
MHID-2	4		14.50-15.20	53.0	158.0	112.8	30.7	144.0	46.0	0.4	34	8	49	31		ML
	4		14.50-15.20	42.0	103.0	150.0	45.4	196.0	58.0	0.4			49	31		ML
MHID-2	5		16.00-16.70	71.0	124.0	115.0	39.0	153.0	75.0	0.7	na		68	39		MH
	7		21.00-21.70	66.0	135.0	116.0	43.9	160.0	81.0	0.7	na		68	40		MH
	8		22.50-23.20	84.8	158.0	114.0	56.0	171.0	80.0	0.7	na		69	42		MH
Gatun Dam GDI-6		1	51.20-51.8	40.6	460	481	150	630	298	0.6	34	29	37	29		SM
		2		43.2	585	592	170	760	421	0.7						
		3		35	665	669	230	920	446	0.7						
Gatun Dam GDI-6		1	34.70-35.30	61.7	210	181	60	250	141	0.8	29	11	69	34		MH
		2		60.1	401	264	130	390	239	0.9						
		3		56.6	594	465	190	650	363	0.8						
Gatun Dam GDI-2 (Hydraulic Fill)		1	15.12-15.73	47.2	98	134	50	90	44	0.3	36	8	32	23		SC
		2		38.6	205	200	90	290	117	0.6						
		3		58.5	395	353	120	480	268	0.8						
TRINIDAD A-25 ORGANIC CLAY		7	94.9-97.4	143	880	867	628	1495	252	0.3	26.7	5	142	64.0	78.0	ORGANIC CLAY
		7			2950	2140	1000	3140	7900	3.7						
		9	99.6-102.3	102	900	817	100	917	7000	8.6			174	78	96	
TRINIDAD A-40 ORGANIC CLAY		3	83.0-85.5	63.6	5480	4750	2180	6930	3300	0.7	30.1	2.5	69	33	36	ORGANIC CLAY
		3		70.5	1550	1490	560	2050	6350	4.3						
		7	93.0-95.5	89.2	432	686	188	874	244	0.4						
		7		88.3	2980	2170	1220	3390	1680	0.8						
TRINIDAD A-40 PEAT		9	98.0-100.5	225	720	1260	58	1318	662	0.5	29.4	16	140	40	100	PEAT
		11	103.0-105.5	283	1210	1438	150	1588	7450	5.2			138	43	95	
TRINIDAD A-25 PEAT		10	102.9-105.7	271	1920	2500	-40	2460	8600		na					PEAT

DIRECT SHEAR & BROMHEAD SHEAR TESTS

Borehole	Shelby No.	Sample	Depth (m)	Moisture Content	Normal Stress	Shear Stress	Residual	Strain	Strain Rate		angle ϕ'	C' (kpa)	Liquid Limit	Plastic Limit	PI	Classific.
Mount Hope MHID-2 remolded direct shear		1	remix	44	50.47	46.21		4	0.003		31	9	54	34	20	MH
		2		41	99.47	83.8		5.3								
		3		38.5	197.29	102.1		5.6								
		4		41.41	393.2	264.9		5.9								
		5		39.9	785.5	490.3		7.7								
Gatun Dam GDI-22 remolded direct shear		1	20.10-20.70	57.81	50.29	42.9		7.1	0.003		28	18	60	37	23	MH
		2		48.6	99.29	83.1		6.7								
		3		51.1	197.2	137		5.6								
		4		36.76	393	183		5.6								
		5		48.71	785	448		10.7								
Mount Hope MHID-2 remolded Bromhead Ring Shear		1	remix	42	51.75	29.8	25.72	2.2	0.003		26	5	54	34	20	MH
		2		39	100.75	54.4	47	5.9			21	1				
		3		35	198.75	100.4	64.3	3.7								
		4		30	394.75	209	143	3.7								
		5		31.4	786.8	392	298	6.9								

ACP

Definitions - Shear Strength Parameters

$$SIN\phi_{CV} = 0.8 - 0.094Ln(PI)$$

where ϕ_{CV} = Critical State Friction Angle

$$M = \frac{6\sin\phi_{CV}}{3-\sin\phi_{CV}}$$

$$\left(\frac{Su}{\sigma_o'}\right)_{OCR=1} = \frac{1.72\sin\phi_{CV}}{3-\sin\phi_{CV}} \approx 0.29M$$

$$\left(\frac{Su}{\sigma_o'}\right) = \left(\frac{Su}{\sigma_0}\right)_{OCR=1} * OCR^{\Lambda}$$

$$\Lambda = \frac{\lambda-\kappa}{\lambda} = 0.8 \qquad when\,\kappa \approx \frac{1}{5}\lambda$$

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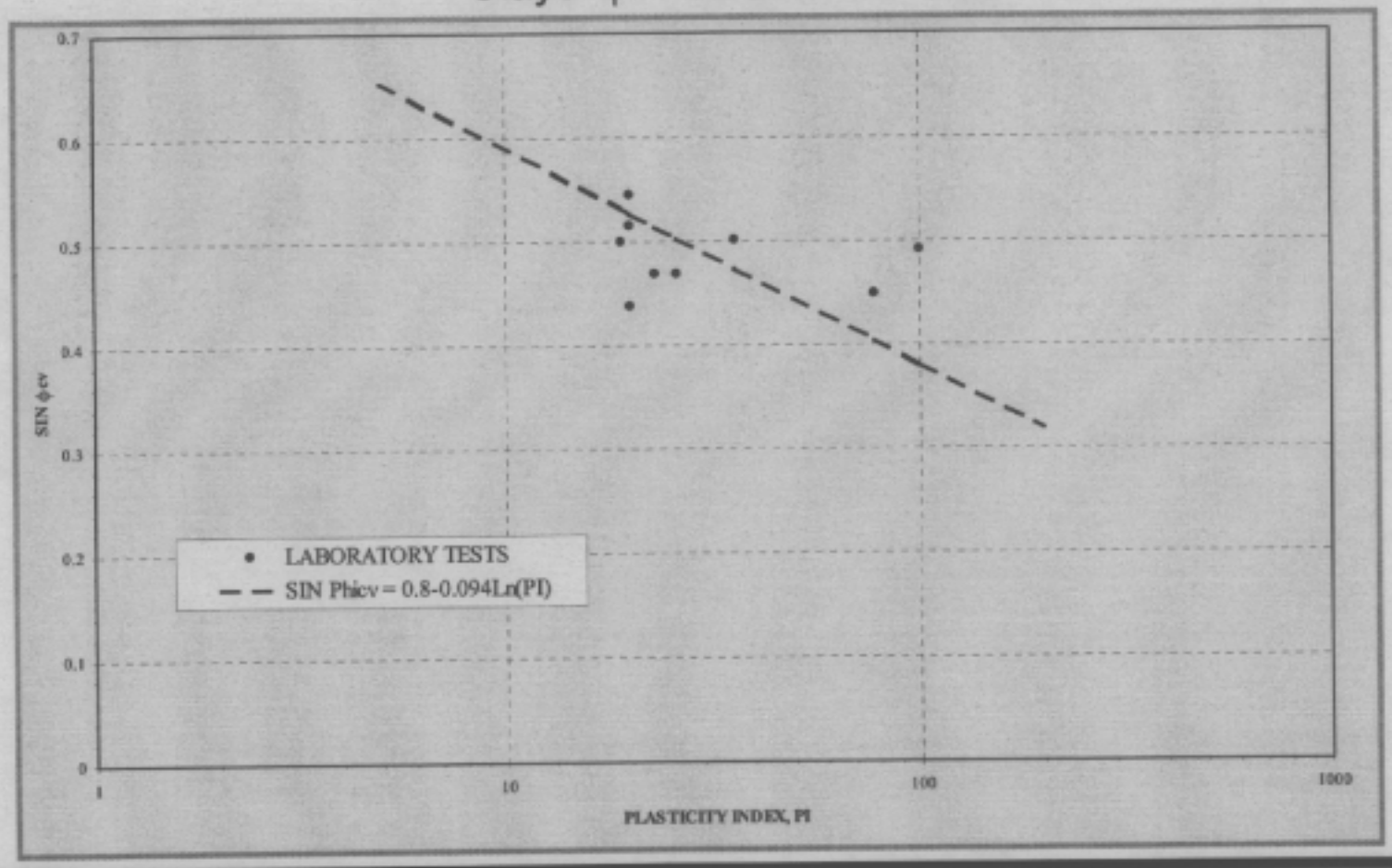
Correlation with the Critical State Friction Angle

Suggested Effective Stress Parameters :

Peat: $\phi' = 25$ & $C = 0.1$ ksf

Clays: $\phi' = 28$ & $C = 0.1$ ksf



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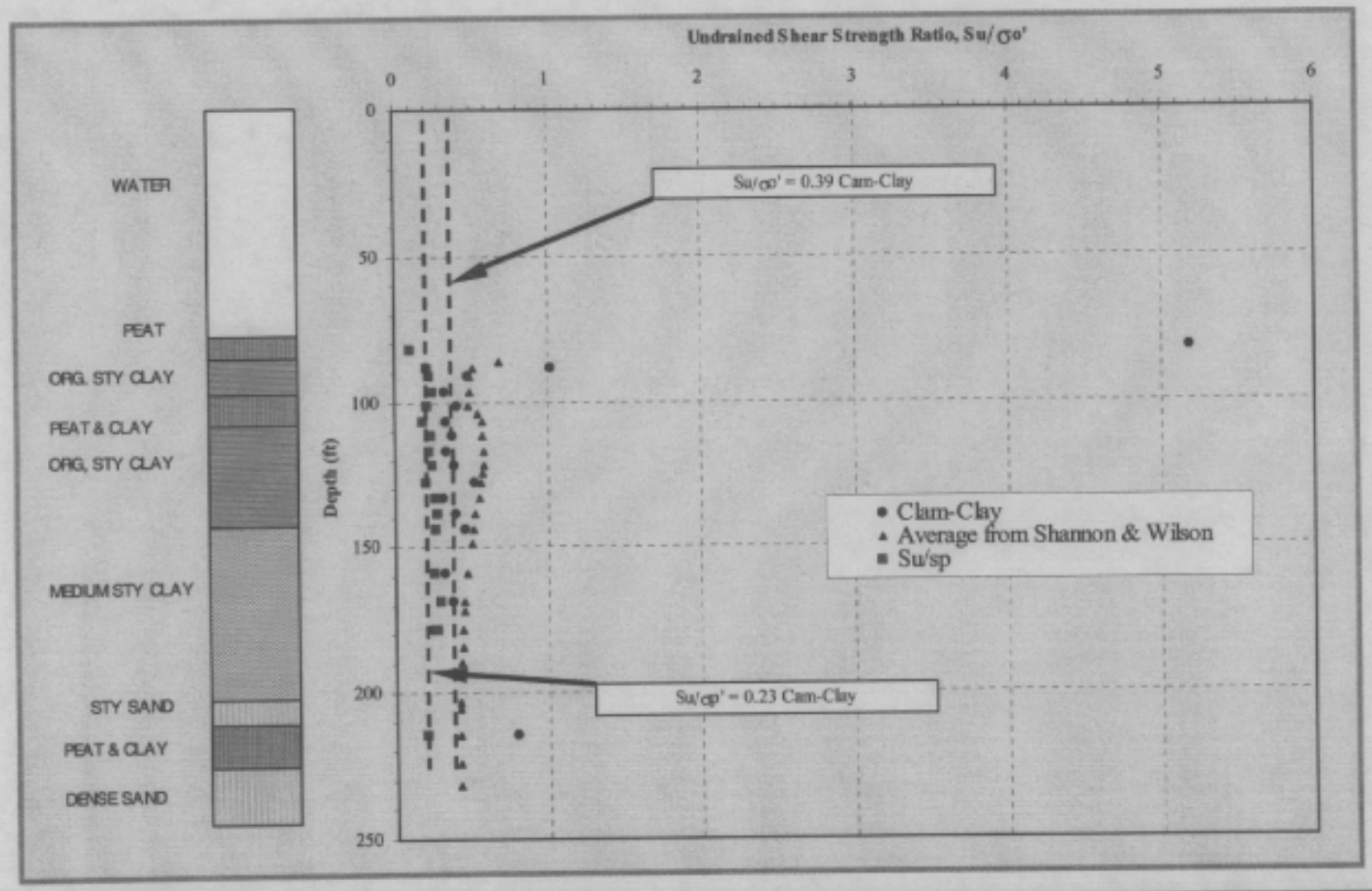
Undrained Shear Strength

MATERIAL	DEPTH	SAMPLE	DEPTH	IP	ϕcv	ϕcv aver	M	Su (Ksf) Average (S&W)	Su=σo'(1.72*sinϕcv/(3-sinϕcv)	OCR	Suocr=Su*(OCR)^Λ	Su/σo'	Su/σp'
VERY SOFT PEAT	77.2	1	78.5	172	18.4	19.1	0.73	0.07	0.0002				
		2	81.9	135	19.8			0.09	0.0029	52.23	0.068	5.19	0.10
VERY SOFT ORGANIC SILTY CLAY	84	3	86.1			24.8	0.97	0.10					
		4	88.6	45	26.2			0.11	0.0666	4.65	0.227	1.02	0.22
		5	91.2	70	23.6			0.13	0.0717	2.07	0.128	0.47	0.23
FIRM PEAT AND SOFT CLAY	96	7	96.2	78	23.0	20.9	0.81	0.19	0.0976	1.32	0.122	0.32	0.24
		9	101.1	96	21.8			0.24	0.1230	1.89	0.205	0.40	0.21
		10	104.2					0.28					
		11	106.7	159	18.9			0.30	0.1106	1.80	0.177	0.33	0.18
SOFT TO MEDIUM ORGANIC SILTY CLAY	108	13	111.7	76	23.1	23.4	0.92	0.36	0.1645	1.58	0.237	0.37	0.24
		15	116.9	94	21.9			0.42	0.1767	1.49	0.243	0.34	0.23
		17	121.9	66	24.0			0.47	0.2203	1.56	0.315	0.39	0.25
		18	124.4					0.50					
		19	127.9	93	22.0			0.54	0.2356	2.56	0.499	0.52	0.20
		21	133.1	60	24.5			0.60	0.3012	1.17	0.342	0.31	0.27
		23	138.3	45	26.2			0.66	0.3756	1.42	0.499	0.39	0.28
MEDIUM ORGANIC SILTY CLAY	142	25	143.8	44	26.4	25.0	0.99	0.72	0.4262	1.68	0.647	0.45	0.27
		27	148.5					0.77					
		31	158.9	70	23.6			0.89	0.4991	1.27	0.606	0.32	0.25
		34	168.4	36	27.6			1.00	0.6903	1.27	0.838	0.38	0.30
		35	171.9	60	24.5			1.03	0.6395				
		51	178.3	65	24.1			1.11	0.6806	0.89	0.620	0.25	0.26
		53	184.3					1.17					
		55	189.8					1.24					
MEDIUM SILTY FINE SAND	201	59	203.3					1.39					
		60	205.3					1.41					
FIRM PEAT AND MEDIUM ORGANIC SILTY CLAY	210	63	214.3	70	23.6	23.6	0.92	1.51	0.9486	3.91	2.825	0.79	0.20
MEDIUM TO DENSE SILTY FINE TO MEDIUM SAND	223	67	224.3					1.62					
		69	231.5					1.70					
SILTSTONE	243												

ACP

Undrained Shear Strength Ratio (Cam-Clay)



ACP

Settlement and Deformation Analysis

1. Manual Computation of Settlements
2. Plaxis Deformation Analysis
   a. Introduction
   b. Mohr-Coulomb Model Analysis
   c. Soft Soil Model (Modified Cam-Clay)
   d. Results

ACP

Columnar Stratrigraphy

MATERIAL	DEPTH
VERY SOFT PEAT	77.2
VERY SOFT ORGANIC SILTY CLAY	84
FIRM PEAT AND SOFT CLAY	96
SOFT TO MEDIUM ORGANIC SILTY CLAY	108
MEDIUM ORGANIC SILTY CLAY	142
MEDIUM SILTY FINE SAND	201
FIRM PEAT AND MEDIUM ORGANIC SILTY CLAY	210
MEDIUM TO DENSE SILTY FINE TO MEDIUM SAND	223
SILTSTONE	243

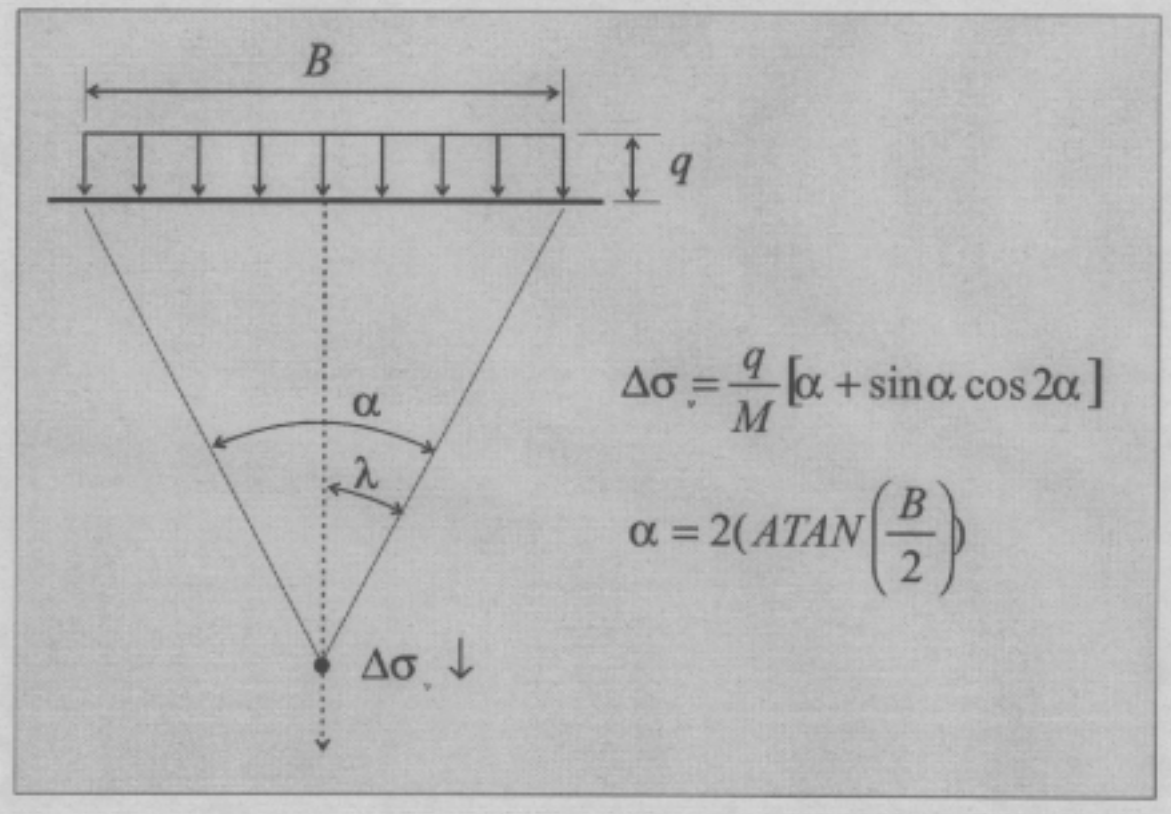
ACP

Cases for Manual Calculation

Cases	CR	Cv (cm2/min)
Layered by samples, Cv equiv (anisotropy correction)	Variable	0.0303
Layered by stratrigraphic unit, Cv equiv (anisotropy correction)	Variable	0.0303
Back-analysis points A-7-B-7	0.2248	0.2645
Back-analysis points SE-SW	0.2089	0.364

ACP

Stress Increment for Manual Calculation

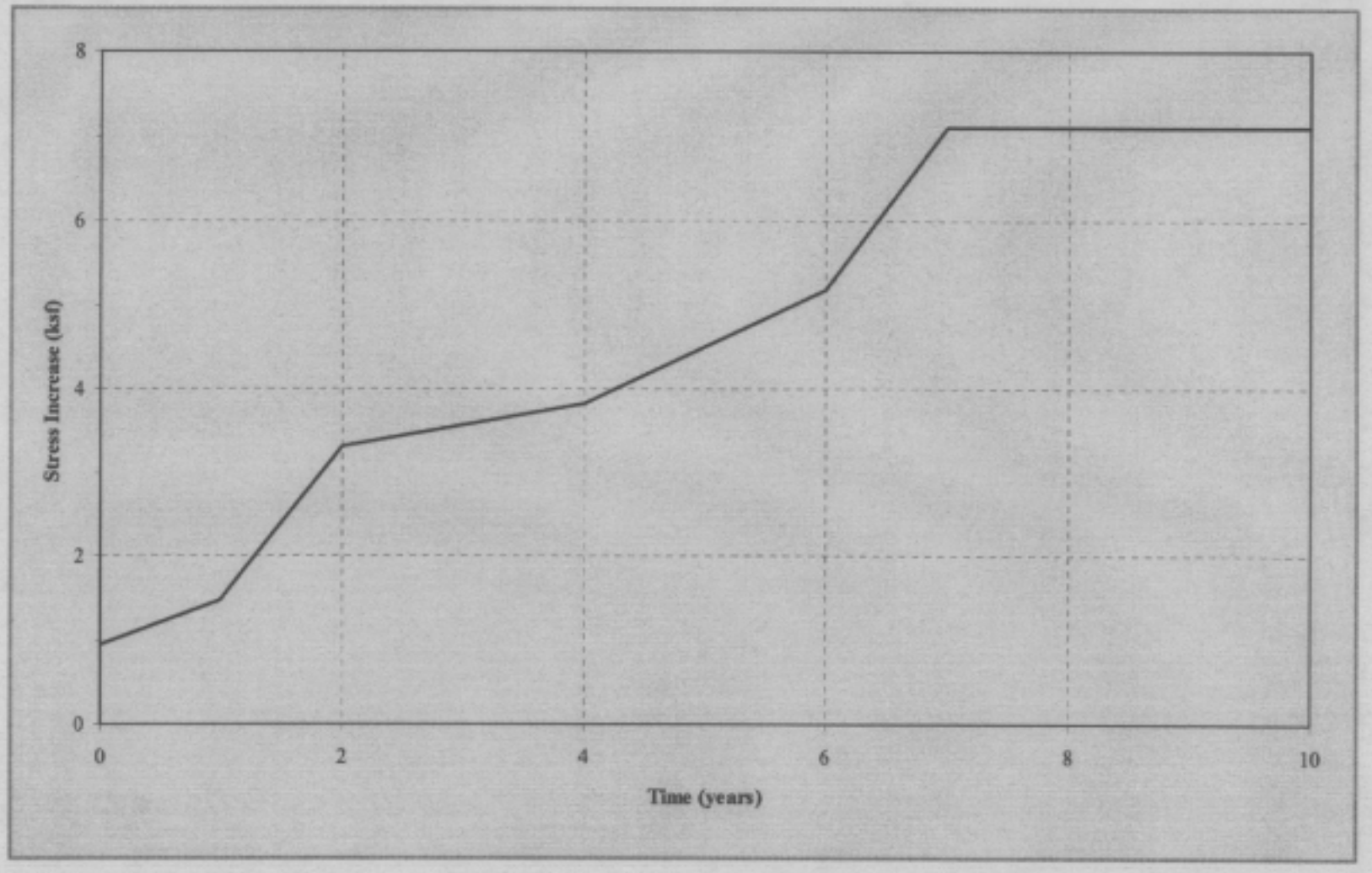


$$\Delta\sigma = \frac{q}{M}\left[\alpha + \sin\alpha\cos 2\alpha\right]$$

$$\alpha = 2\left(ATAN\left(\frac{B}{2}\right)\right)$$

ACP

Stress Increment for Manual Calculation



ACP

Typical Manual Calculation

MATERIAL	DEPTH	γw	ω	H	OR	Qt	(Qu'(kips/ft2)	(Su'(kips/ft2)	hi	log (σ0'+Δσ)/σ0)	ρ	Δσ	log (σ0'+Δσ)/σ0)	ρ	Δσ	log (σ0'+Δσ)/σ0)	ρ	Δσ	log (σ0'+Δσ)/σ0)	ρ	Δσ	log (σ0'+Δσ)/σ0)	ρ	Δσ	ρ
									B			149.6					995.6			680.6			885.6			995.6
									Q			1.465					3.306			3.832			5.178			5.988
VERY SOFT PEAT	77.20					4.817		0.0000																		
		64.2	4.423	3.40	0.6237				0.0061	1.7	2.19	4.64	1.465	2.38	5.05	3.306	3.75	3.80	3.832	2.80	5.90	5.178	2.93	6.21	7.088	6.50
	80.60					5.036		0.0061																		
		64.2	4.423	3.40	0.6237				0.0629	5.1	1.20	2.55	1.465	1.39	2.94	3.306	1.77	3.67	3.832	1.79	3.80	5.178	1.92	4.07	7.087	4.36
VERY SOFT ORGANIC SILTY CLAY	84.00					5.256		0.0122																		
		89.3	3.453	4.00	0.2157				0.1195	8.8	0.95	0.02	1.465	1.11	0.97	3.306	1.46	1.36	3.832	1.52	1.31	5.172	1.65	1.42	7.046	1.53
	88.00					5.611		0.1197																		
		89.3	3.453	4.00	0.2157				0.2272	12.8	0.71	0.61	1.465	0.87	0.75	3.306	1.19	1.05	3.832	1.25	1.08	5.159	1.37	1.19	6.950	1.29
	92.00					5.966		0.2272																		
		89.3	3.453	4.00	0.2157				0.3096	16.8	0.61	0.52	1.465	0.76	0.65	3.306	1.00	0.92	3.831	1.03	0.95	5.155	1.25	1.07	6.796	1.13
FIRM PEAT AND SOFT CLAY	96.00					6.325		0.3346																		
		78.8	3.860	4.00	0.3009				0.3930	20.8	0.53	0.64	1.465	0.68	0.81	3.306	0.95	1.17	3.830	1.03	1.24	5.106	1.15	1.38	6.594	1.51
	100.00					6.672		0.3820																		
		78.8	3.860	4.00	0.3009				0.4694	24.8	0.49	0.59	1.465	0.63	0.76	3.306	0.92	1.11	3.829	0.98	1.18	5.059	1.09	1.31	6.355	1.42
	104.00					6.979		0.4494																		
		78.8	3.86	4.00	0.3009				0.5276	28.1	0.44	0.55	1.465	0.58	0.69	3.303	0.86	1.04	3.828	0.92	1.10	5.009	1.02	1.23	6.100	1.33
SOFT TO MEDIUM ORGANIC SILTY CLAY	108.00					7.246		0.5068																		
		85.7	2.699	4.25	0.2701	0.000			0.6057	32.9	0.41	0.47	1.464	0.53	0.61	3.302	0.81	0.95	3.828	0.86	0.99	4.935	0.96	1.10	5.877	1.18
	112.25					7.610		0.6057																		
		85.7	2.699	4.25	0.2701				0.7046	37.2	0.37	0.42	1.464	0.49	0.56	3.301	0.75	0.87	3.827	0.81	0.93	4.858	0.90	1.03	5.587	1.09
	116.50					7.934		0.7046																		
		85.7	2.699	4.25	0.2701				0.8036	41.4	0.34	0.39	1.464	0.45	0.52	3.299	0.71	0.81	3.825	0.76	0.87	4.771	0.84	0.97	5.352	1.02
	120.75					8.238		0.8036																		
		85.7	2.699	4.25	0.2701				0.9025	45.7	0.31	0.36	1.464	0.42	0.48	3.296	0.67	0.77	3.815	0.72	0.82	4.683	0.79	0.91	5.151	0.95
	125.00					8.202		0.9025																		
		85.7	2.699	4.25	0.2701				1.0014	49.9	0.29	0.33	1.463	0.39	0.45	3.293	0.63	0.73	3.813	0.68	0.78	4.591	0.75	0.86	4.981	0.89
	129.25					9.067		1.0014																		
		85.7	2.699	4.25	0.2701				1.1007	54.2	0.27	0.31	1.463	0.37	0.42	3.289	0.60	0.69	3.806	0.65	0.75	4.505	0.71	0.81	4.839	0.84
	133.50					9.431		1.1003																		
		85.7	2.699	4.25	0.2701				1.1992	58.4	0.25	0.29	1.462	0.35	0.40	3.285	0.57	0.66	3.798	0.62	0.71	4.420	0.67	0.77	4.723	0.80
	137.75					9.795		1.1992																		
		85.7	2.699	4.25	0.2701				1.3042	62.7	0.23	0.26	1.462	0.32	0.36	3.280	0.53	0.61	3.790	0.58	0.66	4.341	0.62	0.71	4.629	0.74
MEDIUM ORGANIC SILTY CLAY	142.00					10.159		1.2991																		
		95.8	2.029	7.38	0.2894				1.5269	65.5	0.21	0.44	1.460	0.29	0.62	3.273	0.50	1.06	3.758	0.54	1.25	4.241	0.58	1.25	4.529	1.26
	148.38					10.850		1.5293																		
		95.8	2.029	7.38	0.2894				1.7805	75.9	0.19	0.39	1.458	0.26	0.56	3.262	0.46	0.97	3.750	0.50	1.06	4.132	0.52	1.12	4.441	1.17
	156.75					11.542		1.7805																		
		95.8	2.029	7.38	0.2894				1.9917	83.2	0.17	0.36	1.456	0.24	0.51	3.249	0.42	0.90	3.739	0.46	0.99	4.042	0.48	1.03	4.381	1.08
	164.13					12.233		1.9917																		
		95.8	2.029	7.38	0.2894				2.2229	90.6	0.15	0.32	1.454	0.22	0.47	3.233	0.39	0.83	3.714	0.42	0.91	3.969	0.44	0.95	4.341	1.00
	171.50					12.924		2.2229																		
		95.8	2.029	7.38	0.2894				2.4541	98.0	0.14	0.30	1.451	0.20	0.43	3.215	0.36	0.78	3.686	0.40	0.83	3.910	0.41	0.88	4.313	0.94
	178.88					13.616		2.4541																		
		95.8	2.029	7.38	0.2894				2.6857	105.4	0.13	0.28	1.448	0.19	0.40	3.195	0.34	0.73	3.655	0.37	0.80	3.862	0.39	0.83	4.250	0.88
	186.25					14.309		2.6857																		
		95.8	2.029	7.38	0.2894				2.9165	112.7	0.12	0.26	1.444	0.17	0.37	3.172	0.32	0.68	3.620	0.35	0.75	3.825	0.36	0.78	4.273	0.84
	193.63					14.999		2.9165																		
		93.750	2.029	7.38	0.2894				3.1811	120.1	0.11	0.24	1.440	0.16	0.35	3.147	0.30	0.64	3.582	0.33	0.70	3.784	0.34	0.73	4.251	0.79
MEDIUM SILTY FINE SAN	201.00					15.690		3.1477																		
		95.5	1.756	9.00					3.3409	128.3	0.11	0.00	1.434	0.16	0.00	3.116	0.29	0.00	3.536	0.31	0.00	3.745	0.33	0.00	4.226	0.00
FIRM PEAT AND MEDIUM ORGANIC SILTY CLAY	210.00					16.550		3.4456																		
		82.8	2.224	4.33	0.5159				3.5340	135.0	0.10	0.22	1.430	0.15	0.33	3.089	0.27	0.61	3.496	0.30	0.67	3.734	0.31	0.70	4.205	0.76
	214.33					16.908		3.5340																		
		82.8	2.224	4.33	0.5159				3.6224	139.3	0.10	0.22	1.426	0.14	0.32	3.071	0.27	0.60	3.484	0.29	0.65	3.694	0.31	0.68	4.186	0.75
	218.67					17.267		3.6224																		
		82.8	2.224	4.33	0.5159				3.8112	145.6	0.08	0.40	1.423	0.25	0.56	3.061	0.45	0.96	3.440	0.48	1.03	3.653	0.48	1.08	4.167	1.16
MEDIUM TO DENSE SILTY FINE TO MEDIUM SAND	223.00					17.626	3.7108				total	16.30		total	30.13		total	28.63		total	30.33		total	32.98		34.58

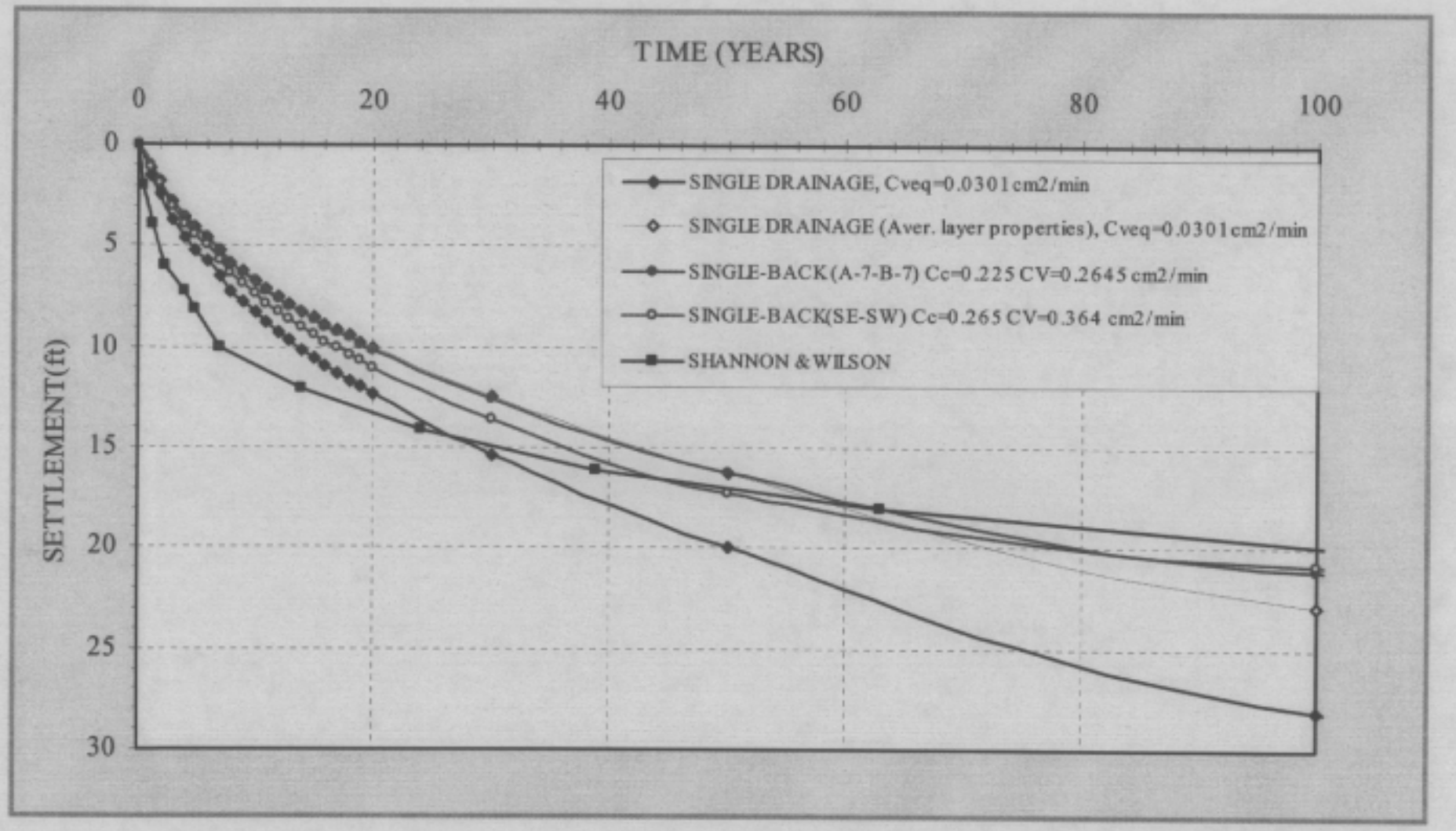
Typical Manual Calculation Consolidation

		B (ft)	1690.6		1490.6		960.6		680.6		145.6		105.6				
		Q (ksf)	0.939		1.465		3.306		3.832		5.178		7.098				
	Single drained	ρ (ft)	22.00		26.3015		35.864		37.768		40.156		42.359				
time(years)	T	U(%)	ρ (ft)	μ (ksf)	ρ (ft)	μ (ksf)	ρ (ft)	μ (ksf)	ρ (ft)	μ (ksf)	ρ (ft)	μ (ksf)	ρ (ft)	μ (ksf)			
0	0.0000	0.00	0.00	0.94	0.00	1.47	0.00	3.31	0.00	3.83	0.00	5.18	0.00	7.10			
1	0.0036	6.77	1.49	0.88	1.78	1.37	2.43	3.08	2.56	3.57	2.72	4.83	2.87	6.62			
2	0.0073	9.58	2.11	0.85	2.52	1.32	3.44	2.99	3.62	3.46	3.85	4.68	4.06	6.42			
3	0.0109	11.73	2.58	0.83	3.09	1.29	4.21	2.92	4.43	3.38	4.71	4.57	4.97	6.27			
4	0.0146	13.55	2.98	0.81	3.56	1.27	4.86	2.86	5.12	3.31	5.44	4.48	5.74	6.14			
5	0.0182	15.15	3.33	0.80	3.98	1.24	5.43	2.81	5.72	3.25	6.08	4.39	6.42	6.02			
6	0.0219	16.59	3.65	0.78	4.36	1.22	5.95	2.76	6.27	3.20	6.66	4.32	7.03	5.92			
7	0.0255	17.92	3.94	0.77	4.71	1.20	6.43	2.71	6.77	3.15	7.20	4.25	7.59	5.83			
8	0.0291	19.16	4.21	0.76	5.04	1.18	6.87	2.67	7.24	3.10	7.69	4.19	8.12	5.74			
9	0.0328	20.32	4.47	0.75	5.34	1.17	7.29	2.63	7.67	3.05	8.16	4.13	8.61	5.66			
10	0.0364	21.42	4.71	0.74	5.63	1.15	7.68	2.60	8.09	3.01	8.60	4.07	9.07	5.58			
11	0.0401	22.47	4.94	0.73	5.91	1.14	8.06	2.56	8.48	2.97	9.02	4.01	9.52	5.50			
12	0.0437	23.46	5.16	0.72	6.17	1.12	8.42	2.53	8.86	2.93	9.42	3.96	9.94	5.43			
13	0.0473	24.42	5.37	0.71	6.42	1.11	8.76	2.50	9.22	2.90	9.81	3.91	10.35	5.36			
14	0.0510	25.34	5.57	0.70	6.67	1.09	9.09	2.47	9.57	2.86	10.18	3.87	10.74	5.30			
15	0.0546	26.23	5.77	0.69	6.90	1.08	9.41	2.44	9.91	2.83	10.53	3.82	11.11	5.24			

		B (ft)	1690.6		1490.6		960.6		680.6		145.6		105.6				
		Q (ksf)	0.939		1.465		3.306		3.832		5.178		7.098				
	Single drained	ρ (ft)	21.9965		26.3015		35.864		37.768		40.156		42.359				
tiempo(years)	T	U(%)	ρ (ft)	μ (ksf)	ρ (ft)	μ (ksf)	ρ (ft)	μ (ksf)	ρ (ft)	μ (ksf)	ρ (ft)	μ (ksf)	ρ (ft)	μ (ksf)	tiempo(years)	ρ (ft)	μ (ksf)
0	0.0000	0.00	0.00	0.94	0.00	0.53	0.00	1.84	0.00	0.53	0.00	1.35	0.00	1.92	0	0.00	0.94
1	0.0036	6.77	1.49	0.88	0.29	0.49	0.65	1.72	0.13	0.49	0.16	1.25	0.15	1.79	1	1.49	0.88
2	0.0073	9.58	2.11	0.85	0.41	0.48	0.92	1.66	0.18	0.48	0.23	1.22	0.21	1.74	1		1.40
3	0.0109	11.73	2.58	0.83	0.51	0.46	1.12	1.63	0.22	0.46	0.28	1.19	0.26	1.69	2	2.40	1.34
4	0.0146	13.55	2.98	0.81	0.58	0.45	1.30	1.59	0.26	0.45	0.32	1.16	0.30	1.66	2		3.18
5	0.0182	15.15	3.33	0.80	0.65	0.45	1.45	1.56	0.29	0.45	0.36	1.14	0.33	1.63	3	3.64	3.02
6	0.0219	16.59	3.65	0.78	0.71	0.44	1.59	1.54	0.32	0.44	0.40	1.12	0.37	1.60	4	4.53	2.94
7	0.0255	17.92	3.94	0.77	0.77	0.43	1.71	1.51	0.34	0.43	0.43	1.10	0.39	1.58	4		3.47
8	0.0291	19.16	4.21	0.76	0.82	0.43	1.83	1.49	0.36	0.43	0.46	1.09	0.42	1.55	5	5.17	3.37
9	0.0328	20.32	4.47	0.75	0.87	0.42	1.94	1.47	0.39	0.42	0.49	1.07	0.45	1.53	6	5.78	3.30
10	0.0364	21.42	4.71	0.74	0.92	0.41	2.05	1.45	0.41	0.41	0.51	1.06	0.47	1.51	6		4.64
11	0.0401	22.47	4.94	0.73	0.97	0.41	2.15	1.43	0.43	0.41	0.54	1.04	0.49	1.49	7	6.49	4.49
12	0.0437	23.46	5.16	0.72	1.01	0.40	2.24	1.41	0.45	0.40	0.56	1.03	0.52	1.47	7		6.41
13	0.0473	24.42	5.37	0.71	1.05	0.40	2.34	1.39	0.47	0.40	0.58	1.02	0.54	1.45	8	7.21	6.19
14	0.0510	25.34	5.57	0.70	1.09	0.39	2.42	1.37	0.48	0.39	0.61	1.00	0.56	1.43	9	7.79	6.05
15	0.0546	26.23	5.77	0.69	1.13	0.39	2.51	1.36	0.50	0.39	0.63	0.99	0.58	1.42	10	8.32	5.94

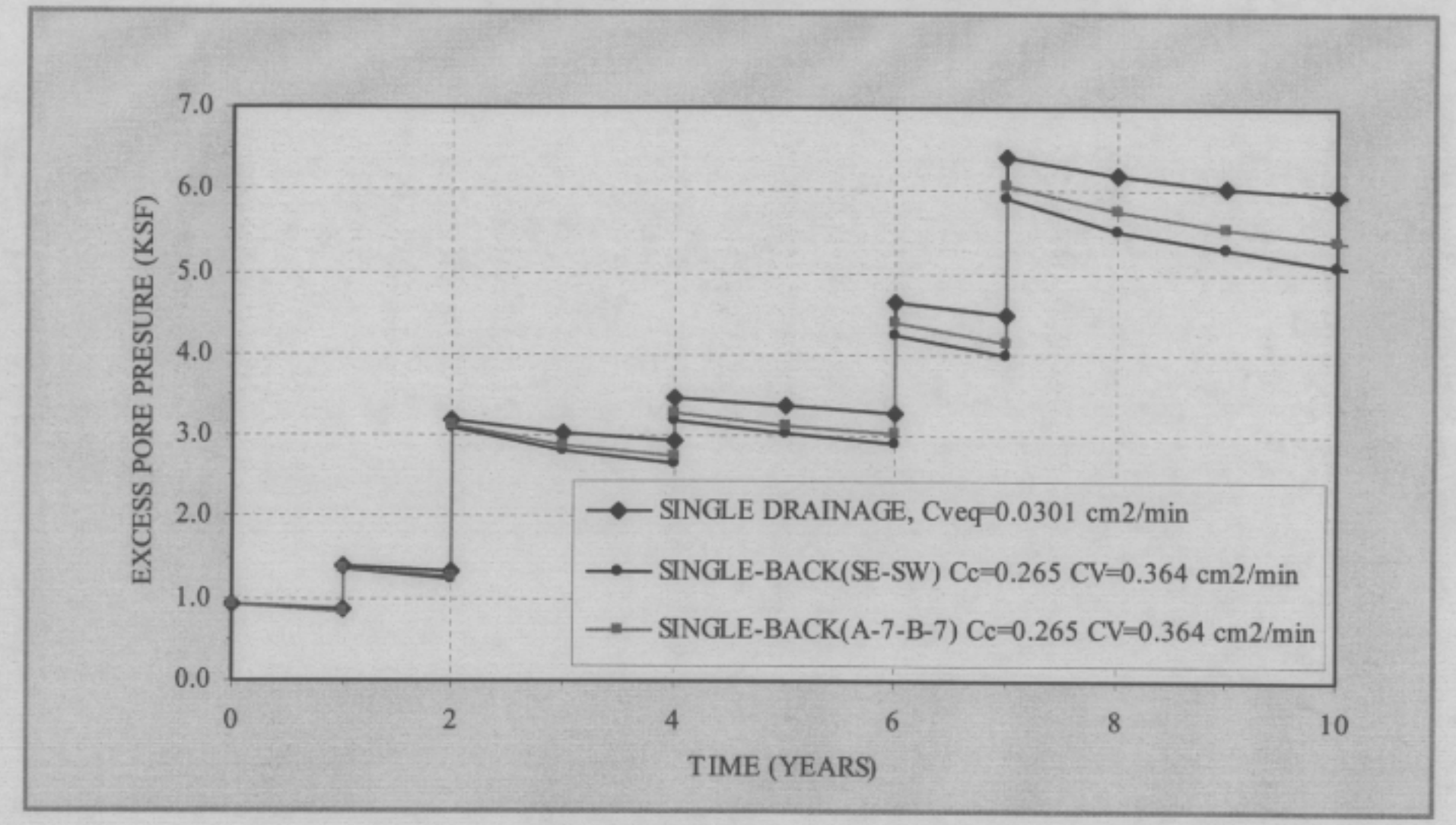
ACP

Settlement



ACP

Excess Pore Pressure



ACP

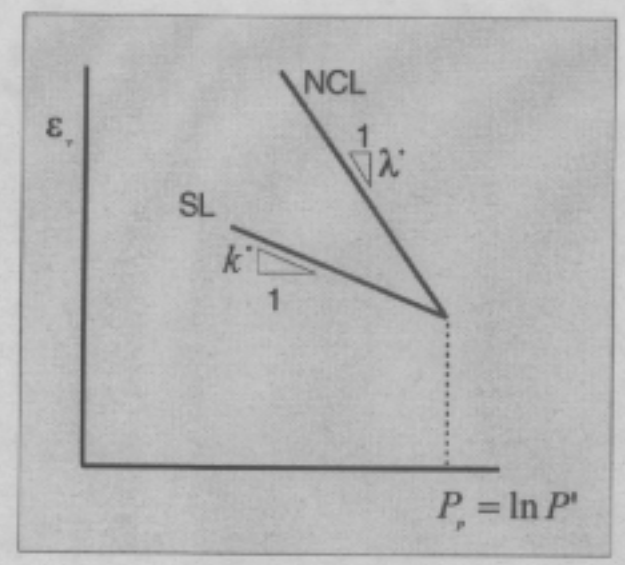
Plaxis Deformation Analysis

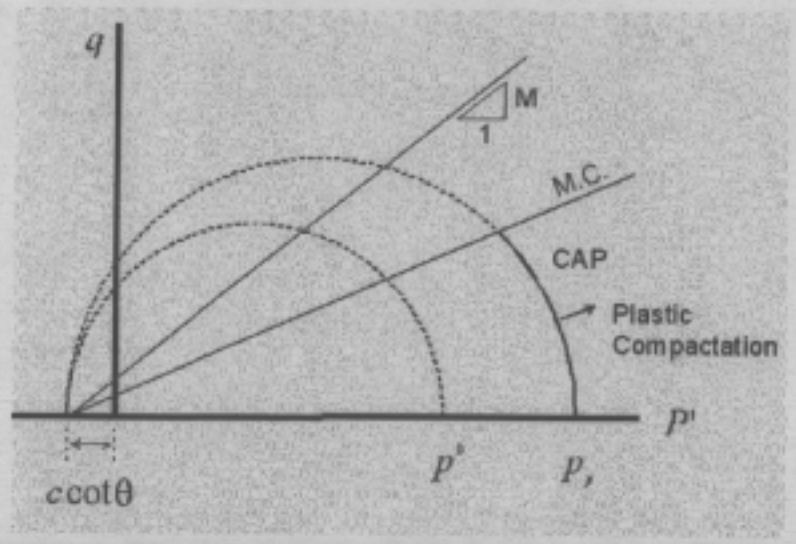
Plaxis is a finite element program for the analysis of elastic-plastic and nonlinear geomechnical problems.

Models Included:

1. Mohr-Coulomb (perfect plasticity)
2. Hardening-Soil (isotropic hardening and hyperbolic stress-strain)
3. Soft-Soil (modified Cam-Clay)
4. Soft-Soil-Creep (Time dependent behavior and Cam-Clay)

The Soft Soil Model in Plaxis





$$\varepsilon_v^e = \varepsilon_v^o - \lambda^* \ln\left(\frac{P'}{P_o}\right) \text{ virgin compresion}$$

$$\varepsilon_v^e = \varepsilon_v^{e_o} - k^* \ln\left(\frac{P'}{P_o}\right) \text{ unloading reloading}$$

$$P' = -\frac{1}{3}(\sigma_1' + \sigma_2' + \sigma_3')$$

$$\varepsilon_v = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$$

$$q = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}$$

$$para\ \sigma_2 = \sigma_3$$

$$q = \sigma_1 - \sigma_3$$

$$Yield\ function\ f = \bar{f} - P_p \qquad \bar{f} = \frac{q^2}{M^2(P' + c\cot\varphi)} + P'$$

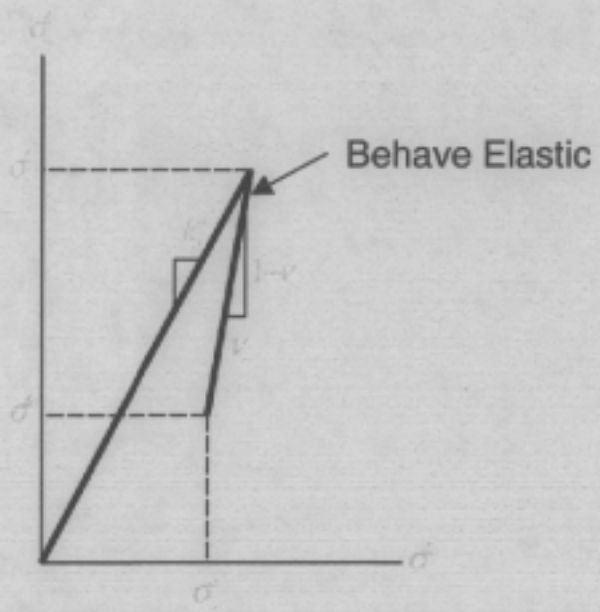
$$P_p = P_p^o \exp\left(\frac{-\varepsilon_v^p}{\lambda^* - k^*}\right)$$

$$P^s = P' + \frac{q^2}{M^2(P' + c\cot\theta)} \qquad M = f(K_o^{nc}, \lambda^*, k^*, V_u)$$

$$k = permeability\{k_x, k_y\} \qquad \log k = \log k_O + \frac{\Delta e}{C_K}$$

$$excess\ pore\ pressure\ \Delta u_w = \frac{K_w}{n} \cdot \Delta\varepsilon_V \qquad Effective\ stress\ \Delta p' = K\Delta\varepsilon_V$$

$$K_{ur} = \frac{E_{ur}}{3(1-2\nu_{ur})} = \frac{p'}{k^*}$$



Initial Stresses

$$\frac{\sigma'_{XX}}{\sigma'_{YY}} = k_O$$

where $k_O = 1 - \sin\phi$

$$\frac{\sigma^O_{XX}}{\sigma^O_{YY}} = k_O^{NC} OCR - \frac{\nu_{ur}}{(1-\nu_{ur})}(OCR-1)$$

Parameter in the Soft-Soil Model

$\lambda^* = Modified\ compression\ Index$

$k^* = Modified\ swelling\ Index$

$c = cohesion$

$\phi = friction\ angle$

$\psi = dilan\tan cy\ angle$

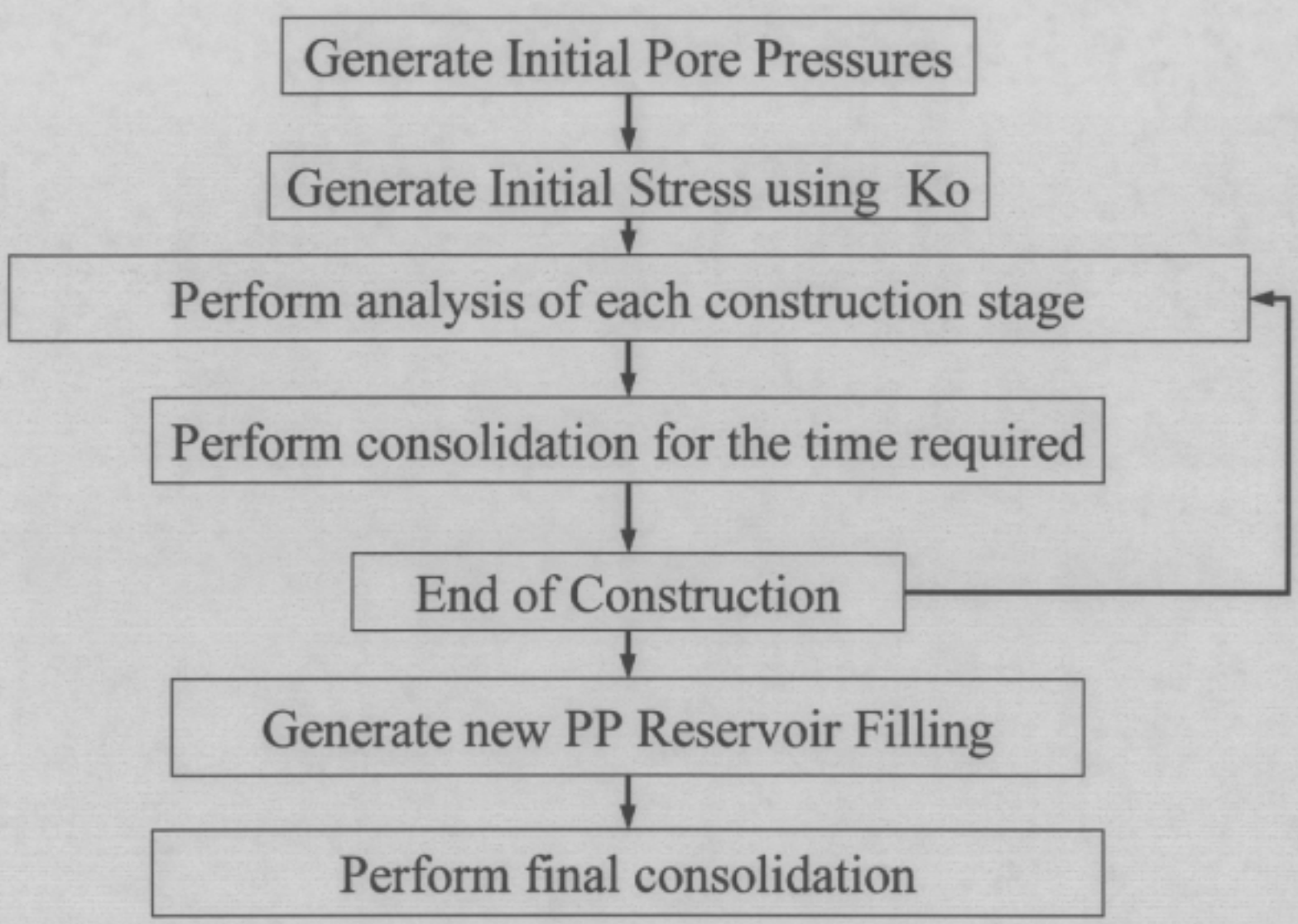
$v_{ur} = Poisson's\ ratio\ for\ unloading / reloading$

$Ko_{nc} = Coefficient\ of\ lateral\ stress\ in\ normal\ consolidation$

$M = Ko_{nc} - parameter$

ACP

Analysis Flow Chart



ACP

Parameters for Mohr-Coulomb Model

Number	Identification	Type	gam_dry	gam_wet	k_x	k_y	υ	E_ref	c_ref	ϕ	ψ	E_incr	c_incr	y_ref	C_k	e_init	T-Strength	R_inter	Interface Permeability
			[kips/f^3]	[kips/f^3]	[f/day]	[f/day]	[-]	[kips/f^2]	[kips/f^2]	[°]	[°]	[kips/f^3]	[kips/f^3]	[f]	[-]	[-]	[kips/f^2]	[-]	[-]
8	Zone 4	Undrained	0.12	0.125	280	280	0.3	1500	0.5	35	0	0	0	0	1.00E+15	1.5	0	1	Neutral
9	Zone 2	Undrained	0.115	0.115	280	280	0.3	1000	0.001	25	0	0	0	0	1.00E+15	1.5	0	1	Neutral
10	Zone 3	Undrained	0.115	0.115	280	280	0.3	1000	0.001	25	0	0	0	0	1.00E+15	1.5	0	1	Neutral
11	Zone 1 (Crushed Rock)	Drained	0.12	0.125	3000	3000	0.25	3000	0.001	35	0	0	0	0	1.00E+15	1.5	0	1	Neutral
4	Very soft Peat	Undrained	0.015	0.0643	0.09749	0.04875	0.35	4	0.1	25	0	0	0	0	1.00E+15	4.4	0	1	Neutral
2	Firm Peat and Soft Clay	Undrained	0.0243	0.0768	0.001407	0.0007036	0.35	10	0.1	25	0	0	0	0	1.00E+15	3.86	0	1	Neutral
5	Very Soft Organic Clay	Undrained	0.0487	0.0893	0.0009507	0.0004754	0.35	4	0.1	28	0	0	0	0	1.00E+15	2.45	0	1	Neutral
7	Medium Organic Silty Clay	Undrained	0.055	0.094	0.0005426	0.0002713	0.35	60	0.1	28	0	0	0	0	1.00E+15	2.03	0	1	Neutral
12	Medium Silty Fine Sand	Drained	0.063	0.0955	0.5669	0.2835	0.25	500	0.001	32	0	0	0	0	1.00E+15	1.756	0	1	Neutral
6	Firm peat & Medium sty clay	Undrained	0.042	0.083	0.0003671	0.0001835	0.35	60	0.1	28	0	0	0	0	1.00E+15	2.22	0	1	Neutral
3	Dense Sand	Drained	0.062	0.095	0.5669	0.283	0.25	700	0.001	32	0	0	0	0	1.00E+15	1.546	0	1	Neutral

ACP

Parameters for Soft Soil Model

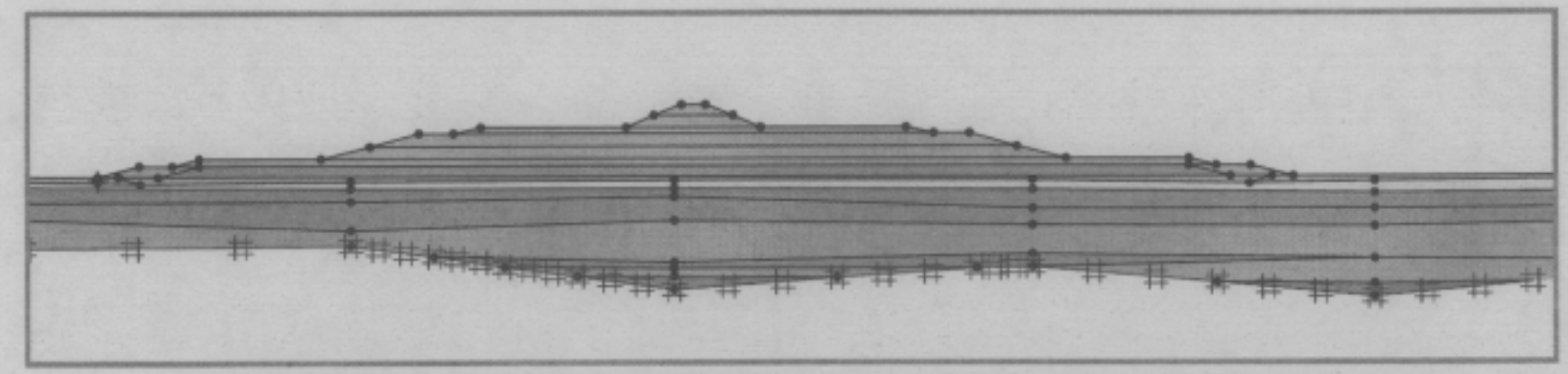
Mohr Coulomb Model																		
Number	Identification	Type	gam_dry	gam_wet	k_x	k_y	υ	E_ref	c_ref	φ	ψ	E_incr	c_incr	y_ref	C_k	e_init	T-Strength	R_inter
			[kips/f^3]	[kips/f^3]	[f/day]	[f/day]	[-]	[kips/f^2]	[kips/f^2]	[°]	[°]	[kips/f^3]	[kips/f^3]	[f]	[-]	[-]	[kips/f^2]	[-]
8	Zone 4	Undrained	0.12	0.125	280	280	0.3	1500	0.5	35	0	0	0	0	1.00E+15	1.5	0	1
9	Zone 2	Undrained	0.115	0.115	280	280	0.3	1000	0.001	25	0	0	0	0	1.00E+15	1.5	0	1
10	Zone 3	Undrained	0.115	0.115	280	280	0.3	1000	0.001	25	0	0	0	0	1.00E+15	1.5	0	1
11	Zone 1 (Crushed Rock)	Drained	0.12	0.125	3000	3000	0.25	3000	0.001	35	0	0	0	0	1.00E+15	1.5	0	1
12	Medium Silty Fine Sand	Drained	0.063	0.0955	2.84	0.284	0.25	500	0.001	32	0	0	0	0	1.00E+15	1.756	0	1
3	Dense Sand	Drained	0.062	0.095	2.83	0.283	0.25	700	0.001	32	0	0	0	0	1.00E+15	1.546	0	1

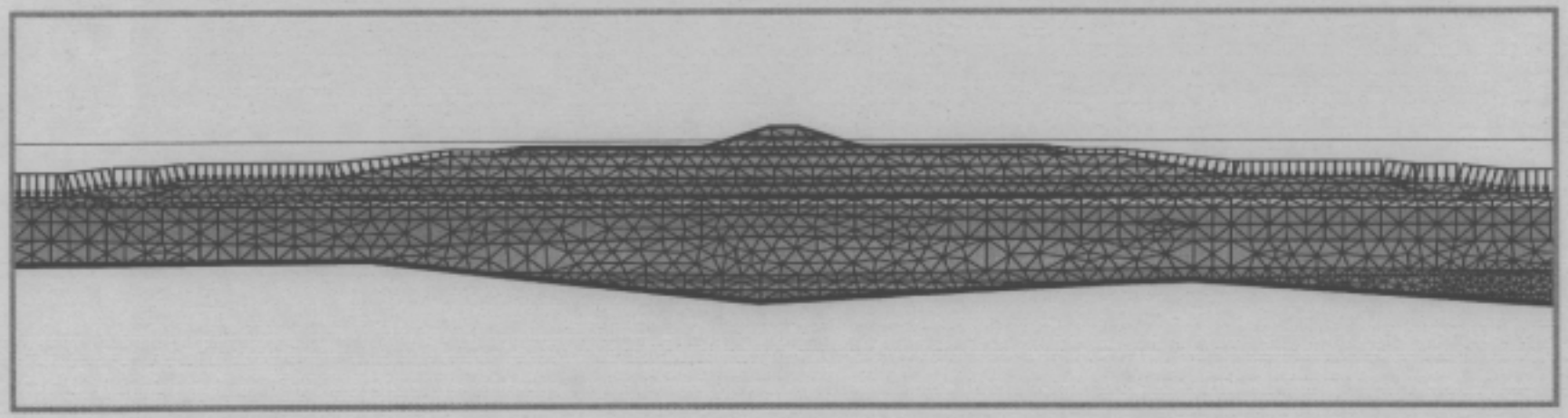
Soft Soil Model (K=constant)																		
Number	Identification	Type	gam_dry	gam_wet	k_x	k_y	λ*	κ*	υ	K0nc	M	c	φ	ψ	C_k	e_init	R_inter	Interface
			[kips/f^3]	[kips/f^3]	[f/day]	[f/day]	[-]	[-]	[-]	[-]	[-]	[kips/f^2]	[°]	[°]	[-]	[-]	[-]	[-]
4	Very soft Peat	Undrained	0.015	0.0643	0.4875	0.0488	0.29	0.0654	0.2	0.5	1.59	0.1	25	0	1.00E+15	4.427	1	Neutral
5	Very Soft Organic Clay	Undrained	0.0487	0.0893	0.0048	0.0005	0.1	0.0224	0.2	0.5	1.59	0.1	28	0	1.00E+15	2.453	1	Neutral
2	Firm Peat and Soft Clay	Undrained	0.0243	0.0768	0.0070	0.0007	0.12	0.0261	0.2	0.5	1.59	0.1	25	0	1.00E+15	3.86	1	Neutral
1	Soft to Medium Organic Silty Clay	Undrained	0.0457	0.0857	0.0028	0.0003	0.12	0.026	0.2	0.5	1.59	0.1	28	0	1.00E+15	2.699	1	Neutral
7	Medium Organic Silty Clay	Undrained	0.055	0.094	0.0027	0.0003	0.13	0.0282	0.2	0.5	1.59	0.1	28	0	1.00E+15	2.029	1	Neutral
6	Firm peat & Medium sty clay	Undrained	0.042	0.083	0.0018	0.0002	0.22	0.0498	0.2	0.5	1.59	0.1	28	0	1.00E+15	2.22	1	Neutral

Soft Soil Model (K=variable)																		
Number	Identification	Type	gam_dry	gam_wet	k_x	k_y	λ*	κ*	υ	K0nc	M	c	φ	ψ	C_k	e_init	R_inter	Interface
			[kips/f^3]	[kips/f^3]	[f/day]	[f/day]	[-]	[-]	[-]	[-]	[-]	[kips/f^2]	[°]	[°]	[-]	[-]	[-]	[-]
4	Very soft Peat	Undrained	0.015	0.0643	0.0975	0.0488	0.29	0.0654	0.2	0.5	1.59	0.1	25	0	3.676	4.427	1	Neutral
5	Very Soft Organic Clay	Undrained	0.0487	0.0893	0.0048	0.0005	0.1	0.0224	0.2	0.5	1.59	0.1	28	0	0.802	2.453	1	Neutral
2	Firm Peat and Soft Clay	Undrained	0.0243	0.0768	0.0070	0.0007	0.12	0.0261	0.2	0.5	1.59	0.1	25	0	1.312	3.86	1	Neutral
1	Soft to Medium Organic Silty Clay	Undrained	0.0457	0.0857	0.0028	0.0003	0.12	0.026	0.2	0.5	1.59	0.1	28	0	0.995	2.699	1	Neutral
7	Medium Organic Silty Clay	Undrained	0.055	0.094	0.0027	0.0003	0.13	0.0282	0.2	0.5	1.59	0.1	28	0	0.884	2.029	1	Neutral
6	Firm peat & Medium sty clay	Undrained	0.042	0.083	0.0018	0.0002	0.22	0.0498	0.2	0.5	1.59	0.1	28	0	1.663	2.22	1	Neutral

ACP

Materials and Mesh





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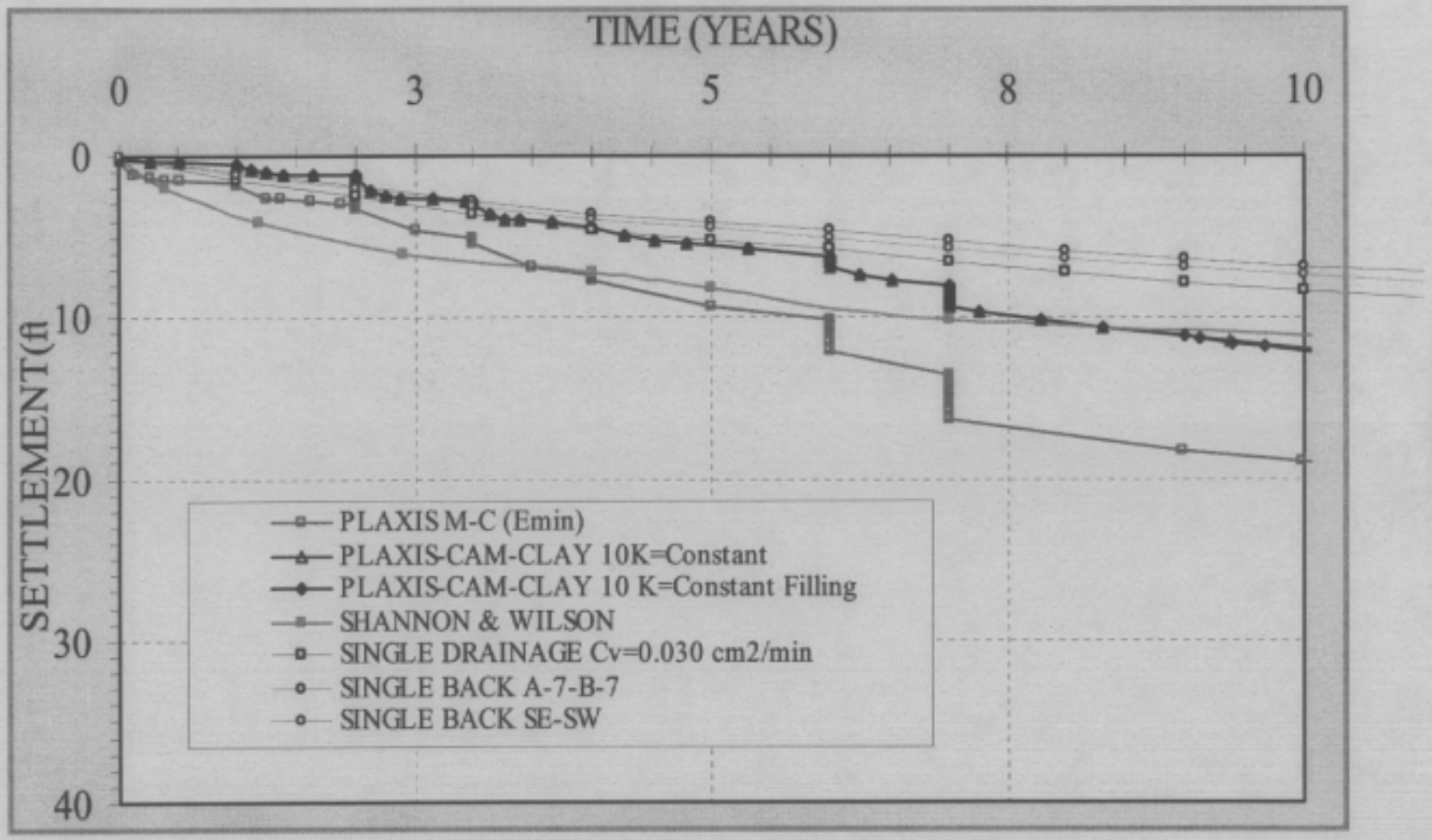
Deformation Comparison by Model



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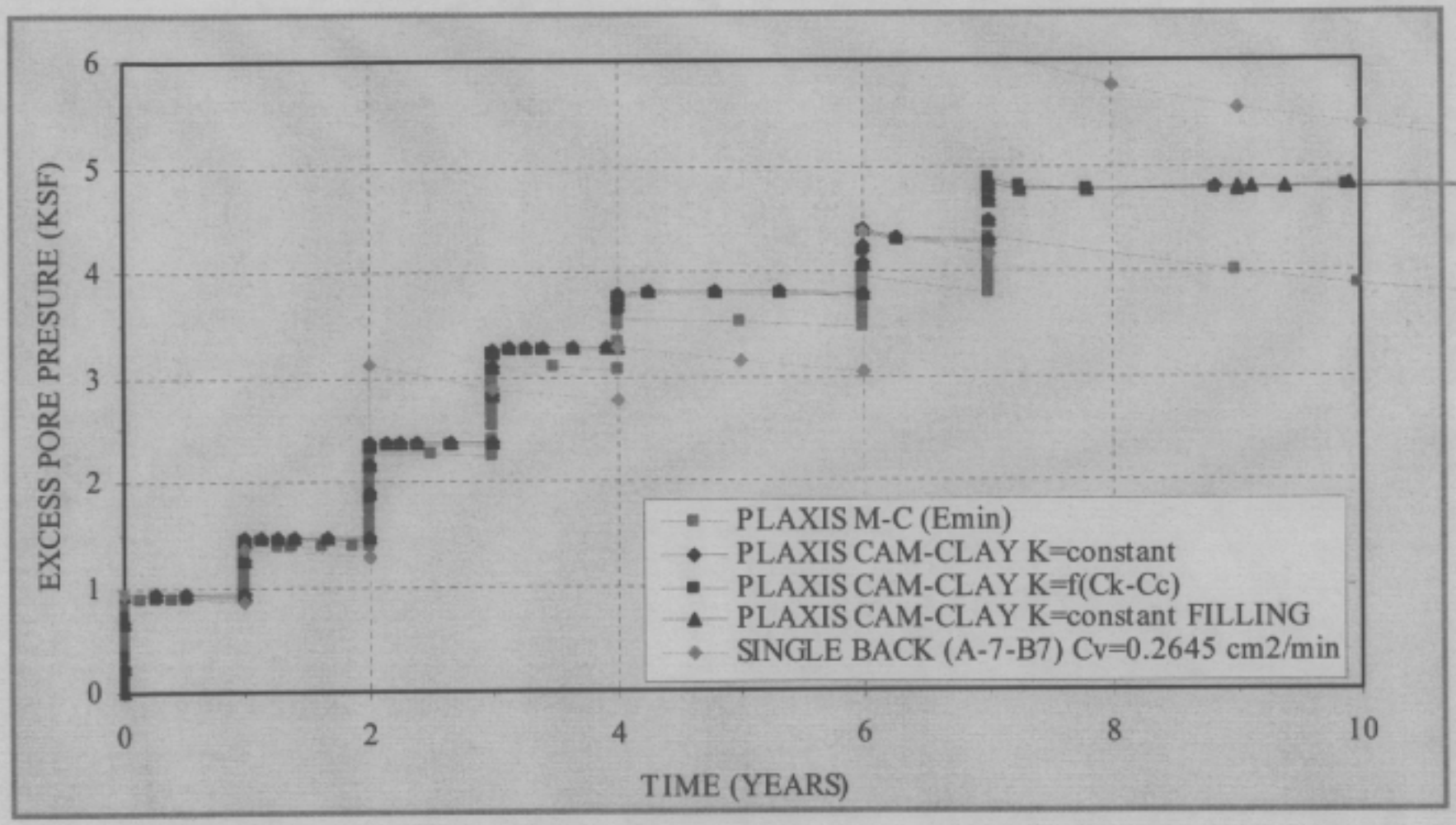
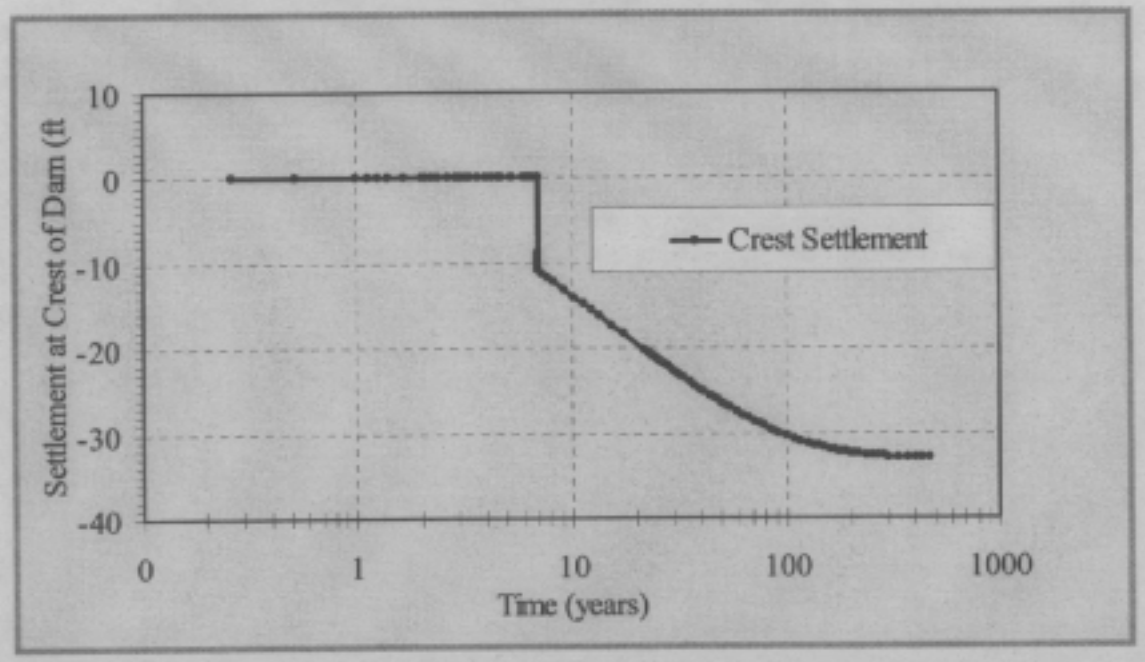
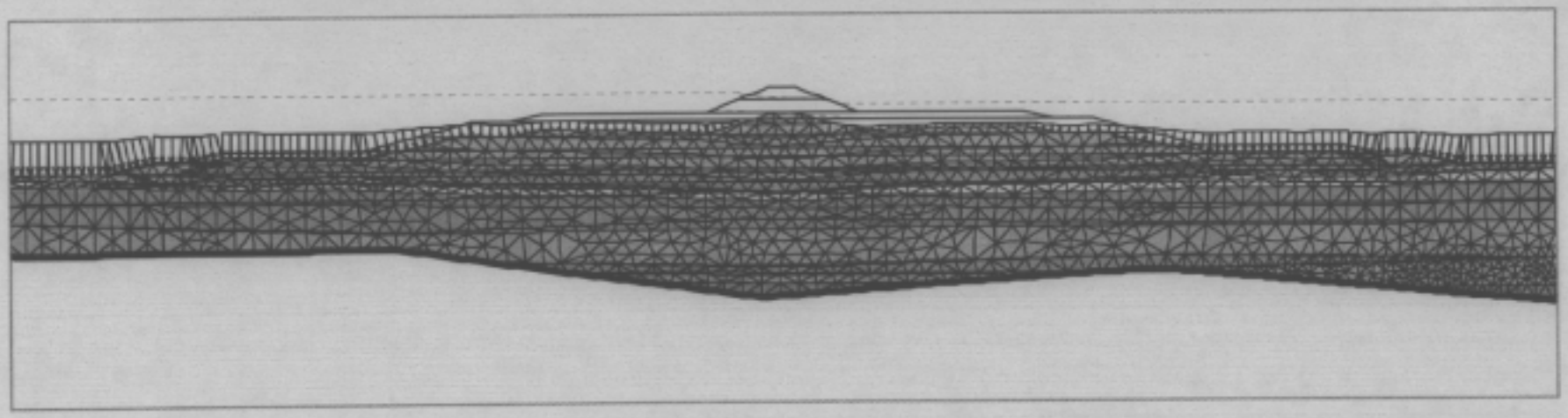
Excess Pore Pressure



ACP

Typical Deformation of the Dam





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Results

Cases	CR	Cv (cm2/min)	Settlement End of Constrution (7 Years)	Single Drainage	End of Filling Reservoir (9 Years)	Settlement End of Consolidation
			ft	ft	ft	ft
Layered by samples, Cv equiv (anisotropy correction)	Variable	0.0303		6.49		42.36
Layered by stratrigraphic unit, Cv equiv (anisotropy correction)	Variable	0.0303		5.20		34.58
Back-analysis points A-7-B-7	0.2248	0.2645		5.22		23.69
Back-analysis points SE-SW	0.2089	0.364		5.69		22.02
Plaxis Mohr-Coulomb	na	na	16.20			28.37
Plaxis Cam-clay 10k=constant	na	na	10.90			33.06
Plaxis Cam-clay 10k=constant - Reservoir	na	na	10.90		12.90	30.97
Shannon & Wilson	na	na	10.10			> 20

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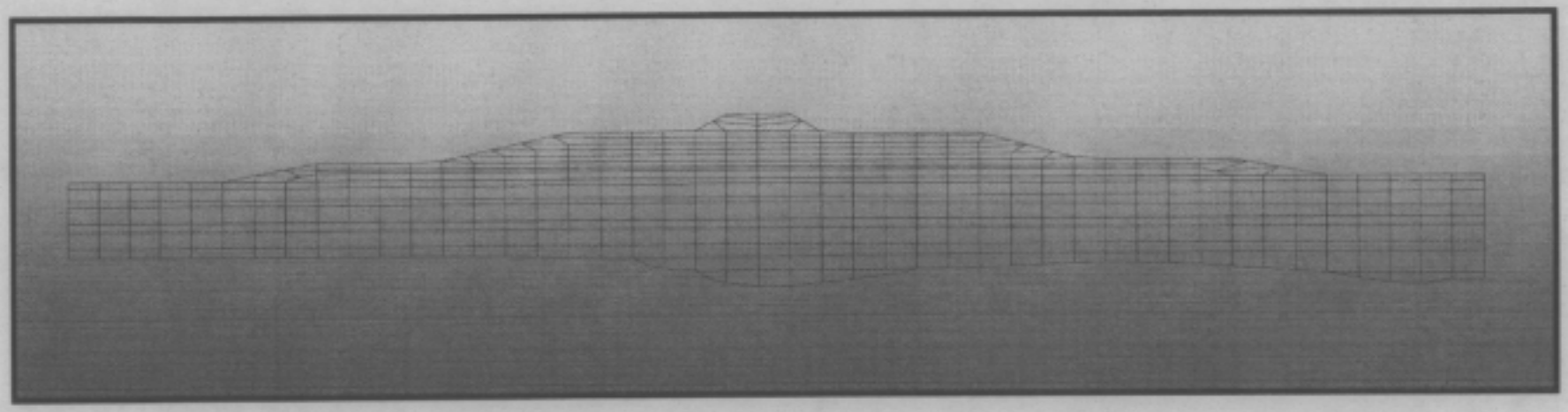
Settlements Profile

ACP

Seepage Analysis of Trinidad Dam



Geotechnical Branch

Engineering Division

ACP

Content

- Introduction
- Material Properties
- Analysis
  - Flac Analysis
  - Simplified Analysis
- Results

- **Objectives**:

  - To evaluate the groundwater flow pattern through Trinidad Dam for various lake level conditions.

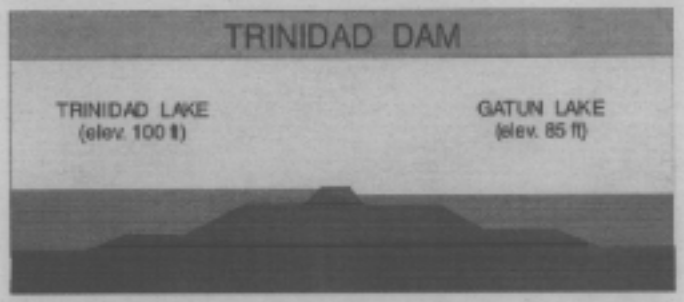
  - To determine the water infiltration rate from/to Trinidad Lake for various lake level conditions.

  - To determine the most critical flow line pattern along the dam which may cause stability problems (piping)

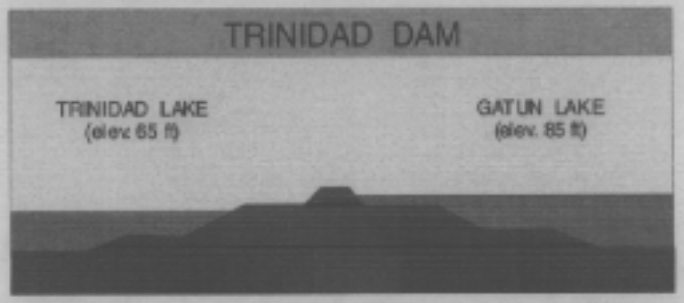
- **Methodology**

  - Since the Trinidad Dam is located between the Gatun Lake (+85.0 feet PLD) and the Trinidad Lake (+100.0 feet PLD) the analysis was performed using different lake elevations:

    - Trinidad Lake elevation = 100 ft
      Gatun Lake elevation = 85 ft



    - Trinidad Lake elevation = 75 ft
      Gatun Lake elevation = 85 ft

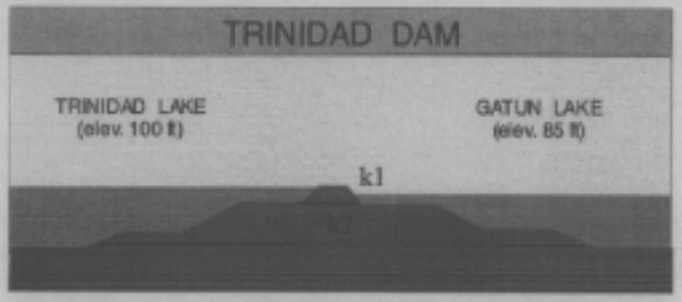


- In addition, the permeability values of the materials in the dam were changed to analyze their effects on the flow pattern and the infiltration rate:

  - Permeability values were varied from 0.01 cm/sec (28 ft/day) to 10 cm/sec (28,000 ft/day)

  - Permeability values were also modified to obtain permeability ratio contrast of different materials:

    - k1 / k2 = 1
    - k1 / k2 = 2
    - k1 / k2 = 4
    - k1 / k2 = 10



MATERIAL PARAMETERS FOR THE SEEPAGE ANALYSIS

Layer (from Top to Bottom)	Material	γ_{dry} (pcf)	k_x (ft/day)	k_y (ft/day)
Zone 4	----	120	280	280
Zone 2	----	115	280	280
Zone 3	----	115	280	280
Zone 1	Crushed Rock	120	3000	3000
Foundation 1	Very Soft Peat	15	9.75E-02	4.88E-02
Foundation 2	Very Soft Organic Clay	48.7	9.51E-04	4.75E-04
Foundation 3	Firm Peat & Soft Soil	24.3	1.41E-03	7.04E-04
Foundation 4	Soft to Medium Organic Silty Clay	45.7	5.62E-04	2.81E-04
Foundation 5	Medium Organic Silty Clay	55	5.43E-04	2.71E-04
Foundation 6	Medium Silty Fine Sand	N/A	N/A	N/A
Foundation 7	Firm Peat & Medium Organic Silty Clay	42	3.67E-04	1.84E-04
Foundation 8	Dense Sand	62	5.67E-01	2.83E-01

- **Introduction:**

  - FLAC models the flow of groundwater through a permeable solid, such as soil.

  - Flow-only calculations were performed with FLAC to establish the Pore-Pressure distribution throughout the model.

  - All mechanical calculations were inhibited from the analysis. However, mechanical properties of materials should be assign to prevent error messages, but correct values of permeability are specified.

- Bulk modulus of fluid has been assigned a low value to enable the phreatic surface to develop quickly (consolidation time is not important).

- Pore pressures are specified taking into account the appropriate lake level on each side of the model, and the saturation has been fix correspondingly, to ensure the fully saturated state of the material.

FLAC MODEL
Grid & Permeability

FLAC (Version 3.40)

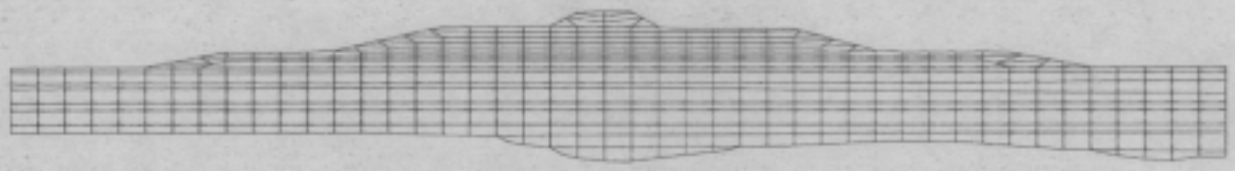
LEGEND

8-Feb- 1 20:34
step 90
-3.750E+02 <x< 2.125E+03
-1.281E+03 <y< 1.220E+03

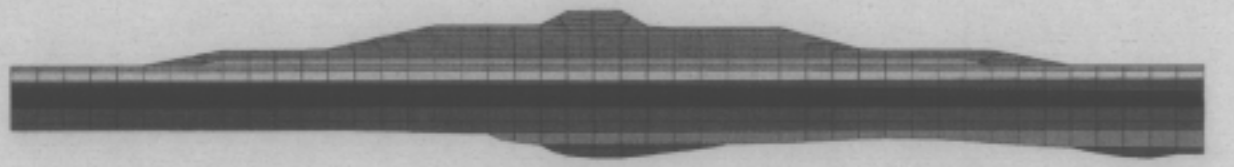
Cons. Time 2.4757E+05
Permeability

5.110E-11
7.565E-11
7.805E-11
1.321E-10
1.965E-10
1.357E-08
7.900E-08
5.200E-05
5.600E-04

Grid of Model



Permeability Layout



FLAC MODEL
Pore Pressure Distribution

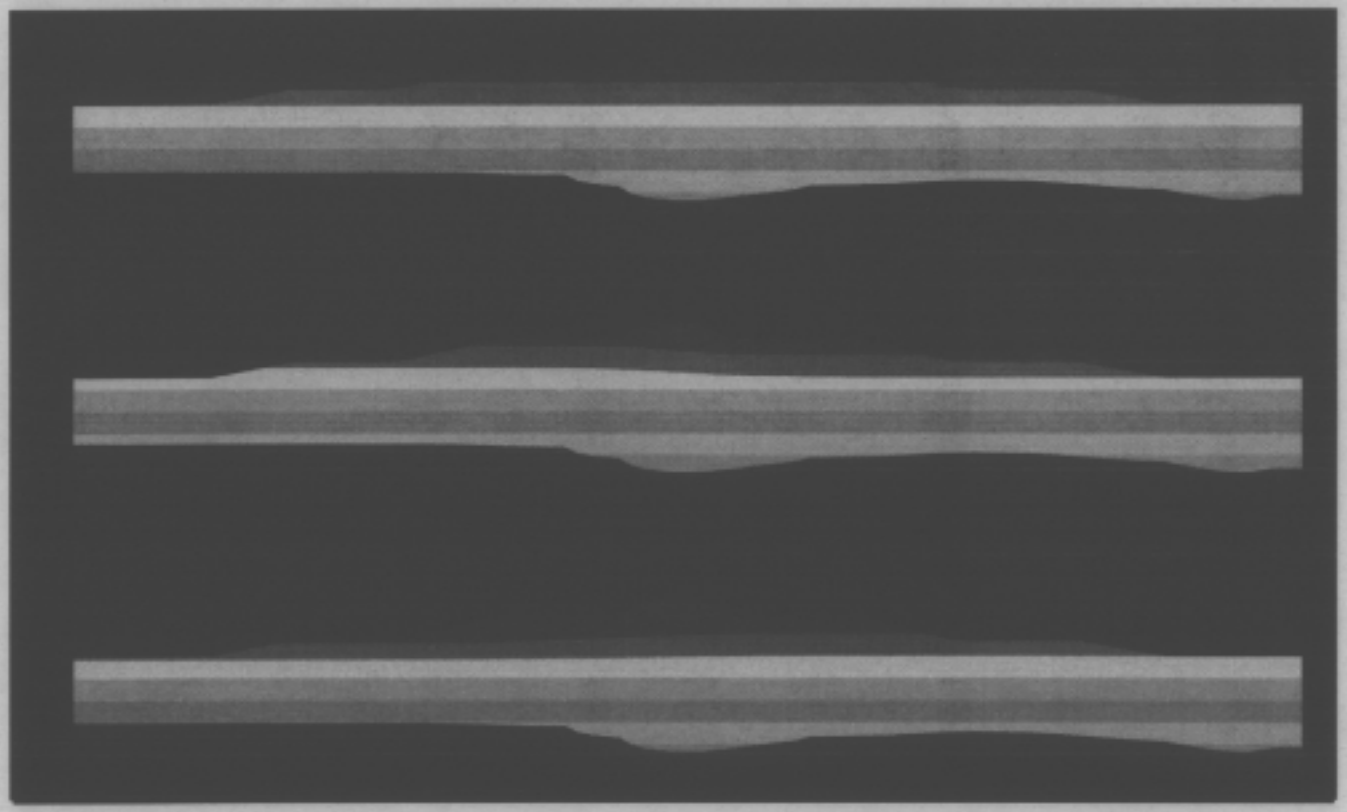
FLAC (Version 3.40)

LEGEND

8-Feb- 1 13:59
step 74
-3.750E+02 <x< 2.125E+03
-1.281E+03 <y< 1.220E+03

Cons. Time 1.7880E+05
Pore pressure contours
0.00E+00
2.50E+03
5.00E+03
7.50E+03
1.00E+04
1.25E+04
1.50E+04

Contour interval= 2.50E+03



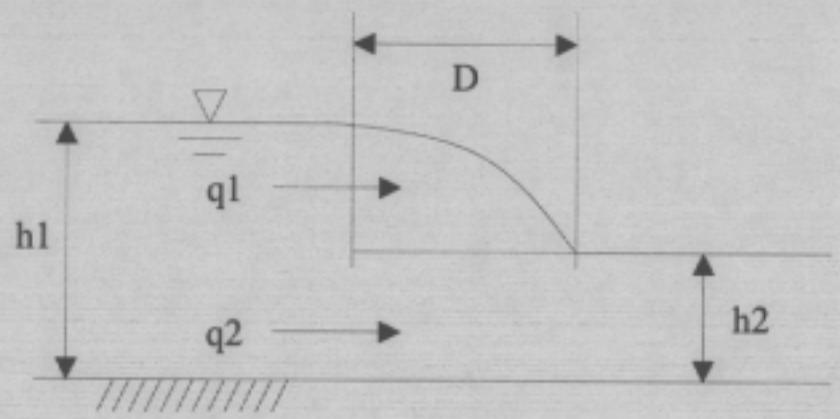
SIMPLIFIED ANALYSIS
Darcy & Dupuit Theory

- For any dam having a free surface, the flow patterns is considered to be confined & unconfined

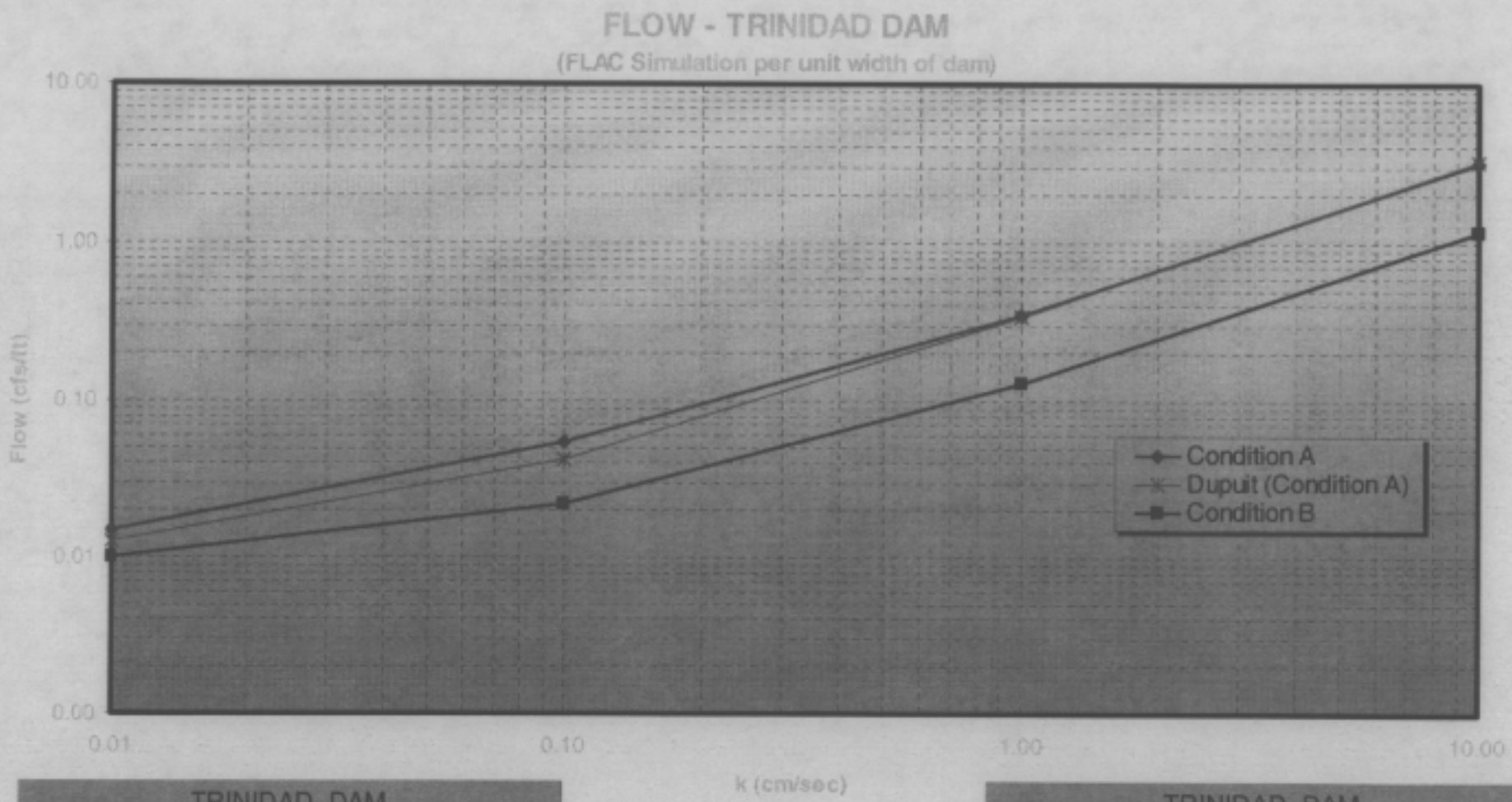
- Darcy's theory deals with the confined pattern while Dupuit theory deals with the unconfined pattern of the flow

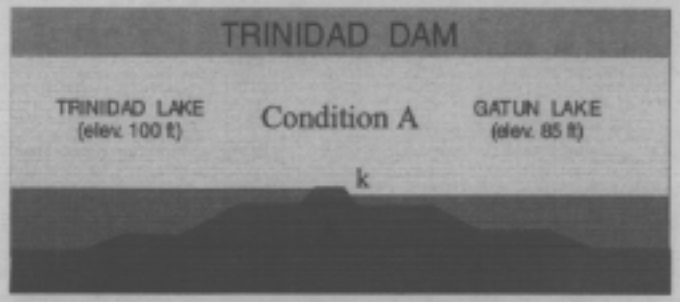
Dupuit Theory $$q_1 = k\frac{h_1^2 - h_2^2}{2D}$$

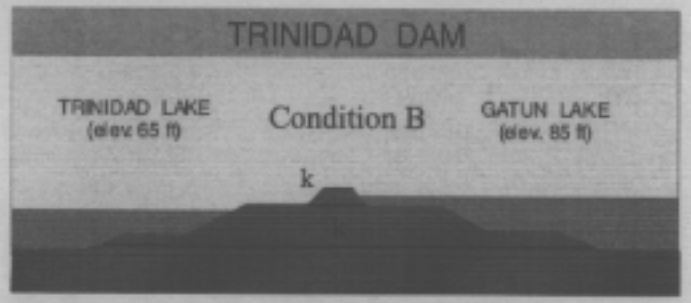
Darcy's Law $$q_2 = k\frac{h_1 - h_2}{D}h_2$$



ACP

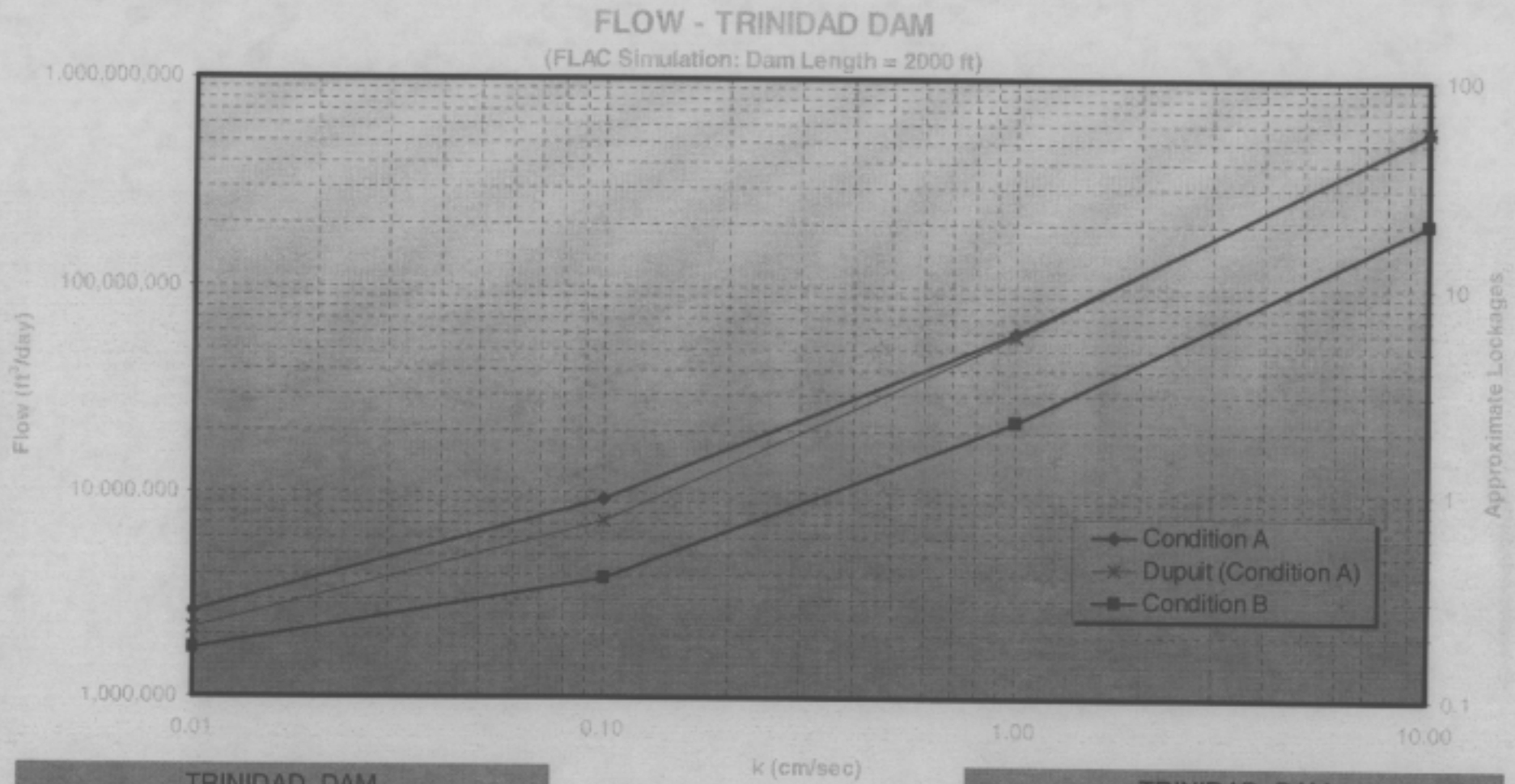

FLOW - TRINIDAD DAM
(FLAC Simulation per unit width of dam)
10.00
1.00
0.10
0.01
0.00
Flow (cfs/ft)
0.01
0.10
1.00
10.00
k (cm/sec)
Condition A
Dupuit (Condition A)
Condition B

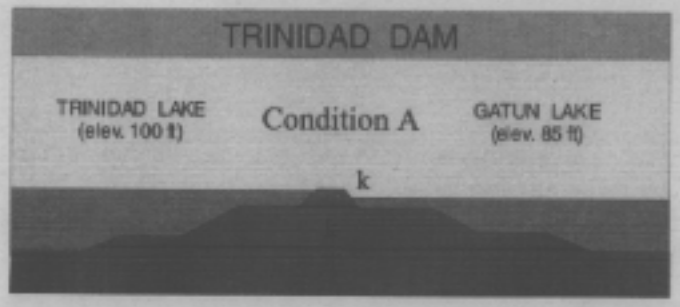

TRINIDAD DAM
TRINIDAD LAKE
(elev. 100 ft)
Condition A
GATUN LAKE
(elev. 85 ft)
k

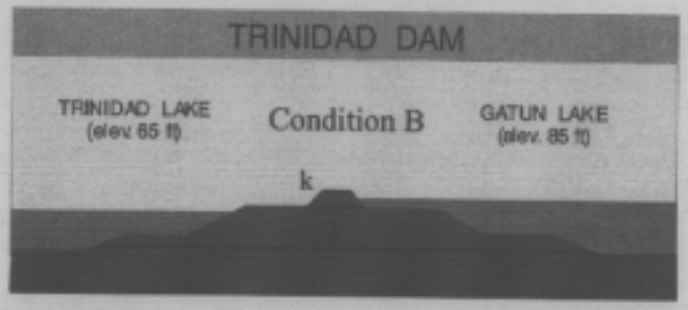

TRINIDAD DAM
TRINIDAD LAKE
(elev. 65 ft)
Condition B
GATUN LAKE
(elev. 85 ft)
k

Results

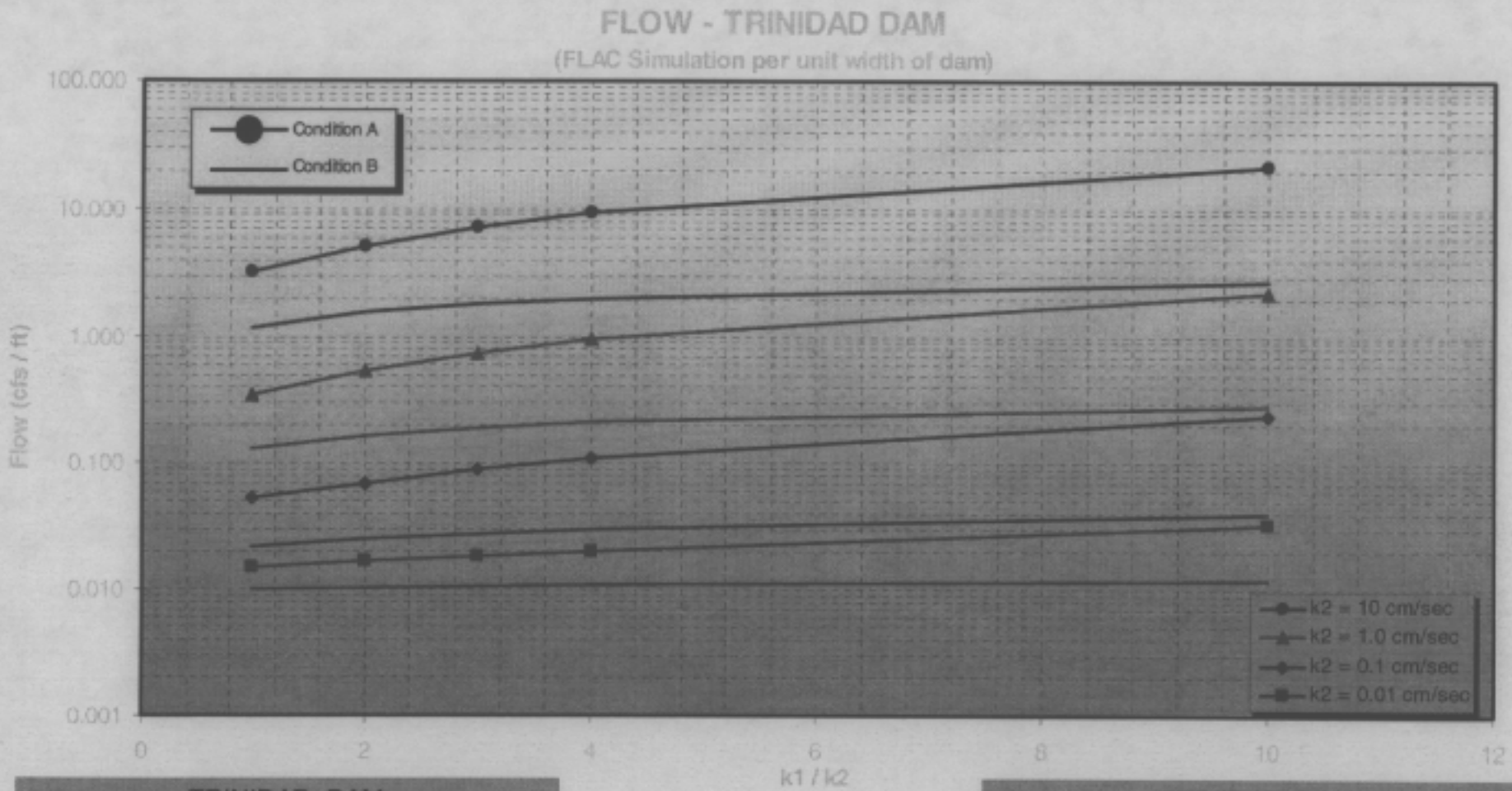
ACP

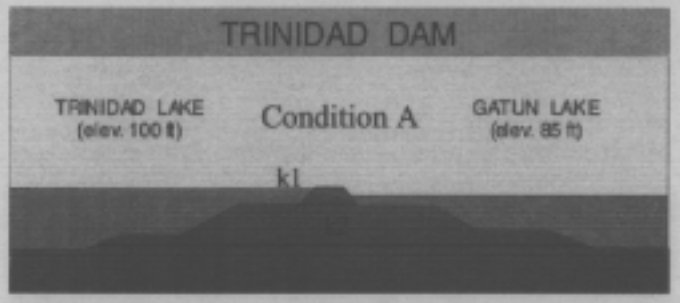

FLOW - TRINIDAD DAM
(FLAC Simulation: Dam Length = 2000 ft)
1,000,000,000
100,000,000
10,000,000
1,000,000
Flow (ft³/day)
100
10
1
0.1
Approximate Lockages
0.01
0.10
1.00
10.00
k (cm/sec)
Condition A
Dupuit (Condition A)
Condition B

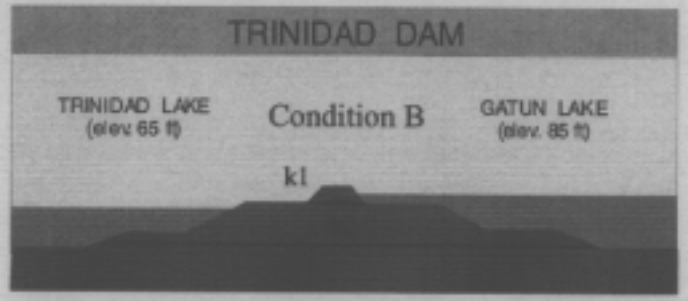

TRINIDAD DAM
TRINIDAD LAKE
(elev. 100 ft)
Condition A
GATUN LAKE
(elev. 85 ft)
k


TRINIDAD DAM
TRINIDAD LAKE
(elev. 65 ft)
Condition B
GATUN LAKE
(elev. 85 ft)
k

ACP

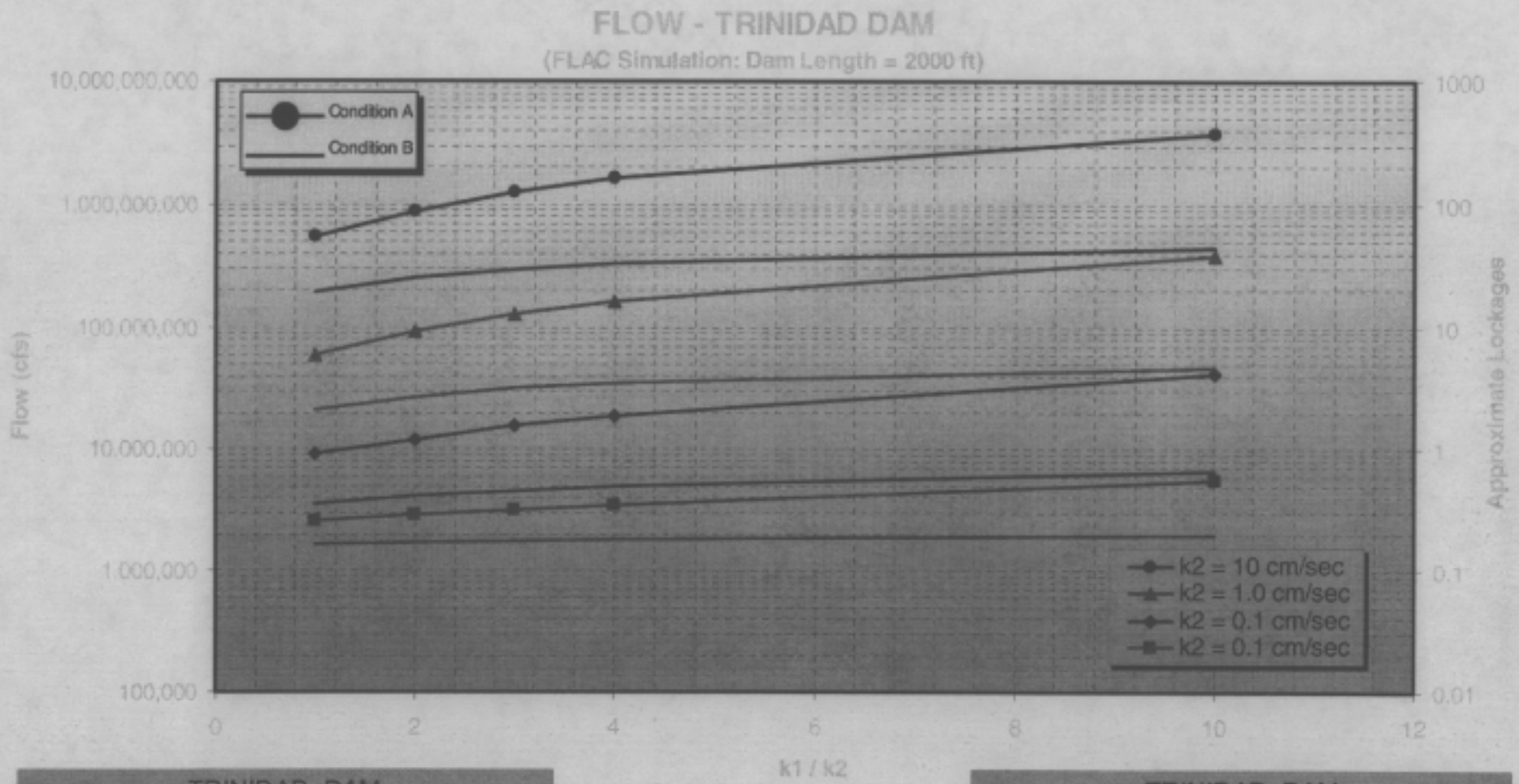

FLOW - TRINIDAD DAM
(FLAC Simulation per unit width of dam)
Condition A
Condition B
Flow (cfs / ft)
100.000
10.000
1.000
0.100
0.010
0.001
0
2
4
6
8
10
12
k1 / k2
k2 = 10 cm/sec
k2 = 1.0 cm/sec
k2 = 0.1 cm/sec
k2 = 0.01 cm/sec

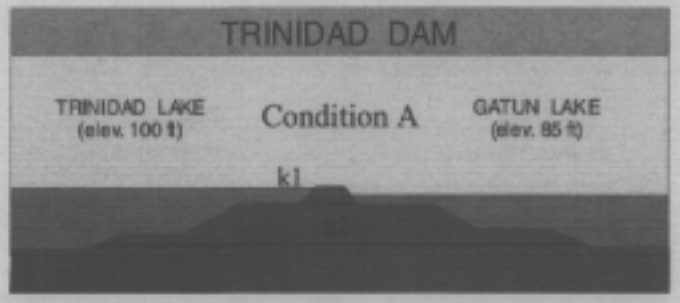

TRINIDAD DAM
TRINIDAD LAKE
(elev. 100 ft)
Condition A
GATUN LAKE
(elev. 85 ft)
k1

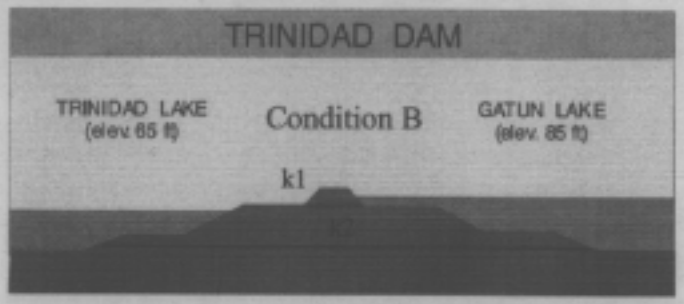

TRINIDAD DAM
TRINIDAD LAKE
(elev. 65 ft)
Condition B
GATUN LAKE
(elev. 85 ft)
k1

Results

ACP


FLOW - TRINIDAD DAM
(FLAC Simulation: Dam Length = 2000 ft)
Condition A
Condition B
k2 = 10 cm/sec
k2 = 1.0 cm/sec
k2 = 0.1 cm/sec
k2 = 0.1 cm/sec
Flow (cfs)
10,000,000,000
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
Approximate Lockages
1000
100
10
1
0.1
0.01
0
2
4
6
8
10
12
k1 / k2


TRINIDAD DAM
TRINIDAD LAKE
(elev. 100 ft)
Condition A
GATUN LAKE
(elev. 85 ft)
k1


TRINIDAD DAM
TRINIDAD LAKE
(elev. 65 ft)
Condition B
GATUN LAKE
(elev. 85 ft)
k1

ACP

END

Stability Analysis by Stress and Deformations

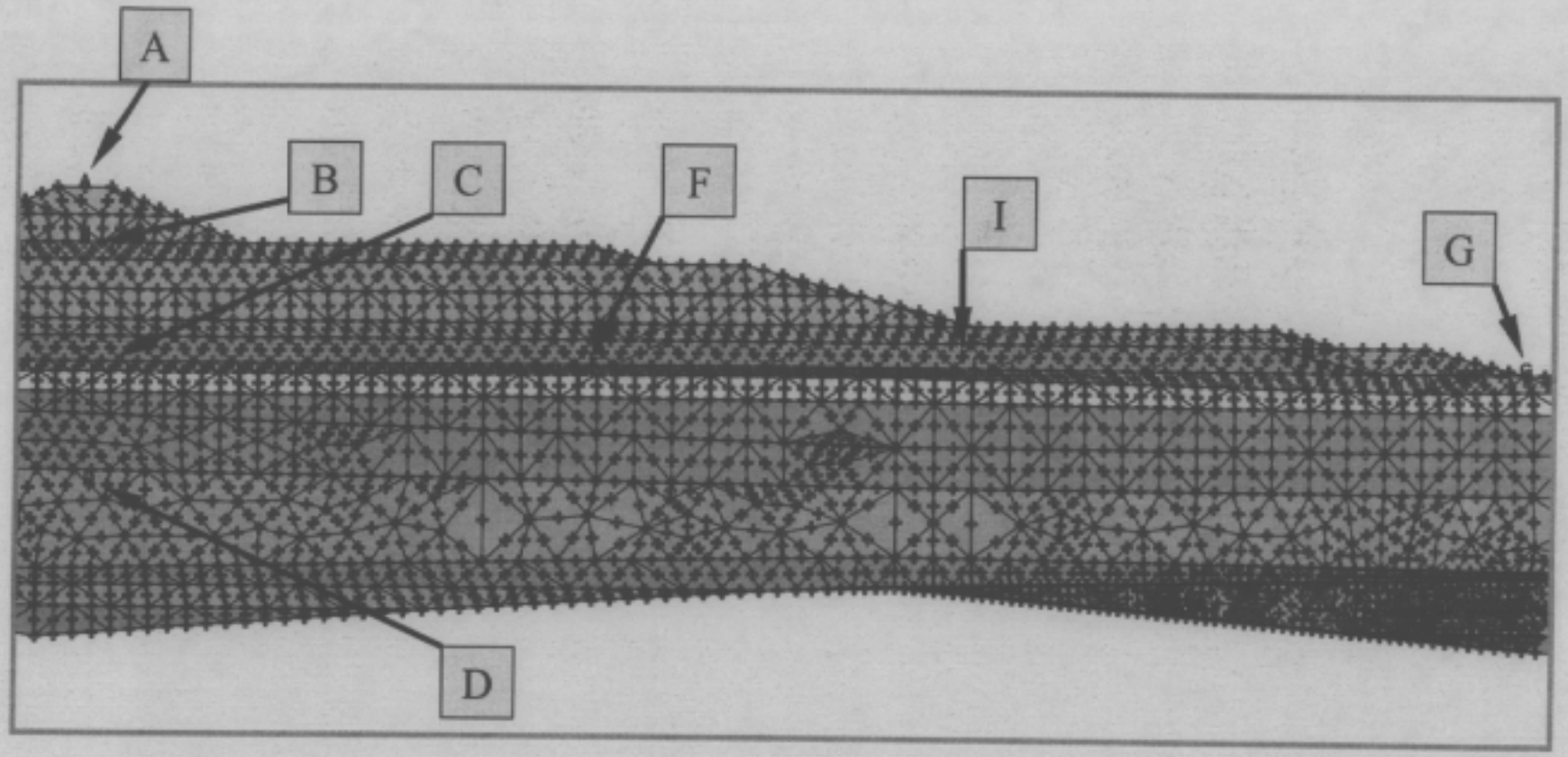
Procedure:

1. **Start from a quasi-equilibrium stress condition**
2. **The Factor of Safety is obtained by reducing progressively the strength parameters ϕ and C until failure occurs**
3. **At this point the Factor of Safety is given by:**

$$FS = \frac{available\ strength}{strength\ at\ failure}$$

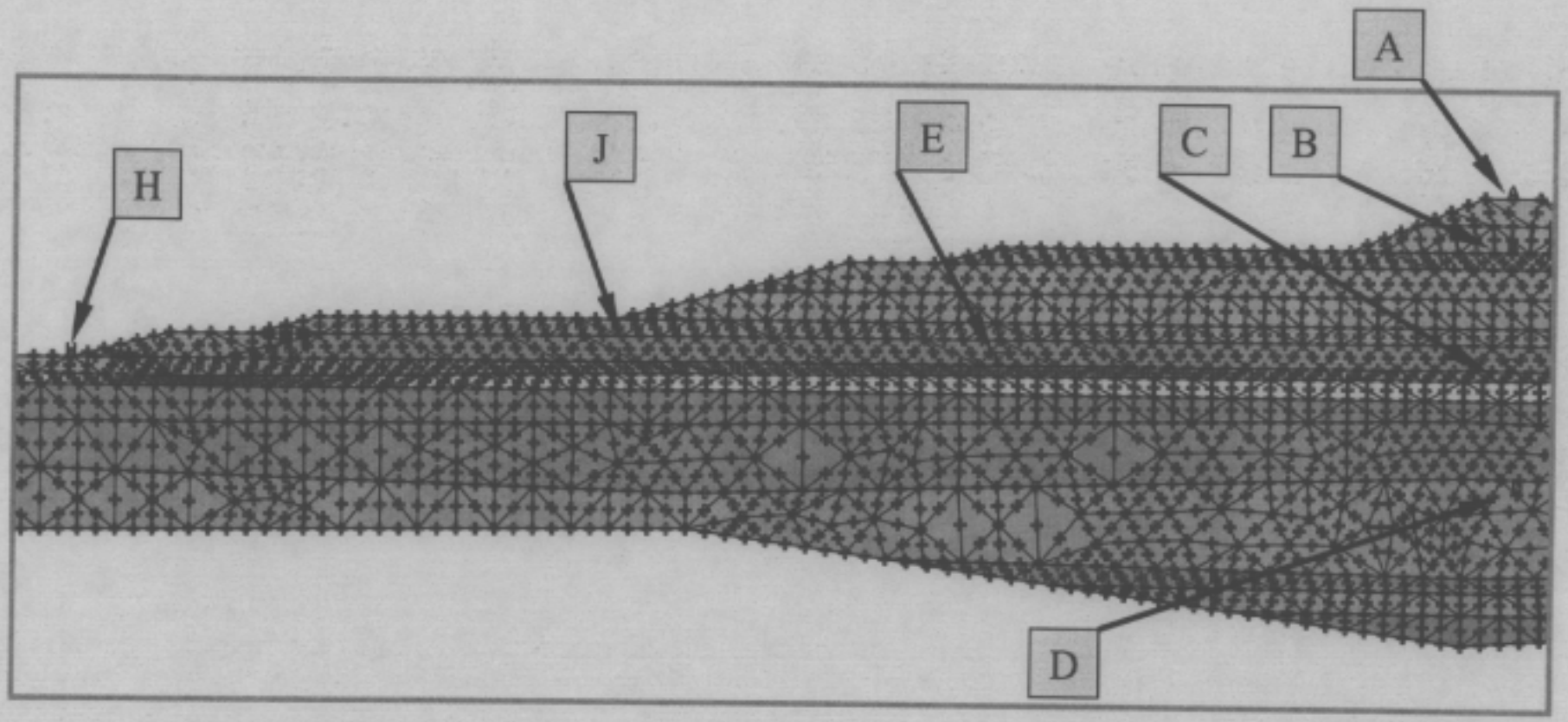
ACP

Control Points



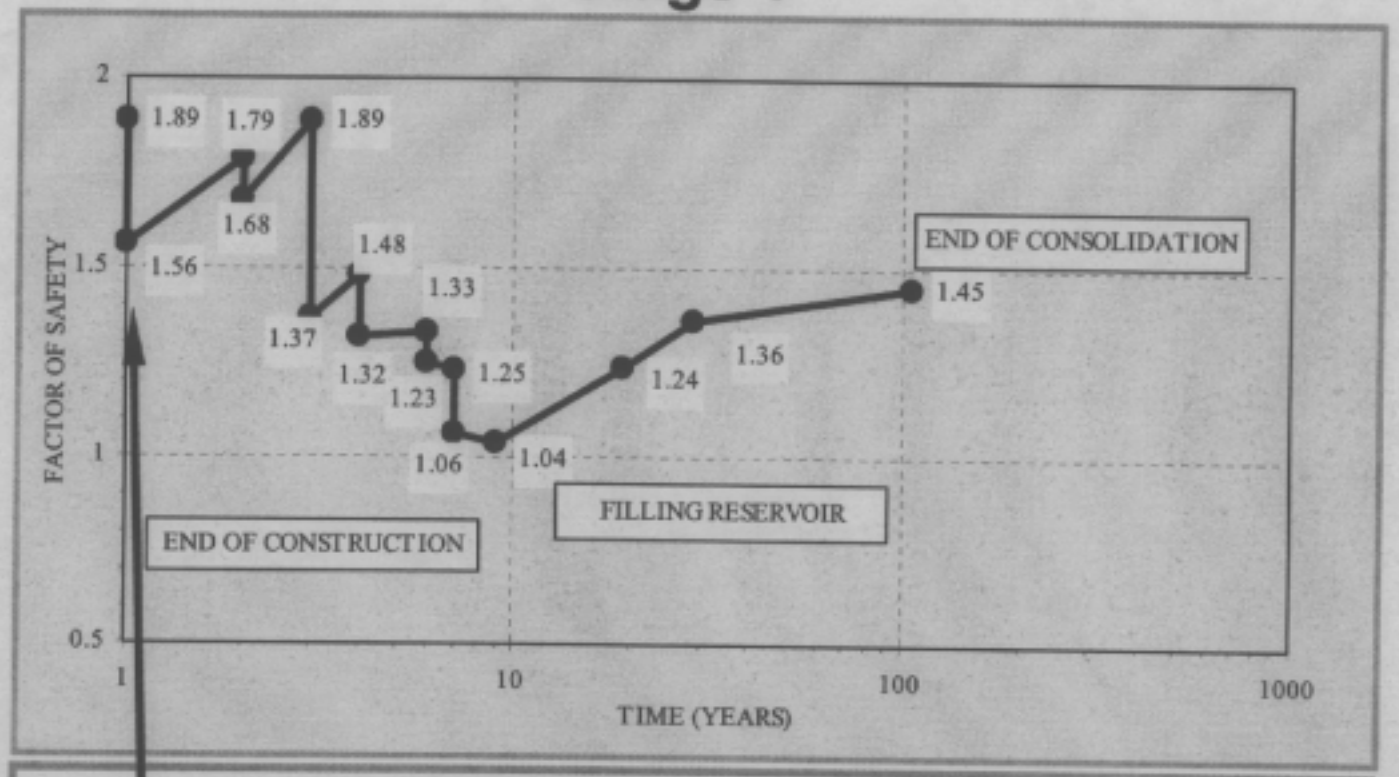
ACP

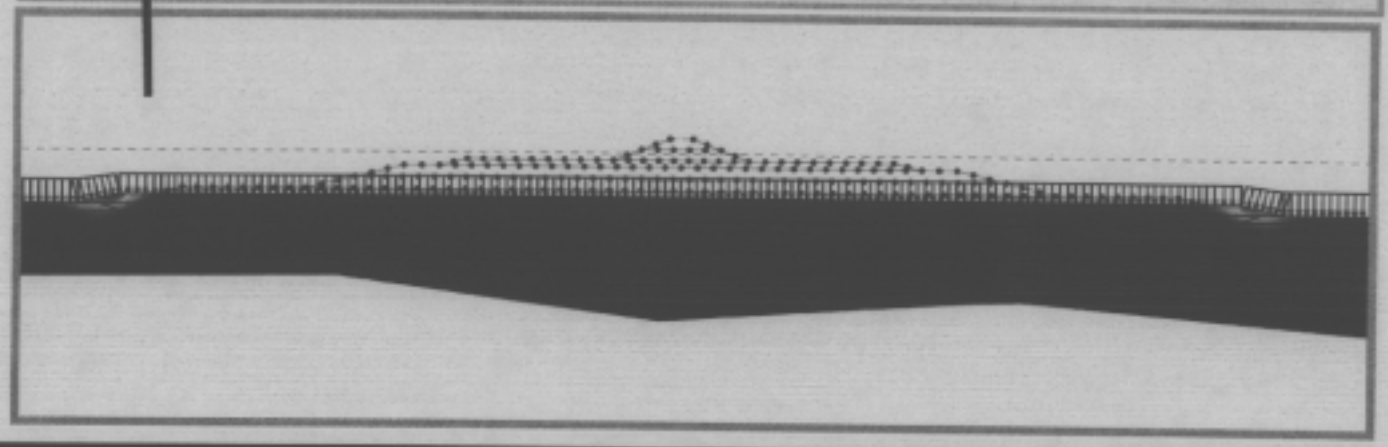
Control Points



ACP

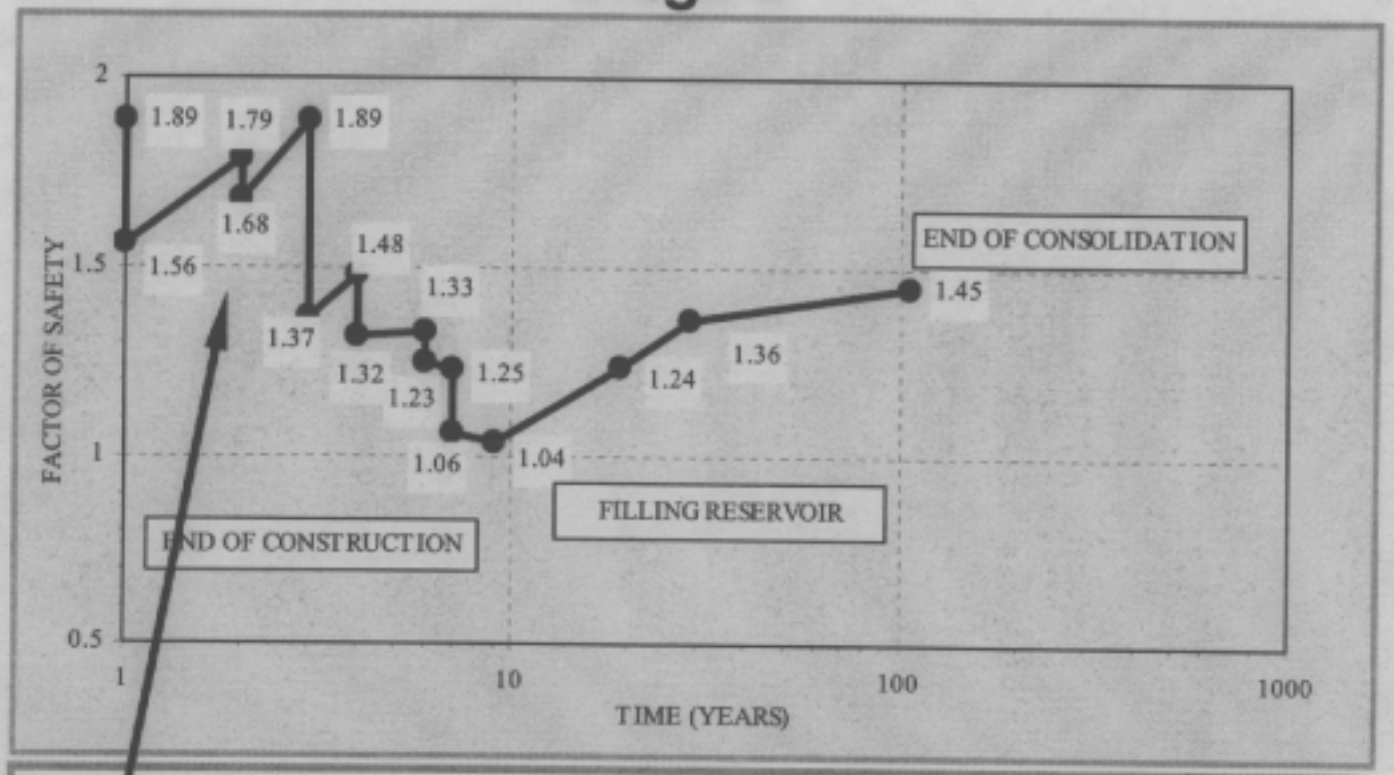
Stage 1

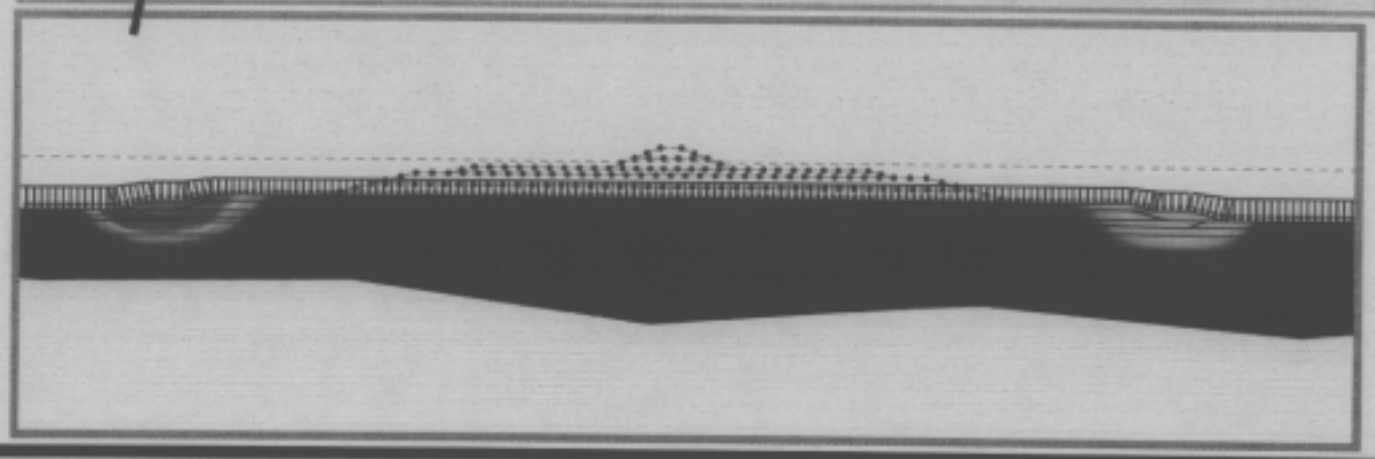

2
1.5
1
0.5
FACTOR OF SAFETY
1.89
1.79
1.89
1.68
1.56
1.48
1.33
1.37
1.32
1.23
1.25
1.06
1.04
1.24
1.36
1.45
END OF CONSOLIDATION
FILLING RESERVOIR
END OF CONSTRUCTION
1
10
100
1000
TIME (YEARS)



ACP

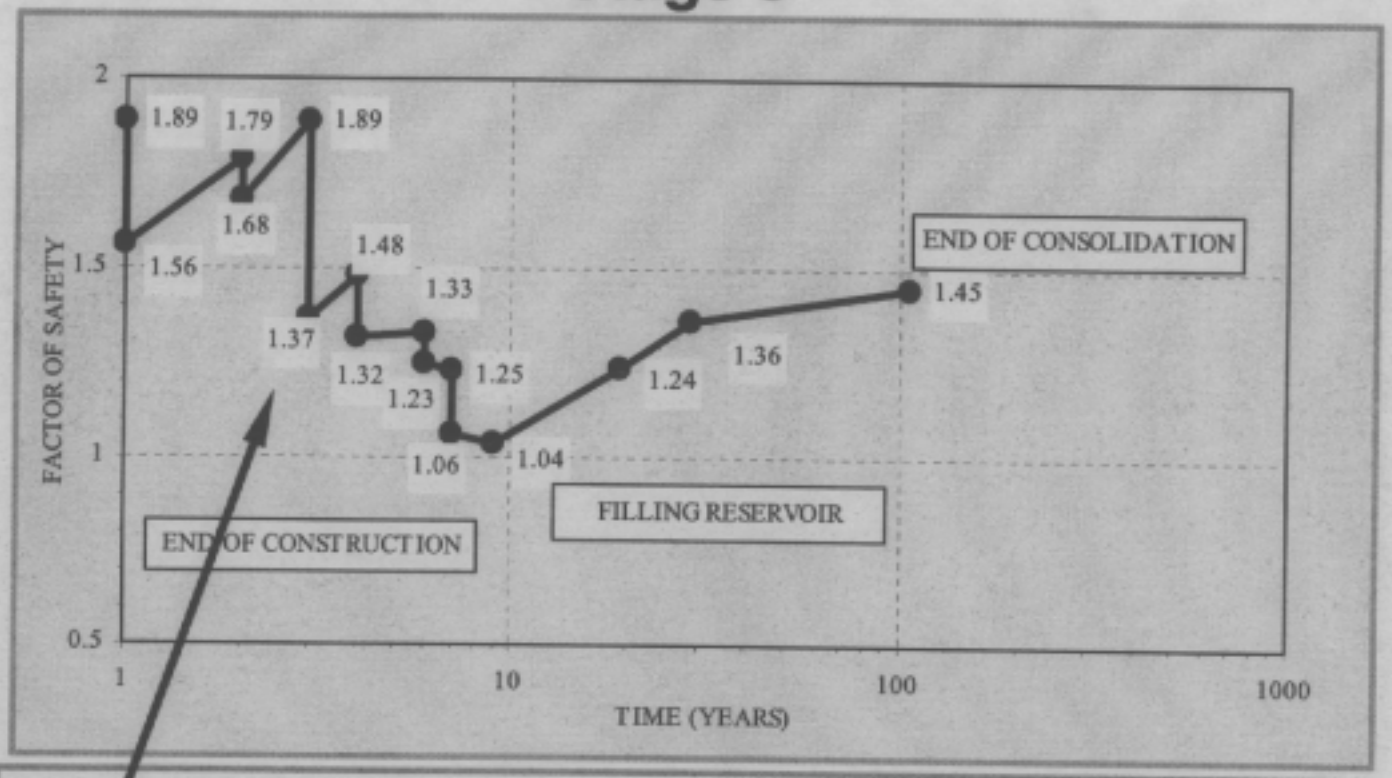
Stage 2

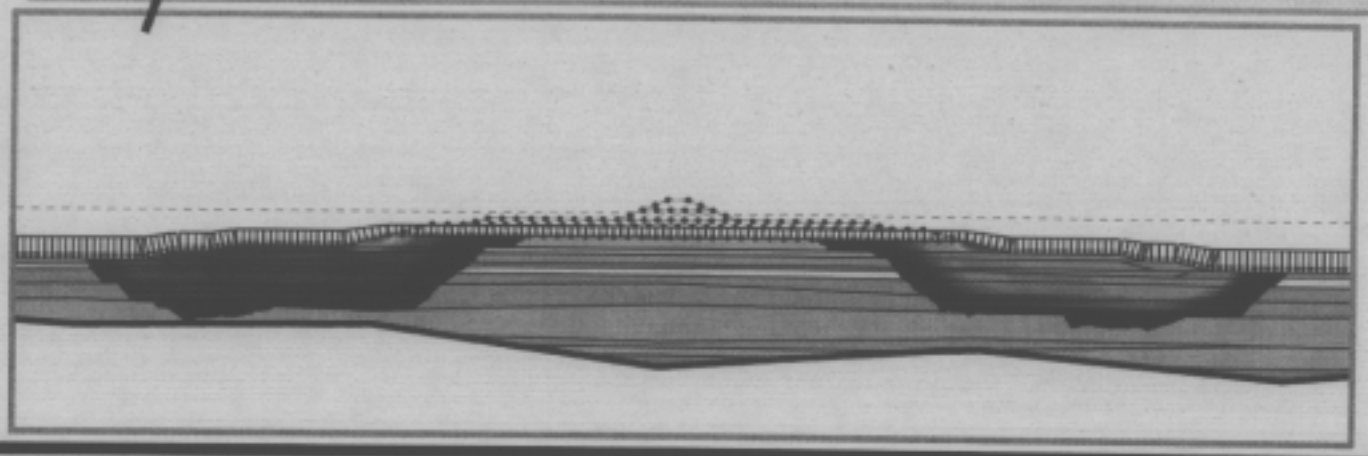

2
1.5
1
0.5
FACTOR OF SAFETY
1.89
1.79
1.89
1.68
1.56
1.48
1.33
1.37
1.32
1.23
1.25
1.06
1.04
1.24
1.36
1.45
END OF CONSOLIDATION
FILLING RESERVOIR
END OF CONSTRUCTION
1
10
100
1000
TIME (YEARS)



ACP

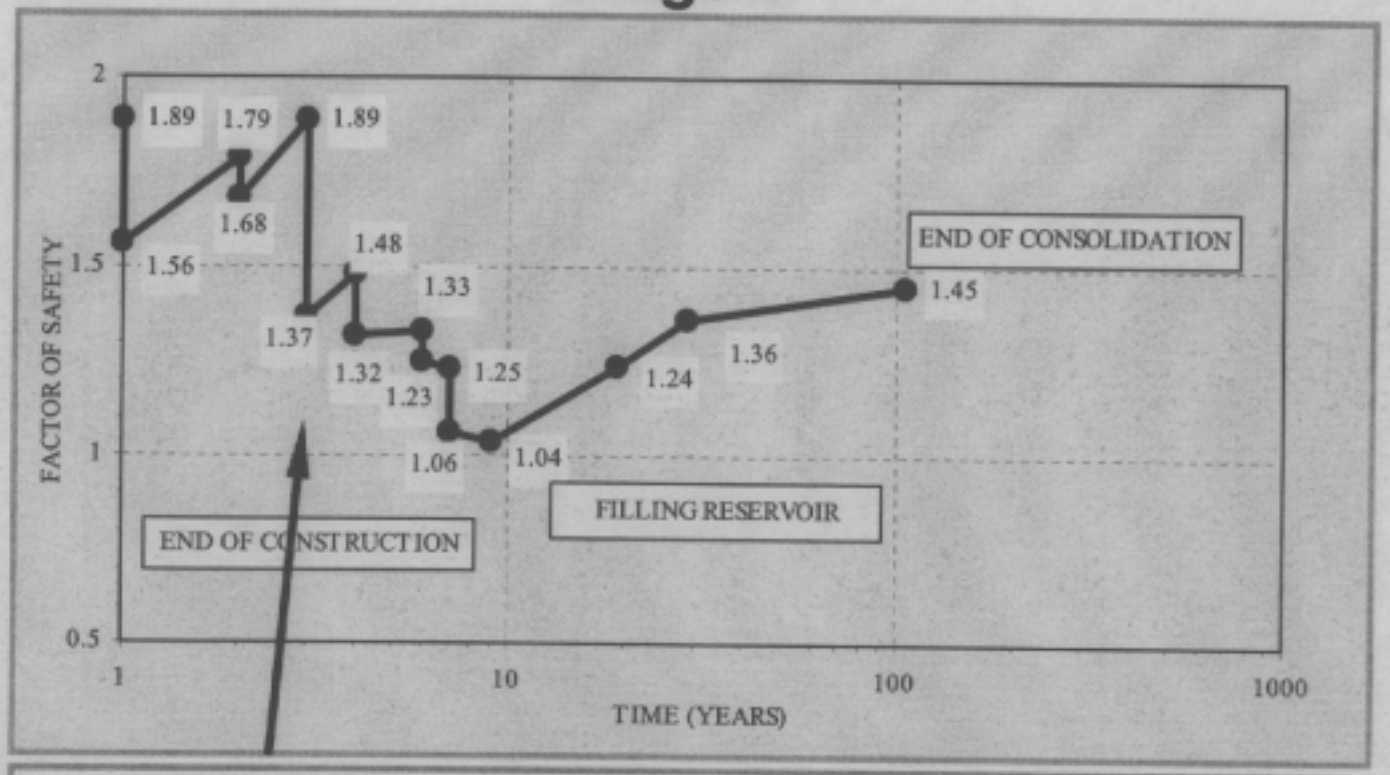
Stage 3

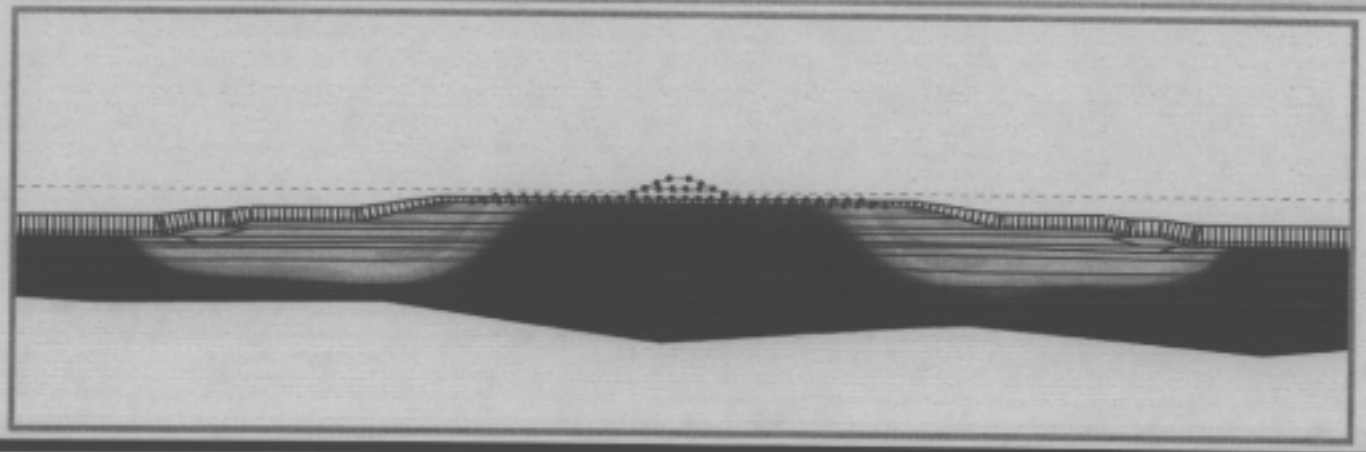

FACTOR OF SAFETY
2
1.5
1
0.5
1.89
1.79
1.89
1.68
1.56
1.48
1.33
1.37
1.32
1.23
1.25
1.06
1.04
1.24
1.36
1.45
END OF CONSOLIDATION
FILLING RESERVOIR
END OF CONSTRUCTION
1
10
100
1000
TIME (YEARS)



ACP

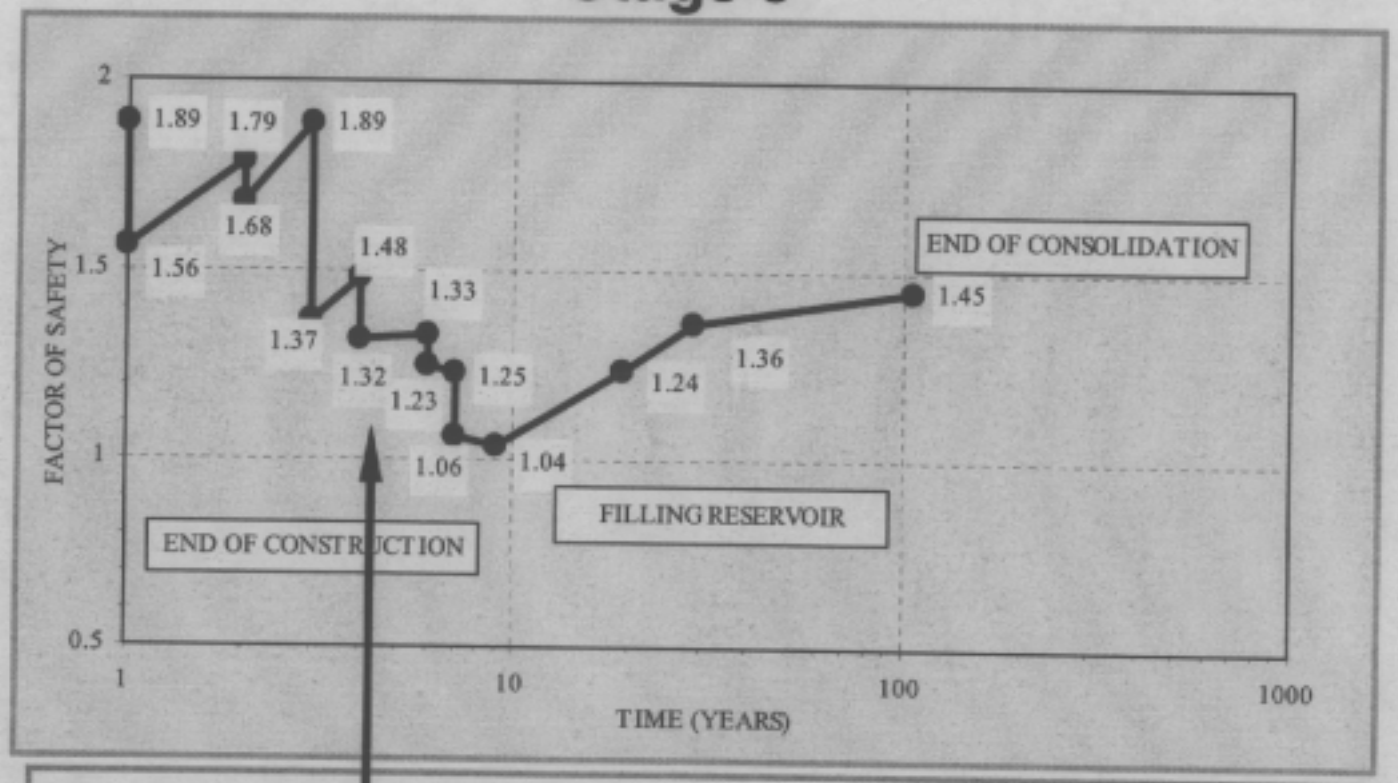
Stage 4

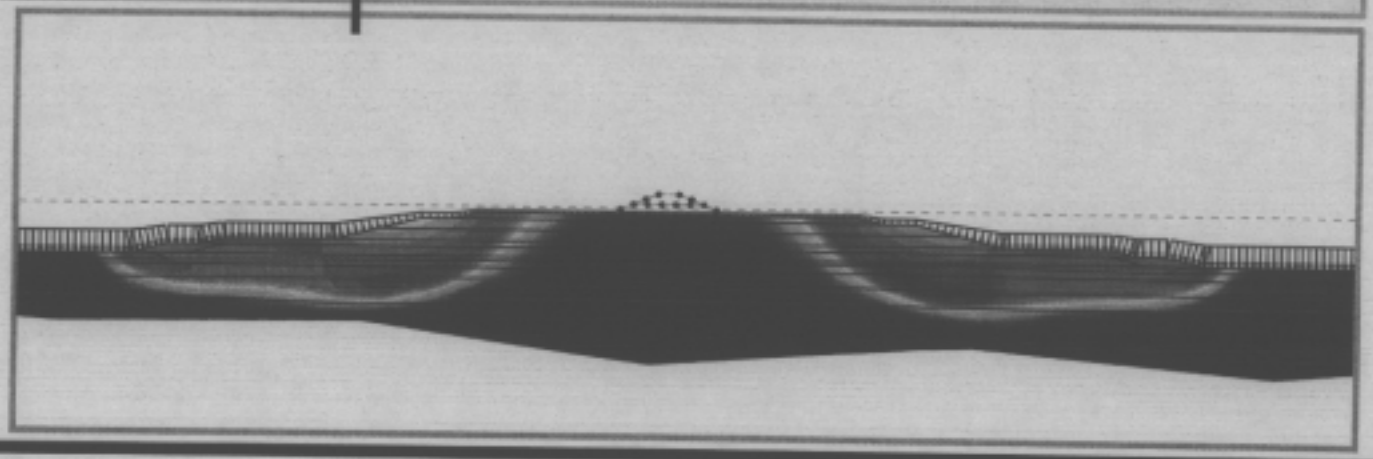

FACTOR OF SAFETY
2
1.5
1
0.5
1.89
1.79
1.89
1.68
1.56
1.48
1.33
1.37
1.32
1.23
1.25
1.06
1.04
1.24
1.36
1.45
END OF CONSOLIDATION
FILLING RESERVOIR
END OF CONSTRUCTION
1
10
100
1000
TIME (YEARS)



ACP

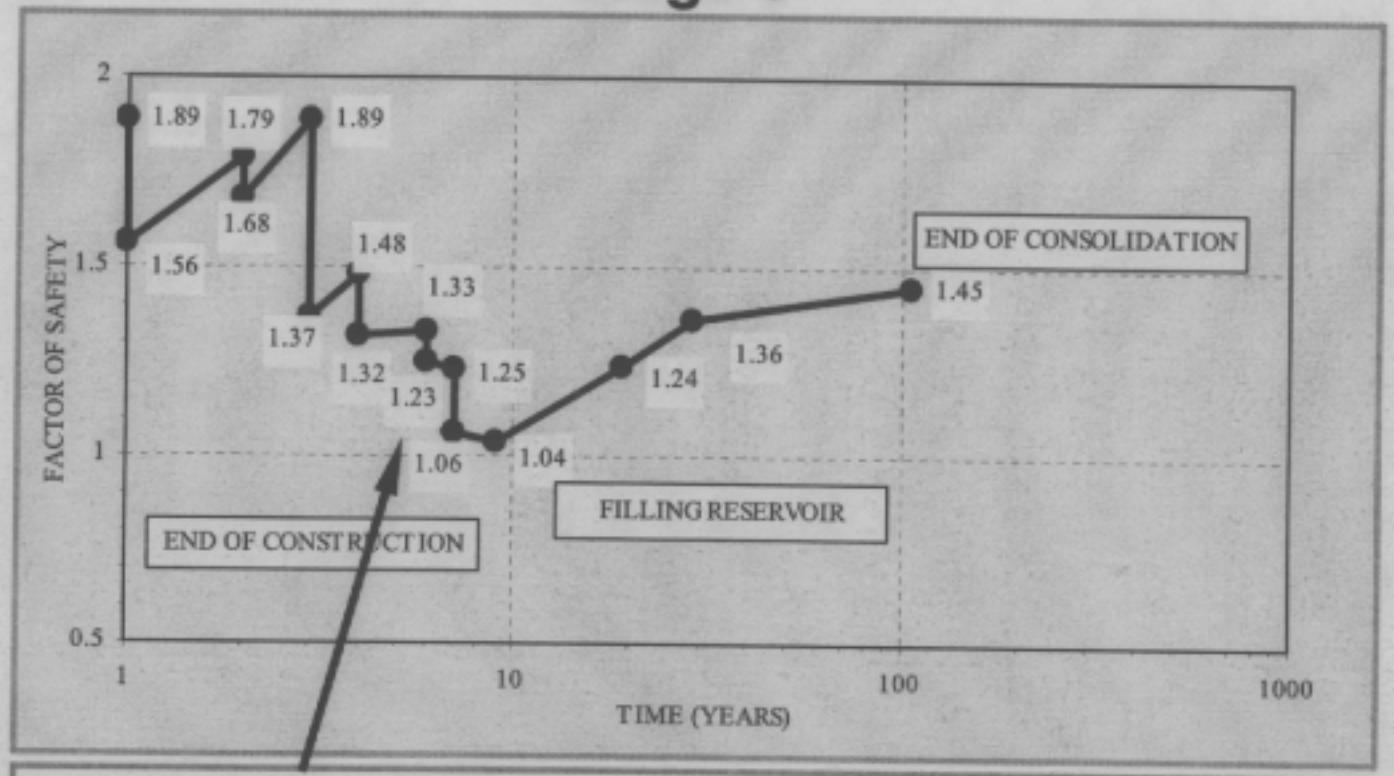
Stage 5

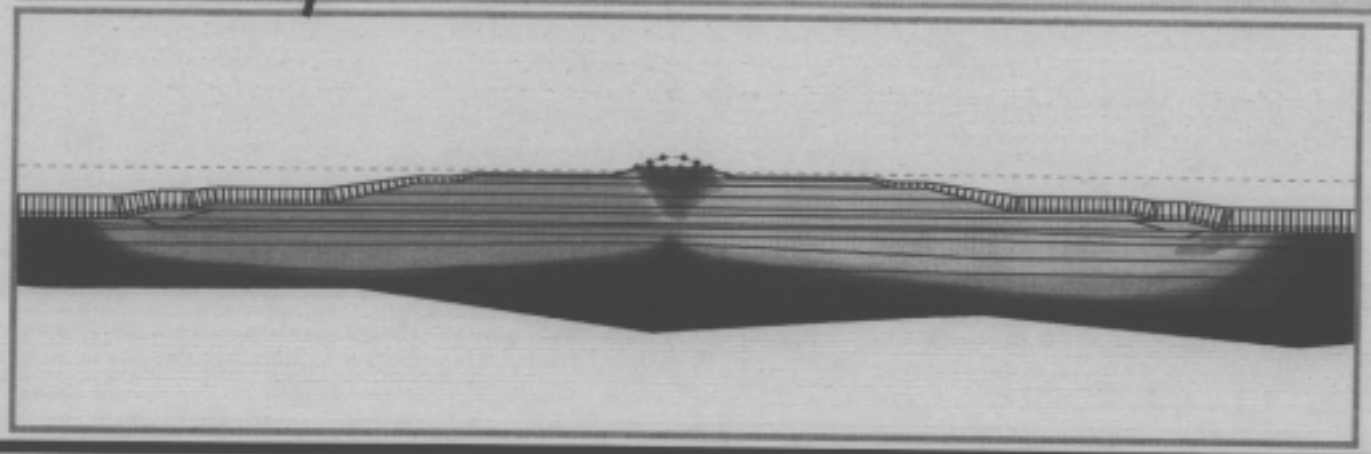

FACTOR OF SAFETY
2
1.5
1
0.5
1.89
1.79
1.89
1.68
1.56
1.48
1.33
1.37
1.32
1.23
1.25
1.06
1.04
1.24
1.36
1.45
END OF CONSOLIDATION
FILLING RESERVOIR
END OF CONSTRUCTION
1
10
100
1000
TIME (YEARS)



ACP

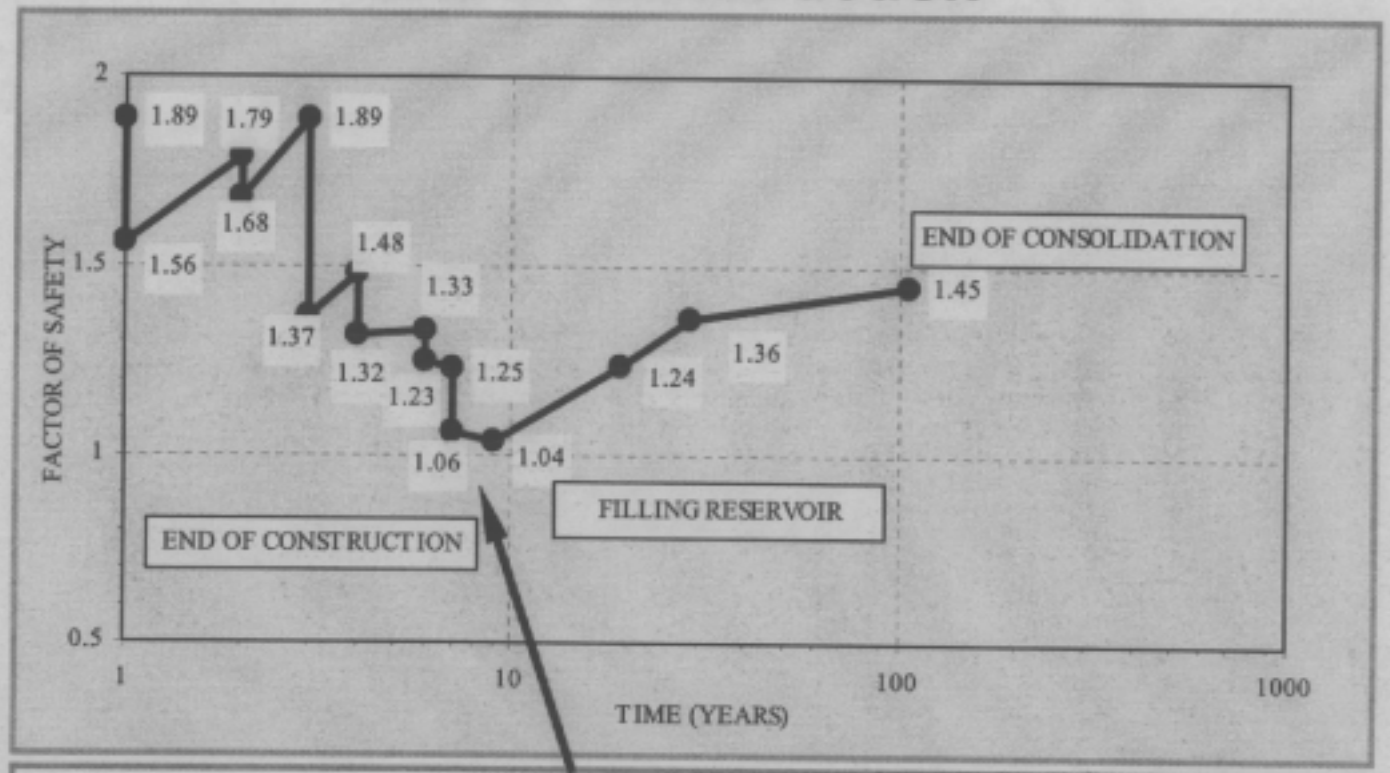
Stage 6

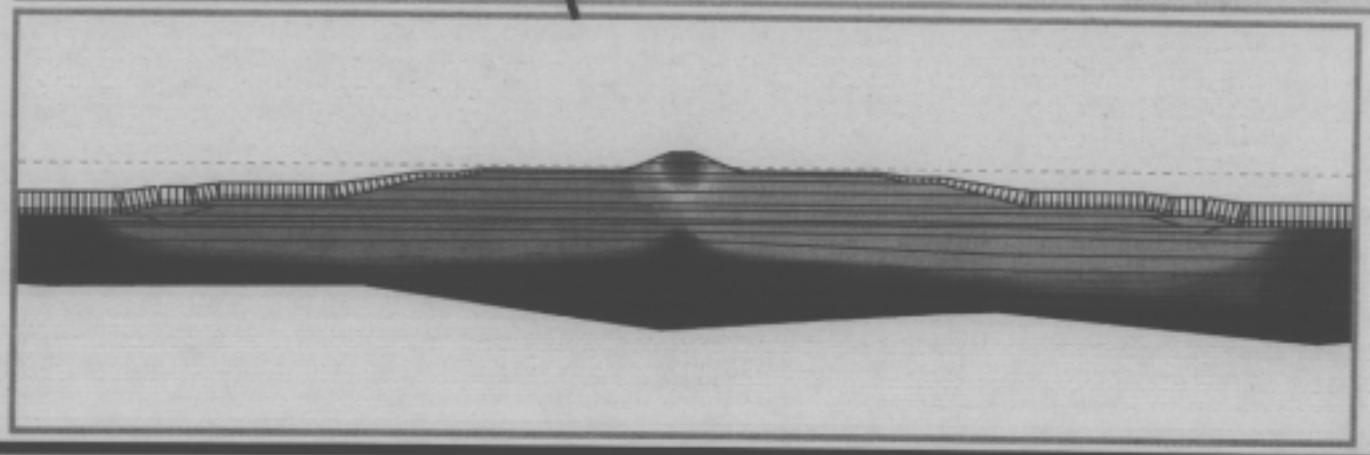

FACTOR OF SAFETY
2
1.5
1
0.5
1.89
1.79
1.89
1.56
1.68
1.48
1.33
1.37
1.32
1.23
1.25
1.06
1.04
1.24
1.36
1.45
END OF CONSOLIDATION
FILLING RESERVOIR
END OF CONSTRUCTION
1
10
100
1000
TIME (YEARS)



ACP

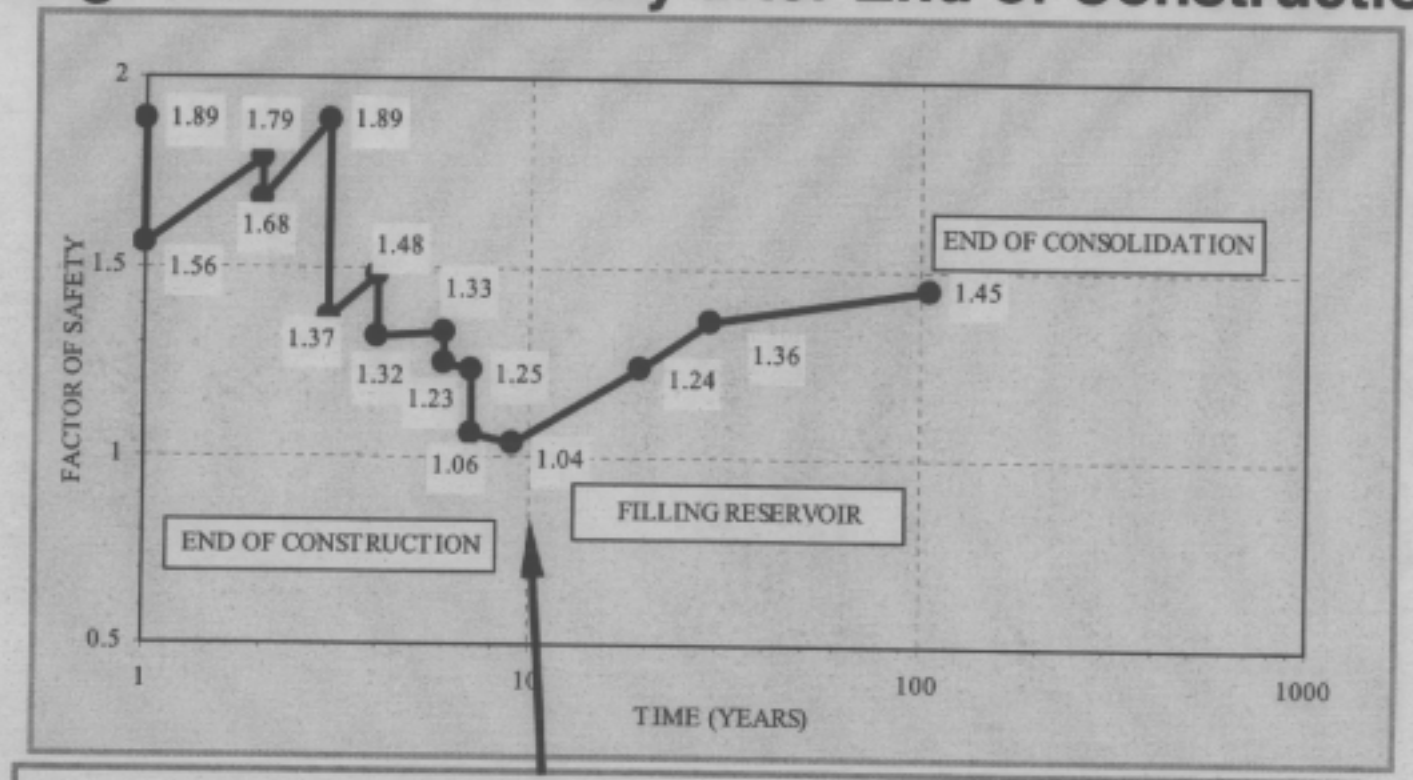
End of Construction

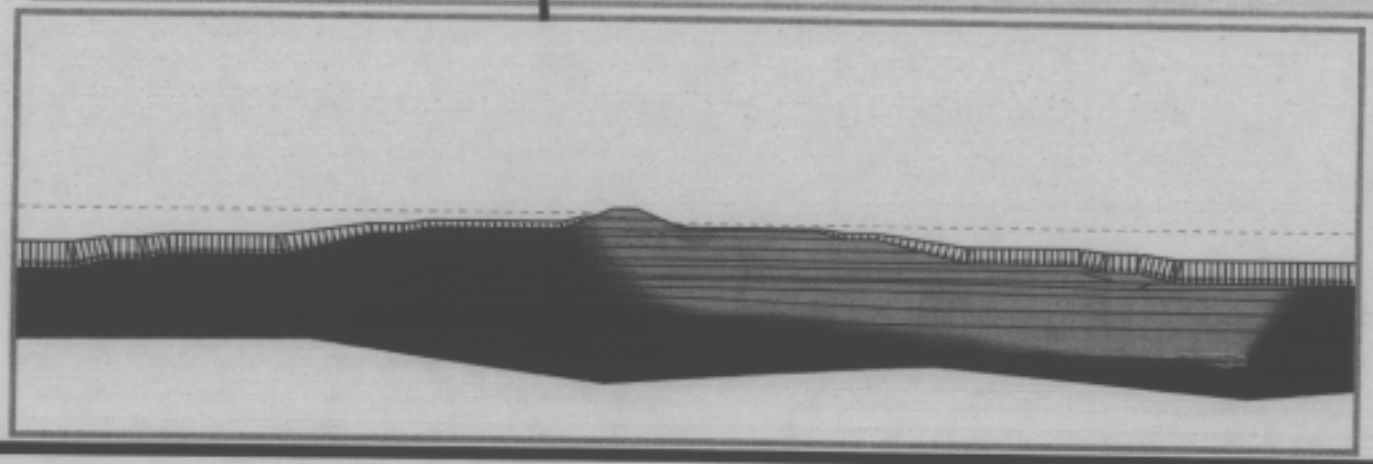




ACP

Filling Reservoir 730 day after End of Construction





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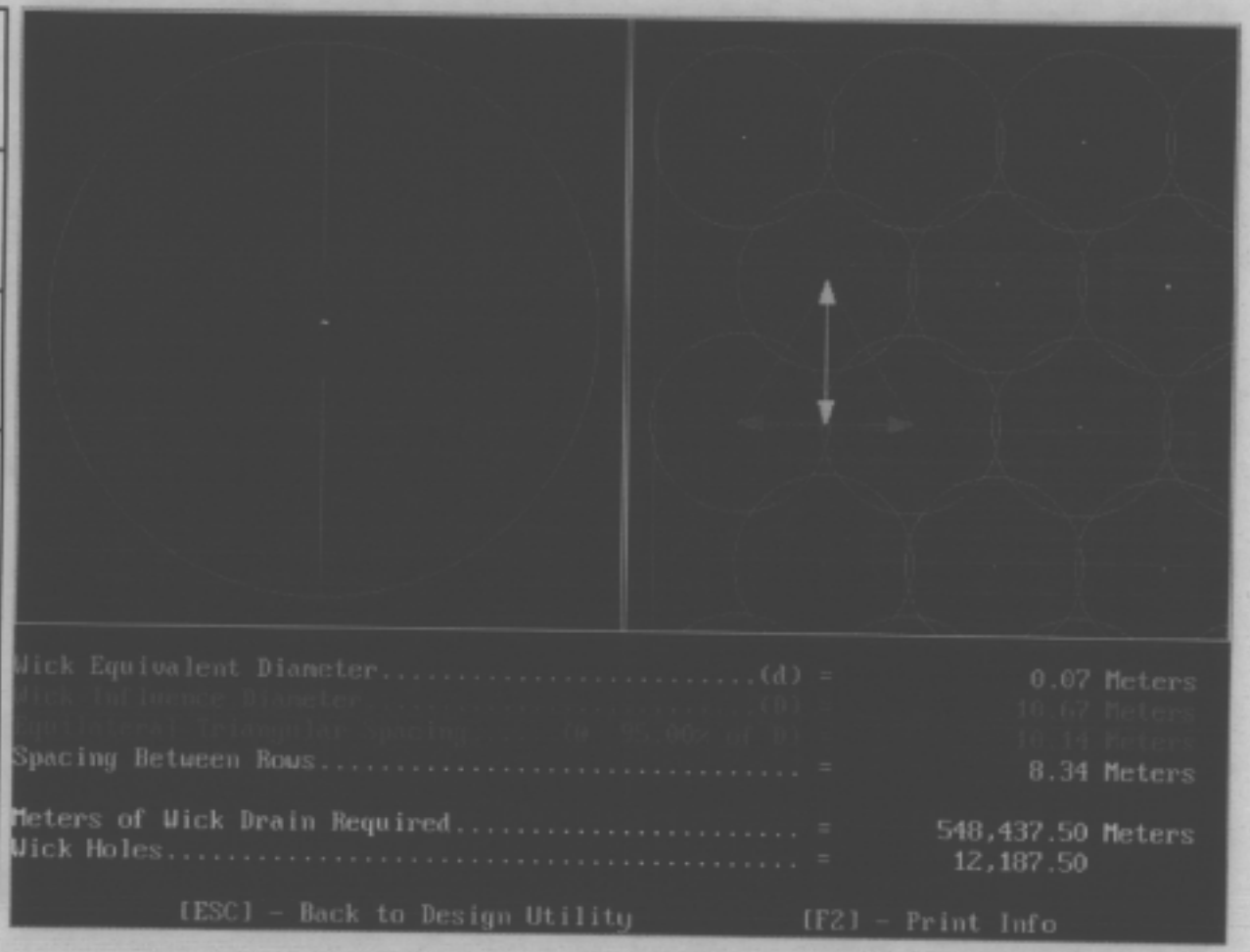
Wick Drains Design

Area	1,070,000 m2
Depth	45 m
Time	2555 days
% consolidation	80 %
K	1.38 e-9 m/s
Cvh	5.0 e-5 m2/s



ACP

Conclusions

1. The slopes of the dam should be slightly flatter than our design. The critical condition is at the end of the construction and after filling the reservoir. With time, the Factor of Safety will increase to acceptable level.
2. Additional volume of material will be required because of the large settlements.
3. The foundation should be improved by any practical and economical technique. Wick Drains
4. The material placed under water can be densified easily by state of the arts equipment and techniques. Vibro-compaction
5. The Dam can be built.....

ACP

Limit Equilibrium Stability Analysis

Geotechnical Branch

Engineering Division

ACP

Table of Contents

- Slope Stability based on Effective Strength Parameters c'and ϕ'.
- Slope Stability based on the Undrained Strength Analysis.

ACP

Slope Stability Based on Effective Strength Parameters c'and ϕ'

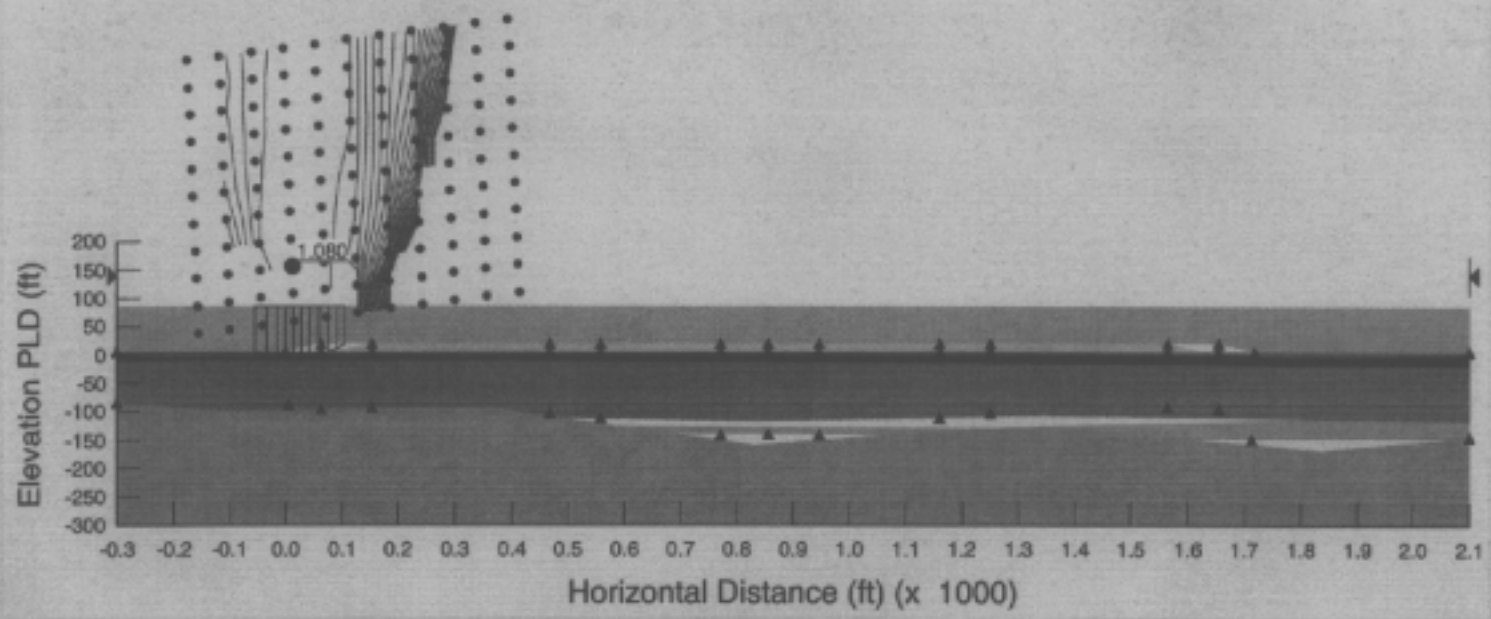
ACP

SUMMARY OF SHEAR STRENGTH PARAMETERS c' and ϕ'

TYPE OF SOIL	c' (ksf)	ϕ'
Zone 4	0.5	35
Zone 3	0.1	25
Zone 2	0.1	25
Zone 1 (Crushed Rock)	0	35
Very Soft Peat	0.1	25
Very Soft Organic Clay	0.1	28
Firm Peat and Soft Clay	0.1	25
Soft to Medium Organic Silty Clay	0.1	28
Medium Organic Silty Clay	0.1	28
Medium Silty Fine Sand	0	32
Firm Peat and Medium Silty Clay	0.1	25
Dense Sand	0	32

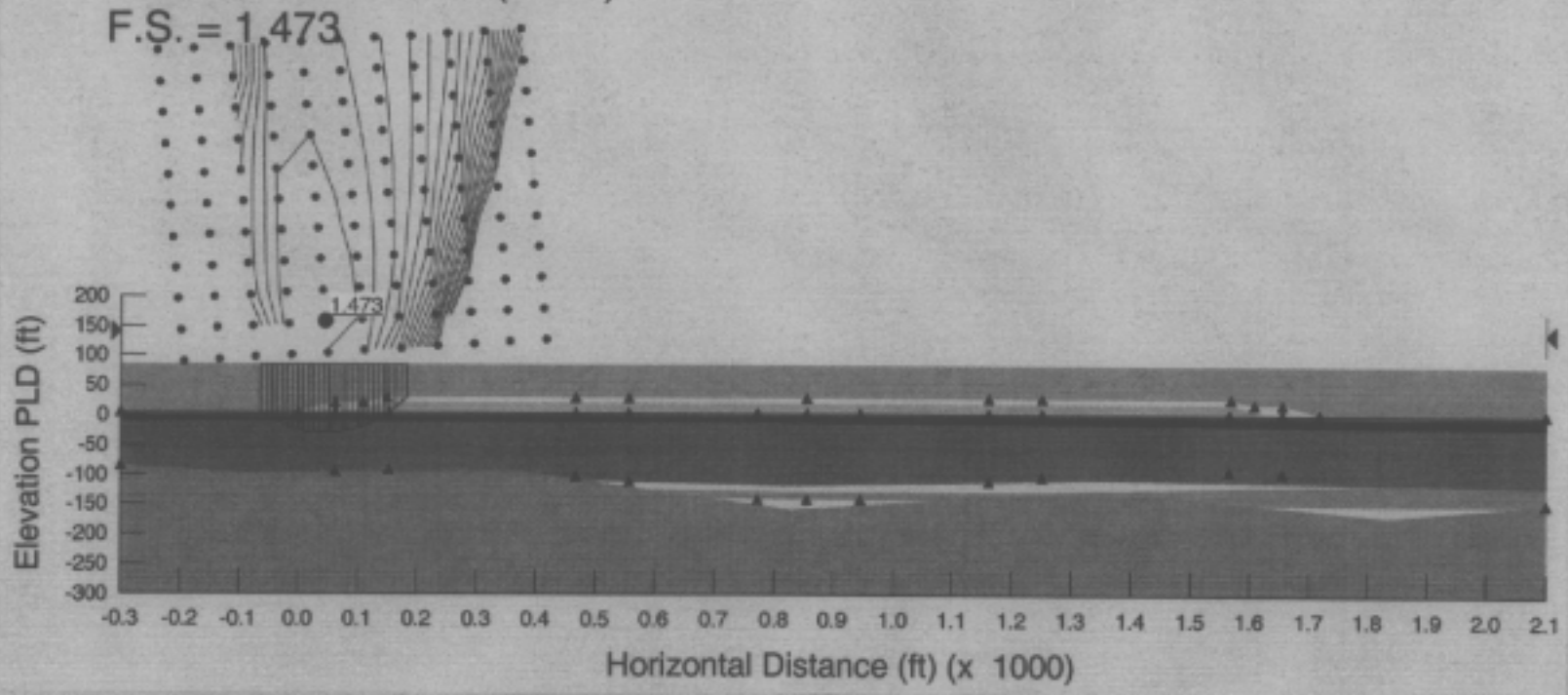
Description: Fill Embankment across Trinidad Dam
Comments: Stage No. 1
File Name: etapa1.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Right to Left
Slip Surface Option: Grid and Radius
P.W.P. Option: Grid of Pressures
Tension Crack Option: (none)
Seismic Coefficient: (none)

F.S. = 1.080



ACP

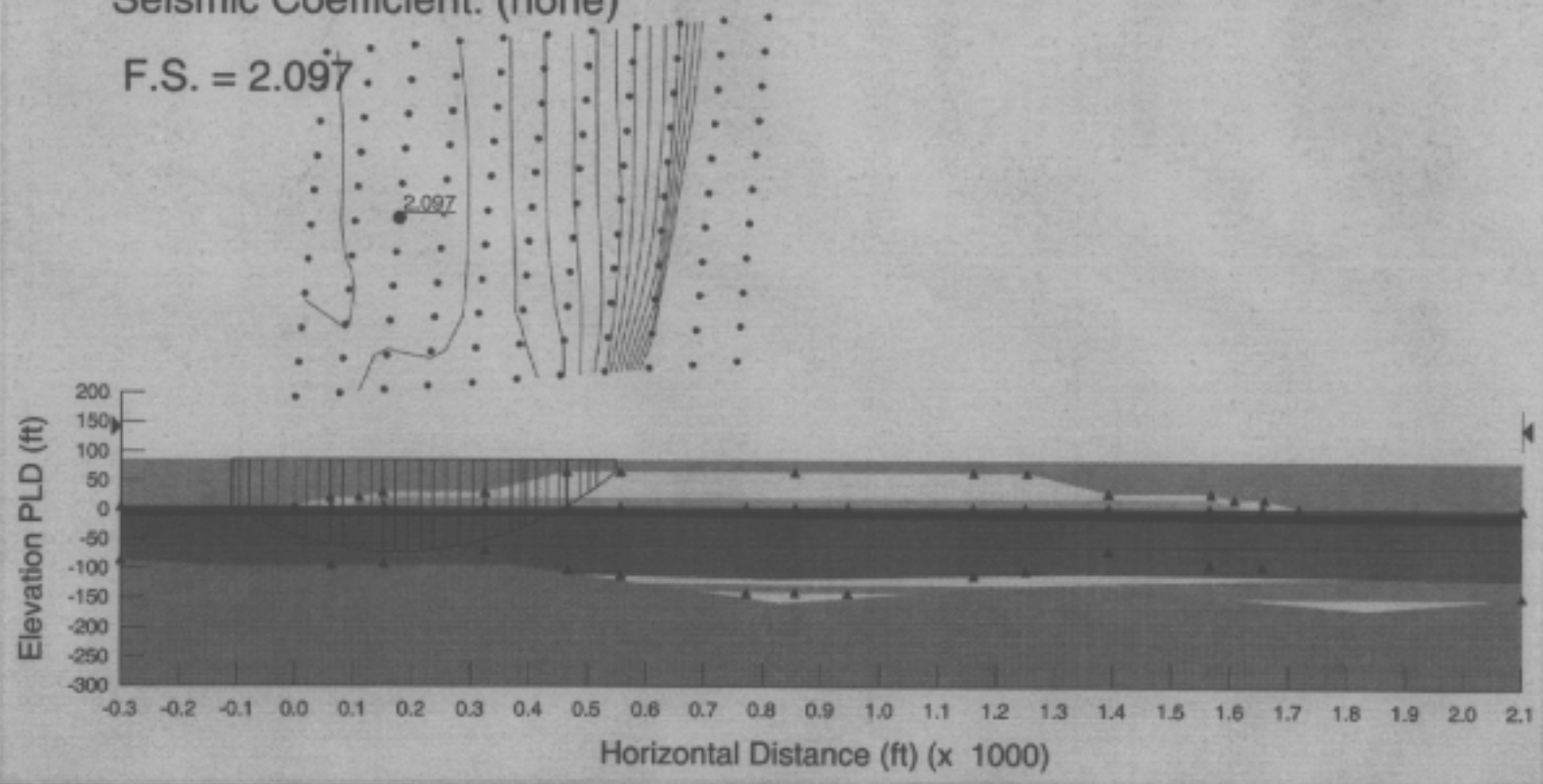
Description: Fill Embankment across Trinidad Dam
Comments: Stage No. 2
File Name: etapa2.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Right to Left
Slip Surface Option: Grid and Radius
P.W.P. Option: Grid of Pressures
Tension Crack Option: (none)
Seismic Coefficient: (none)
F.S. = 1.473



ACP

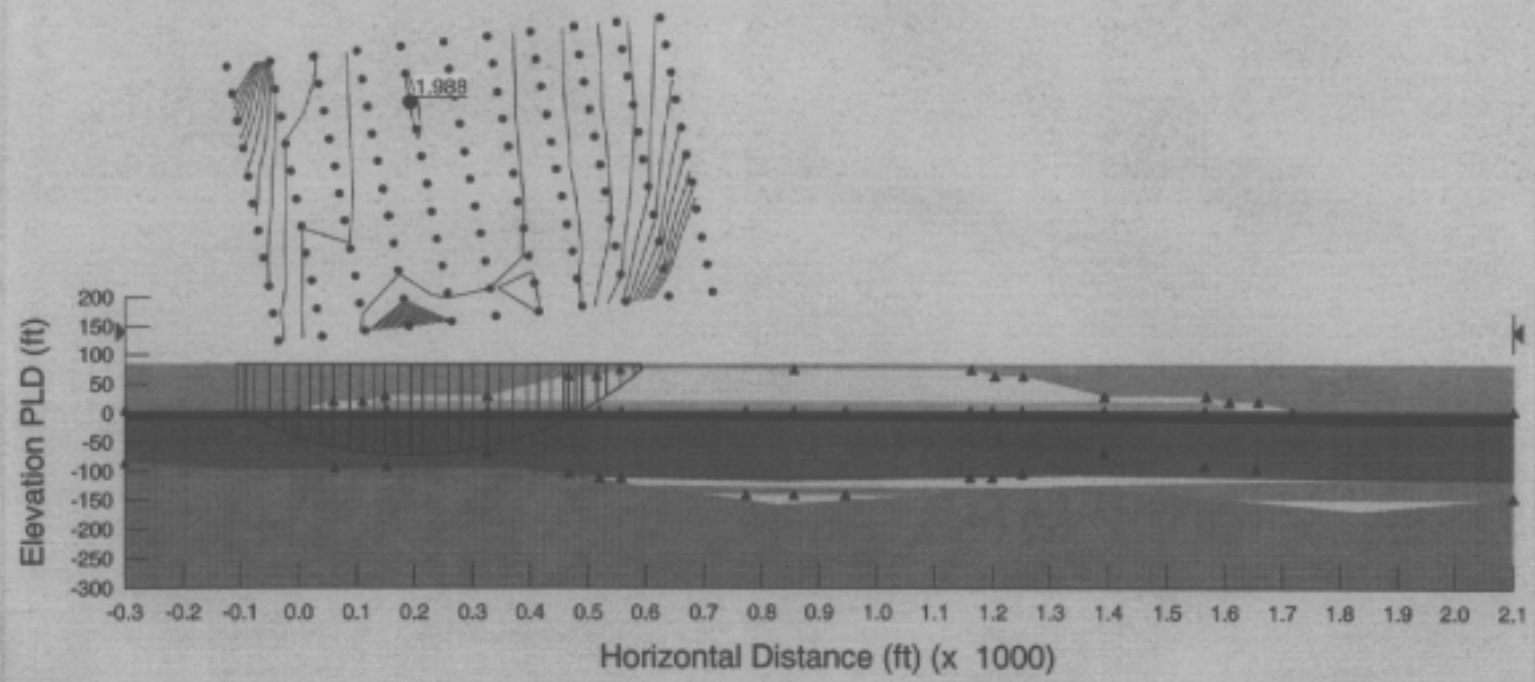
Description: Fill Embankment across Trinidad Dam
Comments: Stage No. 3
File Name: etapa3.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Right to Left
Slip Surface Option: Grid and Radius
P.W.P. Option: Grid of Pressures
Tension Crack Option: (none)
Seismic Coefficient: (none)

F.S. = 2.097



ACP

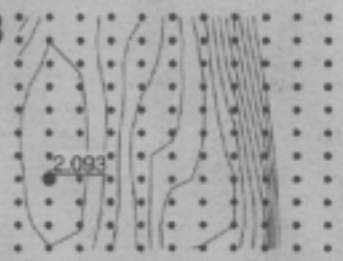
Description: Fill Embankment across Trinidad Dam
Comments: Stage No. 4
File Name: etapa4.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Right to Left
Slip Surface Option: Grid and Radius
P.W.P. Option: Grid of Pressures
Tension Crack Option: (none)
Seismic Coefficient: (none)
F.S. = 1.988

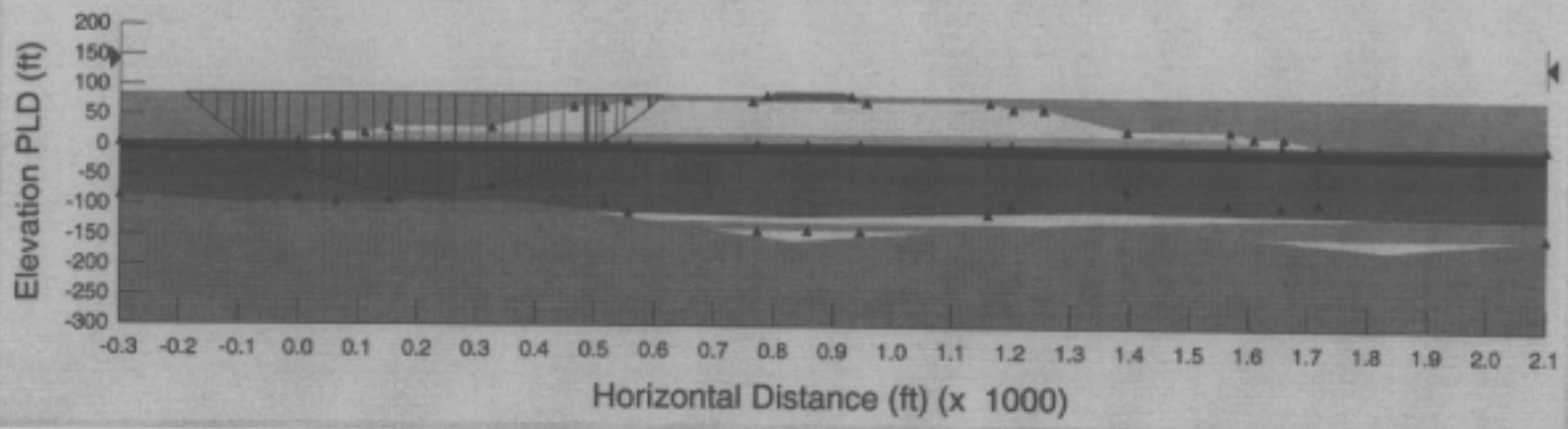


ACP

Description: Fill Embankment across Trinidad Dam
Comments: Stage No. 5
File Name: etapa5.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Right to Left
Slip Surface Option: Grid and Radius
P.W.P. Option: Grid of Pressures
Tension Crack Option: (none)
Seismic Coefficient: (none)

F.S. = 2.093

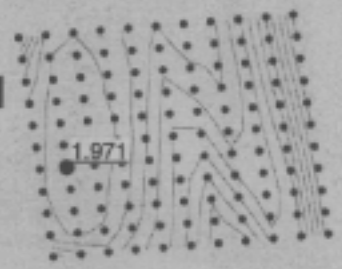


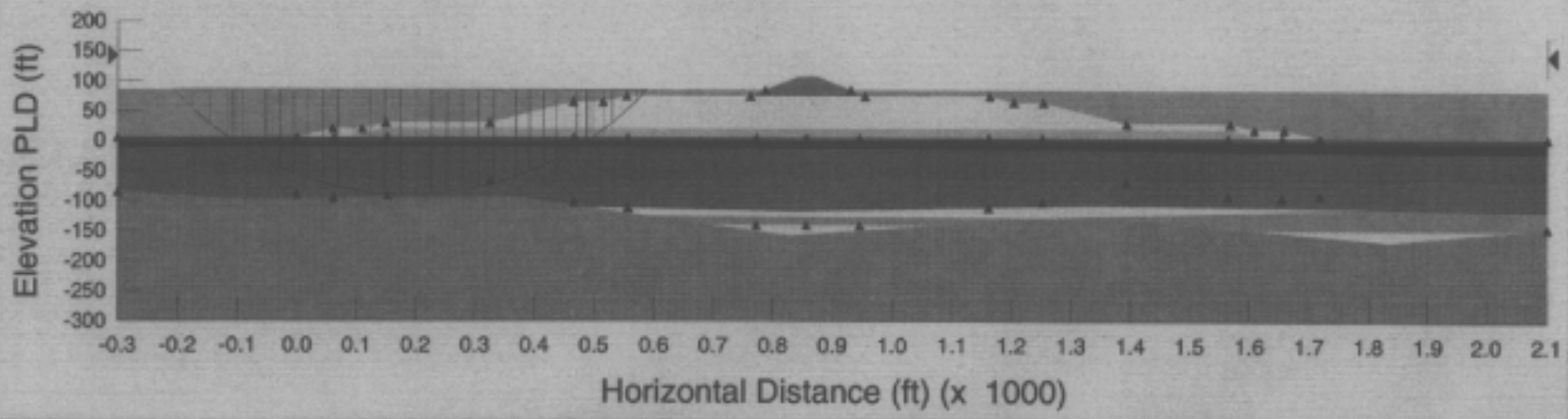


ACP

Description: Fill Embankment across Trinidad Dam
Comments: Stage No. 6
File Name: etapa6.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Right to Left
Slip Surface Option: Grid and Radius
P.W.P. Option: Grid of Pressures
Tension Crack Option: (none)
Seismic Coefficient: (none)

F.S. = 1.971

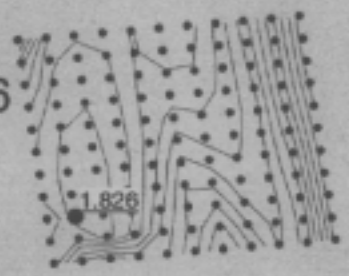


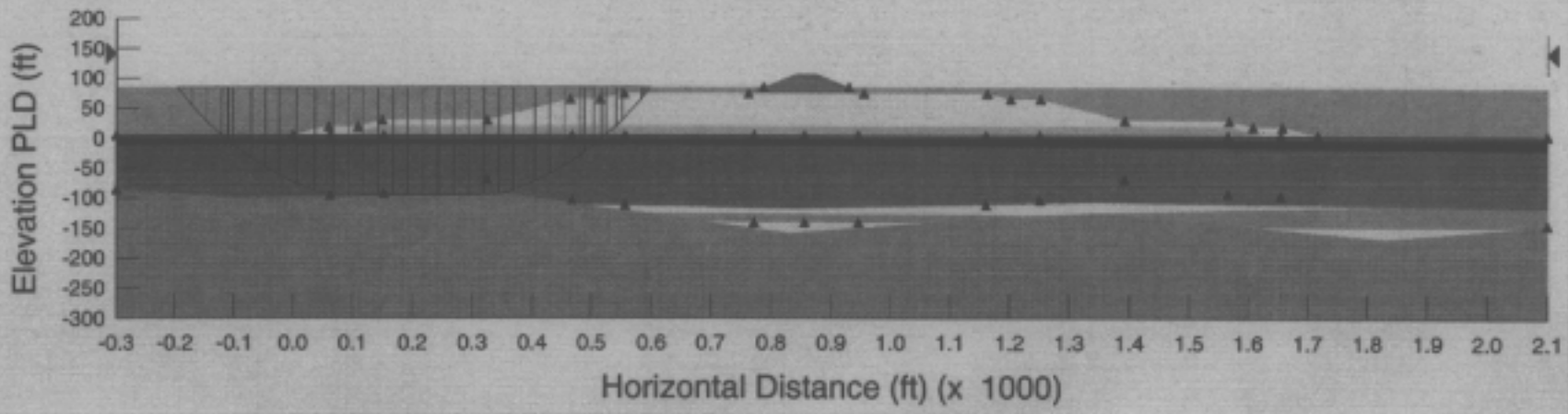


ACP

Description: Fill Embankment across Trinidad Dam
Comments: Condition at end of construction
File Name: endofco.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Right to Left
Slip Surface Option: Grid and Radius
P.W.P. Option: Grid of Pressures
Tension Crack Option: (none)
Seismic Coefficient: (none)

F.S. = 1.826

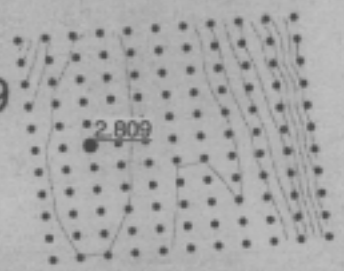


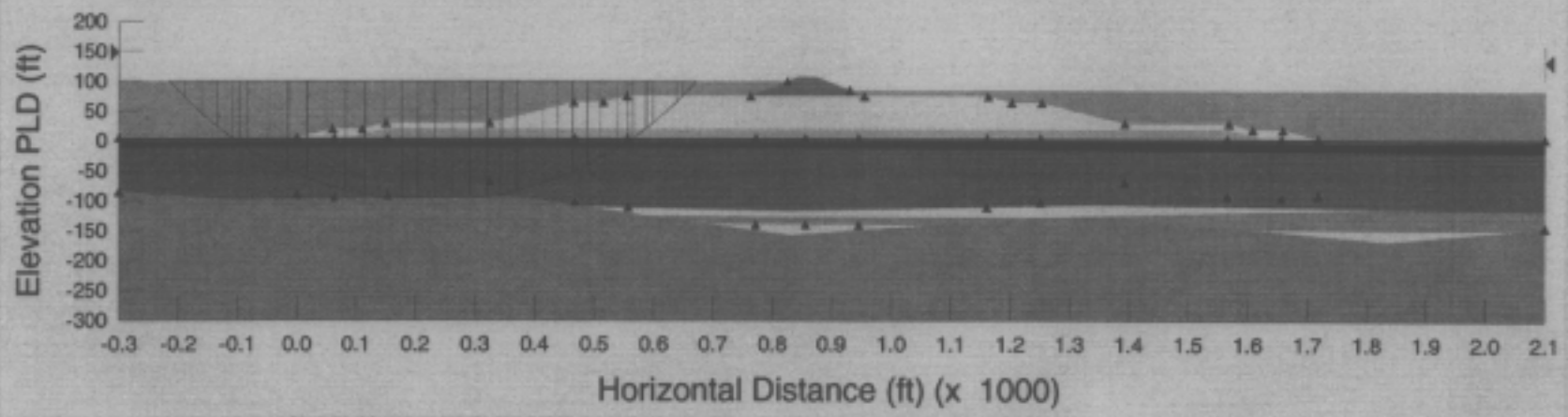


ACP

Description: Fill Embankment across Trinidad Dam
Comments: Condition during reservoir filling
File Name: fillres.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Right to Left
Slip Surface Option: Grid and Radius
P.W.P. Option: Grid of Pressures
Tension Crack Option: (none)
Seismic Coefficient: (none)

F.S. = 2.809

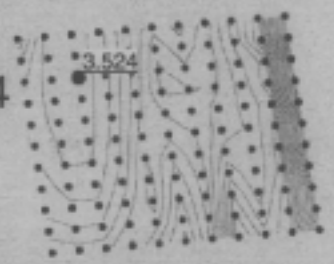


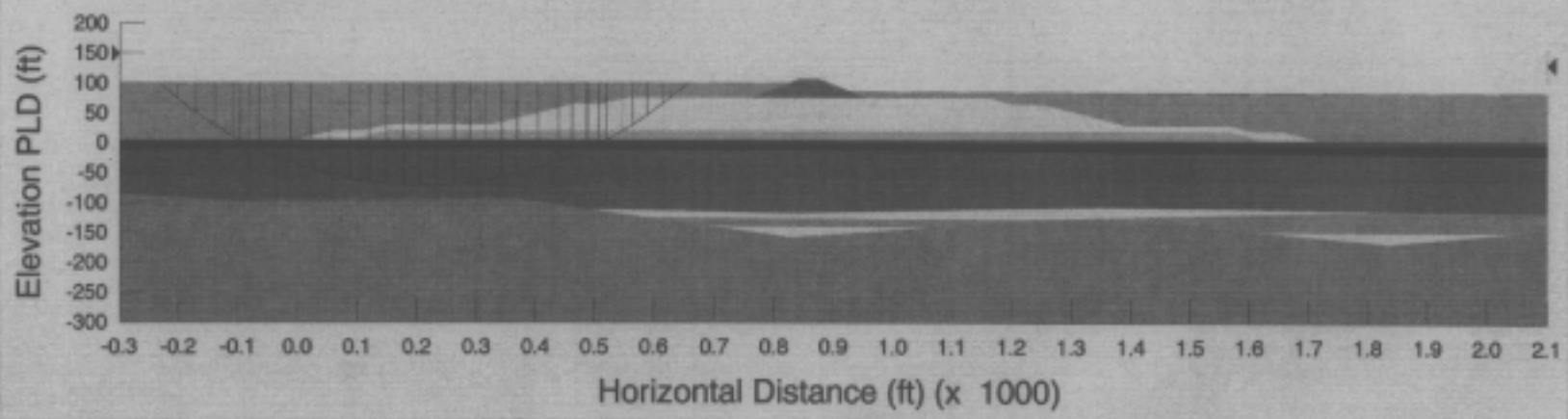


ACP

Description: Fill Embankment across Trinidad Dam
Comments: Long term condition
File Name: longter.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Right to Left
Slip Surface Option: Grid and Radius
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)

F.S. = 3.524

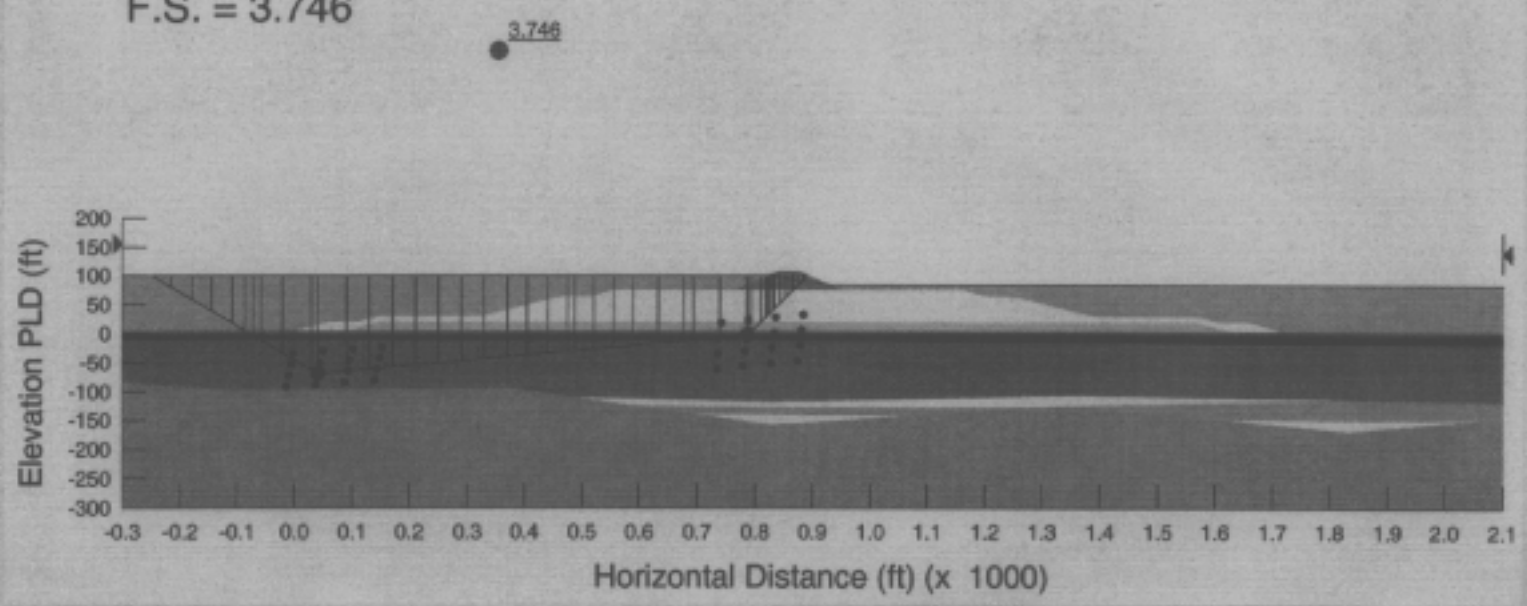




ACP

Description: Fill Embankment across Trinidad Dam
Comments: Long term condition
File Name: longterL.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Right to Left
Slip Surface Option: Block Specified
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)

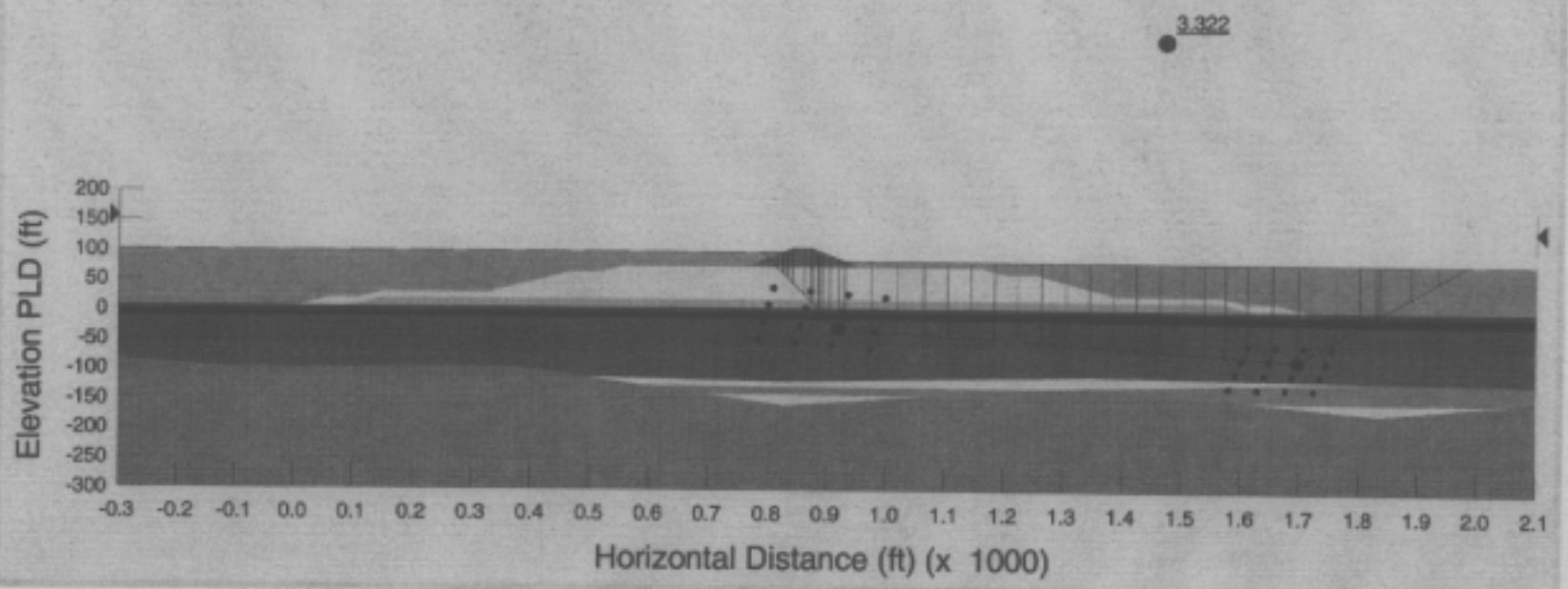
F.S. = 3.746



ACP

Description: Fill Embankment across Trinidad Dam
Comments: Long term condition
File Name: longterR.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Left to Right
Slip Surface Option: Block Specified
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)

F.S. = 3.322



ACP

Slope Stability based Undrained Strength Analysis

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Undrained Strength Analysis

- Undrained strength analysis requires estimates of the in situ Undrained shear strength of the cohesive foundation soil and subsequent increases of Su during staged construction (Ladd, 1991).
- The recommended approach is the recognition of the correlation between the in situ undrained shear strength ratio ($Su/\sigma vc'$) and the overconsolidation ratio ($OCR = \sigma p'/ \sigma vc'$).

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Undrained Strength Analysis

- Under this approach is important to establish the initial stress history of the deposit (profiles of $\sigma p'$ and $\sigma vo'$).
- It is also important to establish changes in the vertical stress history during staged construction ($\sigma vc'$).

ACP

Undrained Strength Analysis

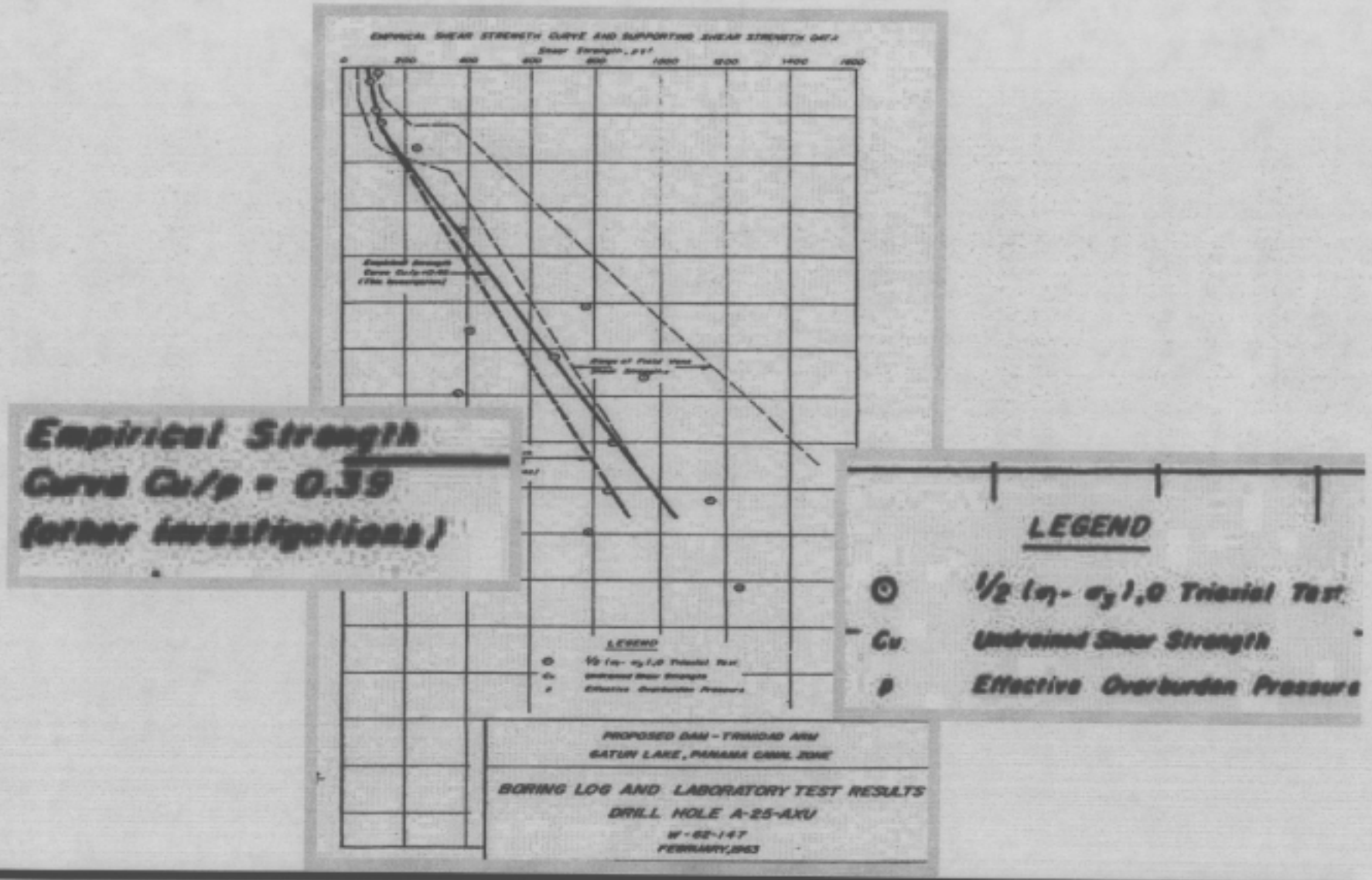
- $Su/\sigma vc' = S*(\sigma p'/\sigma vc')^m$
- where

  $S = 0.23$

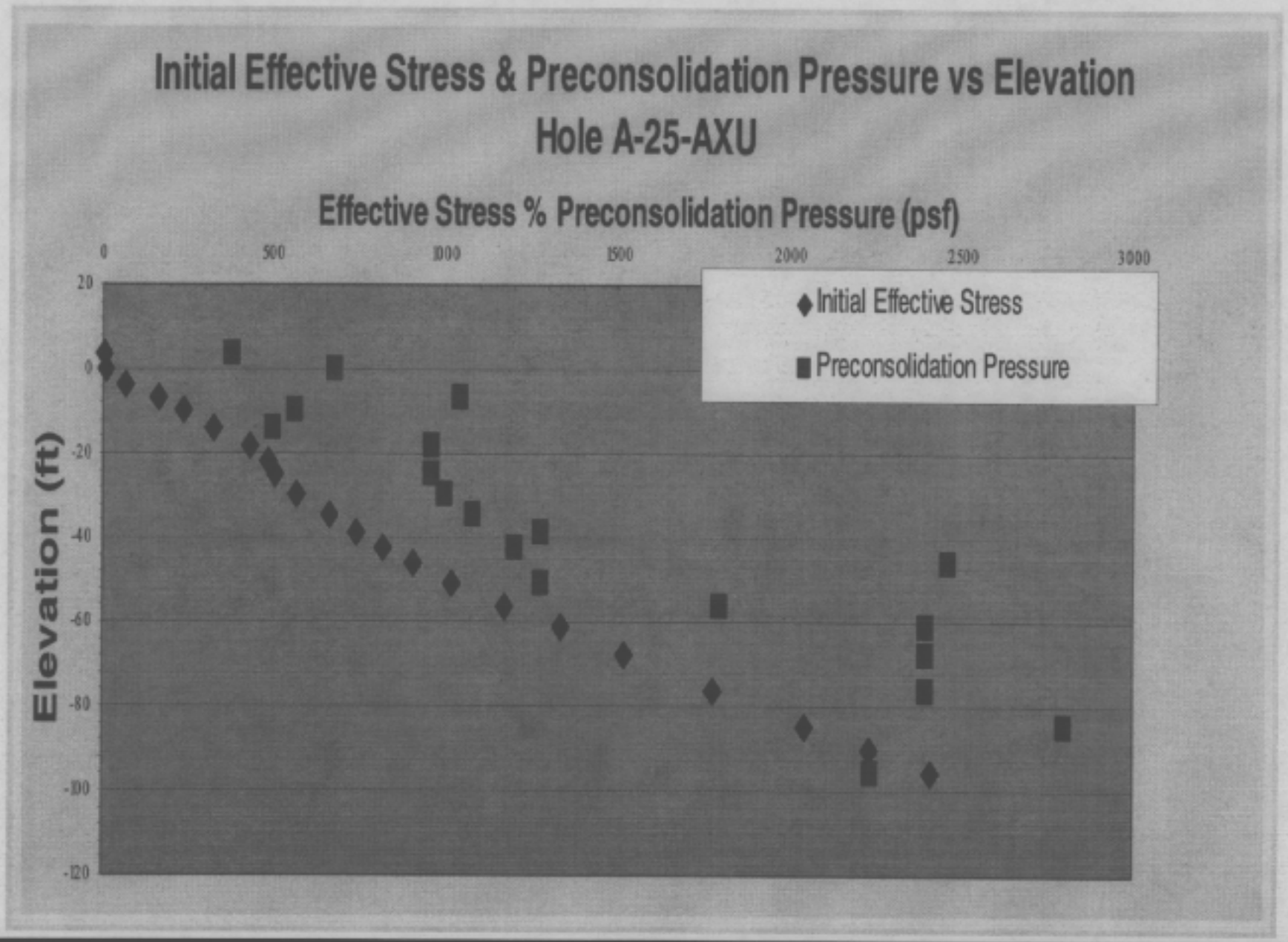
  $m = 0.80$
- if $\sigma p' =< \sigma vc'$ then $Su/\sigma vc' = 0.23$

ACP

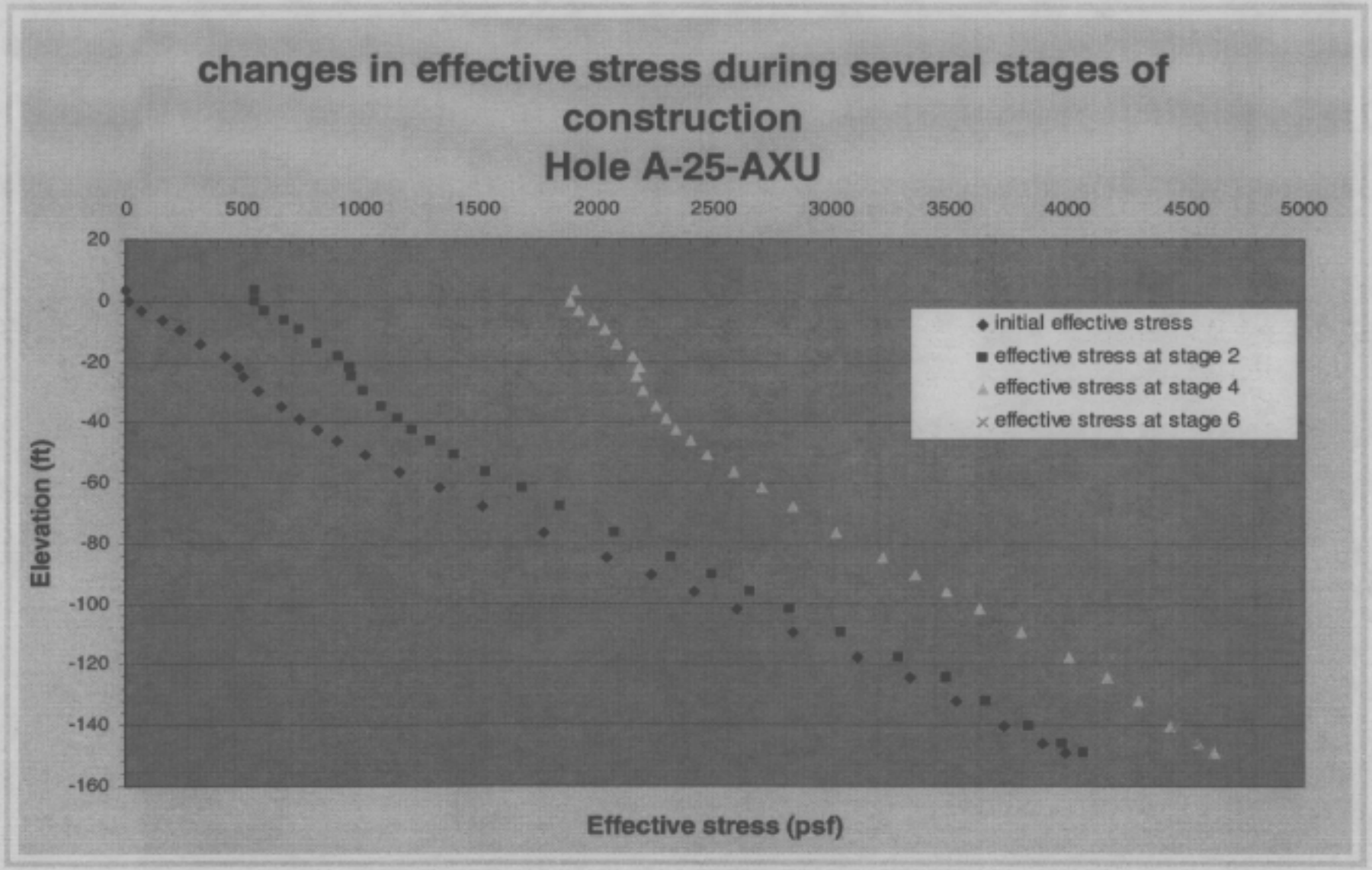
Shear Strength Curve vs Depth from Tudor Engineering



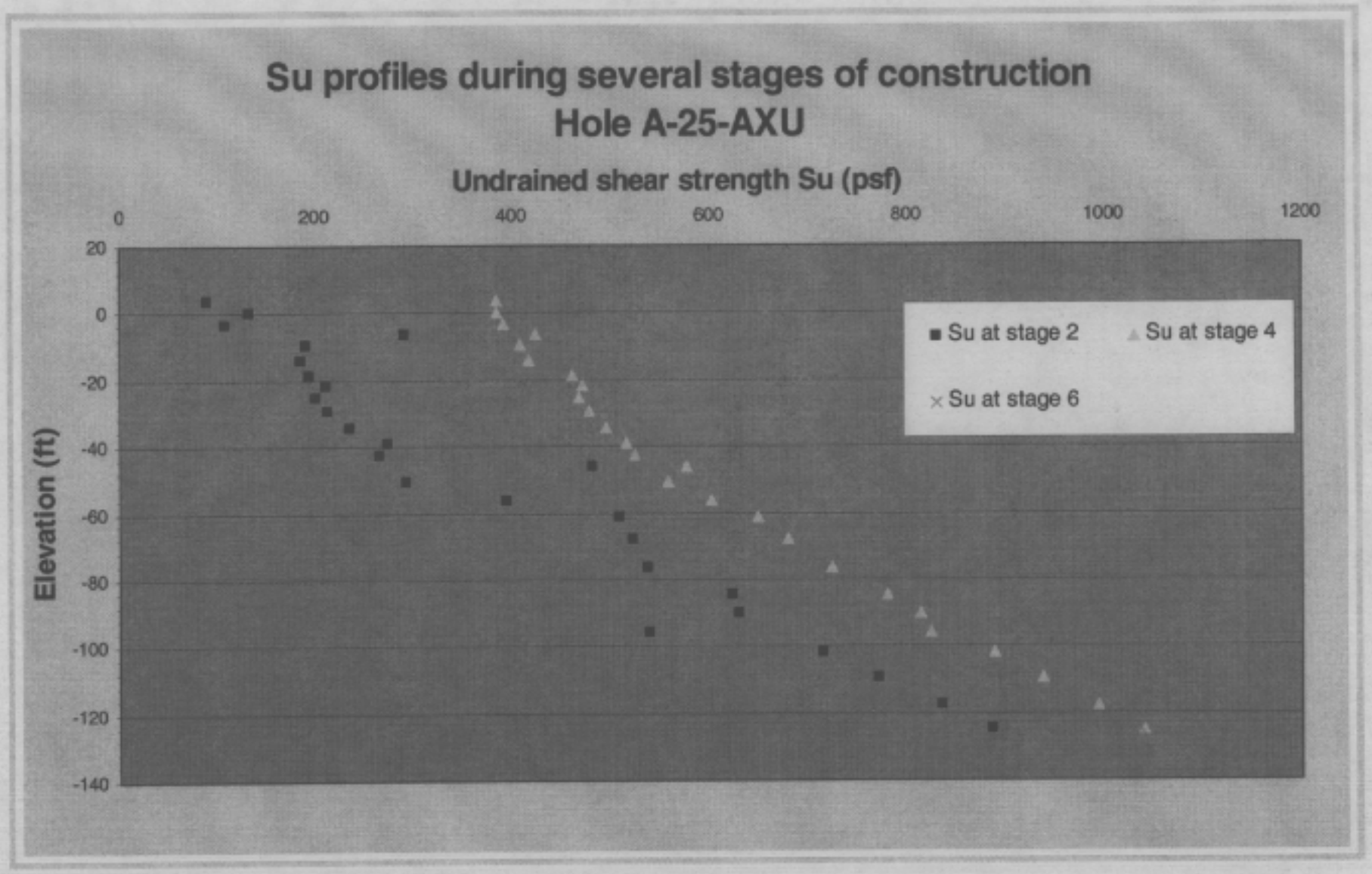
ACP


Initial Effective Stress & Preconsolidation Pressure vs Elevation
Hole A-25-AXU
Effective Stress % Preconsolidation Pressure (psf)
0
500
1000
1500
2000
2500
3000
20
0
-20
-40
-60
-80
-100
-120
Elevation (ft)
Initial Effective Stress
Preconsolidation Pressure

ACP


changes in effective stress during several stages of construction
Hole A-25-AXU
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
20
0
-20
-40
-60
-80
-100
-120
-140
-160
Elevation (ft)
Effective stress (psf)
initial effective stress
effective stress at stage 2
effective stress at stage 4
effective stress at stage 6

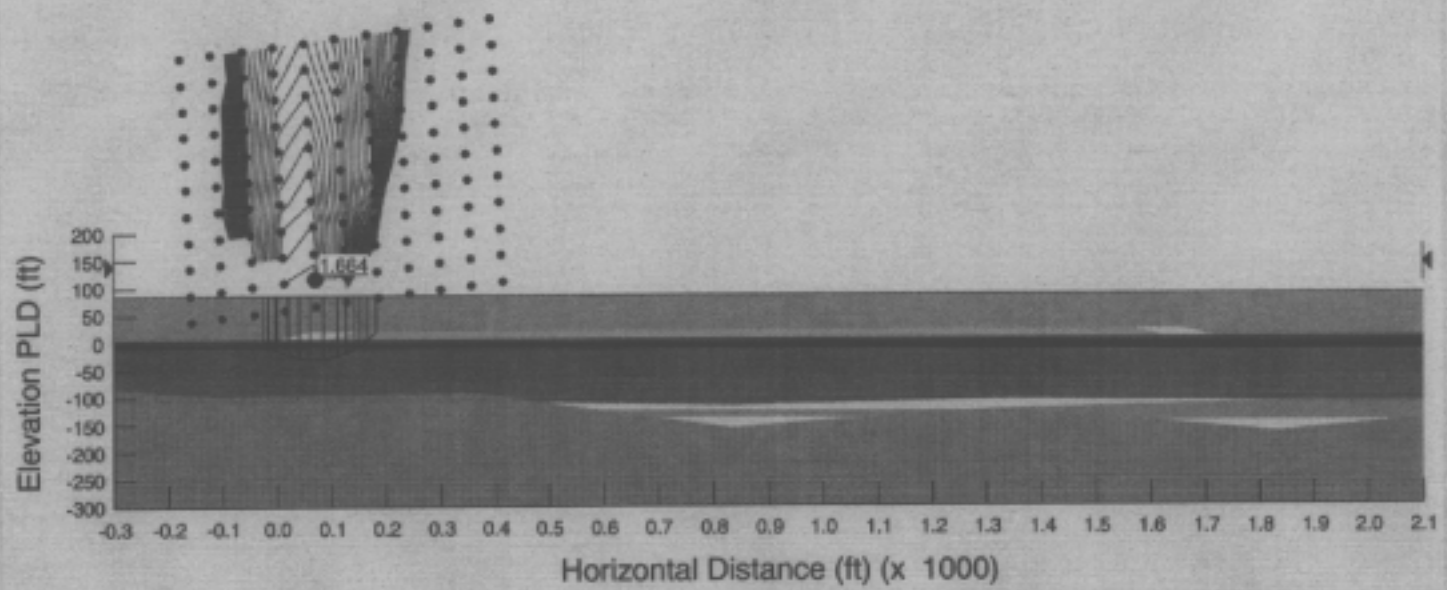
ACP


Su profiles during several stages of construction
Hole A-25-AXU
Undrained shear strength Su (psf)
0
200
400
600
800
1000
1200
20
0
-20
-40
-60
-80
-100
-120
-140
Elevation (ft)
Su at stage 2
Su at stage 4
Su at stage 6

ACP

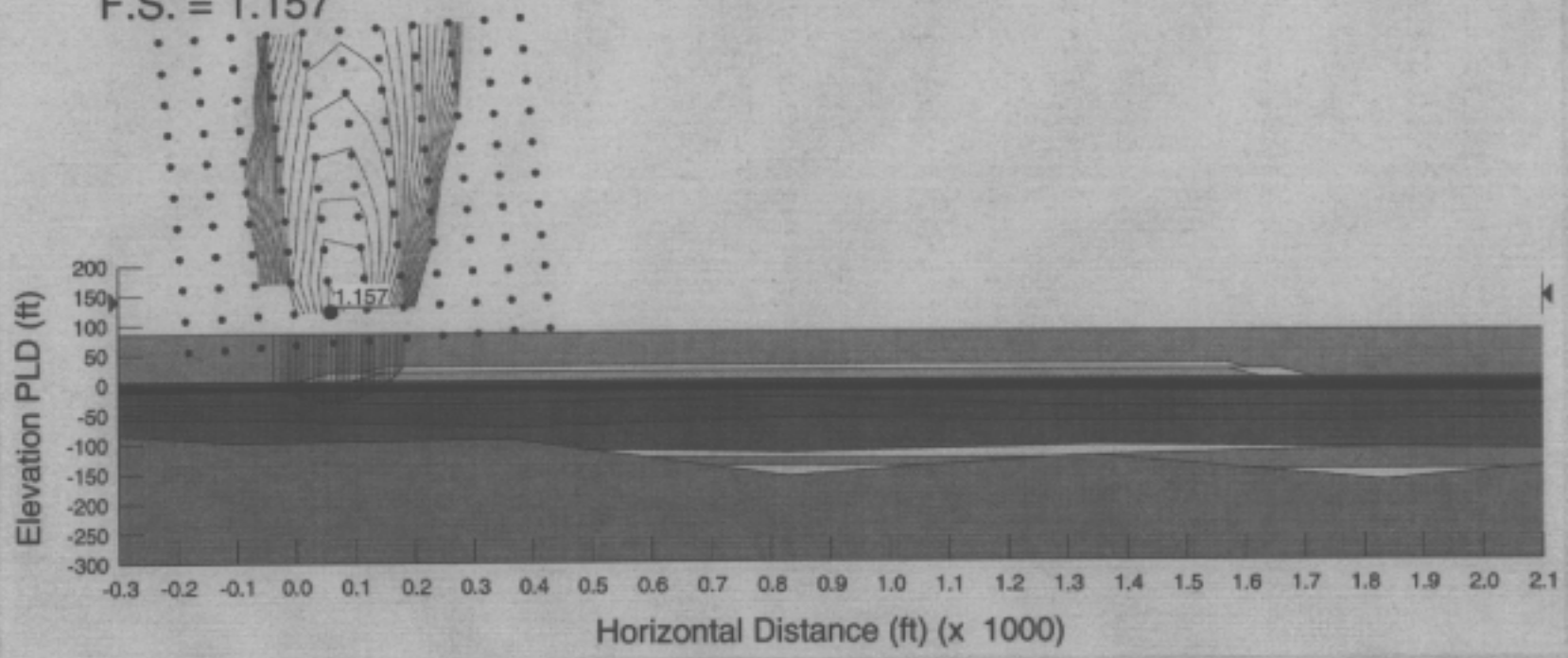
Description: Fill Embankment across Trinidad Dam
Comments: Stage No. 1 Undrained Condition
File Name: etapa1U.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Right to Left
Slip Surface Option: Grid and Radius
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)

F.S. = 1.664



ACP

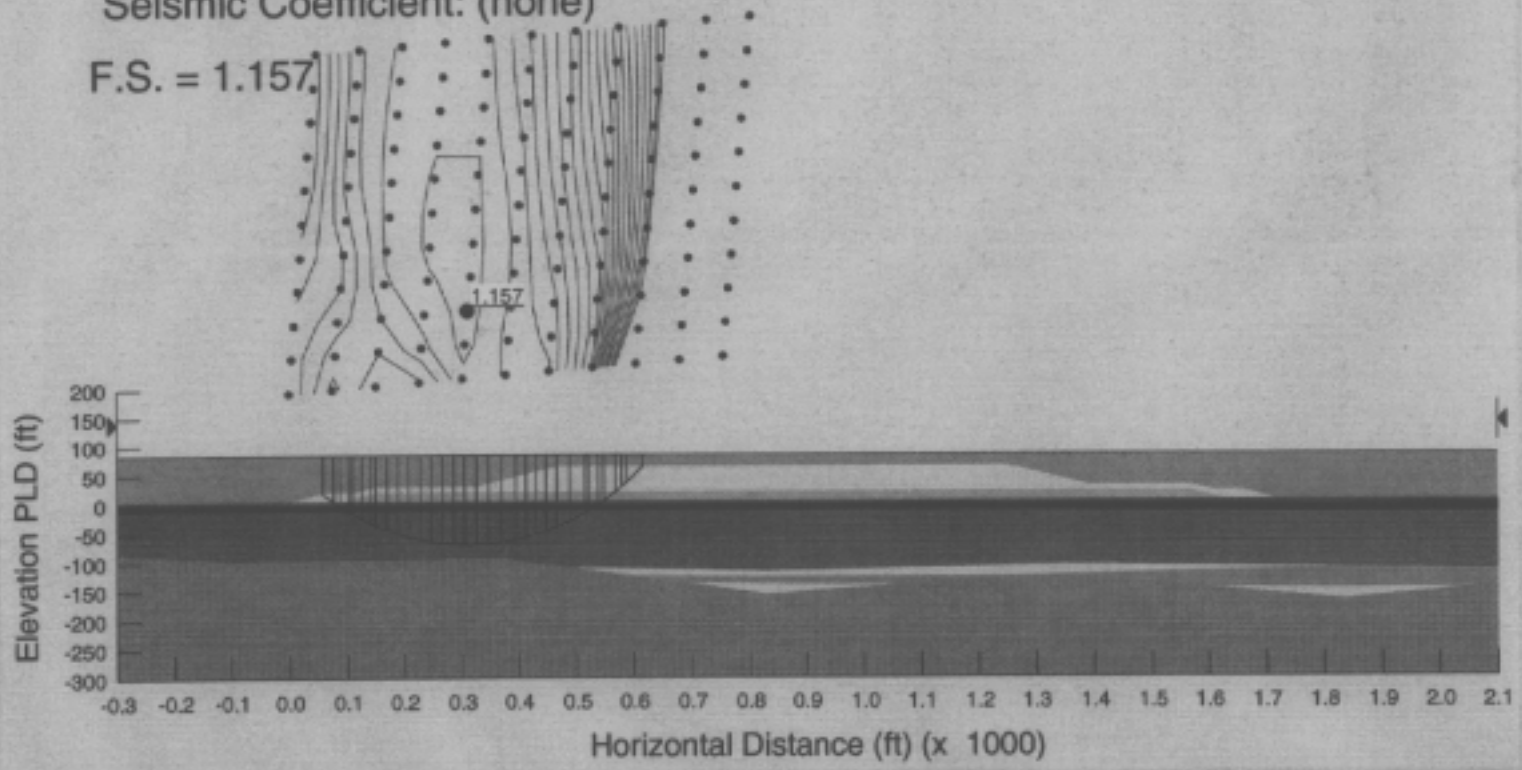
Description: Fill Embankment across Trinidad Dam
Comments: Stage No. 2
File Name: etapa2U.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Right to Left
Slip Surface Option: Grid and Radius
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)
F.S. = 1.157



ACP

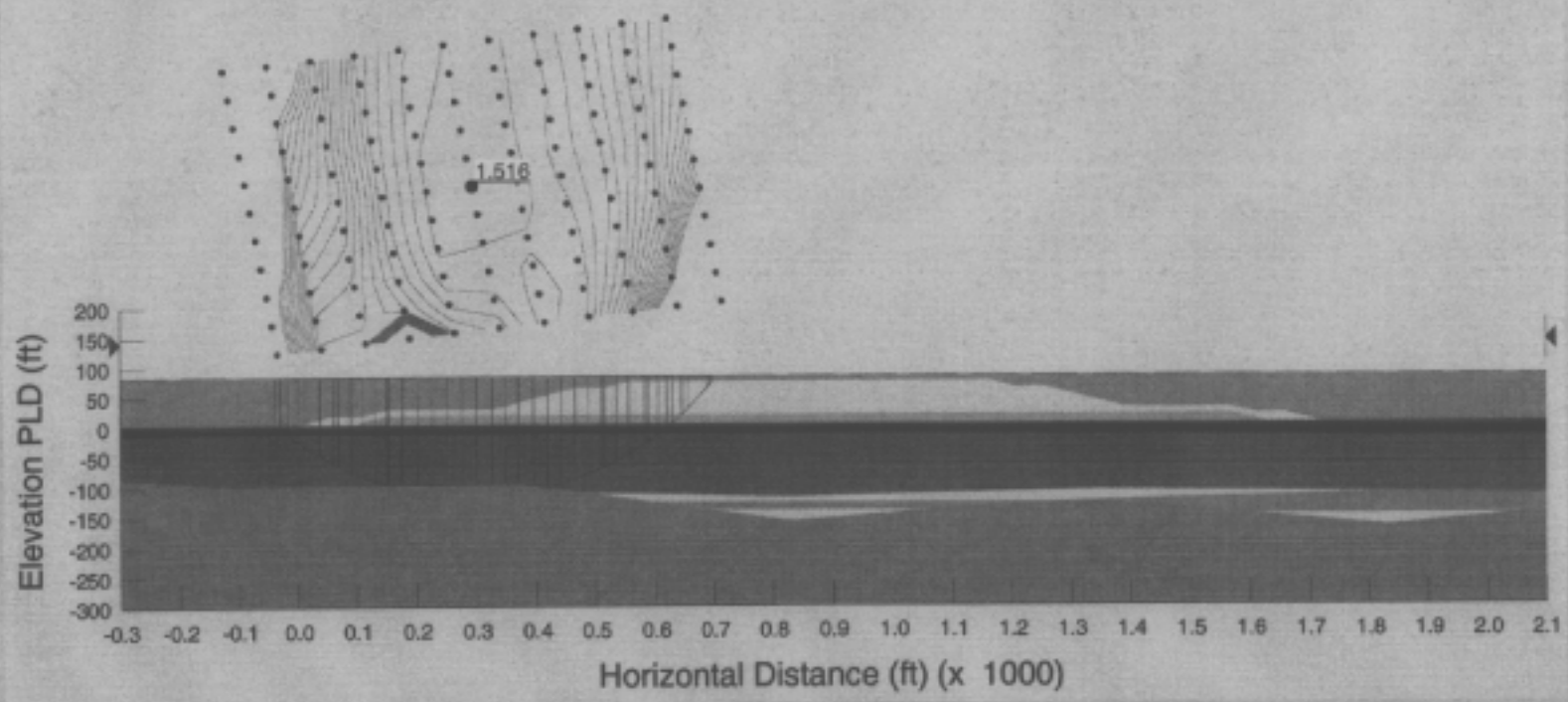
Description: Fill Embankment across Trinidad Dam
Comments: Stage No. 3
File Name: etapa3U.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Right to Left
Slip Surface Option: Grid and Radius
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)

F.S. = 1.157



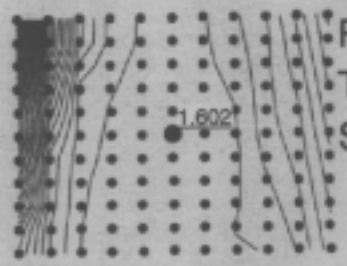
ACP

Description: Fill Embankment across Trinidad Dam
Comments: Stage No. 4
File Name: etapa4U.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Right to Left
Slip Surface Option: Grid and Radius
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)
F.S. = 1.516

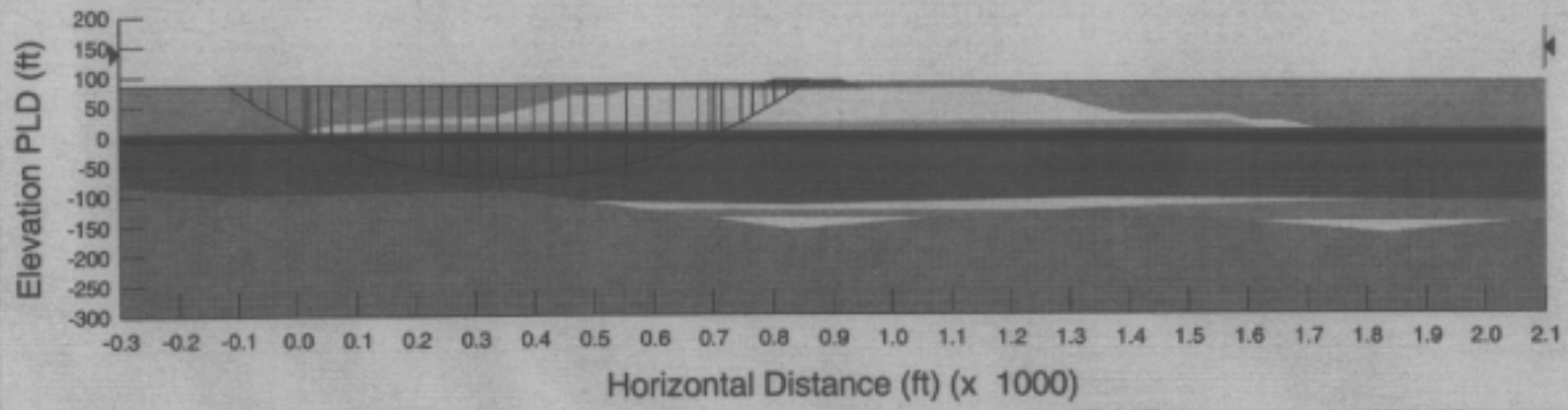


ACP

Description: Fill Embankment across Trinidad Dam
Comments: Stage No. 5
File Name: etapa5U.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Right to Left
Slip Surface Option: Grid and Radius
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)



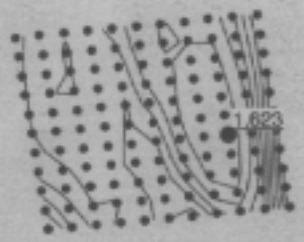
F.S. = 1.602

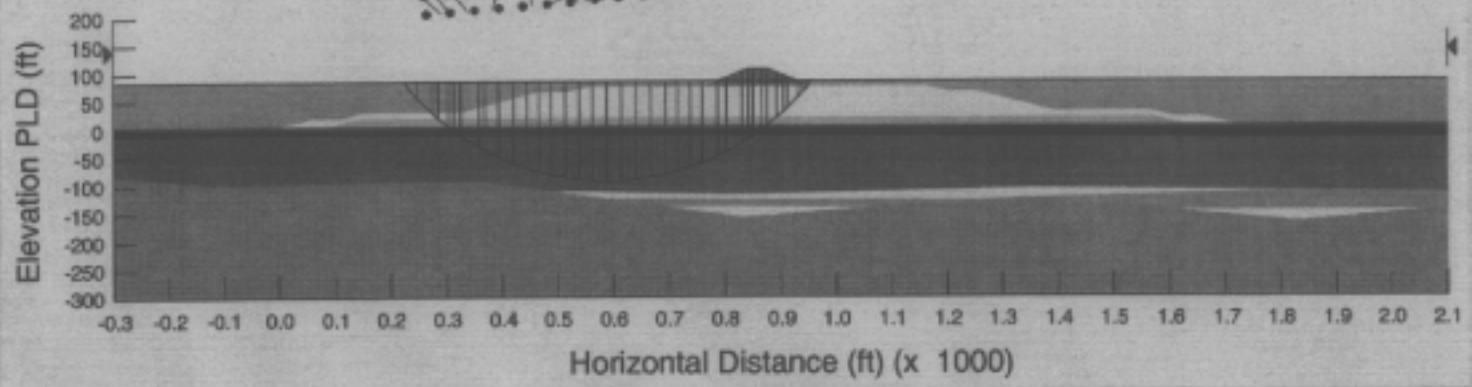


ACP

Description: Fill Embankment across Trinidad Dam
Comments: Stage No. 6
File Name: etapa6U.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Right to Left
Slip Surface Option: Grid and Radius
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)

F.S. = 1.623

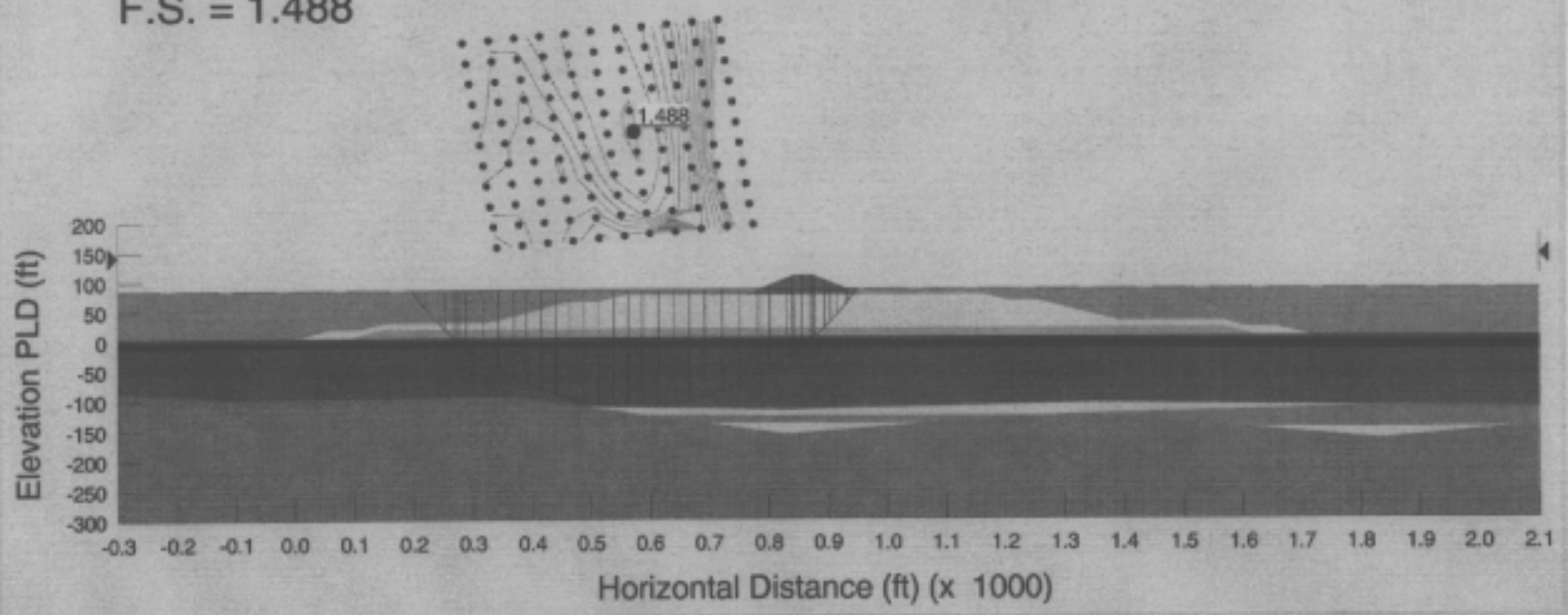




ACP

Description: Fill Embankment across Trinidad Dam
Comments: Condition at end of construction
File Name: endofcoU.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Right to Left
Slip Surface Option: Grid and Radius
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)

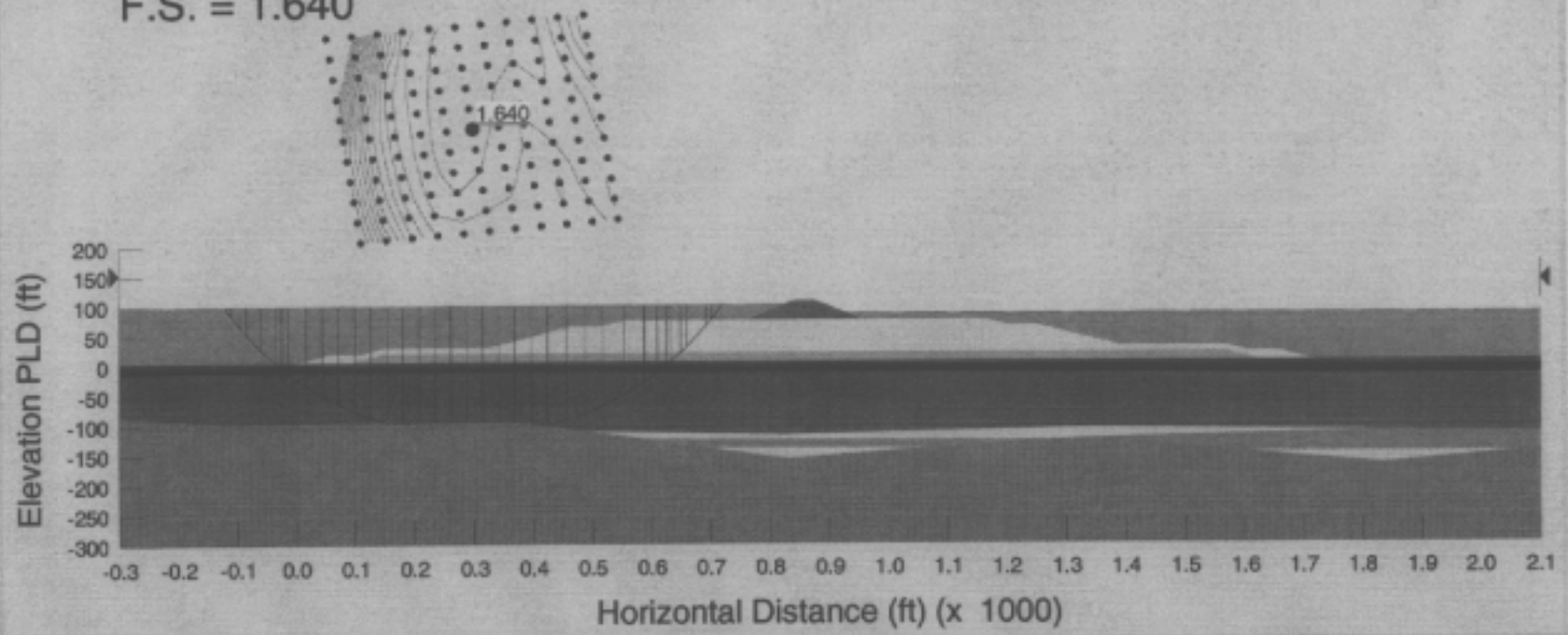
F.S. = 1.488



ACP

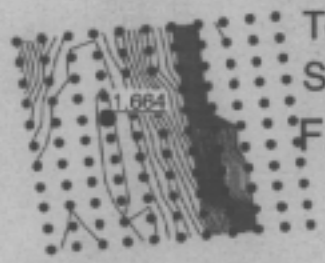
Description: Fill Embankment across Trinidad Dam
Comments: Condition during reservoir filling
File Name: fillresU.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Right to Left
Slip Surface Option: Grid and Radius
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)

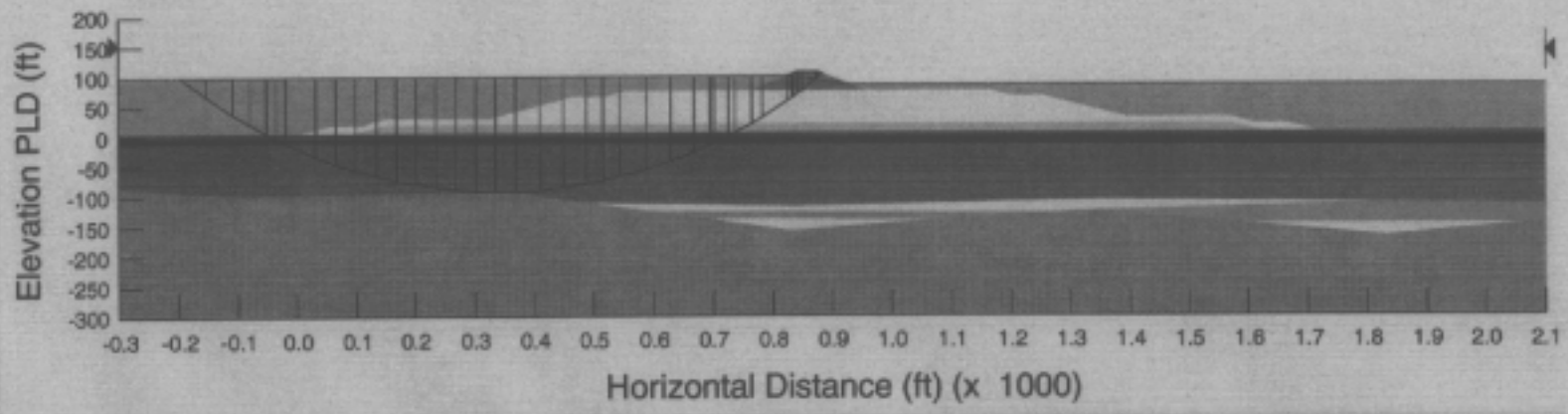
F.S. = 1.640



ACP

Description: Fill Embankment across Trinidad Dam
Comments: Long term condition
File Name: longterU.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Right to Left
Slip Surface Option: Grid and Radius
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)
F.S. = 1.664

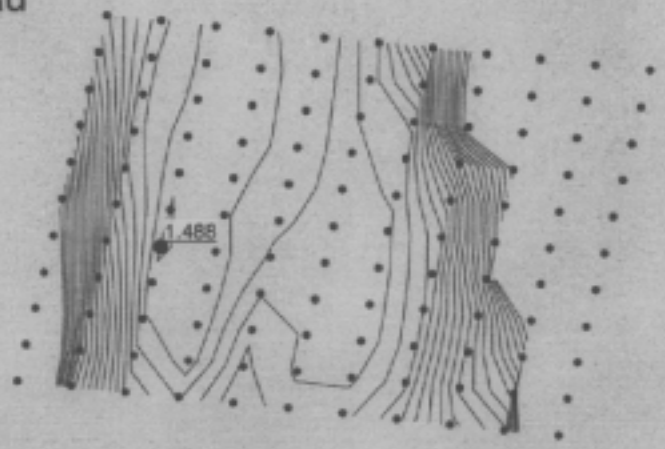


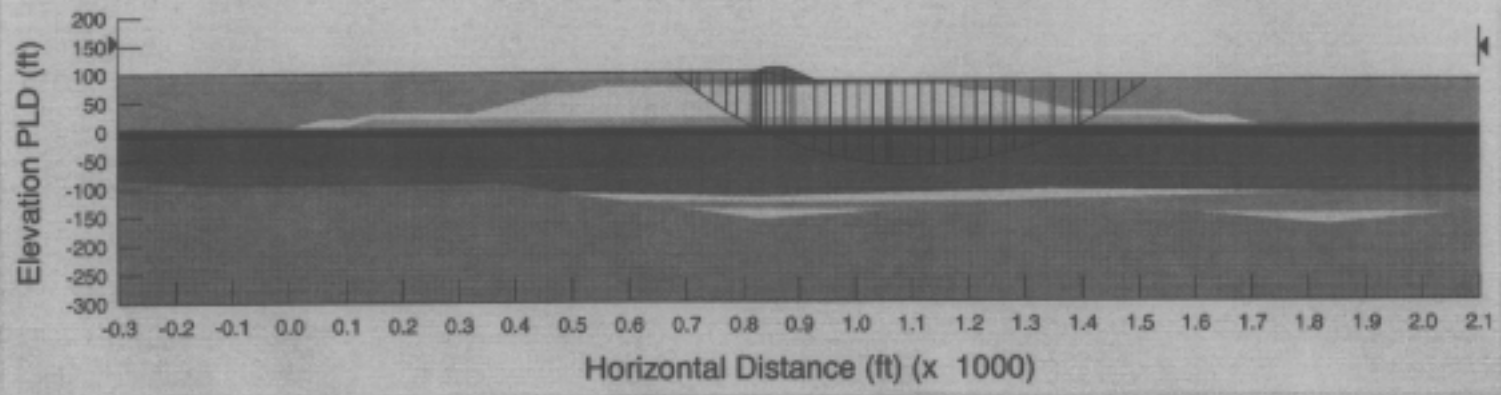


ACP

Description: Fill Embankment across Trinidad Dam
Comments: Long term condition
File Name: longteUR.slp
Analysis Method: Morgenstern-Price
Direction of Slip Movement: Left to Right
Slip Surface Option: Grid and Radius
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)

F.S. = 1.488



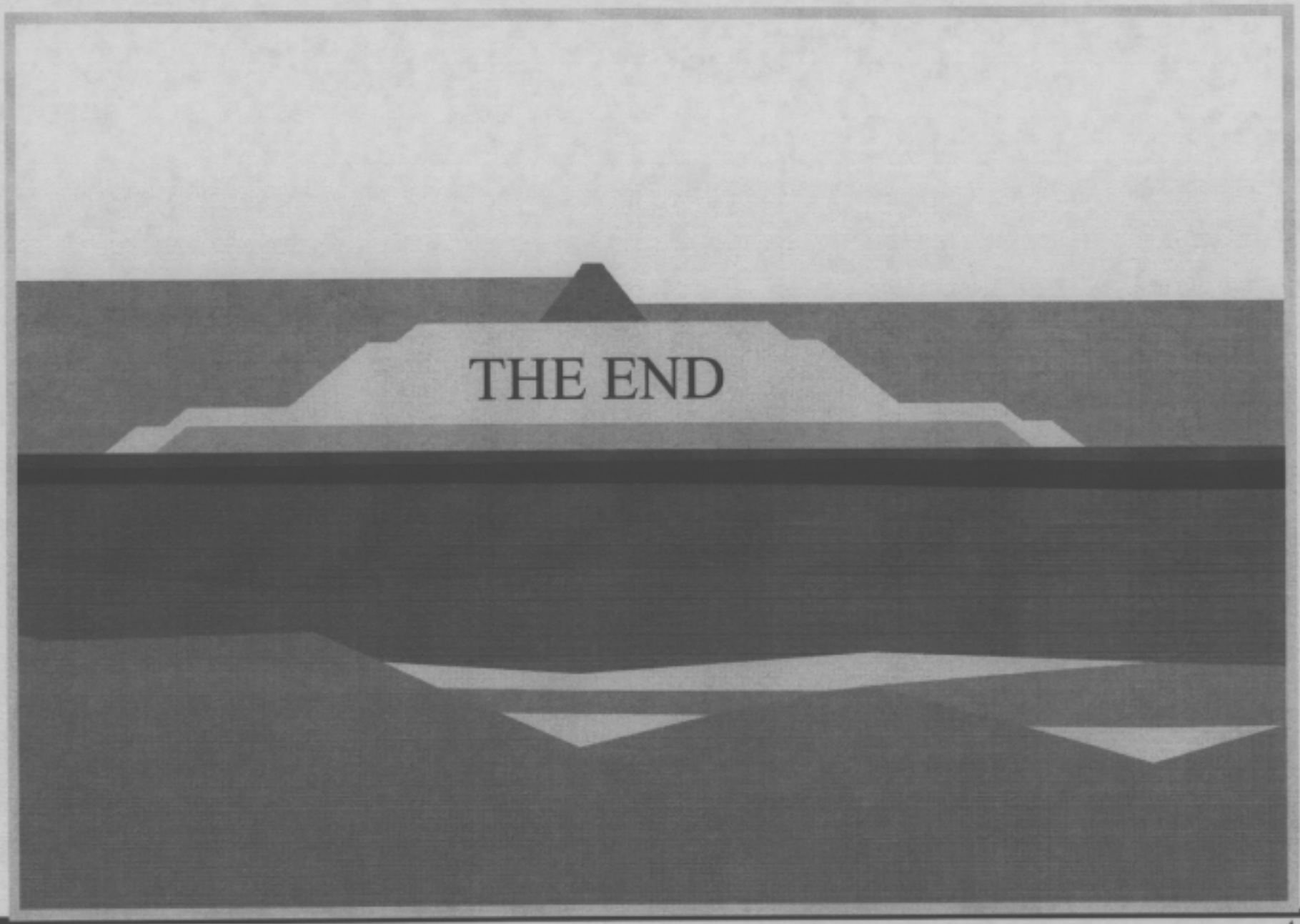


ACP

Summary

	c' & ϕ' parameters	Undrained Strength	Plaxis
Stage 1	1.080	1.664	1.07
Stage 2	1.473	1.157	1.56
Stage 3	2.097	1.157	1.68
Stage 4	1.988	1.516	1.37
Stage 5	2.093	1.602	1.32
Stage 6	1.971	1.623	1.25
End of Construction	1.826	1.488	1.06
Filling Reservoir	2.809	1.640	1.04
Long term after construction (circular slip)	3.524	1.664	
Long term after construction (block specified)	3.322	-	-
Long term after construction	3.322	-	1.43

ACP



ACP