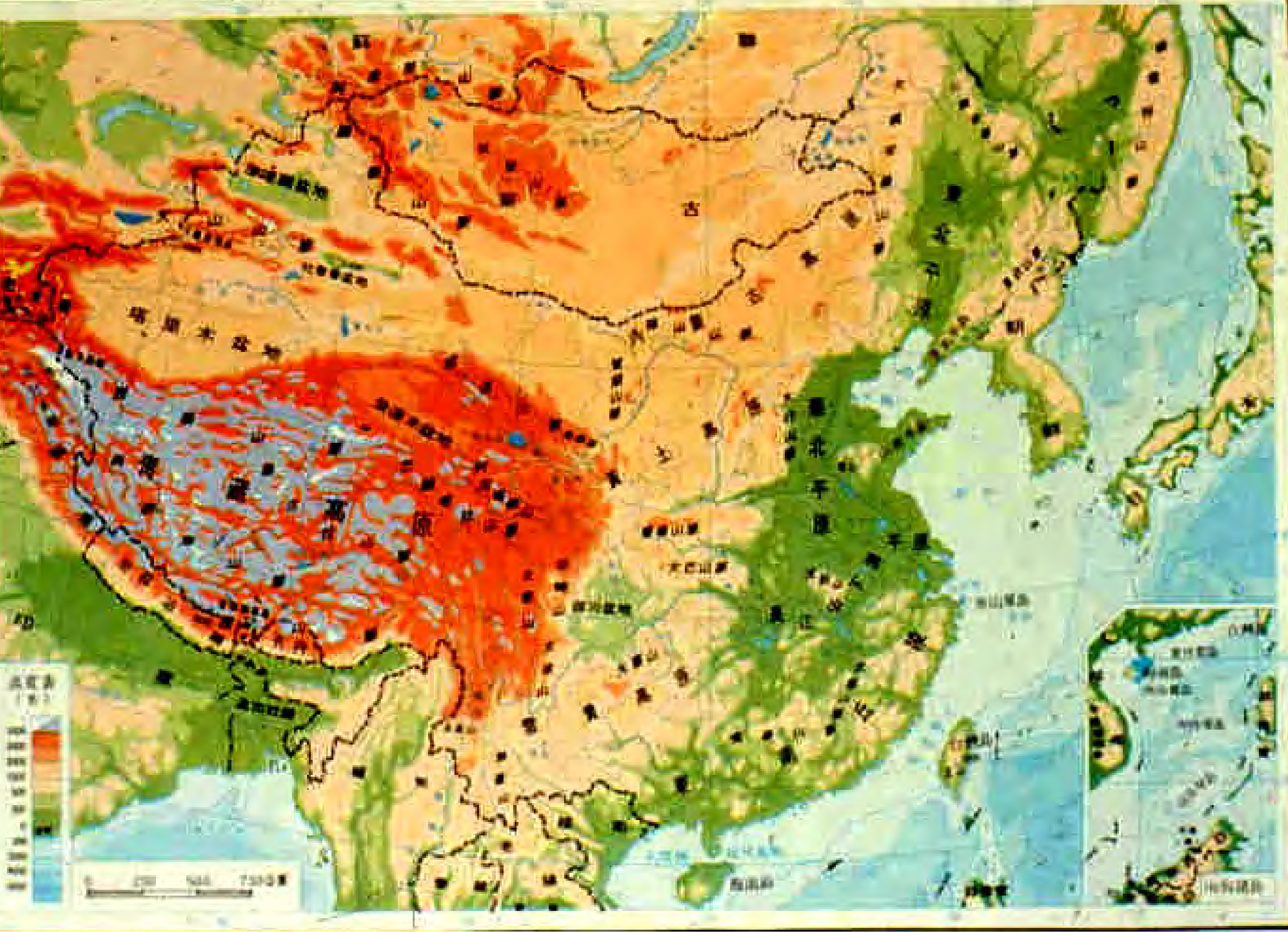
Geotechnical Challenges in Hydropower Development in China

Third Lumb Lecture

October 6, 2004

Hong Kong

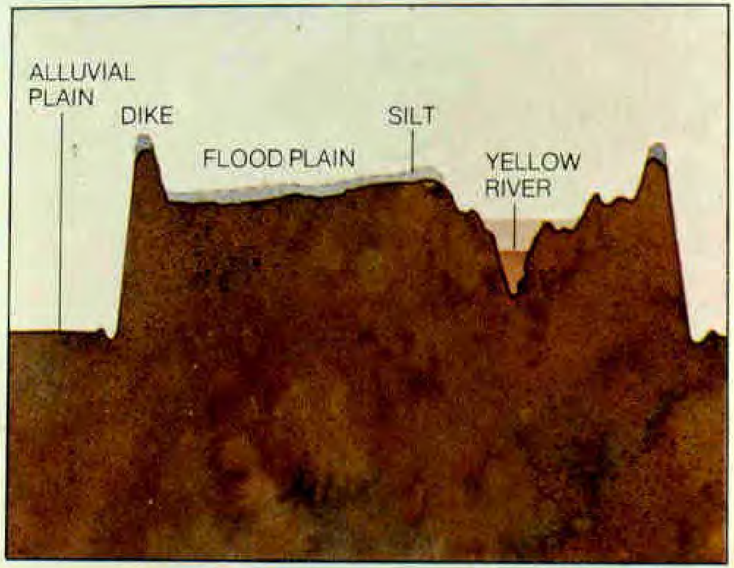


江底走，水在頭上流—荆江懸河

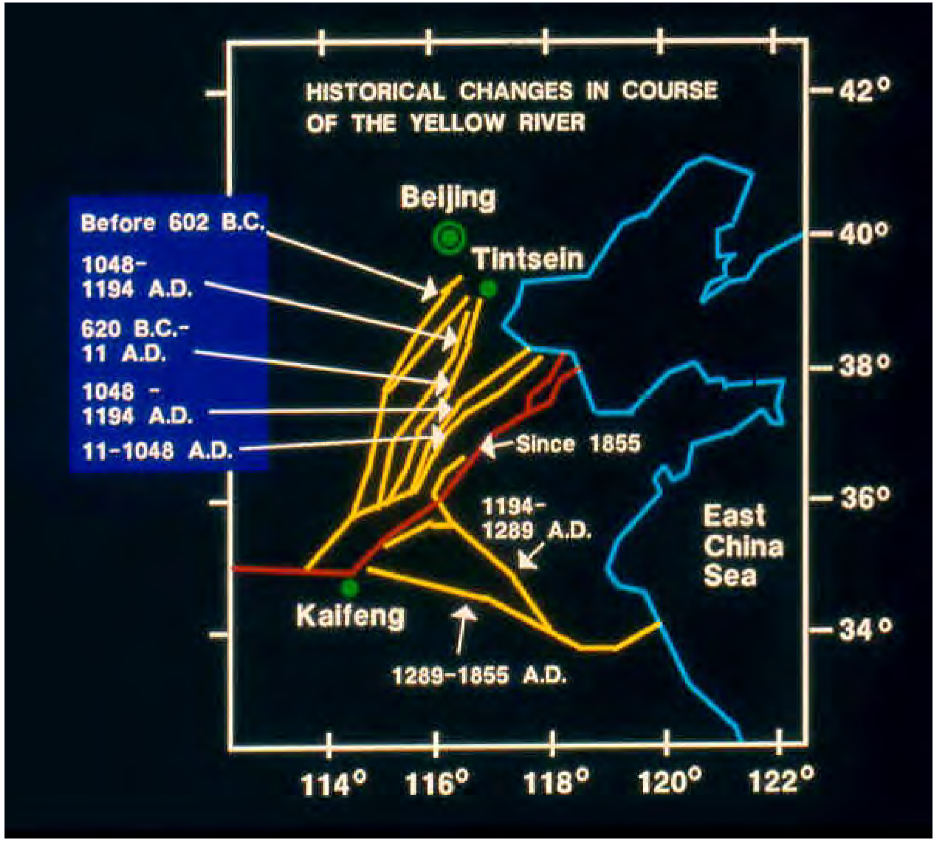
黄河大堤

黃河歷史性大改道

黃河剖面圖（懸河）

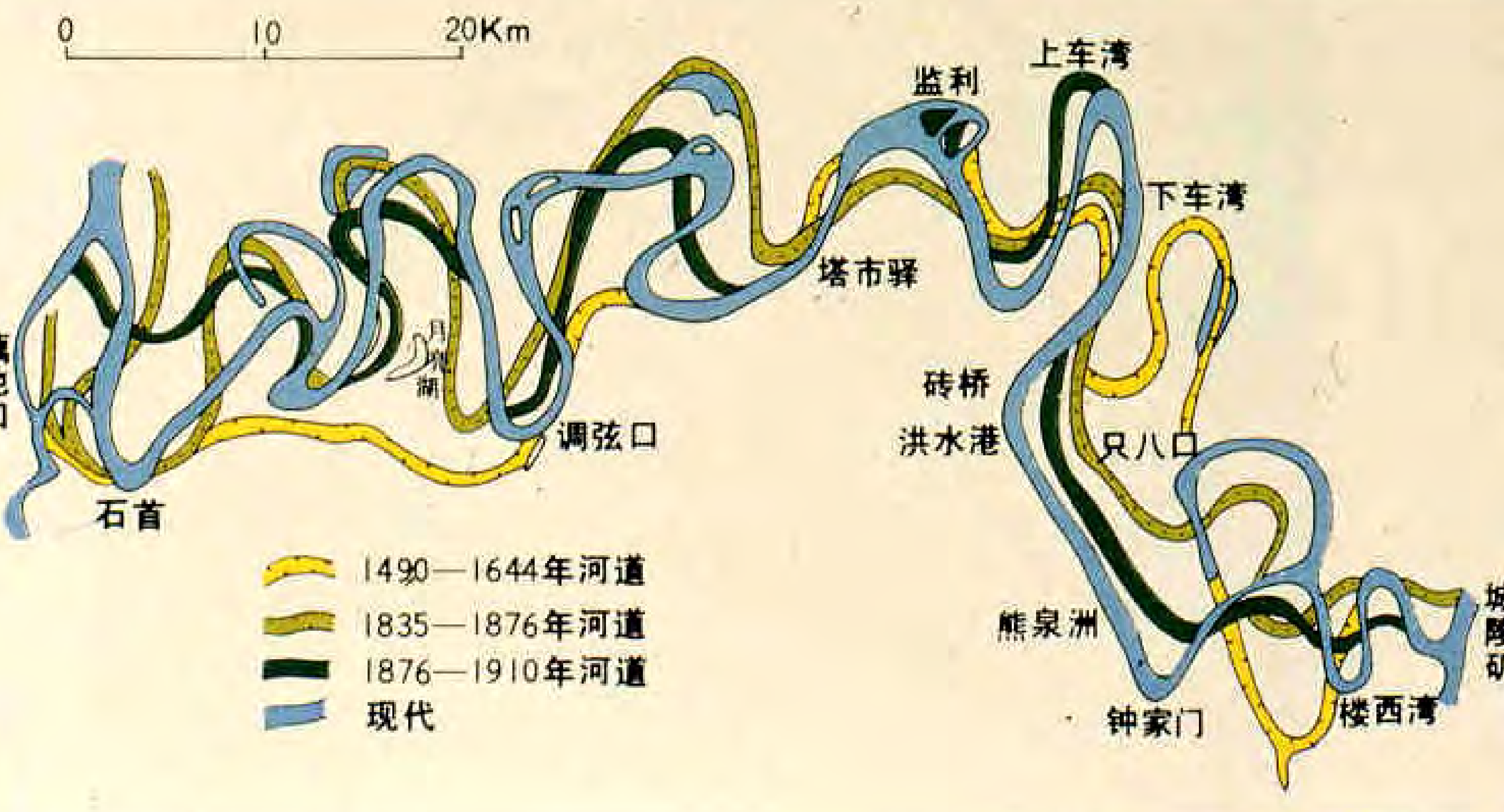


A cross section of the Yellow River illustrates the cycle that causes the river's bed and its protective dike system to grow higher and higher. As it flows toward the sea, the river continually deposits silt, which raises its bed and increases the threat of overtopping its natural banks. To compensate, the Chinese raise the level of the dikes. Over time both the river and the dikes have come to stand well above the surrounding alluvial plain.

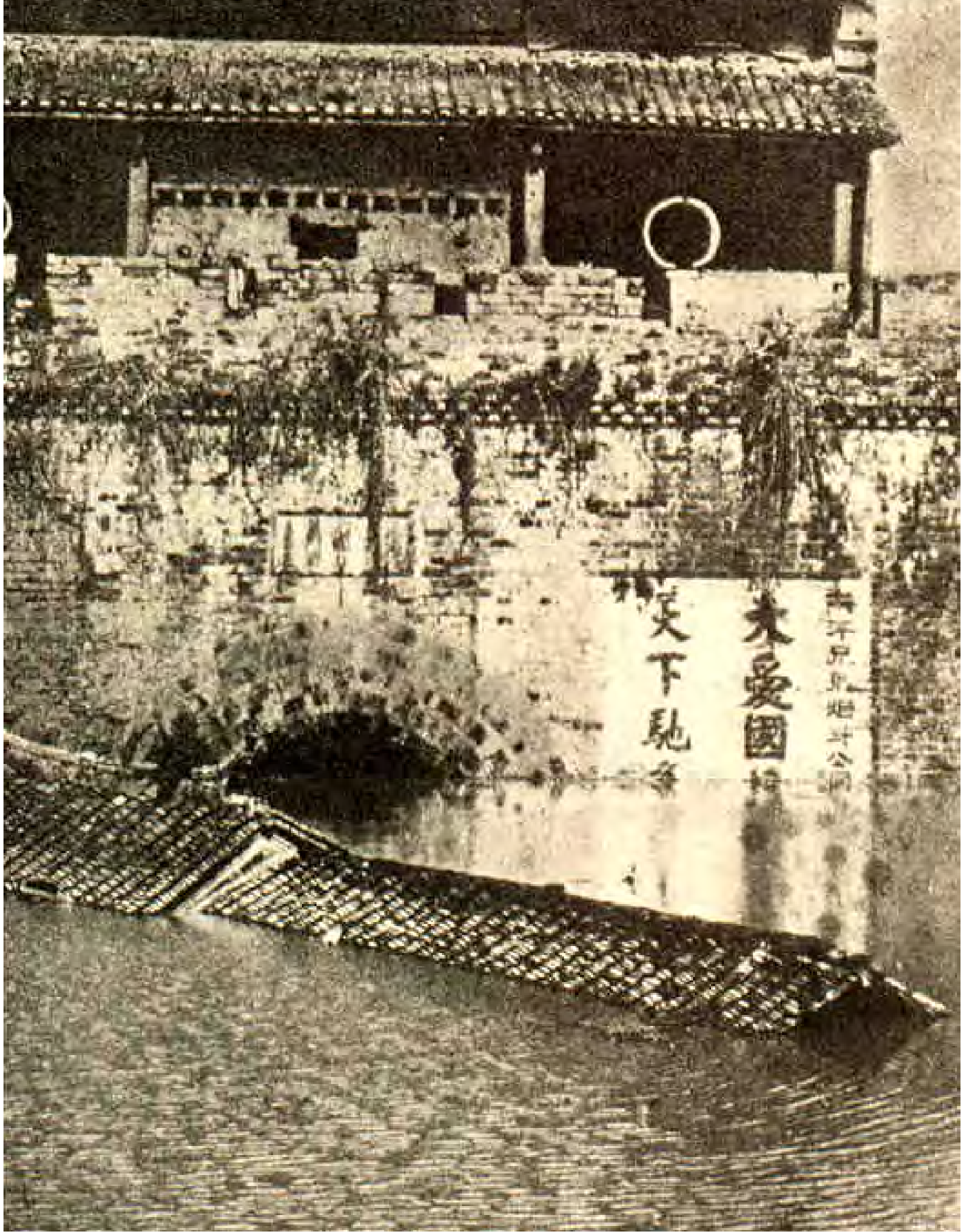


长江下荆江河道变迁图

Migration of lower Jingjiang River bed, Yangtze River



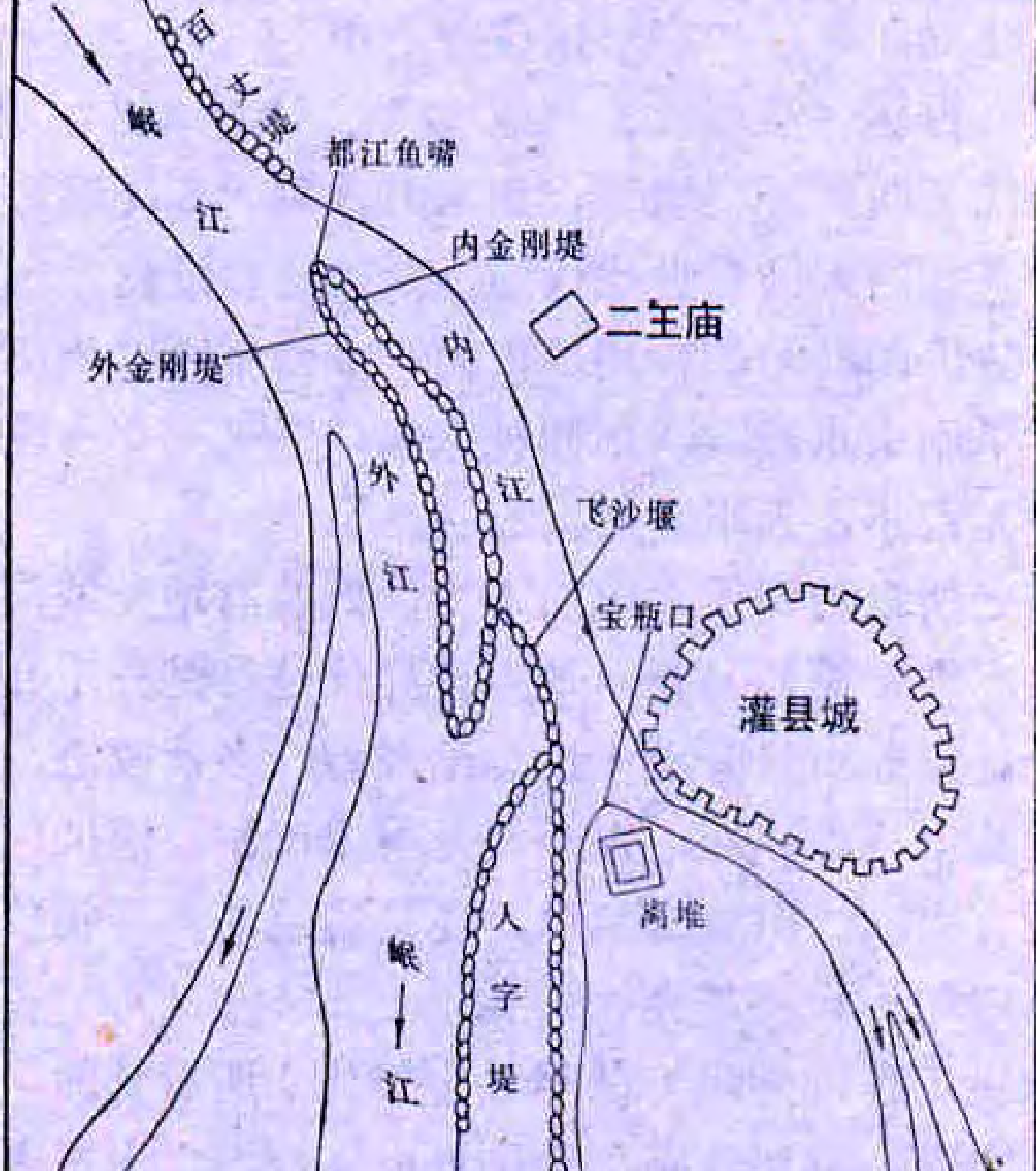
935年長江決
堤於荊州



The Yangtze: China's Second Killer Rive

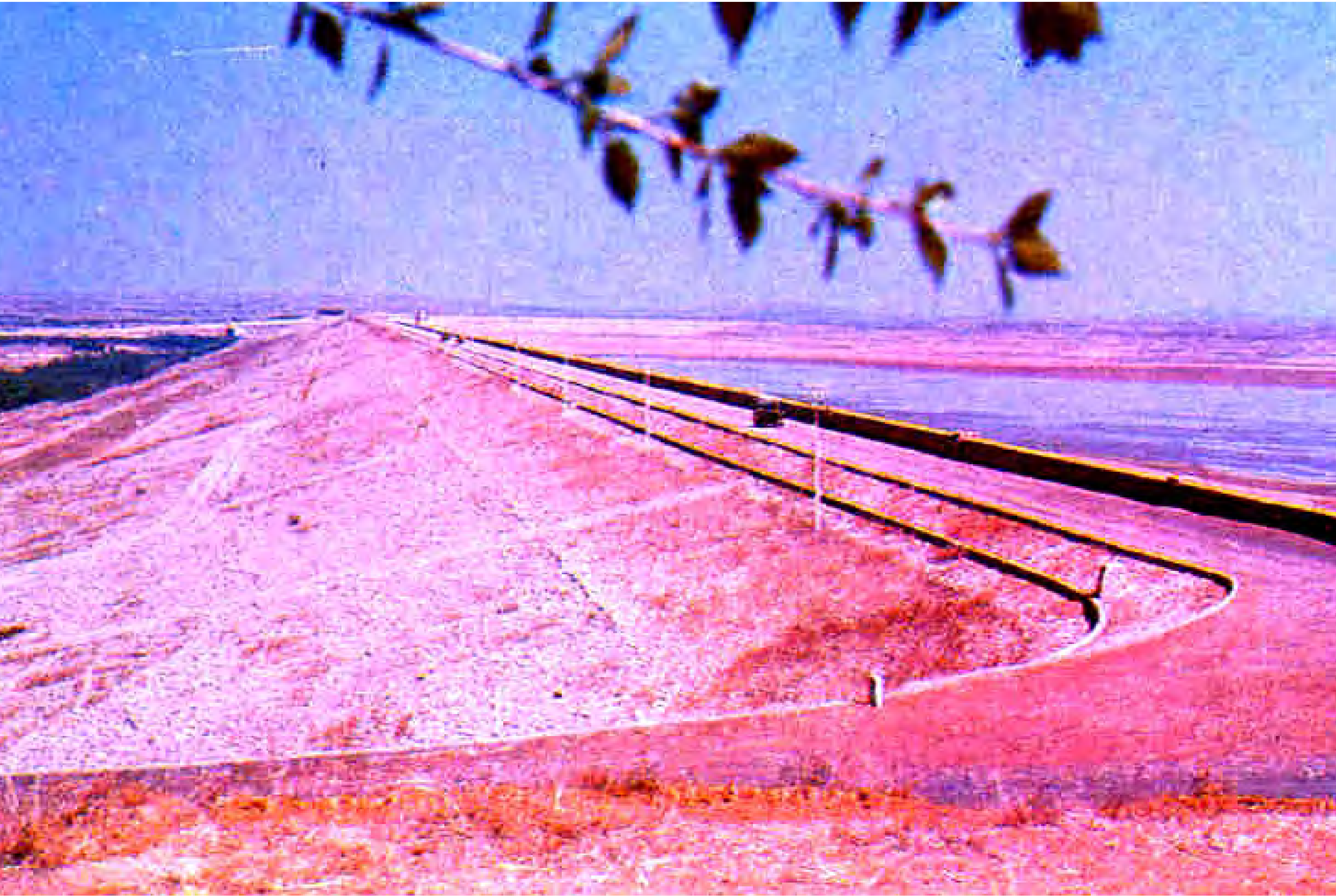
水患

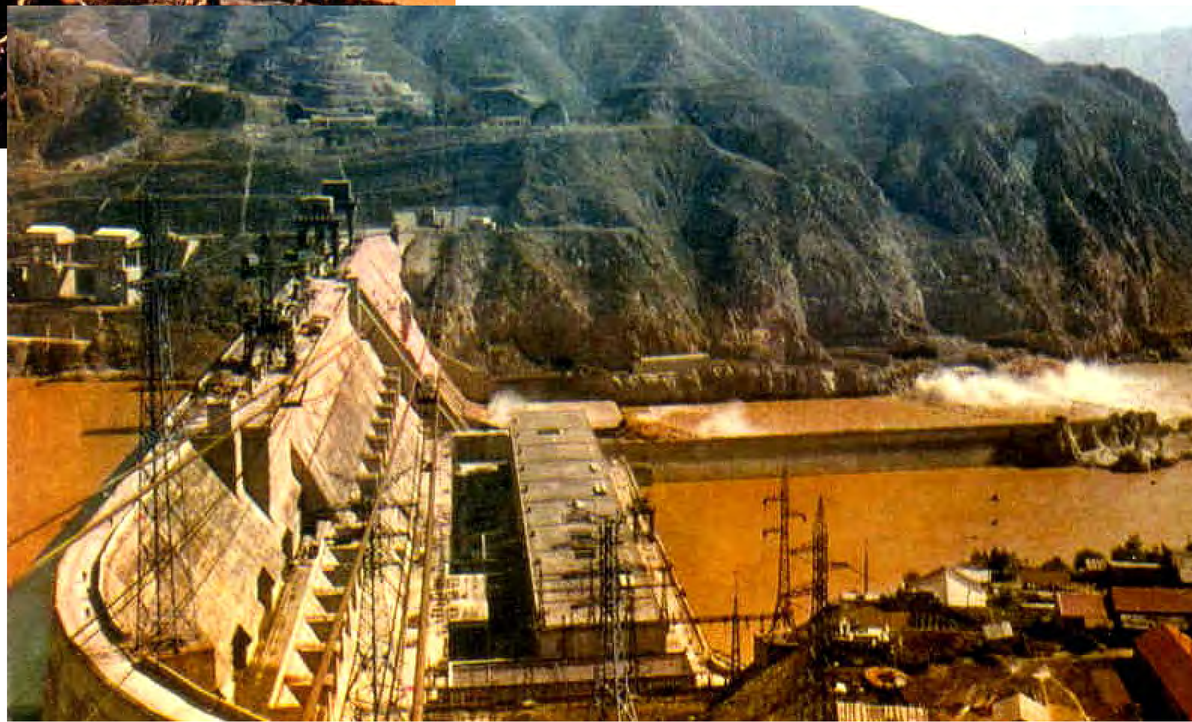
先民治水圖


百丈堤
岷江
都江鱼嘴
内金刚堤
二王庙
外金刚堤
内江
外江
飞沙堰
宝瓶口
灌县城
离堆
人字堤
岷江


史悠久的文明古国

現代大堤





三門峽大壩

心窩水庫
大壩裂縫

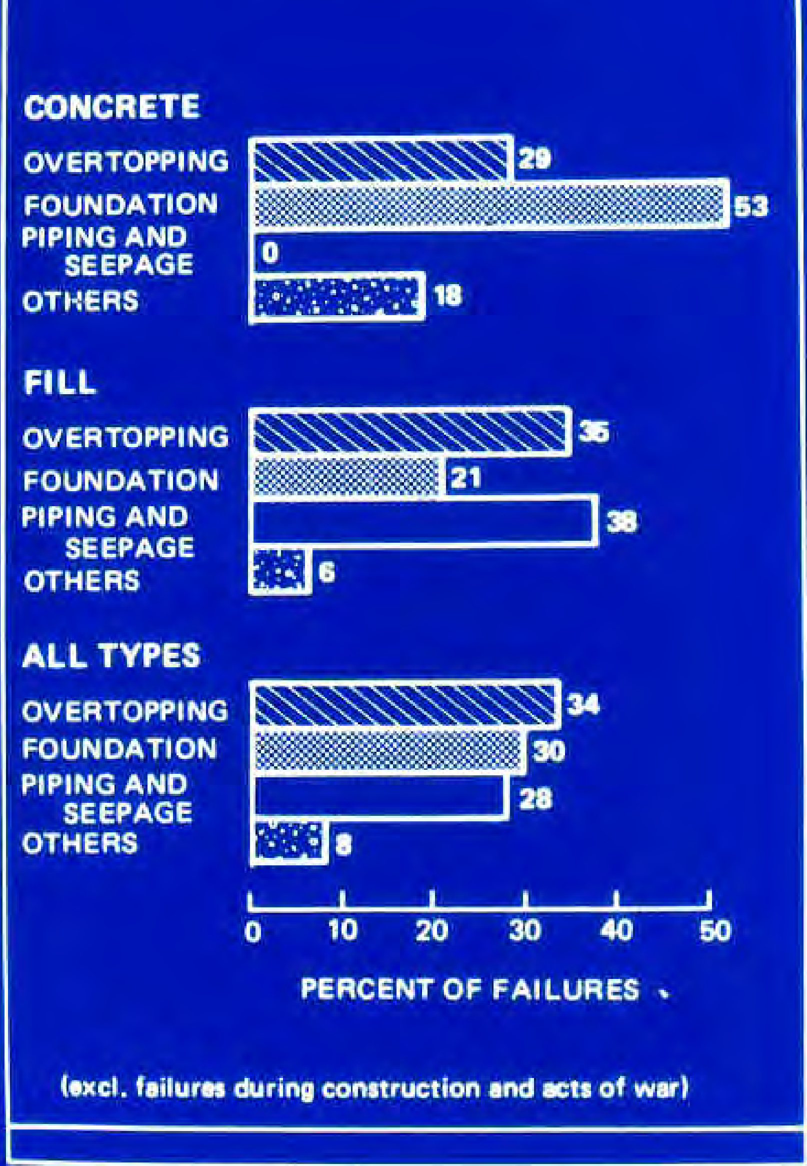


FIGURE 2-1 Cause of failure. SOURCE: ICOLD (1973)

Geotechnical Issues

(A) Earth and Rockfill Dams

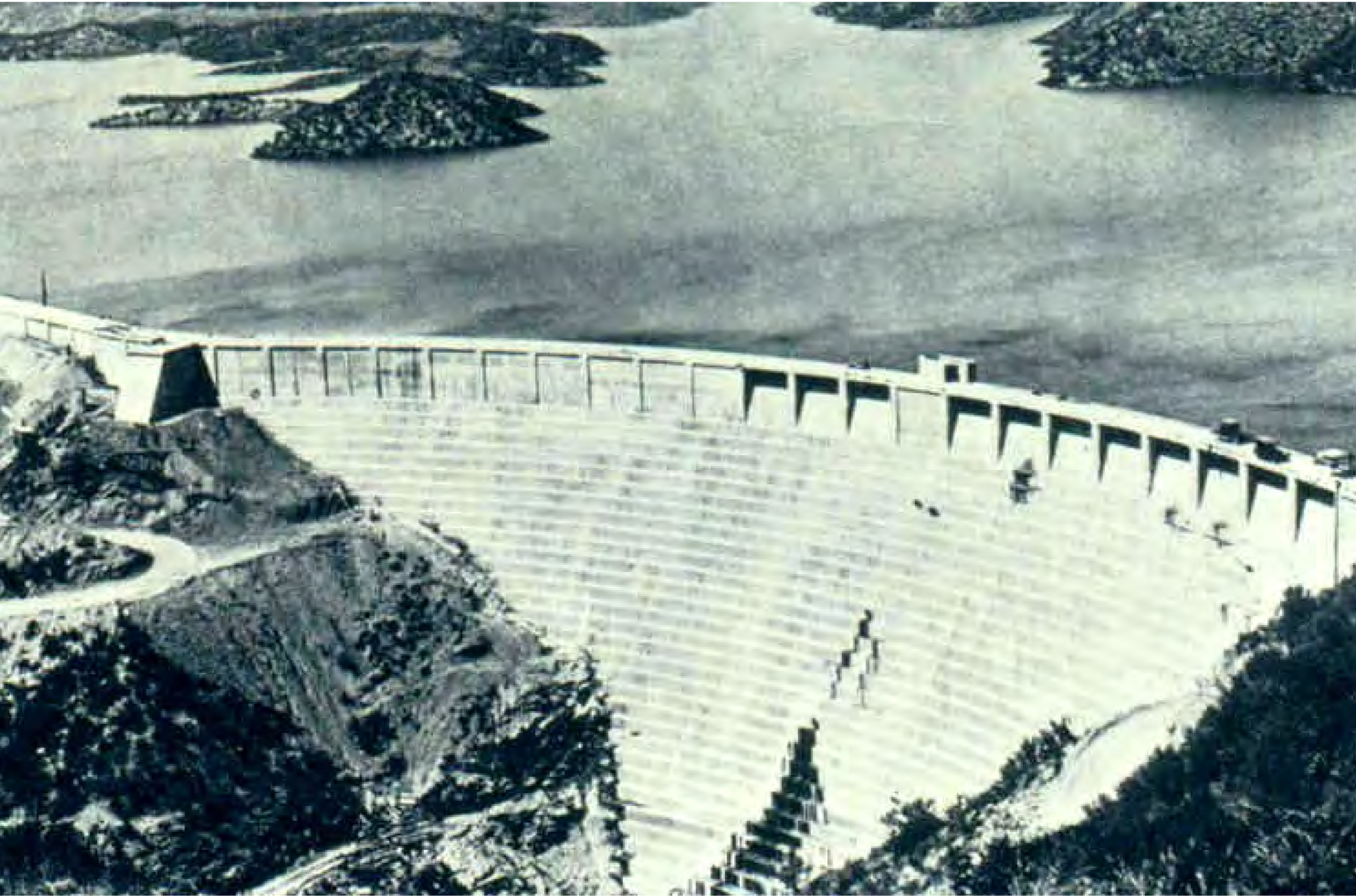
- Piping due to seepage

- Overtopping

Geotechnical Issues

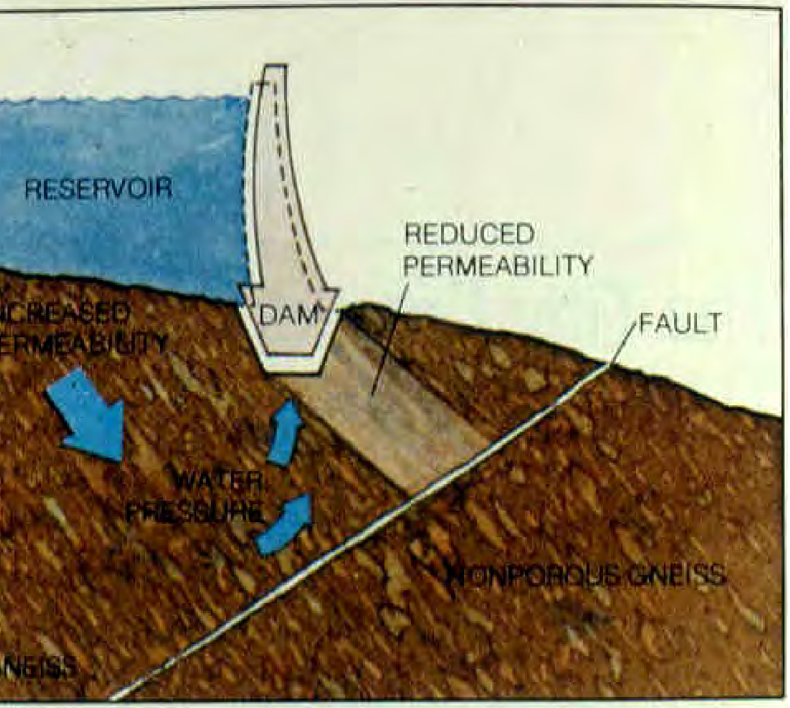
(B) Dam Foundations

- Foundation failure due to seepage and erosion (e.g. St. Francis Dam, Teton Dam)
- Foundation failure due to wedge slide (e.g. Malpasset Dam)
- Foundation failure due to fault movement (e.g. Baldwin Hill Dam)
- Foundation movement due to basal sliding (hydrostatic pressure + seismic load + ice load $\Rightarrow FS < 1$)



Quail Creek Dyke 1988

1959



ow water pressure unseated France's Malpasset Dam d caused it to fail in 1959 is shown above. Water tered microfissures in the gneiss rock beneath the ervoir and gradually built up immense pressure in e area at the base of the dam. When this water der pressure, seeking escape, encountered a zone of permeable gneiss that had been compressed by e dam's weight, it was deflected sharply upward, ing half the dam from its saddle in the steep gorge

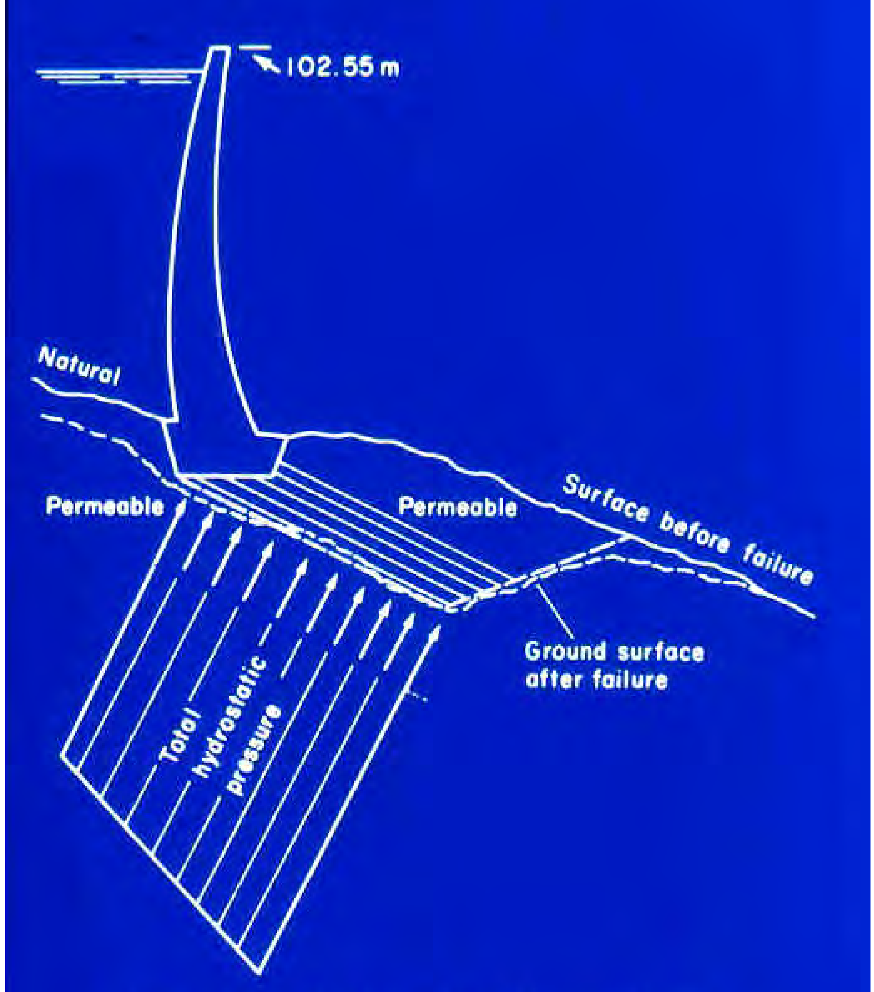


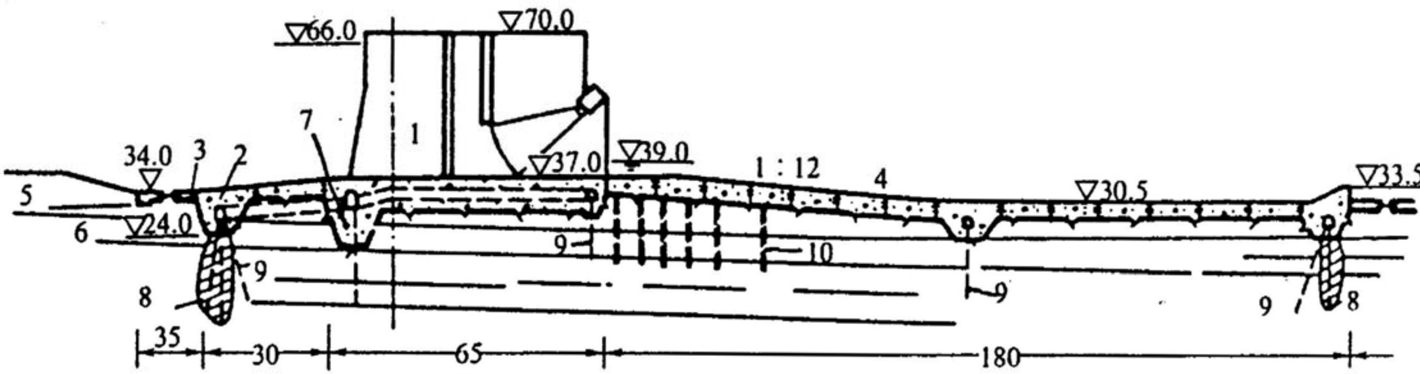
Fig. 3.04 Failure of Malpasset Dam


eepage in
nspection
unnel
RISER AT CH.5+35
(ABOUT 500 GPM)


after
asphalt
grouting


←61.7'
65'
67'→
Stewartville GS
6+83 9'R
Asphalt Grout
61.7' – 67.0'

Ge Zhou Ba Foundation Treatment



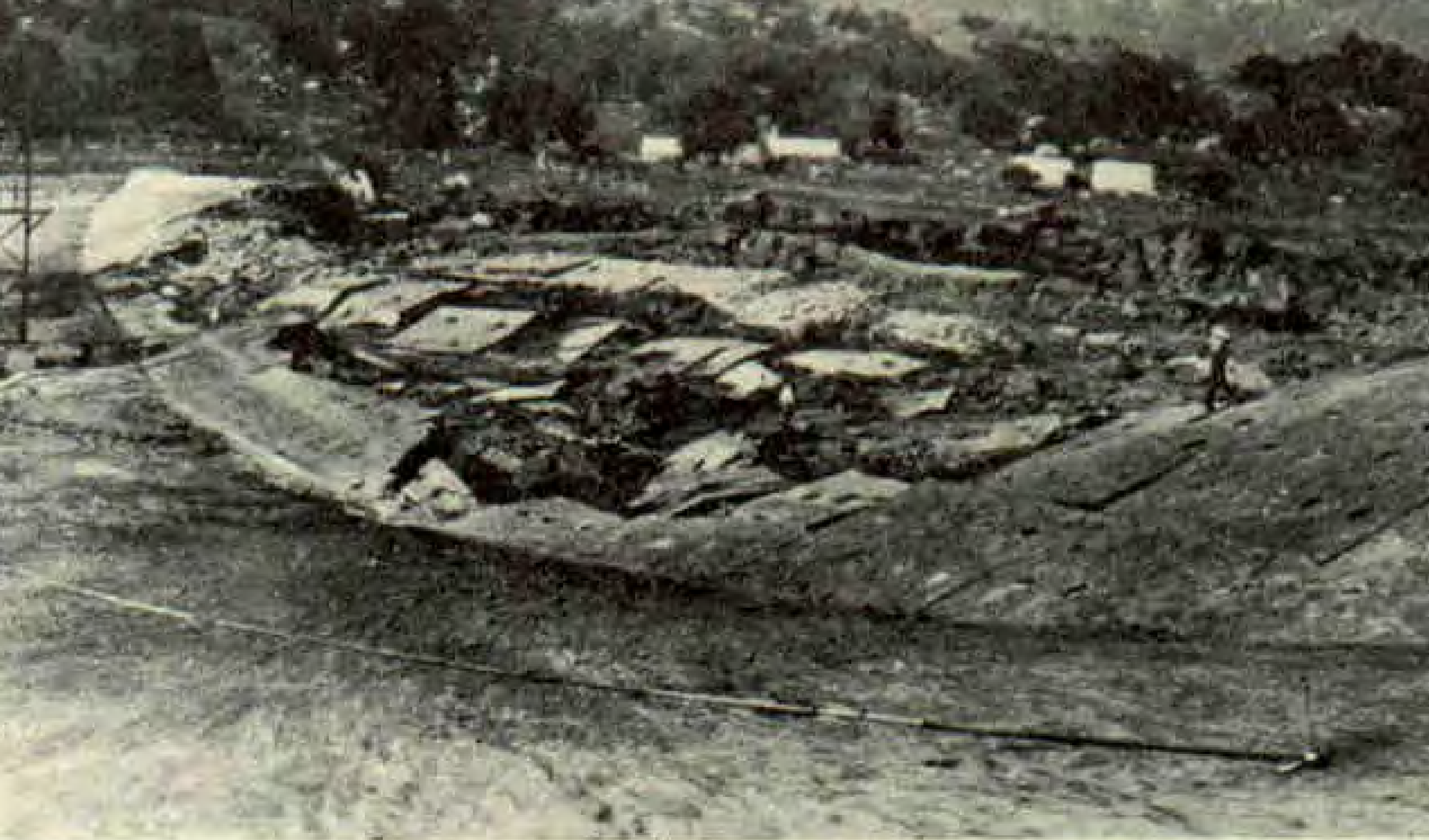
葛洲坝水利枢纽泄水闸基础处理方案示意图(单位:m)

1－闸室;2－防渗板;3－防冲铺盖;4－护坦板;5－212 夹层;6－202 夹层;
7－齿墙;8－防渗帷幕;9－排水孔;10－加固桩。

Geotechnical Issues

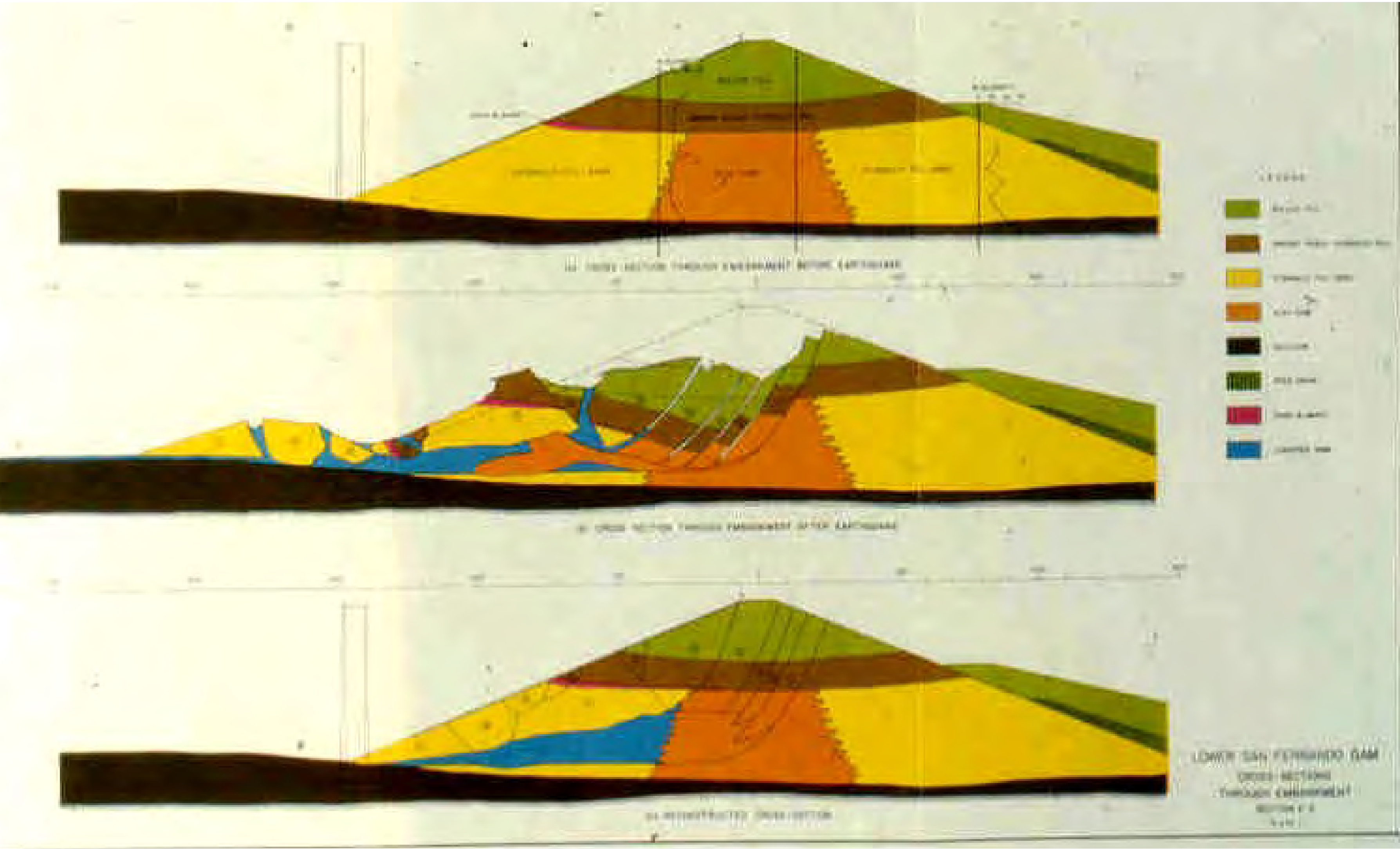
(C) Seismic Hazards

- Natural earthquakes
- Reservoir-induced seismicity
- Fault movement



g. 10.60. Failure of Sheffield Dam during Santa Barbar

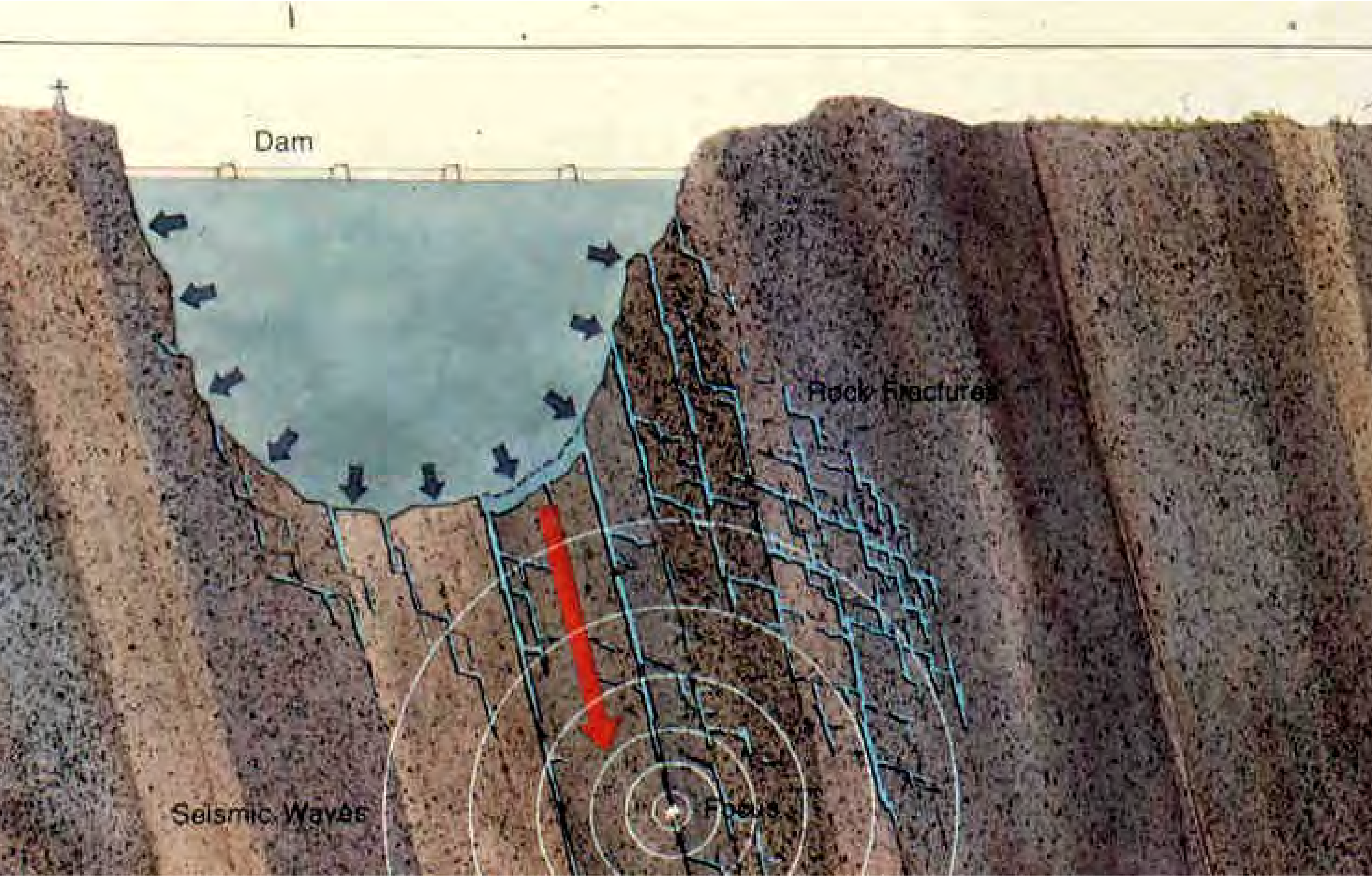
San Fernando cross-section

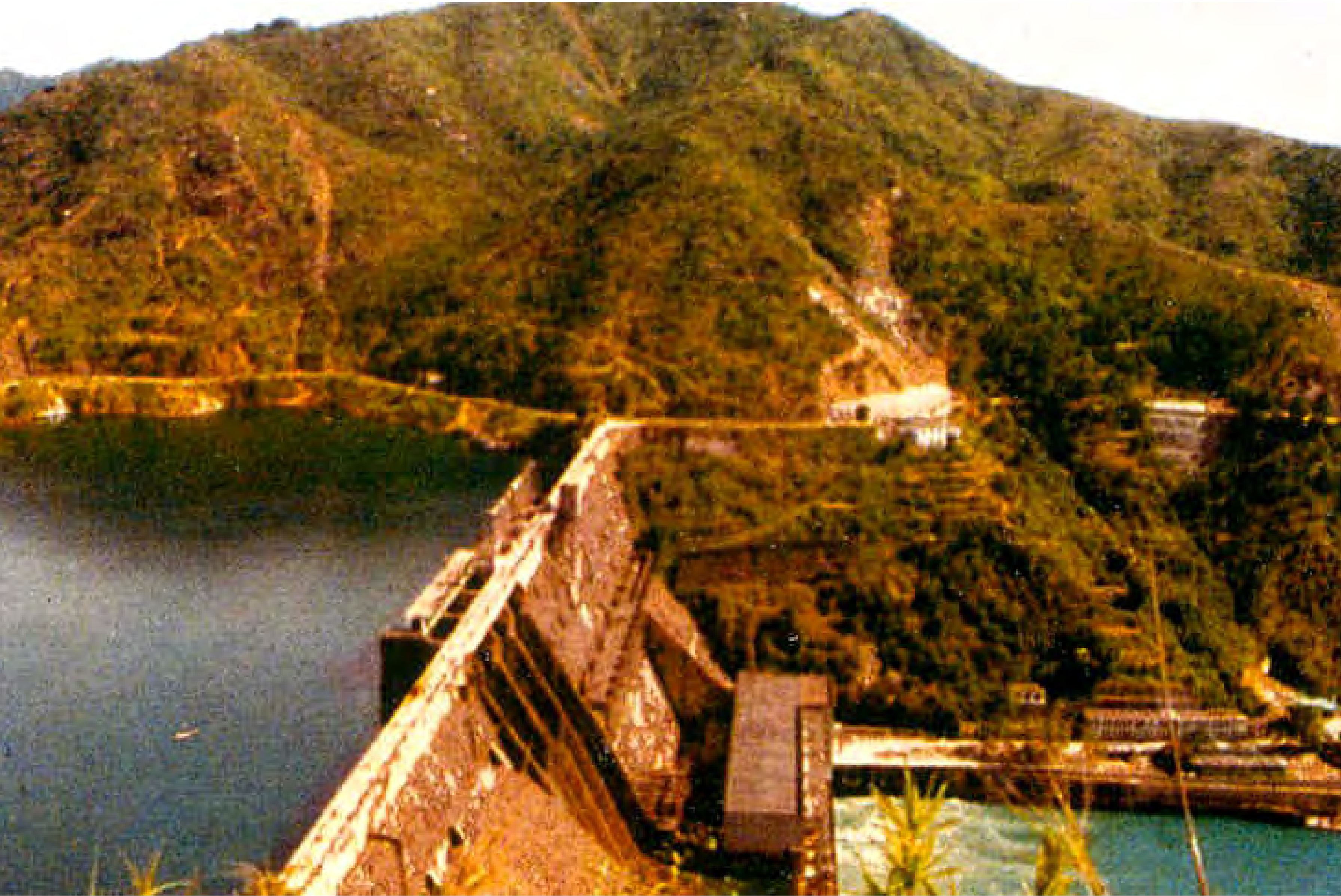


Ⅱ－4－11　唐山陡河水库坝体纵向开裂

Baldwin Hill
Dams, Los
Angeles
1963

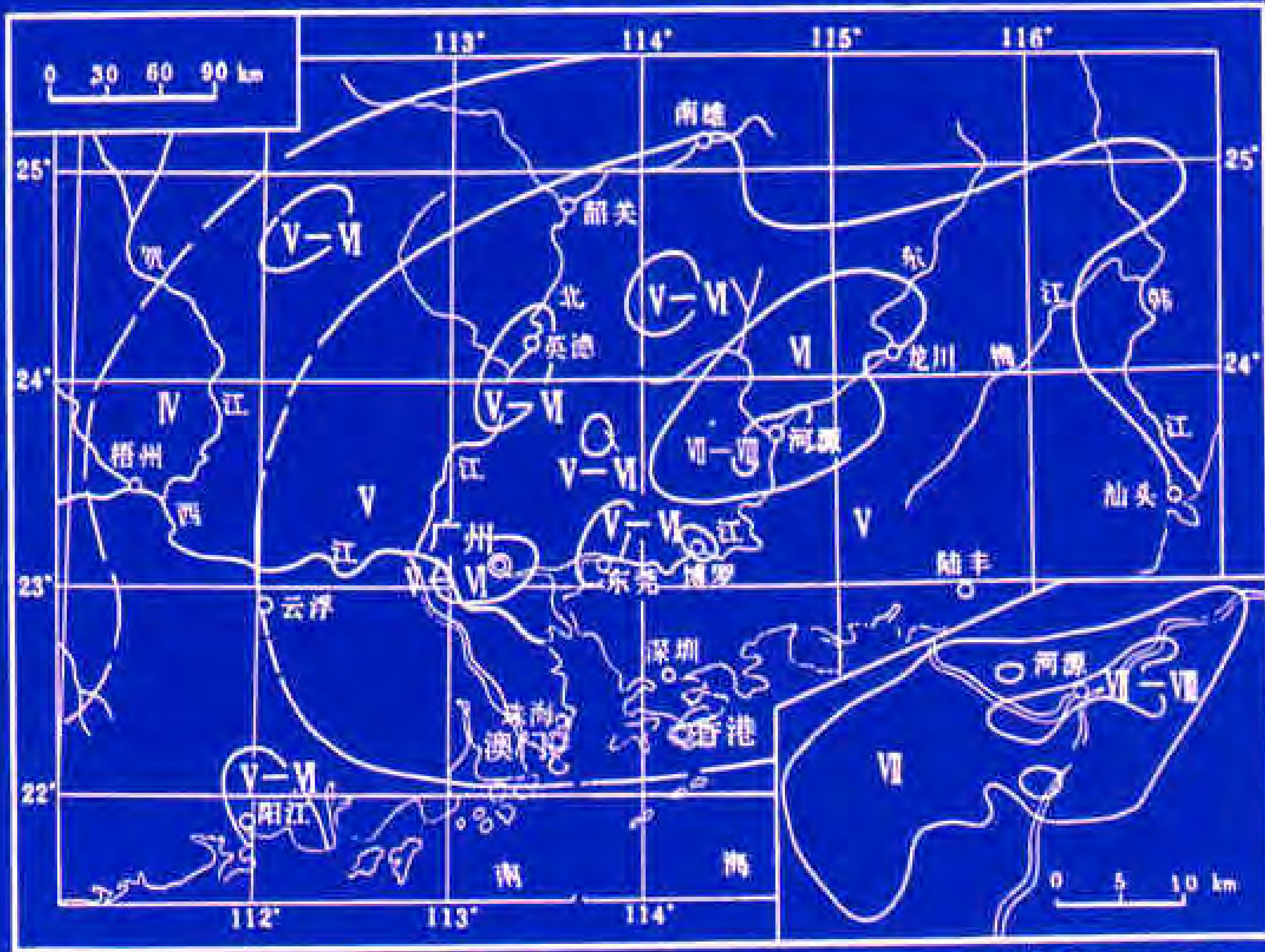
水庫地震



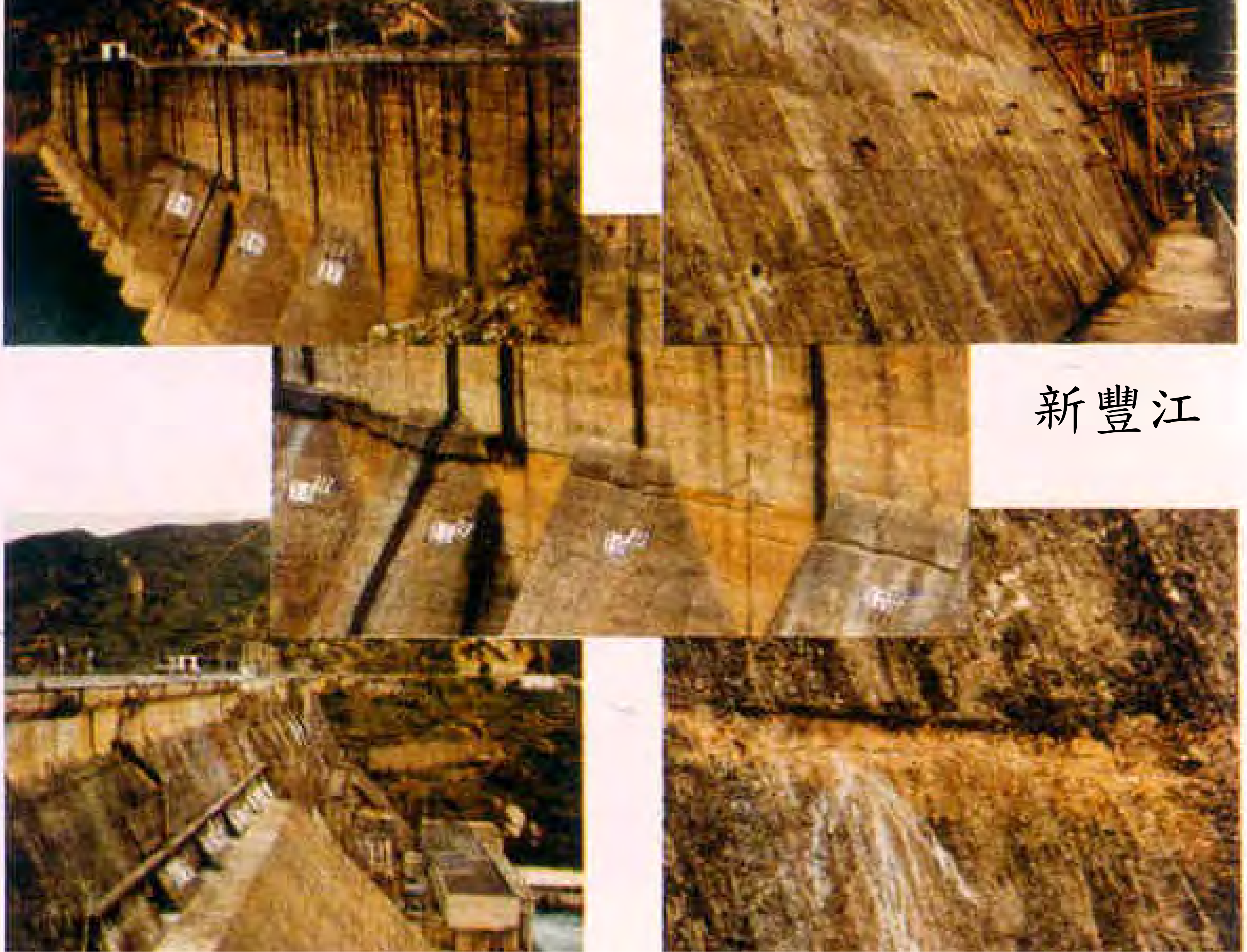


新丰江水库Ⅷ度地震等震线图（1962.3.19）

Isoseismic map of an earthquake of intensity Ⅷ at Xinfengjiang reservoir (March 19, 1962)



（据原广州地震大队）



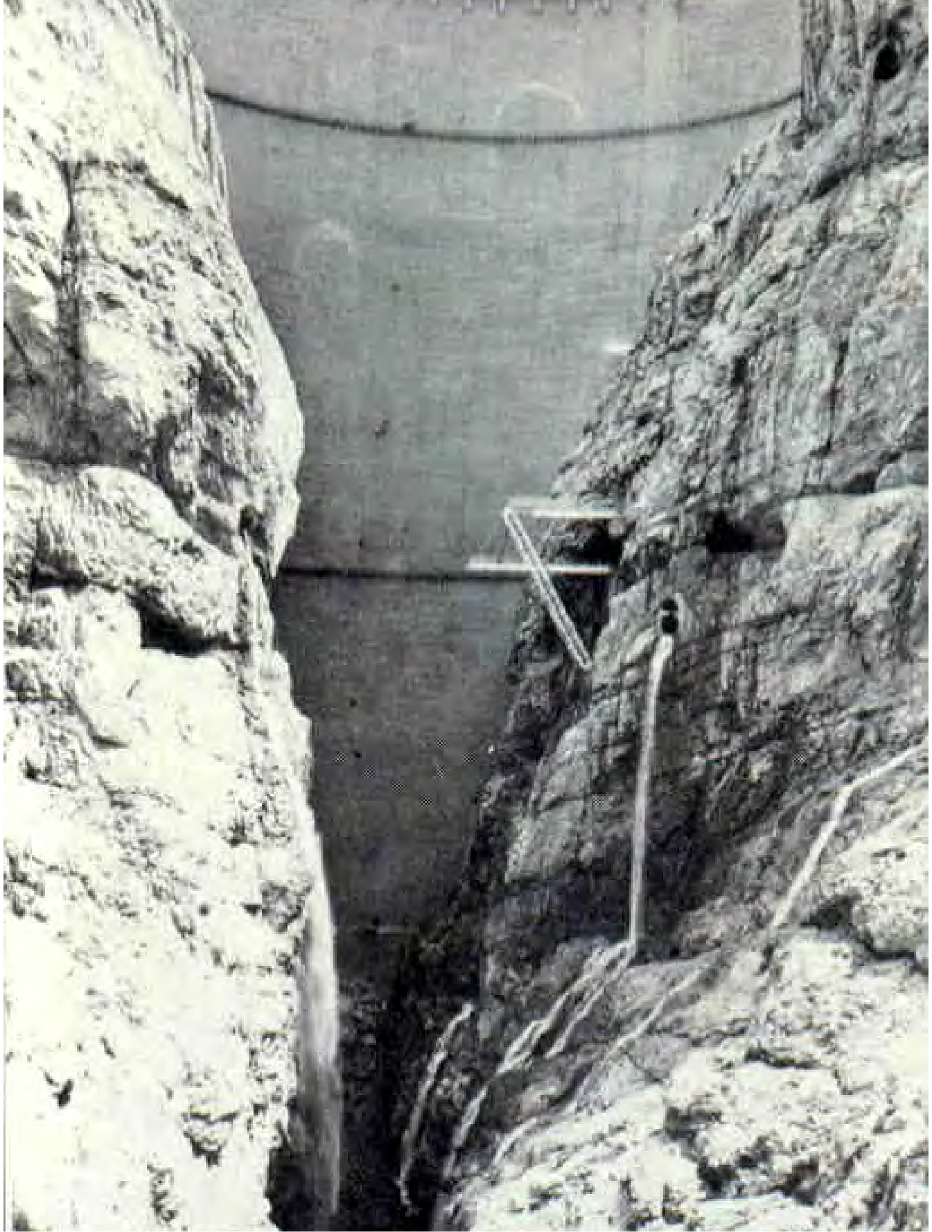
新豐江

Geotechnical Issues

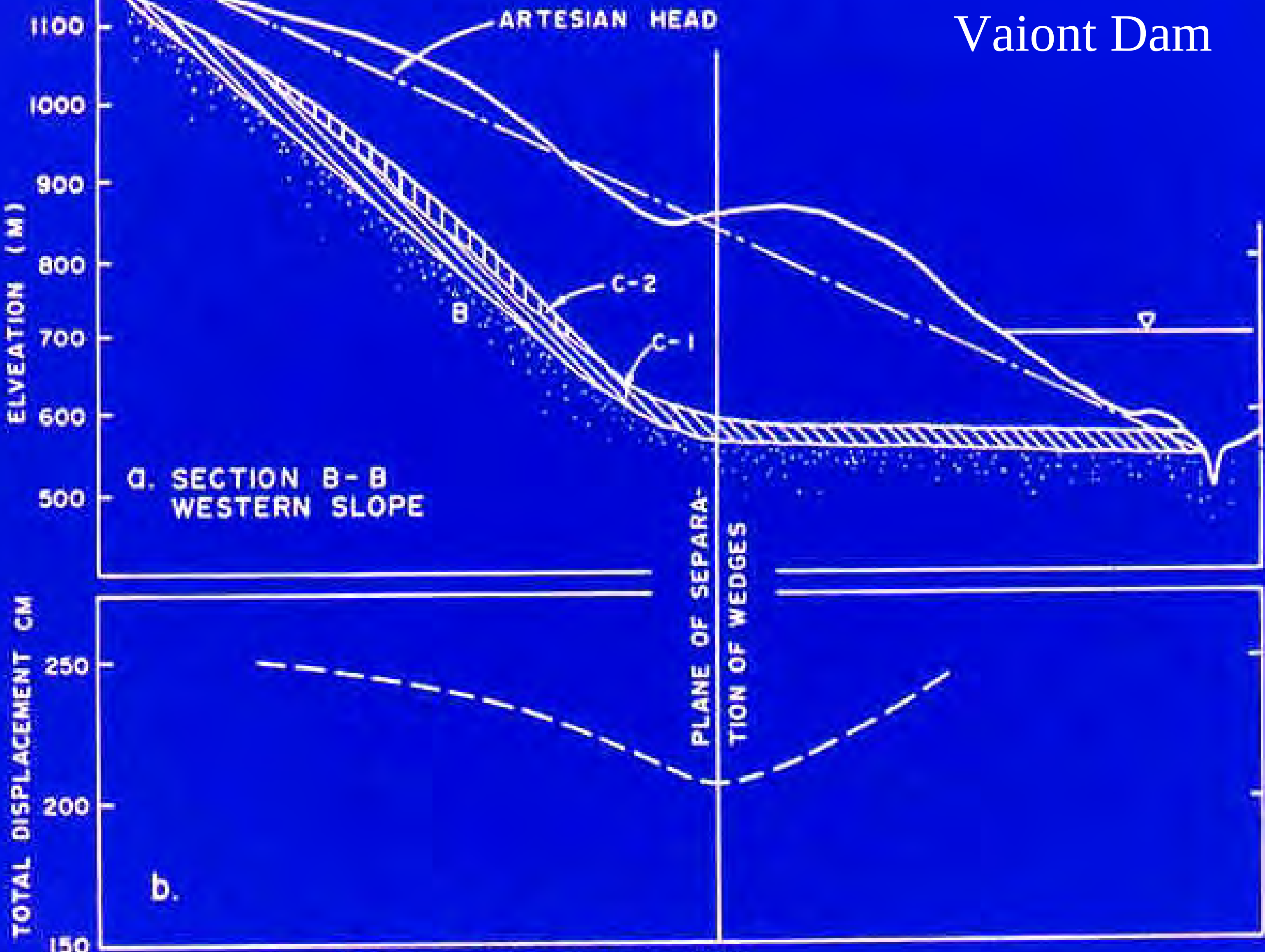
(D) Reservoir Slopes

- Natural terrain landslides (e.g. Xintan)
- Landslides due to reservoir impounding (e.g. Vaiont, Manwan, Huanglungtan, Zigui)
- Landslide dams (e.g. Dadu River, Usoi, Yigong)

Vaiont Dam



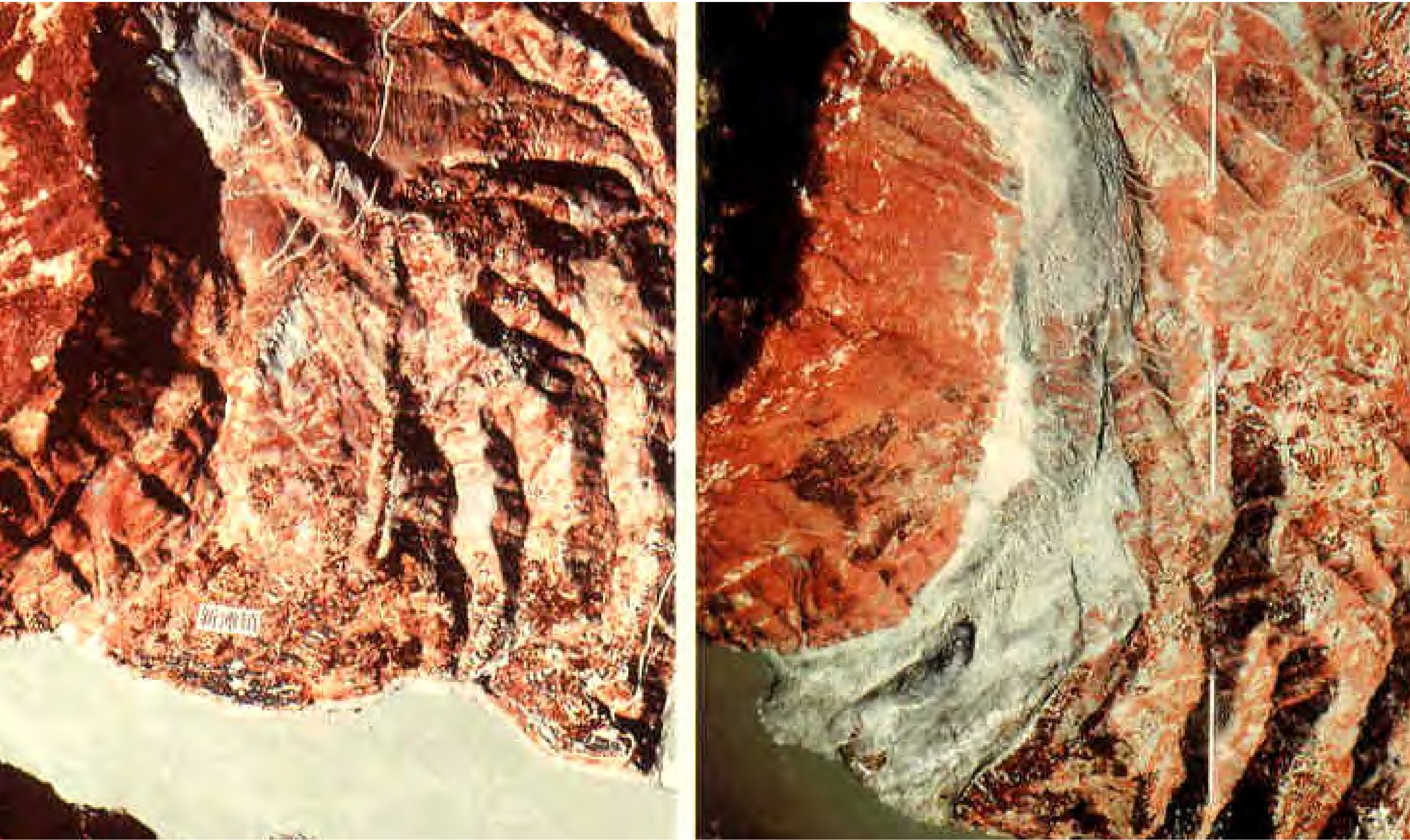
Vaiont Dam



2. (a) Section B-B, western slope

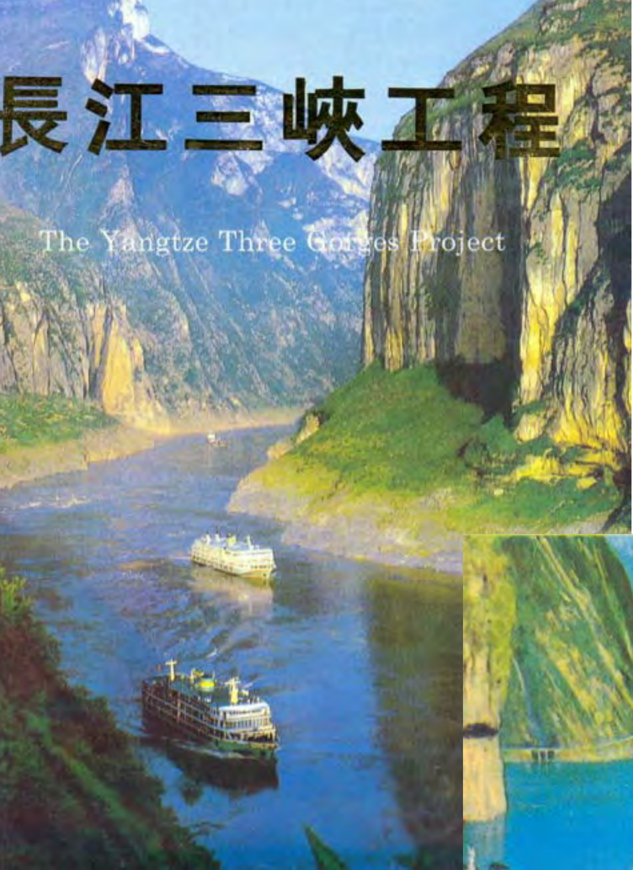
(b) Total displacement of surface of slope before

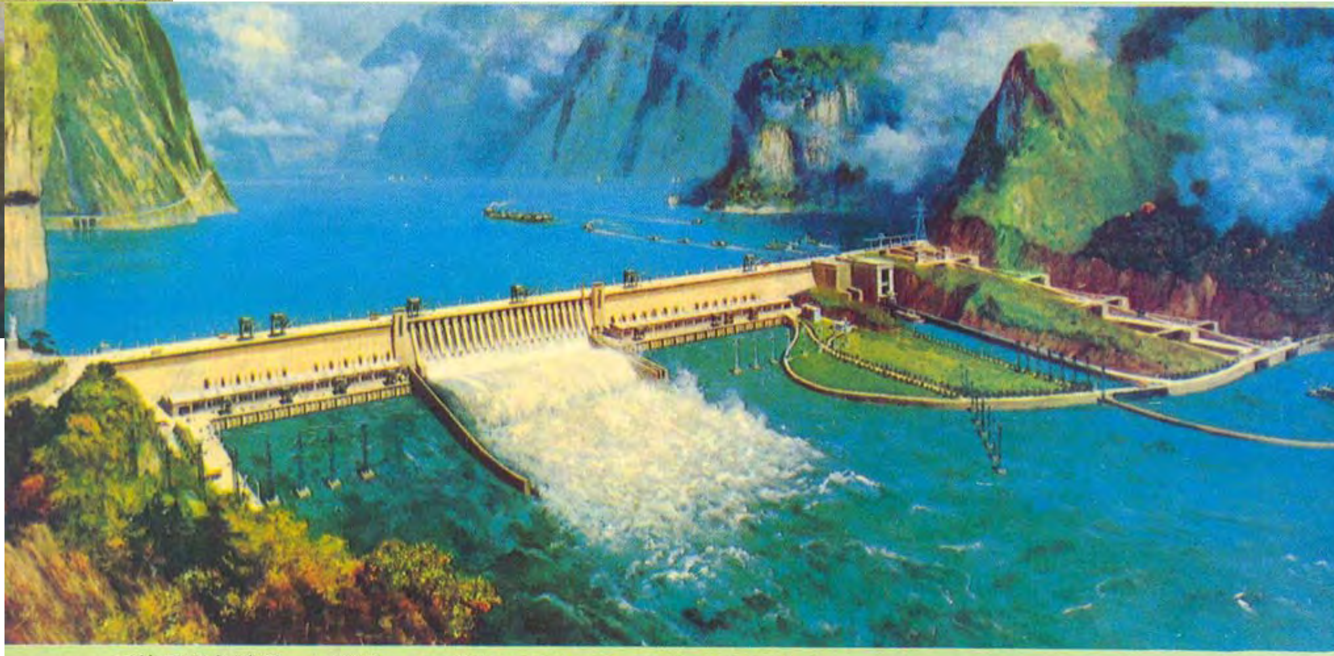
新灘滑坡



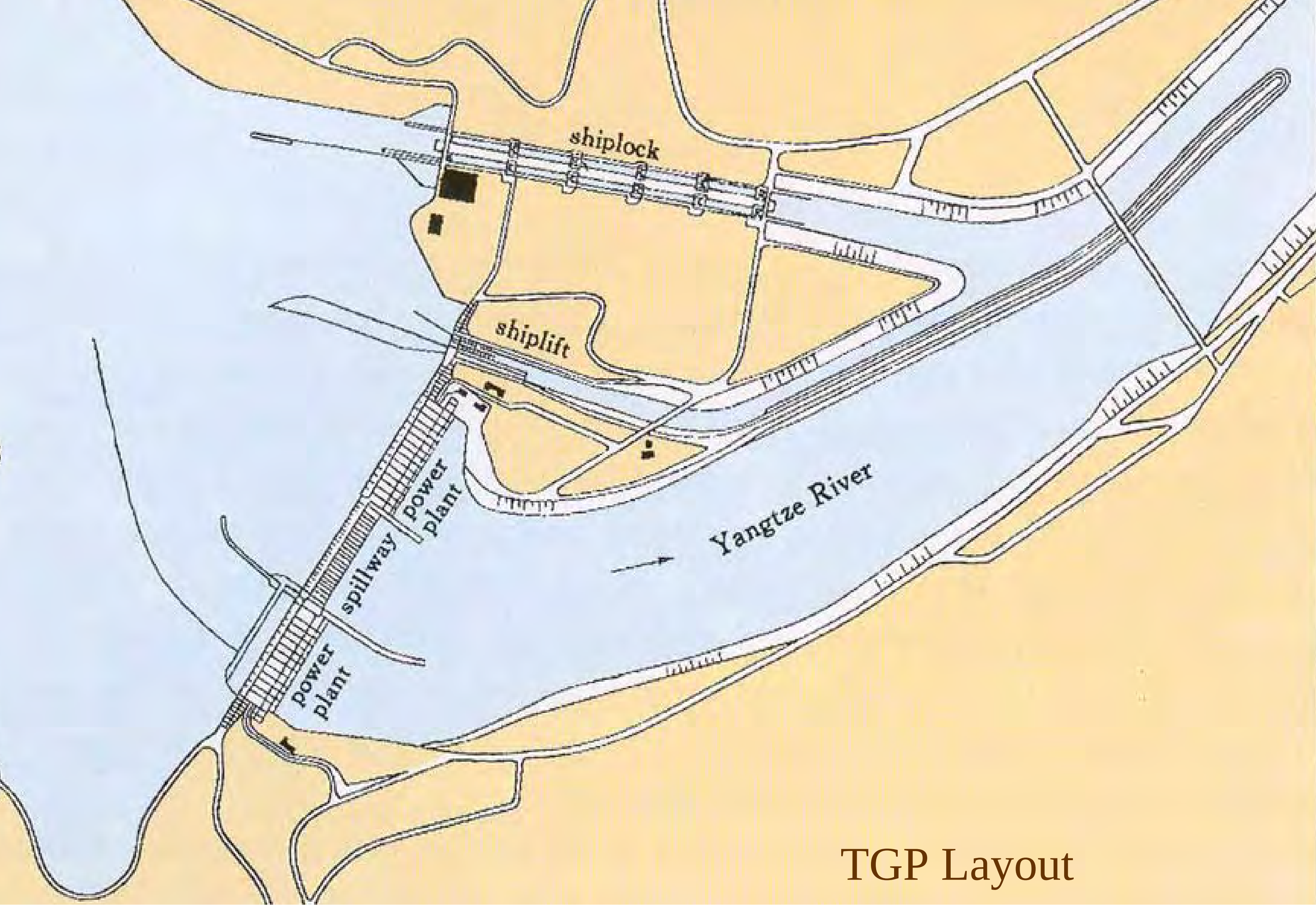
三峽巴東滑坡

陡崖危岩體錨固工程施工排架俯視



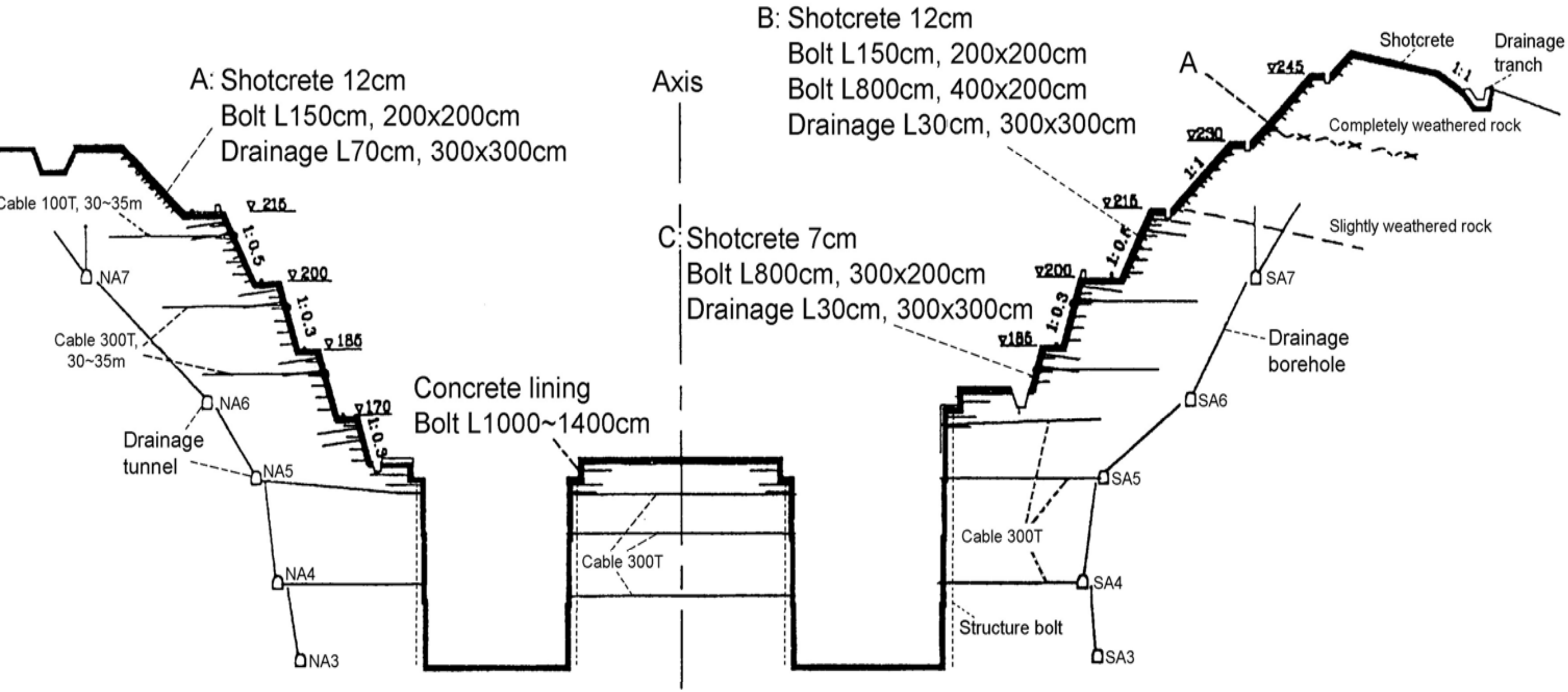


三峡工程鸟瞰图　A Bird's－eye View of the Three Gorges Proiect


shiplock
shiplift
power plant
spillway
power plant
Yangtze River

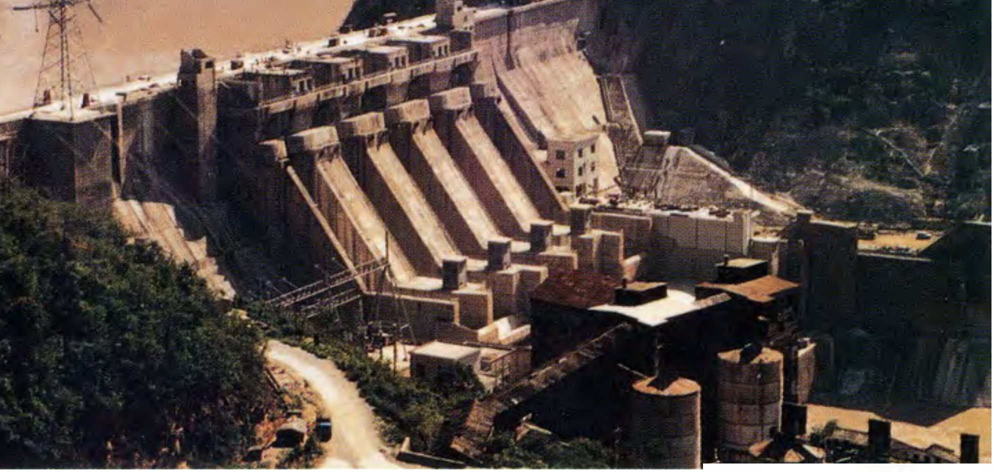
TGP Layout

TGP Shiplock

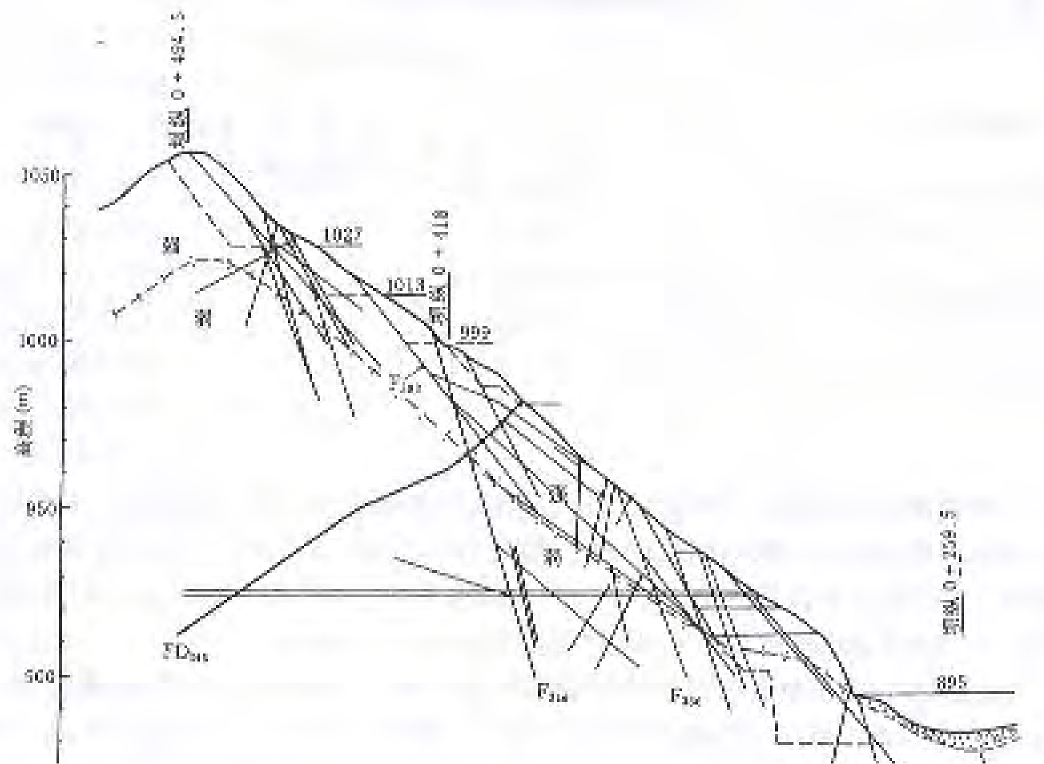


TGP Shiplock Section

TGP Rock Core



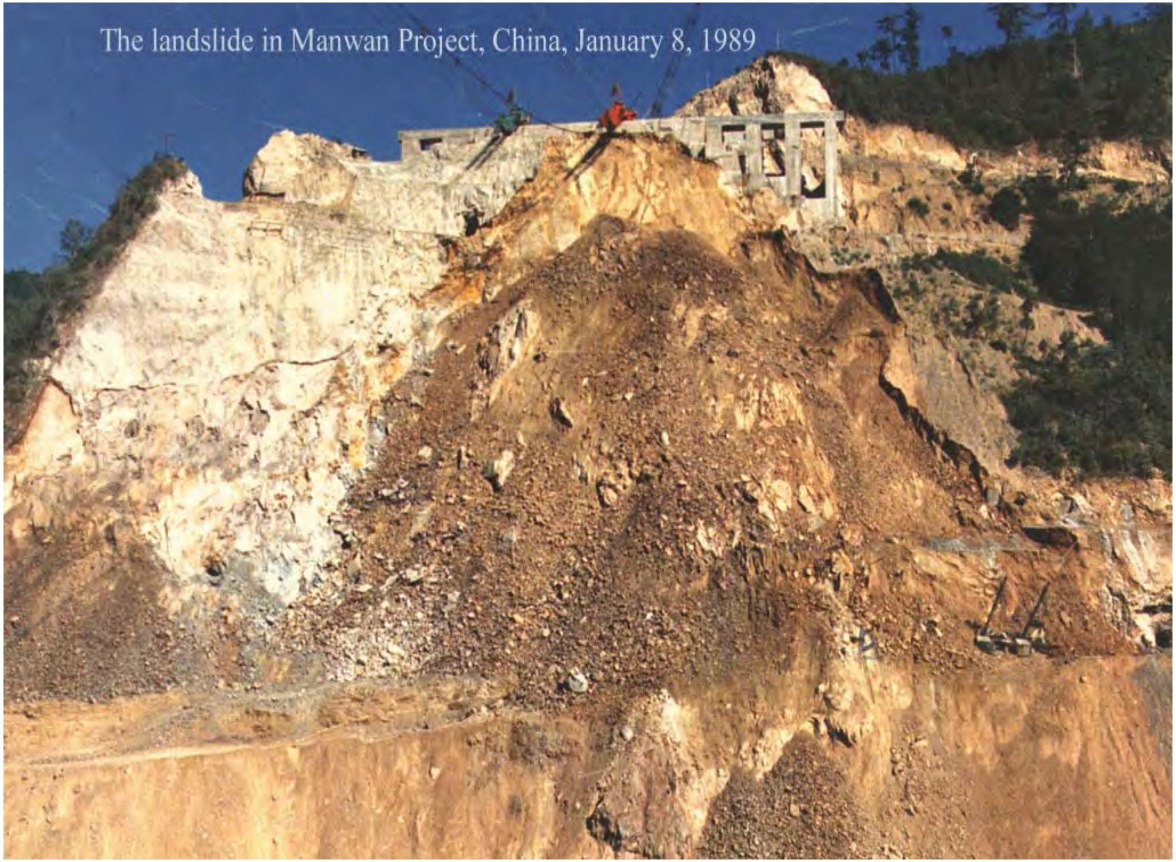
Man Wan Dam



Man Wan Landslide Site

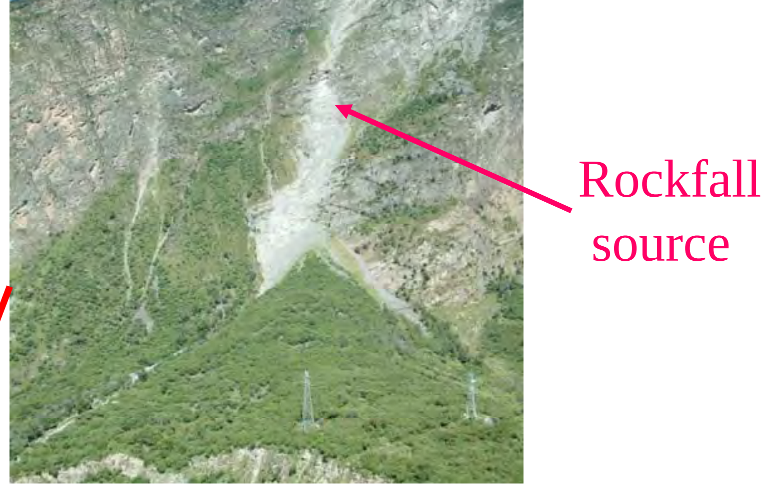
The landslide of the Manwan Hydropower Project

January 8, 1989



云南小湾水电站左岸坝前边坡
开挖时面貌

四川大渡河滑坡壩
(1933年大地震)



MUDFLOW OF THE LONGYANGXIA POWER STATION

Time of occurrence:

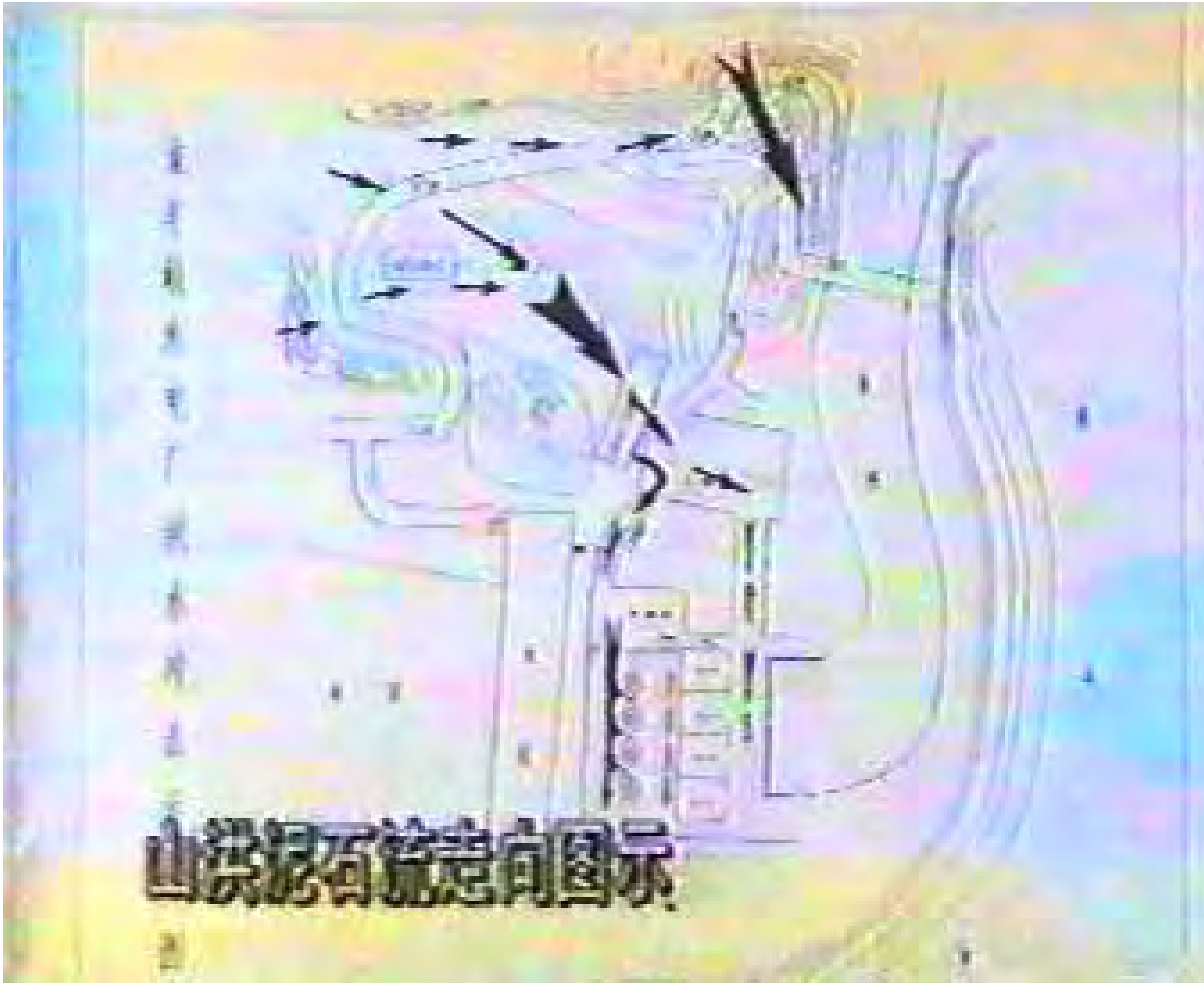
August 4 of 1997 at 23:55

Cause of the incident:

A 2-hour constant rainfall with a total precipitation of 55 mm

Source of the mudflow material :

Natural deposit and construction waste in the Beidagou Gully



山洪泥石流走向图示

128万千瓦

Geotechnical Issues

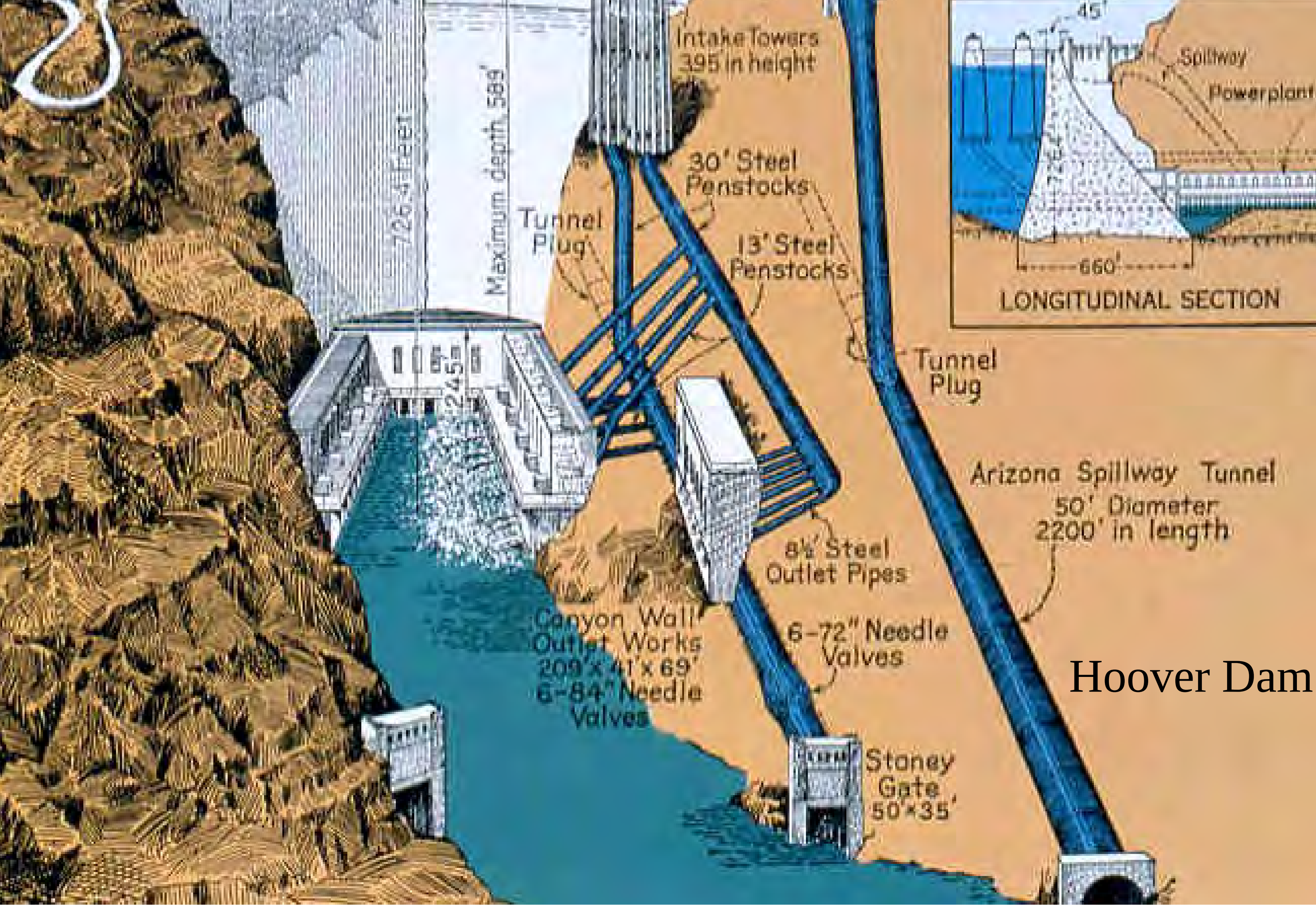
(E) Tunnels and Excavations in Rock

- Fracture-induced instability (rock mass classification and tunnel support design)

- Stress-induced instability

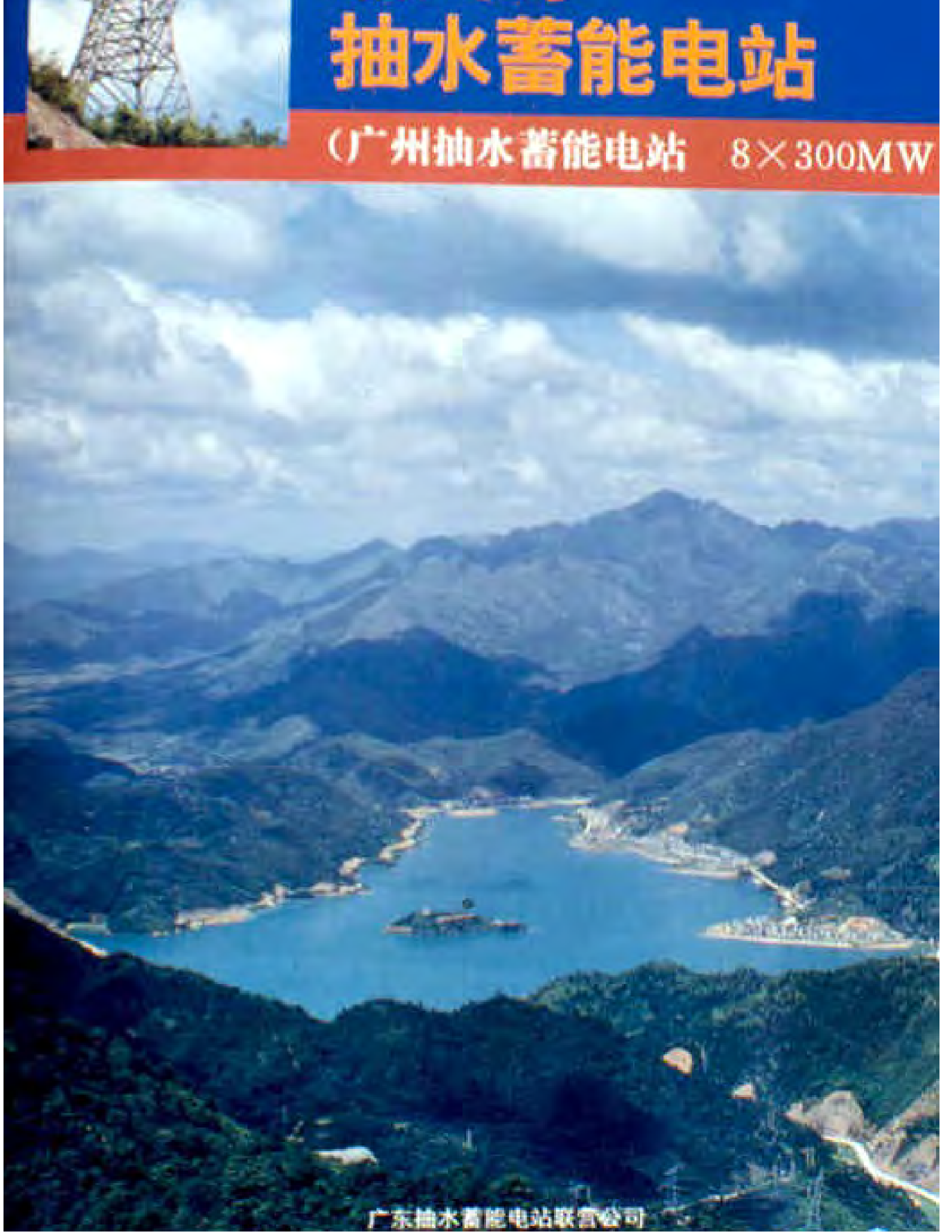
- Time-dependent deformation (e.g. Niagara vs Three Gorges shiplocks)

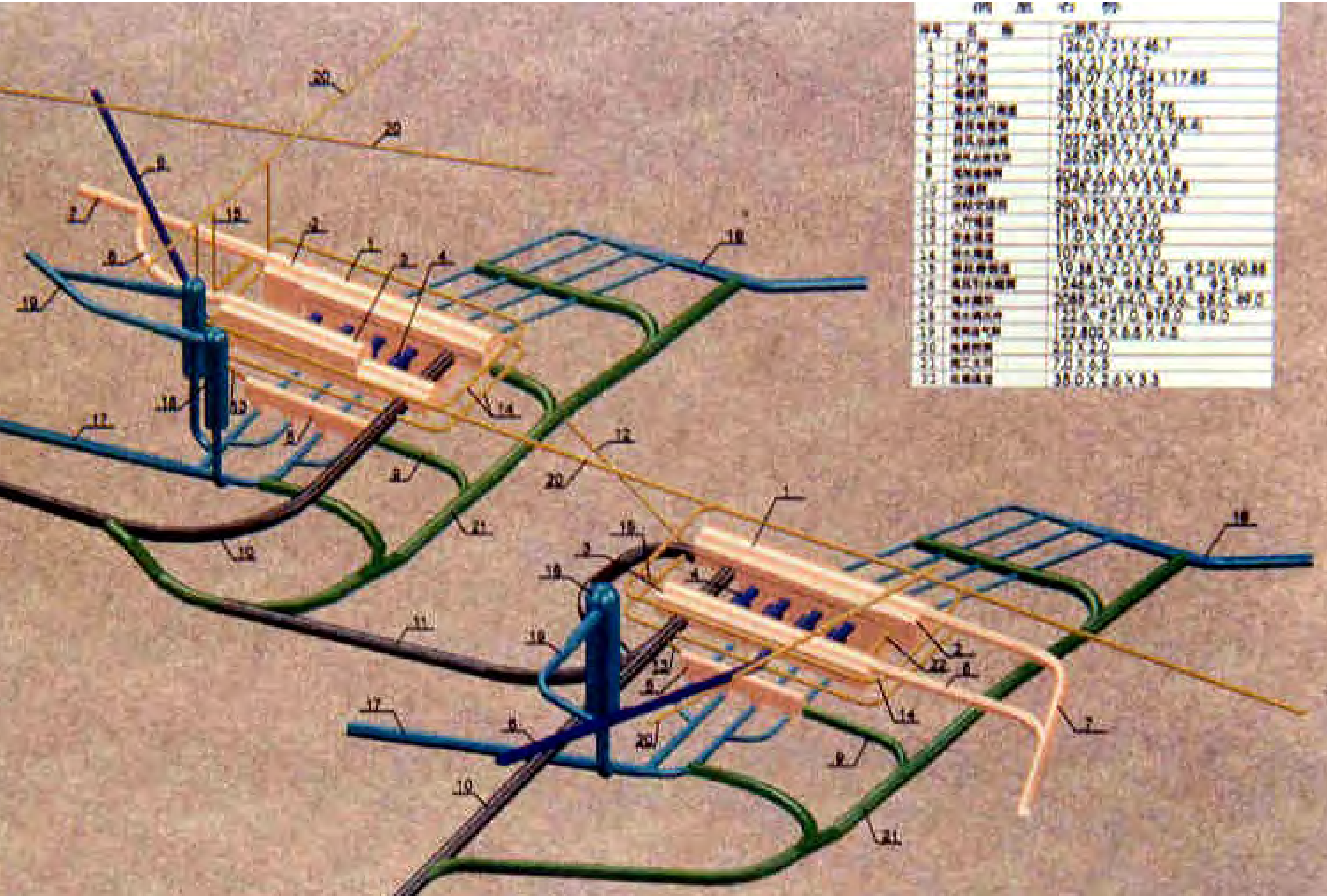
Hoover Dam


Intake Towers
395' in height
726.4 Feet
Maximum depth 589'
Tunnel
Plug
30' Steel
Penstocks
13' Steel
Penstocks
245'
Tunnel
Plug
8½' Steel
Outlet Pipes
Arizona Spillway Tunnel
50' Diameter
2200' in length
Canyon Wall
Outlet Works
209'x 41'x 69'
6-84" Needle
Valves
6-72" Needle
Valves
Stoney
Gate
50'×35'
45'
Spillway
Powerplant
660'
LONGITUDINAL SECTION

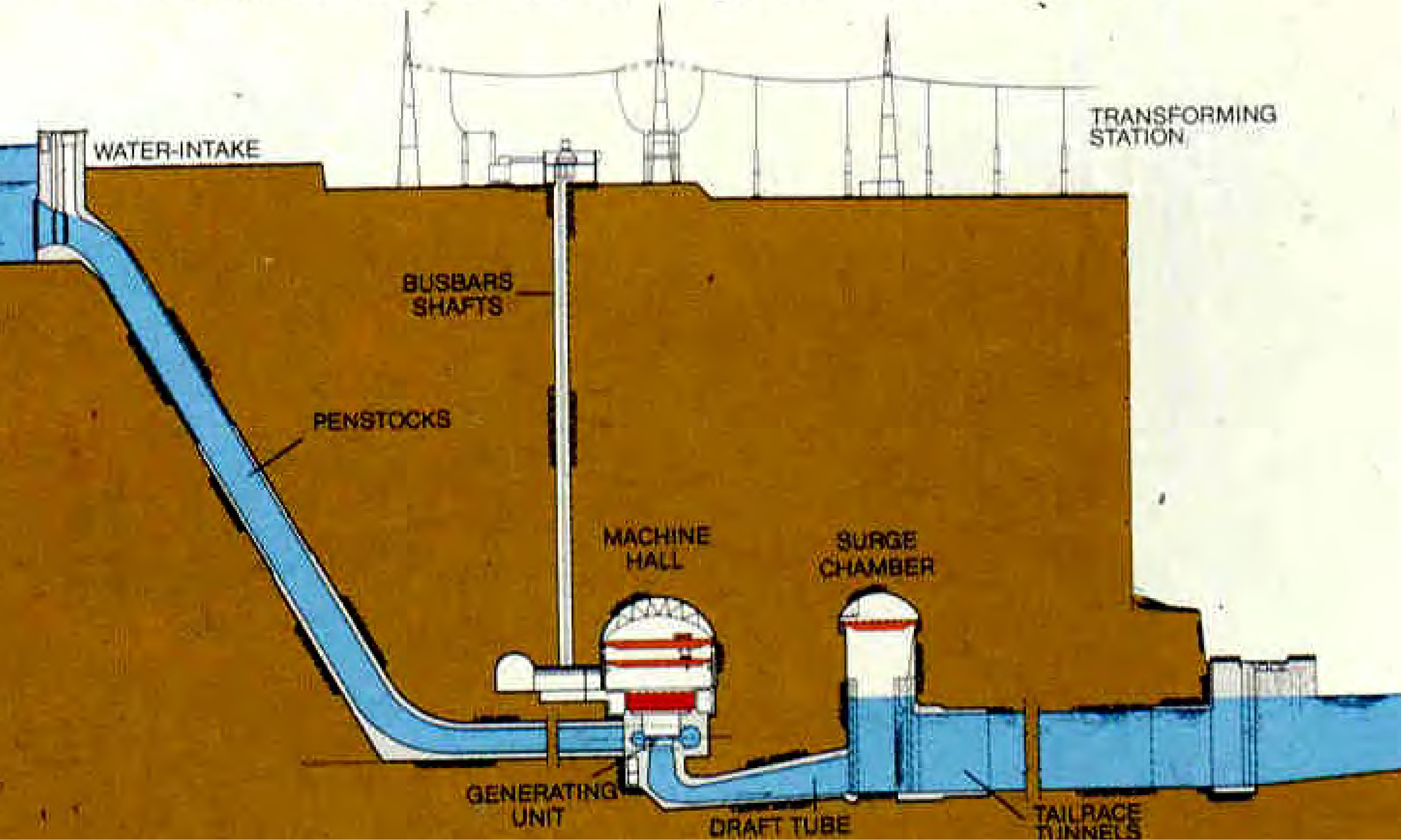
Hoover Dam

州抽水蓄能電站



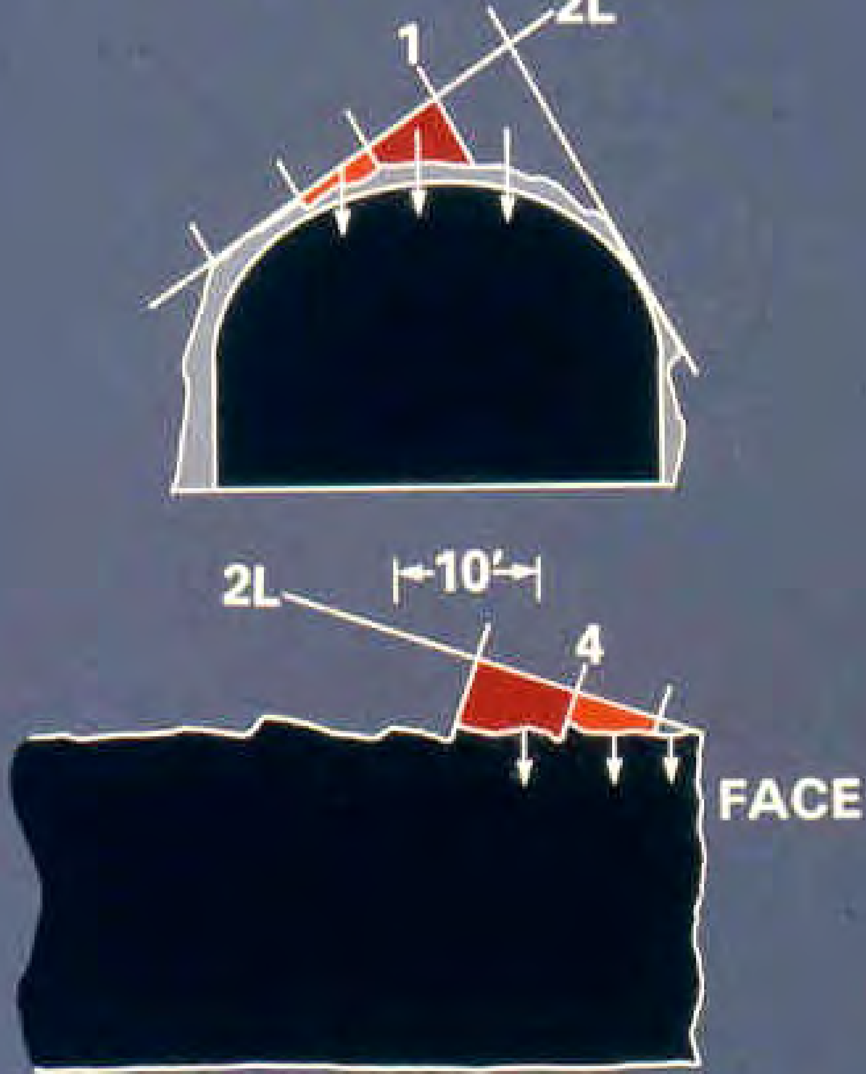


Cross-section of an underground powerstation



Two Types of Instability Underground

- Stress – controlled
- Fracture - controlled



THREE-DIMENSIONAL STABILITY

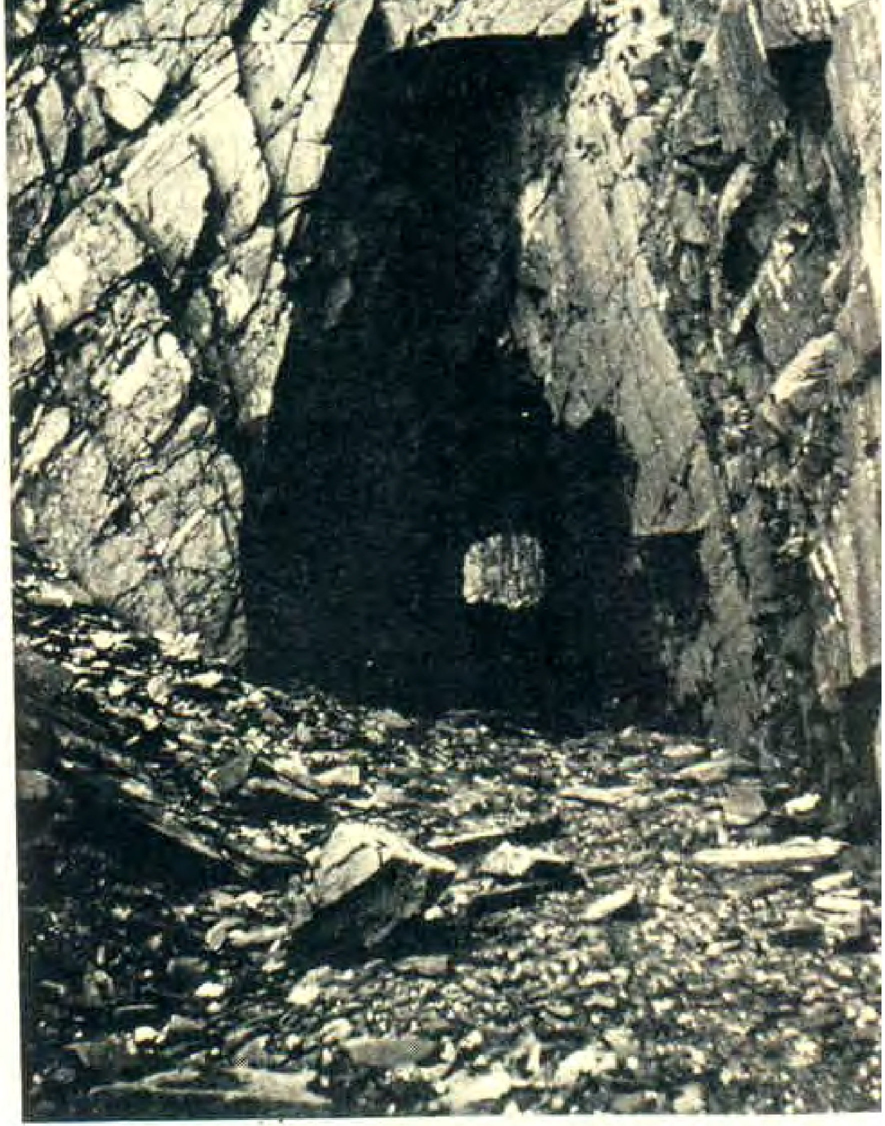


Figure 1 : A tunnel in slate showing the influence of structural discontinuities upon excavation stability.

Rock Mass Classifications

- Rock Quality Designation (RQD)
- Rock Mass Rating System (RMR)
- Rock Tunnelling Quality Index (Q)

Table 1 Basic quality (BQ) of rock mass

Class	Qualitative description	BQ Value
I	Hard rock, intact	> 550
II	Hard rock, relatively intact; Relatively hard rock, intact	550 ~ 451
III	Hard rock, relatively fractured; Relatively hard or interlayered of hard and weak rock, relatively intact; Relatively weak rock, intact	450 ~ 351
IV	Hard rock, fractured; Relatively hard rock, fractured-relatively fractured; Relatively weak rock, or interlayered of weak and hard rock with dominant weak rock, relatively intact or relatively fractured; Weak rock, intact or relatively intact	350 ~ 251
V	Relatively weak rock, fractured; Weak rock, fractured-relatively fractured; Extremely weak rock, extremely fractured	< 250

$$BQ = 90 + 3\,R_c + 250\,K_v$$

where R_c = uniaxial compressive strength (MPa)

K_v = intactness index of rock mass

Table 2 Classification based on uniaxial compressive strength R_c

R_c (MPa)	> 60	60 ~ 30	30 ~ 15	15 ~ 5	< 5
Description	Hard rock	Relatively hard rock	Relatively weak rock	Weak rock	Extremely weak rock

Table 4 Intactness Factor K_v as a function of Joint Index J_v

J_v (number of joints / m^3)	< 3	3 ~ 10	10 ~ 20	20 ~ 35	> 35
K_v	> 0.75	0.75 ~ 0.55	0.55 ~ 0.35	0.35 ~ 0.15	< 0.15

$$K_v = \left(\frac{V_{pm}}{V_{pt}}\right)^2$$

V_{pm}= in-situ velocity of longitudinal elastic wave (km/s)

V_{pr}= velocity of longitudinal elastic wave in intact rock (km/s)

For engineering classification, use [BQ] amended for groundwater, joint orientation and in-situ stress conditions:

$$[BQ] = BQ - 100\,(K_1 + K_2 + K_3)$$

where BQ = basic quality

K_1 = correction factor for groundwater

K_2 = correction factor for orientation of planes of weakness

K_3 = correction factor for in-situ stress conditions

Table 5 K_1 values - Correction factor for groundwater conditions

K_1 / BQ / Groundwater inflow	>450	450 ~ 351	350 ~251	<250
Wet or drops	0	0.1	0.2 ~ 0.3	0.4 ~ 0.6
Shower or flow P < 0.1 MPa Q < 10 L / min . m	0.1	0.2 ~ 0.3	0.4 ~ 0.6	0.7 ~ 0.9
Shower or flow P <0.1 MPa Q < 10 L / min . m	0.2			1.0

Table 6 K_2 values - Correction factor for orientation of planes of weakness

Relation of structure plane to tunnel axis	$\alpha < 30^o$ $= 30^o \sim 75^o$	$\alpha > 30^o$ $\beta > 75^o$	Other combinations
K_2	0.4 ~ 0.6	0 ~ 0.2	0.2 ~ 0.4

* α - angle between strike of structure plane and tunnel axis;
  β - dipping angle of structure plane

Table 7 K_3 values - Correction factor for in-situ stress conditions

K_3 / BQ / Initial stress state	> 550	550 ~ 351	450 ~ 351	350 ~251	< 250
Extremely high stress	1.0	1.0	1.0 ~ 1.5	1.0 ~ 1.5	1.0
High stress	0.5	0.5	0.5	0.5 ~ 1.0	0.5 ~ 1.0

Technical Specifications for Water Resources and Hydropower Projects

Rock Mass Rating for Tunnelling Projects

Rock class	Rock stability	Host rock rating	Strength/ Stress S	Support type
I	Stable, long term stability, generally no unstable block	100 ~ 85	> 4	No support or locally bolting, or thin shotcreting in case of large span systematic shotcrete, bolt and mesh
II	Basically stable, no plasticity deformation	85 ~ 65	> 4; if S < 4, go to III	
III	Poor stability, locally plasticity deformation, or collapse	65 ~ 45	> 2; if S < 2, go to IV	Systematic shotcrete, bolt and mesh if span = 20 ~ 25 m, concrete lining is needed
IV	Unstable, short self-standing time, large scale collapse	45 ~ 25	> 2; if S < 2, go to V	Systematic shotcrete, bolt and mesh, and concrete lining
V	Extremely unstable, severe collapse	< 25	No limits	

Host rock rating (HRR) = A + B + C + D + E
(somewhat similar to Bieniawski's RMR)

Rating on rock strength (A)

Type of rock material		Hard rock		Weak rock	
		Hard rock	Moderately hard rock	Relatively weak rock	Weak rock
Uniaxial strength of saturated rock (MPa)		100 ~ 60	60 ~ 30	30 ~ 15	15 ~ 5
Rating (A)	Hard rock	30 ~ 20	20 ~ 10		
	Weak rock			10 ~ 5	5 ~ 0

* For uniaxial strength σ_c > 100 MPa, rock mass rating is 30.

Rating on rock intactness (B)

Intactness		Intact	Relatively intact	Poor intactness	Relatively fractured	Fractured
Intactness factor K_v		1.0 ~ 0.75	0.75 ~ 0.55	0.55 ~ 0.35	0.35 ~ 0.15	< 0.15
Rating (B)	Hard rock	40 ~ 30	30 ~ 22	22 ~ 14	14 ~ 6	< 6
	Weak rock	25 ~ 19	19 ~ 14	14 ~ 9	9 ~ 4	< 4

Aperture (mm)	Filling	Roughness, evenness	Hard rock	Relatively weak rock	Weak rock
Closed < 0.5		Undulating, rough	27	27	18
		Planar, smooth	21	21	14
Slight open 0.5 ~ 5.0	No filling	Undulating, rough	24	24	17
		Undulating, smooth, or planar, rough	21	21	14
		Planar, smooth	15	15	8
	Slacks	Undulating, rough	21	21	14
		Undulating, smooth, or planar, rough	17	17	11
		Planar, smooth	12	12	8
	Mud	Undulating, rough	15	15	10
		Undulating, smooth, or planar, rough	12	12	8
Open > 5.0		Planar, smooth	9	9	6
	Slacks		12	12	8
	Mud		6	6	4

* For a length of structure plane which is less than 3 m, in hard rock and relatively weak rock, rating would increase by 3; for weak rock, rating would increase by 2. For length > 10 m, decrease rating by 3 and 2 respectively for hard rock and relatively weak rock. If aperture > 10 m, without filling, rating is 0.

Rating on groundwater condition (D)

Basic rating (A + B + C)	State	Wet, Drops	Linear Flow	Flow
	Quantity of flow (L/min.m)	< 25 or < 10	25-125 or 10-100	> 125 or > 100
	Water head (m)			
100-85	Rating on Groundwater Conditions (D)	0	0	-2 ~ -6
85-65		0 ~ -2	0 ~ -2	-6 ~ -10
65-45		-2 ~ -6	-2 ~ -6	-10 ~ -14
45 ~ 25		-6 ~ -10	-10 ~ -14	-14 ~ -18
< 25		-10 ~ -14	-14 ~ -18	-18 ~ -20

Rating on orientation of structure planes (E)

Angle between strike of structure plane and tunnel axis (^{o})		$90^o \sim 60^o$				$60^o \sim 30^o$				$< 30^o$			
Dipping angle (^{o})		>70	75~45	45~20	<20	>70	75~45	45~20	<20	>70	70~45	45~20	<20
Rating (E)	Crown	0	-2	-5	-10	-2	-5	-10	-12	-5	-10	-12	-12
	Wall	-2	-5	-2	0	-5	-10	-2	0	-10	-12	-5	0

tor	Basis for Rating		Rating				
	Saturated Compressive Strength (MPa)		>100	100-60	60-30	30-15	15-5
	Rating for A		>30	30-20	20-10	10-5	5-0
	Intactness Coefficient		1.0-0.75	0.75-0.55	0.55-0.35	0.35-0.15	<0.15
	Rating for B	σ_c > 30 MPa	40-30	30-22	22-14	14-5	<6
		σ_c < 30 MPa	25-19	19-14	14-9	9-4	<4
	Structural surface condition	Degree of openness	Closed <0.5mm	Slightly open, 0.5 – 5.0 mm			Open > 5 mm
		Infillings		Nil	Rock fragments	Clay	Fragmented Clay
		Polishness of surface	Flat, polished to curved, rough				
	Rating for C_1	σ_c > 60 MPa	27-21	24-15	21-12	15-9	12-6
		σ_c 60 - 30 MPa	27-21	24-15	21-12	15-9	12-6
		σ_c < 30 MPa	18-14	17-8	14-8	10-6	8-4

2	Length of structural surface		<3 m	3-10 m	>10m
	Rating for C_2	σ_c > 60 MPa	+3	0	-3
		σ_c < 60 MPa	+2	0	-2

D	$A + B + C_1 + C_2$ Rating		100-85	85-65	64-45	45-25	<25
	Rating for D	Seeping, dripping	0	0 → -2	-2 → -6	-6 → -10	-10 → -14
		Linear flow	0 → -2	-2 → -6	-6 → -10	-10 → -14	-14 → -18
		Gush of water	-2 → -6	-6 → -10	-10 → -14	-14 → -18	-18 → -20

Angle between tunnel alignment and structural orientation (strike)		90° - 60°				60° - 30°				< 30°			
Dip of structural orientation		>70°	70°- 45°	45°- 20°	<20°	> 70°	70° - 4 5°	45° - 20°	< 20°	> 70°	70° - 45°	45° - 20°	< 20°
Rating for E	Roof	0	-2	-5	-10	2	-5	-10	-12	-5	-10	-12	-12
	Sidewall	-2	-5	-2	0	-5	-10	-2	0	-10	-12	-5	0

Recommended rock parameters

Class	Gravity density γ (kN/m³)	Friction angle φ (°)	Cohesion C(MPa)	Deformation module E(MPa)	Poisson ratio ν
I	> 26.5	> 60	> 2.1	> 33	< 0.2
II		60 ~ 50	2.1 ~ 1.5	33 ~ 20	0.2 ~ 0.25
III	26.5 ~ 24.5	50 ~ 39	1.5 ~ 0.7	20 ~ 6	0.25 ~ 0.3
IV	24.5 ~ 22.5	39 ~ 27	0.7 ~ 0.2	6 ~ 1.3	0.3 ~ 0.35
V	< 22.5	< 27	< 0.2	< 1.3	> 0.35

Recommended rock strength parameters

Class	Concrete-rock contact		Rock mass		Deformation modulus
	f′	c′ (MPa)	f′	c′ (MPa)	E_0 X 10^4 (MPa)
I	1.5 ~ 1.3	1.5 ~ 1.3	1.6 ~ 1.4	2.5 ~ 2.0	> 2.0
II	1.3 ~ 1.1	1.3 ~ 1.1	1.4 ~ 1.2	2.0 ~ 1.5	2.0 ~ 1.0
III	1.1 ~ 0.9	1.1 ~ 0.7	1.2 ~ 0.8	1.5 ~ 0.7	1.0 ~ 0.5
IV	0.9 ~ 0.7	0.7 ~ 0.3	0.8 ~ 0.55	0.7 ~ 0.3	0.5 ~ 0.2
V	0.7 ~ 0.4	0.3 ~ 0.05	0.55 ~ 0.40	0.3 ~ 0.05	0.2 ~ 0.02

* f′, c′ - Shear strength

Design Applications of HRR

Rock Type	Rock Mass Stability	Host Rock Rating (HRR)	Strength vs Stress Ratio (S)	Rock Properties			Support Requirements
				f	C (MPa)	E(x 10^4MPa)	
I	Stable, with long-term stability; no unstable blocks in general	100 - 85		1.6 - 1.4	2.5 - 2.0	> 2.0	Unsupported or localized bolts/shotcrete or thin shotcrete; add wire mesh for tunnels with large span
II	Essentially stable, with overall stability; no plastic deformation; localized rockfall	85 - 65	Downgrade to III for S < 4	1.4 - 1.2	2.0 - 1.5	2.0 - 1.0	
III	Poor stability; localized plastic deformation, cave-in if unsupported; temporarily stable in intact, relatively soft rock	65 - 45	Downgrade to IV for S < 2	1.2 - 0.8	1.5 - 0.7	1.0 - 0.5	Bolts and shotcrete, with wire mesh; concrete lining for tunnel span of 20 - 25 m
IV	Unstable; very short standup time; relatively large deformation/failure may occur	45 - 25	Downgrade to V for S < 1	0.8 - 0.55	0.7 - 0.3	0.5 - 0.2	Bolts and shotcrete, with re-bar mesh and concrete lining
V	Very unstable, could not stand up; severe deformation/failure	< 25		0.55 - 0.40	0.3 - 0.05	0.2 - 0.02	

(National Standard for Design of Bolt-shotcrete Support)

Span (m) Rock Class	B < 5 m	5 < B < 10	10 < B < 20	15 < B < 20	20 < B < 25 m
I	No support	Shotcrete 50 mm	(1) Shotcrete 80-100 mm (2) Shotcrete 50 mm bolt 2.0-2.5 m	Shotcrete	Shotcrete 120-150 mm with mesh bolt 3.0-4.0 m
II	Shotcrete 50 mm	(1) Shotcrete 80-100 mm (2) Shotcrete 50 mm bolt 1.5-2m	(1) Shotcrete 120-150 mm mesh, if necessary (2) Shotcrete 80-120 mm bolt 2-3 m mesh, if necessary	Shotcrete 120-150 mm mesh bolt 2.5-3.0 m	Shotcrete 150-200 mm mesh bolt 3-4 m
III	(1) Shotcrete 80-100 mm (2) Shotcrete 50 mm bolt 1.5-2 m	(1) Shotcrete 120-150 mm mesh, if necessary (2) Shotcrete 80-120 mm bolt 2-3 m mesh, if necessary	Shotcrete 100-150 mm mesh bolt 2.0-3.0 m	Shotcrete 150-200 mm mesh bolt 3-4 m	
IV	Shotcrete 80-100 mm bolt 1.5-2.0 m	Shotcrete 100-200 mm mesh bolt 2.0-2.5 m bottom arch if necessary	Shotcrete 150-200 mm mesh bolt 2.5-3.0 m bottom arch if necessary		
V	Shotcrete 120-150 mm mesh bolt 1.5-2.0 m bottom arch if necessary	Shotcrete 150-200 mm mesh bolt 2.0-3.0 m bottom frame, if necessary			

Comparison of Rock Mass Classification Systems

System	Range	# of Classes	Main Factors
Q	0.01-1000	9	RQD; J_n (joint set number), J_r (joint roughness number), J_a (joint alteration number); Stress reduction factor SRF
RMR	0-100	5	Rock strength; RQD; Spacing, conditions and orientation of joints; Groundwater
HRR	0-100	5	Rock strength; Intactness; Conditions and Orientation of Weakness Planes; Groundwater; Initial Stresses
BQ	< 250->500	5	Rock strength; Intactness; Groundwater; Orientation of Weakness Planes; Initial Stresses

Important Factors that are common among the various systems

1. Rock strength
2. Intactness
3. Condition of planes of weakness
4. Groundwater
5. Orientation of discontinuities
6. Initial stresses

ock ass	Span (m)	Shotcrete	Steel Mesh		Bolt			Concrete Lining		Total Number of Projects
		Thickness (cm)	Diameters (mm)	Spacing (m)	Diameter (mm)	Length (m)	Spacing (m)	Thickness (cm)	Number of Works	
I	5-10	3-15	no	no	18-22	1.2-3.0	Random	no		9
	10-15	3-20	6-12	0.25-1.5	18-22	1.5-3.5	1.0-1.5	no		9
	15-20	10-20	no	no	20-22	1.0-3.0	1.0-1.5	no		3
II	5-10	5-15	6-10	0.2-1.3	16-20	1.2-2.1	1.0-1.2	no	2	10
	10-15	4-20	6-18	0.2-1.3	18-22	1.5-3.5	0.8-1.5	30-50		13
	15-20	8-16	8-12	0.2-1.3	16-32	2.0-4.0	1.2-1.5	no		10
II	5-10	5-20	6-10	0.2-1.0	18-22	1.6-3.0	1.0-1.5	wall	1	12
	10-15	5-20	5-12	0.2-1.0	16-24	1.5-3.5	1.0-1.5			11
	15-20	10-16	6-12	0.2-0.8	16-30	2.0-4.0	0.8-1.2			8
V	5-10	15-20	6-14	0.2-0.25	18-22	1.8-4.0	0.75-1.25	40	4	10
	10-15	5-20	6-12	0.2-0.3	16-22	2.5-4.0	0.8-1.25	50	2	5
	15-20	20	10-19	0.25	22	2.0	1.2			1
V	5-10	10-15	8-14	0.2-0.25	16-22	1.5-3.6	0.8-1.2	40	2 4	7
	10-15	18-20	6-12	0.2-0.3	20-22	2.5-3.5	0.8-1.0	60		4

Three Gorges Project
Amended [BQ] Values for Granite

Maximum $[BQ]_{max} = 630$

Minimum $[BQ]_{min} = 500$

Average $[BQ]_{mean} = 565$

Class I^- to II^+

Guangzhou Pumped Storage Project

- Location: north of Guangzhou, Guangdong Province

- Underground Powerhouse

  146.5 m x 22 m x 44.5 m (L x W x H)

  at 330 - 400 m depth; completed in 1993

- Host Rock: Biotite granite

- Support System: Bolts (at 2 x 1.5 m spacing)
  + 15 cm shotcrete in both crown and
  sidewalls

Xiaolangdi Project

- Location: on Yellow River, Henan Province
- Underground Powerhouse

  251.5 m x 26.2 m x 61.4m (L x W x H)

  At 70 – 100 m depth; completed in 1999
- Host Rock: Sandstone, with argillaceous beds
- Support System: Bolts (at 1.5 spacing) with wiremesh

  and shotcret (20 cm) in crown

  Bolts (at 1.5 spacing) in sidewalls

  Anchors locally where required

Xiaolangdi Project on Yellow River

Proposed support parameters in design stage

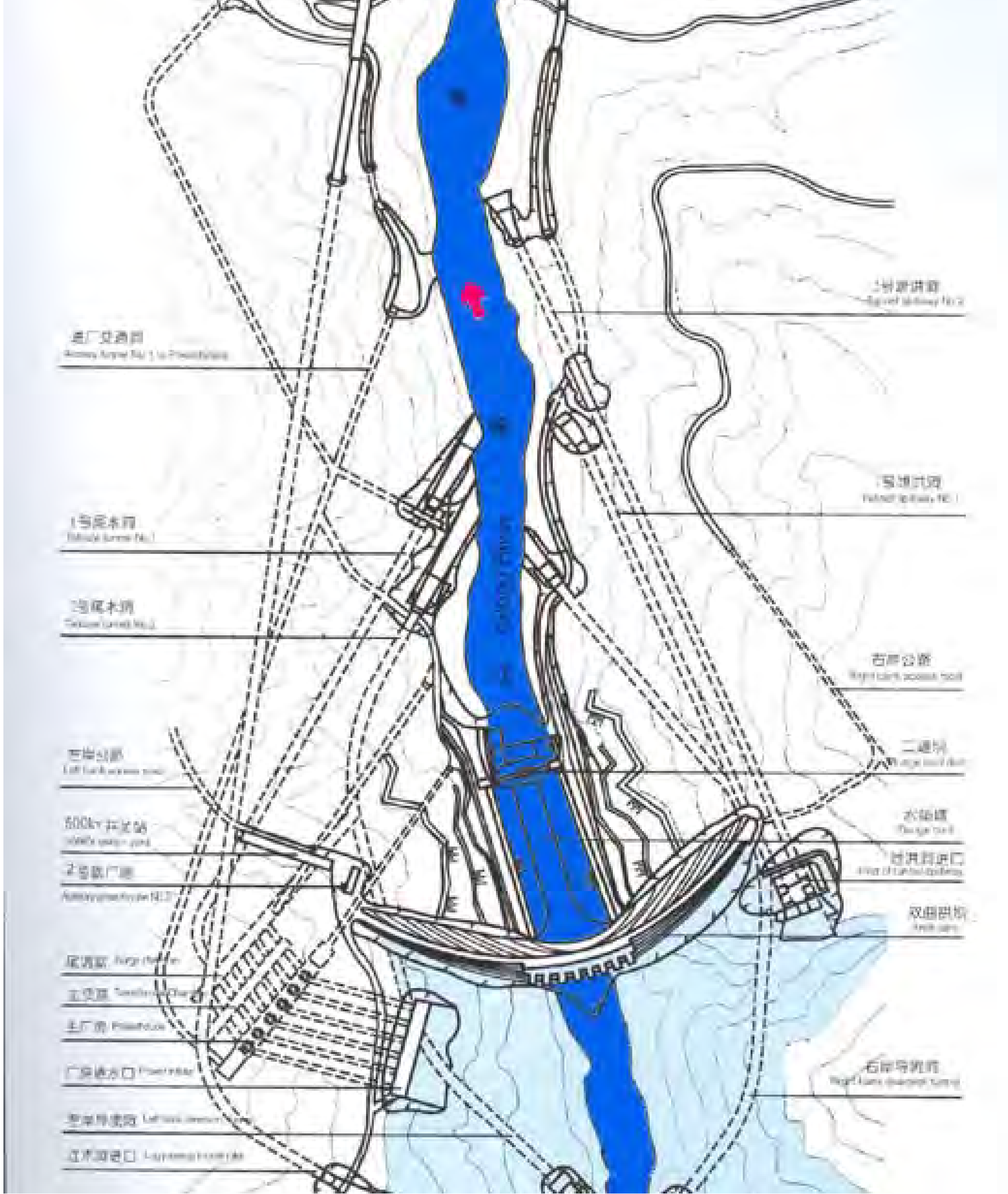
Cavern Type	Location	Rock Type	Rock Grade	Support Design	
				Tensile Bolt	Re. Shotcrete
Main Power-house	Top	T_1^4	III	Φ 28 @ 1.5 X 1.5 m, L = 8/4 m (alternatively)	Φ 8 @ 20 X 20 cm δ = 20 cm (C20)
	Sidewall	T_1^4 T_1^{3-2}	III	Φ 25 @ 1.5 X 1.5 m, L = 12/8 m (alternatively)	Φ 8 @ 20 X 20 cm δ = 15 cm (C20)
Transformer Cavern	Top	T_1^4	II^-	Φ 25 @ 1.5 X 1.5 m, L = 7/3 m (alternatively)	Φ 6 @ 20 X 20 cm δ = 15 cm (C20)
	Sidewall	T_1^4	II^-	Φ 25 @ 1.5 X 1.5 m, L = 5/3 m (alternatively)	Φ 6 @ 20 X 20 cm δ = 10 cm (C20)
Tailrace Cavern	Top	T_1^4	III	Φ 25 @ 1.5 X 1.5 m (mortar bolt), L = 5/3 m (alternatively)	Φ 6 @ 20 X 20 cm δ = 10 cm (C20)
	Sidewall	T_1^4	III	Φ 25 @ 1.5 X 1.5 m (mortar bolt), L = 4 m	Φ 6 @ 25 X 25 cm δ = 10 cm (C20)

T_1^4: thick to massive siliceous fine-grained sandstone;
T_1^{3-2}: thick to massive argillaceous and calcareous silty fine-grained sandstone

Xiaolangdi Project on Yellow River
Actual support used at construction stage

vern Type	Location	Rock Type	Rock Grade	Support Design		Support Pres. (MPa)
				Tensile Bolt	Re. Shotcrete	
in Power-use	Top	T_1^4	III	Φ 32 @ 3 X 3 m, L = 8 m, P = 150 KN Φ 32 @ 3 X 3 m, L = 6 m, P = 150 KN Cable: L = 25 m, 4.5 X 6 m, P = 1500 KN	Φ 8 @ 20 X 20 cm δ = 20 cm (C20)	0.112
	Sidewall	T_1^4 T_1^{3-2}	III	Φ 32 @ 3 X 3 m, L = 10 m, P = 150 KN Φ 32 @ 3 X 3 m, L = 6 m, P = 150 KN Two rows of pre-stressed bolt added for argillized interlayers 500 KN, L = 15 m	Φ 8 @ 20 X 20 cm δ = 20 cm (C20)	0.056
ansformer vern	Top	T_1^4	II^-	Φ 32 @ 2.4 X 2.4 m, L = 8 m, P = 150 KN Φ 32 @ 2.4 X 2.4 m, L = 4 m, P = 150 KN	Φ 6 @ 20 X 20 cm δ = 20 cm (C20)	0.104
	Sidewall	T_1^4	II^-	Φ 32 @ 2.4 X 2.4 m, L = 6 m, P = 150 KN Φ 32 @ 2.4 X 2.4 m, L = 4 m, P = 150 KN	Φ 6 @ 25 X 25 cm δ = 15 cm (C20)	0.104
ilrace vern	Top	T_1^4	III	Φ 32 @ 3 X 3 m, L = 5 m, P = 150 KN Φ 32 @ 3 X 3 m, L = 3 m, P = 150 KN	Φ 6 @ 25 X 25 cm δ = 15 cm (C20)	0.56
	Sidewall	T_1^4	III	Φ 32 @ 1.5 X 1.5 m, L = 4 m, P = 100 KN	Φ 6 @ 25 X 25 cm δ = 10 cm (C20)	0.044

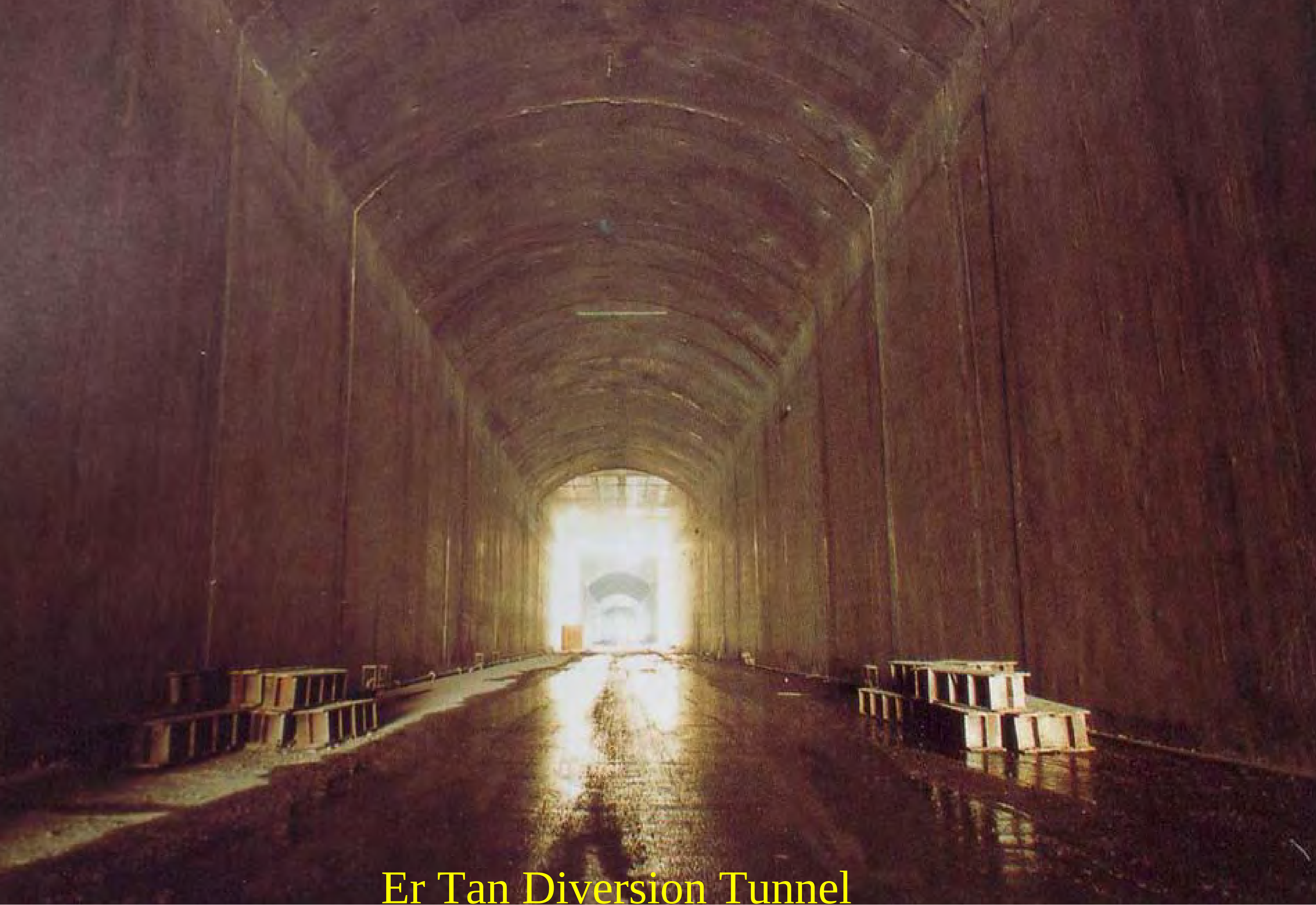
Er Tan Dam



Er Tan Dam
Layout

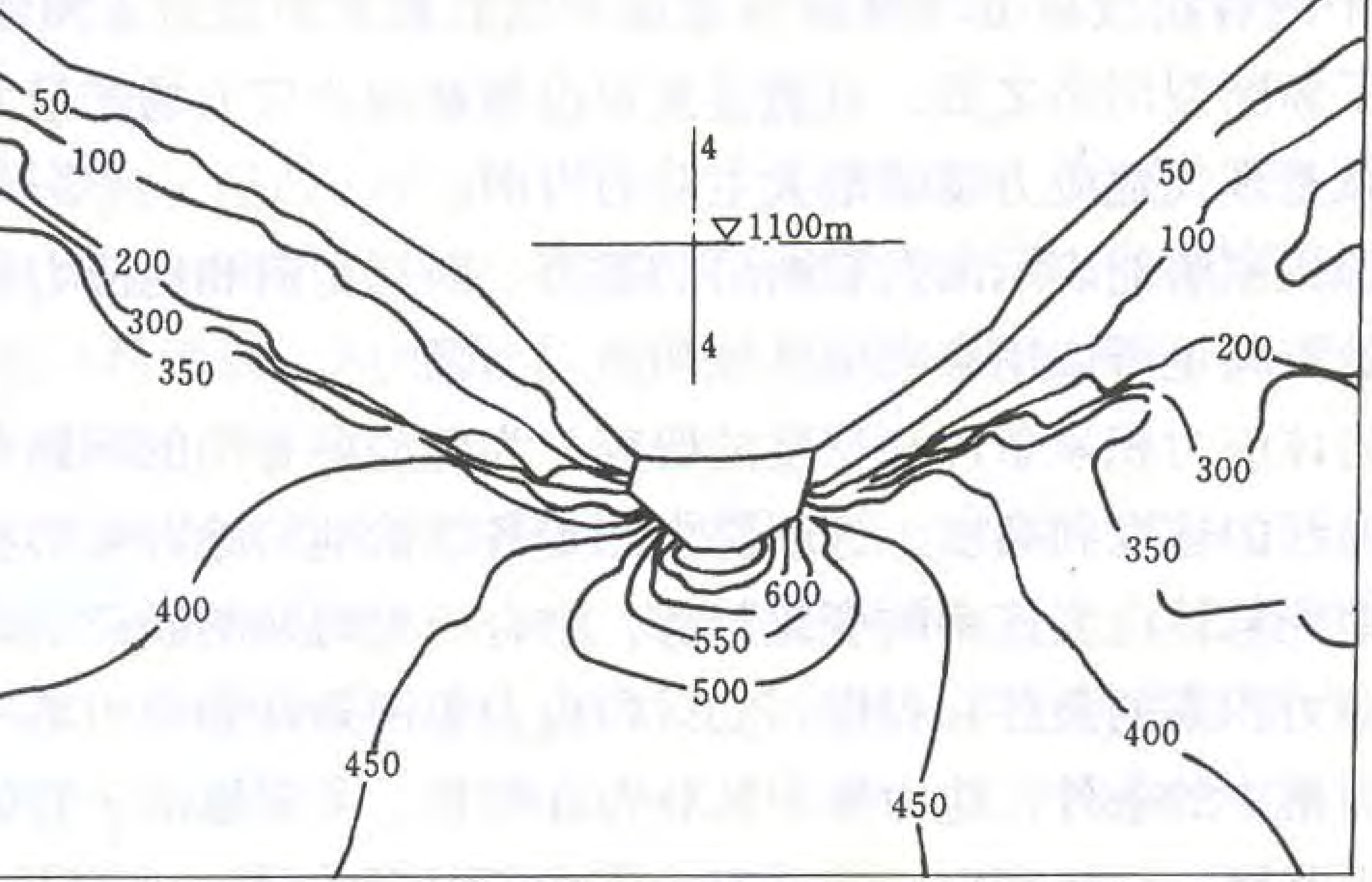
r Tan Under Construction

Er Tan Underground Power House

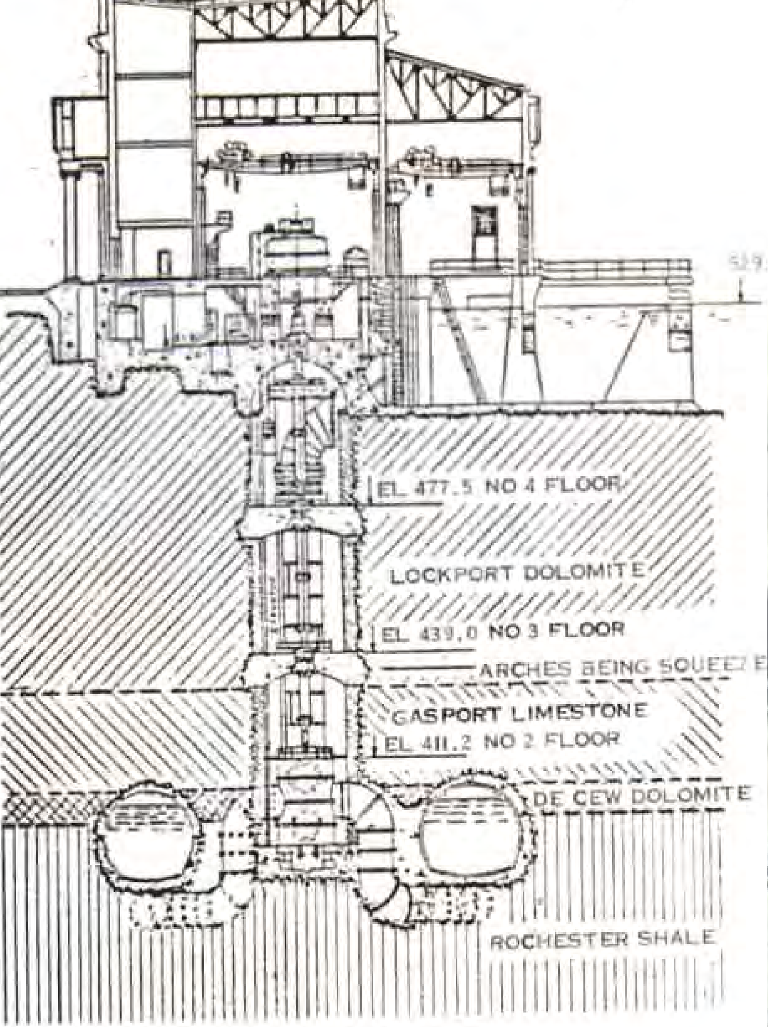


Er Tan Diversion Tunnel


Er Tan Rock Discing

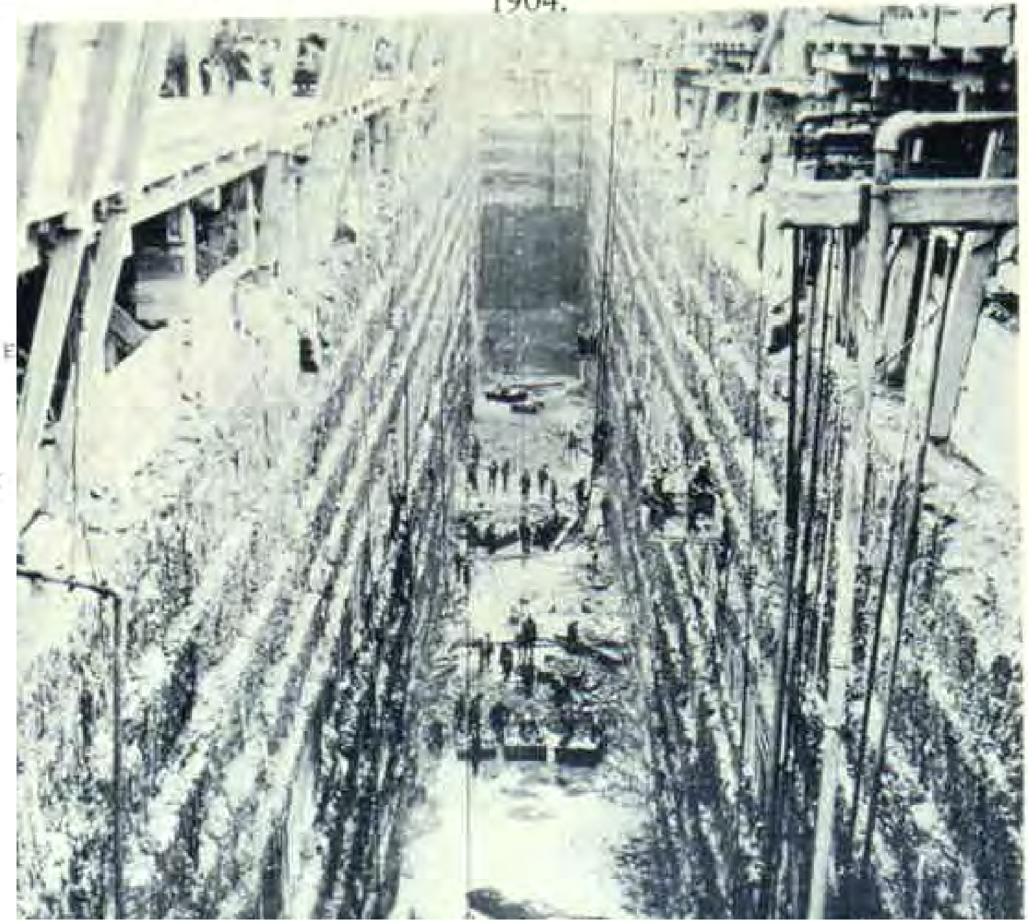


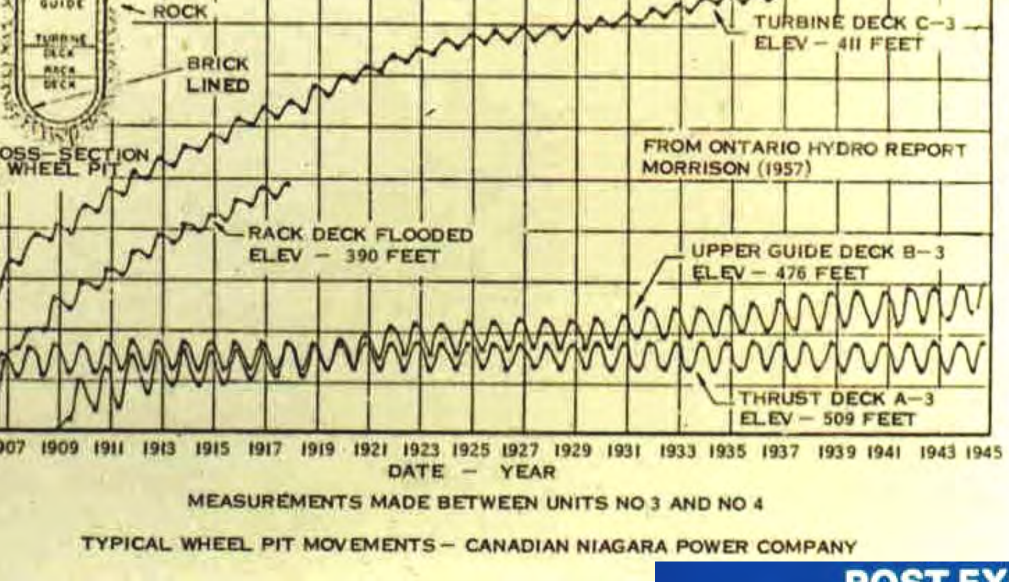
Er Tan Geostress(kg/cm²)



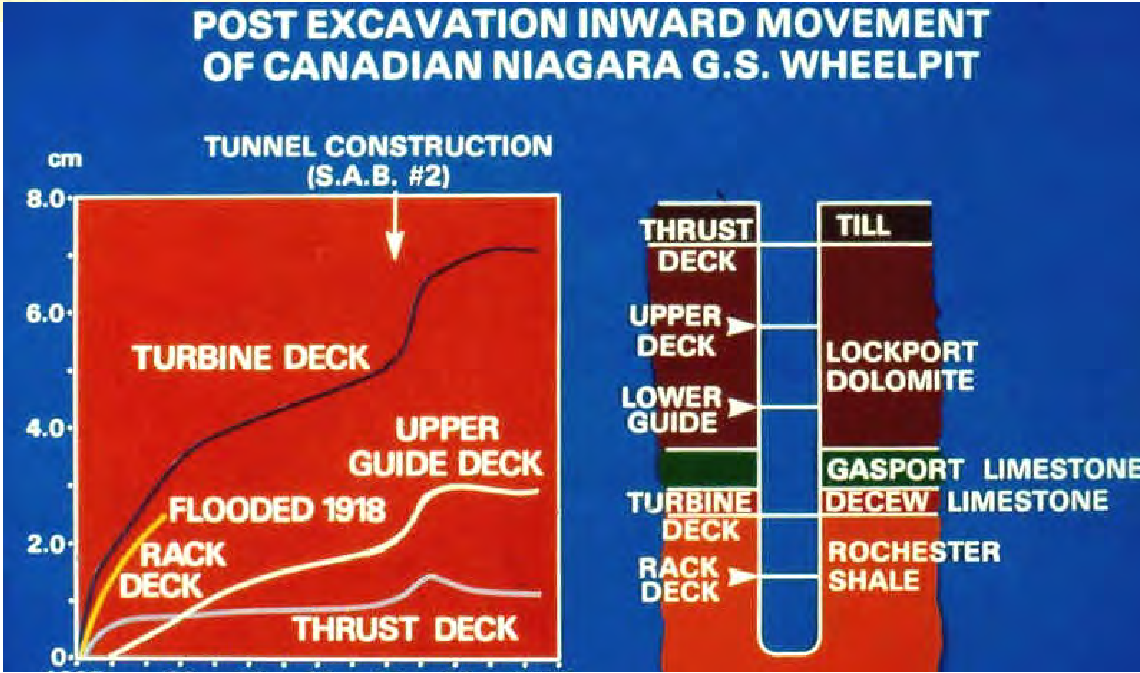
CROSS—SECTION OF TORONTO POWER GS

Excavation of wheelpit, Toronto Power plant, 1904.





ROCK
BRICK LINED
OSS-SECTION WHEEL PIT
TURBINE DECK C-3 ELEV - 411 FEET
FROM ONTARIO HYDRO REPORT MORRISON (1957)
RACK DECK FLOODED ELEV - 390 FEET
UPPER GUIDE DECK B-3 ELEV - 476 FEET
THRUST DECK A-3 ELEV - 509 FEET
907 1909 1911 1913 1915 1917 1919 1921 1923 1925 1927 1929 1931 1933 1935 1937 1939 1941 1943 1945
DATE - YEAR
MEASUREMENTS MADE BETWEEN UNITS NO 3 AND NO 4
TYPICAL WHEEL PIT MOVEMENTS - CANADIAN NIAGARA POWER COMPANY

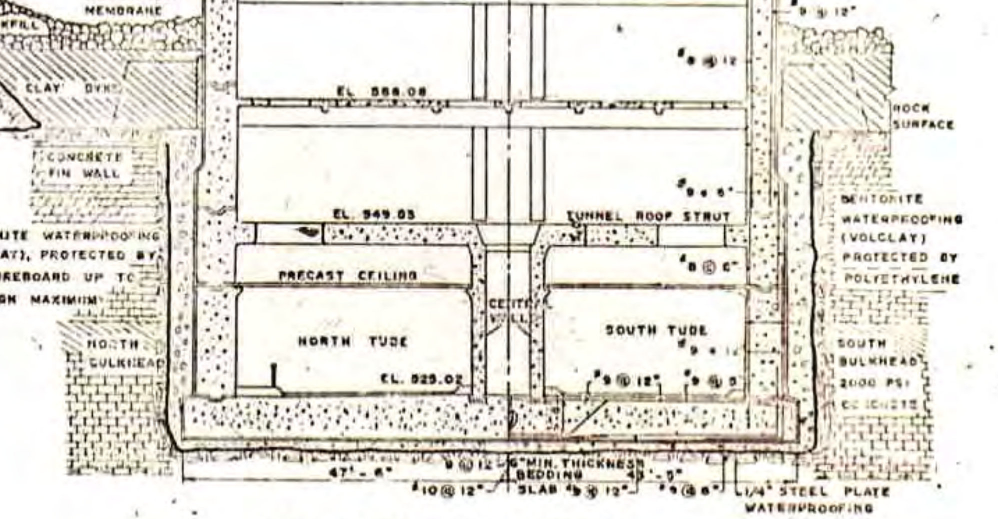


POST EXCAVATION INWARD MOVEMENT
OF CANADIAN NIAGARA G.S. WHEELPIT
TUNNEL CONSTRUCTION (S.A.B. #2)
cm
8.0
6.0
4.0
2.0
0
TURBINE DECK
UPPER GUIDE DECK
FLOODED 1918
RACK DECK
THRUST DECK
THRUST DECK
UPPER DECK
LOWER GUIDE
TURBINE DECK
RACK DECK
TILL
LOCKPORT DOLOMITE
GASPORT LIMESTONE
DECEW LIMESTONE
ROCHESTER SHALE

FIG. 4-1 Wheel Pit, Lower Arch No. 11 Spalling, underside, south half

IG. 11-1 Wheel Pit Turbine Deck, Unit No. 11. Buckling of deck support beam, east wall

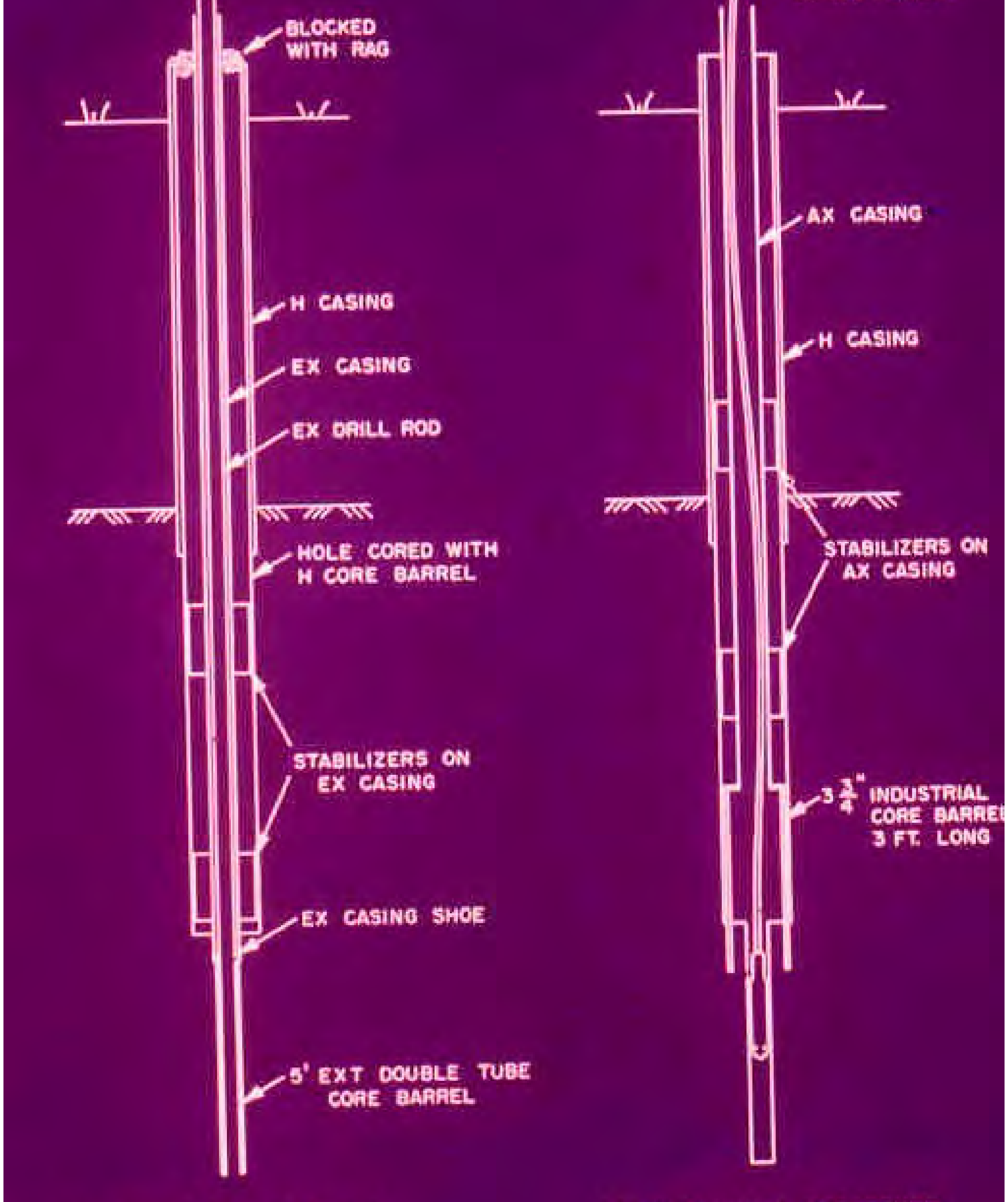

Oct 5/21
Paving .
Oct 5. 1921.



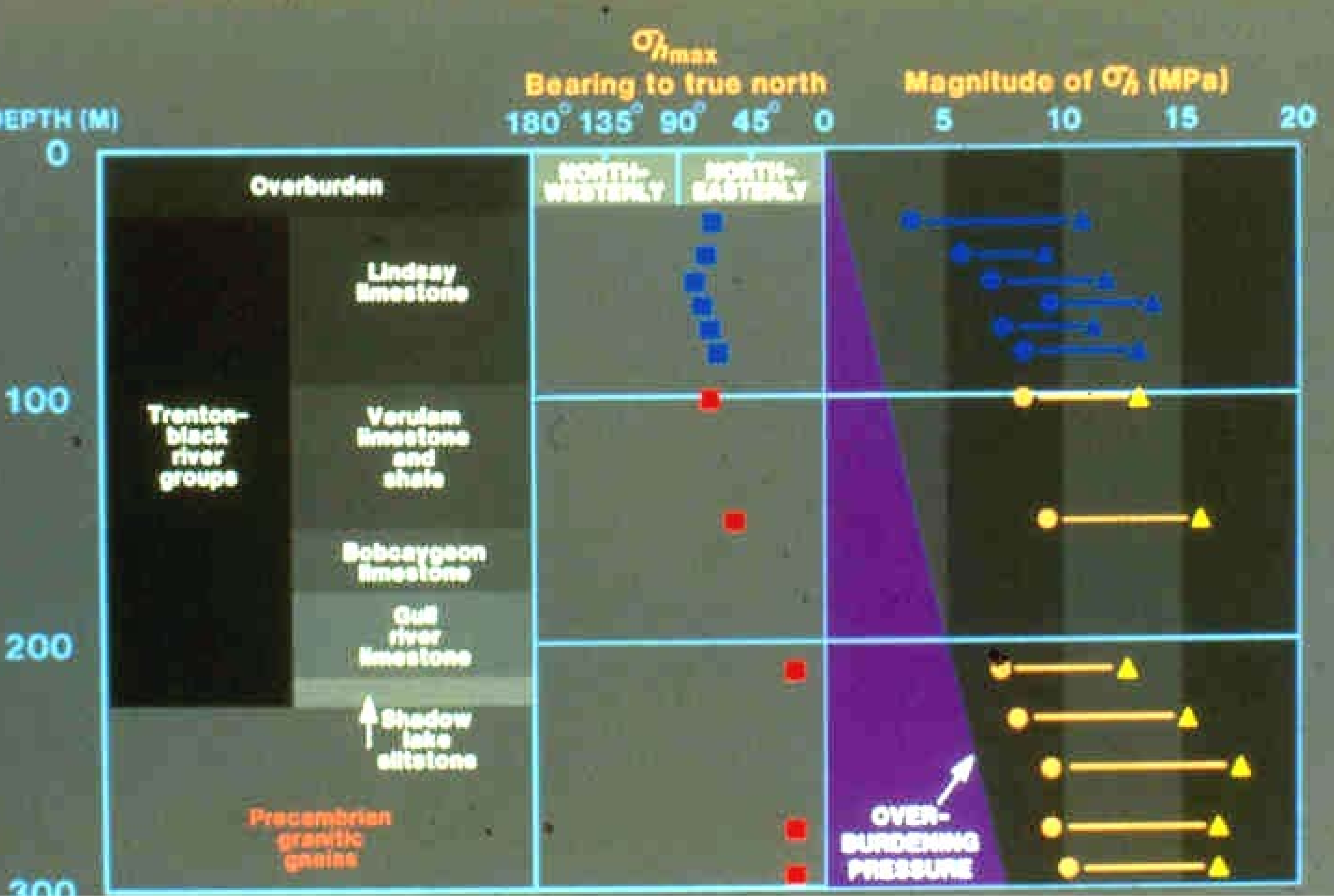
SECTION A–A AT STATION 54 + 55

CROSS–SECTION OF WEST SERVICE BUILDING
THOROLD TUNNEL

EAVED—Shale moved up into cross-section requiring invert re-excavation

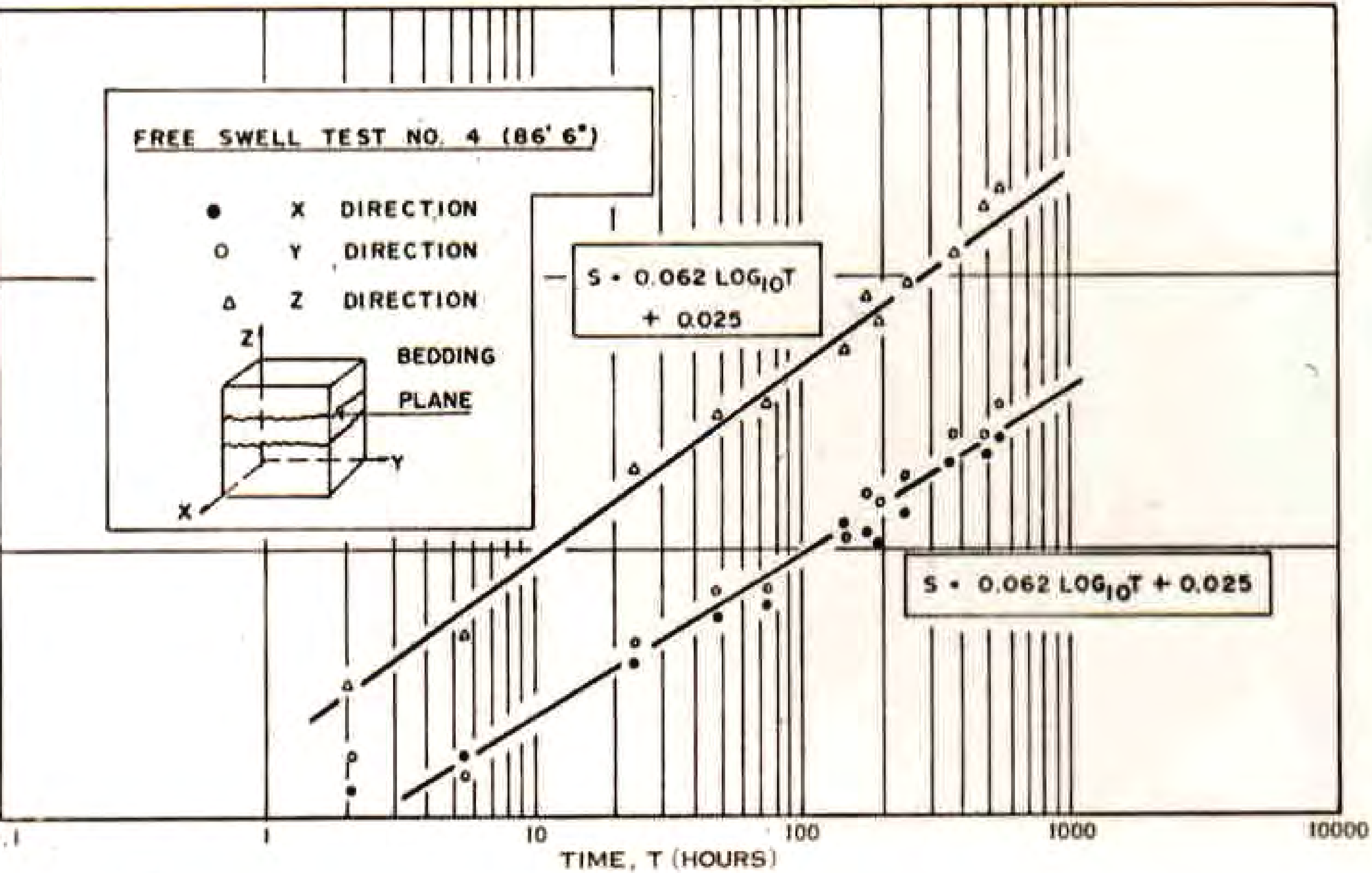


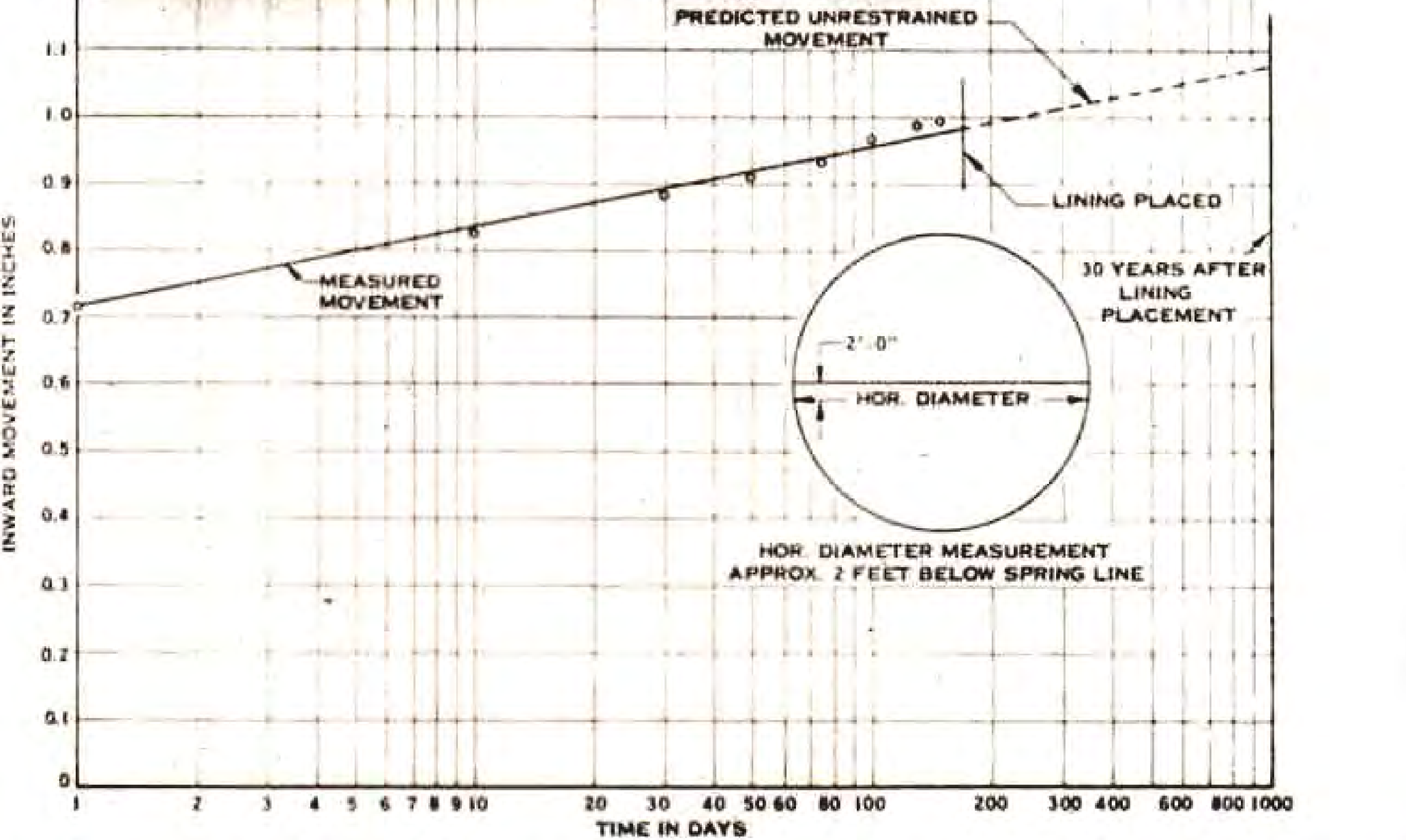
b) OVERCORING PROCEDURE



$\sigma_{h\,max}$
Bearing to true north
Magnitude of σ_h (MPa)
EPTH (M)
180° 135° 90° 45° 0
5 10 15 20
0
100
200
Overburden
NORTH-WESTERLY
NORTH-EASTERLY
Lindsay limestone
Trenton-black river groups
Verulam limestone and shale
Bobcaygeon limestone
Gull river limestone
Shadow lake siltstone
Precambrian granitic gneiss
OVER-BURDENING PRESSURE


100
DH2—
13A1
13A


FREE SWELL TEST NO. 4 (86' 6")
● X DIRECTION
o Y DIRECTION
Δ Z DIRECTION
Z
BEDDING
PLANE
Y
X
S = 0.062 LOG10T + 0.025
S = 0.062 LOG10T + 0.025
.1
1
10
100
1000
10000
TIME, T (HOURS)



ure 9. - S. A. B. N. G. S. No. 2: Rock movement vs. time (log) after bench removal
Tunnel Section No. 4, Station 290+84

Strain Energy Approach to Modelling Rock Squeeze Problems

For a virtual displacement $\{\delta\}^e$

Work Done = Force x Displacement

$= \{F\}^e\{\delta\}^e = (\{\delta\}^e)^T\{F\}^e$

where $\{F\}^e$ = corresponding nodal force

Strain energy recovered from unit volume of rock

= Stress x Strain

$= \{\sigma\}\{\varepsilon\}$

$= \{\varepsilon\}^T\{\sigma\}$

$= ([B]\{\delta\}^e)^T([D]\{\varepsilon\})$

$= (\{\delta\}^e)^T[B][D]\{\varepsilon\}$

Work Done = Strain Energy Released

$$(\{\delta\}^e)^T\{F\}^e = (\{\delta\}^e)^T\int_{vol}[B]^T[D]\{\varepsilon\}dv$$

$$\text{or } \{F\}^e = \int_{vol}[B]^T[D]\{\varepsilon\}dv$$

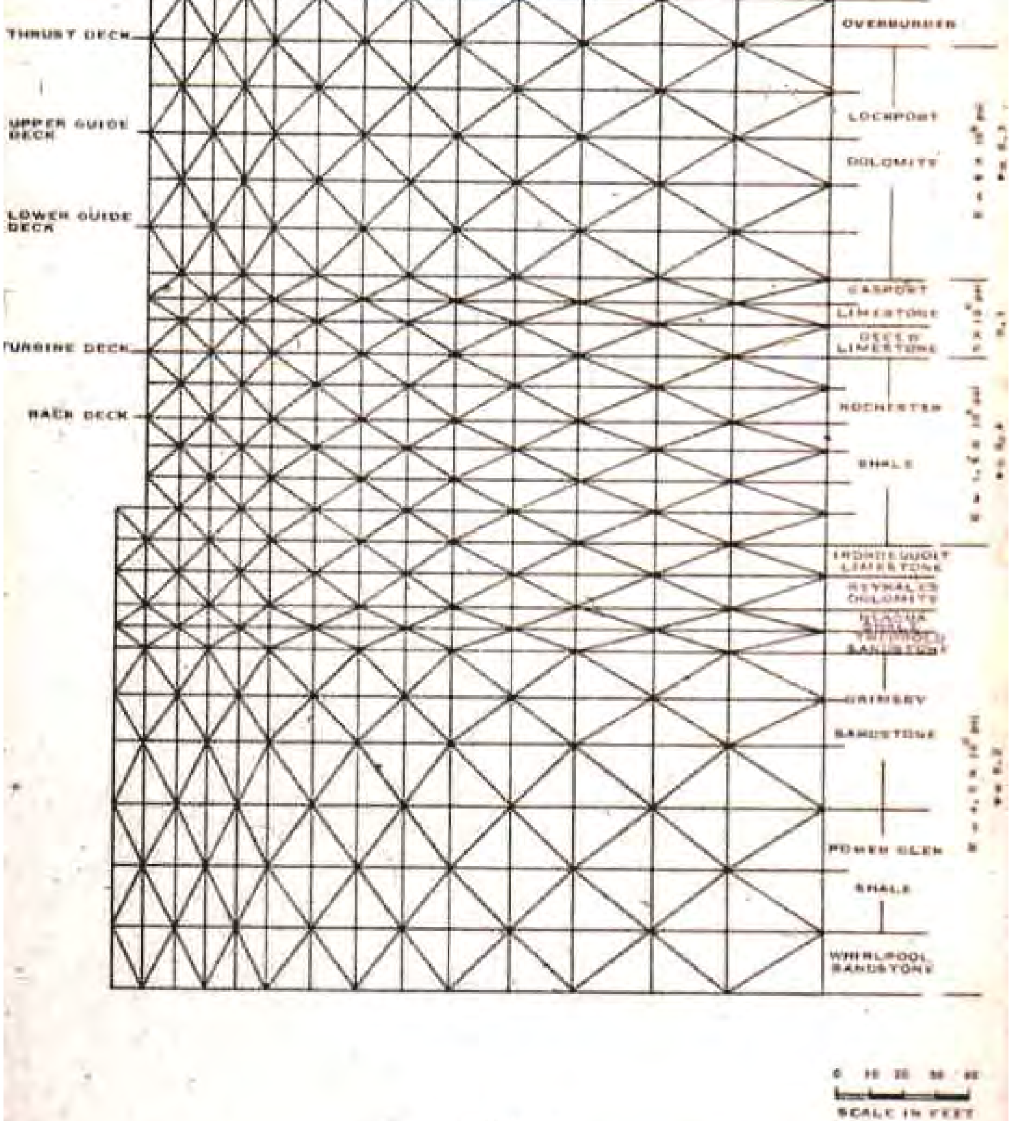


FIGURE 3

FINITE ELEMENT MESH FOR THE CANADIAN NIAGARA WHEELPIT

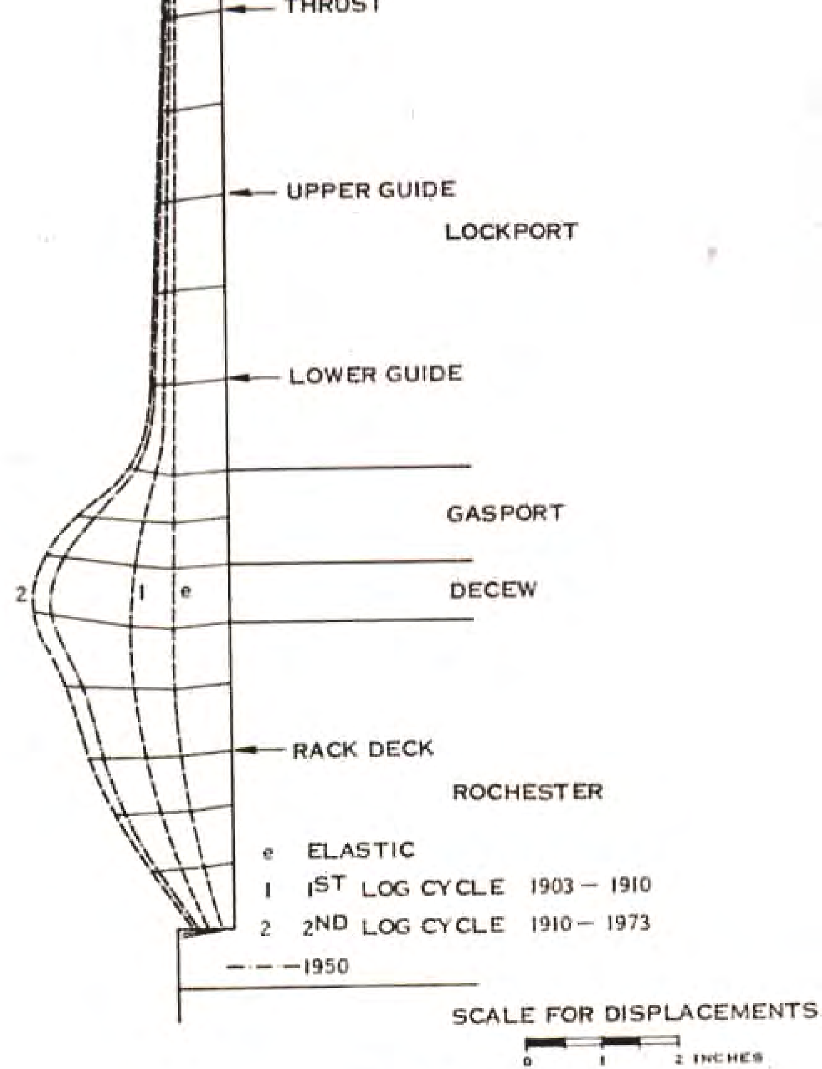


FIGURE 6

COMPUTED INWARD PIT MOVEMENTS FROM 1903 TO 1973

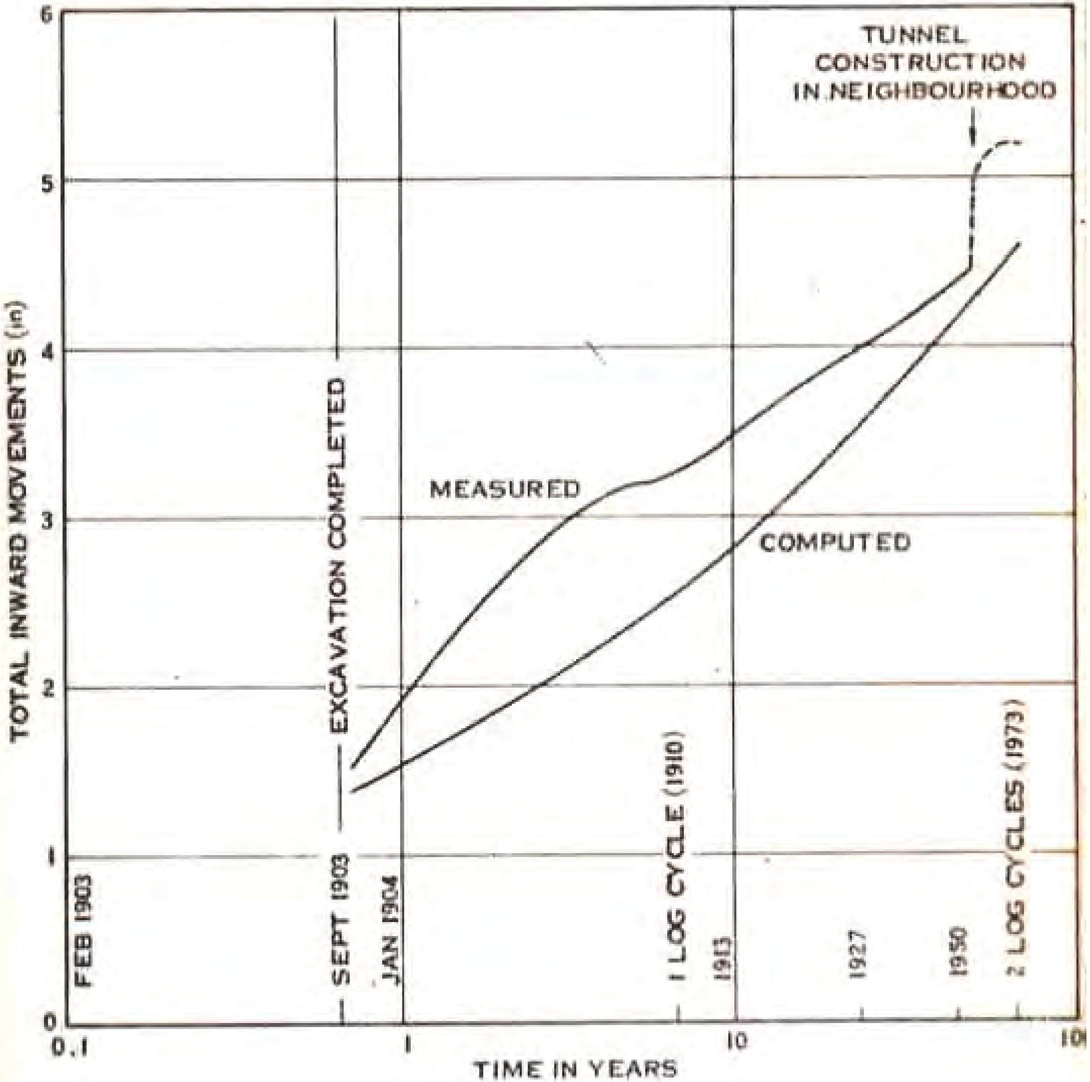
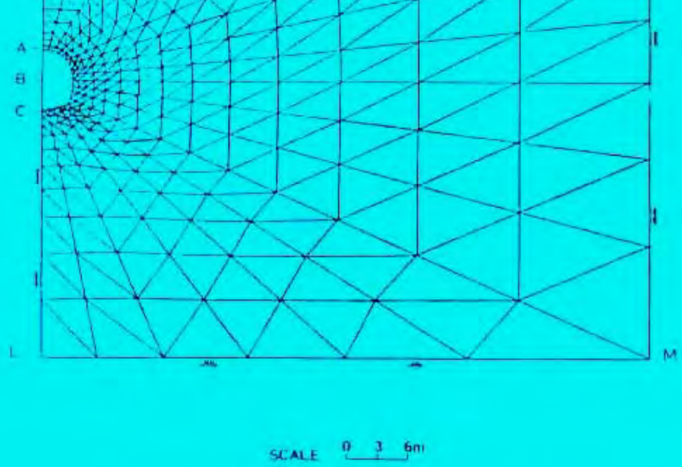
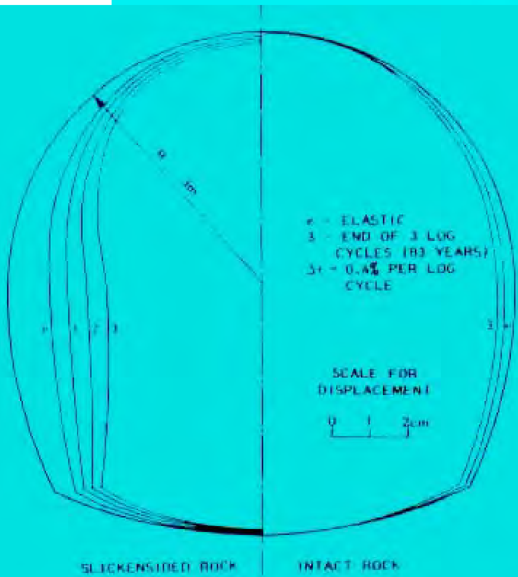


FIGURE 5

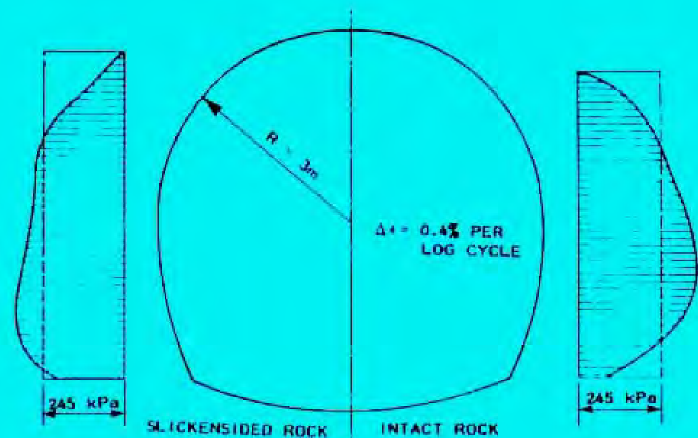
CUMULATIVE INWARD MOVEMENTS IN WHEELPIT



FINITE ELEMENT GRID FOR ROCK SQUEEZE ANALYSIS
OF CW INTAKE TUNNEL



ELASTIC AND TIME DEPENDENT DEFORMATION OF TUNNEL CIRCUMFERENCE

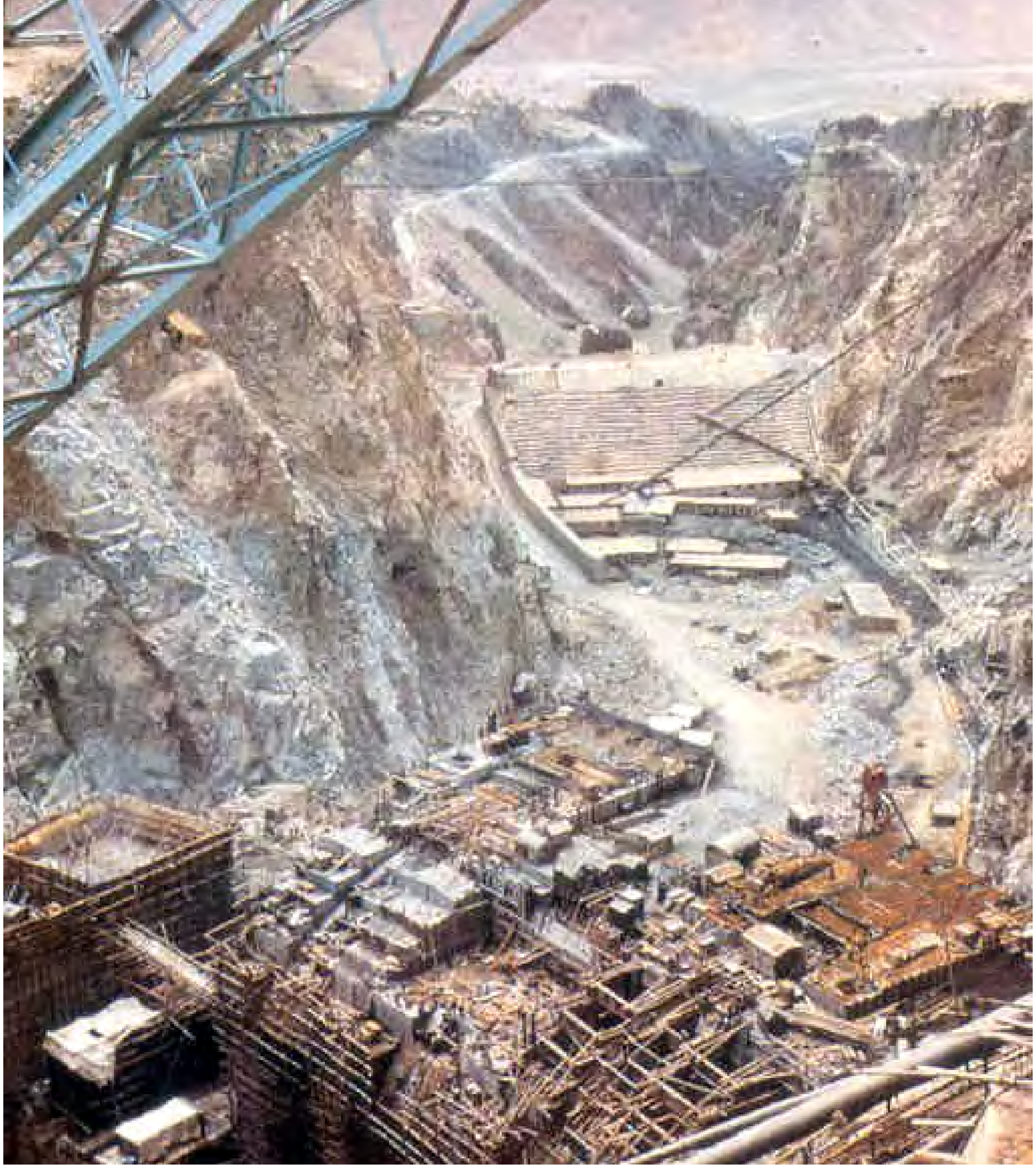


LATERAL PRESSURE ON LINING PER LOG CYCLE OF TIME

Some Features of Chinese Hydro Projects

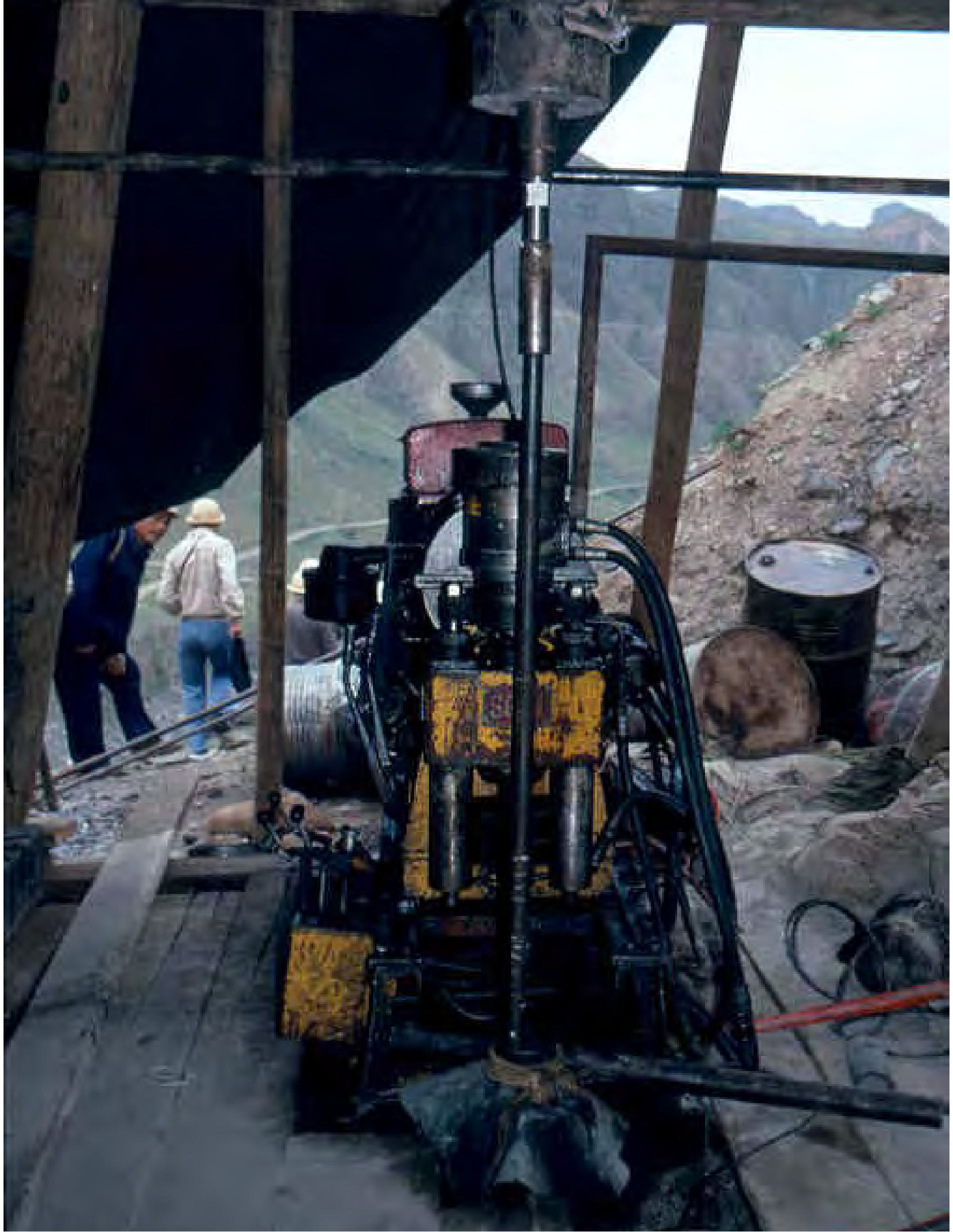
- Same design framework as in the West
- Very detailed site investigations
- Including numerous adits
- Sometimes leads to significant cost savings
- (e.g. Ertan dam allowed to be founded on Class III rock instead of Class II as called for by Design Standard
- Strong emphasis on geology and rock mass structure studies
- Very detailed analysis, including numerical modelling, AI, etc

青海龍羊峽

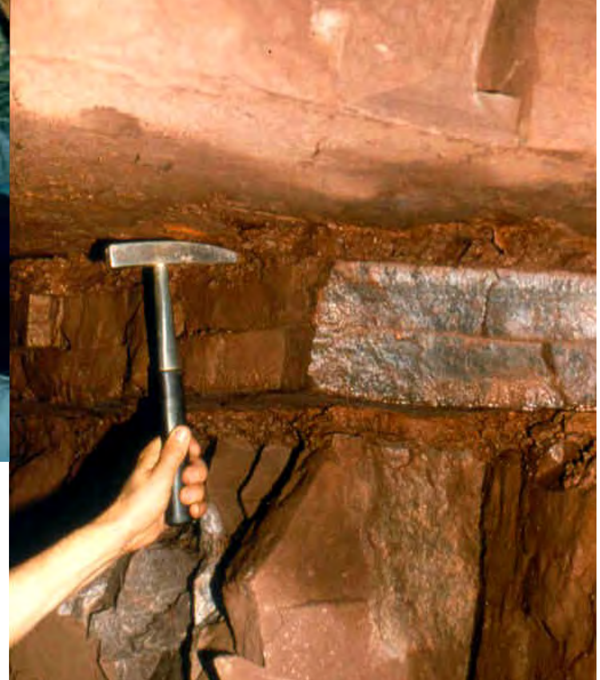


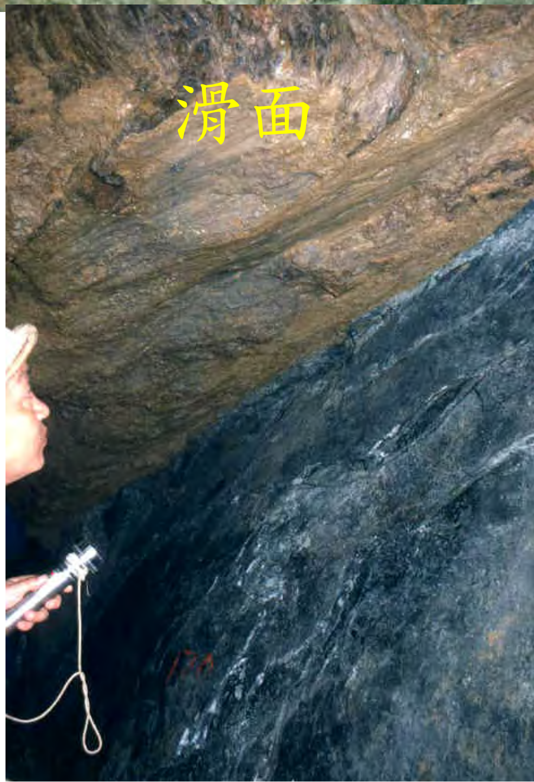
青海 黃河 李家峽　拱壩壩址

海 李家峡



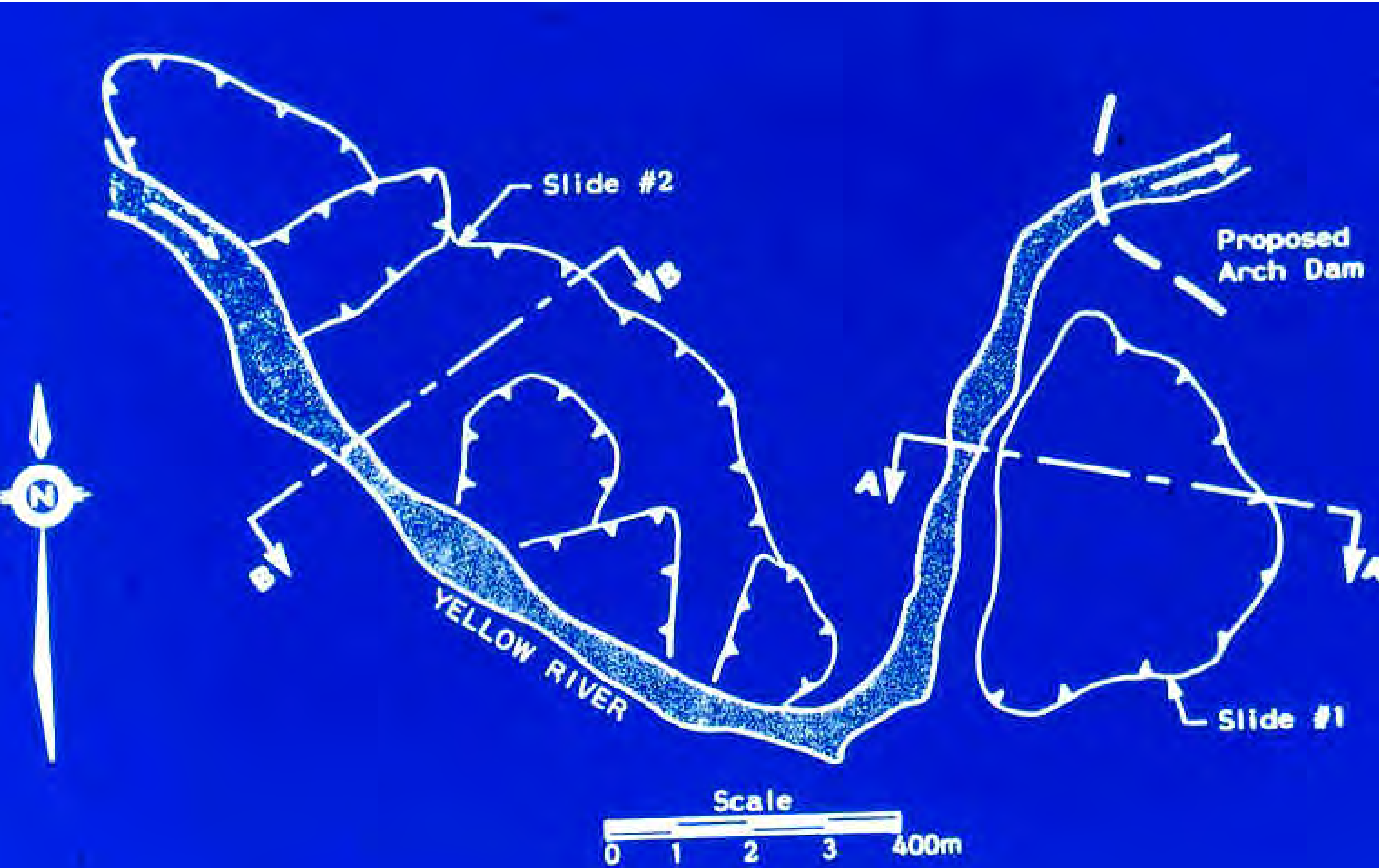
探洞



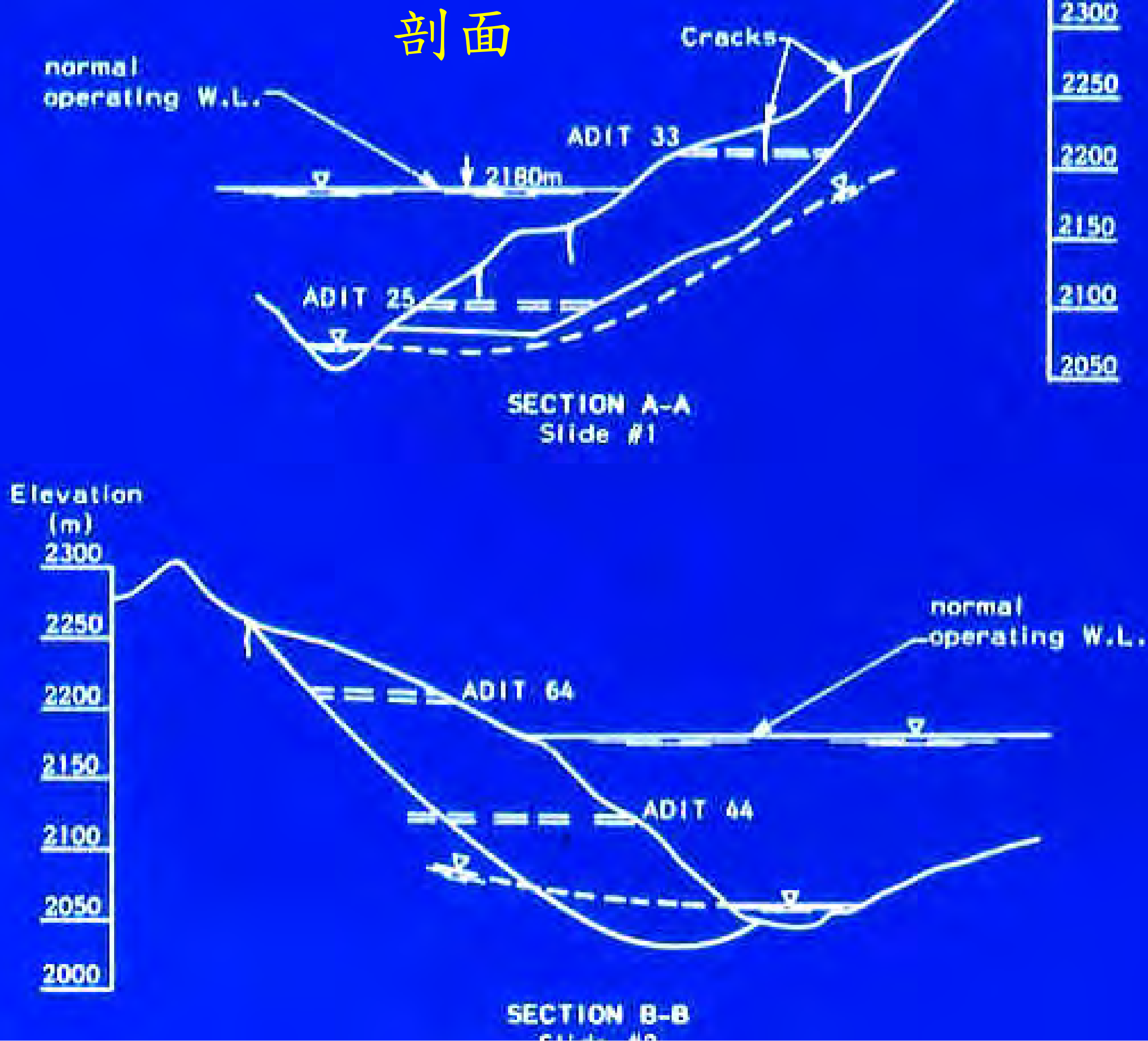

滑面


(F44)
F5

李家峽水庫 老滑坡體


Slide #2
B
B
Proposed
Arch Dam
A
A
N
YELLOW RIVER
Slide #1
Scale
0 1 2 3 400m

剖面


normal
operating W.L.
2180m
Cracks
ADIT 33
ADIT 25
2300
2250
2200
2150
2100
2050
SECTION A-A
Slide #1
Elevation
(m)
2300
2250
2200
2150
2100
2050
2000
normal
operating W.L.
ADIT 64
ADIT 44
SECTION B-B

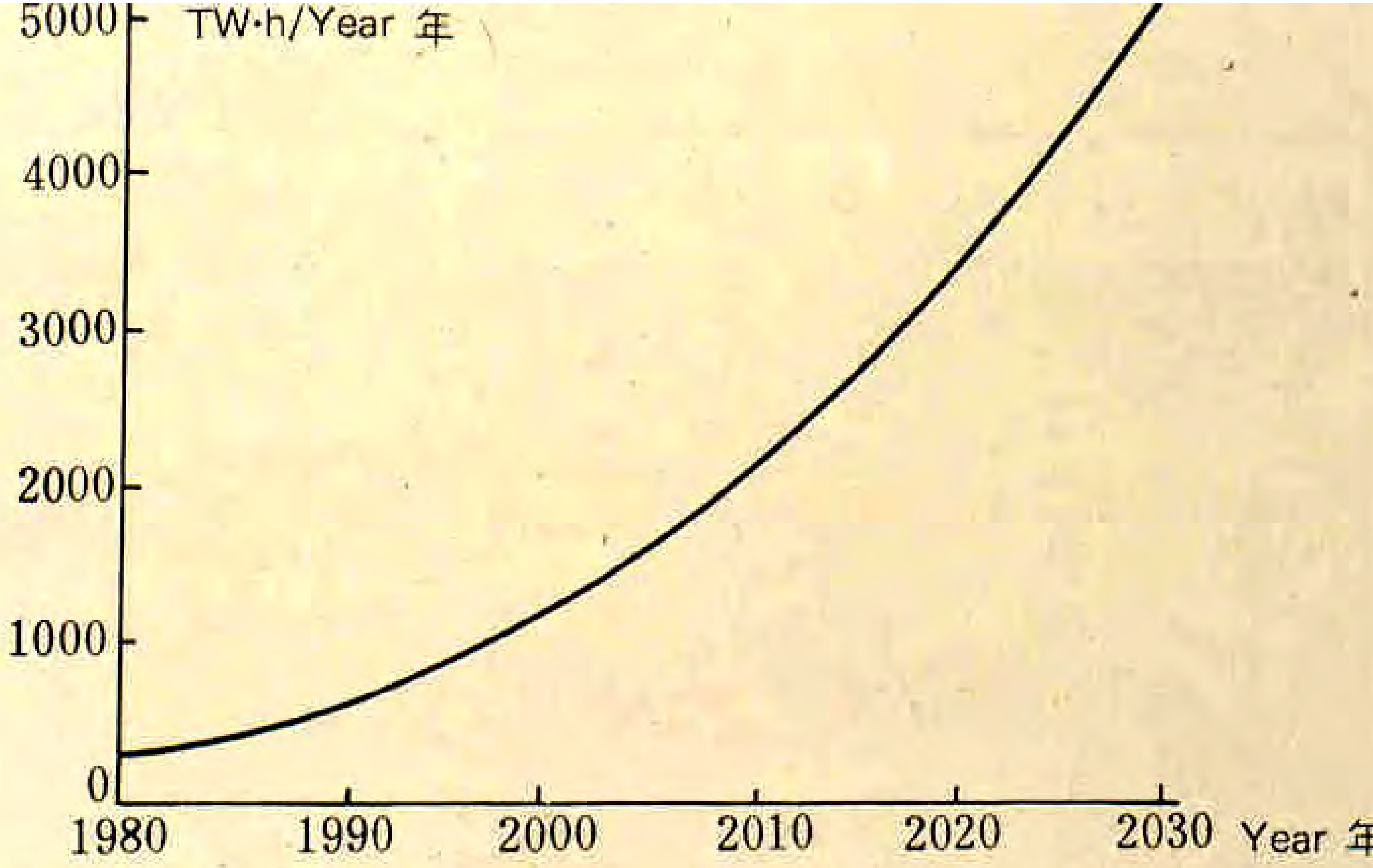
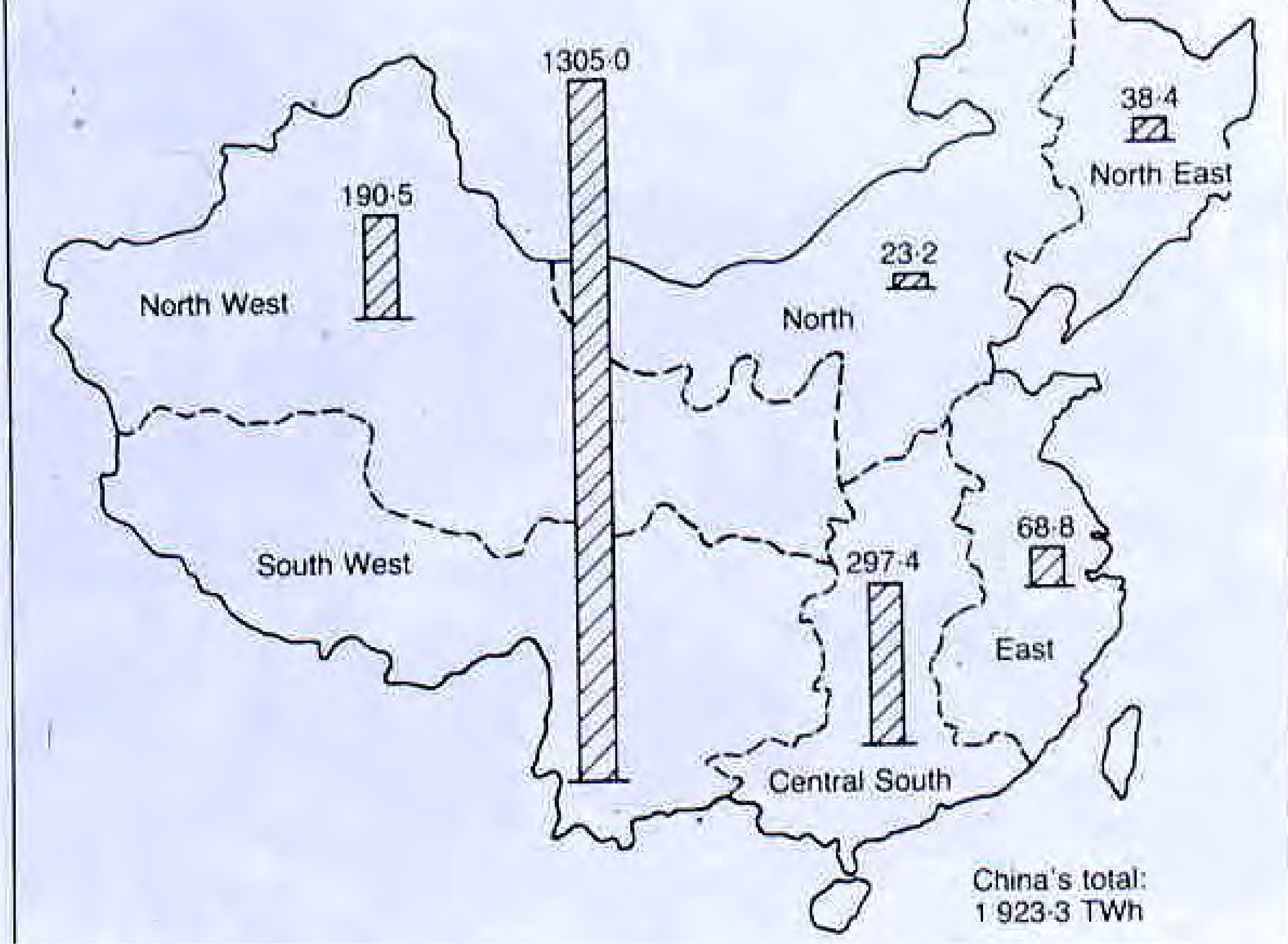
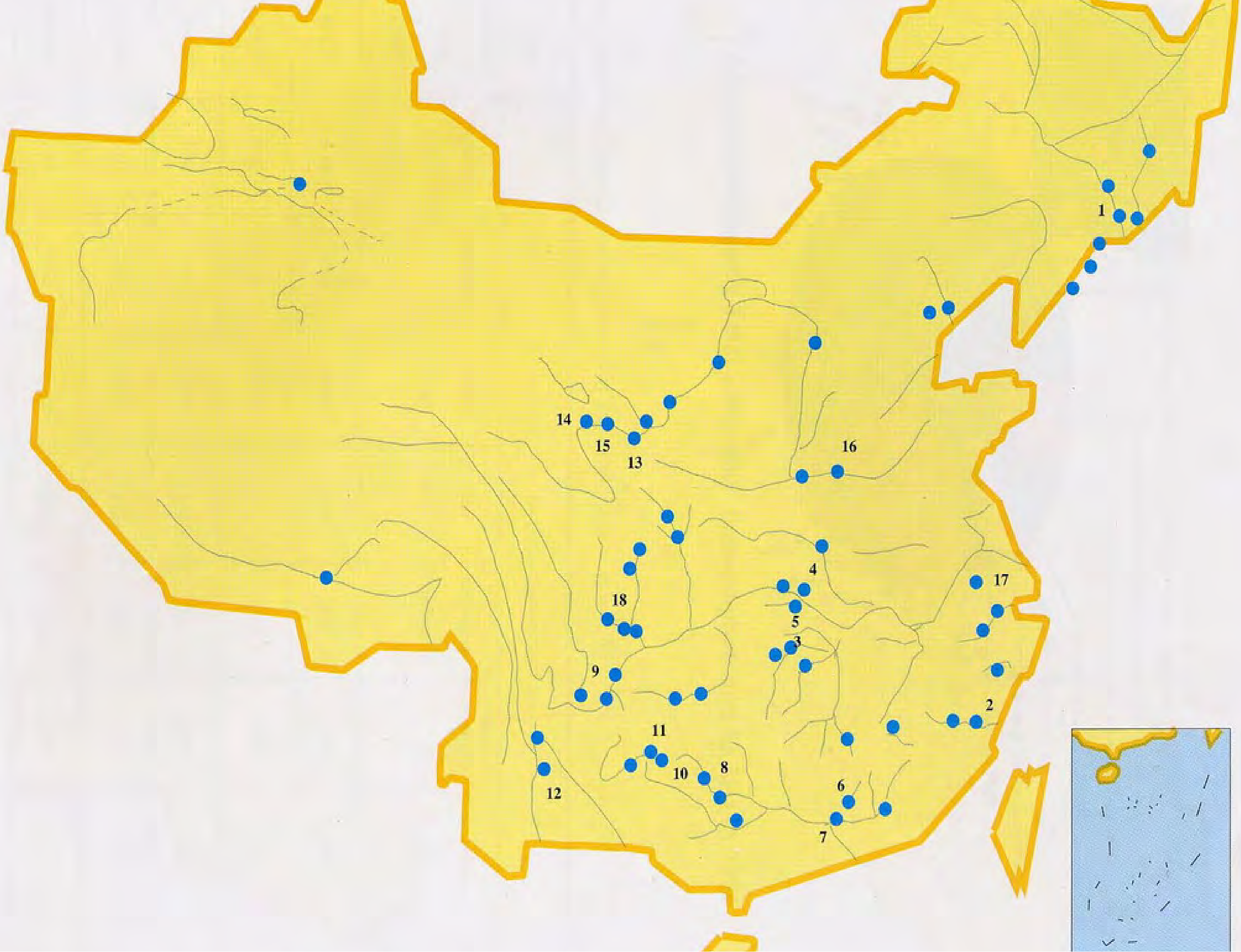


Fig. 5B Forecasts on China's long-term power supply


1305·0
190·5
North West
38·4
North East
23·2
North
South West
68·8
297·4
East
Central South
China's total:
1 923·3 TWh



1
14
15
13
16
4
17
18
5
3
9
2
11
8
10
6
12
7

Jin Sha River Hydro Power


西线
中线
东线
北京
天津
石家庄
太原
济南
青岛
郑州
徐州
连云港
南京
上海
杭州
合肥
武汉
西安
兰州
西宁
成都
重庆
长沙
南昌
贵阳
拉萨
格尔木
延安
宝鸡
呼和浩特
大同
二连浩特
沈阳
锦州
丹东
大连
Yellow River
Qinghai Lake
Bohai Sea
Yellow Sea
East Sea

南水北调线路示意图

Method of Generation	Pros	Cons	Capital Construction Cost (Ratio)	Fuel Cost
Fossil	• Short construction period (2-3 years) • Easy to start up	• Air pollution • Ash/sludge disposal	1	Relatively high
Hydraulic	• Longer construction period (> 5 years)	• Resettlement of affected population • Preservation of cultural & historic relics	2	/
Nuclear	• Relatively long construction period (≥ 10 years)	• Nuclear safety concern • Nuclear waste disposal needs	5	Relatively low

ther generation methods: solar, wind, biomass, etc.

The Joy of being a Hydro Project Engineer

- Free helicopter / jet rides

  (safe, most of the time)

- Exotic places with breathtaking scenery and colorful folklore

  (no tourists around; no phone calls, etc.)


A2-1

攔路酒(四川 涼山)

中国水利

钱正英 主编

大禹传人

与李焯芬先生共勉

钱正英

一九九三年九月六日

水利电力出版社


13×11 24×11 38×11 49×11
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Thank you for your patience