

Concrete Face Rockfill Dams

Andrea Abati, Anton Tzenkov

Gruner

- **Main Design Features**
 - Zoning
 - Slab
 - Plinth
- **Design Check by Numerical Analysis**
- **Monitoring Concept**

- **Zoning : nomenclature following Cruz et al. (2009)**

- **Zone 1 Impervious** (perimetral joint protection)

- 1A self-healing silt (preferably) or fine-sand
- 1B support (random) fill

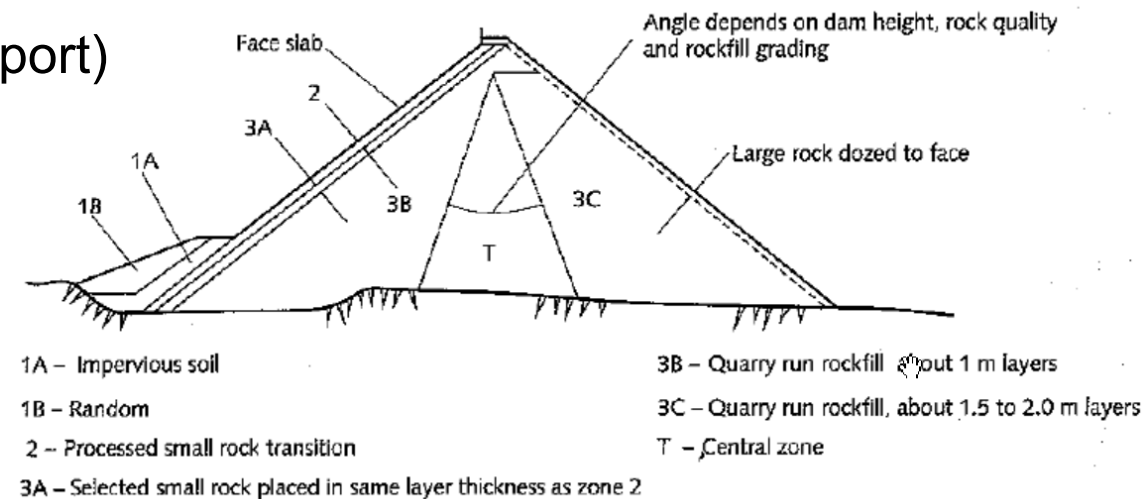
- **Zone 2 Filter / Transition** (under the slab / curb)

- 2A processed fine filter (perimetral joint)
- 2B crushed rock transition (slab / curb support)

- **Zone 3 Rockfill**

- 3A transition between 2B and 3B
- 3B main upstream rockfill downstream
- T central rockfill between 3B and 3C
- 3C downstream rockfill
- 3D material close to the DS slope

- **Zone 4 Protection of DS Slope**

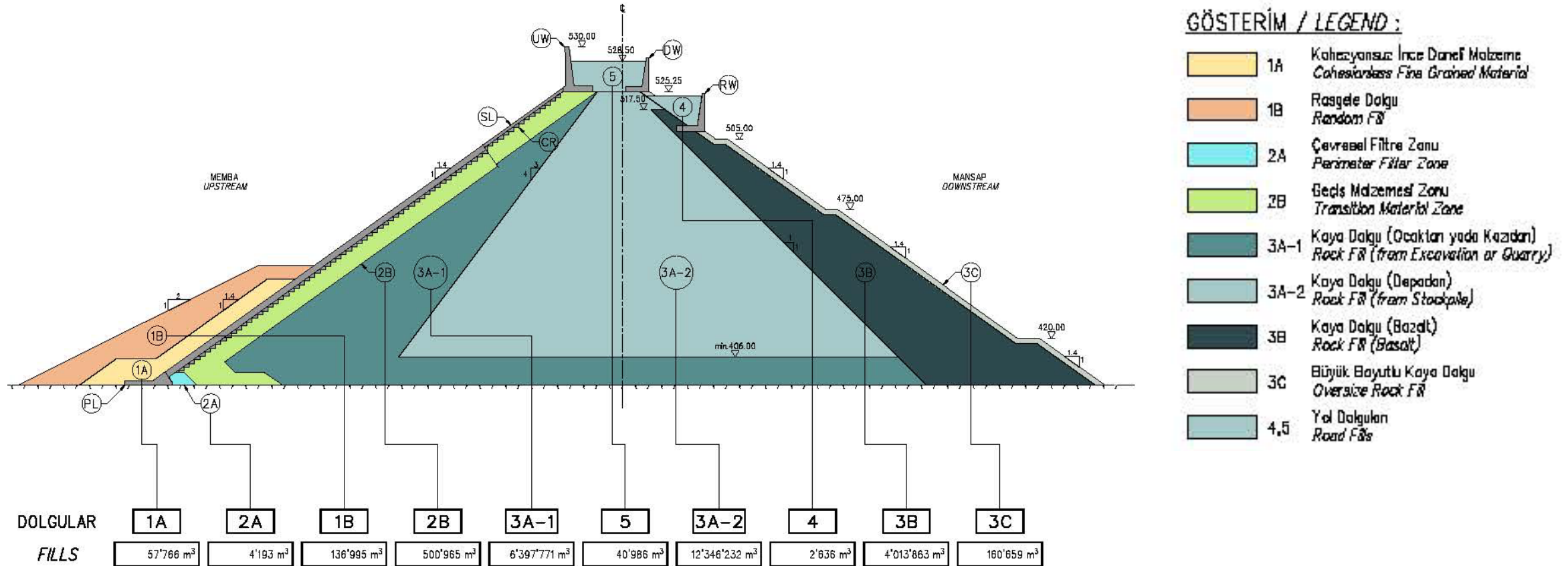


*Typical Zones in CFRD
Cooke and Sherard (1987)*

CFRD – Design Principles



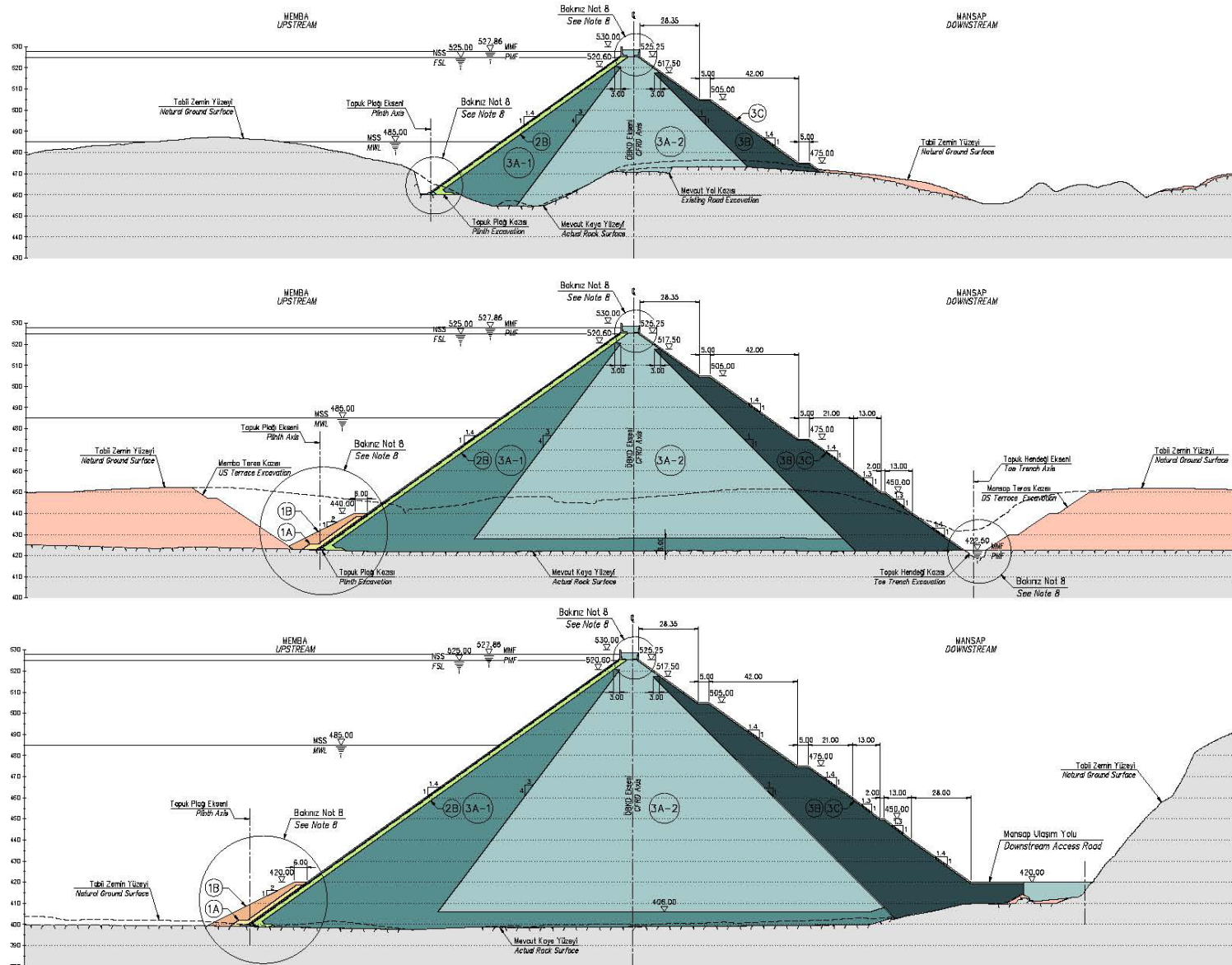
CFRD – Design Principles



1A cohesionless fine-grained material
 1B random fill
 2A Sand
 2B Crushed sand-gravel mixture

3A-1 Marly Limestone (excavation or quarry)
 3A-2 Marly Limestone (stockpiles)
 3B Basalt
 3C Basalt (Oversize)

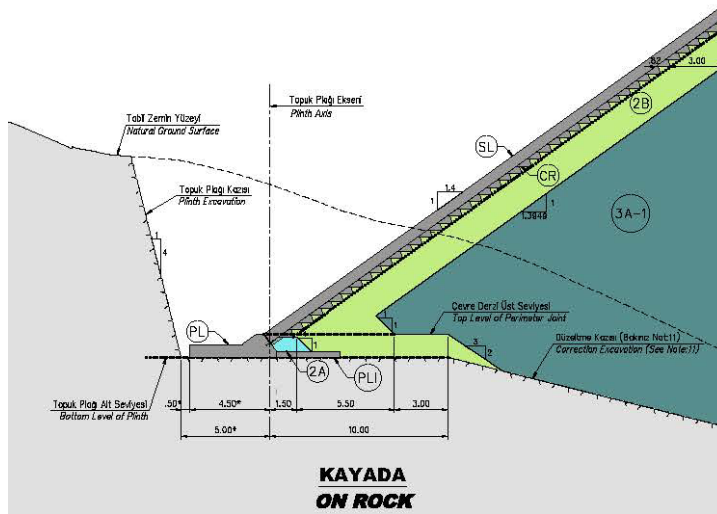
CFRD – Design Principles



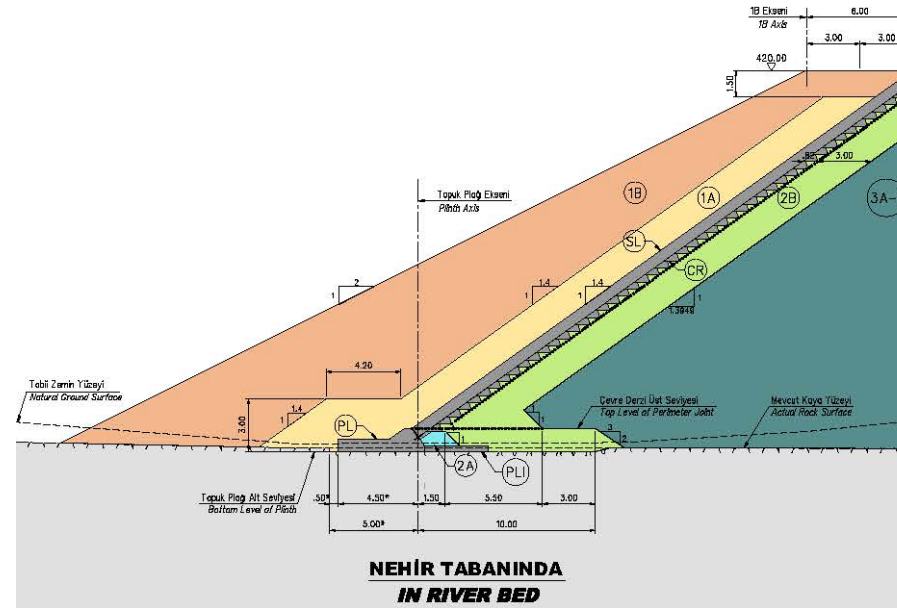
GÖSTERİM / LEGEND :

- 1A Kahçıyansız İnce Daneli Malzeme
Cohesionless Fine Grained Material
- 1B Rasgele Dolgu
Random Fll
- 2A Çevresel Filtre Zonu
Perimeter Filter Zone
- 2B Geçiş Malzemesi Zonu
Transition Material Zone
- 3A-1 Kaya Dolgu (Ocakları yada Kazıları)
Rock Fll (from Excavation or Quarry)
- 3A-2 Kaya Dolgu (Depodan)
Rock Fll (from Stockpile)
- 3B Kaya Dolgu (Bazalt)
Rock Fll (Basalt)
- 3C Büyük Boyutlu Kaya Dolgu
Oversize Rock Fll
- 4.5 Yol Dolguları
Road Flls

CFRD – Design Principles



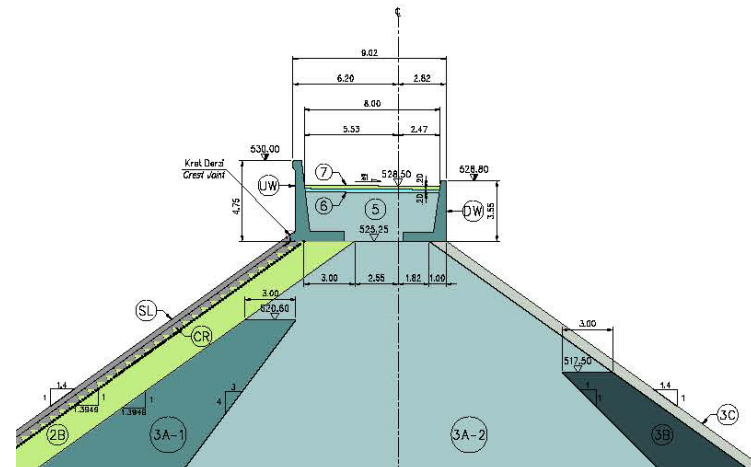
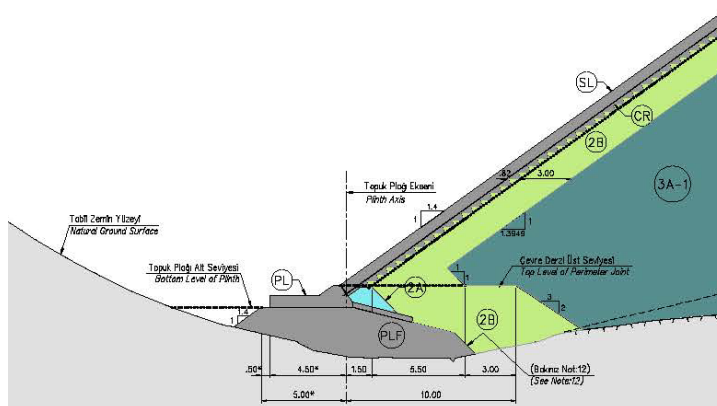
TOPUK PLAĞI ALTI BETON DOLGUSU
CONCRETE FILL UNDER PLINTH 1 / 150



TİP KRET DETAYI
TYPICAL CREST DETAIL 1 / 150

GÖSTERİM / LEGEND :

- 1A Kahçıyansız İnce Daneli Malzeme
Cohesionless Fine Grained Material
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Rock Fill (from Stockpile)
- 3B Kaya Dolgu (Bazalt)
Rock Fill (Basalt)
- 3C Büyük Boyutlu Kaya Dolgu
Oversize Rock Fill
- 4.5 Yol Dalgulan
Road Fills



- **Slab**

- **Thickness** for high dams

- Cooke and Sherard (1987) $0.3 \text{ m} + 0.002H$
 - ICOLD Bulletin 141 $0.3 \text{ m} + 0.0025H$
 - Chinese projects $0.3 \text{ m} + (0.002 \div 0.004)H$

- **Slab Width** between 12 m and 18 m

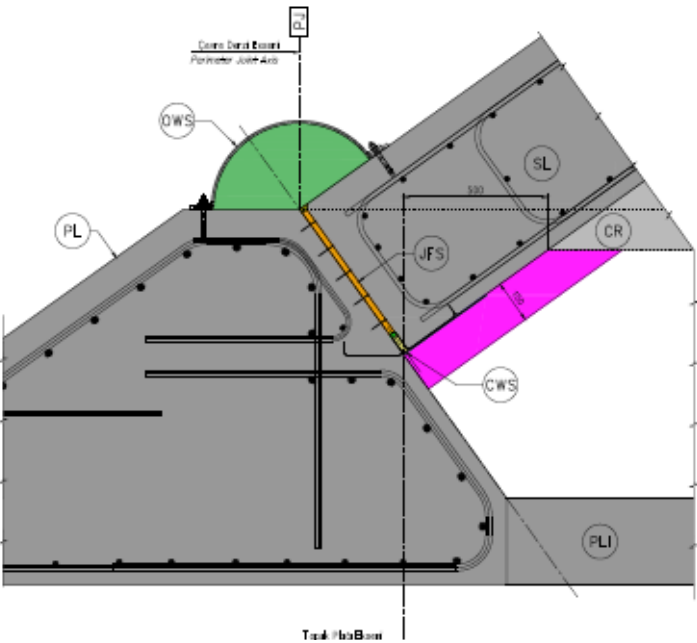
- Reinforcement 0.4% up to 0.5%
 - Special provisions for seismic loading

- **Joints**

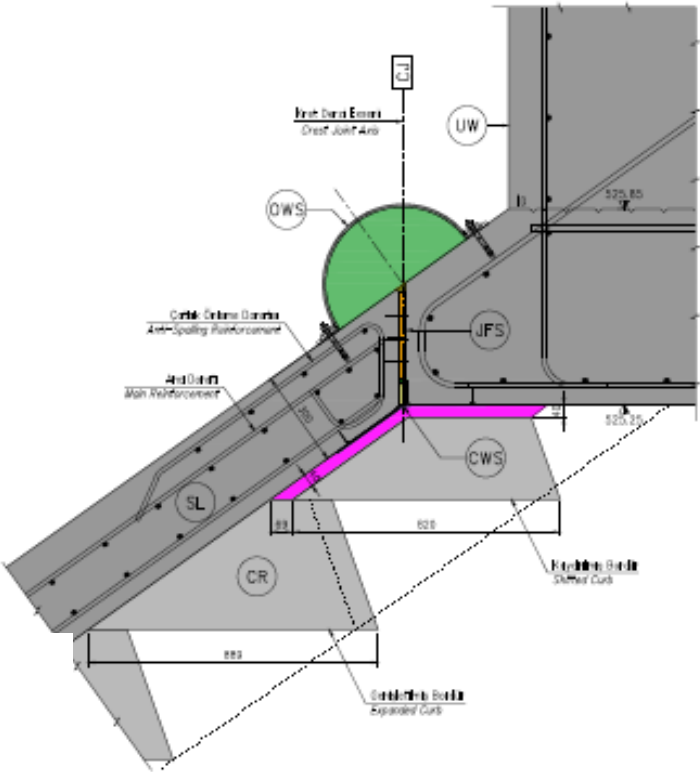
- Vertical compression
 - Vertical expansion
 - Perimetral
 - Horizontal movement (not typical)

CFRD – Slab Joints

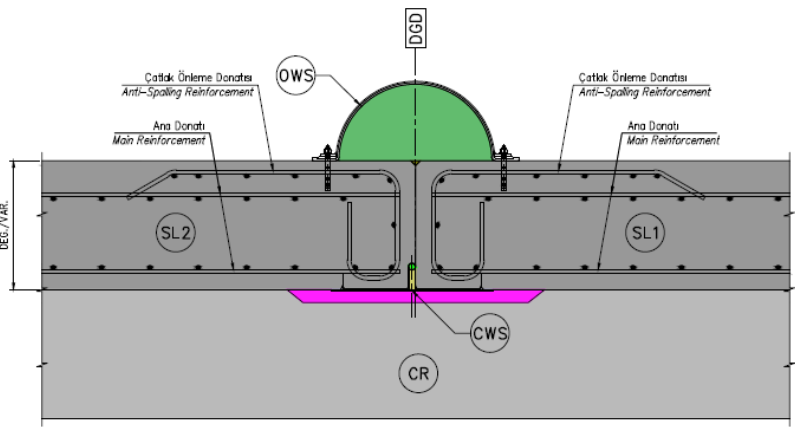
Perimetral joint detail



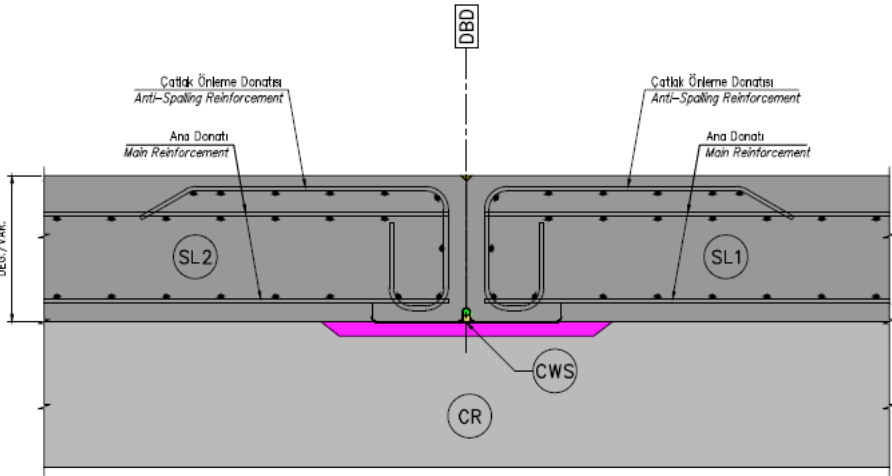
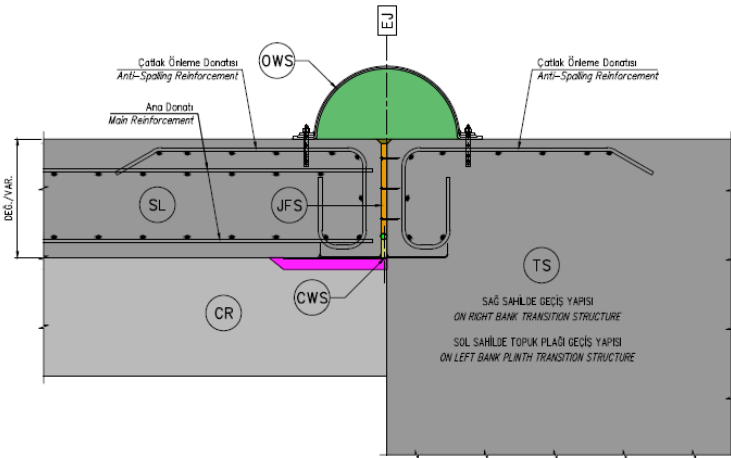
Crest joint detail



Vertical expansion joint detail



Edge structure joint detail

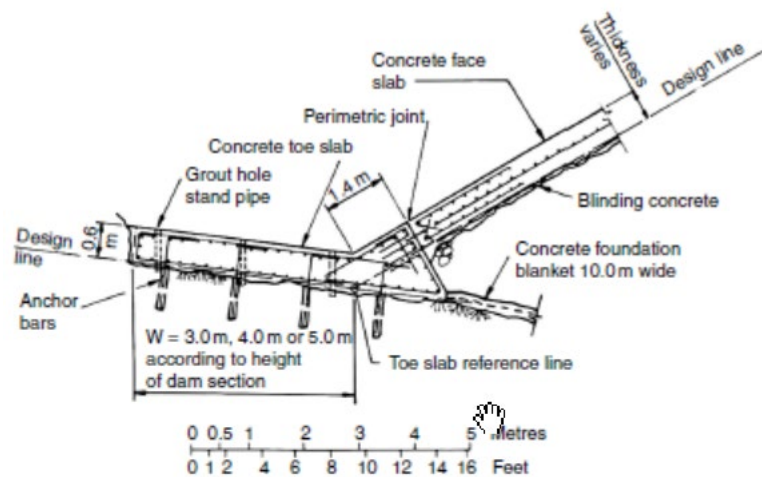


Vertical compression joint detail

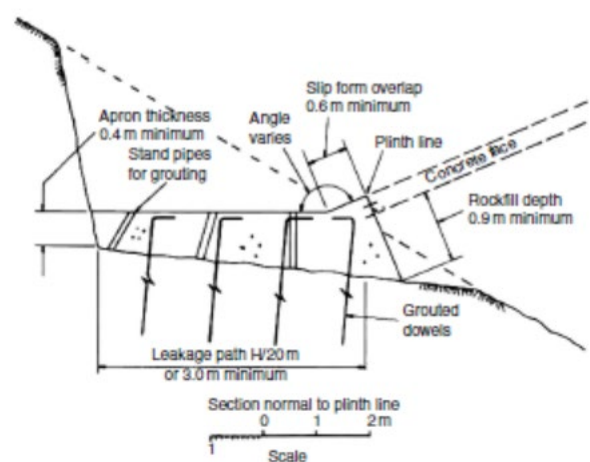
- **Plinth**

- Usually founded on strong, non-erodible, groutable rock
- **Width**
 - ICOLD Bulletin 141 $1/20 \div 1/25 H_{\max}$
 - Cruz et al. (2009) (gradient) depending on RMR
 - Sierra et al. (1985) (gradient) depending on Rock Conditions
 - ICOLD (2010) (gradient) depending on Erodibility Class
 - Minimum width 2 m to 3 m on the abutments
 - Inner plinth («internal slab») optimization in the main section
- **Thickness** : from 0.3 m to 1.0 m for high dams
- **Reinforcement** : from 0.3% to 0.6%
- **Stability**
 - Dowels (grouted bars) 25-35 mm, 3-5 m long, spaced every 1.0-1.5 m
 - Special conditions plinth on rock reconstructions

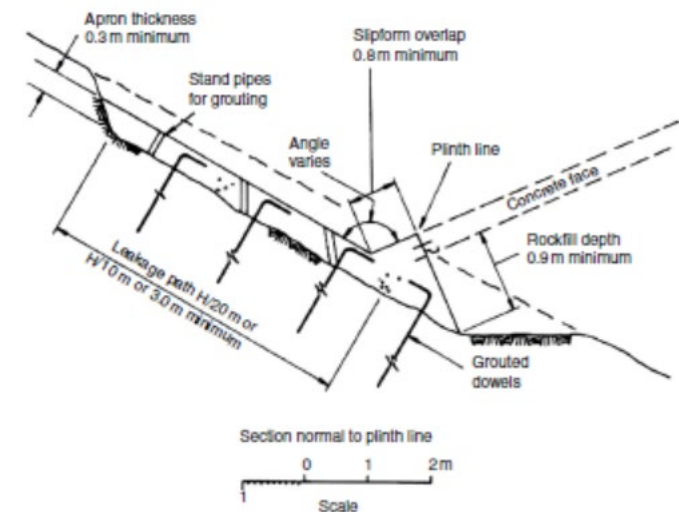
CFRD – Slab and Plinth Design



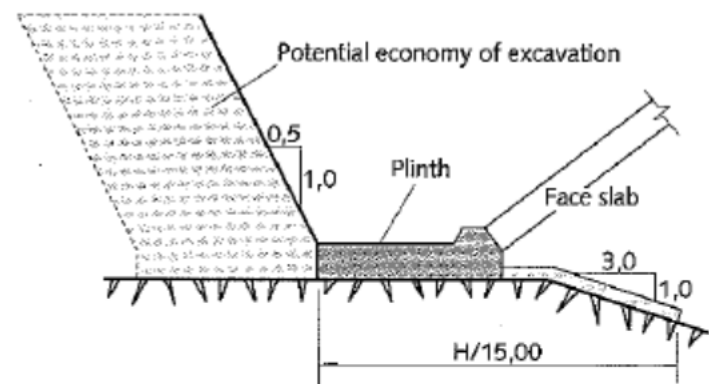
Mangrove Creek CFRD



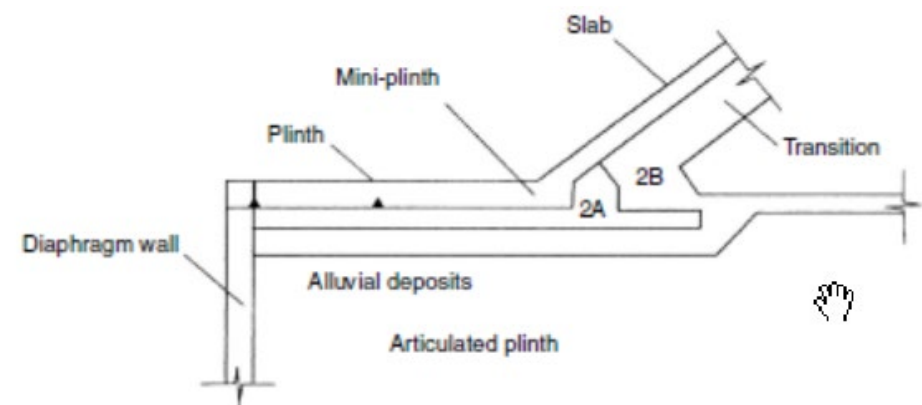
Cethana CFRD



Reece CFRD

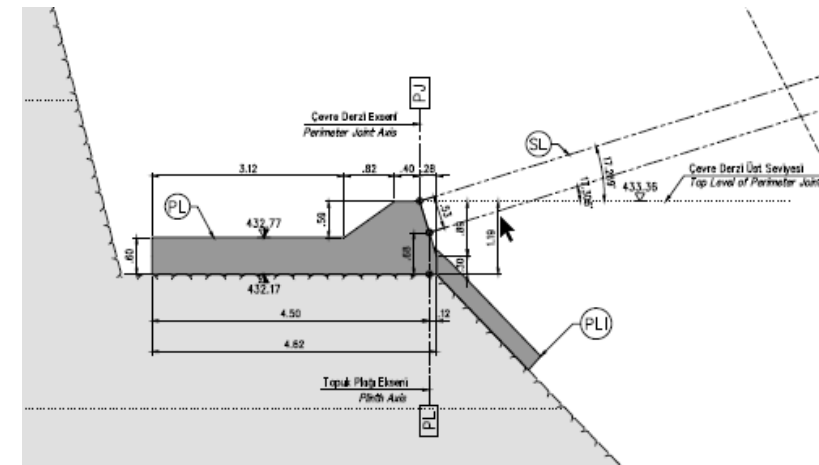
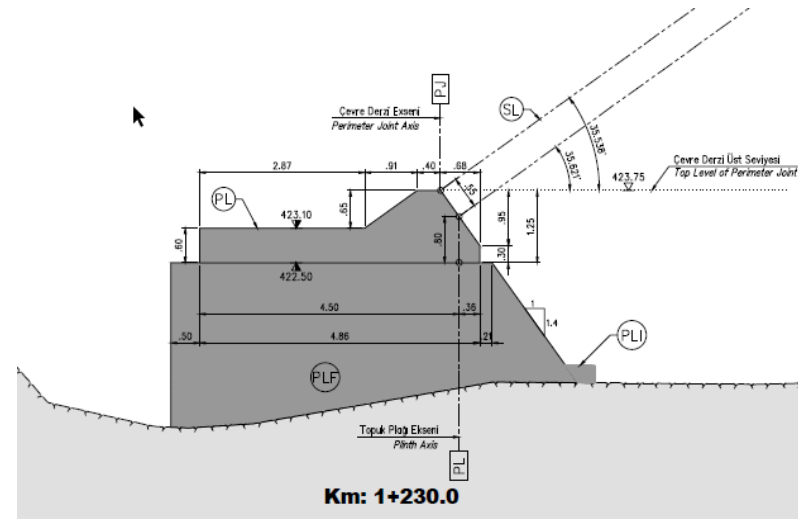
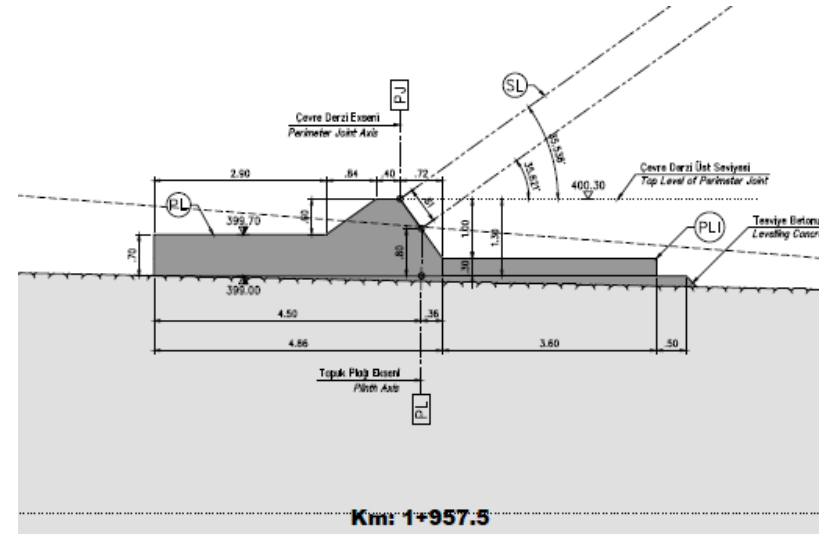
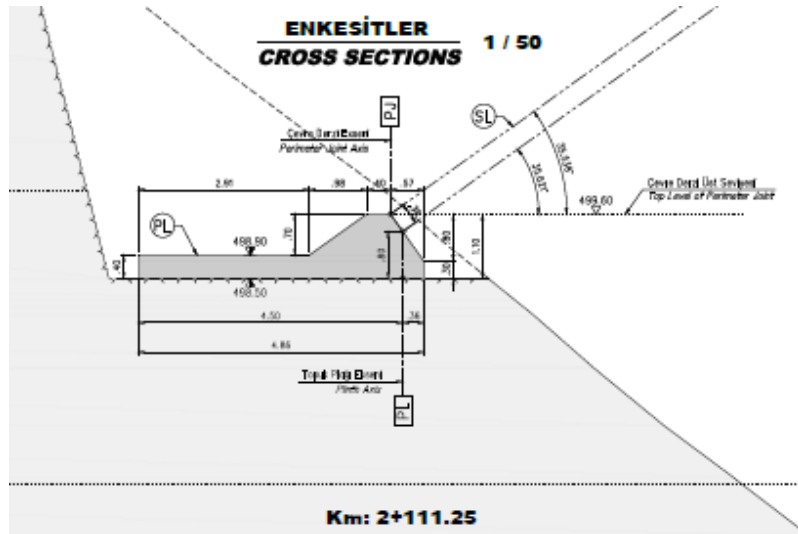


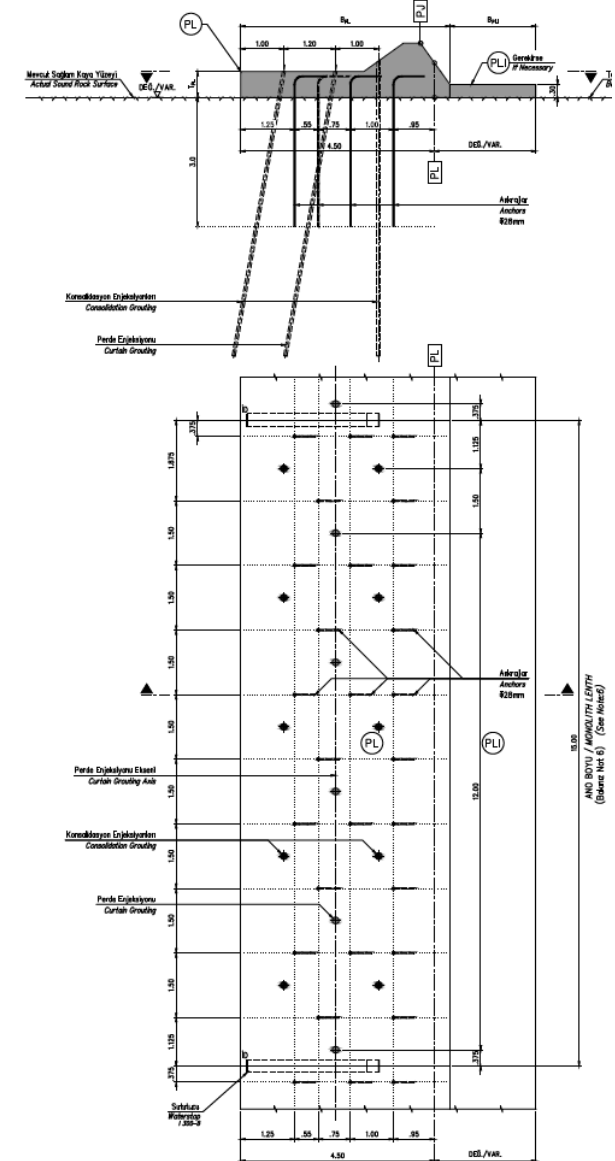
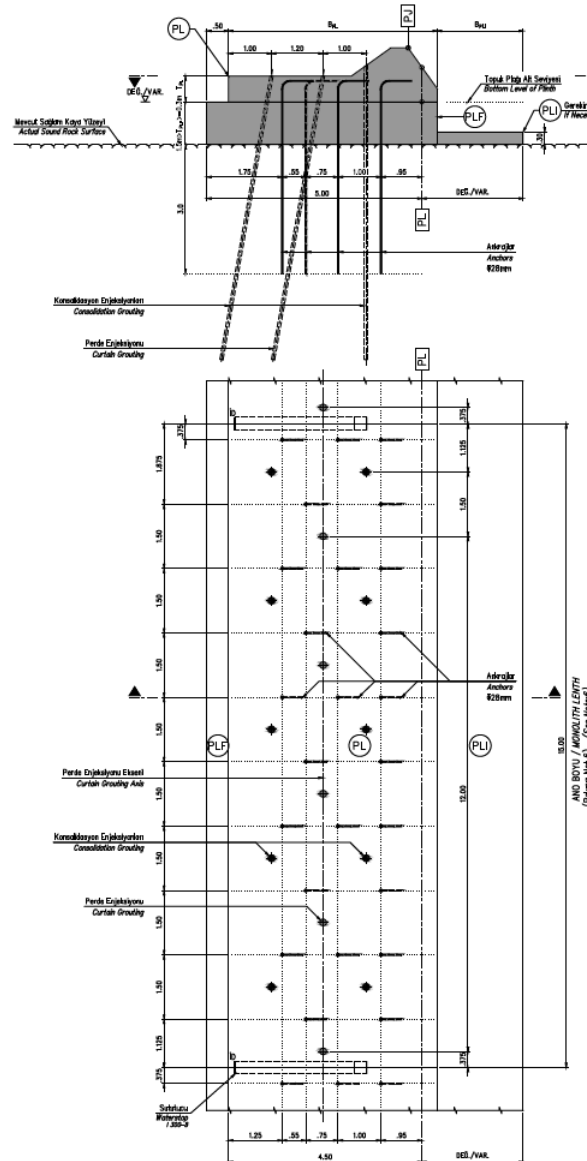
Inner slab
Marulanda and Pinto (2000)



Articulated plinth on alluvial deposit
Cruz et al. (2009)

CFRD – Slab and Plinth Design





- **Main Goals**

- Assess the global **performance** to **static** and **dynamic** loading conditions
 - **Construction sequence** for dam filling and concrete face construction
 - Reservoir **impounding**
 - Post-construction and **long-term** deformation
 - **Seismic** loading to OBE (Service Limit State) SEE (Ultimate Limit State)
- **Stability** conditions of the slopes
- Maximum **deformation** / settlement at the **crest**
- Structural performance of the **concrete face**
 - **Stress / Strain analysis** for reinforced concrete design / check
 - **Joint deformation** for joint layout design / check
- **Seepage** through dam body in case of concrete face cracking

- **Main Features**

- Foundation and dam body **geometrical model**
 - Abutment profiles and valley shape
- **Construction sequence** and reservoir **impounding**
 - Focus on **staged dam filling** / **concrete face** construction / **impounding**
- **Structural elements** modelling
 - Reinforced concrete **slab** and **plinth**
 - **Joint types**
- **Constitutive** modelling
 - Dam body **fill materials**
 - **Reinforced concrete** elements
 - **Interfaces** (facing – dam body, slab – slab, slab – plinth)

• Three-dimensional Geometrical model of the Dam and the Foundation

○ Dam foundation

- Canyon and abutment shapes : critical for narrow gorges and / or steep abutments
- Geology : critical for dynamic performance and / or alluvium deposits

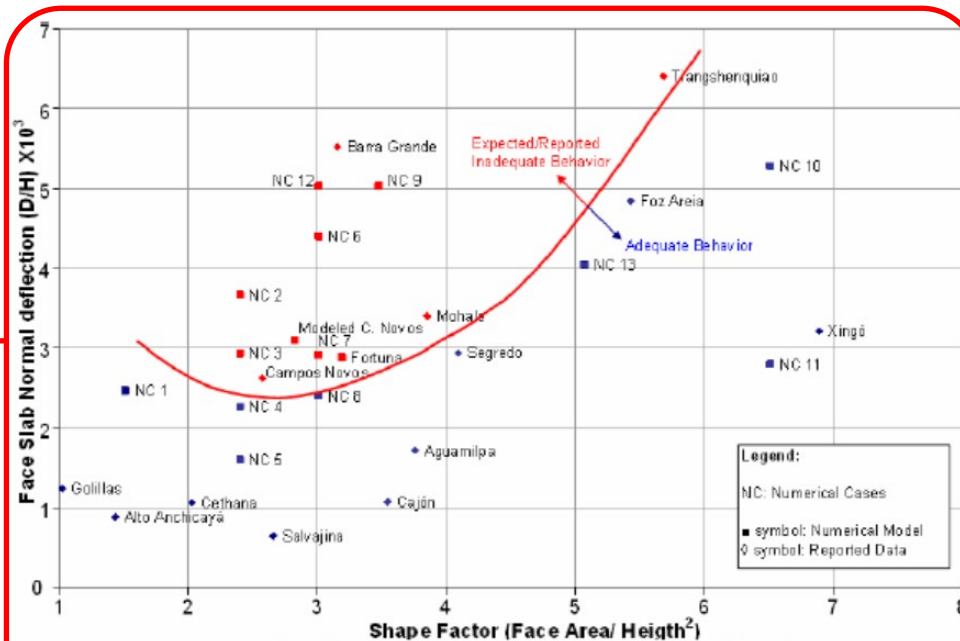
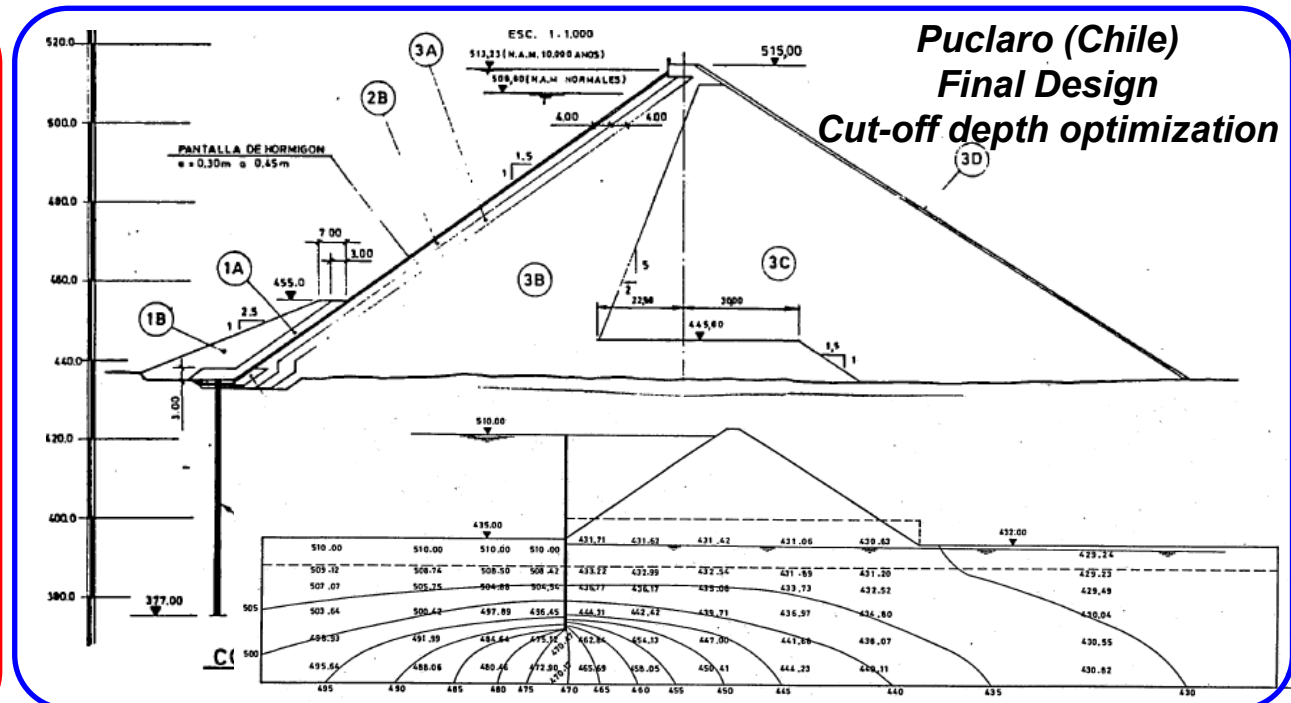


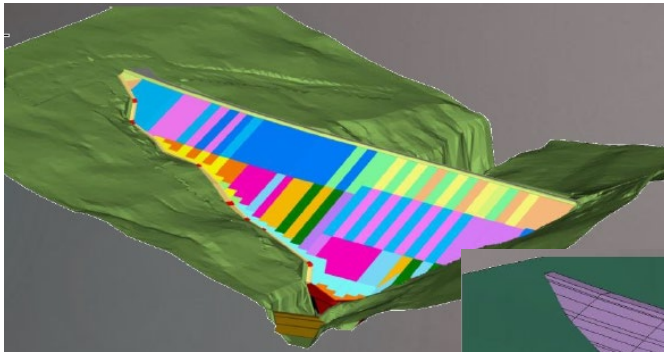
Fig 3 Normal Deflection of the face as a function of the shape factor

Marulanda and Marulanda (2008)

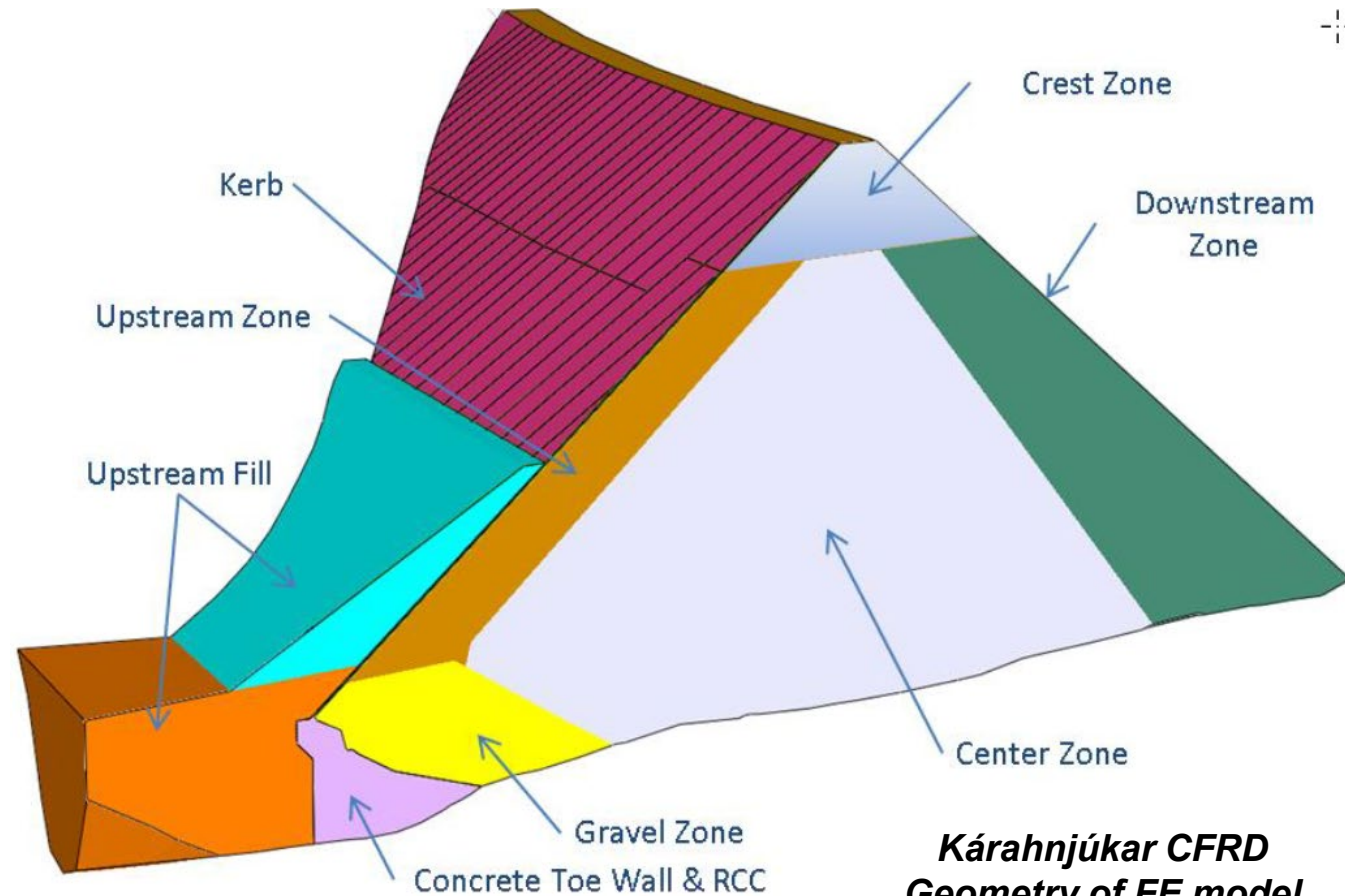
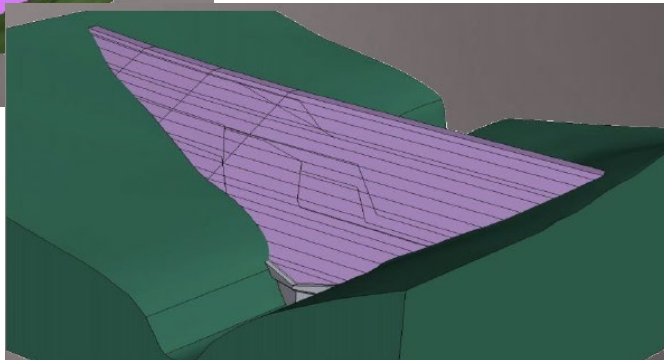


- **Three-dimensional Geometrical model of the Dam and the Foundation**

- Dam geometry
 - Fill zoning
 - Construction stages
 - Structural elements : facing, plinth



*Kárahnjúkar CFRD
Geometry of FE model
Quiroz and Modares (2014)*

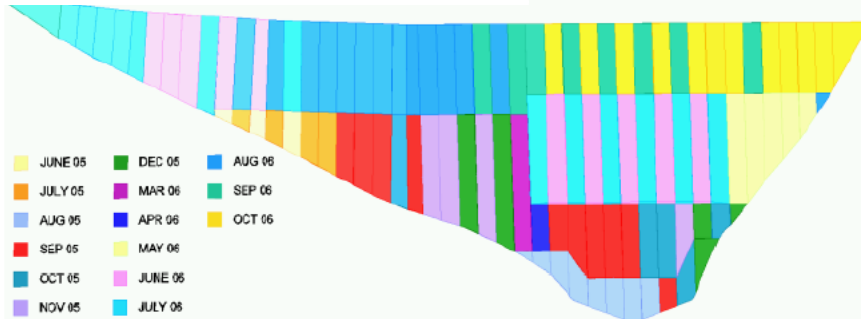
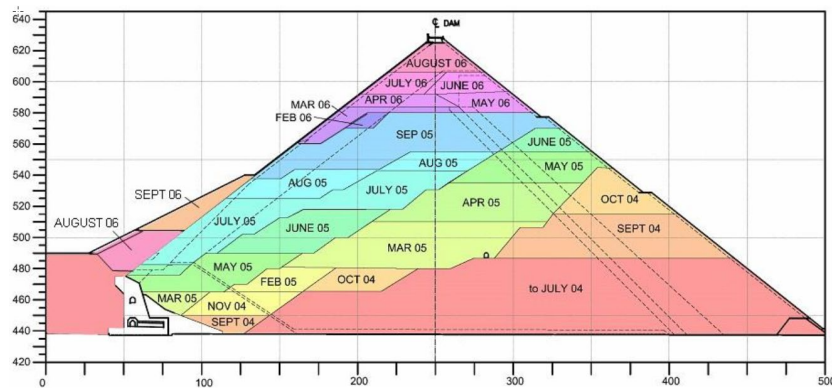


*Kárahnjúkar CFRD
Geometry of FE model
Quiroz and Modares (2014)*

- **Construction Sequence and Reservoir Impounding**

- **Dam Construction**

- Fill staged construction
- Construction of slabs
- (if any) upstream self-healing fill



Kárahnjúkar CFRD
Geometry of FE model
Quiroz and Modares (2014)

- **Structural Elements**

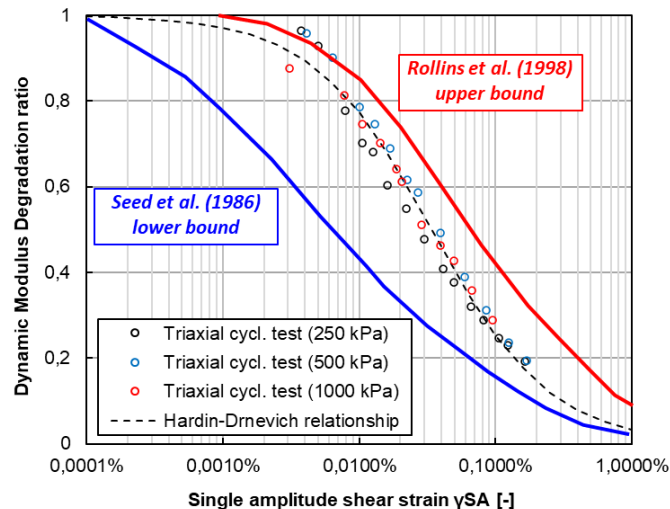
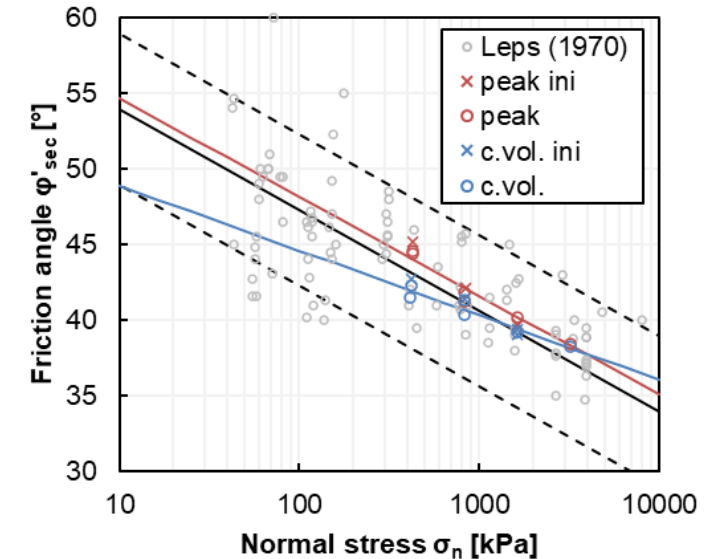
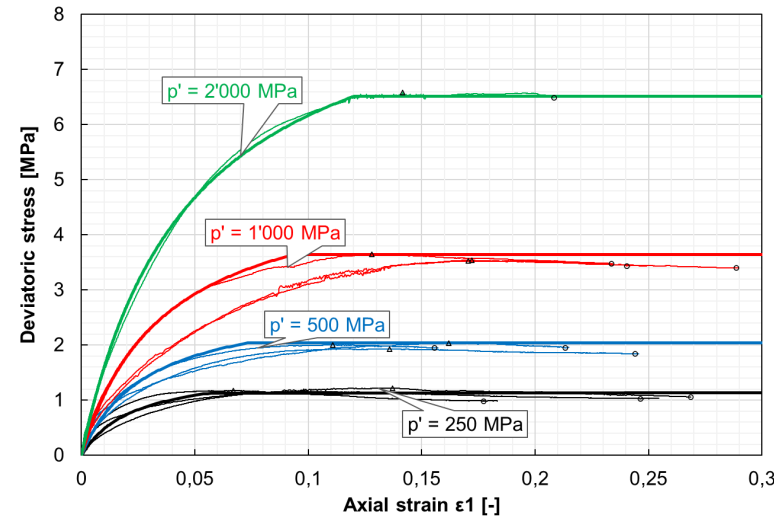
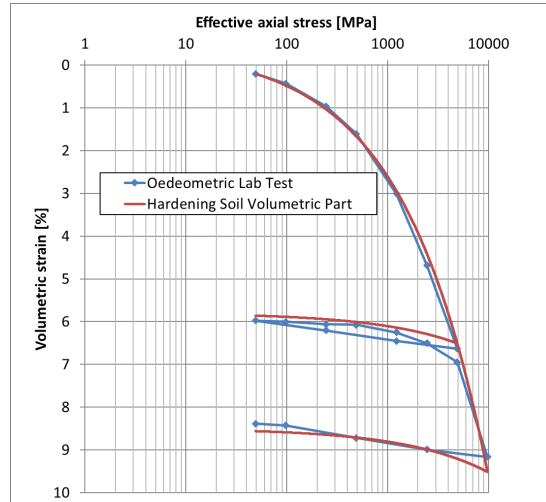
- Reinforced Concrete Slabs and Plinth
- Joints
 - Vertical expansion joints
 - Vertical compression joints
 - Edge structure joints
 - Perimetral joints



- **Constitutive Modelling**

- Dam fill material : from linear elastic to advanced elasto-plastic models
- A simple EP model : Hardening Soil Model extended to the Small Strains
 - Deviatoric and volumetric yielding and hardening
 - Stress (effective confinement) dependency of deviatoric and volumetric stiffness
 - Dilatancy
 - Incorporation of dynamic features (initial dynamic shear modulus, cyclic degradation)
 - Recent advanced options : confinement dependent shear strength
- Calibration
 - Laboratory testing (design stage) with “large” equipment (oedometric, monotonic and cyclic triaxial)
 - In-situ testing (construction stage), plate load tests, geophysical investigations, etc...
 - Monitoring (construction and operation), back-analysis

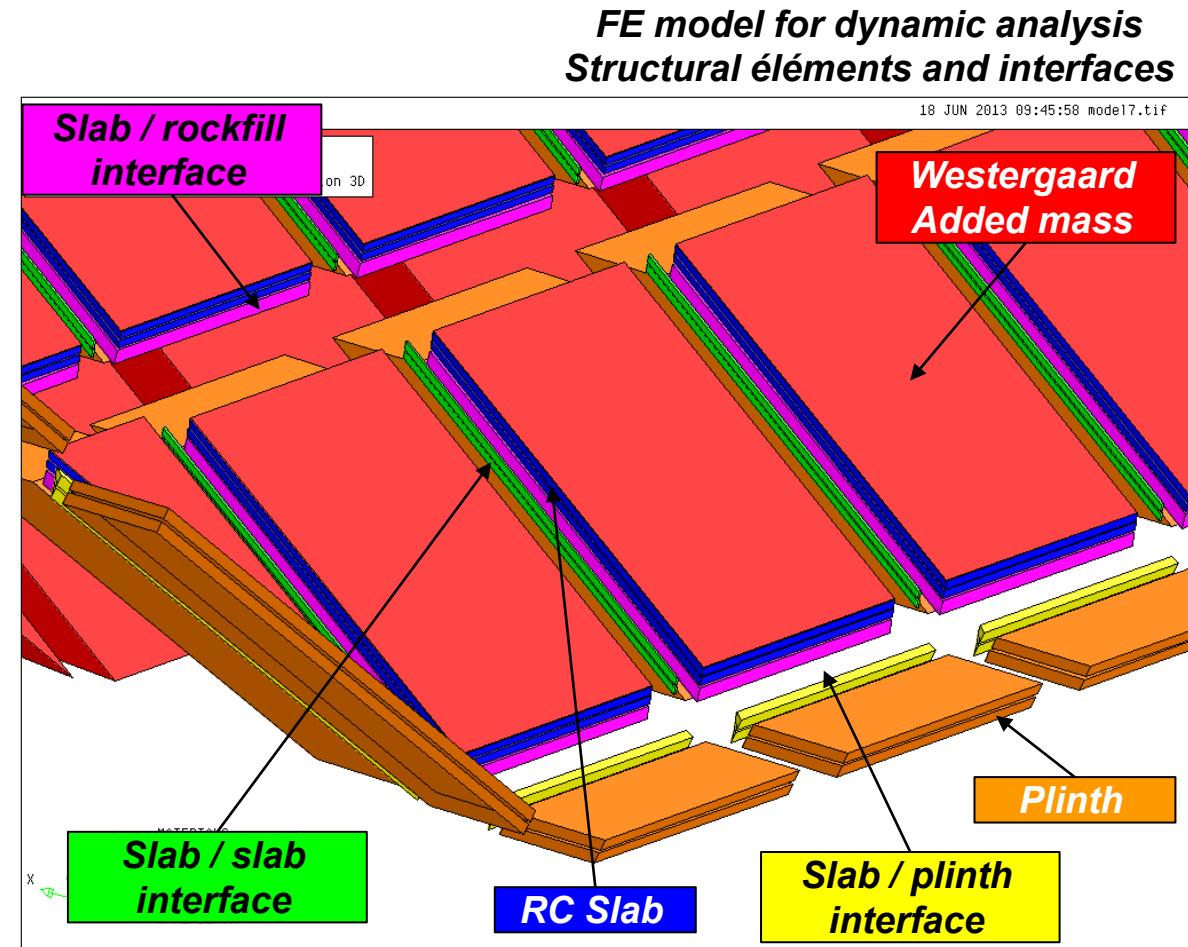
• Constitutive Modelling

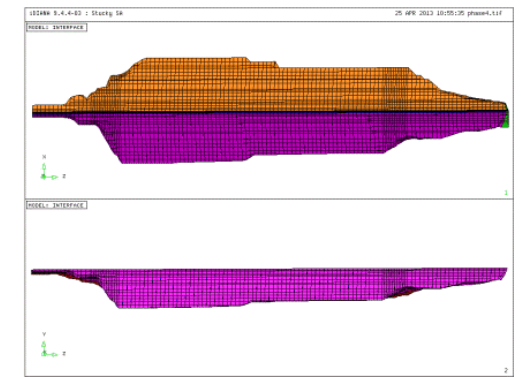
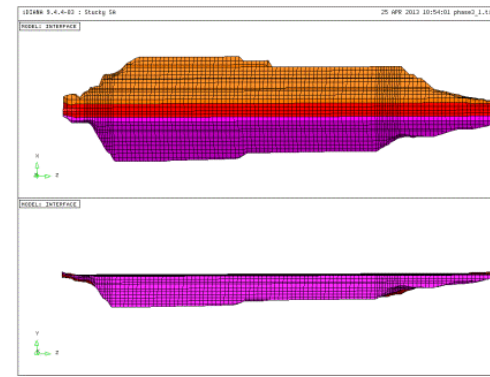
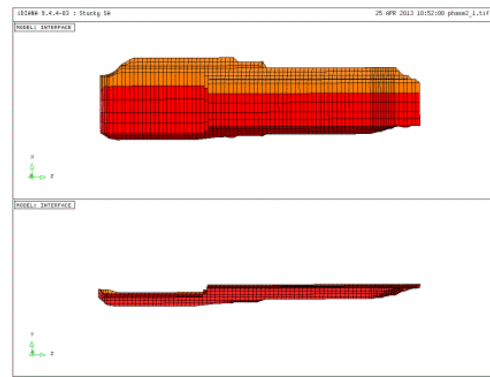
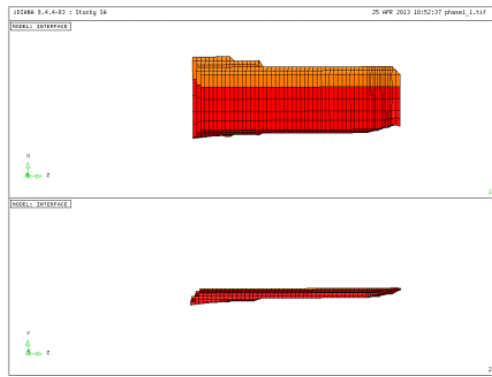


- Calibration with laboratory testing
 - Volumetric elasto-plastic behavior
 - Deviatoric elasto-plastic behavior
 - Confinement dependency of stiffness and shear strength
 - Cyclic degradation of dynamic shear modulus

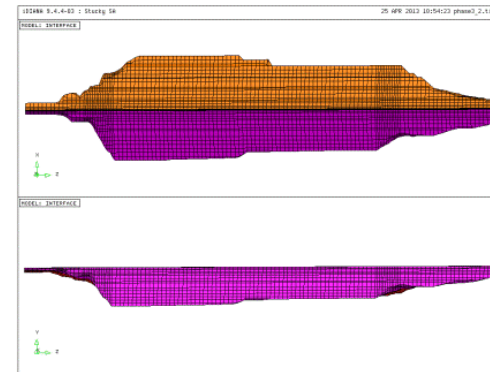
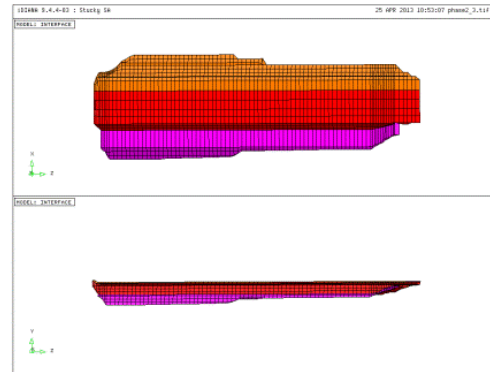
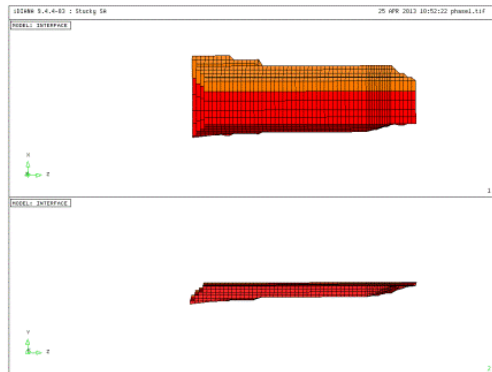
- **Constitutive Modelling**

- Reinforced concrete elements
 - Linear elastic
 - Elasto-plastic
 - Damage plasticity
 - Fracture (smeared / discrete cracking)
 - Reinforcement modelling
- Interfaces
 - Slab / rockfill
 - Slab / Slab
 - Slab / Plinth
 - No-tension material
 - Frictional behavior

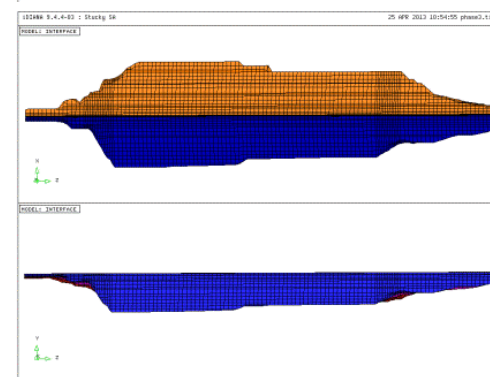
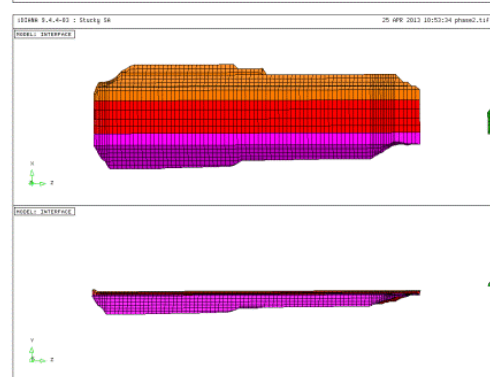




Phase 4
Concrete face



Phase 1



Phase 2

Phase 3

CFRD – Numerical Analyses



CFRD – Numerical Analyses



- Horizontal displacements and settlements

Impounding

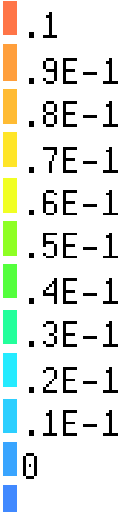
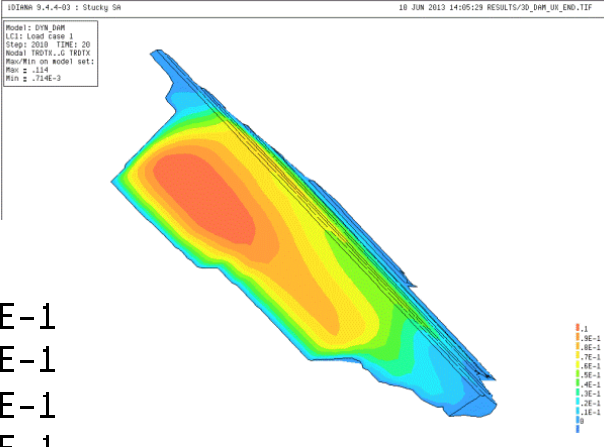
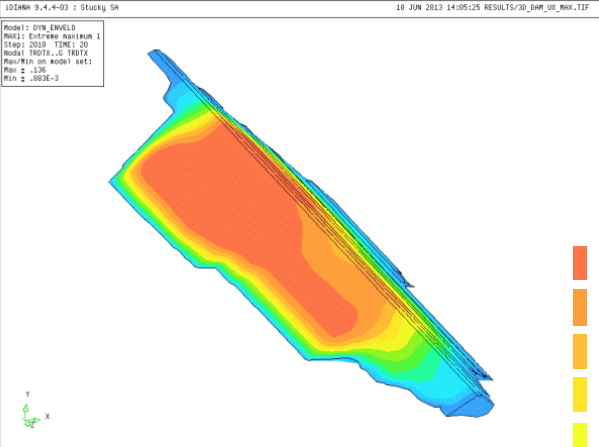
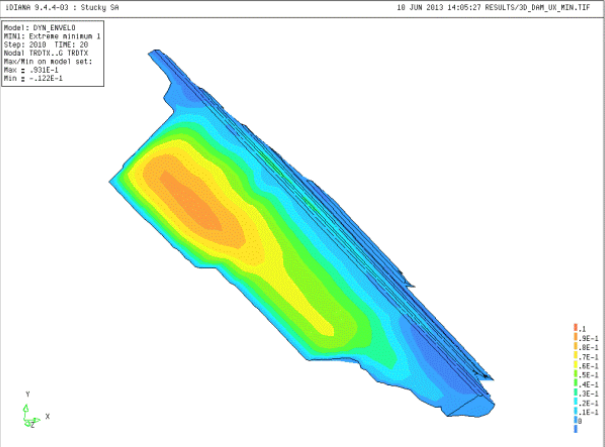
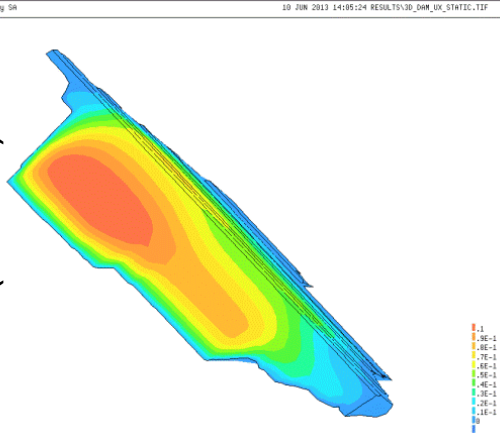
SEE (minimum)

SEE (maximum)

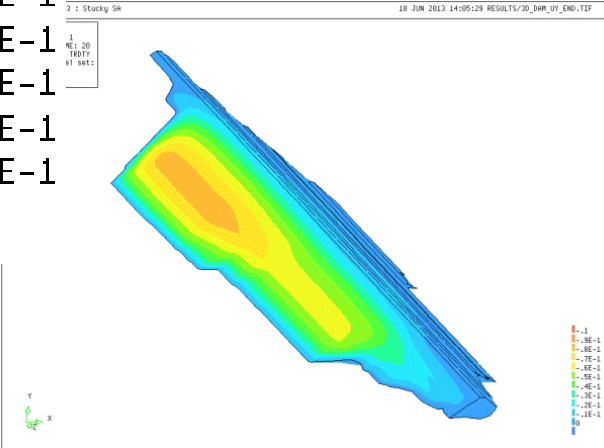
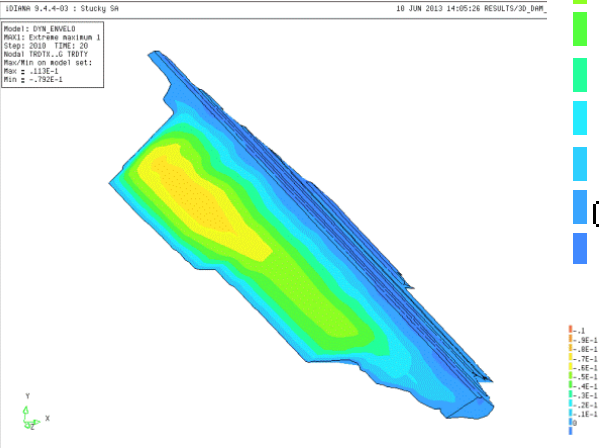
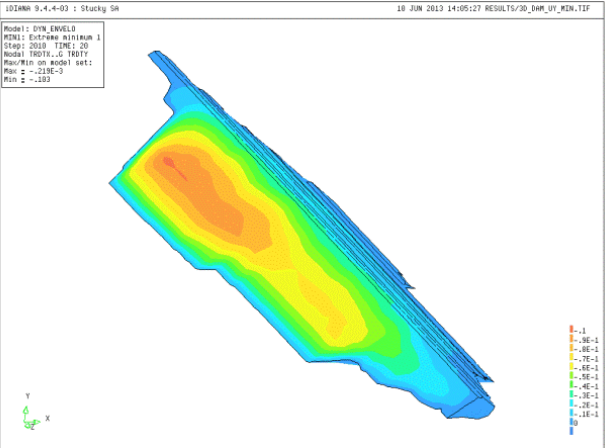
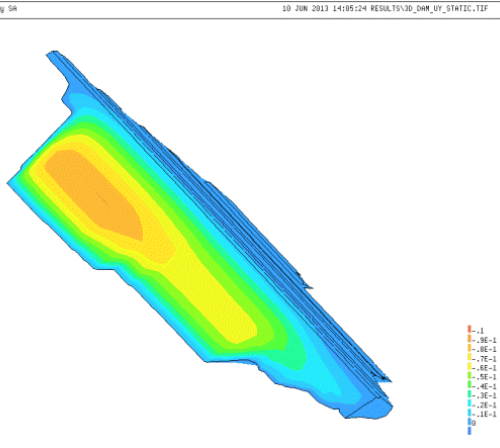
Post-SEE

Horizontal displ.

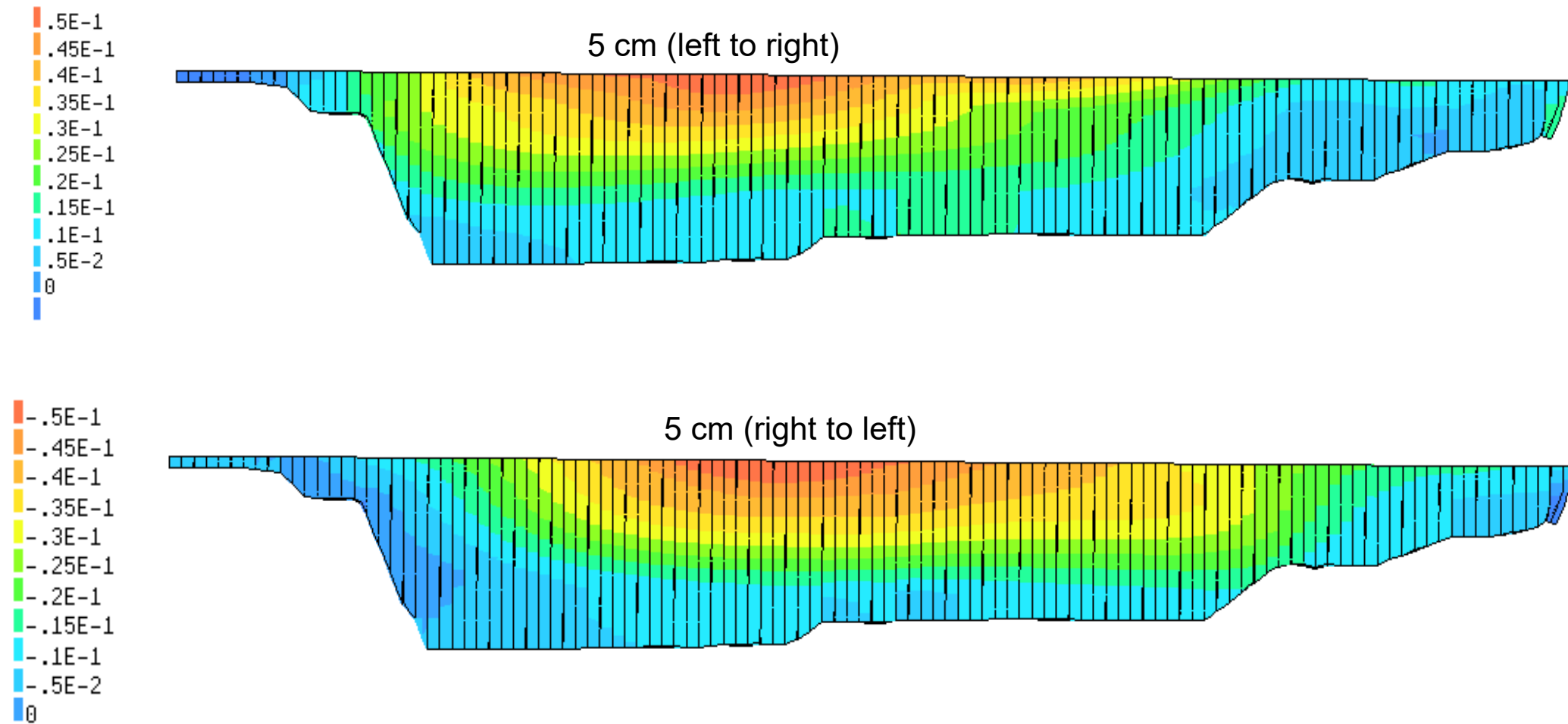
(US-DS)



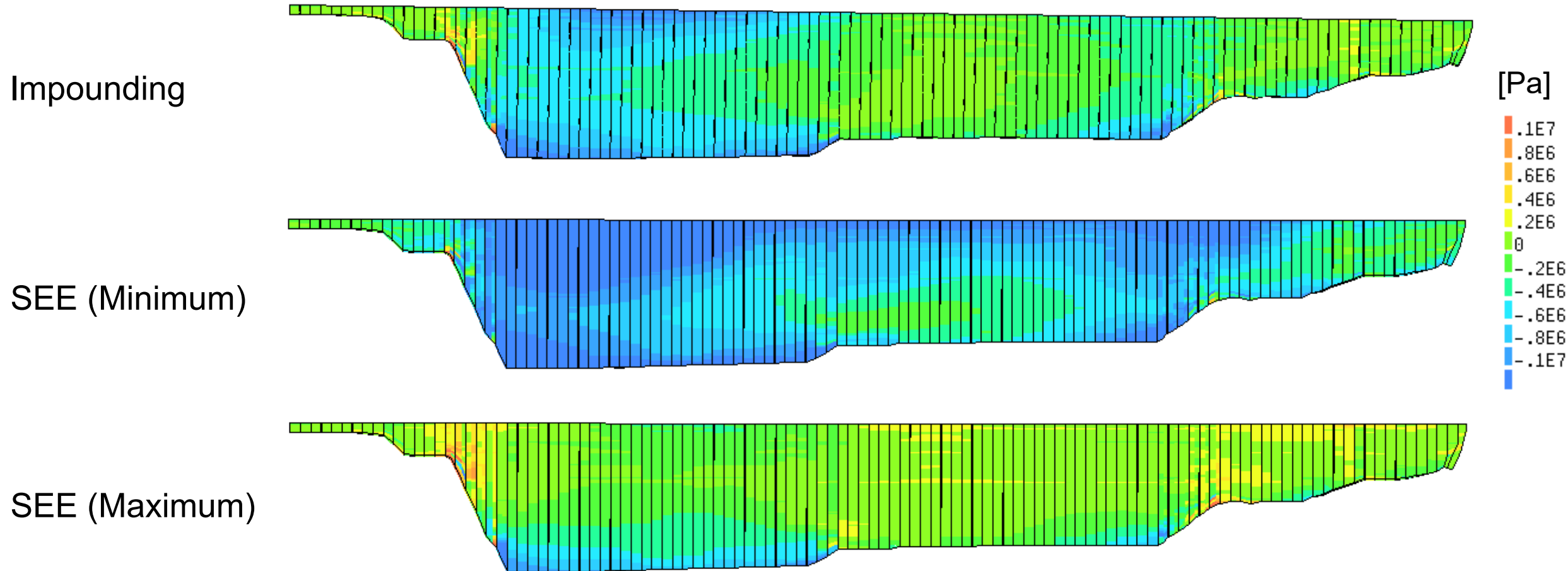
Settlements



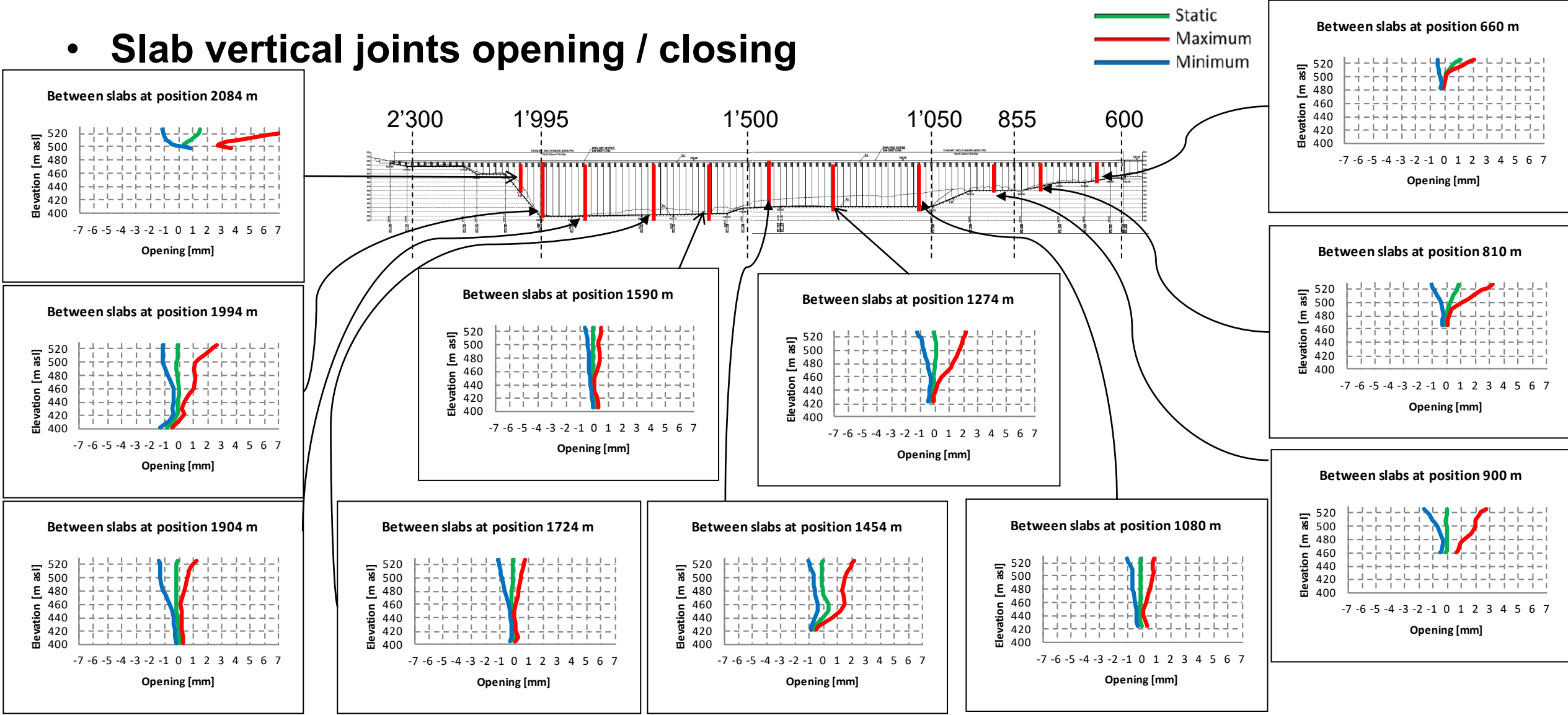
- **Slab dynamic (maximum) horizontal displacements**



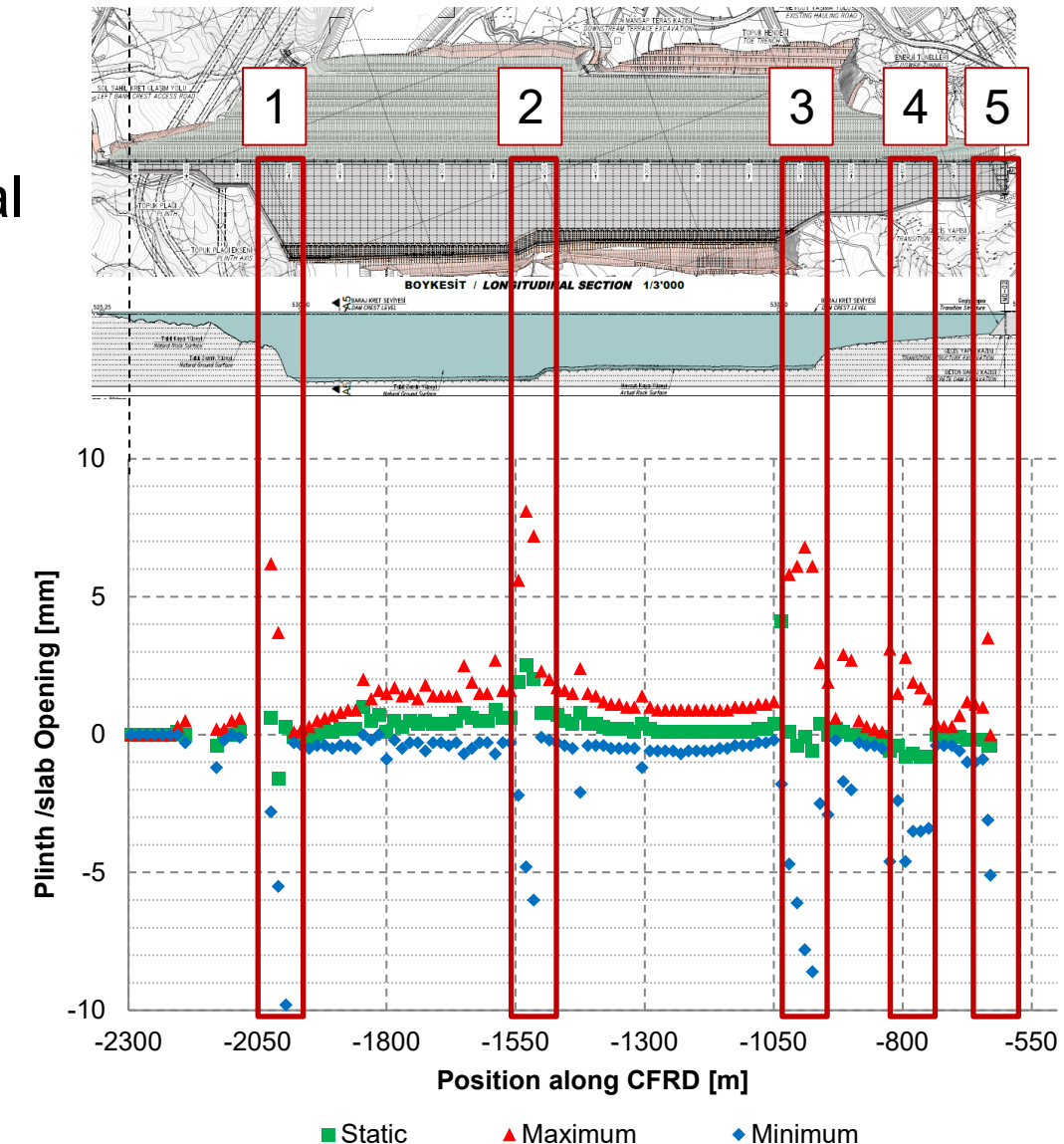
- Slab dynamic horizontal in-plane stress



- Slab vertical joints opening / closing

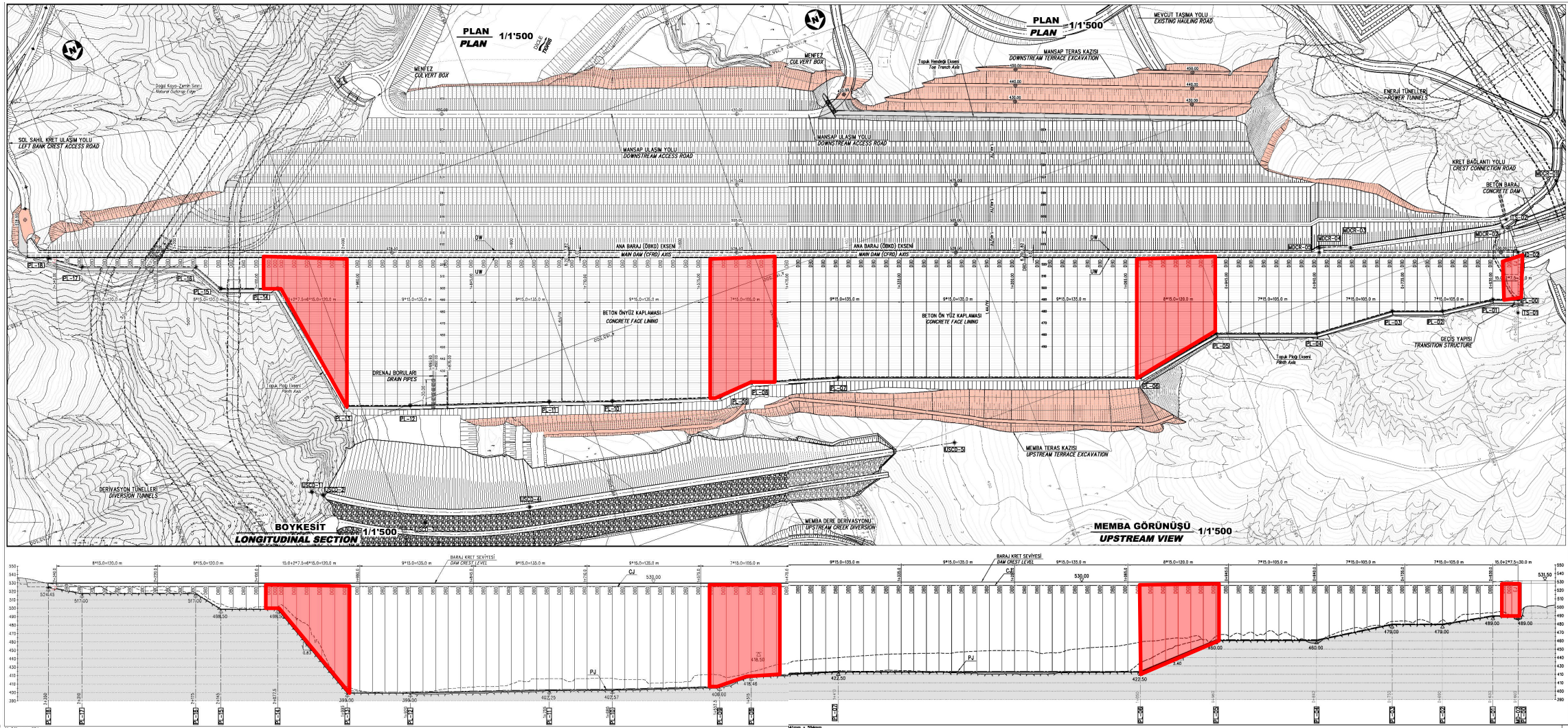


- **Plinth / Slab joint opening / closing**
 - Scattered results due to localized geometrical singularities (areas 1, 2, 3, 4 and 5)
 - Static opening smaller than 1 mm
 - Dynamic opening smaller than 3 mm

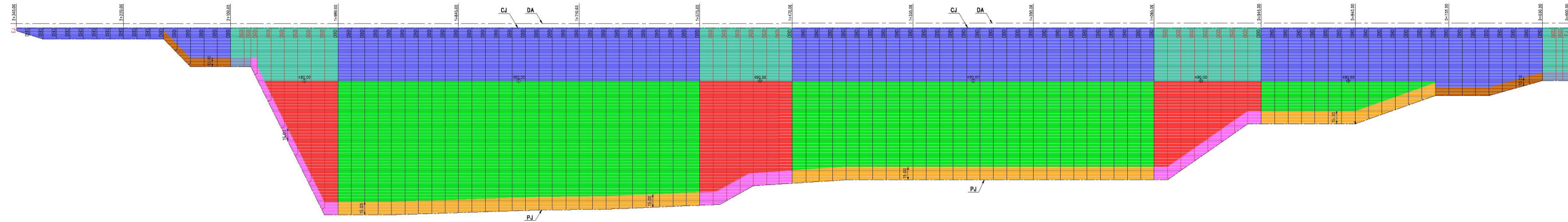


CFRD – Numerical Analyses

- Vertical joints layout : distribution of expansion joints



- Concrete face structural analysis : reinforcement design



BASINÇ BÖLGESİ COMPRESSION REGION		ÇEKME BÖLGESİ TENSION REGION	
490.00 Kotu Üstünde Düşey Donatı Vertical Reinforcement Above Elevation 490.00 m a.s.l	Ø 12/15	490.00 Kotu Üstünde Düşey Donatı Vertical Reinforcement Above Elevation 490.00 m a.s.l	Ø 12/15
490.00 Kotu Üstünde Yatay Donatı Horizontal Reinforcement Above Elevation 490.00 m a.s.l	Ø 12/20	490.00 Kotu Üstünde Yatay Donatı Horizontal Reinforcement Above Elevation 490.00 m a.s.l	Ø 12/15
490.00 Kotu Altında Düşey Donatı Vertical Reinforcement Below Elevation 490.00 m a.s.l	Ø 14/15	490.00 Kotu Altında Düşey Donatı Vertical Reinforcement Below Elevation 490.00 m a.s.l	Ø 14/15
490.00 Kotu Altında Yatay Donatı Horizontal Reinforcement Below Elevation 490.00 m a.s.l	Ø 14/20	490.00 Kotu Altında Yatay Donatı Horizontal Reinforcement Below Elevation 490.00 m a.s.l	Ø 14/15
Çevre Derzine 10.00m Mesafede Düşey Donatı Vertical Reinforcement 10.00m Distance From Perimeter Joint	Ø 14/15	Çevre Derzine 10.00m Mesafede Düşey Donatı Vertical Reinforcement 10.00m Distance From Perimeter Joint	Ø 14/15
Çevre Derzine 10.00m Mesafede Yatay Donatı Horizontal Reinforcement 10.00m Distance From Perimeter Joint	Ø 14/20	Çevre Derzine 10.00m Mesafede Yatay Donatı Horizontal Reinforcement 10.00m Distance From Perimeter Joint	Ø 14/15
Çevre Derzine 15.00m Mesafede Düşey Donatı Vertical Reinforcement 15.00m Distance From Perimeter Joint	Ø 16/15	Çevre Derzine 15.00m Mesafede Düşey Donatı Vertical Reinforcement 15.00m Distance From Perimeter Joint	Ø 16/15
Çevre Derzine 15.00m Mesafede Yatay Donatı Horizontal Reinforcement 15.00m Distance From Perimeter Joint	Ø 16/20	Çevre Derzine 15.00m Mesafede Yatay Donatı Horizontal Reinforcement 15.00m Distance From Perimeter Joint	Ø 16/15

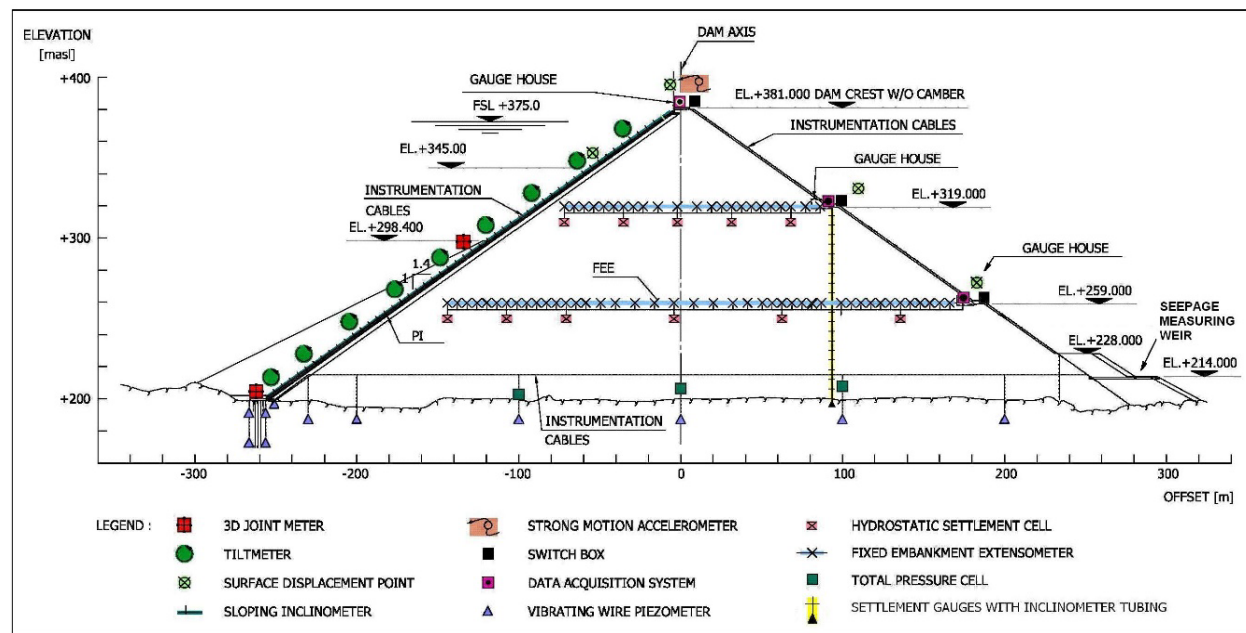
- **Main Goals**

- Measure dam behaviour
 - Construction
 - Impounding
 - Operation (short and long term, during earthquakes)
- Parameters
 - Slab movements (deflections, joint relative displacements)
 - Embankment deformations (horizontal and vertical)
 - Seepage and pore pressures
- Use of data
 - Check dam performance and safety
 - Check and calibrate model with real scale behaviour

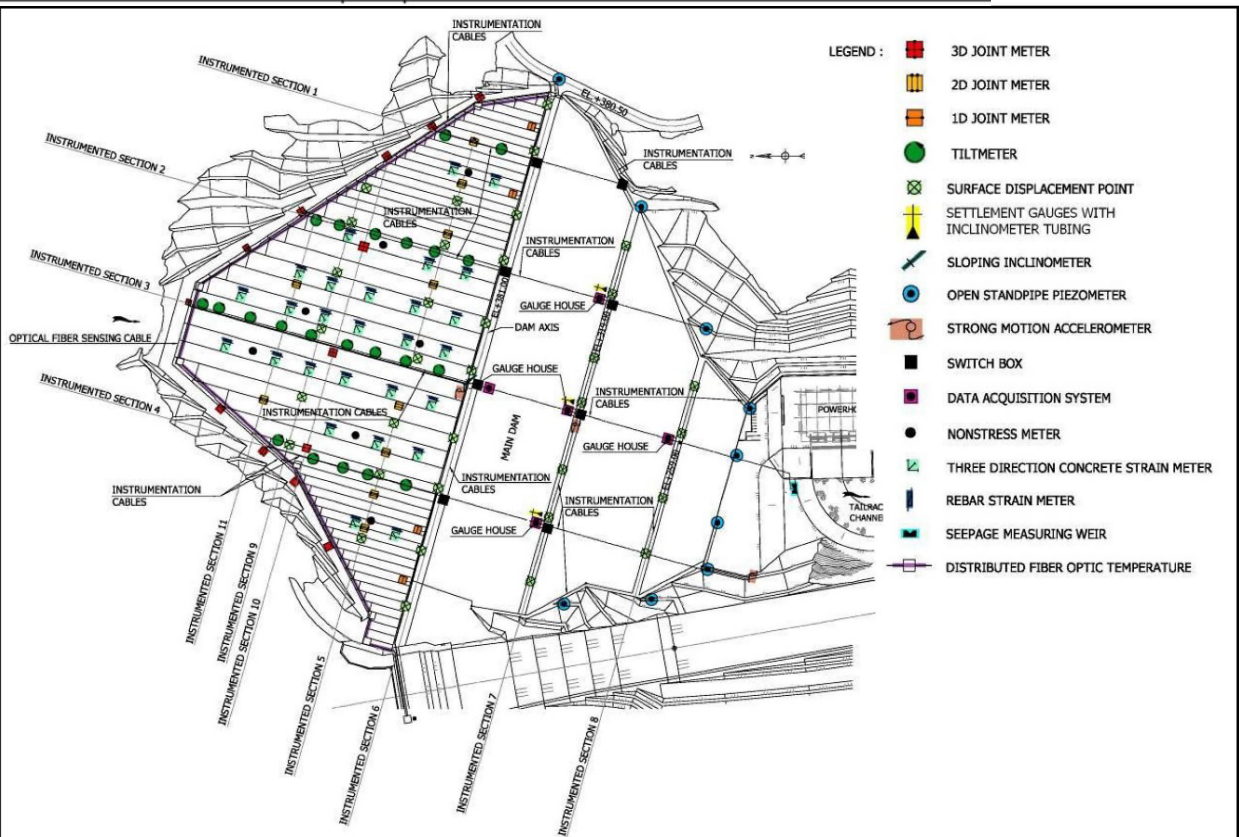
CFRD – Monitoring

Instrument	No.	Measured Parameter
3D Joint Meters	13	Movements of face slab joints and perimeter joint
2D Joint Meters	10	Movements of face slab joints
1D Joint Meters	4	Movements of face slab joints
Sloping Incliner	1	Deflection of concrete face slab
Tiltmeters	23	Deflection of concrete face slab
Rebar Strain Gauges	27	Strain in the concrete face slab
Concrete Strain Gauges	27	Strain in the concrete face slab
Non Stress Strain Gauges	7	Reference strain in concrete
Magnetic Extensometers with Incliner Tubing	3	Transverse movement and settlements of the dam body
Hydrostatic Settlement Cells	22	Settlement of the dam body
Fixed Embankment Extensometers	113	Transverse movement of the dam body
Surface Displacement Points	35	Movements on the surface

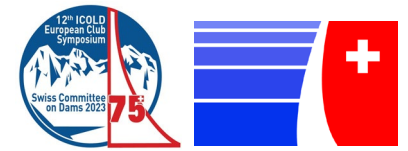
Nam Ngum 2 CFRD Monitoring System Moll and Straubhaar (2011)



Instrument	No.	Measured Parameter
Surface Displacement Points	35	Movements on the surface
Strong Motion Accelerometer	3	Earthquake acceleration
Total Pressure Cells	3	Total pressure at dam foundation
Distributed Fibre Optic Temperature Sensing System	1	Leakage detection along plinth (perimeter joint)
Vibrating Wire Piezometers	35	Water pressure in dam and dam foundation
Open Standpipe Piezometers	9	Ground water pressure / seepage through the abutments
Seepage Measuring Weir	1	Seepage through the dam body (concrete face slab) and abutments



CFRD – Monitoring

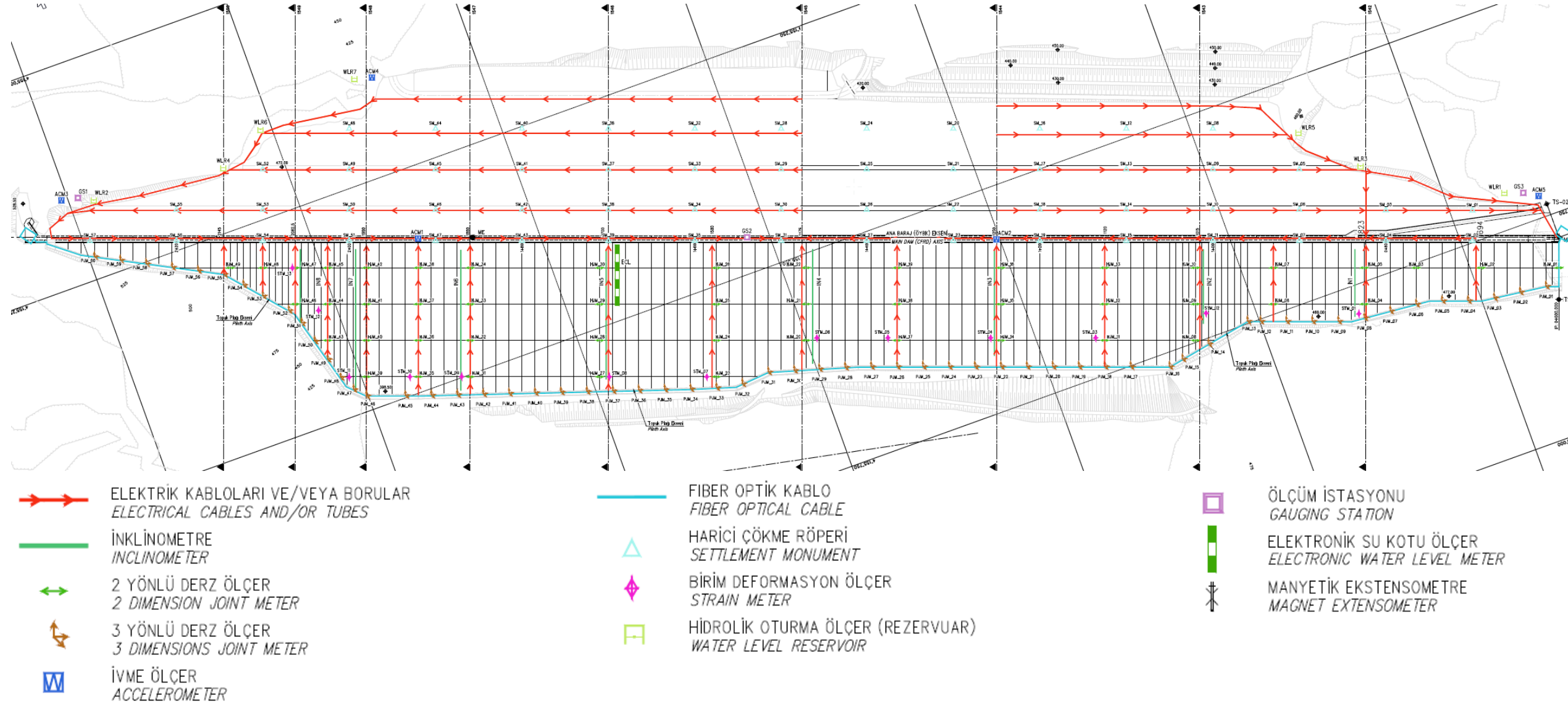


Measured Properties	Location	Type of Instrument	Designation
Dam horiz. displacements & surface settlements	Dam crest and slopes	Survey monuments, survey equipment	SM
Settlements of dam body and dam foundation	Inside dam and dam foundation	Hydraulic settlement cell	SC
Settlements of dam body in central section	Inside dam on the dam axis at 1km860	Magnet extensometer	ME
Horizontal displacement of dam body	Dam body	Fill type horizontal extensometer	EX
Deformation of upstream dam face	On the surface of the concrete slabs	Conventional inclined inclinometer	IN
Displacement in joints	Across construction joints of slabs	Two dimensional electr. joint meter	HJM
Displacements of perimeter joint	Across, parallel and perpendicular to perimeter joint	Three dimensional electr. joint meter	PJM
Stresses in dam body	Inside dam body	Electrical total pressure cell	TPC
Strain in concrete	Inside concrete slab of surface sealing	Electrical strain meter	STM
Seepage water pressure	In dam foundation and on both sides of grout curtain	Electrical vibrated wire piezometer	TP
Seepage water flow through vertical construct. joints and perimeter joint	Beneath perimeter joint and beneath vertical constr. joints of dam sealing on steep abutment	Leakage detection system using fiber optics	
Ground water table	At downstream dam toe	Standpipe piezometer	SP
Seepage water flow through dam	In drainage trench at downstream dam toe	V-notch measuring weir	
Reservoir level	On the surface of the concrete slabs	High precision electrical pressure gauge and staff gauge	
Seismic acceleration	On firm rock at dam site and on dam crest	Seismic accelerometer and seismograph	ACM

Settlement Monuments	57
Hydraulic Settlement Cell	93
Reservoir of Hydraulic Settlement Cell	7
Magnet Extensometer	4
Horizontal Extensometer	42
Inclinometer	8
2D Jointmeter	49
3D Jointmeter	60
Total Pressure Cell	93
Strainmeter	13
Pore Water Pressure Cell	72
Fiber Optical Cable	1
Piezometer Standpipe	9
Reservoir Level Gauge (electronic + water level indicator)	1
Scaled Water Level Indicator Template	1
Accelerometer	5
Portable Read-out Device	3

Type of Instrument	Frequency of Monitoring		
	Dam Construction	Reservoir Impounding	Up to end of Defects Liability
Survey Monuments	monthly	monthly	monthly
Hydraulic Settlement Cells	every 15 days	daily	daily
Horizontal Extensometer	every 15 days	daily	daily
Magnet Extensometer	every 15 days	weekly	weekly
Inclinometer	after construction	every 15 days	monthly
Total pressure cells	every 15 days	daily	daily
Jointmeter	after construction	daily	daily
Strainmeter	after construction	daily	daily
Electrical Piezometer	every 15 days	daily	daily
Standpipe Piezometer	every 15 days	every 15 days	monthly
V-notch measuring weirs	after construction	daily	daily
Leakage detection syst.	after construction	automatically	automatically
Reservoir Level	after construction	automatically & manual checks	
Seismograph	when installed	automatically	

CFRD – Monitoring



CFRD – Monitoring

GÖSTERİM / LEGEND :

- EX DOLGU TİPİ YATAY EXTENSOMETRE
FILL TYPE HORIZONTAL EXTENSOMETER
- SC HİDROLİK OTURMA ÖLÇER
HYDRAULIC SETTLEMENT CELL
- TPC TOPLAM BASINÇ HÜCRESİ
TOTAL PRESSURE CELL
- TP TEMEL TİPİ PİEZOMETRE
ELECTRICAL VIBRATED WIRE PIEZOMETER
- ME MANYETİK EKSTENSOMETRE
MAGNET EXTENSOMETER
- PS BASINÇ ÖLÇER BORUSU
PIEZOMETER STANDPIPE
- ELEKTRİK KABLOLARI VE/VEYA BORULAR
ELECTRICAL CABLES AND/OR TUBES
- İNKLİNOMETRE
INCLINOMETER

ENKESİT CROSS SECTION 1 / 750

DETAY DETAIL A

