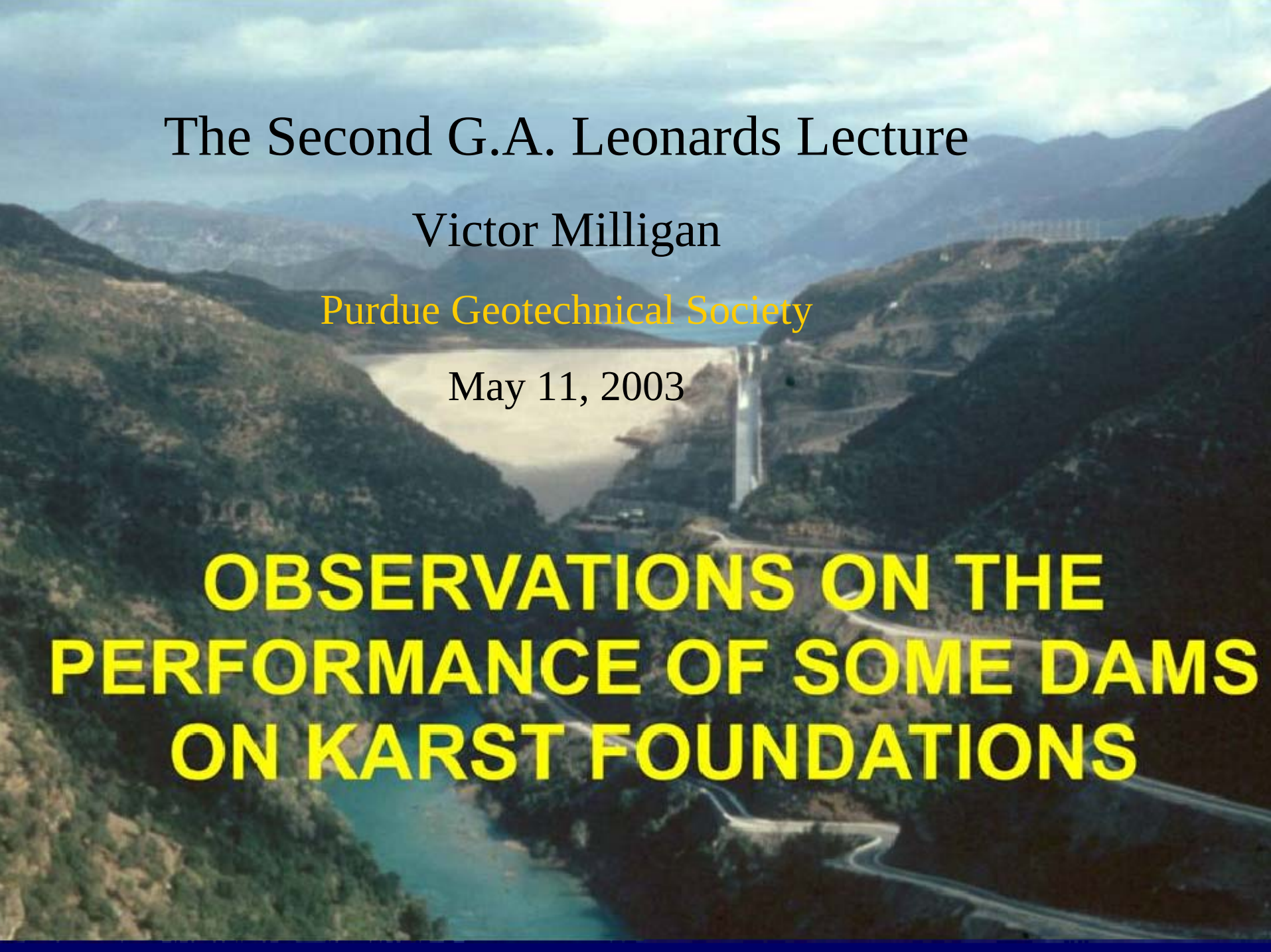

The Second G.A. Leonards Lecture
Victor Milligan
Purdue Geotechnical Society
May 11, 2003
OBSERVATIONS ON THE PERFORMANCE OF SOME DAMS ON KARST FOUNDATIONS

Dams on pervious foundations involve three possible courses of action:

- Eliminate or reduce seepage to a minimal amount by construction of seepage barriers.
- Reduce seepage as much as economically practicable and provide for control of any subsequent water losses.
- Do nothing to reduce seepage – but provide for control of anticipated water losses.

Generally speaking, most engineers endeavour to design almost all embankment dams to satisfy the first premise.

However – where the foundation is extremely pervious, construction of a complete barrier to seepage is rarely possible – and even more rarely achieved. An extreme of this situation is represented by the construction of dams on KARST.

The term KARST refers to regions or terranes where sinkholes and solution channels have been formed by water in soluble rocks – generally, but not exclusively, in limestones, dolomites and carbonate conglomerates.

Because this condition is dependent on the regional geology – not just the geology specific to the dam site – water may seep from the reservoir and below the dam for great distances and in considerable amounts.

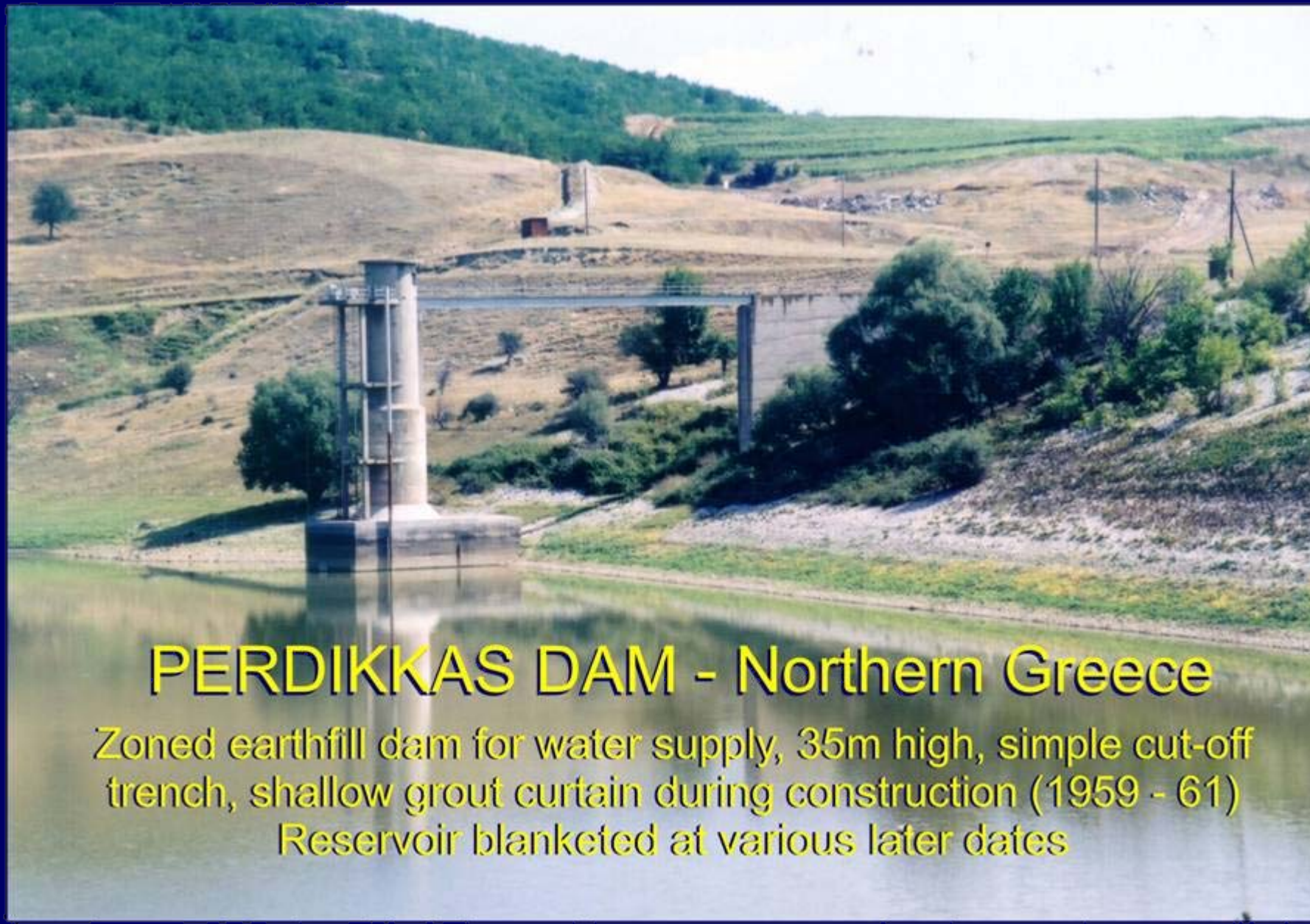
Thus the critical questions are:

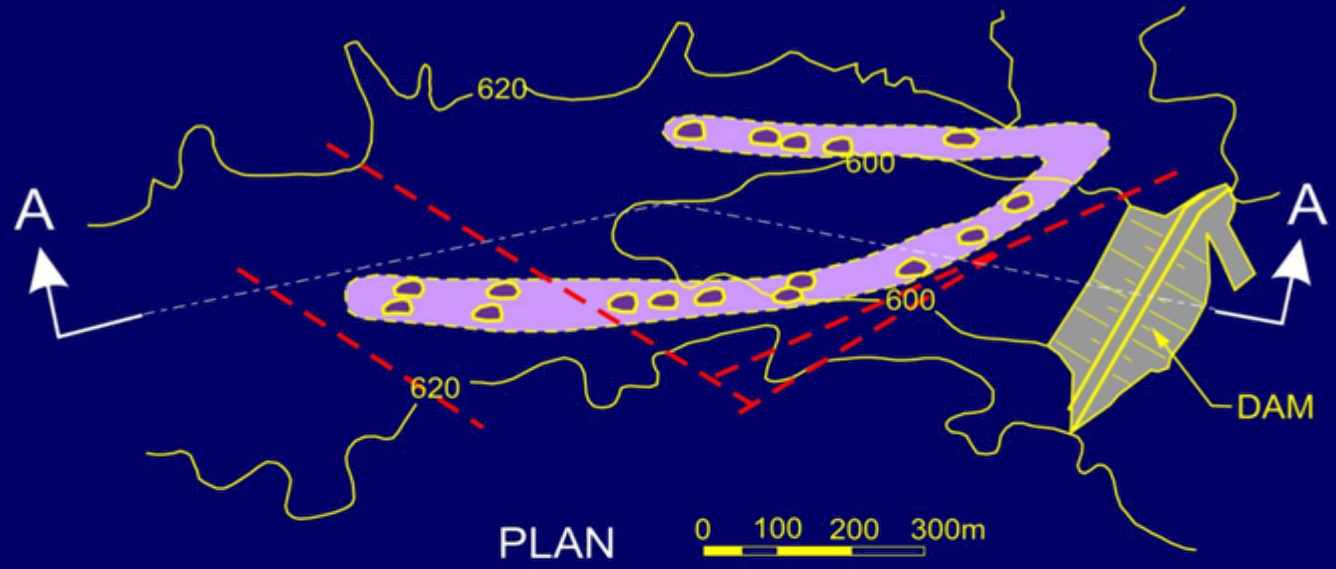
- What can be done – in realistic, economical terms – to reduce the likely seepage to reasonable amounts?
- What amount of seepage is reasonable?
- What will be the effect of such seepage on the safety of the dam and reservoir.

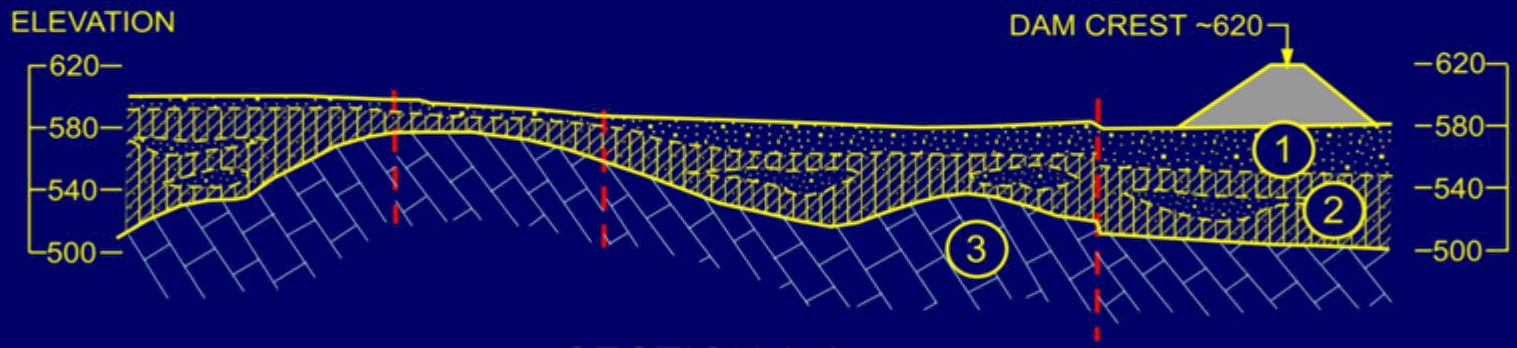
These critical questions and the use of grout curtains and reservoir blankets to inhibit possible seepage discussed by reference to four embankment dams – located variously in:

- Greece (2)
- Turkey
- USA


PERDIKKAS
KREMASTA
ATATURK
MACEDONIA
GREECE
ASIA MINOR
ARMENIA
Adriatic Sea
Ionian Sea
Aegean Sea
Black Sea
Mediterranean Sea
Caspian
Sea of Azov
Crimea
Caucasus Mountains
Transylvanian Alps
Dinaric Alps
Apennine Mts.
Taurus Mts.
Syrian Desert
Mesopotamia
Zagros
Lorestan
CRETE
CYPRUS
CYRENAICA
LIBYA
LOWER EGYPT
UPPER
Nafud
Sicily
Malta
Corfu (Corcyra)
Cephalonia
Zacynthos
Cythera
Khania (Canea)
Rhodes
Carpathos
Sparta
Athens
Chios
Lesbos
Samos
Ephesus
Cyclades
Dodecanese
Sea of Marmara
Bosphorus
Hellespont
Olympus
Pindus Mts.
Rhodope Mts.
Balkan Mts.
R. Danube
R. Dnieper
R. Kuban
R. Euphrates
R. Tigris
R. Khabur
R. Balikh
R. Orontes
R. Jordan
R. Arak
R. Aras
R. Kura (Cyrus)
L. Van
L. Urmia
L. Sevan
Nineveh
Great Zab
Little Zab
R. Diyala
Antioch
Byblos
Sidon
Tyre
Damascus
Joppa
Jerusalem
Dead Sea
Babylon
Ur
Echatana
Memphis
L. Qarun
Qattara Depression
Siwa Oasis
Jalo Oasis
Libyan Plateau
Alexandria
Arabah
Wadi Rimah
Dumah
Sinai Penin.
Coastline ?


PERDIKKAS DAM - Northern Greece
Zoned earthfill dam for water supply, 35m high, simple cut-off trench, shallow grout curtain during construction (1959 - 61)
Reservoir blanketed at various later dates





SECTION A-A

620 GROUND SURFACE (ELEV. IN METRES)

FAULT

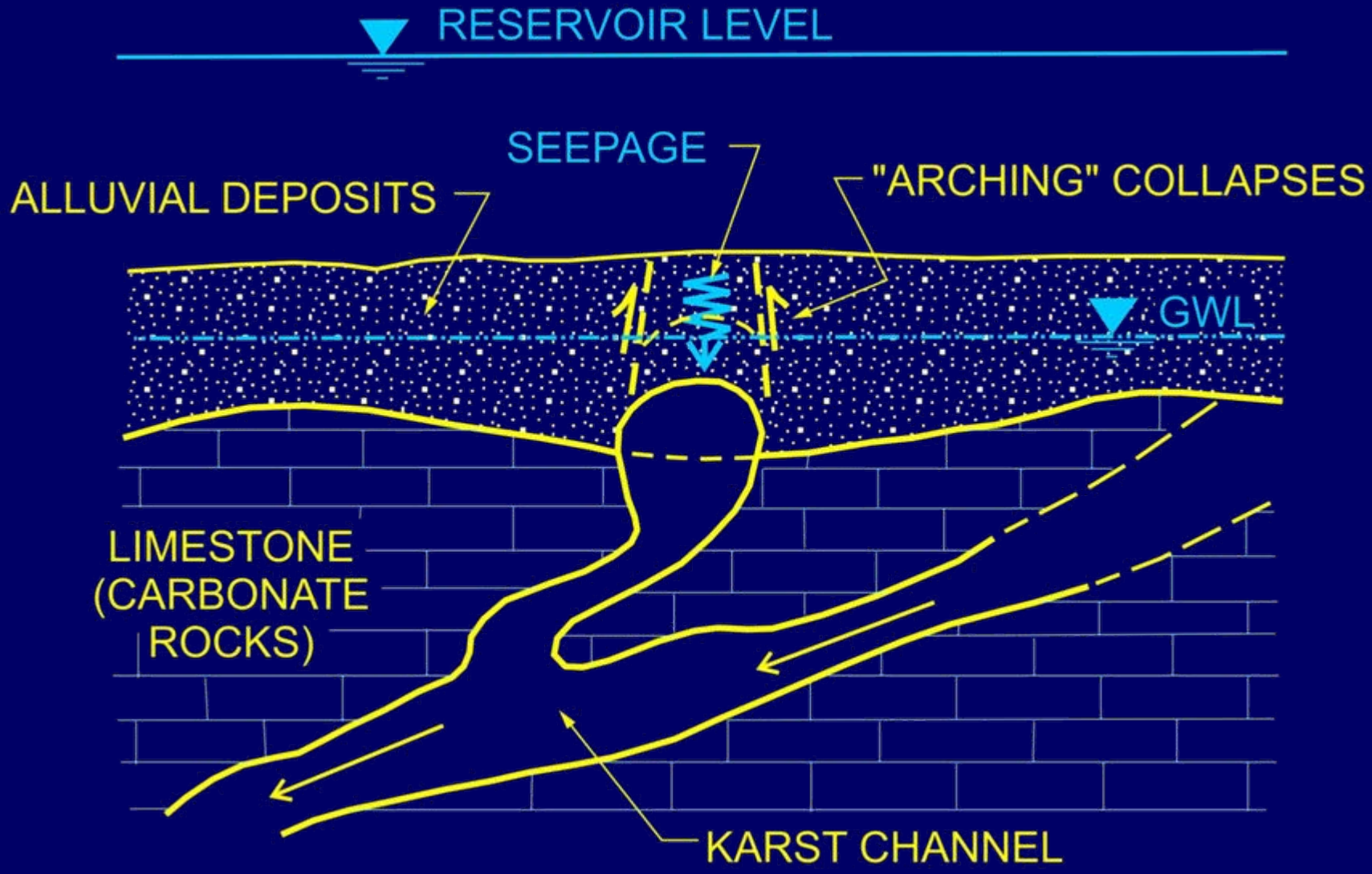
ZONE OF SUBSIDENCE

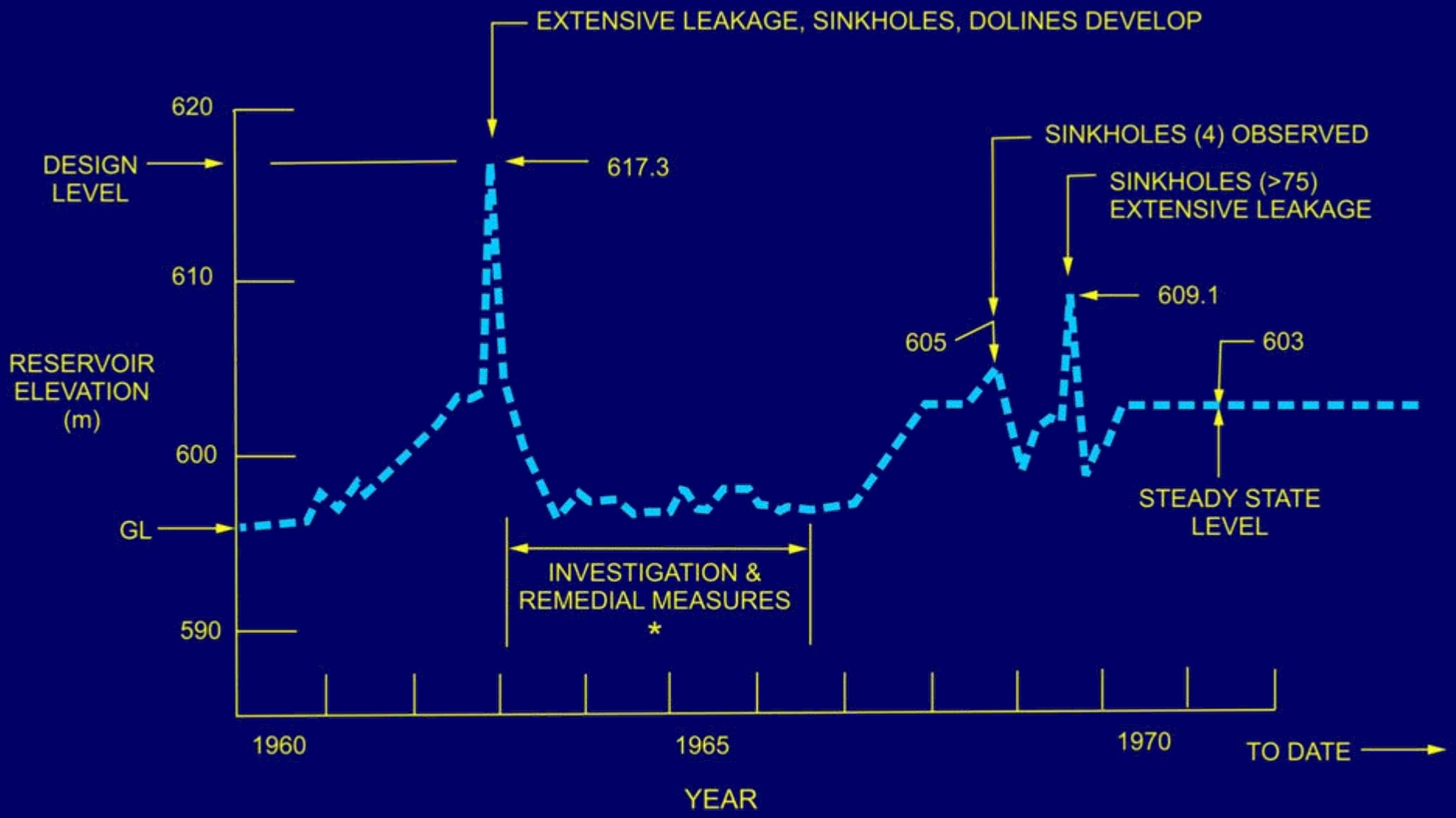
DOLINES, SINKHOLES

1 ALLUVIAL SANDS, GRAVELS

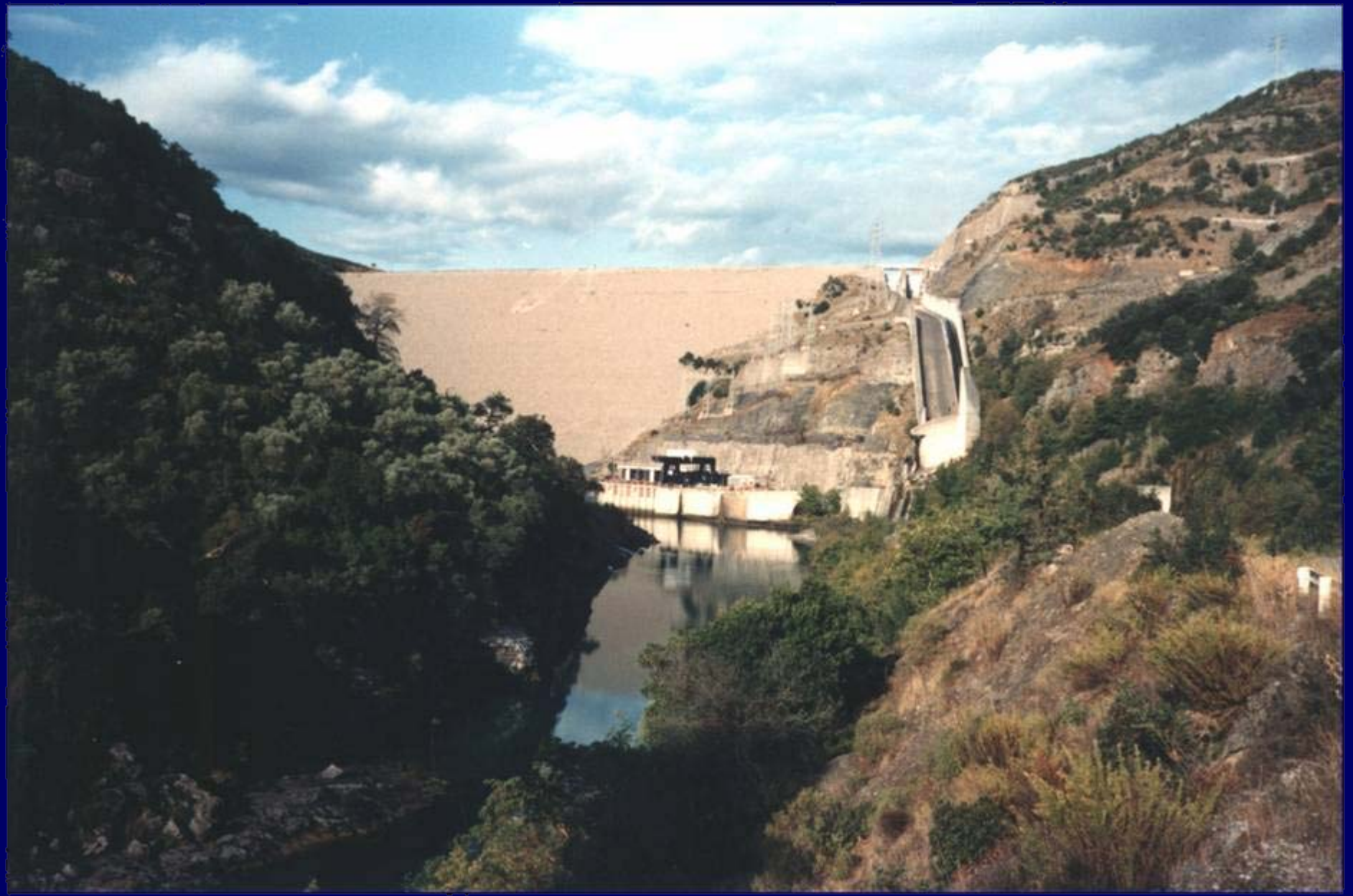
2 COLLUVIUM, CONTAINING LENSES OF COARSE SANDS AND GRAVELS

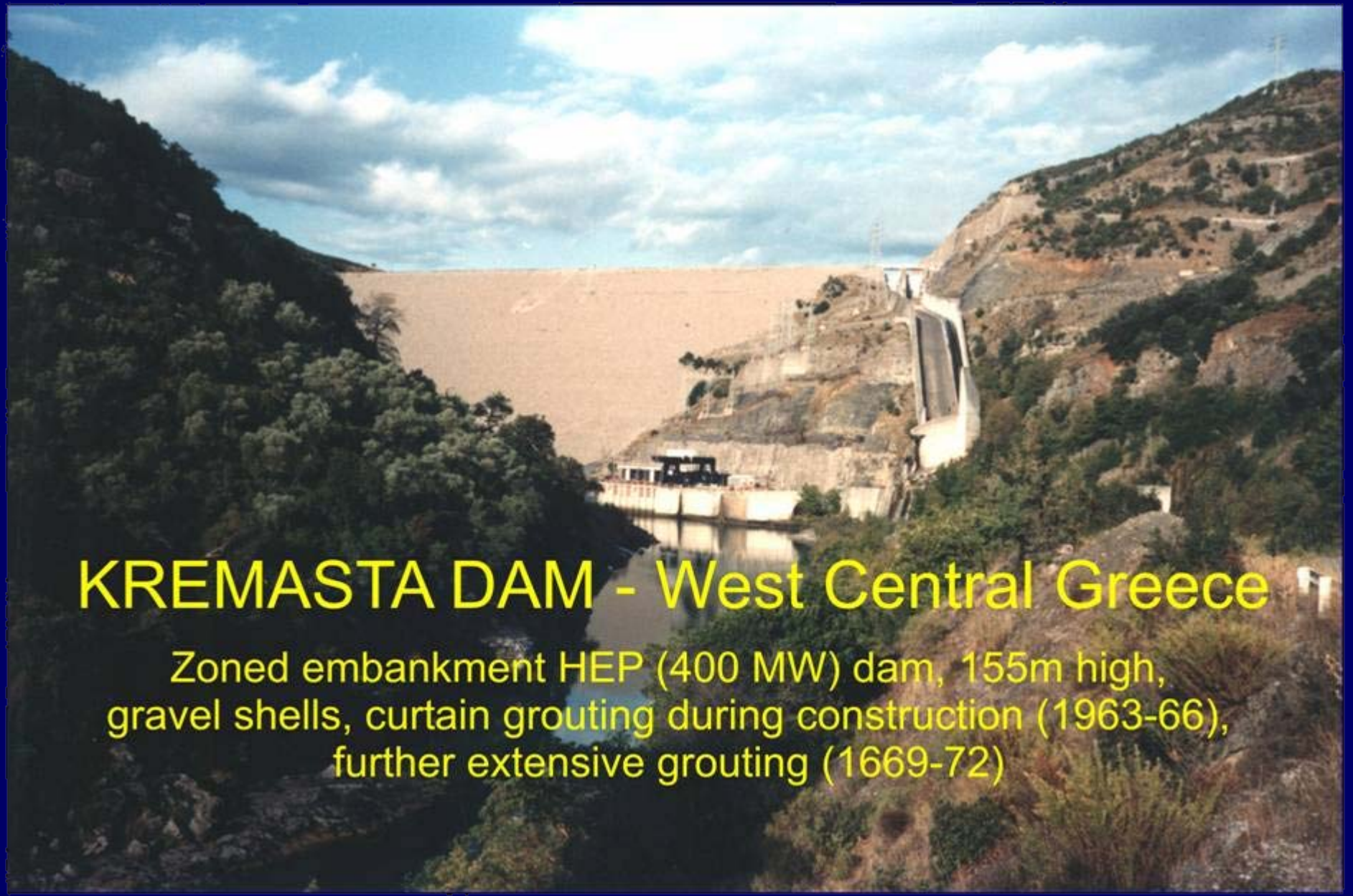
3 KARSTIC LIMESTONE

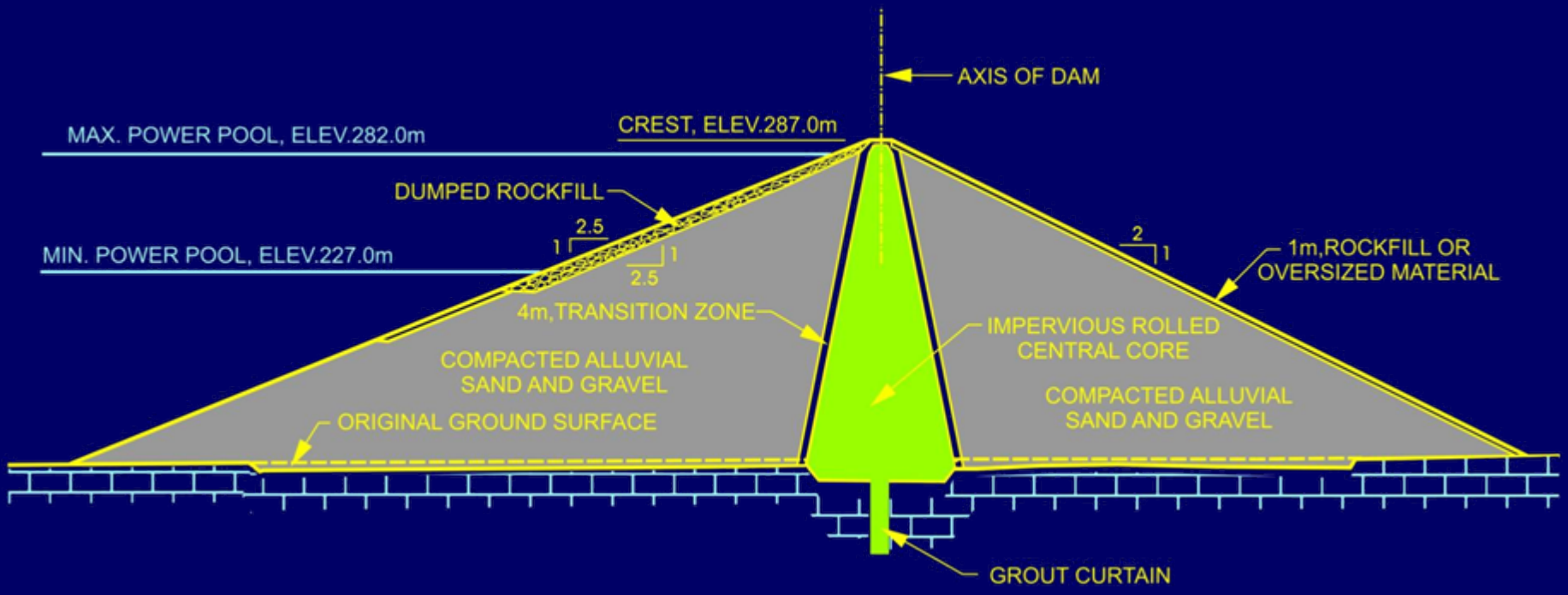

RESERVOIR LEVEL
SEEPAGE
ALLUVIAL DEPOSITS
"ARCHING" COLLAPSES
GWL
LIMESTONE
(CARBONATE
ROCKS)
KARST CHANNEL

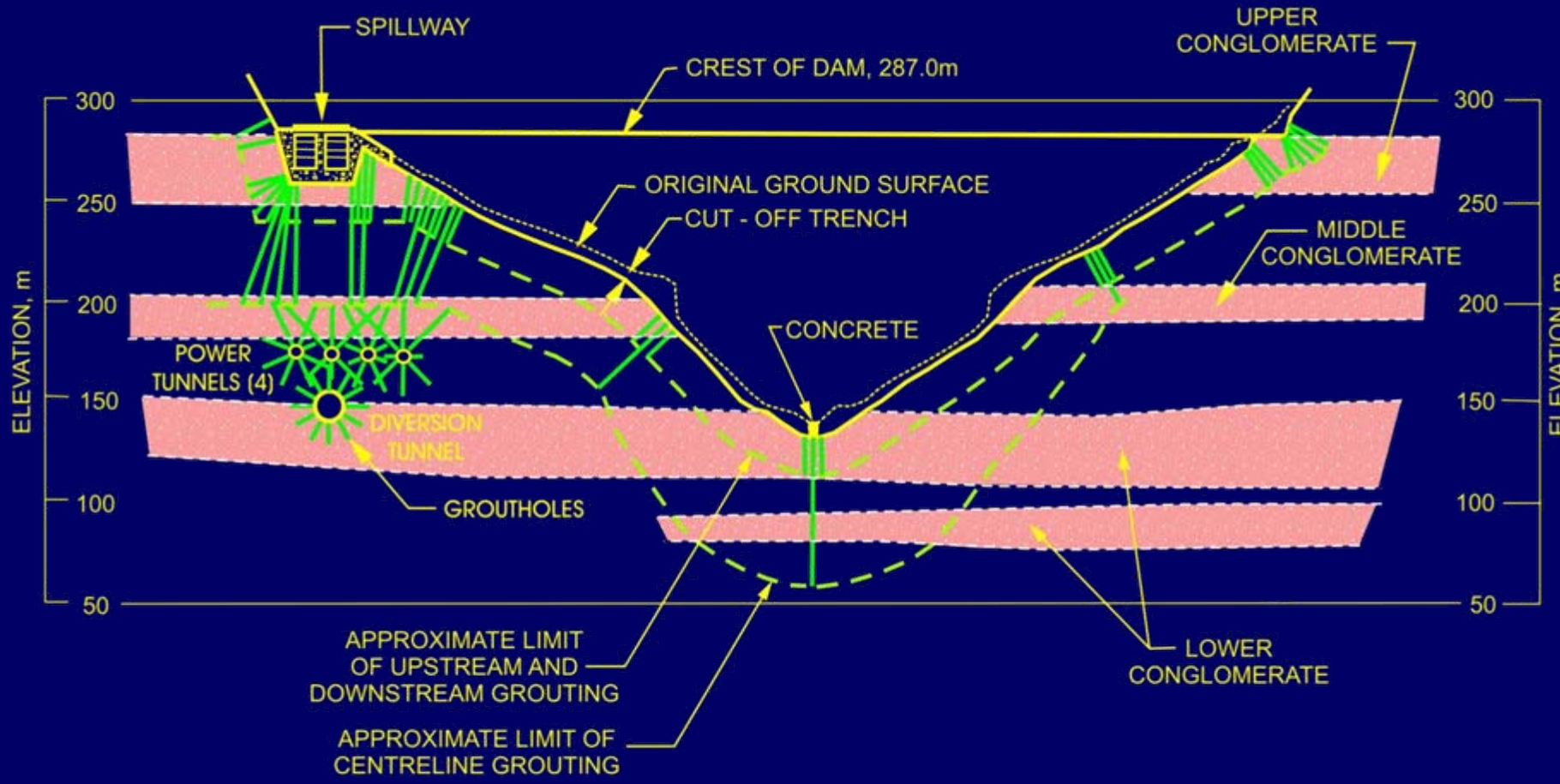


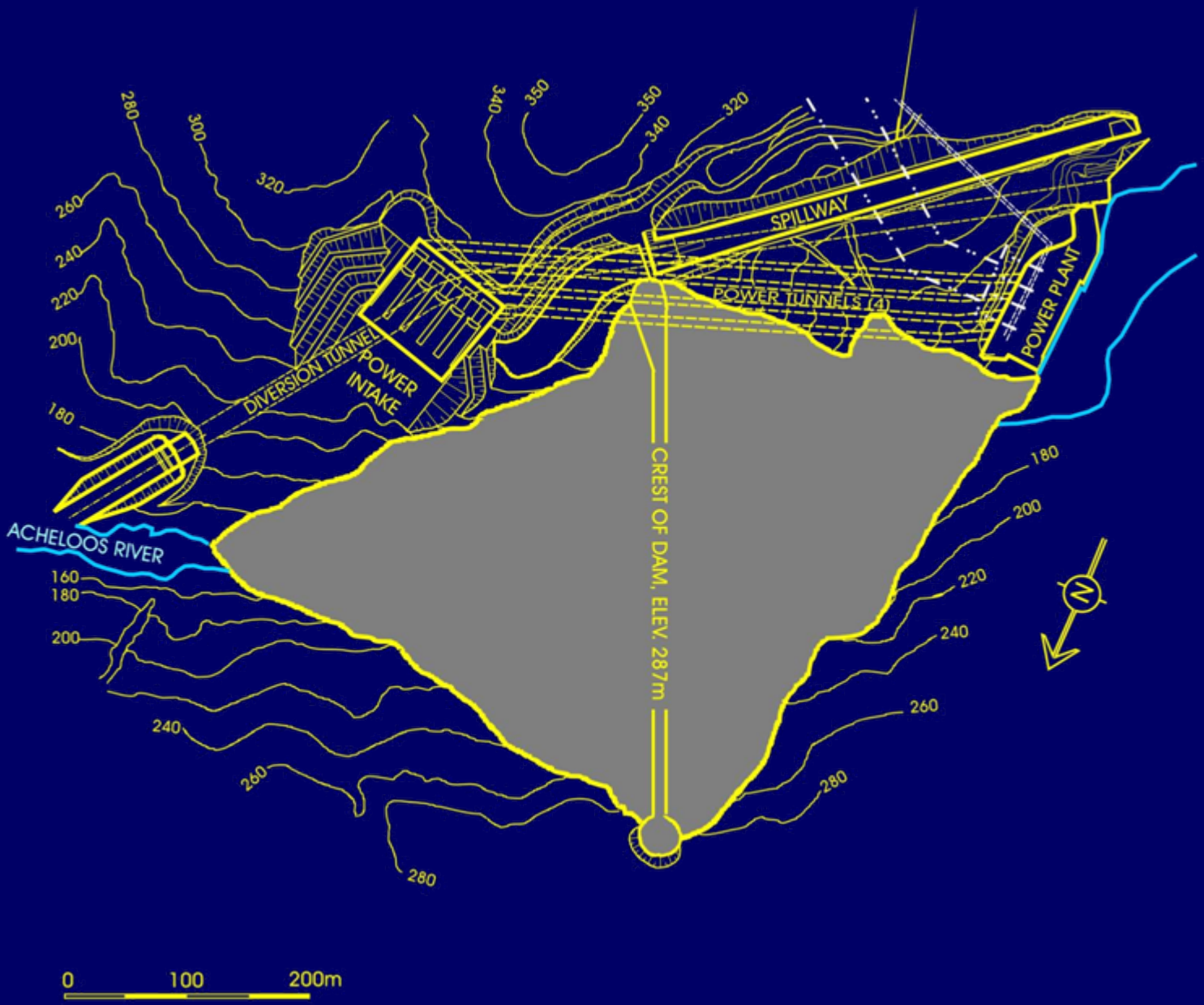
* GROUTING, PLACING BLANKET LINING, BACKFILLING HOLES AND DOLINES.

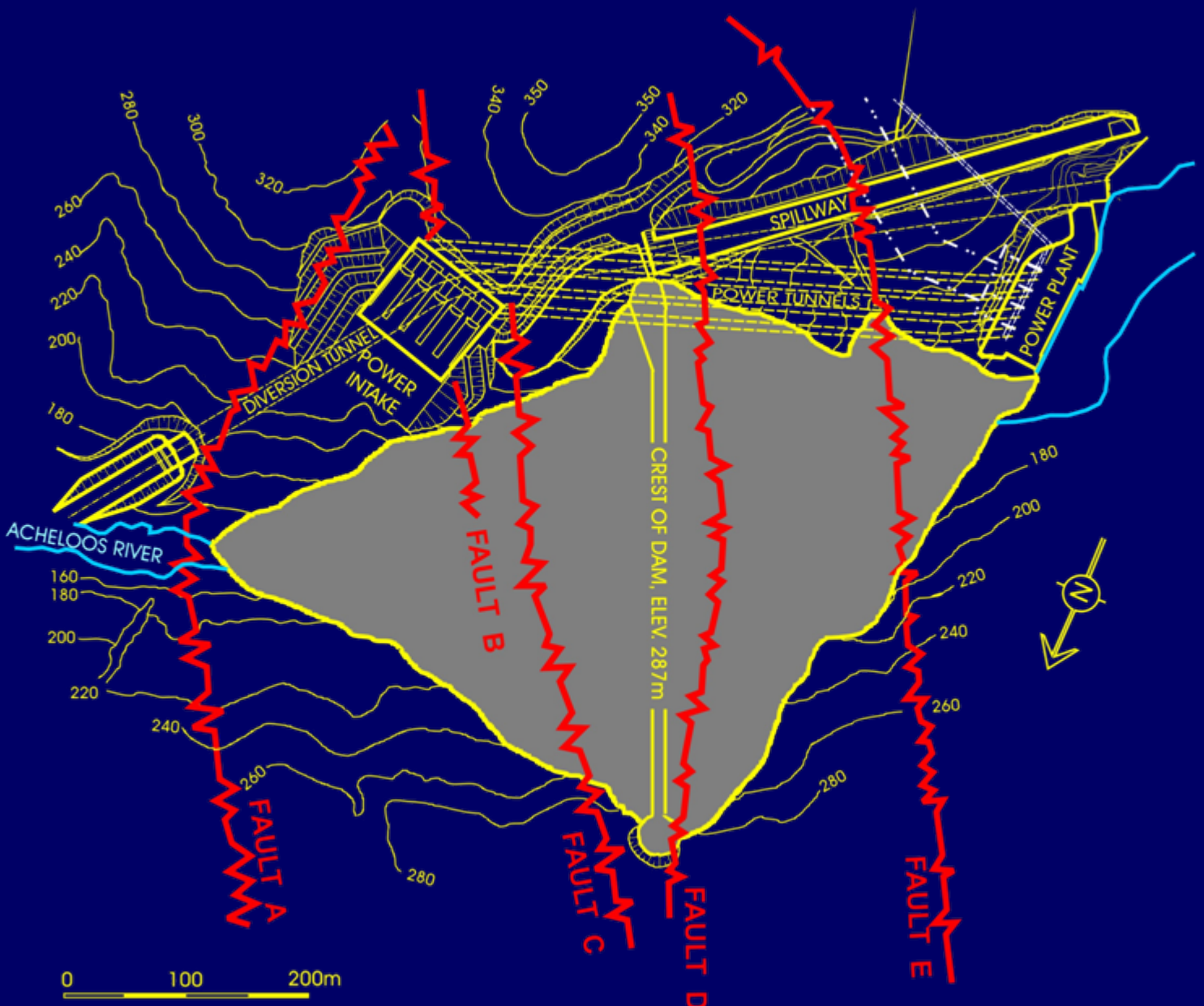


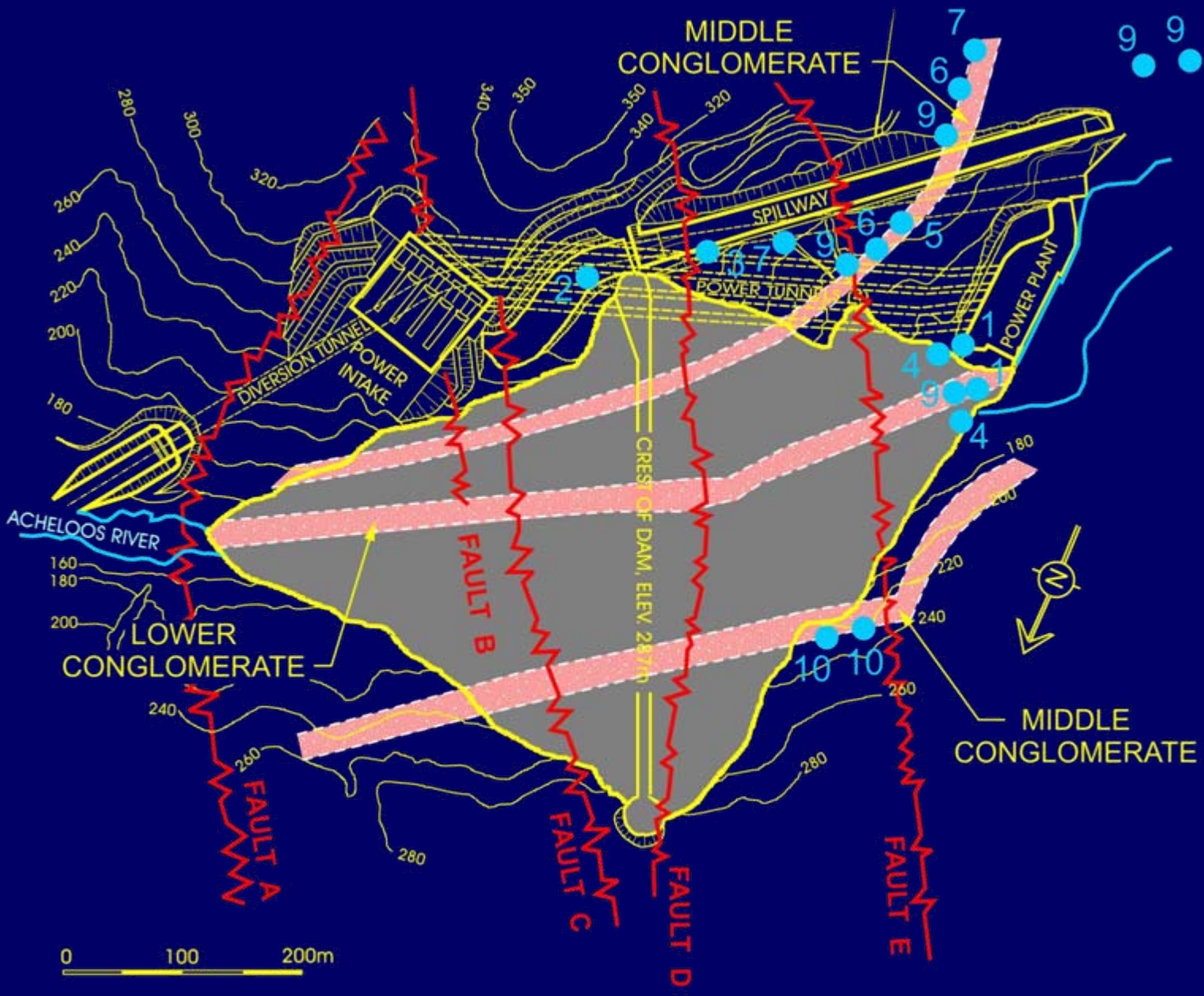

KREMASTA DAM - West Central Greece
Zoned embankment HEP (400 MW) dam, 155m high,
gravel shells, curtain grouting during construction (1963-66),
further extensive grouting (1669-72)


AXIS OF DAM
CREST, ELEV.287.0m
MAX. POWER POOL, ELEV.282.0m
DUMPED ROCKFILL
2.5
1
MIN. POWER POOL, ELEV.227.0m
1
2.5
2
1
1m,ROCKFILL OR
OVERSIZED MATERIAL
4m,TRANSITION ZONE
IMPERVIOUS ROLLED
CENTRAL CORE
COMPACTED ALLUVIAL
SAND AND GRAVEL
COMPACTED ALLUVIAL
SAND AND GRAVEL
ORIGINAL GROUND SURFACE
GROUT CURTAIN

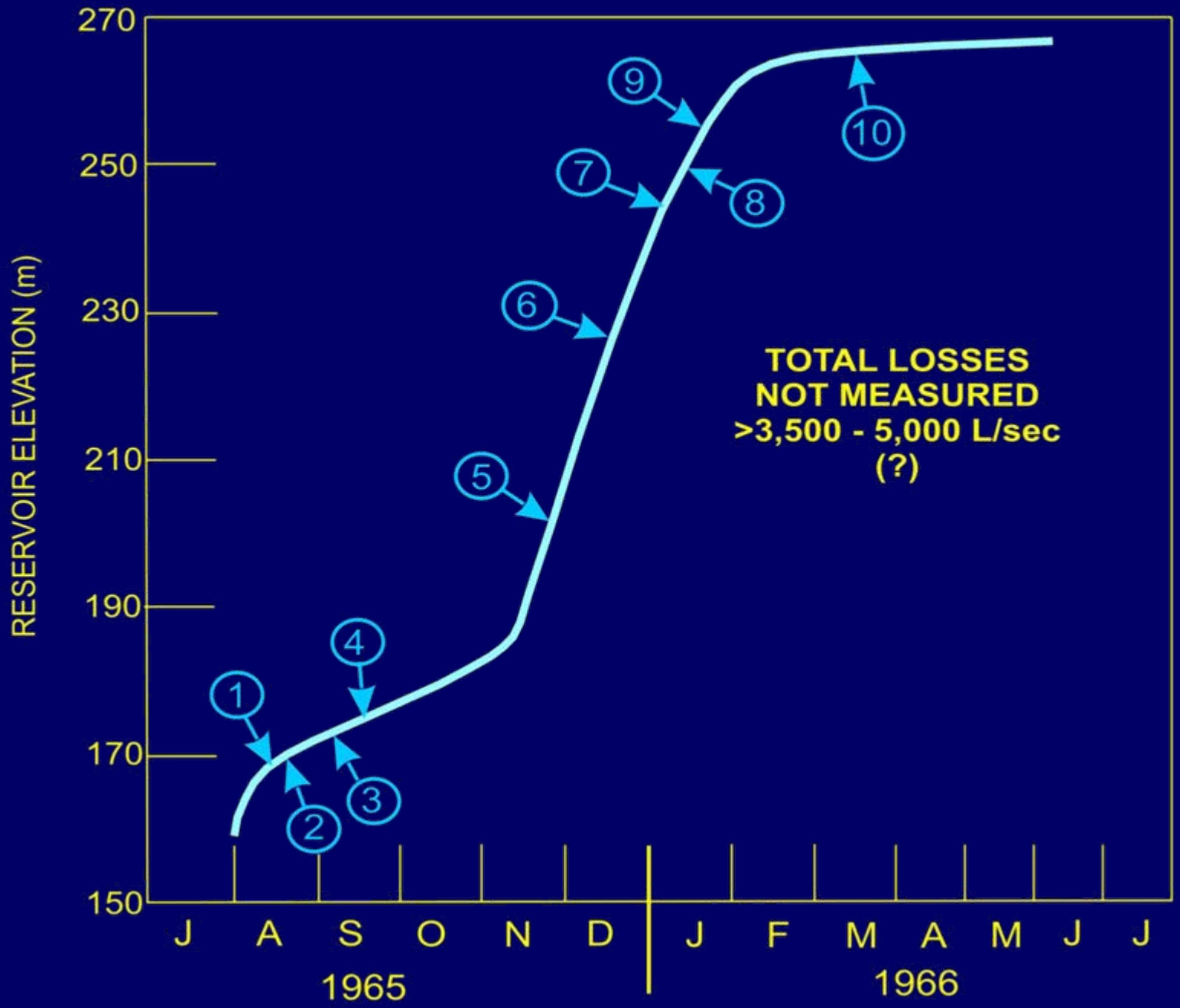

SPILLWAY
CREST OF DAM, 287.0m
UPPER CONGLOMERATE
ORIGINAL GROUND SURFACE
CUT - OFF TRENCH
MIDDLE CONGLOMERATE
CONCRETE
POWER TUNNELS (4)
DIVERSION TUNNEL
GROUTHOLES
APPROXIMATE LIMIT OF UPSTREAM AND DOWNSTREAM GROUTING
APPROXIMATE LIMIT OF CENTRELINE GROUTING
LOWER CONGLOMERATE
ELEVATION, m
300
250
200
150
100
50

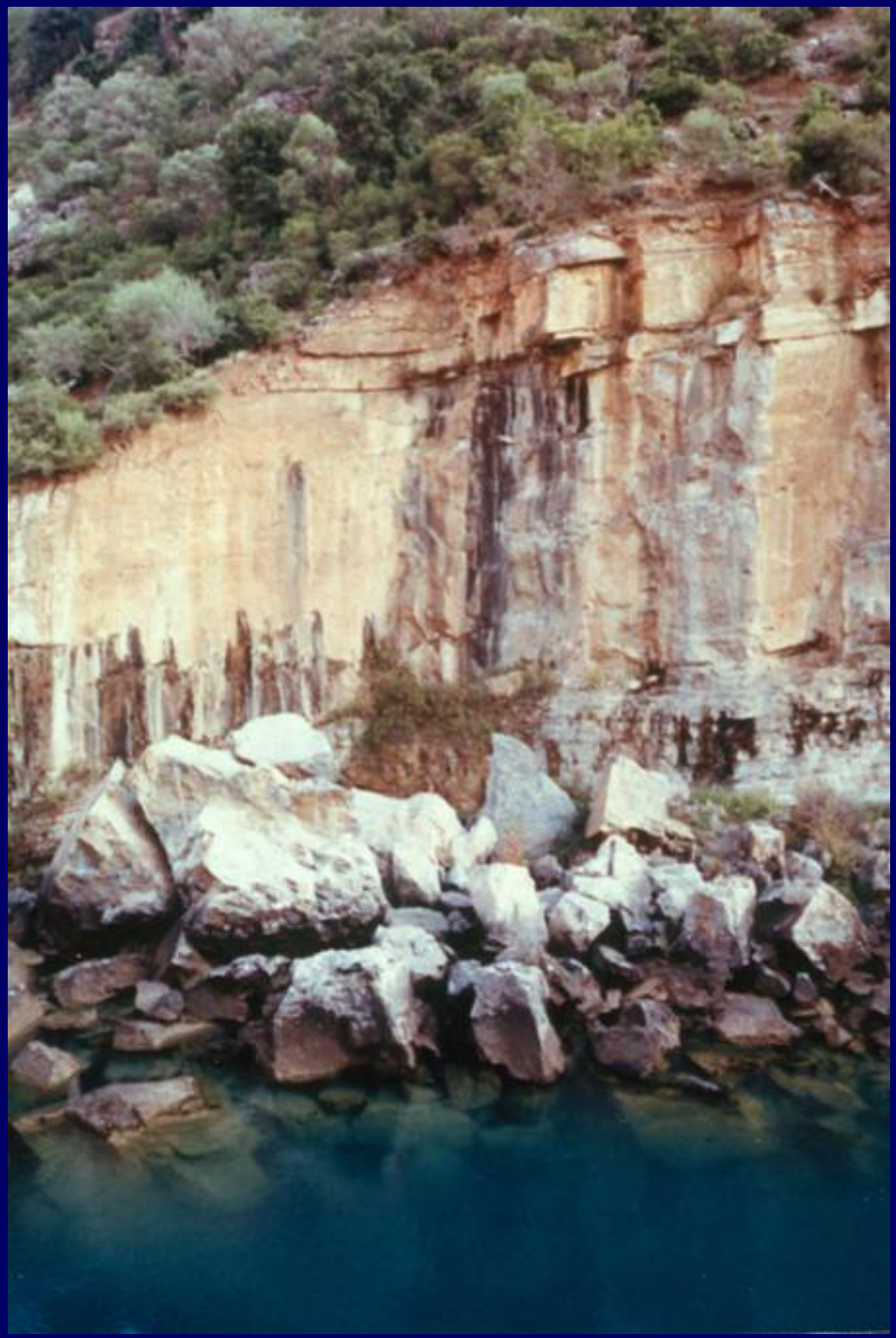

280
300
320
340
350
350
340
320
260
240
220
200
180
SPILLWAY
POWER TUNNELS (4)
POWER PLANT
DIVERSION TUNNEL
POWER INTAKE
CREST OF DAM, ELEV. 287m
ACHELOOS RIVER
160
180
200
240
260
280
180
200
220
240
260
280
N
0
100
200m

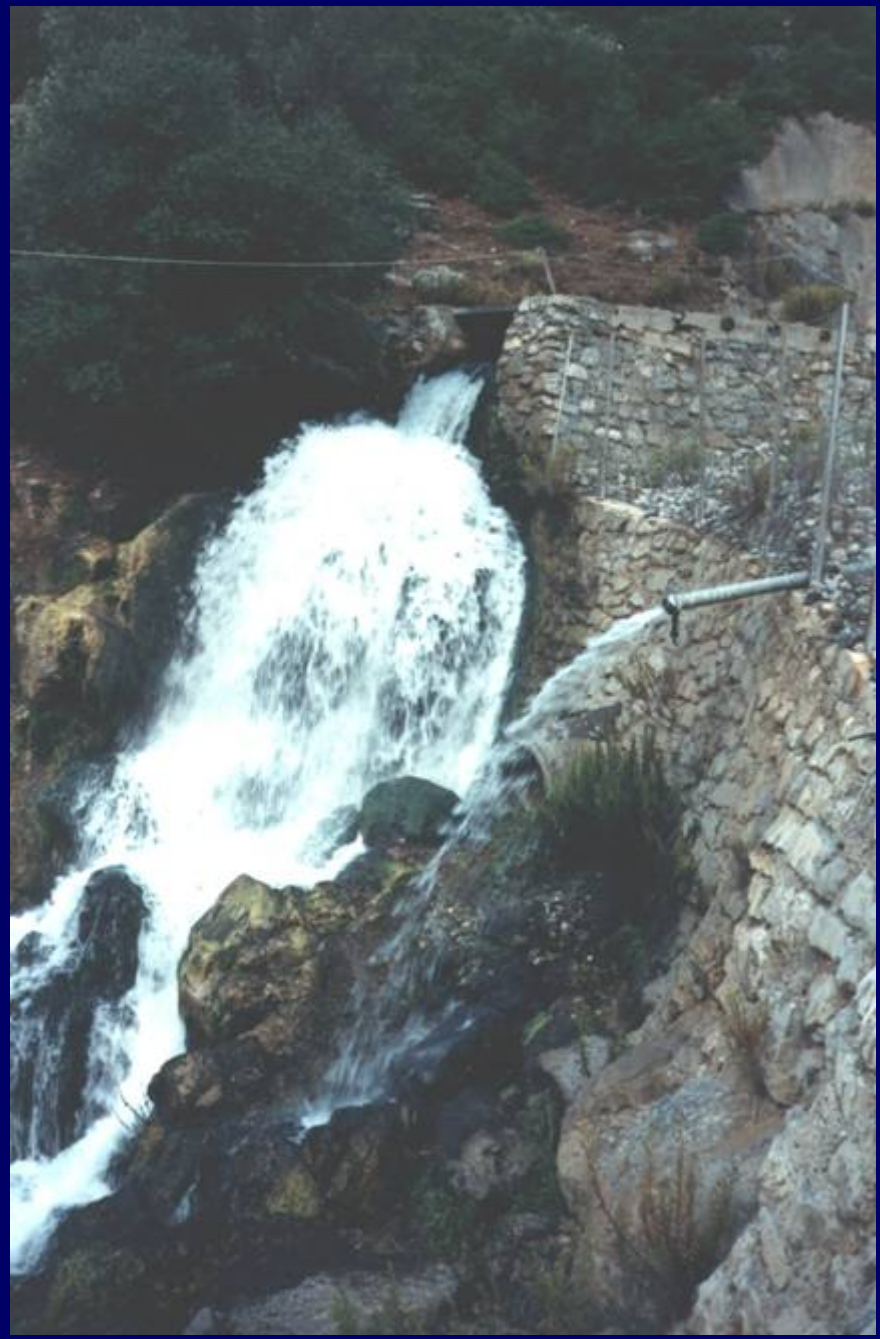

SPILLWAY
POWER TUNNELS
POWER PLANT
DIVERSION TUNNEL
POWER INTAKE
CREST OF DAM, ELEV. 287m
FAULT A
FAULT B
FAULT C
FAULT D
FAULT E
ACHELOOS RIVER
N
0
100
200m

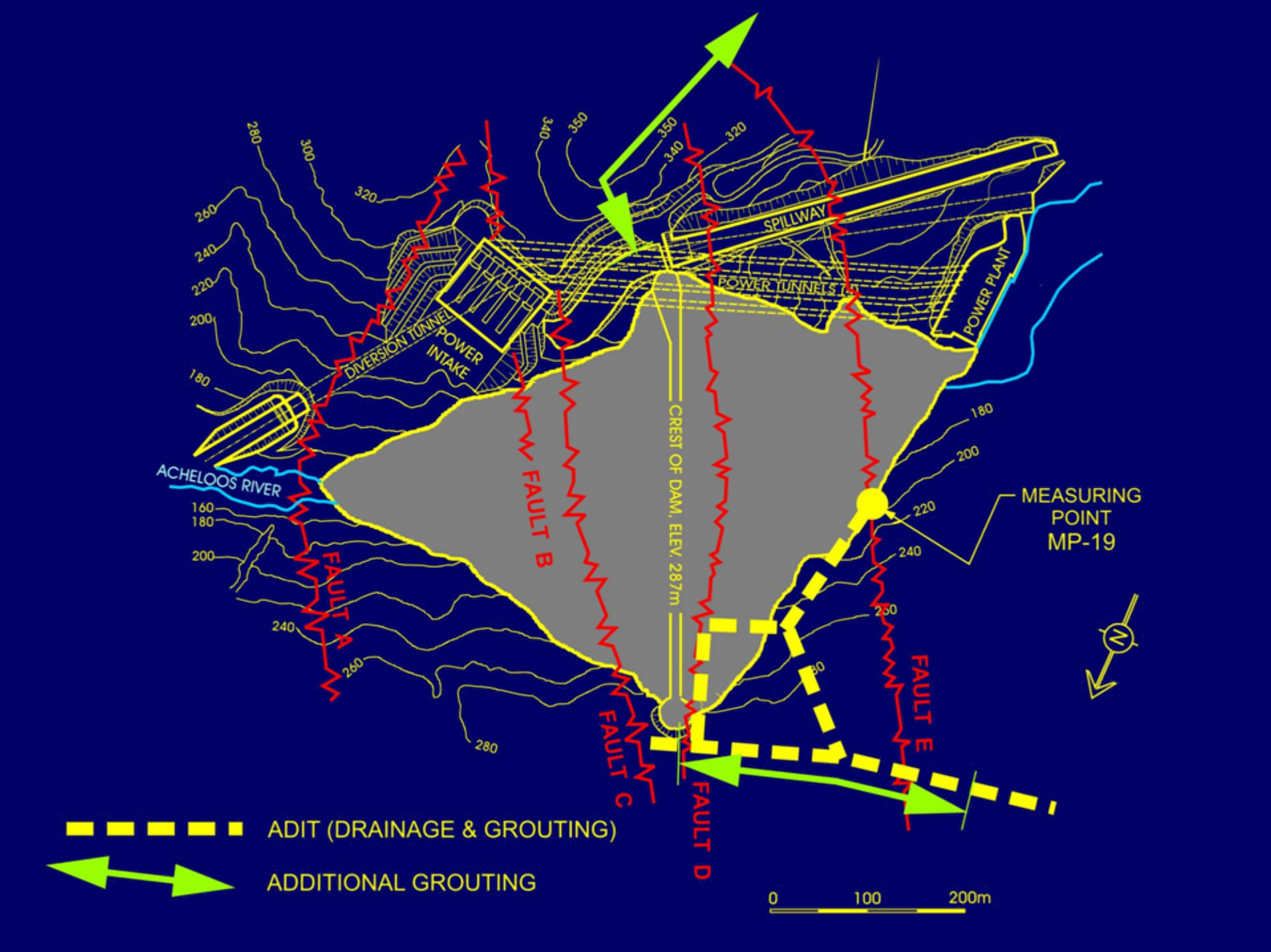


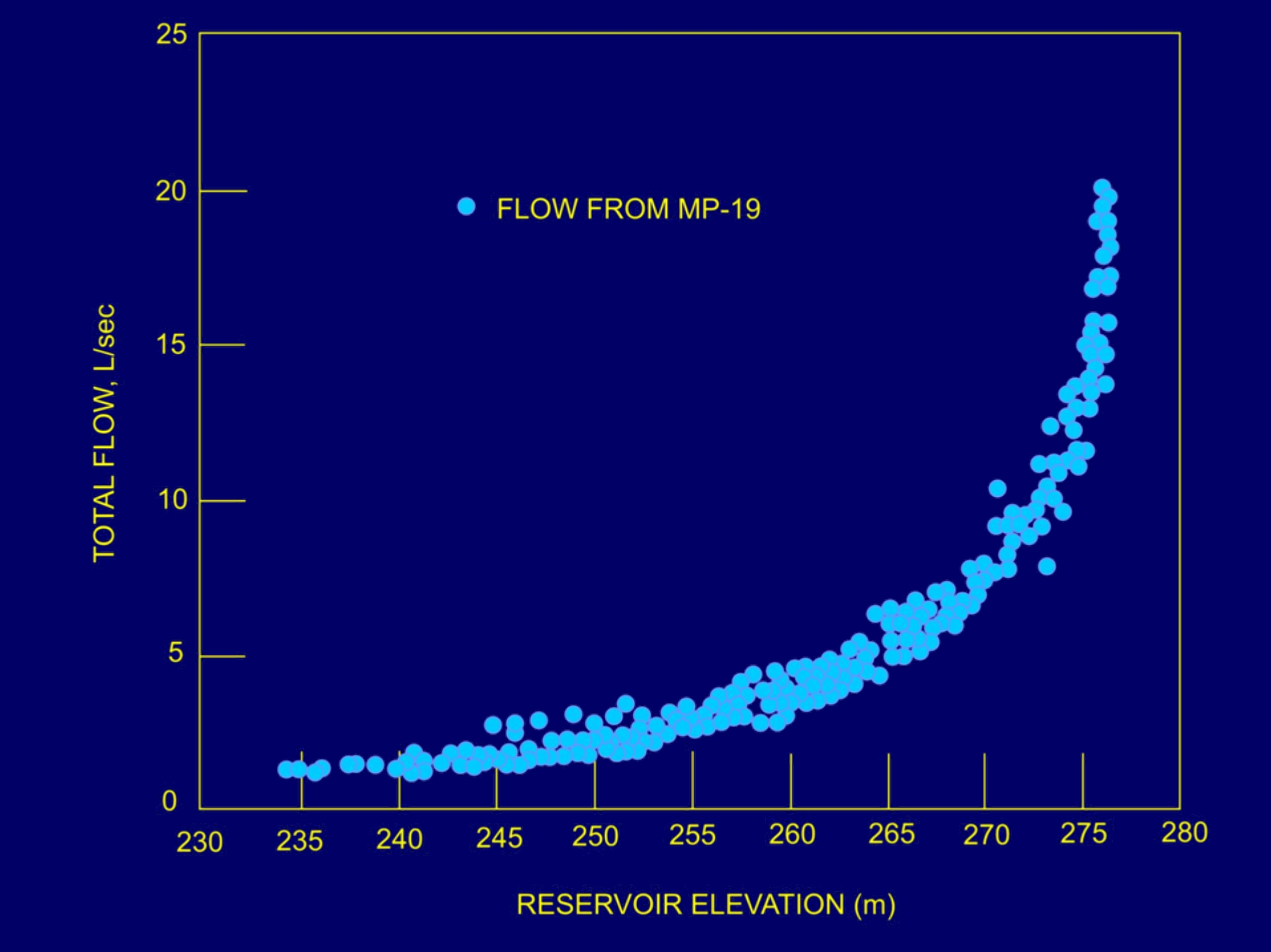
9 DEVELOPMENT OF LEAKAGES ON FIRST FILLING (1965-66)

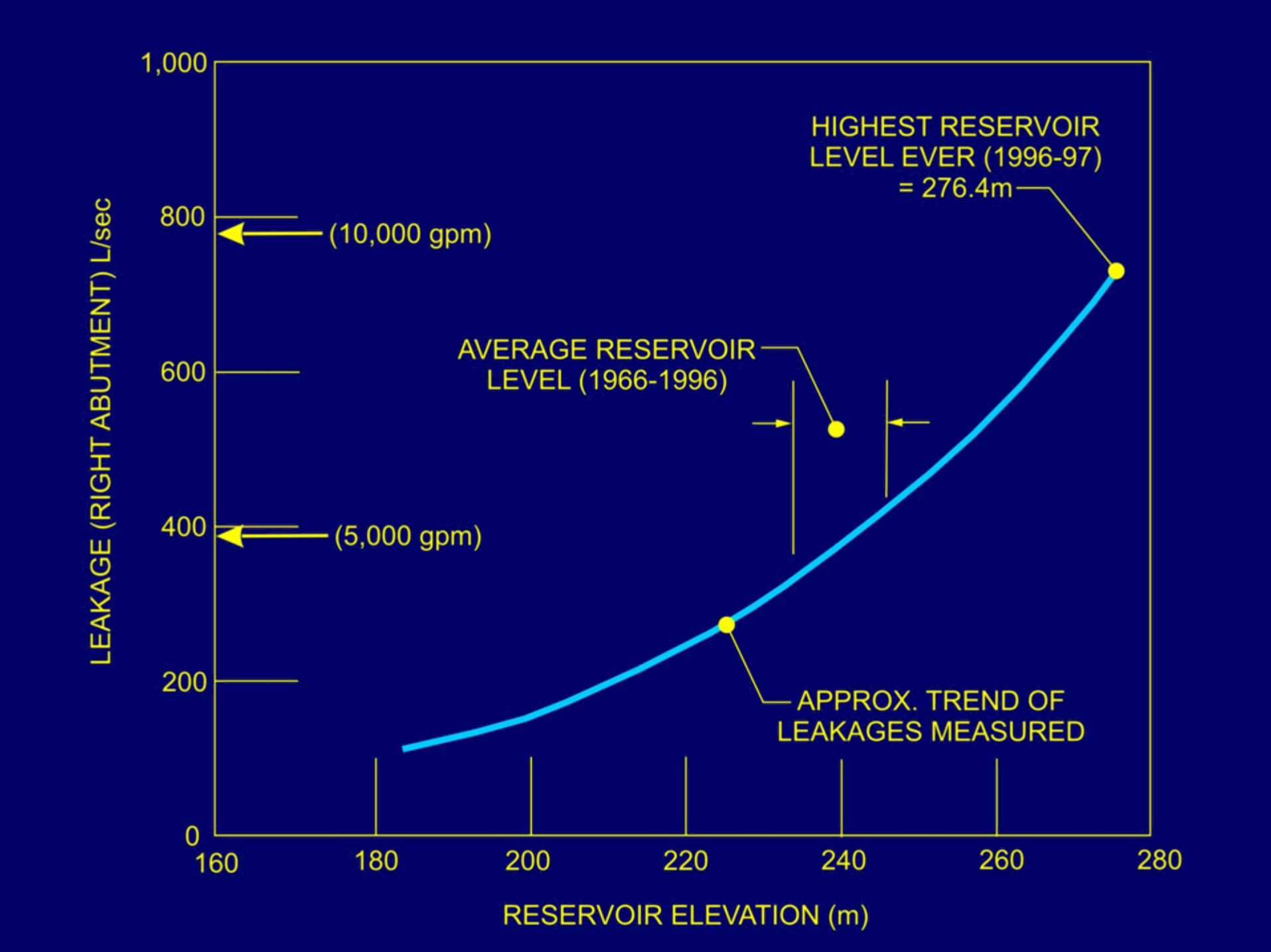

RESERVOIR ELEVATION (m)
270
250
230
210
190
170
150
J
A
S
O
N
D
J
F
M
A
M
J
J
1965
1966
1
2
3
4
5
6
7
8
9
10
TOTAL LOSSES
NOT MEASURED
>3,500 - 5,000 L/sec
(?)






SPILLWAY
POWER TUNNELS
POWER PLANT
DIVERSION TUNNEL
POWER INTAKE
CREST OF DAM, ELEV. 287m
FAULT A
FAULT B
FAULT C
FAULT D
FAULT E
ACHELOOS RIVER
MEASURING POINT MP-19
ADIT (DRAINAGE & GROUTING)
ADDITIONAL GROUTING
0
100
200m


25
20
15
10
5
0
TOTAL FLOW, L/sec
FLOW FROM MP-19
230
235
240
245
250
255
260
265
270
275
280
RESERVOIR ELEVATION (m)

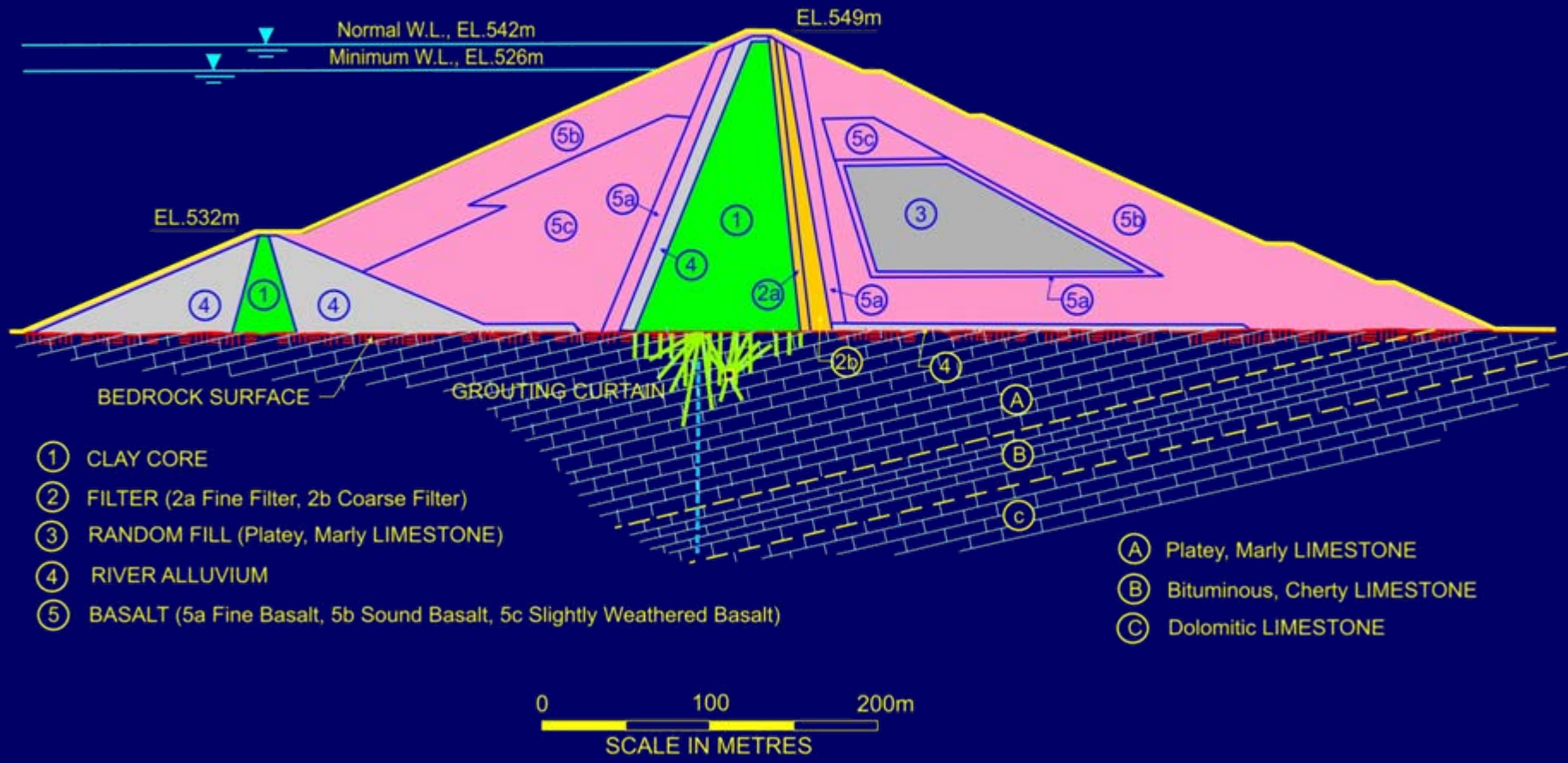

1,000
800
600
400
200
0
LEAKAGE (RIGHT ABUTMENT) L/sec
(10,000 gpm)
(5,000 gpm)
HIGHEST RESERVOIR
LEVEL EVER (1996-97)
= 276.4m
AVERAGE RESERVOIR
LEVEL (1966-1996)
APPROX. TREND OF
LEAKAGES MEASURED
160
180
200
220
240
260
280
RESERVOIR ELEVATION (m)

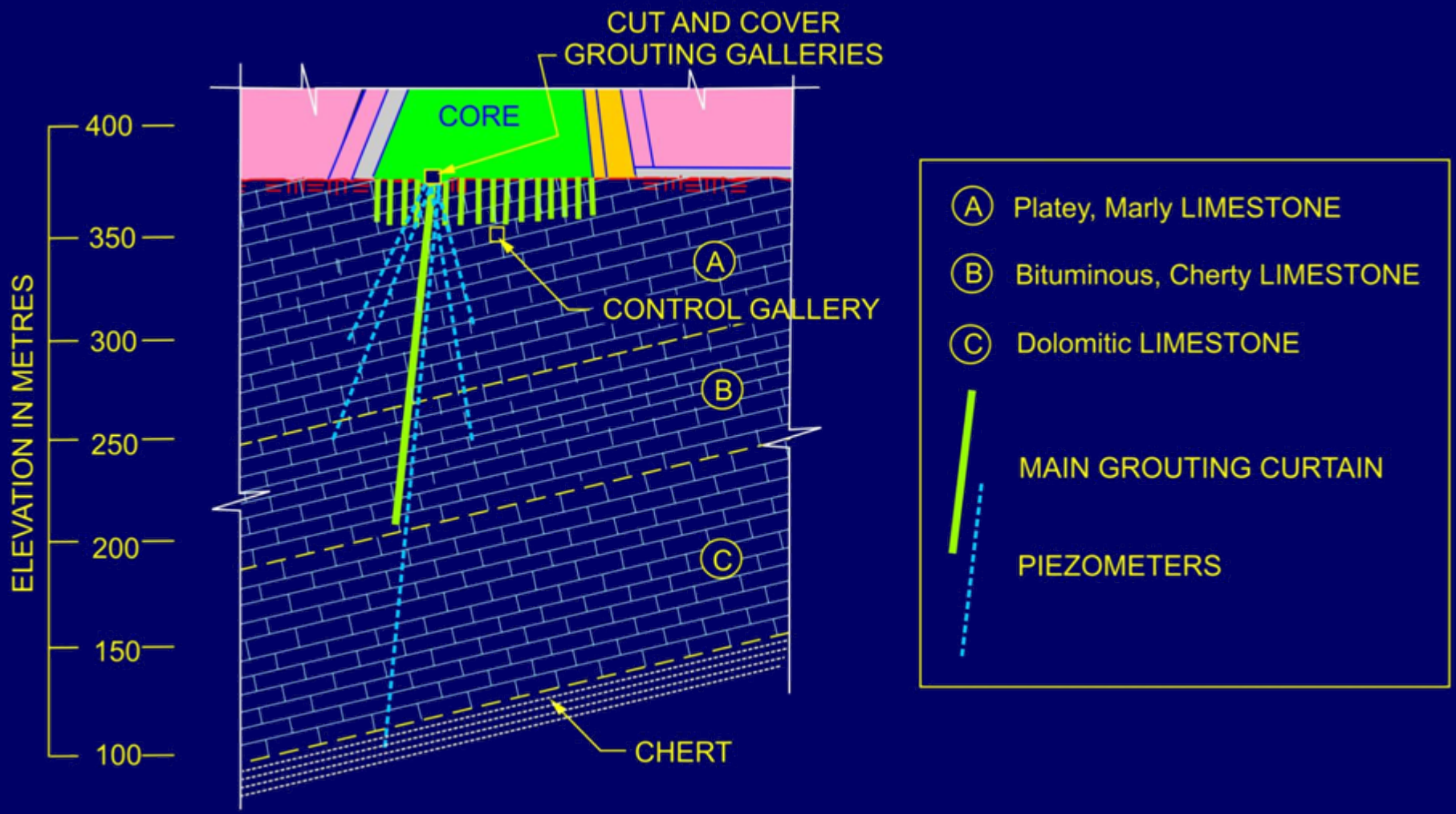

D S İ

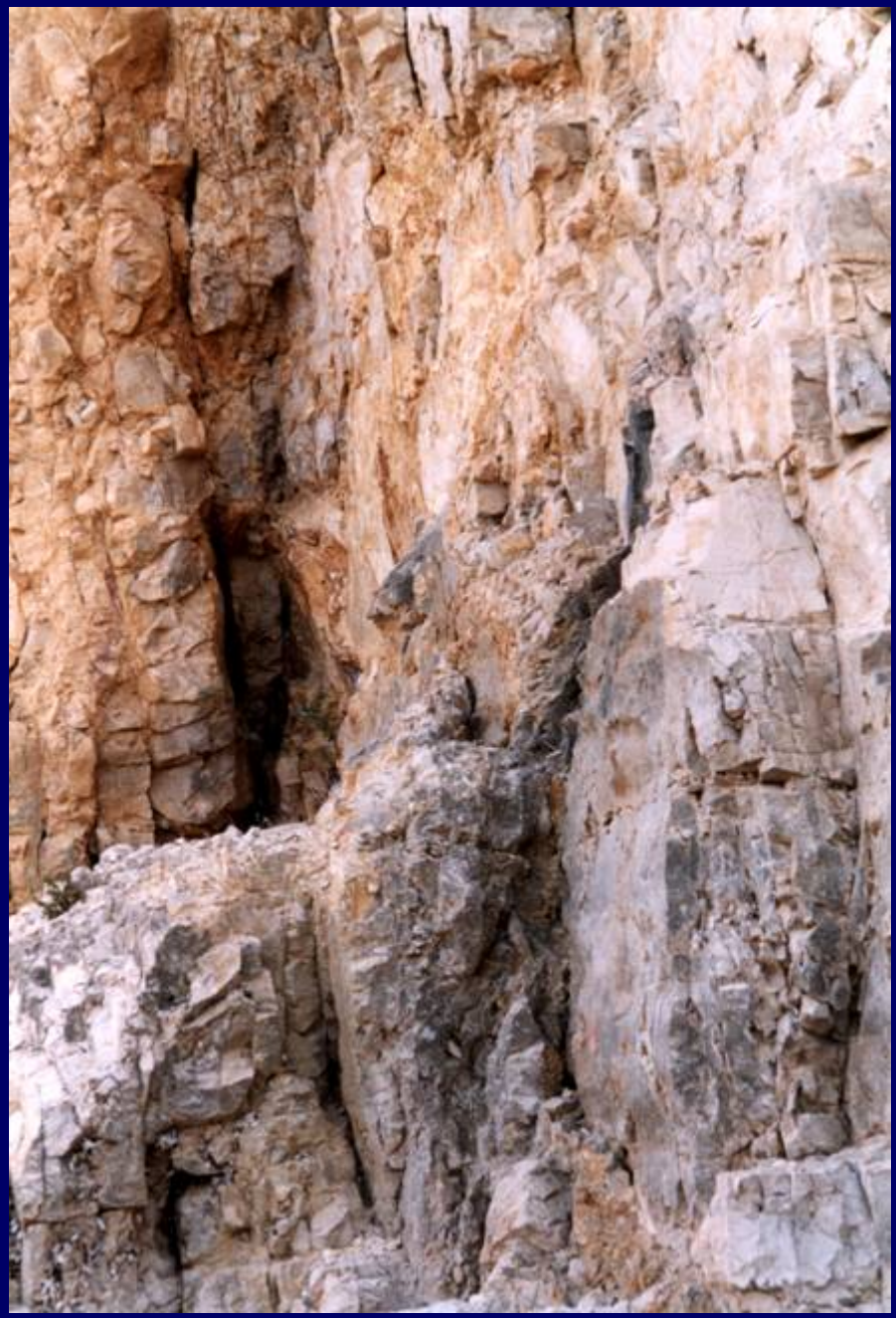
ATATURK DAM - South Eastern Turkey

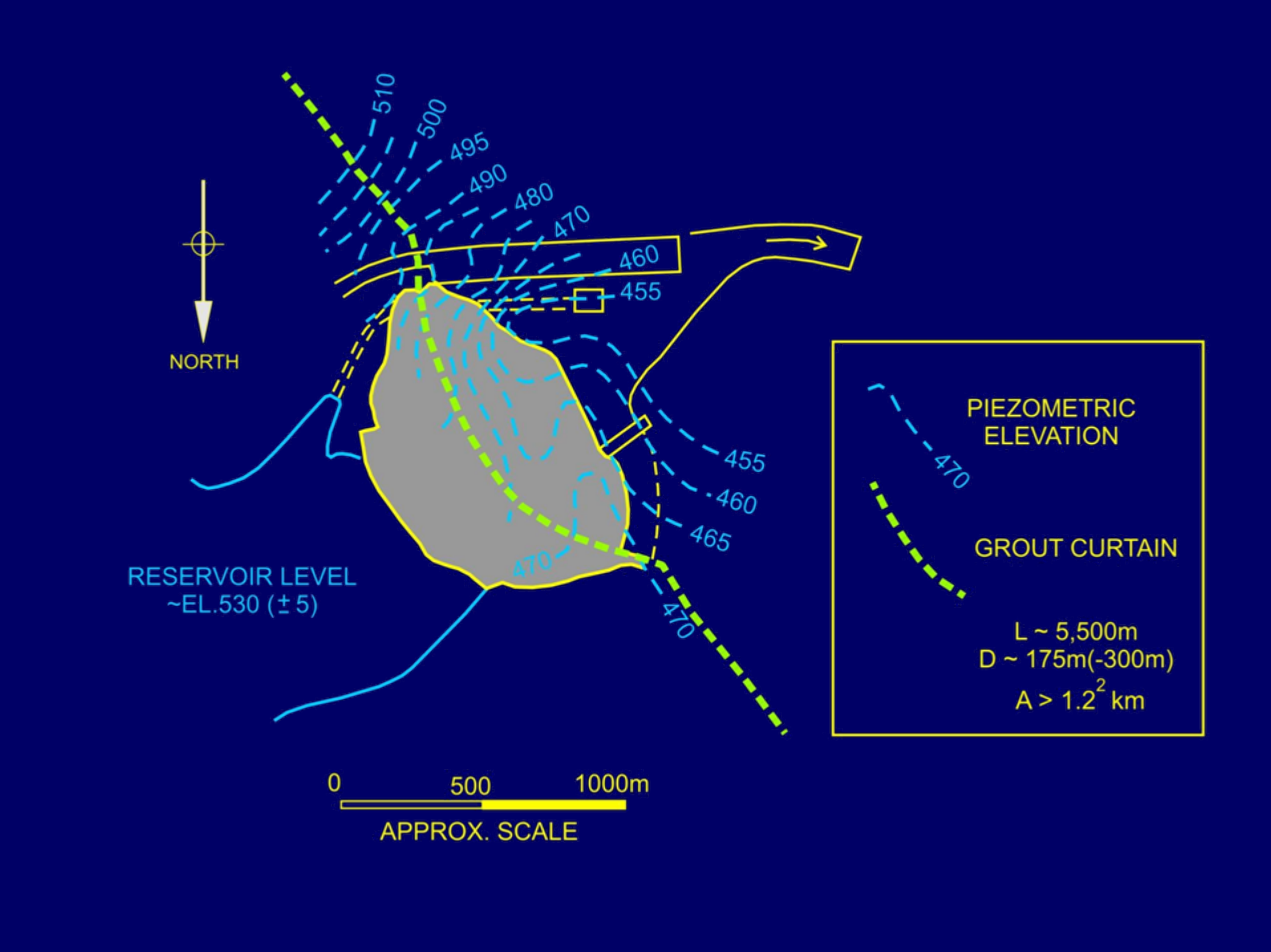
Zoned embankment HEP (2,400 MW) and
irrigation dam, 170m high, rockfill shells, very extensive
grout curtain during construction (1985-91).

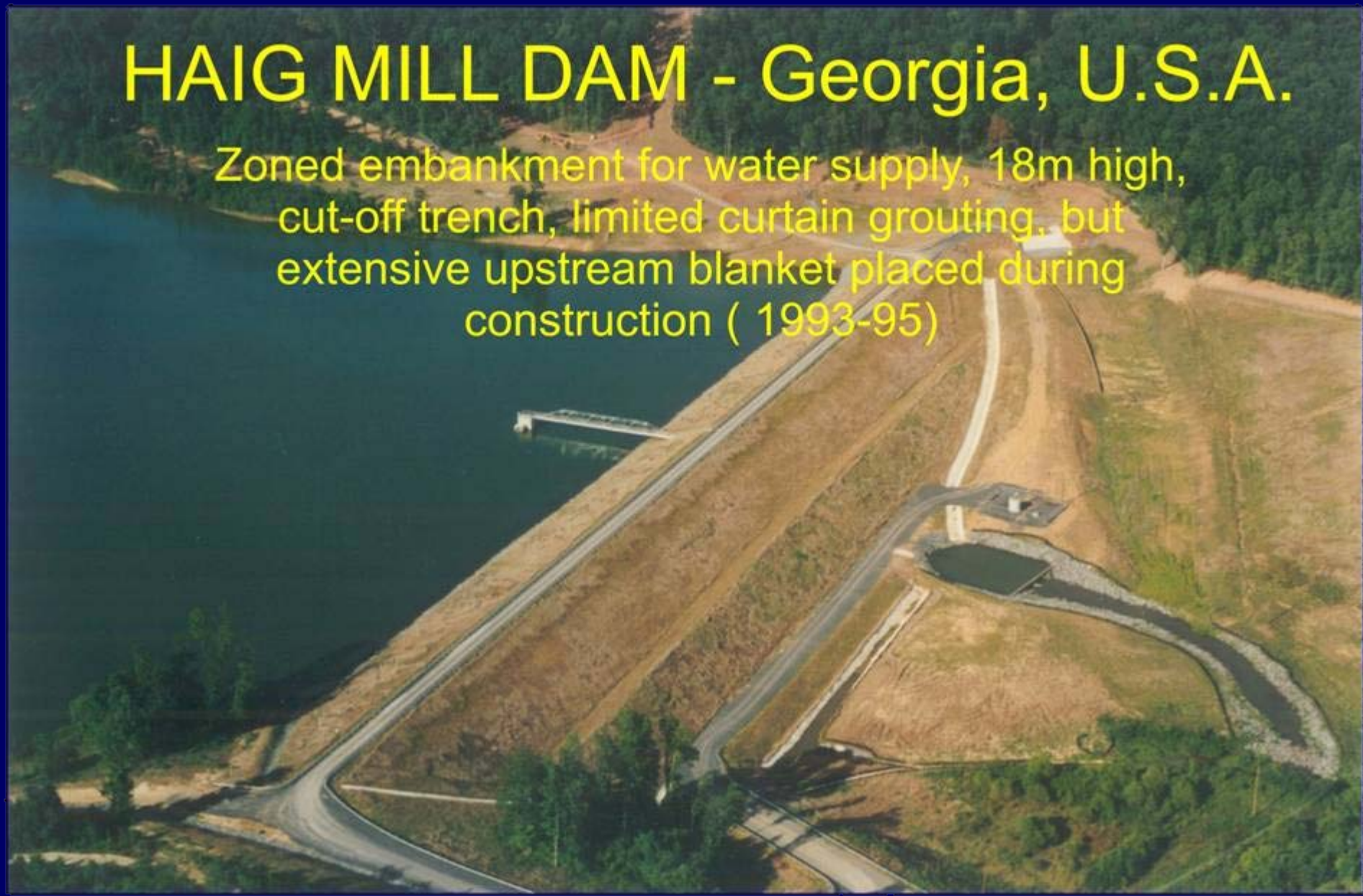
Dam crest 1,700m : Fill volume 85×10^6 cubic metres
(Fourth largest in world ?)

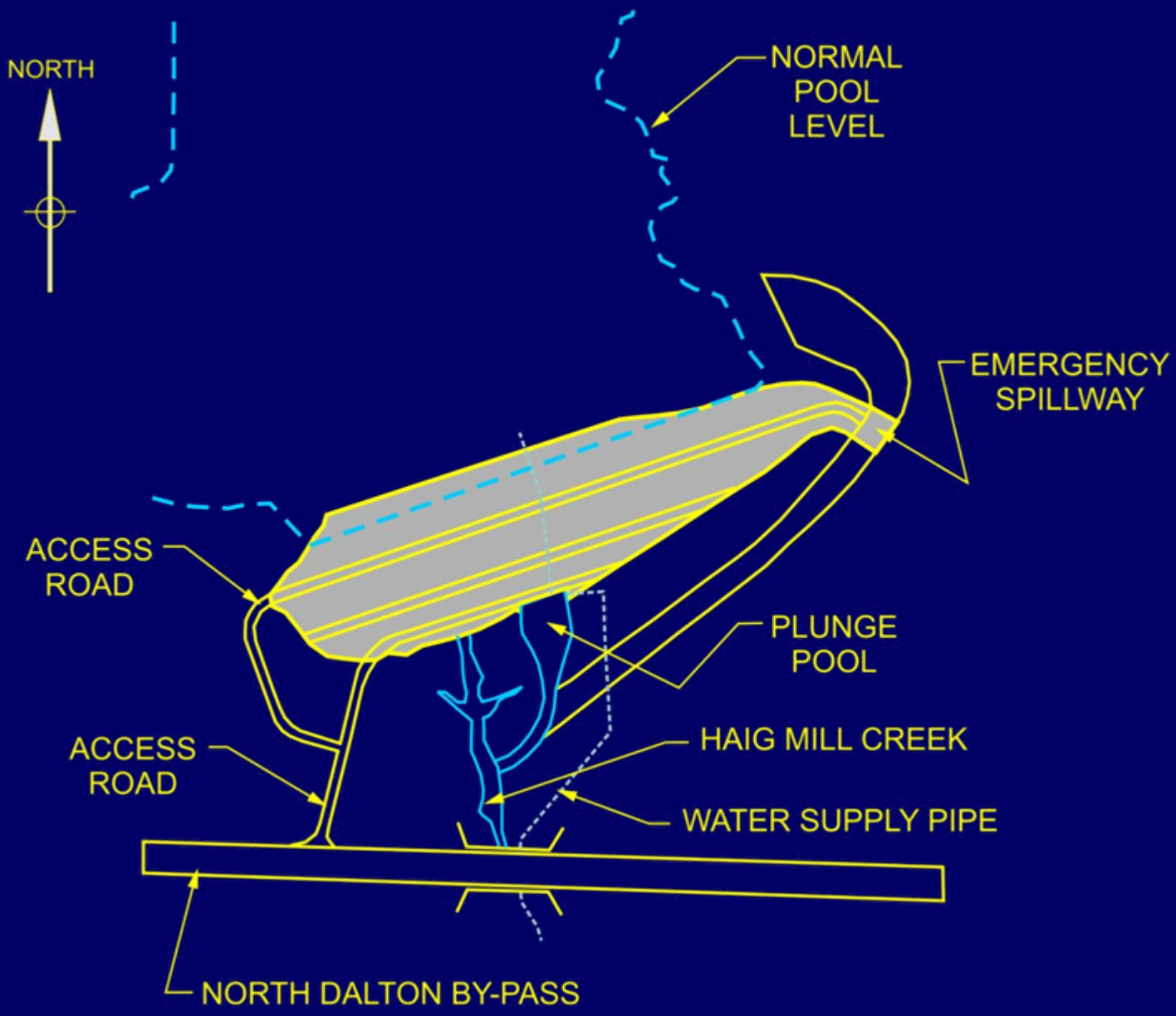

Normal W.L., EL.542m
Minimum W.L., EL.526m
EL.549m
EL.532m
BEDROCK SURFACE
GROUTING CURTAIN
1 CLAY CORE
2 FILTER (2a Fine Filter, 2b Coarse Filter)
3 RANDOM FILL (Platey, Marly LIMESTONE)
4 RIVER ALLUVIUM
5 BASALT (5a Fine Basalt, 5b Sound Basalt, 5c Slightly Weathered Basalt)
A Platey, Marly LIMESTONE
B Bituminous, Cherty LIMESTONE
C Dolomitic LIMESTONE
0
100
200m
SCALE IN METRES

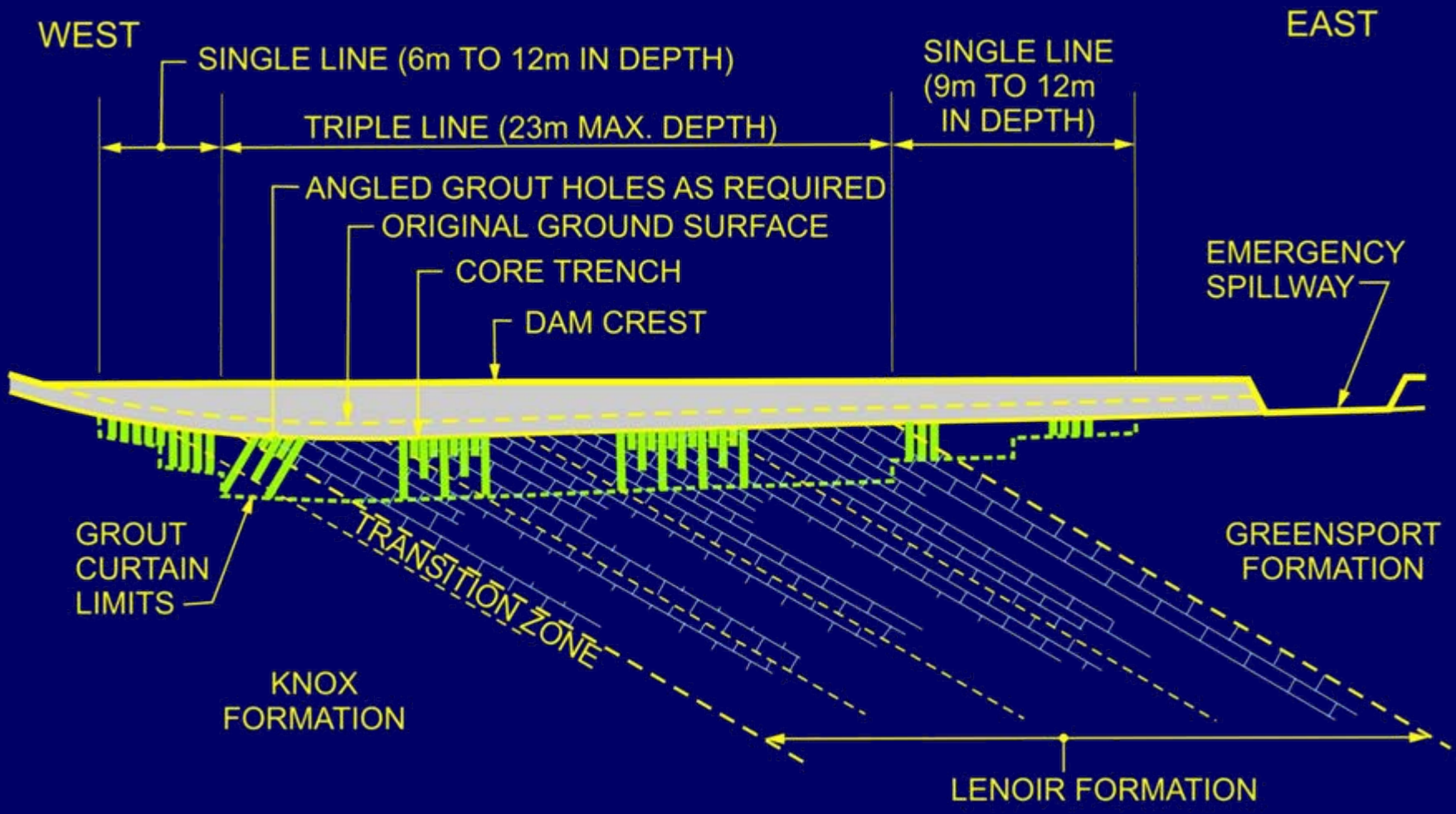

CUT AND COVER
GROUTING GALLERIES
CORE
ELEVATION IN METRES
400
350
300
250
200
150
100
A
B
C
CONTROL GALLERY
CHERT
A Platey, Marly LIMESTONE
B Bituminous, Cherty LIMESTONE
C Dolomitic LIMESTONE
MAIN GROUTING CURTAIN
PIEZOMETERS



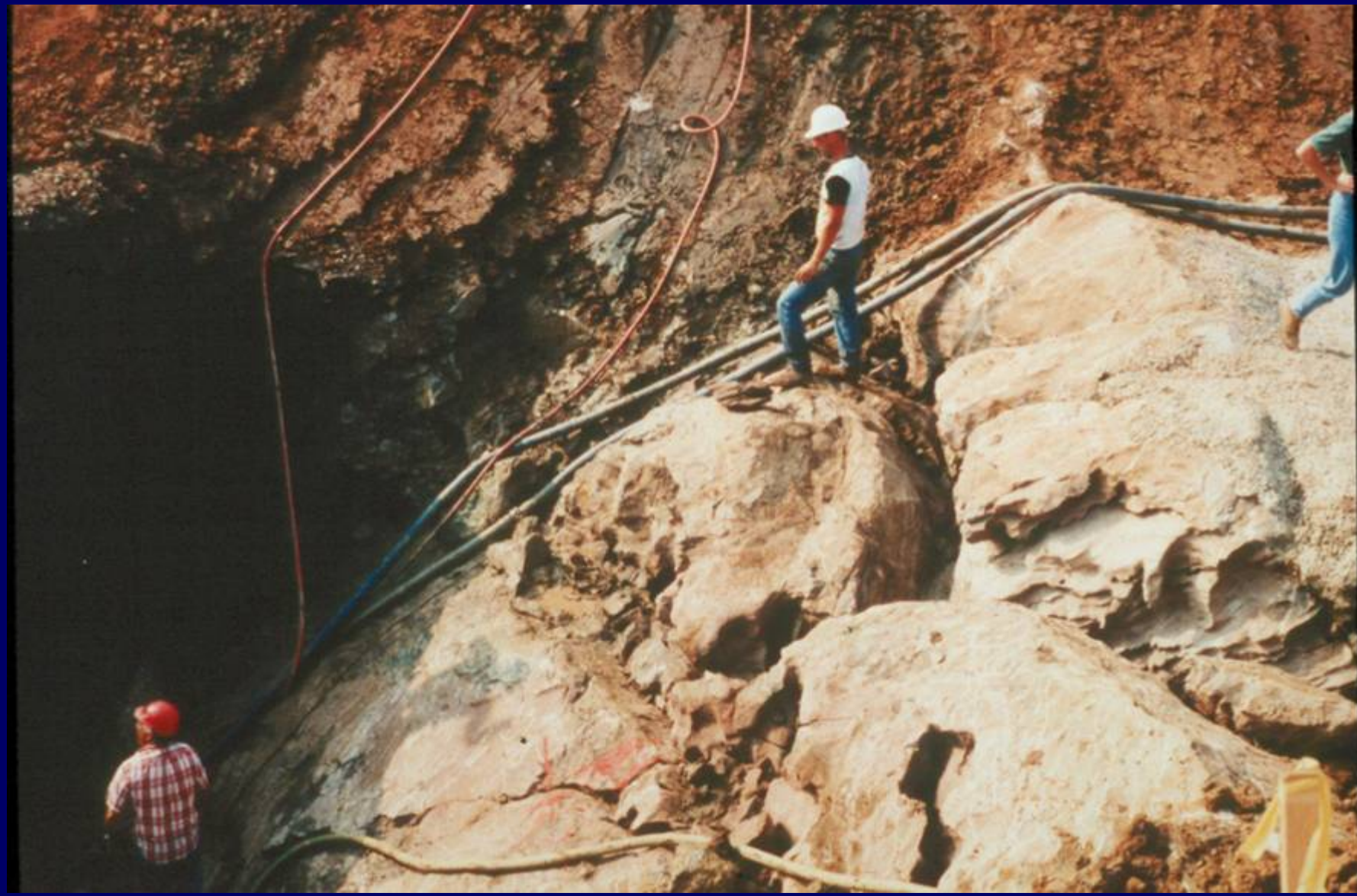

510
500
495
490
480
470
460
455
NORTH
455
460
465
470
470
RESERVOIR LEVEL
~EL.530 (± 5)
PIEZOMETRIC
ELEVATION
470
GROUT CURTAIN
L ~ 5,500m
D ~ 175m(-300m)
A > 1.2 km²
0
500
1000m
APPROX. SCALE

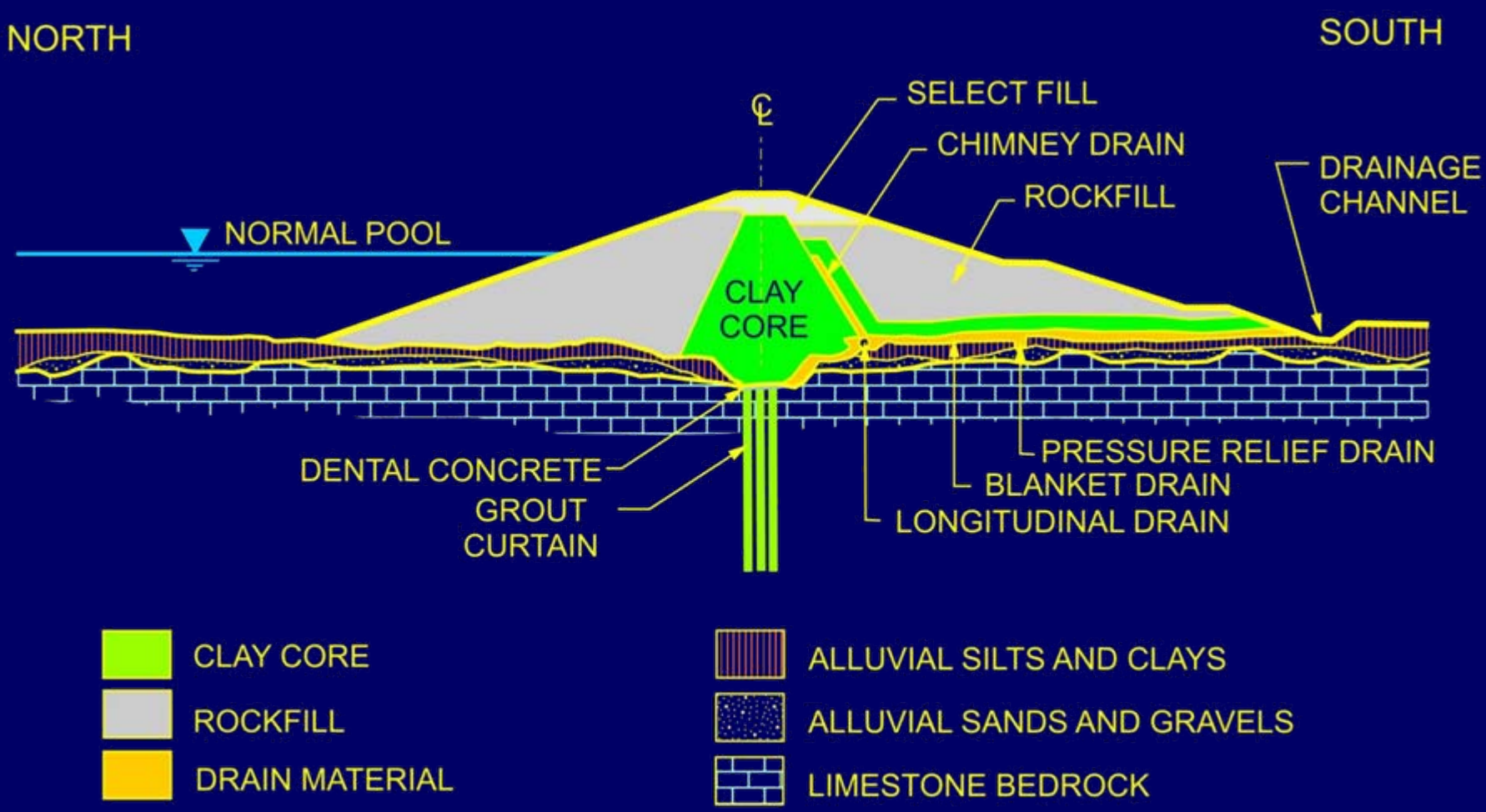

HAIG MILL DAM - Georgia, U.S.A.
Zoned embankment for water supply, 18m high,
cut-off trench, limited curtain grouting, but
extensive upstream blanket placed during
construction (1993-95)

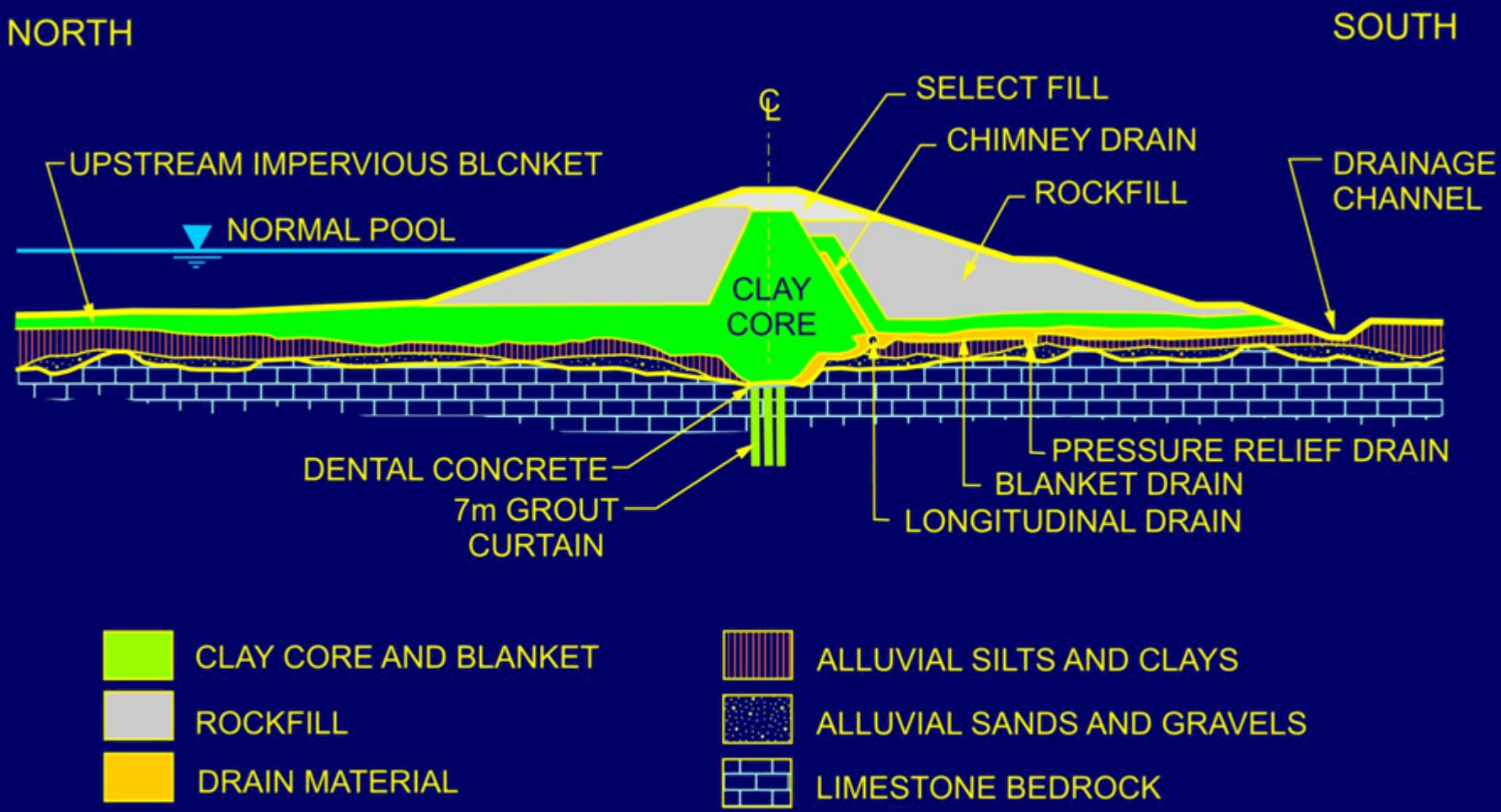

NORTH
NORMAL POOL LEVEL
EMERGENCY SPILLWAY
ACCESS ROAD
PLUNGE POOL
ACCESS ROAD
HAIG MILL CREEK
WATER SUPPLY PIPE
NORTH DALTON BY-PASS

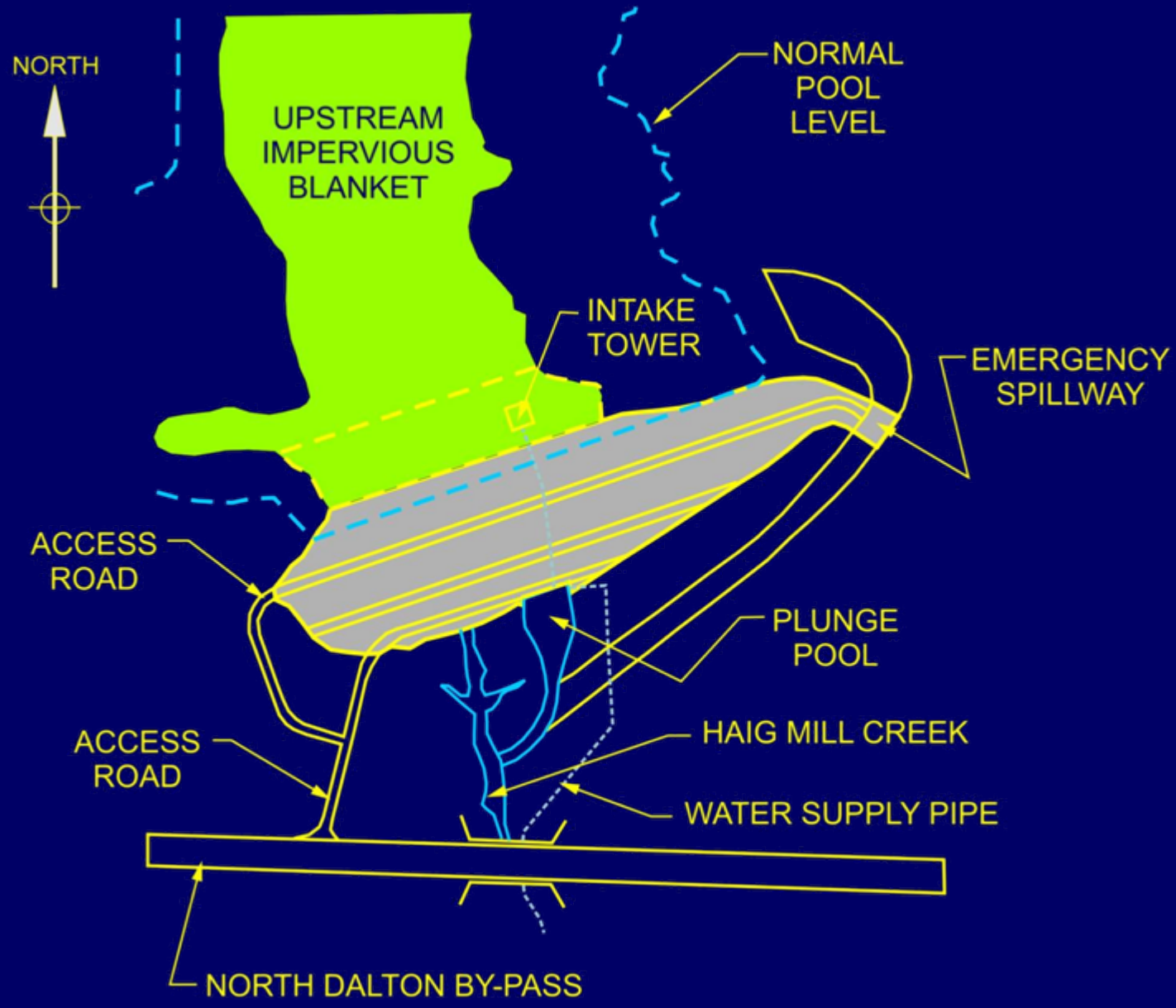

WEST
EAST
SINGLE LINE (6m TO 12m IN DEPTH)
TRIPLE LINE (23m MAX. DEPTH)
SINGLE LINE (9m TO 12m IN DEPTH)
ANGLED GROUT HOLES AS REQUIRED
ORIGINAL GROUND SURFACE
CORE TRENCH
DAM CREST
EMERGENCY SPILLWAY
GROUT CURTAIN LIMITS
TRANSITION ZONE
GREENSPORT FORMATION
KNOX FORMATION
LENOIR FORMATION


CAT




NORTH
SOUTH
℄
SELECT FILL
CHIMNEY DRAIN
ROCKFILL
DRAINAGE CHANNEL
NORMAL POOL
CLAY CORE
DENTAL CONCRETE
GROUT CURTAIN
PRESSURE RELIEF DRAIN
BLANKET DRAIN
LONGITUDINAL DRAIN
CLAY CORE
ROCKFILL
DRAIN MATERIAL
ALLUVIAL SILTS AND CLAYS
ALLUVIAL SANDS AND GRAVELS
LIMESTONE BEDROCK


NORTH
SOUTH
℄
SELECT FILL
CHIMNEY DRAIN
ROCKFILL
DRAINAGE CHANNEL
UPSTREAM IMPERVIOUS BLCNKET
NORMAL POOL
CLAY CORE
DENTAL CONCRETE
7m GROUT CURTAIN
PRESSURE RELIEF DRAIN
BLANKET DRAIN
LONGITUDINAL DRAIN
CLAY CORE AND BLANKET
ROCKFILL
DRAIN MATERIAL
ALLUVIAL SILTS AND CLAYS
ALLUVIAL SANDS AND GRAVELS
LIMESTONE BEDROCK


NORTH
UPSTREAM IMPERVIOUS BLANKET
NORMAL POOL LEVEL
INTAKE TOWER
EMERGENCY SPILLWAY
ACCESS ROAD
PLUNGE POOL
ACCESS ROAD
HAIG MILL CREEK
WATER SUPPLY PIPE
NORTH DALTON BY-PASS

Closing Remarks

- On karstic foundations, even after extensive site investigations it is generally extremely difficult, if not impossible, to make reasonably exact estimates of the extent and quantity of seepage to be expected.
- Curtain grouting below the embankment is invariably carried out, but even if extensive, usually only moderates rather than prevents seepage losses.
- The permissible amount of seepage losses is specific to each site and is related to inflows, the reservoir volume and required downstream river flows.
- First impoundment of the reservoir is the decisive test and the only indicator of what remedial measures, if any, should be implemented.
- In all cases, because of the likelihood of further solution and erosion of karst features in the foundation, or the possibility of clogging of drains or the like within abutments, or the embankment, it is essential that continuous monitoring and supervision be carried out throughout the life of the dam.