Reference:
อภิชาติ สระมูล. 2554. กรณีศึกษาการออกแบบและคุมงานเขื่อนน้ำงึม 2. เอกสารประกอบการอบรม "การวิเคราะห์เพื่อออกแบบและประเมินความปลอดภัยเขื่อน", ระหว่างวันที่ 5,7 และ 8 เมษายน 2554, จัดโดย ศูนย์วิจัยและพัฒนาวิศวกรรมปฐพีและฐานราก มหาวิทยาลัยเกษตรศาสตร์ ร่วมกับ Thai Geotechnical Society (TGS), ณ โรงแรมมิราเคิล แกรนด์ คอนเวนชั่น, กรุงเทพฯ.

DESIGN, CONSTRUCTION AND PERFORMANCE OF NAM NGUM 2 CFRD

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1. INTRODUCTION

The Nam Ngum River is one of the major tributaries of the Mekong River which forms the border between Laos and Thailand in this area. The Nam Ngum River originates on the Tran Ninh Plateau, north of Xeong Khuang, and after flowing past both dam sites, joins the Nam Lik River and flows into the Mekong River about 100km downstream of Vientiane. The Nam Ngum 2 Hydroelectric Power Project (NN2 HPP) is located approximately 90km north of Vientiane in central Laos and approximately 35km upstream of existing Nam Ngum 1 reservoir.

Nam Ngum 2 Power Company Limited (NN2PC), the client, agreed to make a contract with Ch. Karnchang (Lao) Company Limited as the EPC contractor to design, engineer, manufacture, supply, install, procure, construct, test and commission a 615MW (3 Nos. of 205MW turbines) hydroelectric power plant.

The NN2 Concrete Face Rockfill Dam (CFRD) has the lowest foundation level at 199.0masl and the crest elevation at 381.0masl, which corresponds to the dam height of 182.0m. The NN2 CFRD will be the second highest of CFRD in SouthEast Asia.

The face slab is the primary water barrier of the NN2 CFRD, which consists of concrete face slab poured on underlying extruded curb laid above support zones of the rockfill body of the dam. Thus, the design and construction of face slabs has to concentrate on watertightness and durability. Attention has been paid to identification and control of crack development in the face slabs.

Construction of NN2 CFRD has mainly divided into 5 stages for embankment in order to corporate with face slab construction, which has divided into two stages. The total volume of rockfill is approximately 10 million m^3, whereas the total area of concrete face slab is approximately 88,000 m^2.

The extensive instrumentations have been installed within rockfill embankment and concrete face slab to assess the performance of NN2 CFRD.

2. DESIGN OF NN2 CFRD

The design of the CFRD has evolved empirically over 40 years. As successful and unsuccessful experiences of previous CFRD projects, understood and thoroughly discussed with the experts, so that the design of NN2 CFRD can be assured.

The configuration of NN2 CFRD is illustrated in Fig. 1. The NN2 CFRD is consisting of compacted rockfill found on a rock foundation, plinth, face slab and wave wall. Outer slopes for upstream and downstream are defined as 1V:1.4H to suit with available rockfill material. The rockfill materials are generally classified into three designated zones as follows:

(1) Zone 1 (1A and 1B) is concrete face slab protection zone in the upstream of face slab,

(2) Zone 2 (2A and 2B) is concrete face slab supporting zone in the downstream of face slab, and

(3) Zone 3 (3A, 3B, 3C, 3D and 3E) is the rockfill zone, which is the major part of the rockfill material.

The plinth is usually made of reinforced concrete, which connects the foundation with face slab. The face slab is the primary water barrier of the CFRD, which is poured on underlying supporting zone of the rockfill body of the dam.

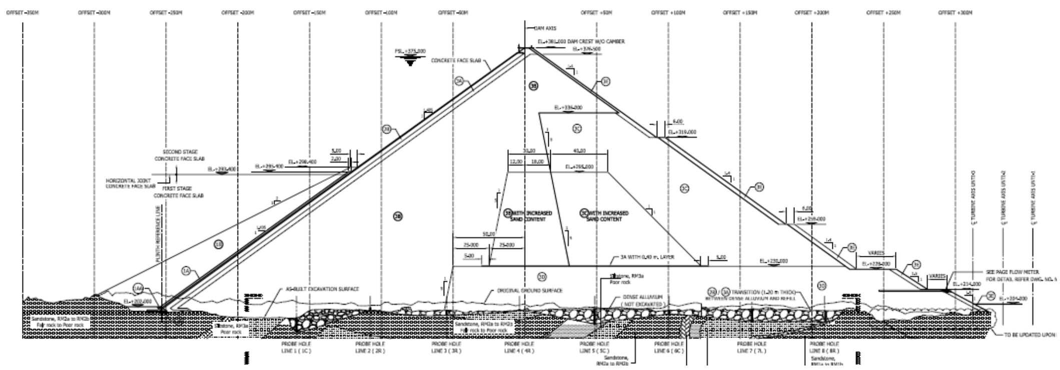


Fig. 1 NN2 CFRD Dam zoning

The joints of face slabs are of importance for CFRD. The perimeter joint is the most importance, since it connects between plinth and face slab. The vertical and horizontal joints of the face slabs have to provide with sufficient deformation in order not to cause disruption of the face slab.

2.1 DAM ZONING

The designation of the rockfill zones of NN2 CFRD, as shown in Fig. 1, are adopted as suggested by ICOLD (2004). The NN2 CFRD dam zoning is further validated by FEM. 2D and 3D FEM have been carried out to assess the rockfill material properties in order to make use of available rockfill material at potential quarry (IWHR, 2008). The non-linear properties employed in the 2D and 3D FEM is determined based on large triaxial test (IWHR, 2007). The analyses results revealed that the material properties for Zone 3C is of importance to deformation of upper part of the face slab. Therefore, material property for this zone has to be improved.

From 3D FEM analysis results, it is recommended to construct the rockfill layer from upstream to downstream horizontally. The purpose is to eliminate the possible impacts of differential deformation of rockfill on the concrete face slab. For retaining the first year's flood, the priority section is necessary. However, the height difference from the top of the priority section to the downstream rockfill should be limited. Normally, this height difference should not more than 40m. The stage of dam embankment is finalized based on experiences and 3D FEM as shown in Fig. 2.

2.2 DESIGN OF FACE SLAB

Design of NN2 CFRD face slabs begins with the selection of face slab thickness, width and location of vertical and horizontal joints. Selection of face

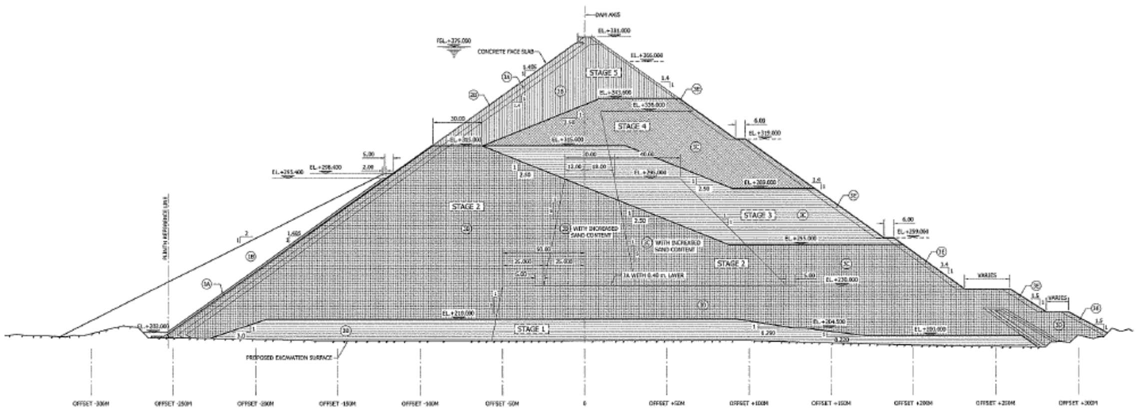


Fig. 2 NN2 CFRD Embankment construction stages

slab thickness is based on past experiences. Face slab widths are controlled with respect to dam abutments as well as valley shape. Current guidelines used for determining the thickness of face slabs for NN2 CFRD is reservoir head dependent.

The minimum design thickness of the face slab is usually on the order of 0.3m with thickness varying with reservoir head, H, in accordance with the following:

Face Slab Thickness, T (m) = 0.3 + 0.003H

From the practices of recent high CFRDs in the world, it is noticed that the face slabs in the riverbed section may be subjected to high compressive stress if the deformation of rockfill dam is not strictly controlled. To avoid the rupture of concrete face slabs in the riverbed section, it is proposed to increase thickness of the face slabs in the riverbed section. Considering the fact that the ruptures of face slabs are happened in upper part of face slab, the increase of the slab thickness could only be applied for the second stage face slabs. The thickness of the first stage face slab is remain unchanged. The suggested starting thickness at the top of face slab is 40cm. Thus, thickness of the face slab for second stage face slab at riverbed section can be determined from

Face Slab Thickness, T (m) = 0.4 + 0.00178H

Panel widths for the face slabs are typically classified into two categories. Narrower panel widths (7.5m wide) are used where vertical joints are desired as tension joints, which are located on the abutments. Wider panel widths (15.0m wide) are used where vertical joints are treated as compression joints, which are mostly located in the riverbed area.

For improving the performance of concrete face slab, double layers of reinforcement is recommended with 0.4% of the gross area of the concrete face slab for each way. The reinforcement is increased up to 0.5% in the area close to the dam plinth.

2.3 PREVENTIVE MEASURES

Measures adopted to prevent rupture of face slab during design stage for NN2 CFRD include following:

(1) Increase the thickness of the 10 central panels in second staged face slab.

(2) The reinforcement is separated into two layers, top and bottom, in both directions as opposed to the usual location in the center of the slab. The

stirrups against reinforcement buckling are also provided at the high compression area.

(3) The additional reinforcements are employed for anti-spalling and bending stress resistant at the face slab rims.

(4) Increase the face slab protection zone, Zones 1A and 1B to EL +298.4 masl, which is about 50% of the dam height.

(5) The copper waterstops and mortar pad is outside the theoretical thickness of face slab at compression joints.

(6) The height of the central loop of the copper waterstop is reduced to keep the theoretical slab thickness at compression joints.

(7) Increase the compressible filler thickness from 10mm to 20mm at compression joints.

(8) The conventional V-notch at the top of the face slab is eliminated at compression joints.

3. CONSTRUCTION OF NN2 CFRD

3.1 EMBANKMENT CONSTRUCTION

Prior to commencement of embankment work, the river bed cleaning and foundation improvement is required to achieve the competent foundation. The main dam embankment has mainly divided into 5 stages to corporate with face slab construction sequences, as shown in Fig. 2.

Stage 1: Constructed the rockfill embankment of 10m height from downstream and left the area of 30m at upstream in order to construct the plinth at river bed section.

Stage 2: Constructed the main dam embankment to accommodate the construction of first stage face slab upto elevation 315 masl, which corresponds to 115m in height.

Stage 3: This stage had to construct parallel with the construction of the first stage first slab. Partial construction of the embankment at downstream portion has been carried out by controlling the different height of embankment between upstream portion and downstream portion of not more than 40m. This is to control the differential settlement and stress in rockfill for upstream and downstream.

Stage 4: After completion of the first stage face slab concrete, the upstream portion has been embanked upto the wave wall foundation. Whenever complete this stage, the second stage face slab started commencement. In parallel the face slab protection zone, Zone 1A and 1B, have also been started in this stage.

Stage 5: After completion of the second stage face slab and the wave wall, the last portion of embankment above the wave wall foundation will be constructed.

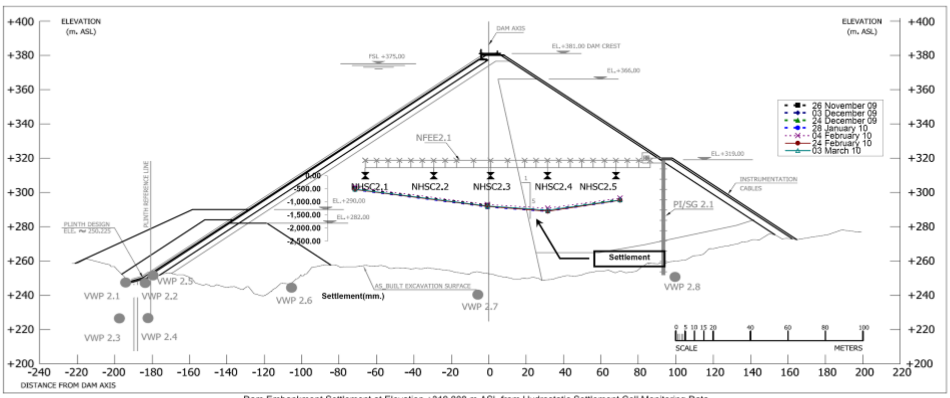
The total volume of rockfill is approximately 10 million m^3, which have been completed within 20 months. The peak production of rockfill is 700,000 m^3 per month, which have been transported by 25 units of 35 tons-off high way trucks and 50 units of 15 tons trucks. The compacted rockfill has been controlled to achieve the dry unit weight of more than 21.5 kN/m^3. The 15 tons vibrating rollers with 8 passes and with 150-200 liters/m^3 of rockfill for water sluicing have been conducted to achieve the requirement. The 0.80m lift thickness of 3B and 3C material has been employed depending on the maximum size of rockfill material.

3.2 FACE SLAB CONSTRUCTION

The total area of concrete face slab is approximately 88,000 m^2. The concrete mix design of C25/38 has been developed for concrete face slab, which is suitable for 2.0m long slip form. The concrete has been delivered by transit mixer trucks and distributed into 4 chutes, which the pouring controlled speed is 2.0m per hour. The construction of face slab is divided into two stages, first and second stage concrete face slab.

4. PERFORMANCE OF NN2 CFRD

The extensive instrumentations were installed within rockfill embankment and concrete face slab. Instrumented data are reading and analyzed continuously to assess the performance of NN2 CFRD during construction, during reservoir impounding and in-service of the dam. The instrumentations installed for NN2 CFRD within rockfill embankment and concrete face slab are summarized in Table 1.

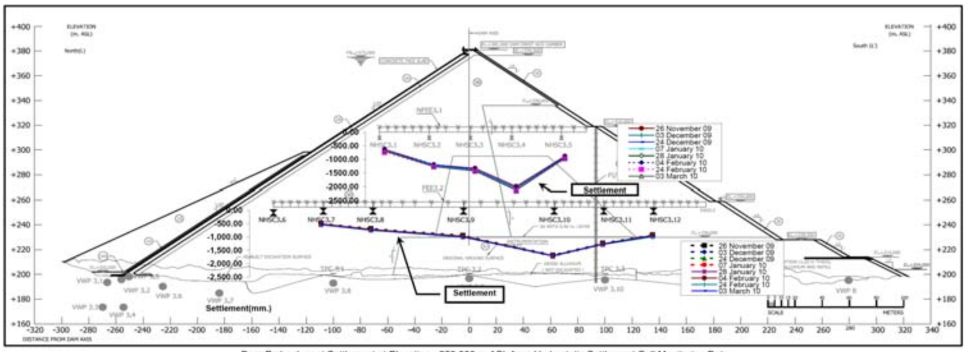


Dam Embankment Settlement at Elevation +319.000 m.ASL from Hydrostatic Settlement Cell Monitoring Data

Fig. 3 Settlement in rockfill on left abutment

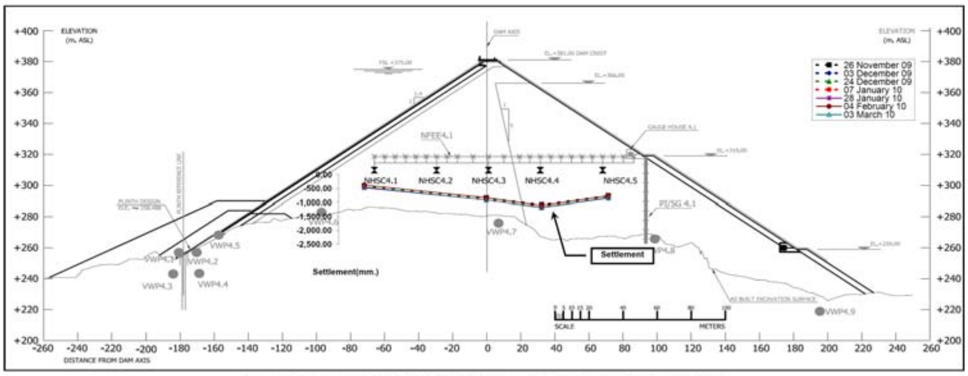
Table 1 Summary of instrumentations installed at NN2 CFRD

Location	Instrumentation	Quantity
Rockfill	Vibrating Wire Piezometer	35
	Total Earth Pressure Cell	3
	Probe inclinometer & Magnetic Settlement Gauge	3 sets
	Distributed Fiber Optic Temperature (DFOT)	900 m.
	Weather Station	1 set
	Hydrostatic Settlement Cell	22
	Fixed Embankment Extensometer	111
	V-notch Measuring Weir	1
	Strong Motion Accelerometer	1
	Gauge House	5
	Open Standpipe Piezometer	7
Face slab	Probe Inclinometer on Faceslab	1
	1 Dimensional Joint Meter	4
	2 Dimensional Joint Meter	10
	3 Dimensional Joint Meter	13
	Electro Level (Tilt Meter)	23
	3D Concrete Strain Gauge	27
	Rebar Strain Gauge	27
	Non Stress Strain Meter	7



Dam Embankment Settlement at Elevation +259.000 m.ASL from Hydrostatic Settlement Cell Monitoring Data

Fig. 4 Settlement in rockfill on riverbed section



Dam Embankment Settlement at Elevation +319.000 m.ASL from Hydrostatic Settlement Cell Monitoring Data

Fig. 5 Settlement in rockfill on right abutment

At the present stage, during construction, some instrumented data are reading and analyzed continuously to assess the performance of NN2 CFRD. An example of the performance derived from the monitoring results of hydrostatic settlement cells, which are installed in the cross-section at left abutment, center and right abutment, are illustrated as shown in Fig. 3 to 5 respectively. The maximum settlement observed in the rockfill is 2.13m, approximately 1.15% of the dam height, which appeared at central part of the dam towards downstream. This performance is considered as normal, which is similar to previous high CFRDs. According to the observed performance of NN2 CFRD during construction, additional measure is adopted to prevent rupture of the concrete face slab. The thickness of compressible filler material at compression joint is adopted to increase to 30mm for five panels of second staged face slab in the riverbed section.

5. CONCLUDING REMARKS

The design of NN2 CFRD is taken into consideration of recent experiences of high CFRDs with comparative considerations of the numerical analysis results. Some CFRD phenomenon can be explained by the numerical analysis results.

The dam zoning, face slab and joints are initially based on experiences from recent high CFRDs. 2D and 3D FEM are employed to assess the NN2 CFRD behavior with some modifications of initial design. According to analysis results, preventive measures are applied to prevent rupture of the concrete face slab. The actual behavior of NN2 CFRD during construction is observed by extensive instrumentations. During construction, modification of the design is required according to the observed performance.

The project is expected to be completed by March 2011 and the impounding is scheduled on March 18, 2010.

REFERENCES

[1] ICOLD Committee on Materials for Fill Dams. *Concrete Face Rockfill Dams Concepts for Design and Construction*, Draft, 2004.

[2] IWHR. *Report on Laboratory Tests of the Rockfill Materials of Nam Ngum 2 CFRD*, 36p, 2007.

[3] IWHR. *Numerical Analysis of Nam Ngum 2 Concrete Face Rockfill Dam in Laos*, Final Report, 2008.

[4] IWHR. *Three-Dimensional Numerical Analysis of Nam Ngum 2 Concrete Face Rockfill Dam*, Final Report, 2008.

Nam Ngum 2 CFRD
Design, Construction and Performance

Nam Ngum 2 Hydroelectric Power Project (NN2 HPP)

Aphichat SRAMOON

NN2 HPP

Owner: Nam Ngum 2 Power Co., Ltd. (NN2PC)

EPC Contractor: Ch. Karnchang Public Co., Ltd.

Design Engineer: TEAM Group

Independent Engineer: Poyry

Location: Vientiane, Lao PDR

Construction Period: 5 years

Commissioning: November 2010

EPC Contract Packages

Project Packages:

Package 1 **Civil Works,** ***Awarded to Ch. Karnchang (Lao) Co., Ltd.***

Package 2A **Gates and Stop Logs,** ***Awarded to Alstom, India***

Package 2B **Steel Liners for Penstock,** ***Awarded to Wheesoe, Malaysia***

Package 3 **Electro-Mechanical Equipt.,** ***Awarded to Mitsui-Toshiba, Japan***

Package 4A **Main Transformer and Switchgear,** ***Awarded to Sri U Thong, Thailand***

Package 4B **Transmission Line,** ***Awarded to CERIECO, China***

Package 5 **Associated Works (Access Road and Permanent Camp),** ***Awarded to PT Construction Co., Ltd., Lao PDR***

NN2 HPP

Main Components

Reservoir

River Diversion Facility

Main Dam

Spillway

Power Waterway System

Powerhouse & Switchyard

Project Location and Suitability

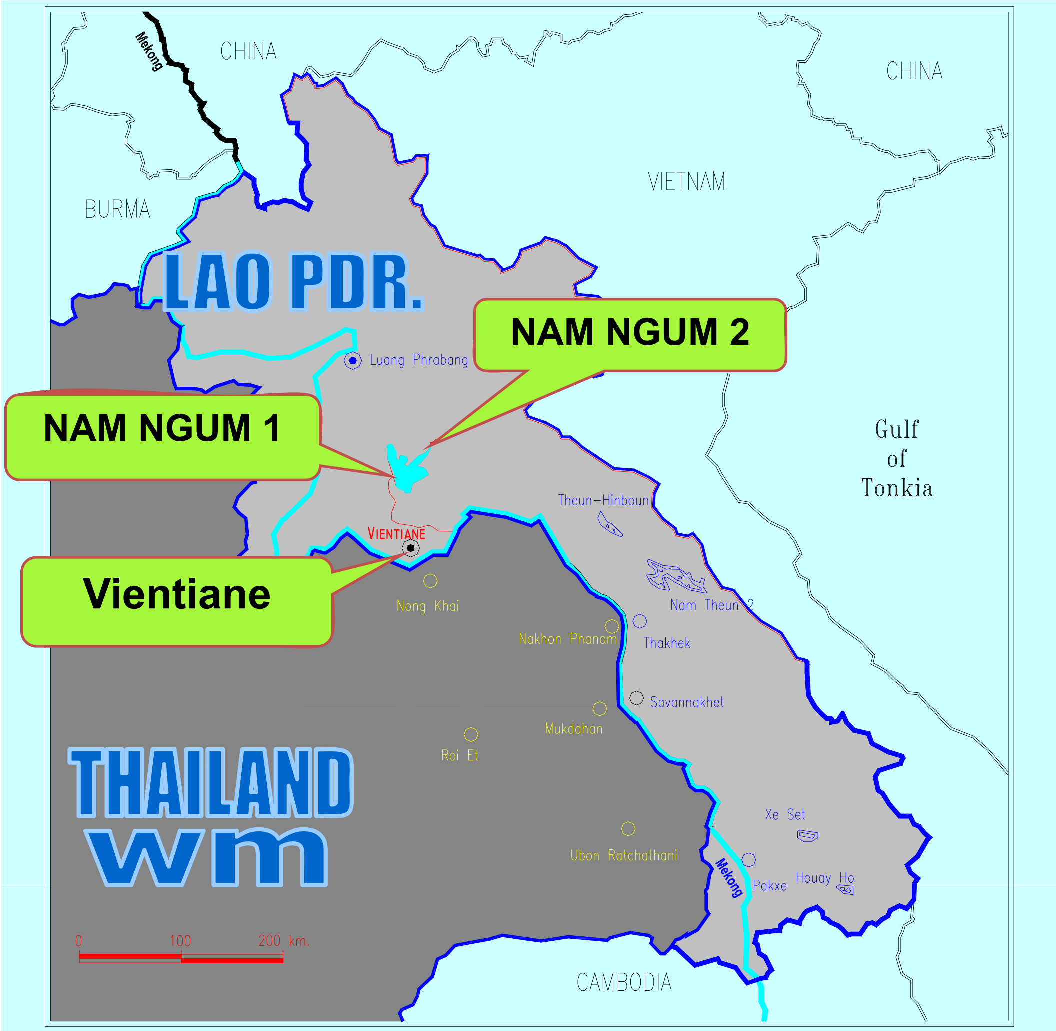
Location

- 35 Km. Upstream of Nam Ngum 1
- 95 Km. Northeast of Vientiane

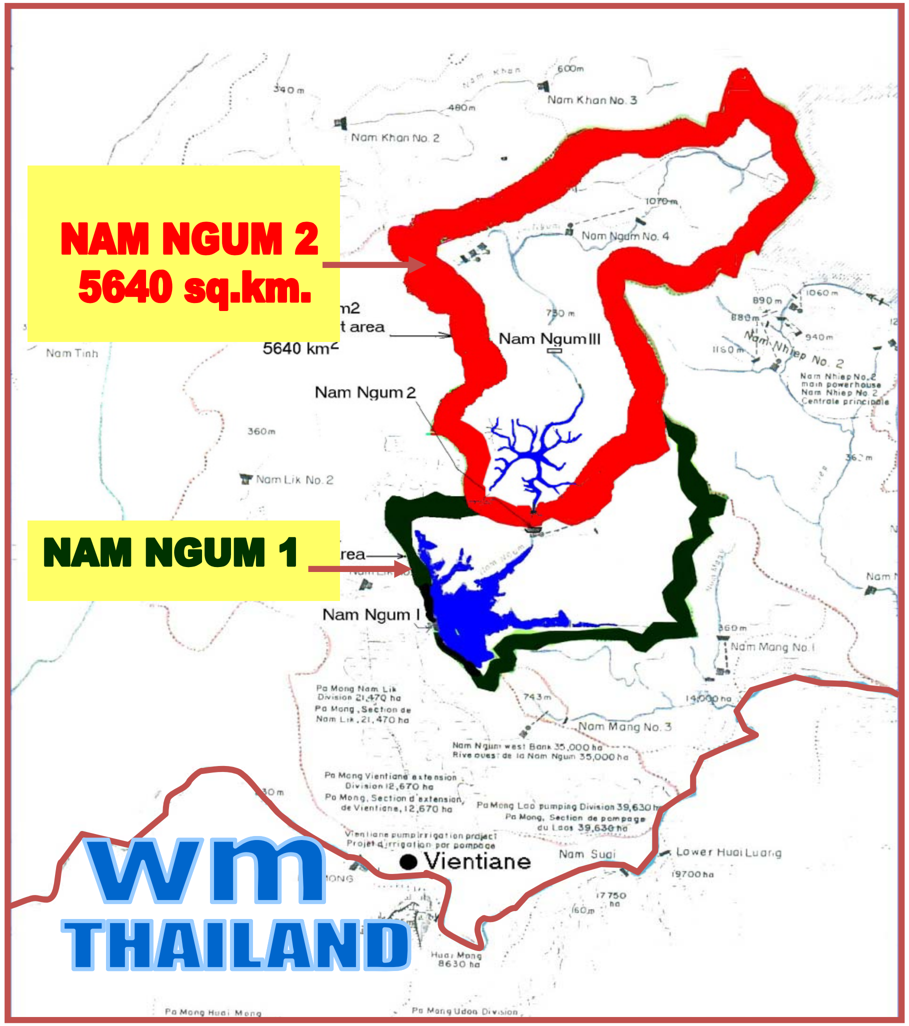
Suitability

- Large catchments - 5,640 km^2
- Topography - steep slope
- Geology - sandstone/siltstone
- Hydrology - 50 year records
- Rainfall - bet. 1,800 – 3,700 mm.
  - average 2,510 mm.
- Inflow - bet. 4,000 – 9,500 MCM.
  - average 6,270 MCM.

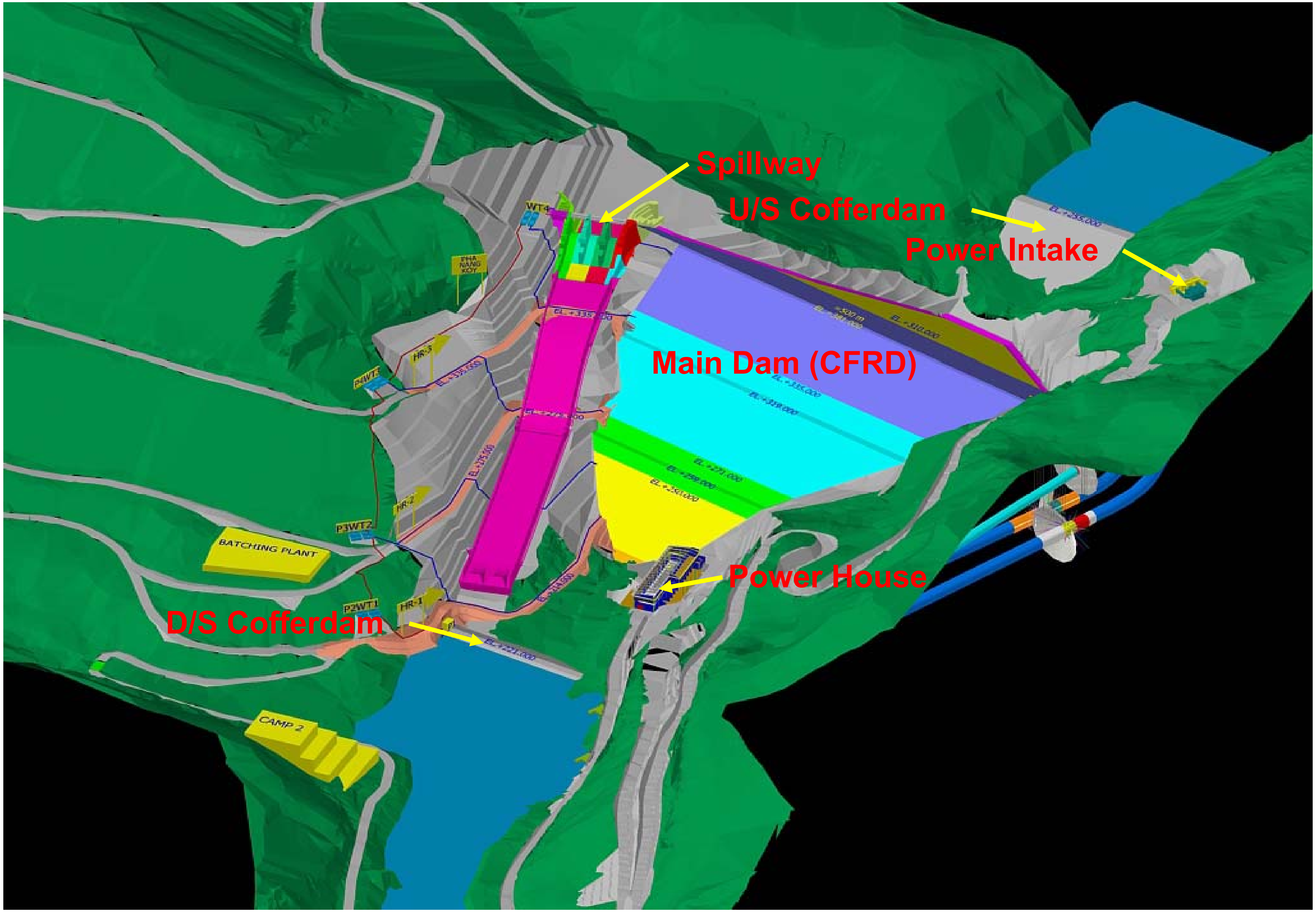
NN2 HPP Project



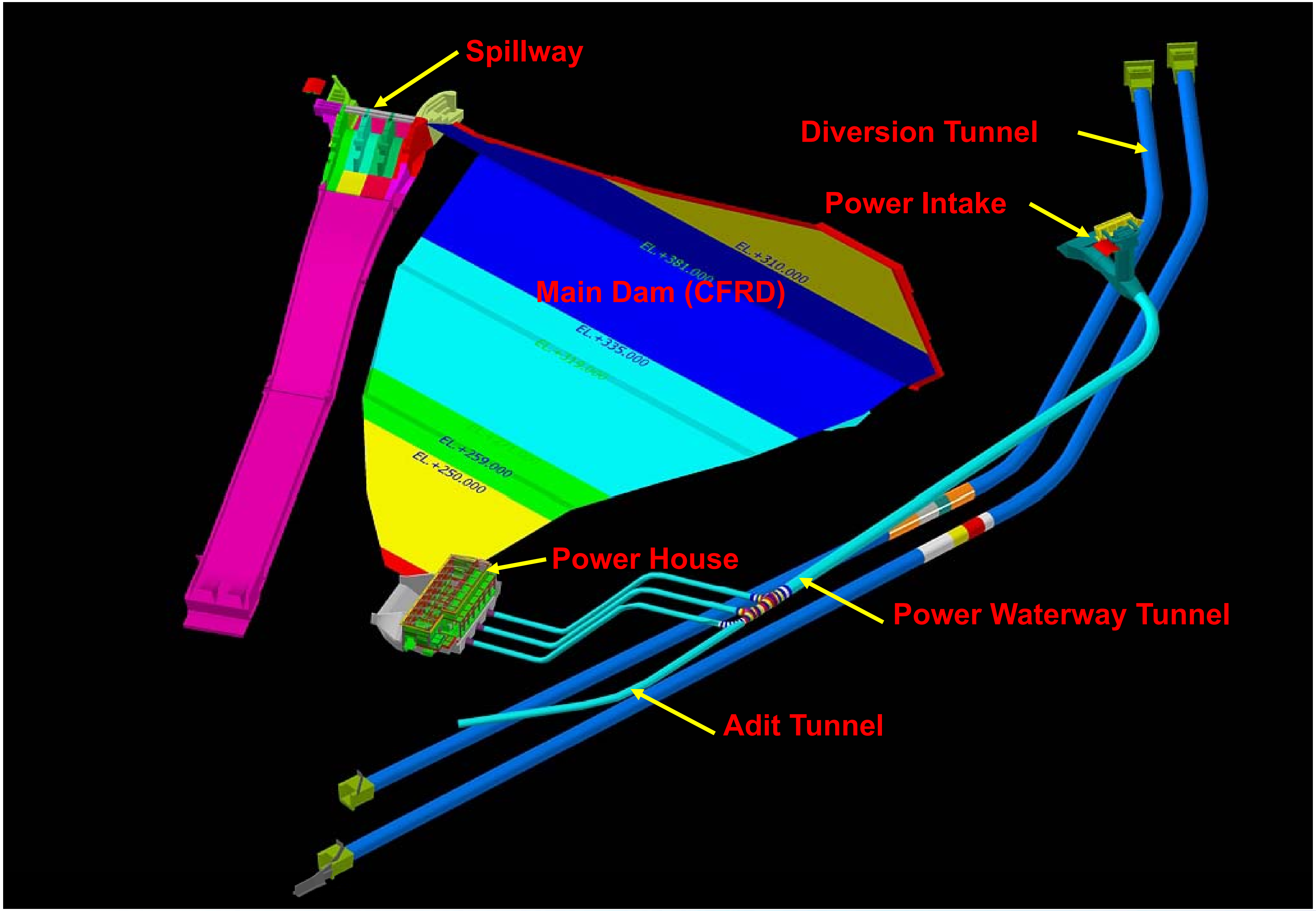
Project Location



Catchment Area



Project Overview



Project Components

GFE
"The Geotechnical Expert"

Aerial Photo

A Member of TEAM GROUP

Reservoir

Catchment Area	= 5,640 km^2
Average Annual Inflow	= 6,270 MCM
Maximum Flood Level	= 378.75 masl
Full Supply Level	= 375.00 masl
Minimum Operation Level	= 345.00 masl
Reservoir Area at FSL	= 122 km^2
Storage at FSL	= 6,774 MCM
Storage at MOL	= 3,780 MCM
Active Storage	= 2,994 MCM

River Diversion Facility

Design Flood during Construction = 3,850 cms

Diversion Tunnels (Two Tunnels)

Type : Concrete Lined-Horse Shoe Shape	
Diameter	= 11.70 m.
Length	= 1,100 and 1,200 m.
Inlet Level	= 210.50 masl
Outlet Level	= 209.10 masl

Cofferdams

Crest Level of U/S	= 255.00 masl
Crest Level of D/S	= 221.00 masl

Diversion Tunnels

Spillway

Spillway Type: Open Chute with Control Gates

Crest Level	= 359 masl
Crest Length	= 51 m.
Radial Gates 3 sets	= 16.9x15.0 m.
Chute Width	= 50 m.
Energy Dissipater	= Flip Bucket

Spillway Test

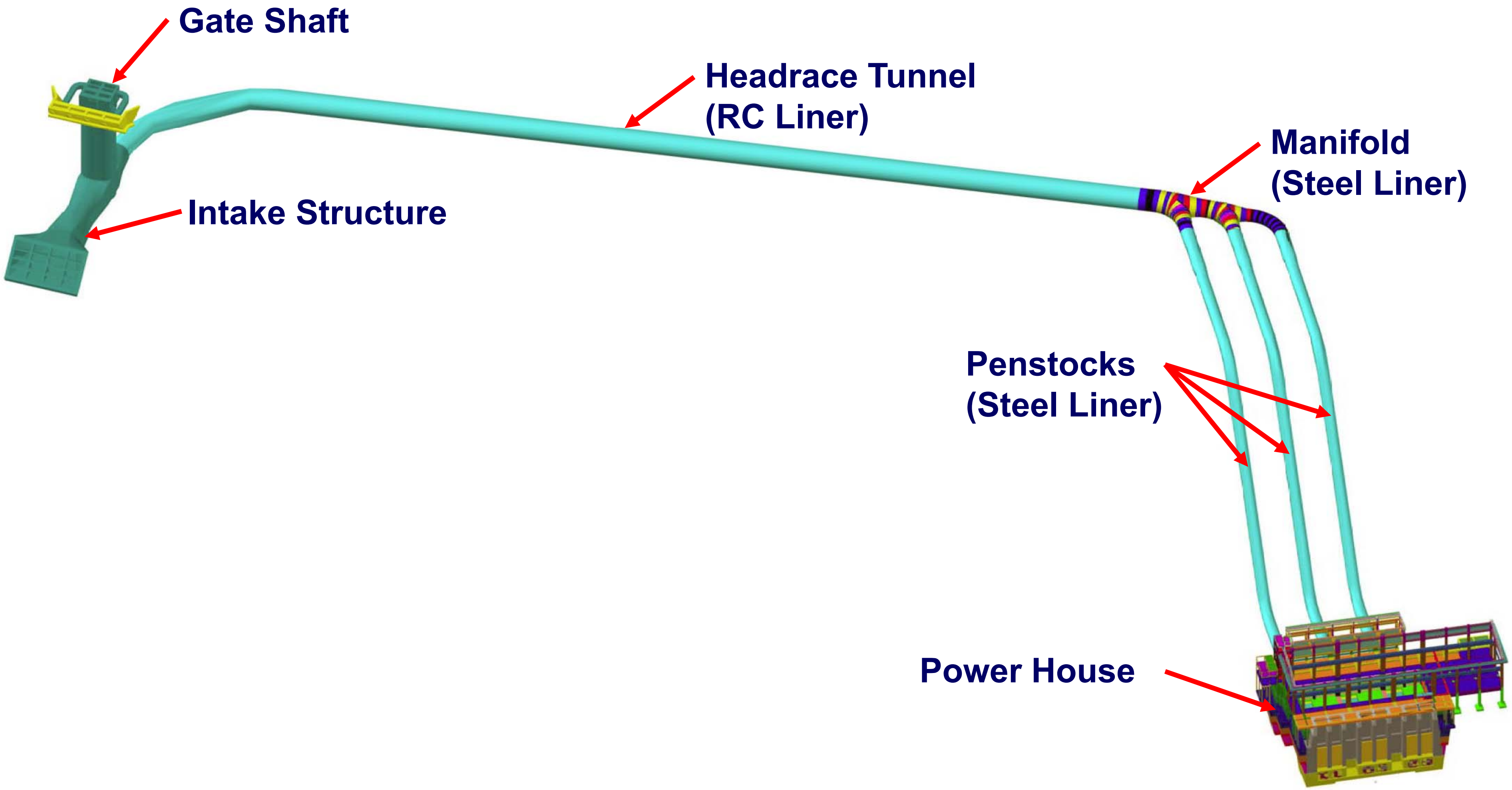
Power Waterway System

Intake Structure: **Front End Opening-**
Shaft Type Control Structure

Inlet Sill Level	= 320 masl
Stoplog 2 sets	= 5.6x10.7 m.
Roller Gate 2 sets	= 5.6x10.7 m.

Power Waterway System

Headrace Tunnel:	**Concrete Lined-Circular Tunnel**
Diameter	= 10.7 m.
Length	= 460 m.
Penstocks 3 nos:	**Inclined-Underground-Steel Lined-Circular-Shaft**
Diameter	= 5.35 m.
Length	= 265 m.



Power Waterway System

Intake Structure and Gate Shaft

Headrace Tunnel

Powerhouse

PH: Onground-Reinforced Concrete Structure

Finished Ground Level	= 226.8 masl

Turbine: Vertical Shaft-Francis Turbine

Number	= 3 Units
Rated Output	= 3x215 MW

Generator: Synchronous

Number	= 3 Units
Rated Output	= 3x205 MW

Switchyard

Type: Indoor-Gas Insulated Switchyard

Dimension	= 10x50 m.
Finished Level	= 242.3 masl

Powerhouse

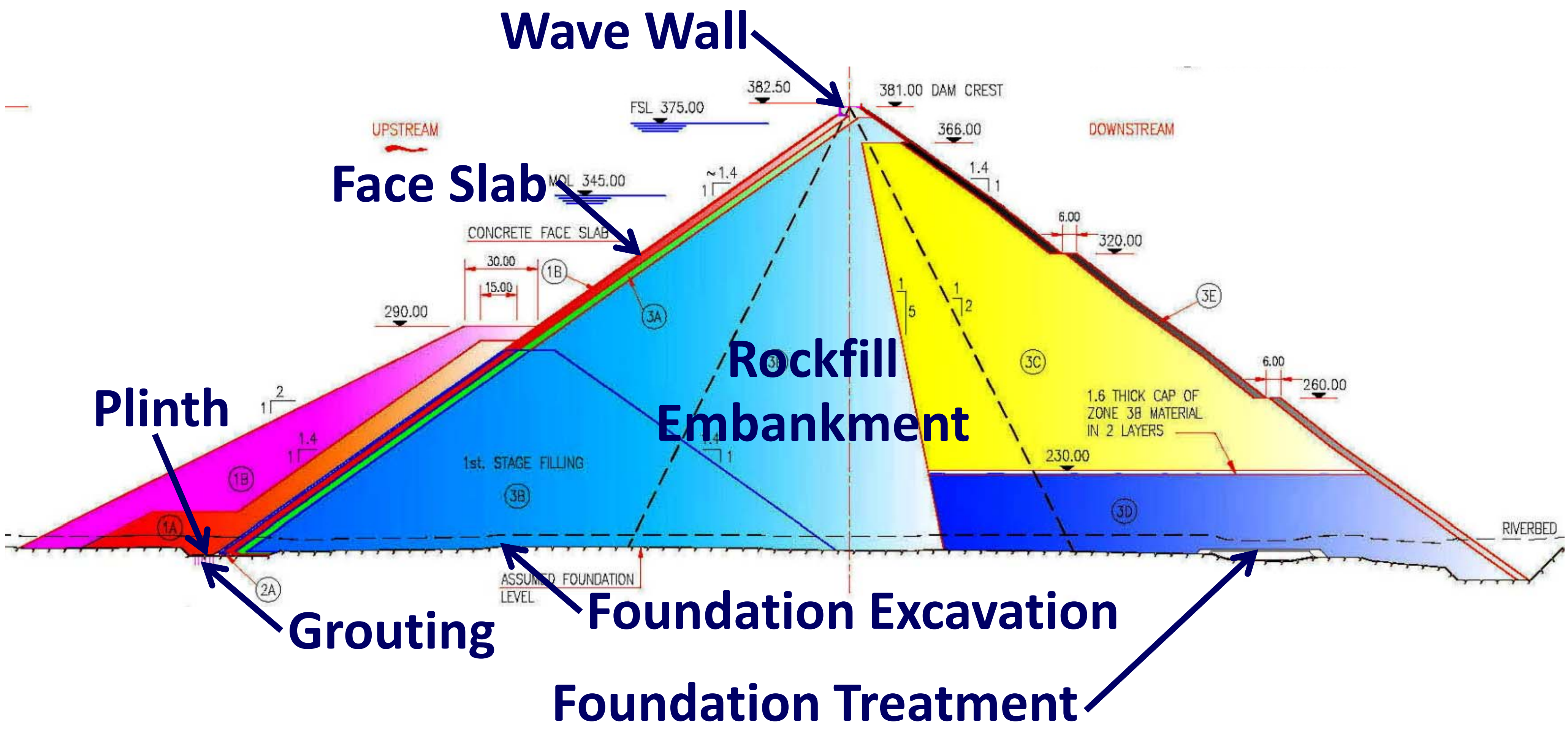
Main Dam (CFRD)

Dam Type: Concrete Face Rockfill Dam (CFRD)

Narrow Valley A/h^2	= 2.66
Dam Slope V:H	= 1:1.4
Crest Level	= 381 masl
Dam Height	= 182 m.
Crest Length	= 512 m.
Dam Width	= 518.80 m.
Plinth Width	= 6.0-10.0 m.
Thickness of Face Slab	= 0.30-0.83 m.

Design of NN2 CFRD

- Design of Excavation
- Design of Foundation Treatment
- Design of Grouting Works
- Design of Plinth
- Design of Dam Embankment
- Design of Face Slab
- Design of Dam Crest
- Design of Joints and Waterstops
- Design of Instrumentations



NN2 CFRD Components

Design of Excavation

Plinth Area

- Excavate to slightly weathered rock or better

Dam Upstream Area

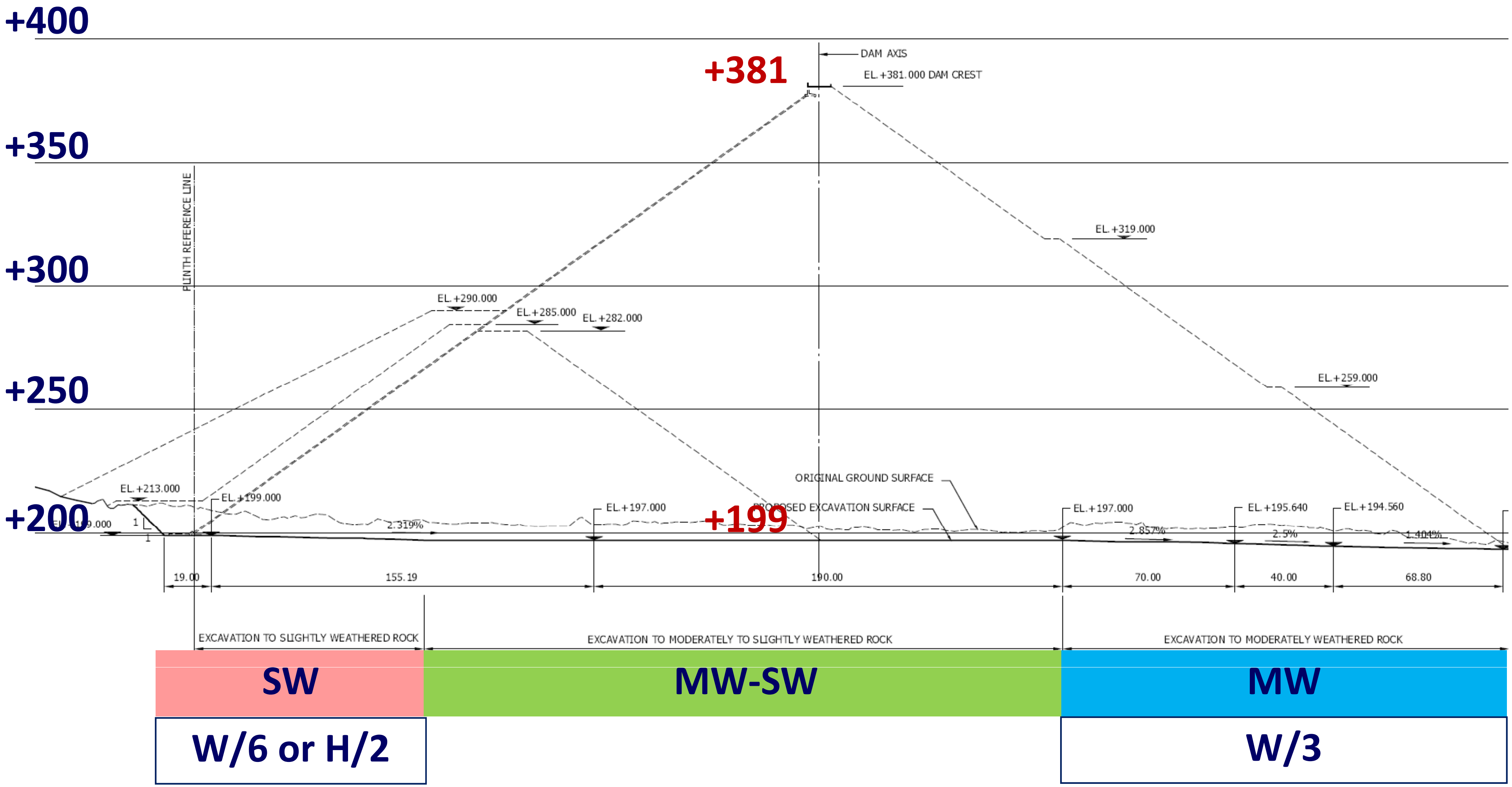
- Excavate to slightly weathered rock or better
- 1/6 of the foundation width or 0.5H, i.e., about 90m

Dam Central Area

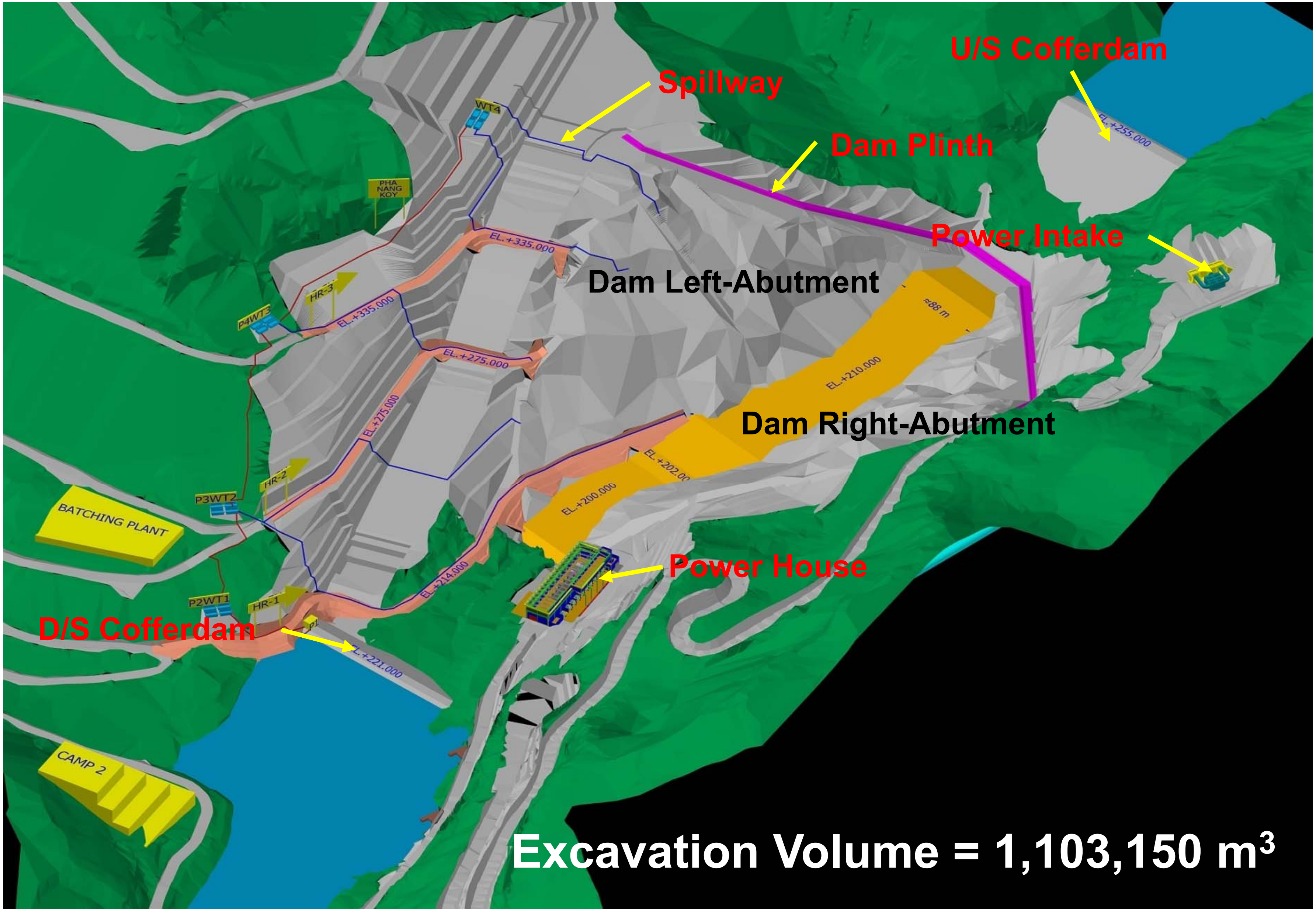
- Excavate to moderately to slightly weathered rock or better
- End of U/S area to starting point of the D/S area

Dam Downstream Area

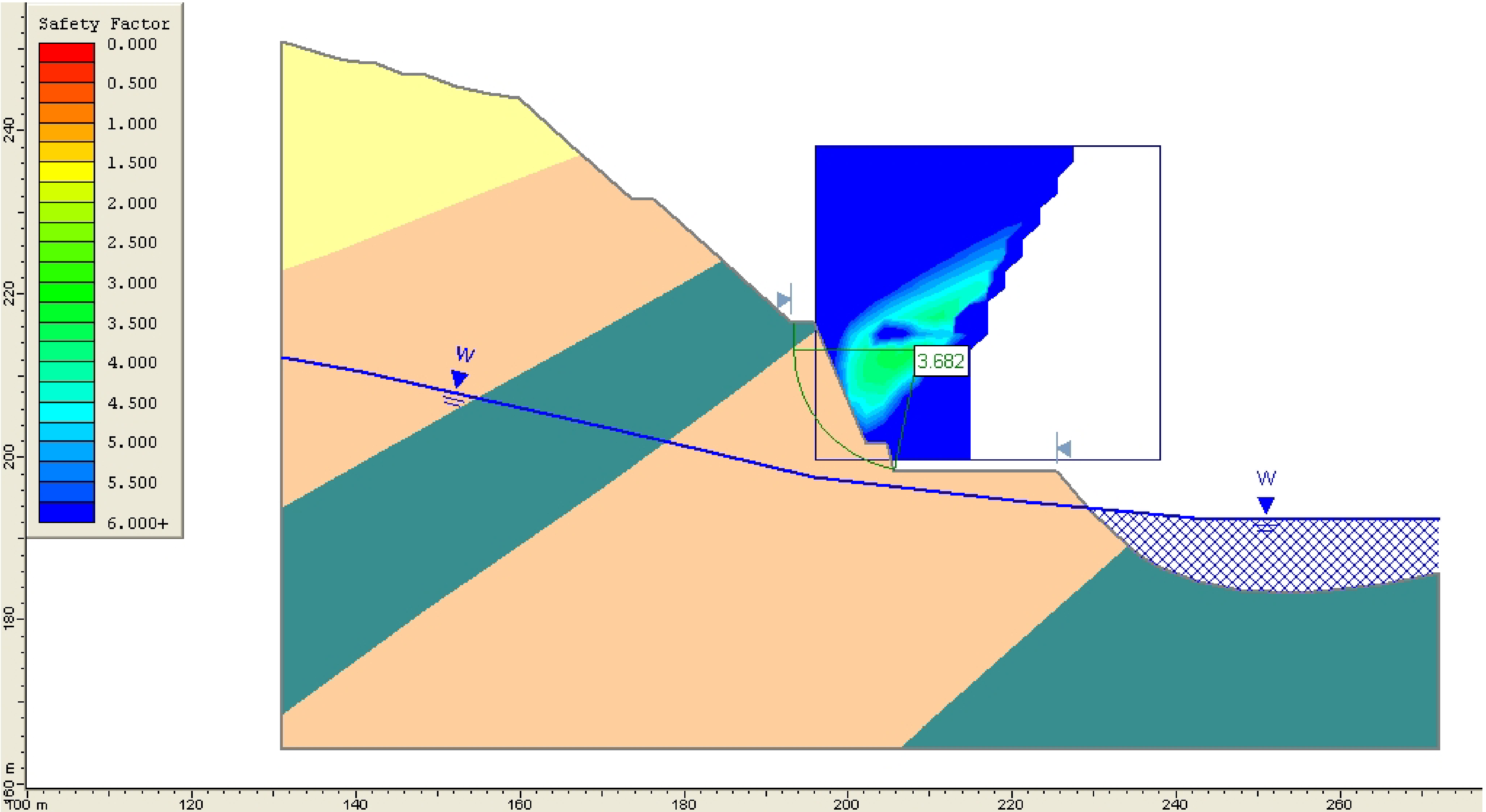
- Excavate to moderately weathered rock or better
- 1/3 of the foundation width, i.e., about 175m



Rock Foundation Excavation



Dam Excavation

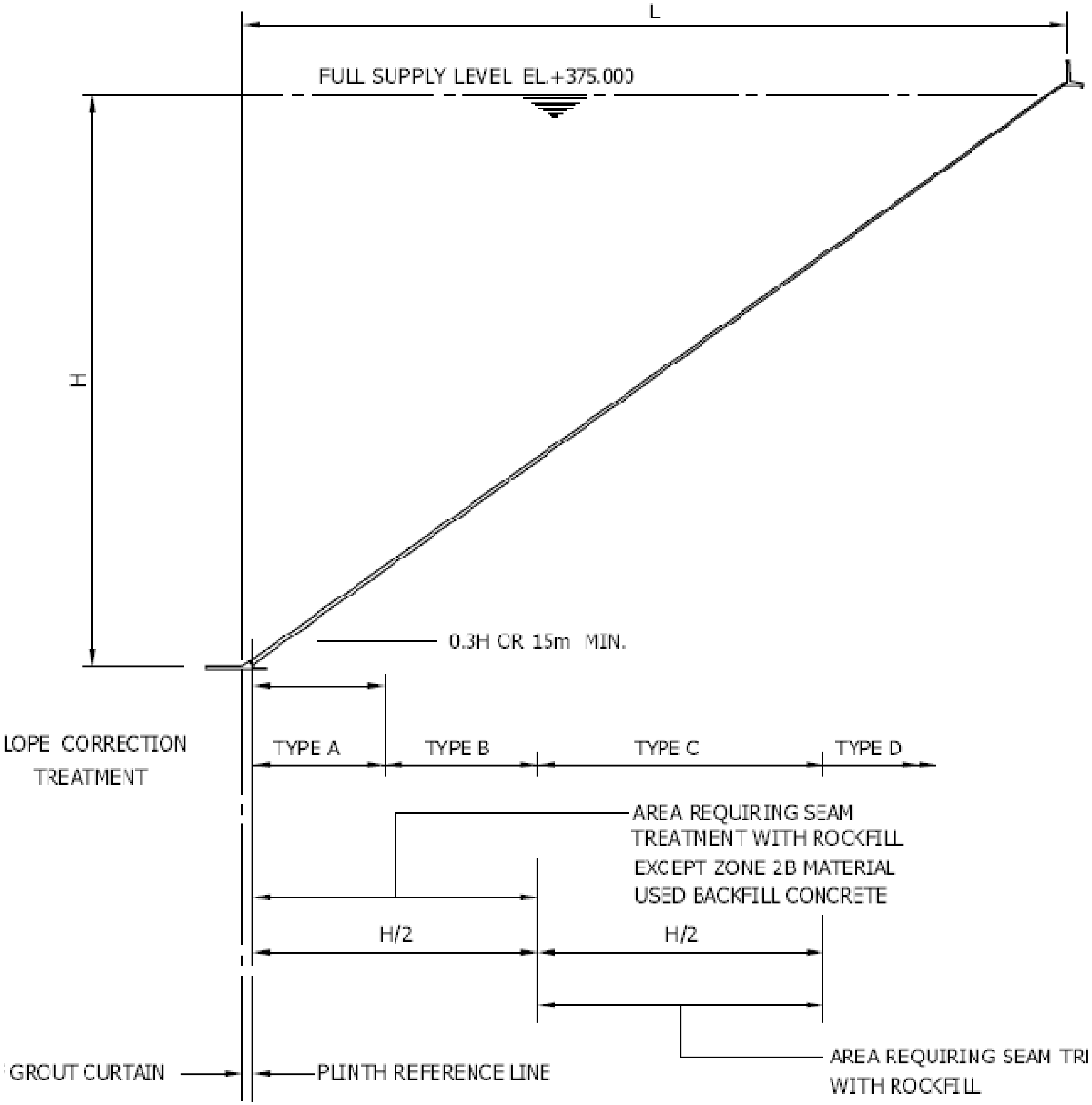


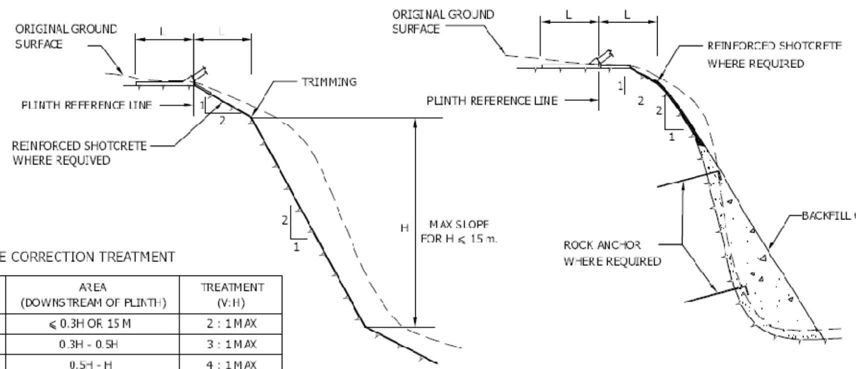
Slope Stability Analysis (F.S. > 1.3)

Design of Foundation Treatment

Foundation Treatment Objectives

- Positive control of seepage beneath or around the plinth.
- Removal of unstable or unsuitable foundation material from beneath the plinth and the body of the dam.
- Preparation of foundation surfaces to receive concrete, filters and rockfill.
- Limiting differential settlements of the plinth, the face slab and the perimeter joint.



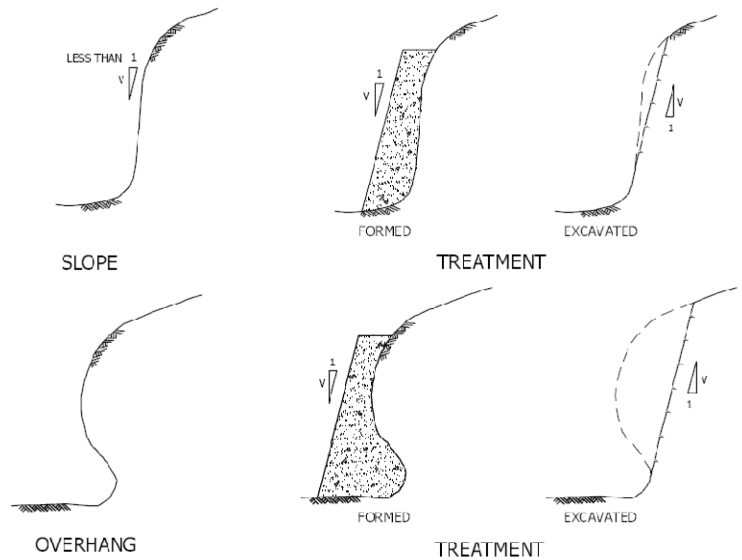


SLOPE CORRECTION TREATMENT

TYPE	AREA (DOWNSTREAM OF PLINTH)	TREATMENT (V:H)
A	⩽ 0.3H OR 15 M	2 : 1 MAX
B	0.3H - 0.5H	3 : 1 MAX
C	0.5H - H	4 : 1 MAX
D	> H	4 : 1 MAX

SLOPE CORRECTION TREATMENT TYPE A

NOT TO SCALE



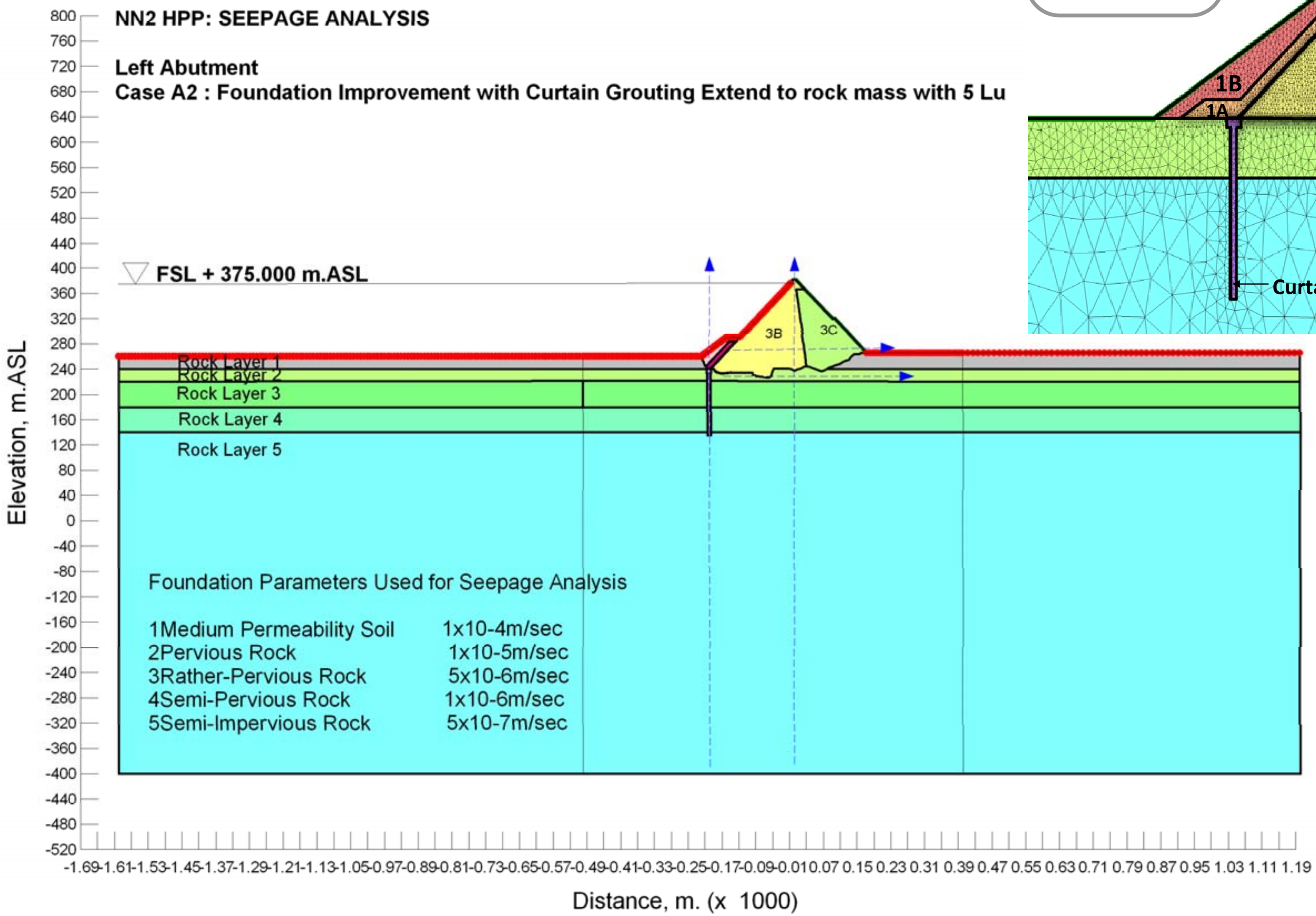
SLOPES AND OVERHANGS GREATER THAN 1 m. IN HEIGHT
REQUIRING TREATMENT (TYPE B, C AND D)

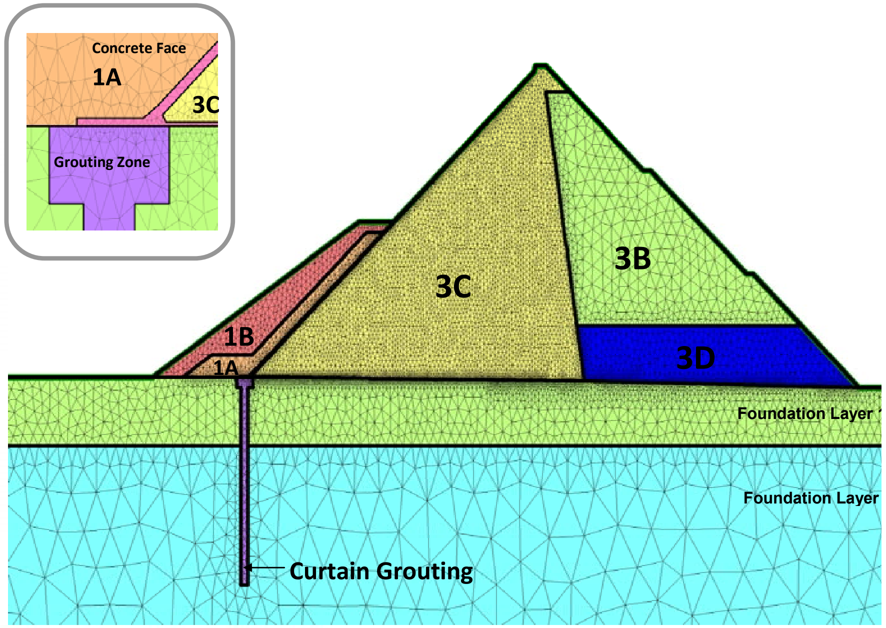
NOT TO SCALE

Design of Grouting Works

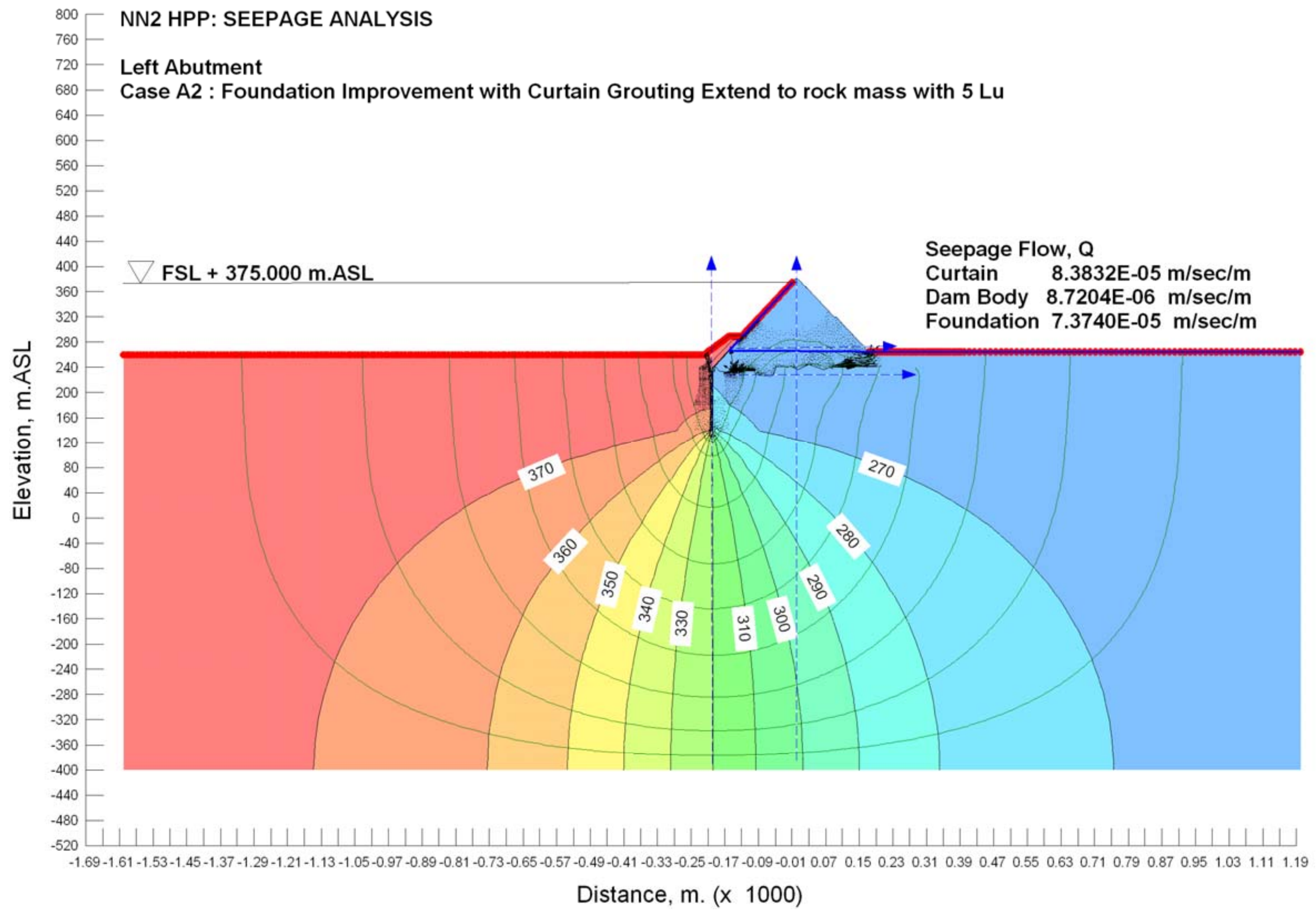
Acceptance Criteria

- Permeability < 5 Lugeons ($5x10^{-7}$ m/sec)
- Seepage Flow < 1% of full storage capacity during dry season (972 liters/sec)
- Exit Gradient at Plinth < 14 for SS and 8 for SiS
- Exit Gradient at Dam Base < 1





Seepage Analysis



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Total Pressure Head

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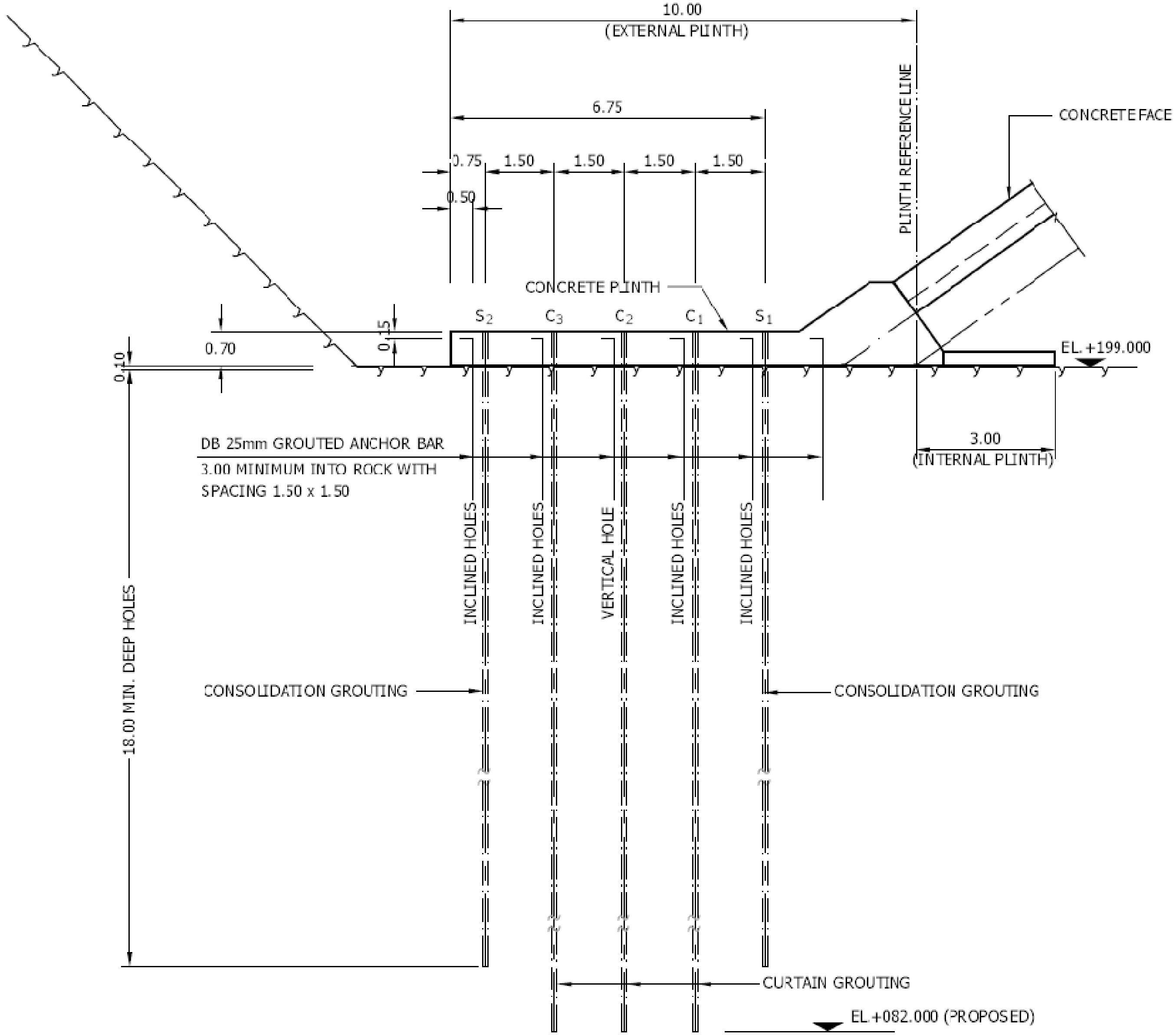
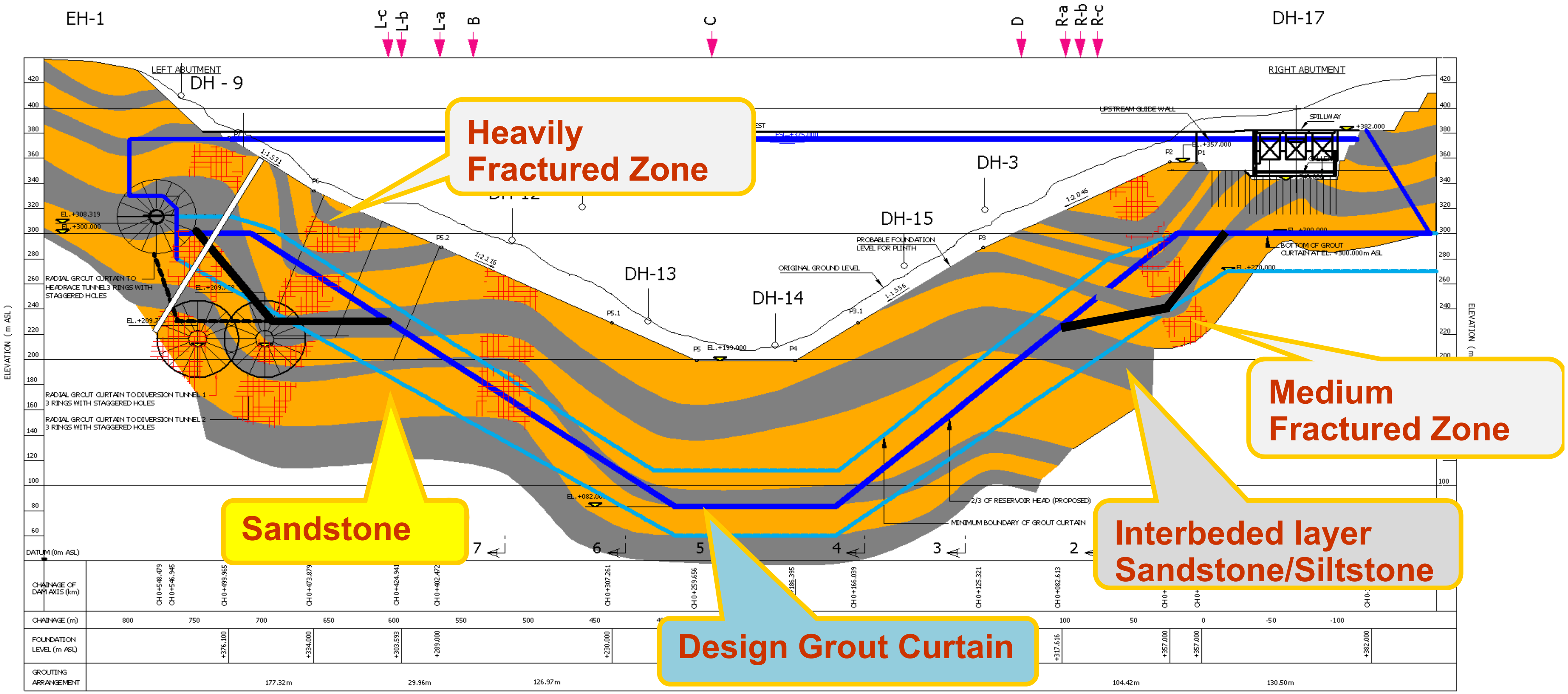
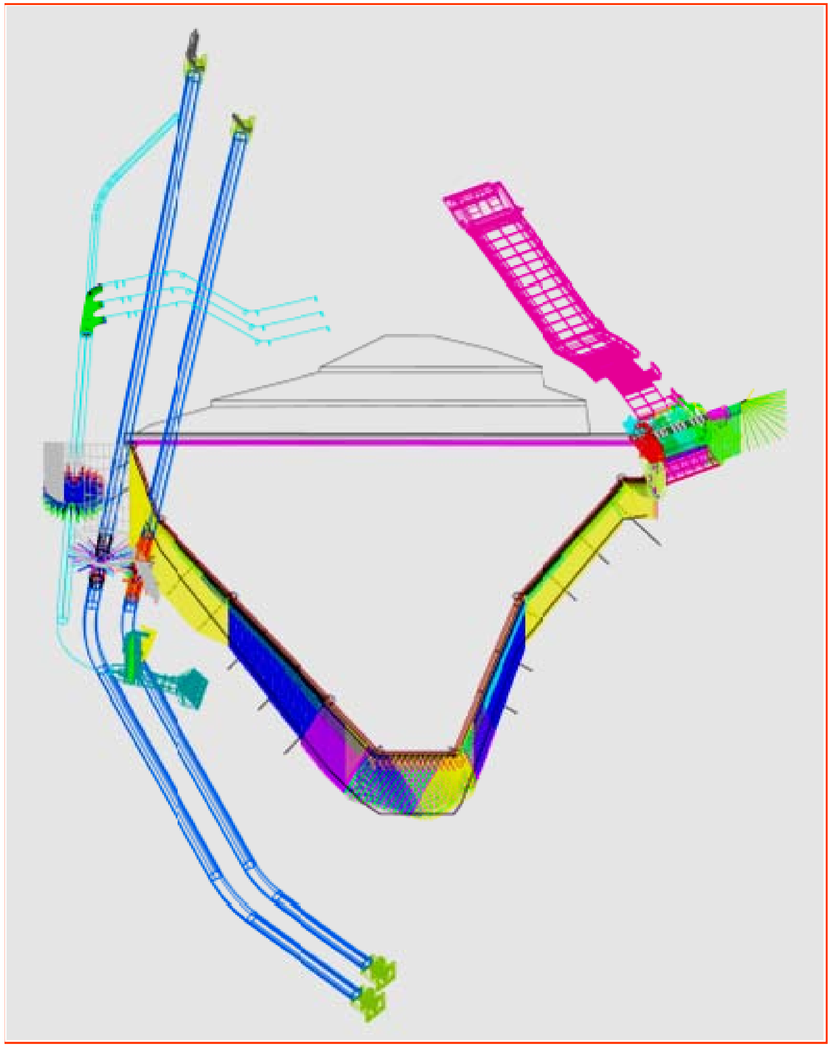


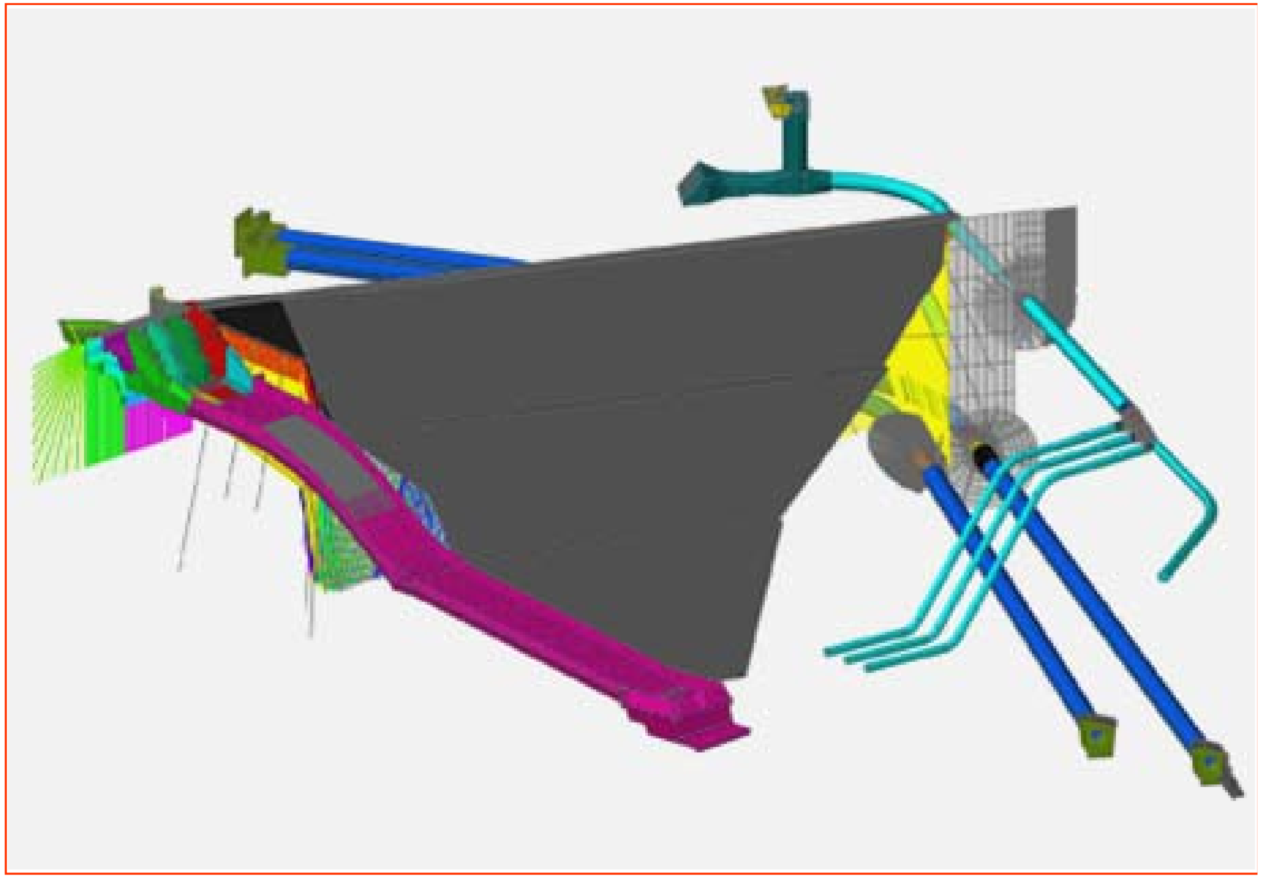
Grouting Arrangement



Geology along Dam Plinth



U/S View



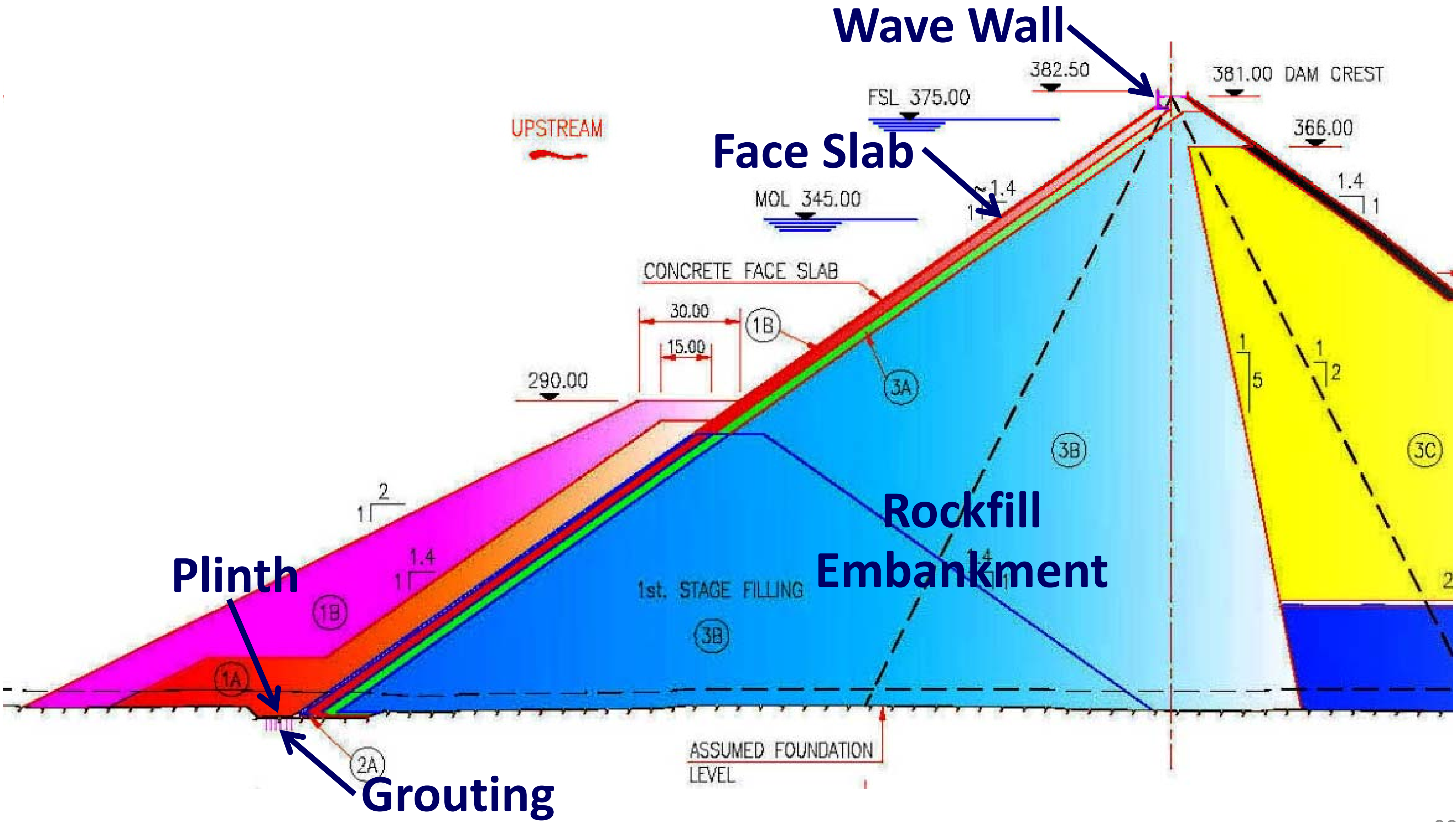
D/S View

Grout Curtain: 3D View

Design of Plinth

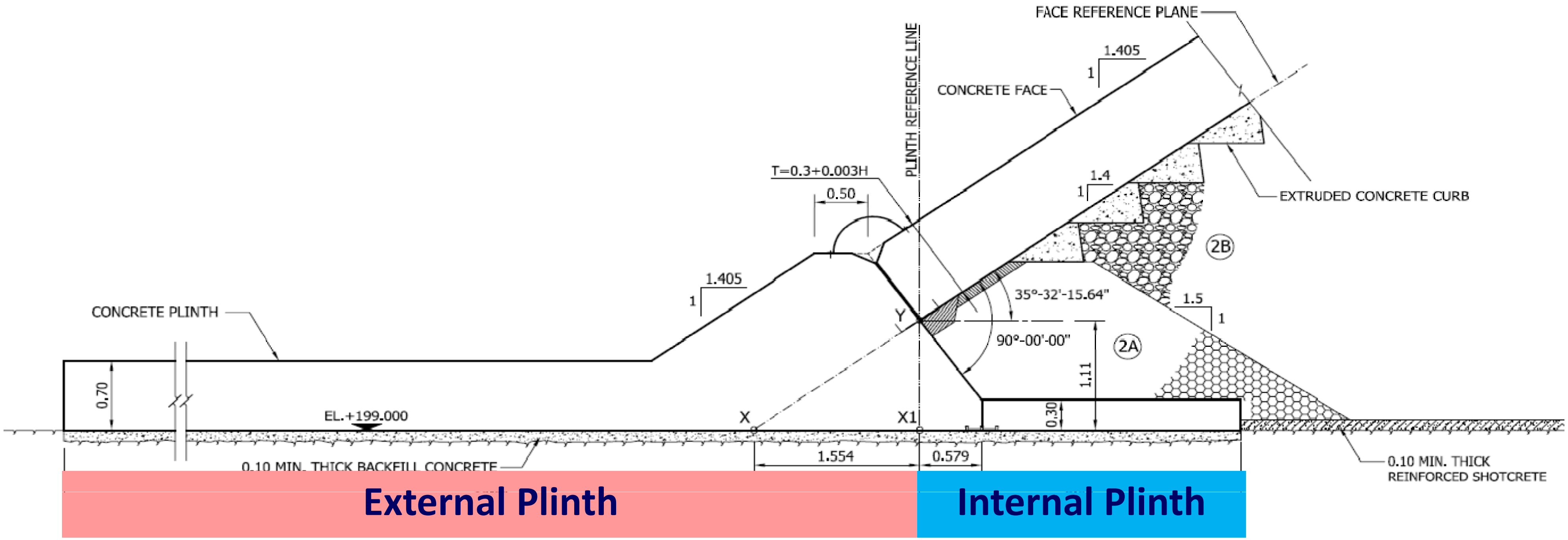
Plinth Function

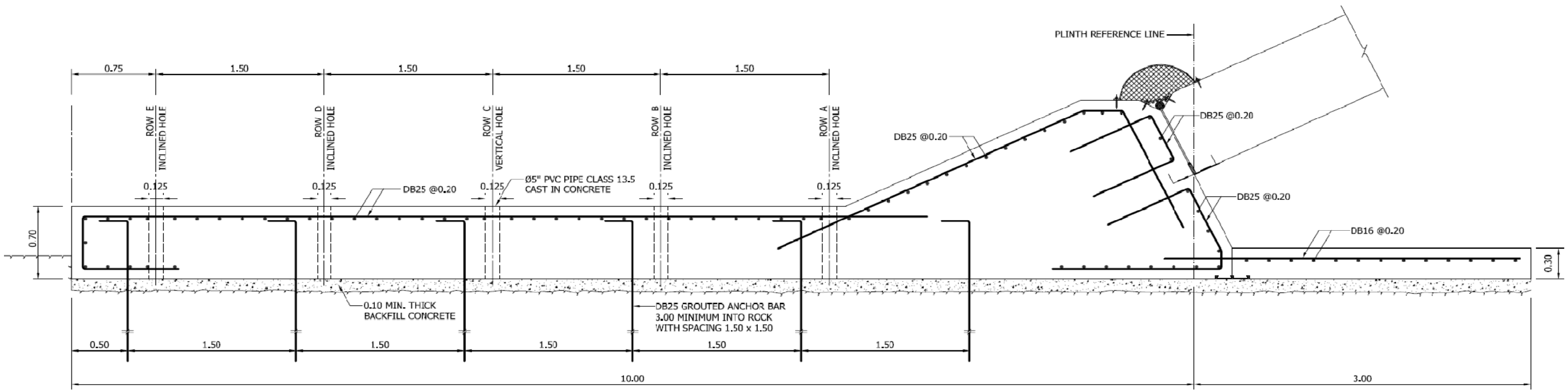
- Connects the face slab to the foundation rock.
- Act as a grout cap during grouting.
- Provides a starting position for concrete face slab slipforming equipment.



39

NN2 CFRD Components

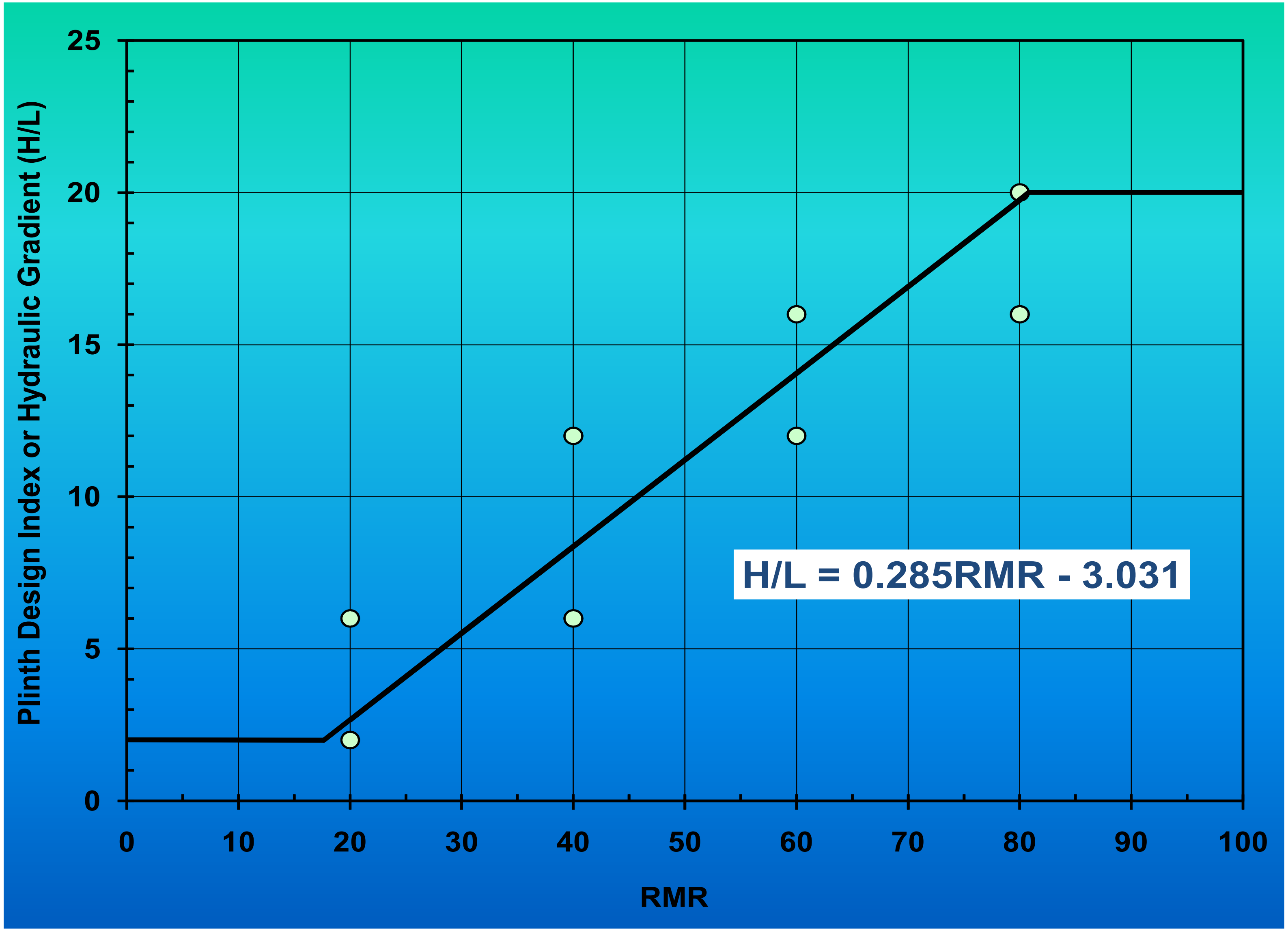




Plinth Section

Plinth Dimension

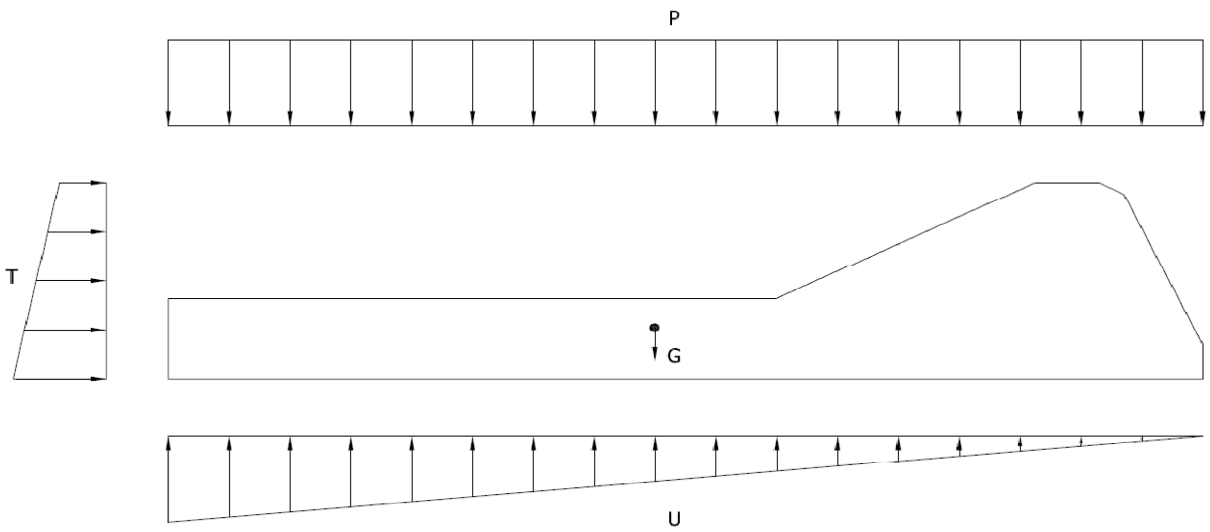
- Constant Thickness = 0.70 m
- Total Plinth Width = 6.0 ~ 23.0 m
- External Plinth Width = 6.0 m, 8.0 m and 10.0 m



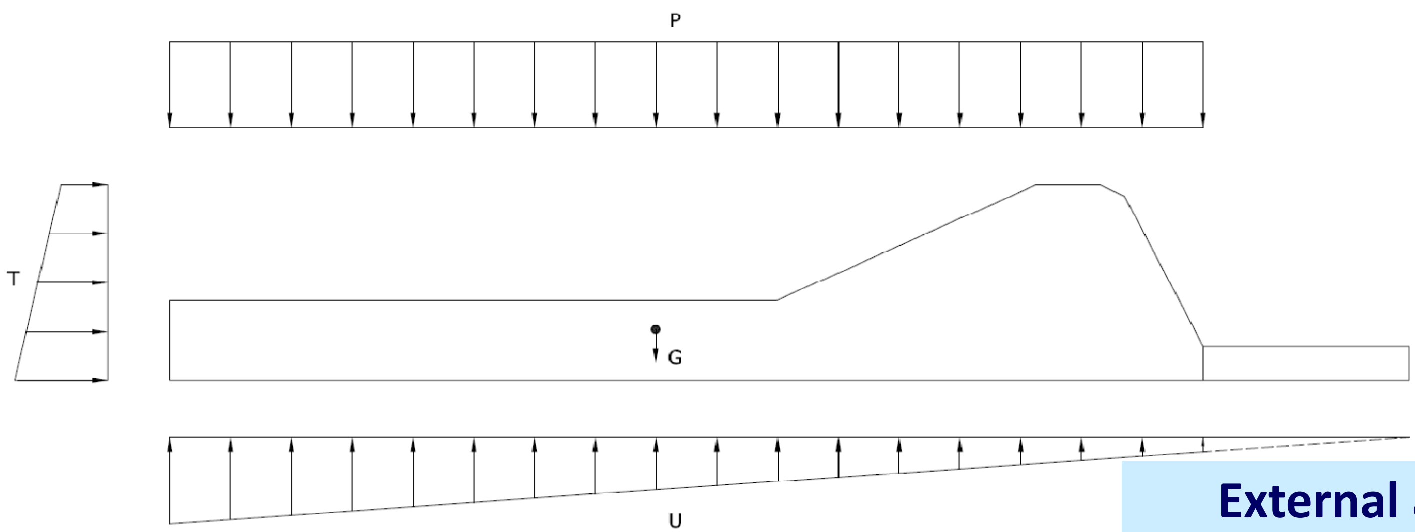
Total Plinth Width Determination

Plinth Stability

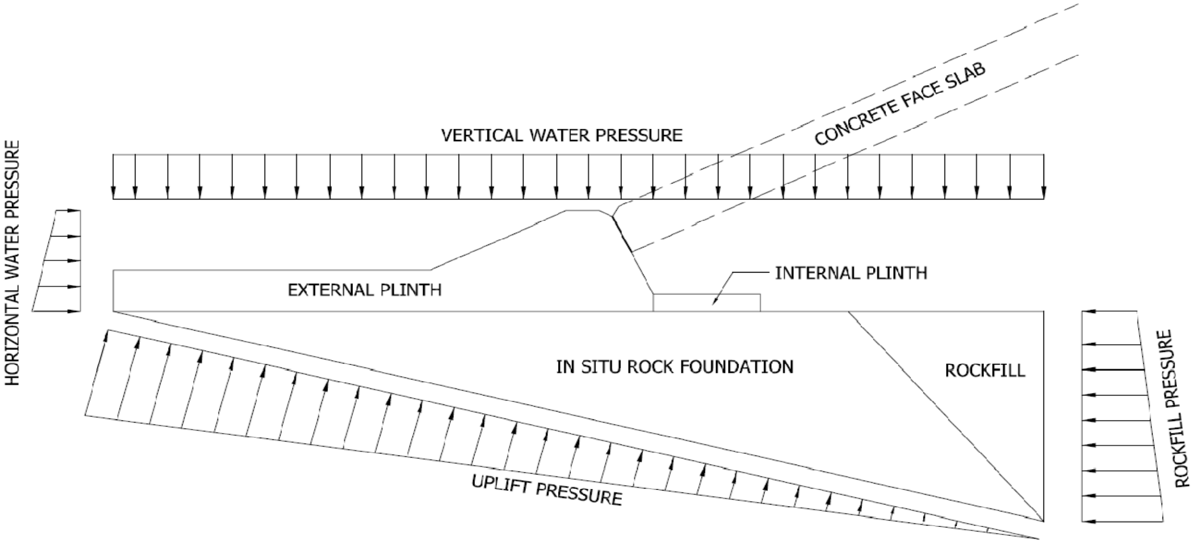
- Stability against Sliding F.S. > 1.5
- Stability against Overturning F.S. > 1.3
- Stability against Wedge Sliding F.S. > 1.3



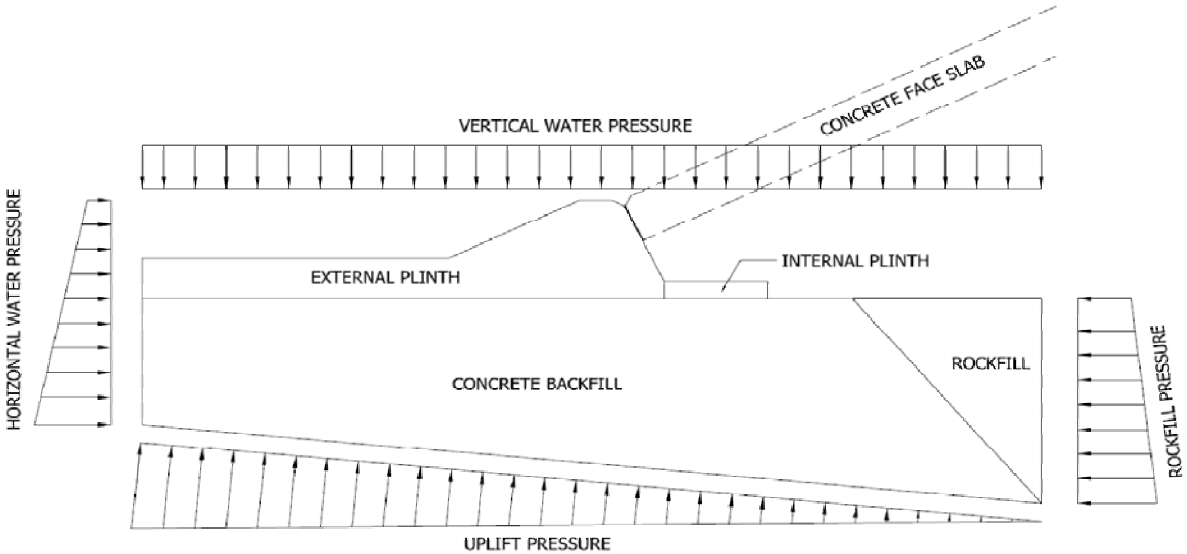
External Plinth



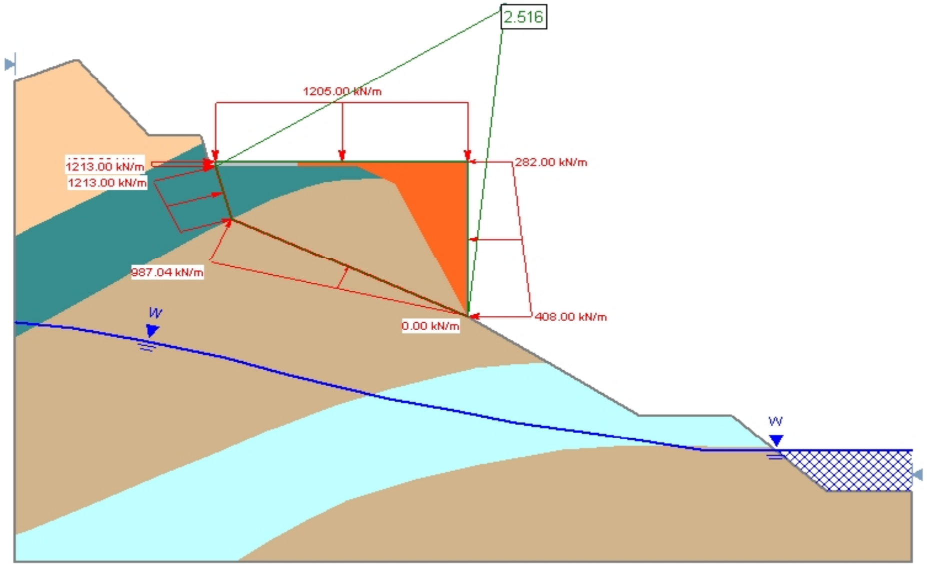
External and Internal Plinth



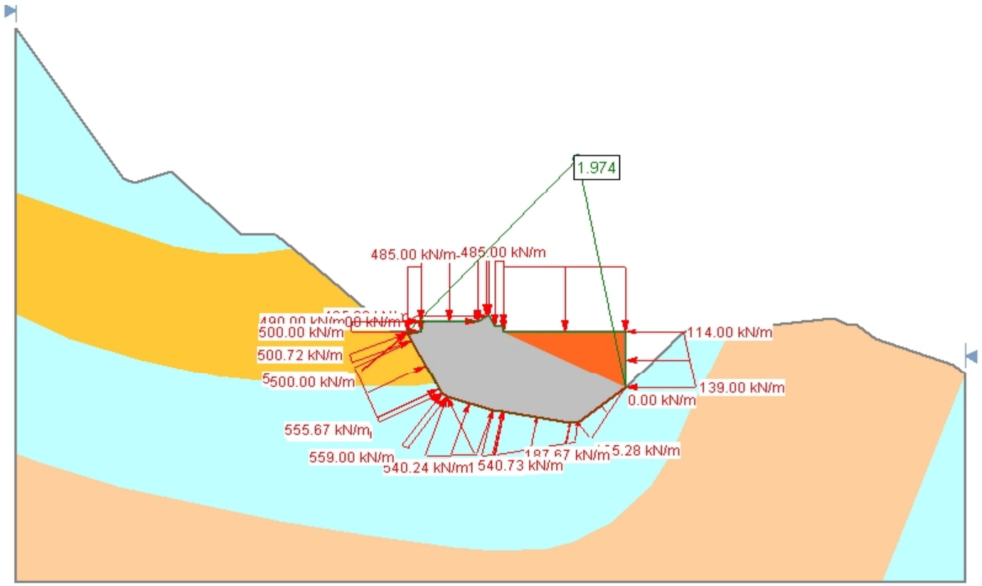
Discontinuities



Concrete Backfill

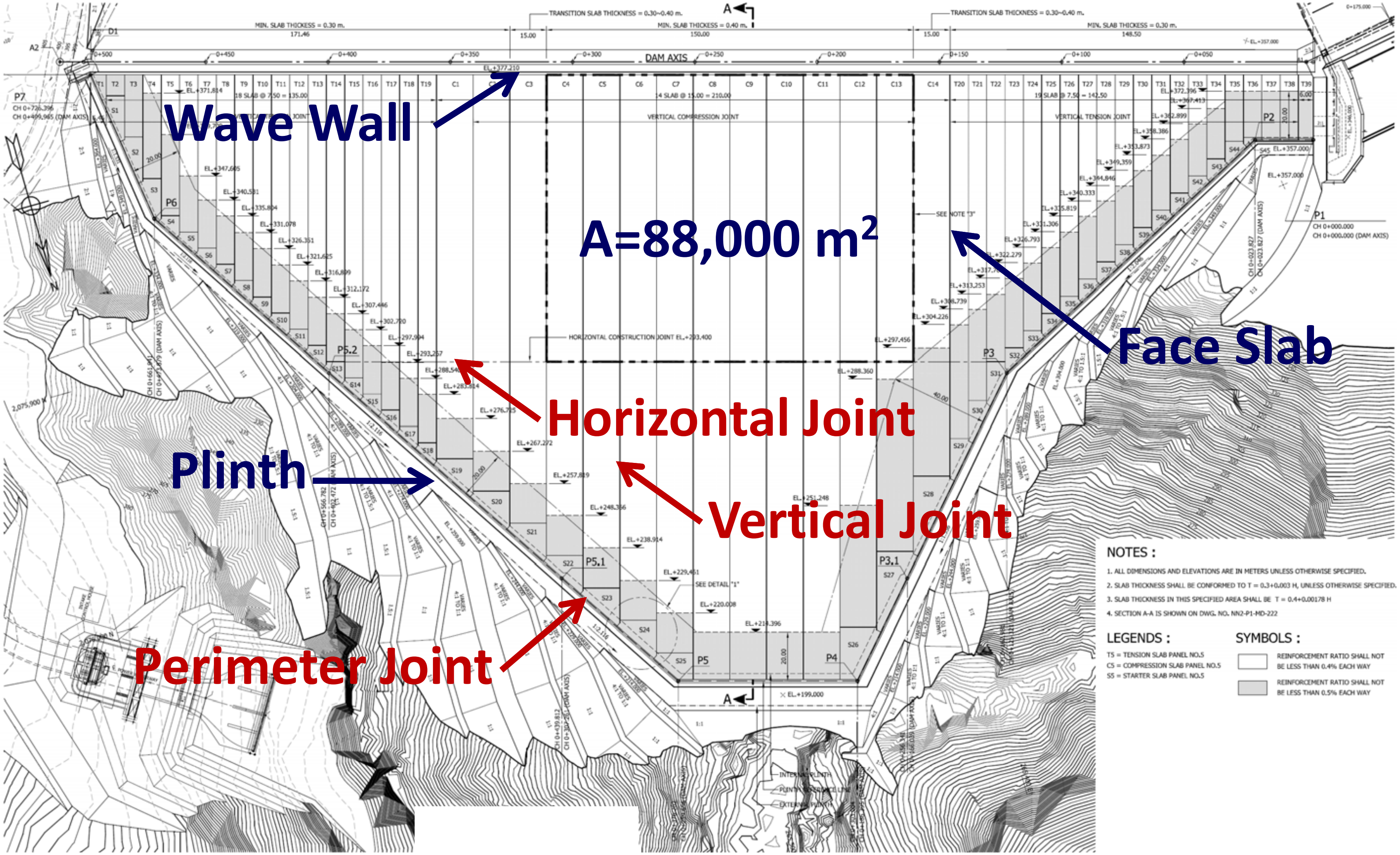


Discontinuities



Concrete Backfill

Plinth Stability Analysis



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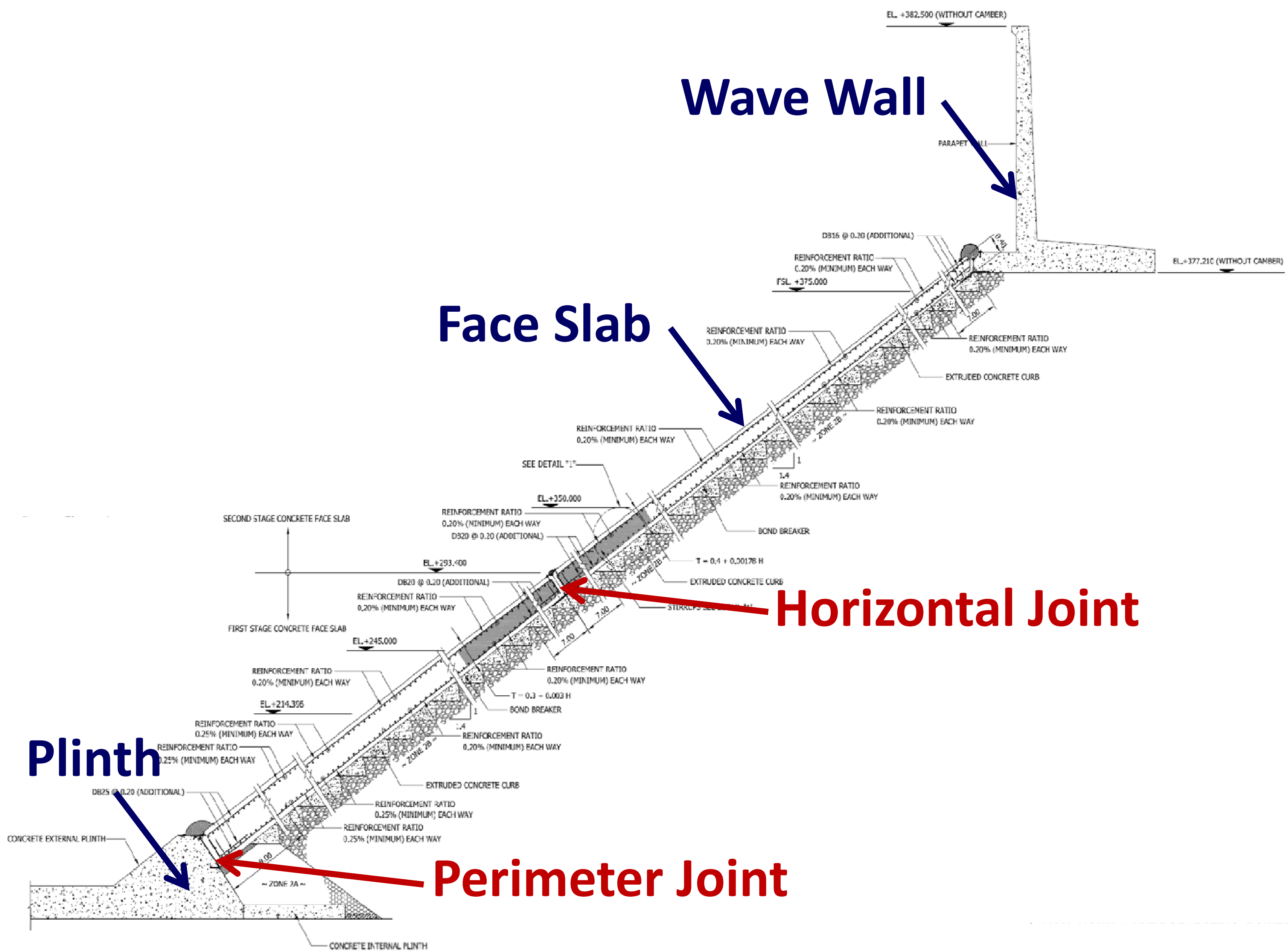
Face Slab Layout



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Face Slab Configuration

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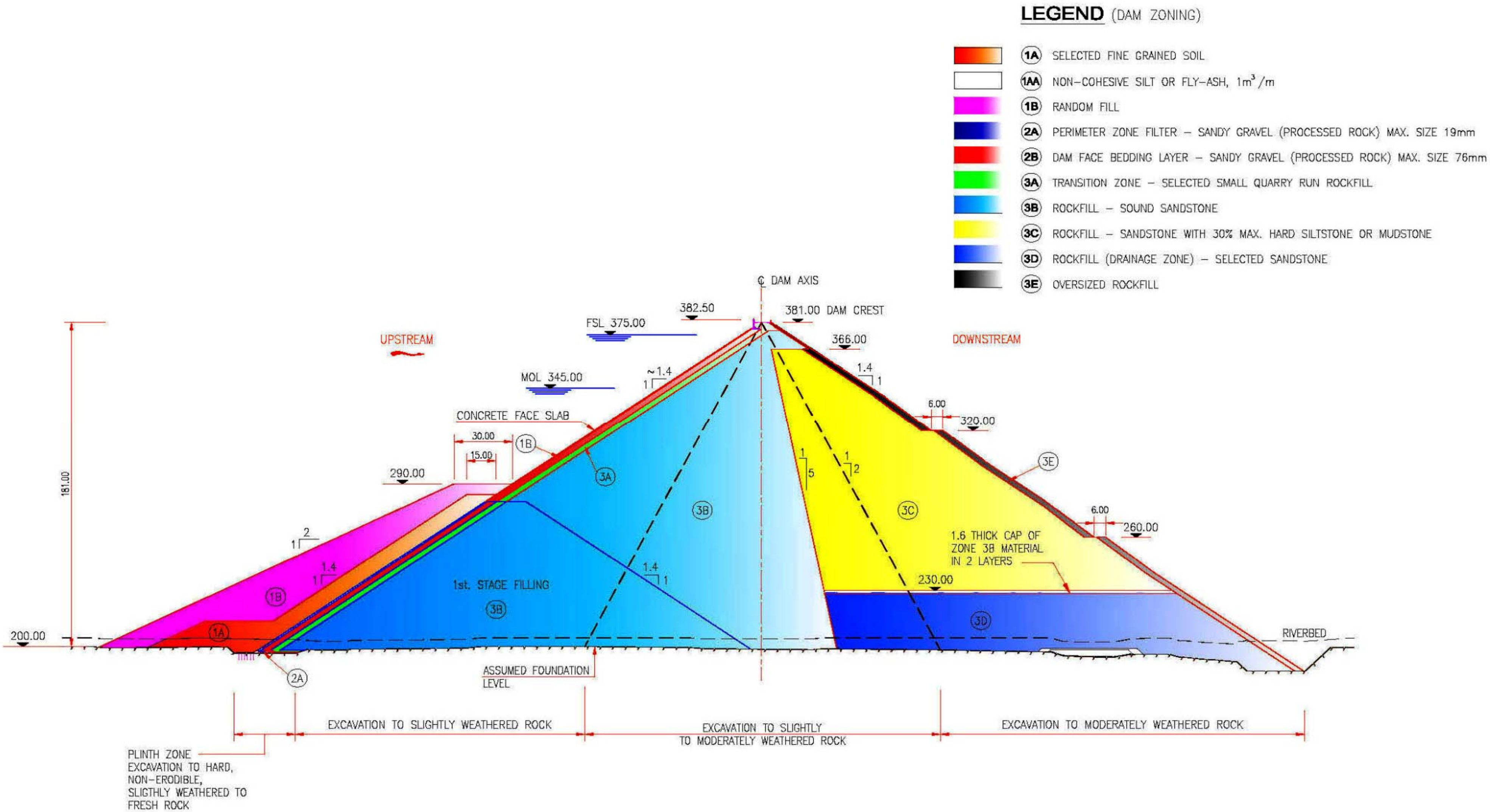
Design of Dam Embankment

Dam Zoning Designation

- Zone 1: Concrete Face Slab Protection Zone
- Zone 2: Concrete Face Slab Supporting Zone
- Zone 3: Rockfill Zone



Original Rockfill Arrangement

Large Triaxial Test

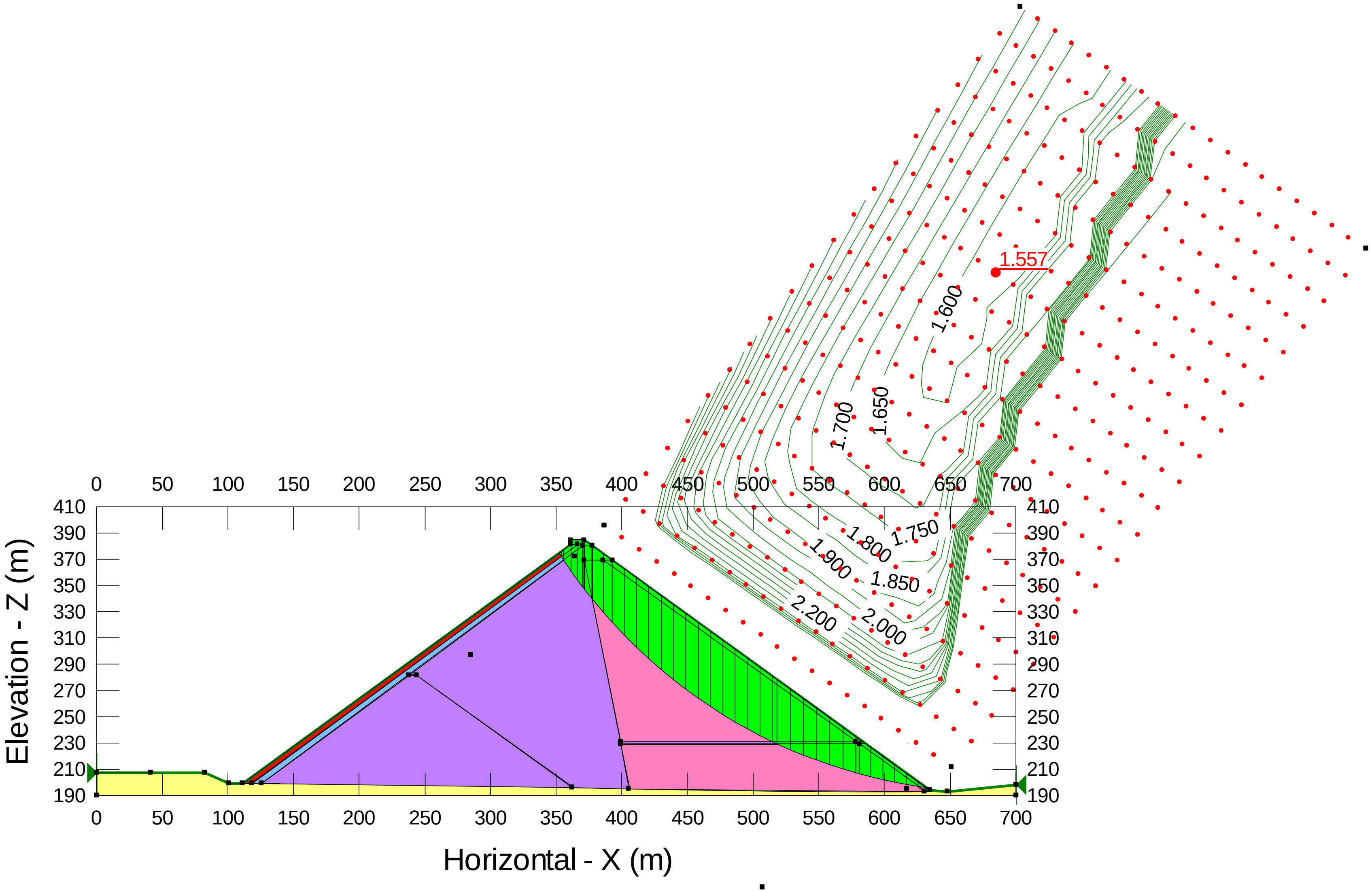
Large Compression Test

No	Rockfill materials		Triaxial tests				Compression tests	
			σ_3=0.5 MPa	σ_3=1.0 MPa	σ_3=1.5 MPa	σ_3=2.0 MPa	Dry	Saturated
1	Zone 2B (SS: 100%)		√	√	√	√	√	√
2	Zone 3A (SS: 100%)		√	√	√	√	√	√
3	Zone 3B	SI:0%; SS:100%	√	√	√	√	√	√
		SI:15%; SS:85%	√	√	√	√	√	√
4	Zone 3C	SI:30%; SS:70%	√	√	√	√	√	√
		SI:45%; SS:55%	√	√	√	√	√	√

Note: Triaxial tests: 24 samples, compression tests: 12 samples
SI: siltstone; SS: sandstone
Compression tests: σ_1 = 0.0~4.0MPa

Duncan's E-B Model Parameters

Materials	γ_d (t/m^3)	K	K_{ur}	n	R_f	K_b	m	c (kPa)	φ_0 (°)	$\Delta\varphi$ (°)
Zone 2B	2.15	1,600	3,200	0.38	0.918	800	0.20	-	44.1	4.2
Zone 3A	2.15	1,040	2,080	0.31	0.820	520	0.20	-	45.9	5.7
Zone 3B	2.15	1,000	2,000	0.38	0.864	500	0.20	-	46.5	6.2
Zone 3C	2.10	630	1,260	0.37	0.802	520	0.0	-	45.1	5.4



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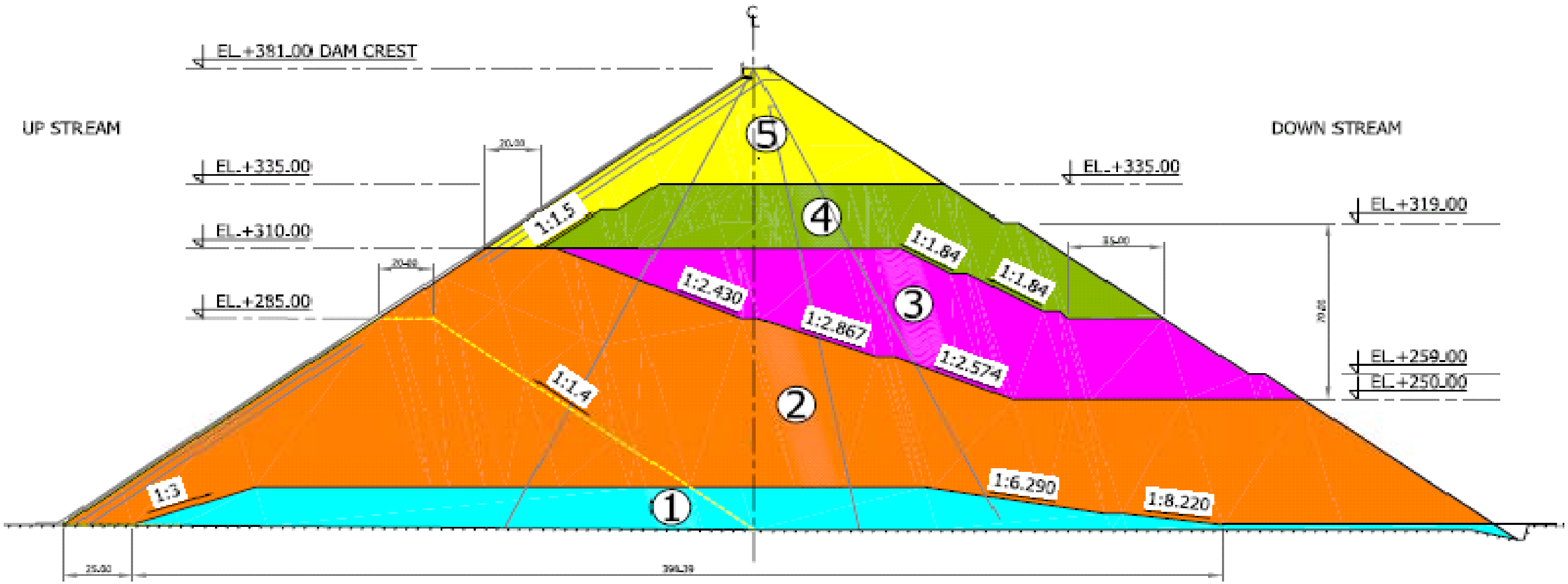
Stability Analysis

A Member of TEAM GROUP

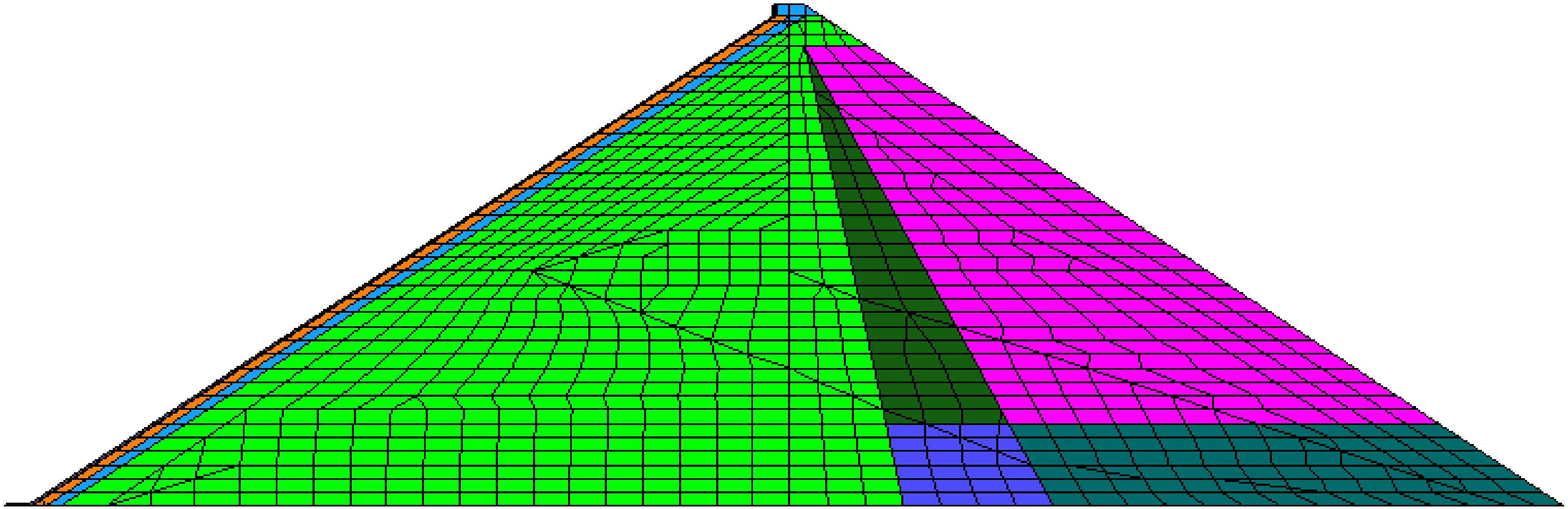
02 June 2007
11:30 Hrs.

DAM EMBANKMENT CONSTRUCTION SEQUENCES



NOTE:
1. 1st Stage Face slab Below EL.+285.00 will start after completing rockfill placement stage 1 and 2 to EL.+310.00
2. While working on 1st Stage Face slab, CK intend to work on stage 3 and 4 rockfill placement
3. CK expects to complete rockfill placement to EL.+310.00 (Stage 1 and 2) in 7 months.

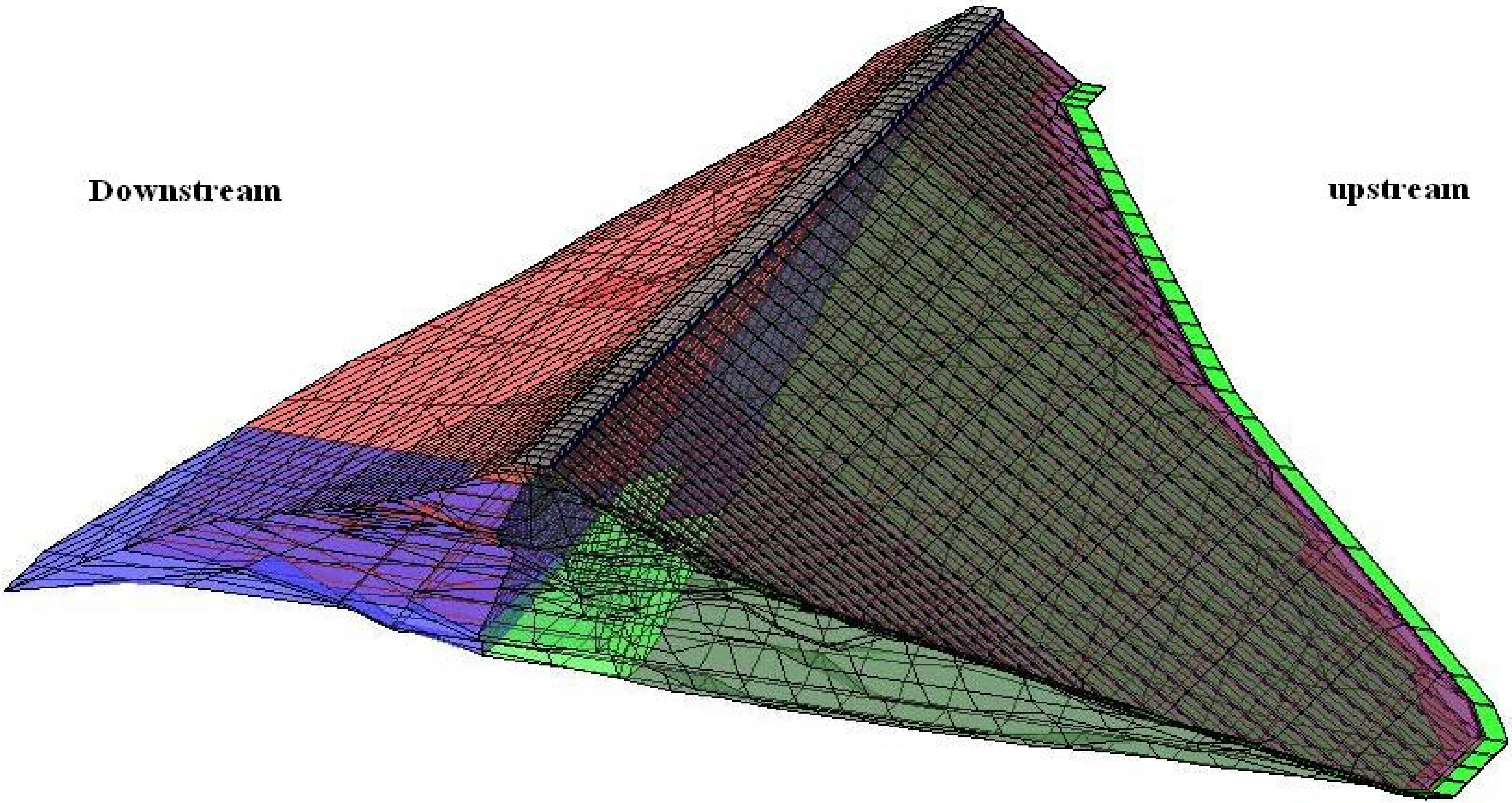
2D FEM Model



1158 elements, 1172 nodal points.
Interface: thin layer contact elements

32 construction steps
7 water load steps

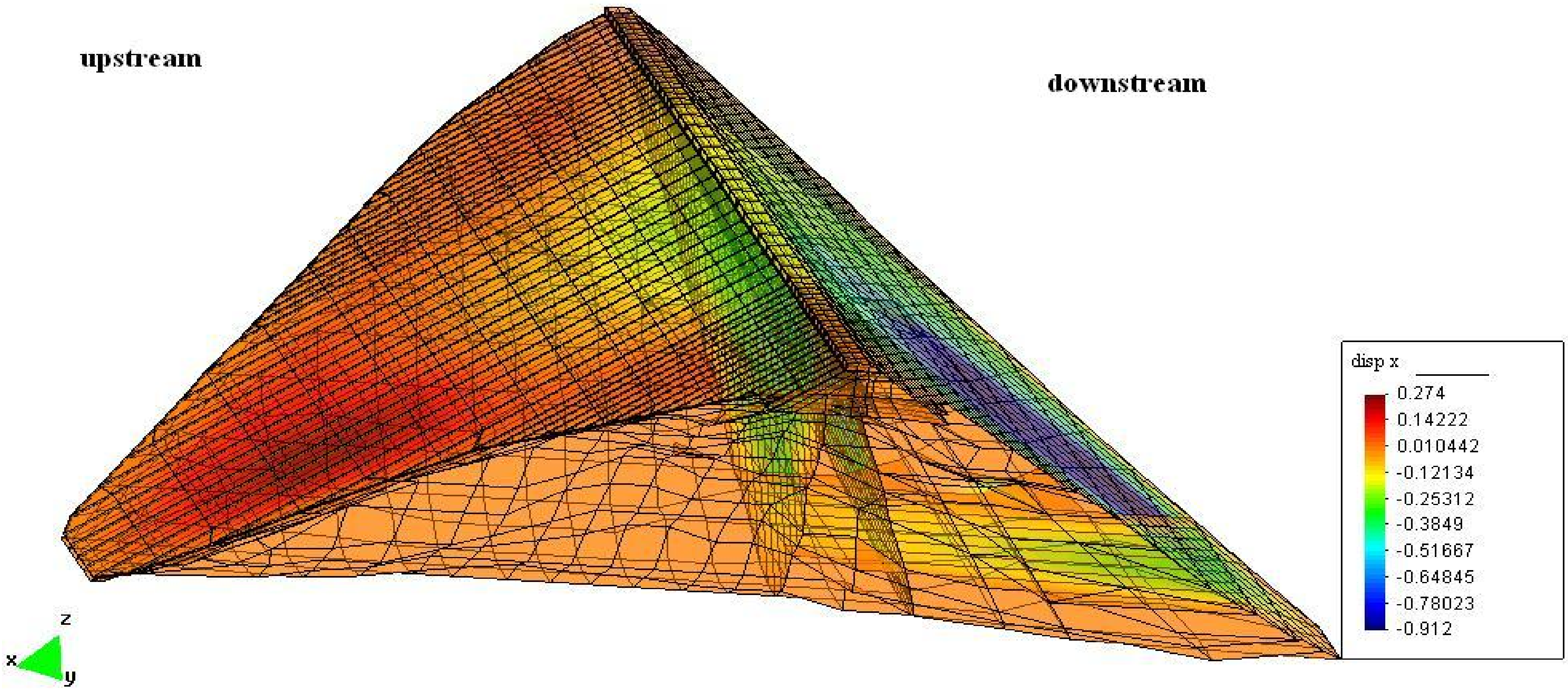
3D FEM Model



7795 nodes and 6370 elements

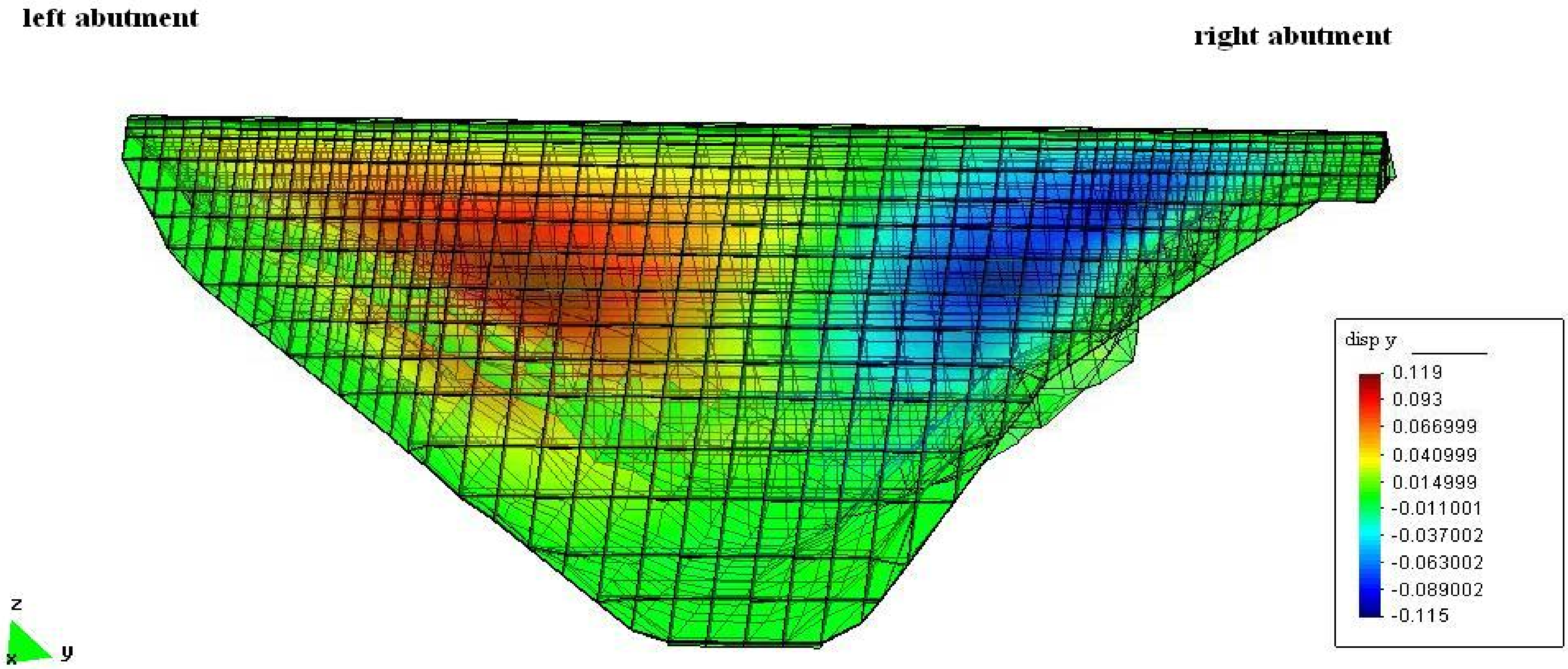
26 construction steps
9 water load steps

Results of 3D FEM Analysis



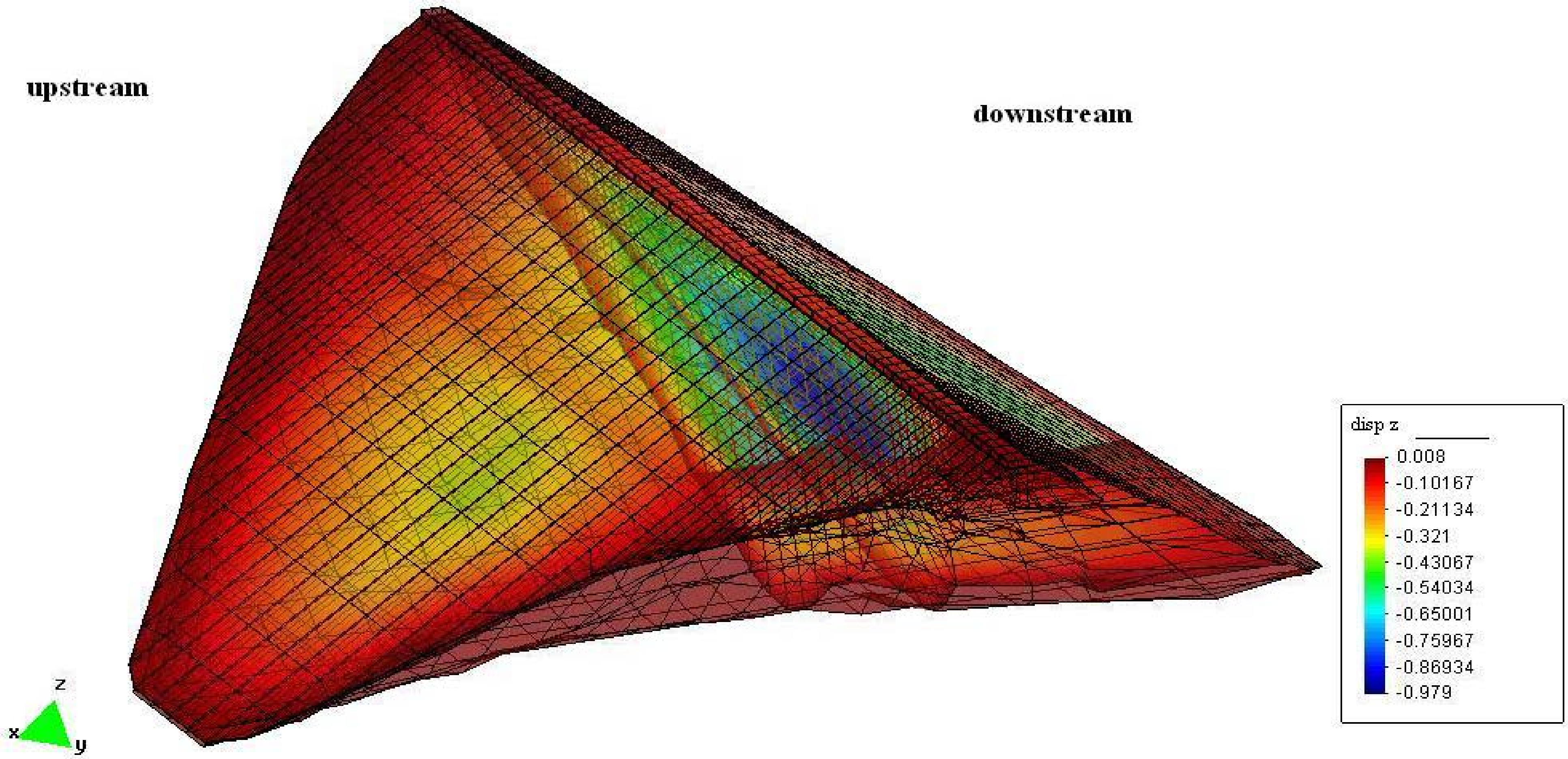
Displacements in the Direction Along the River

Results of 3D FEM Analysis



Displacements in the Direction Along the Dam Axis

Results of 3D FEM Analysis

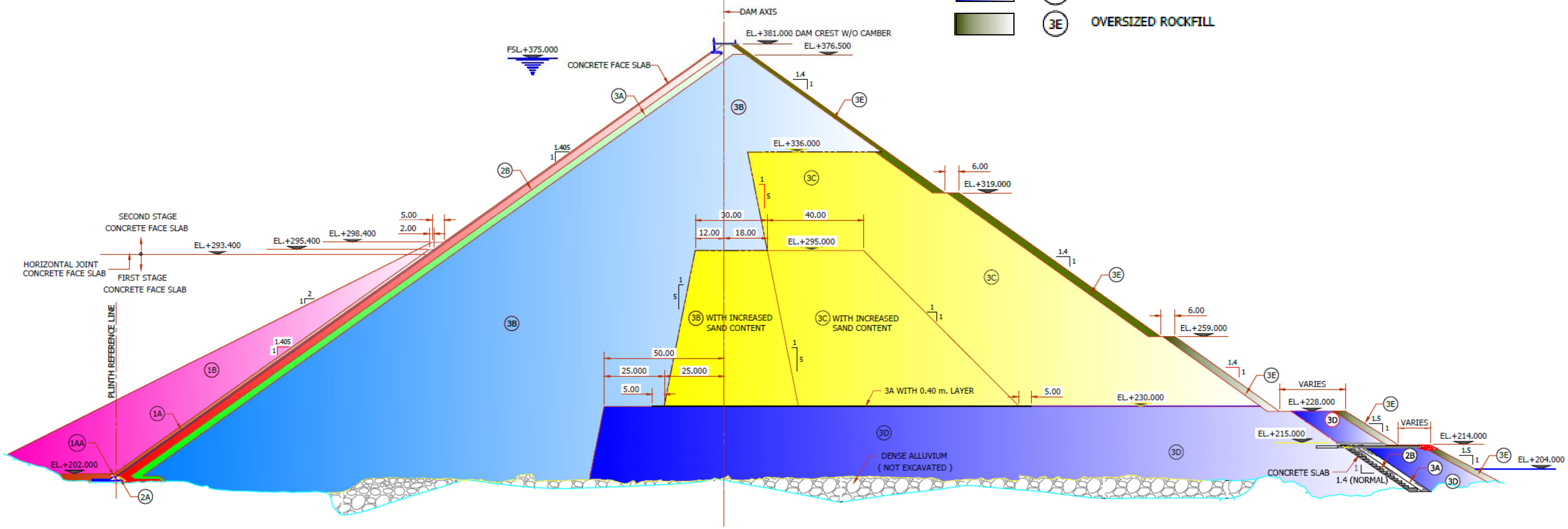


Displacements in the Vertical Direction

Total Embankment Volume = 10 Million m^3

LEGEND

- 1A SELECTED FINE GRAINED
- 1AA NON-COHESIVE SILT OR FIY-ASH, $1m^3/m$
- 1B RANDOM FILL
- 2A PERIMETER ZONE FILTER - SANDY GRAVEL (PROCESSED ROCK) MAX. SIZE 19mm
- 2B DAM FACE BEDDING LAYER - SANDY GRAVEL (PROCESSED ROCK) MAX. SIZE 76mm
- 3A TRANSITION ZONE - SELECTED SMALL QUARRY RAN ROCKFILL
- 3B ROCKFILL - SOUND SANDSTONE
- 3C ROCKFILL - SANDSTONE WITH 30% MAX. HARD SILTSTONE OR MUDSTONE
- 3D ROCKFILL - (DRAINAGE ZONE) - SELECTED SANDSTONE
- 3E OVERSIZED ROCKFILL



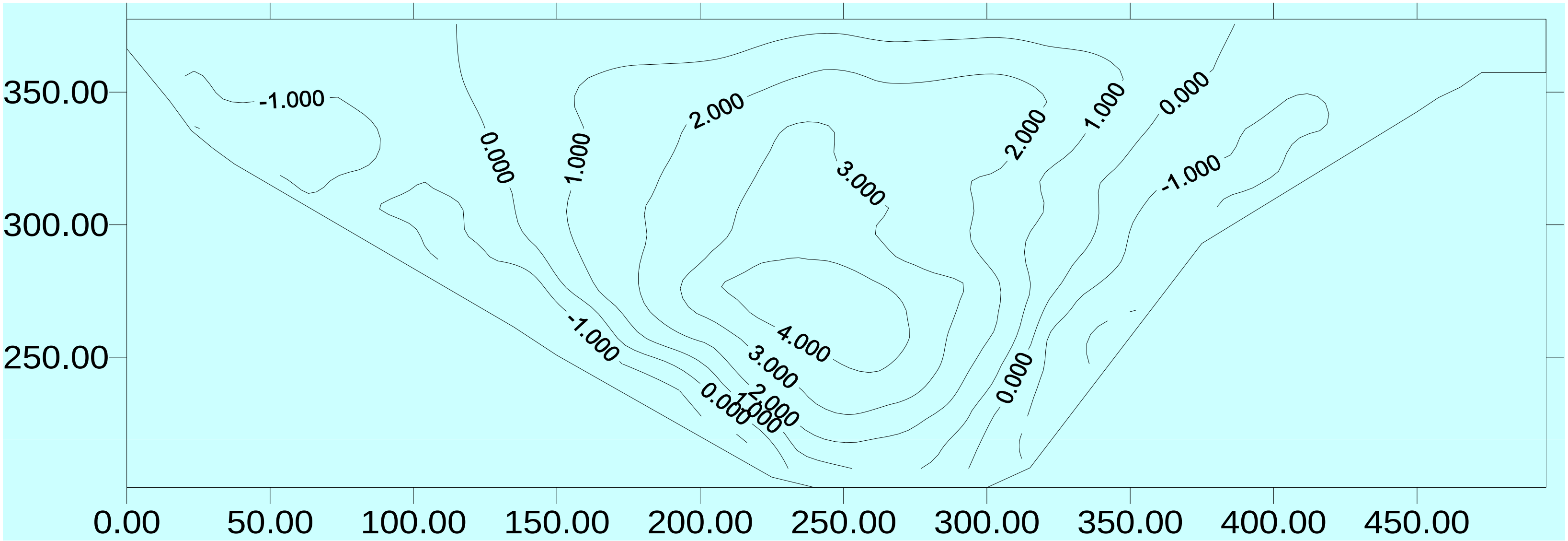
Revised Rockfill Arrangement

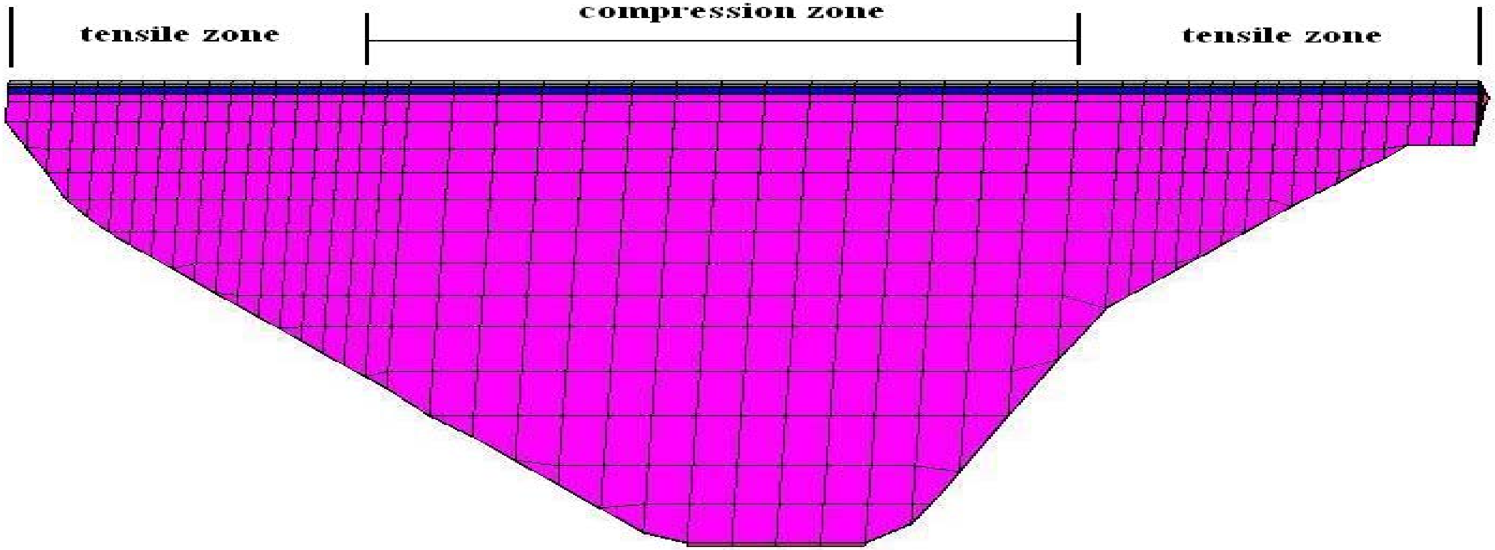
Design of Face Slab

1. Empirical
2. 3D-FEM
3. Beam Spring Model

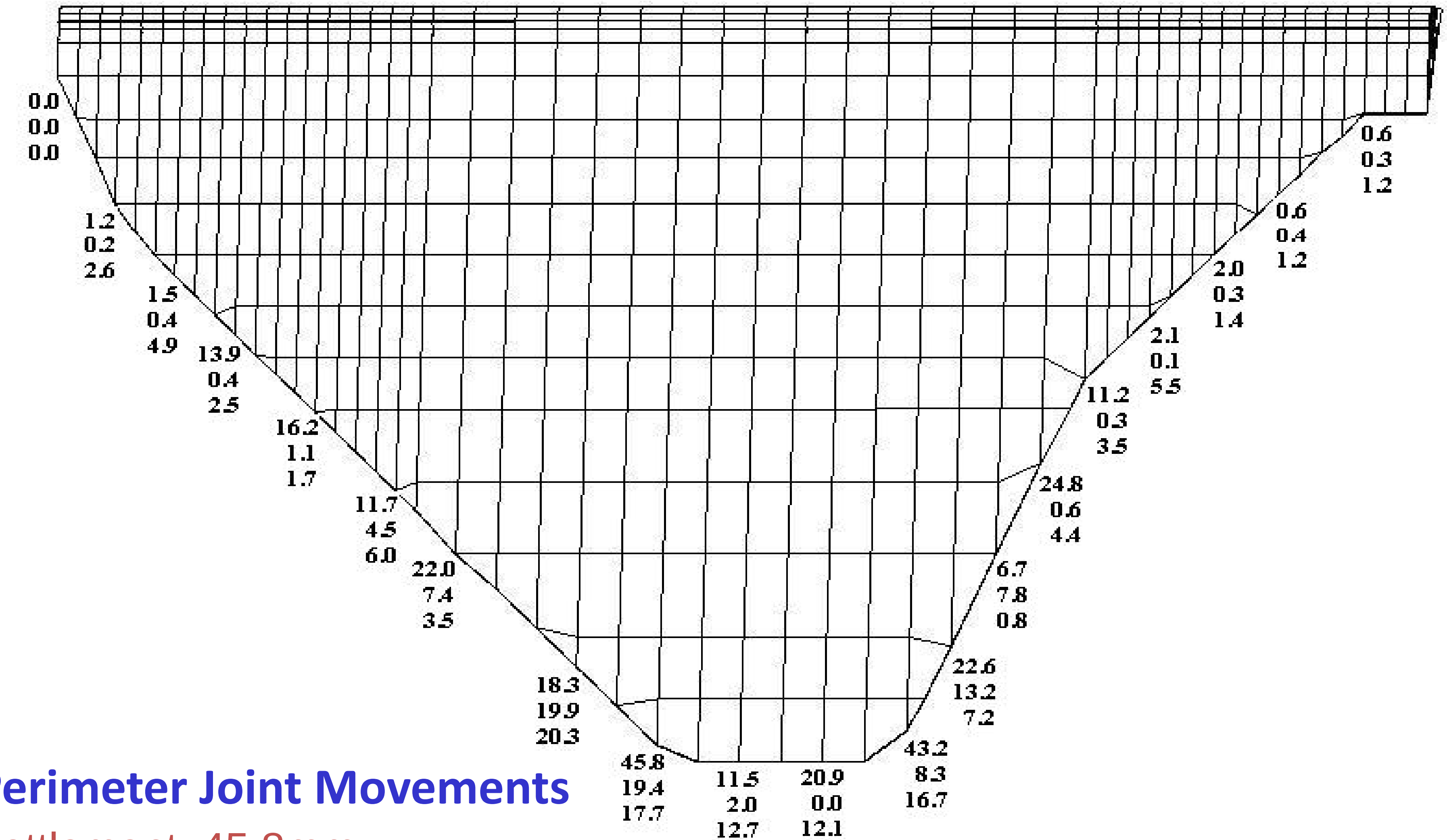
Empirical Considerations

1. Barra Grande
2. Campos Novos
3. Mohale
4. Shuibuya
5. Bakun





Face Slab Arrangement

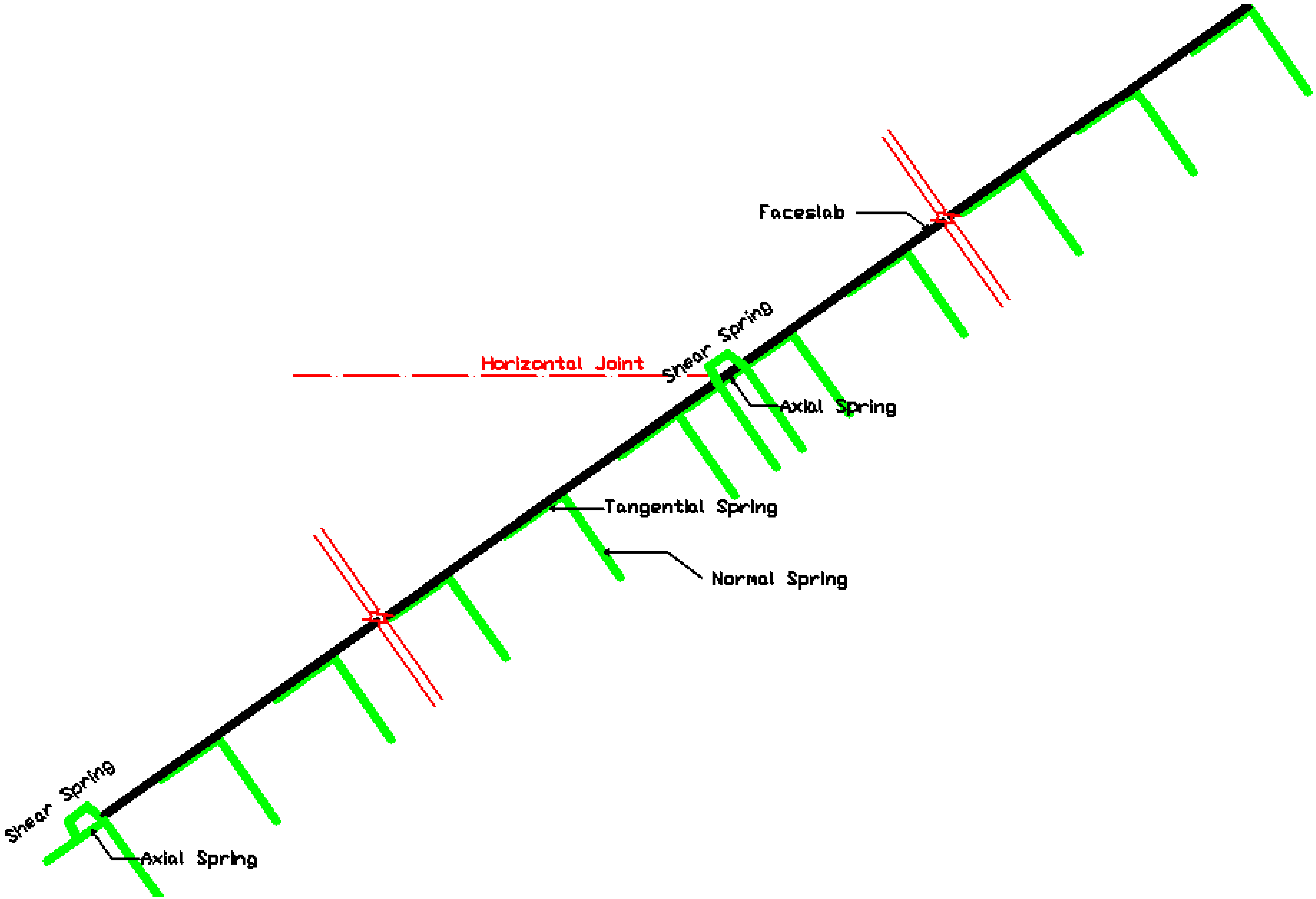


Perimeter Joint Movements

Settlement: 45.8mm

Shear movement: 19.4mm

Open displacement: 17.7mm



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Beam Spring Model

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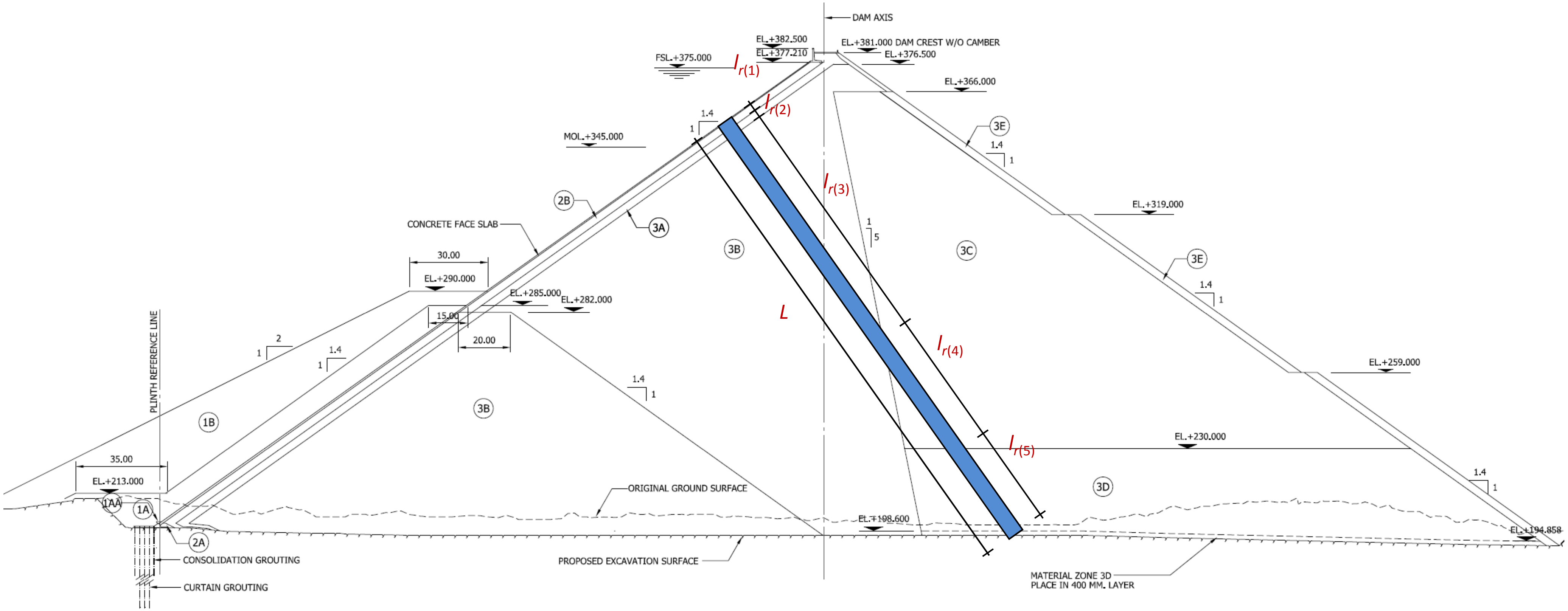
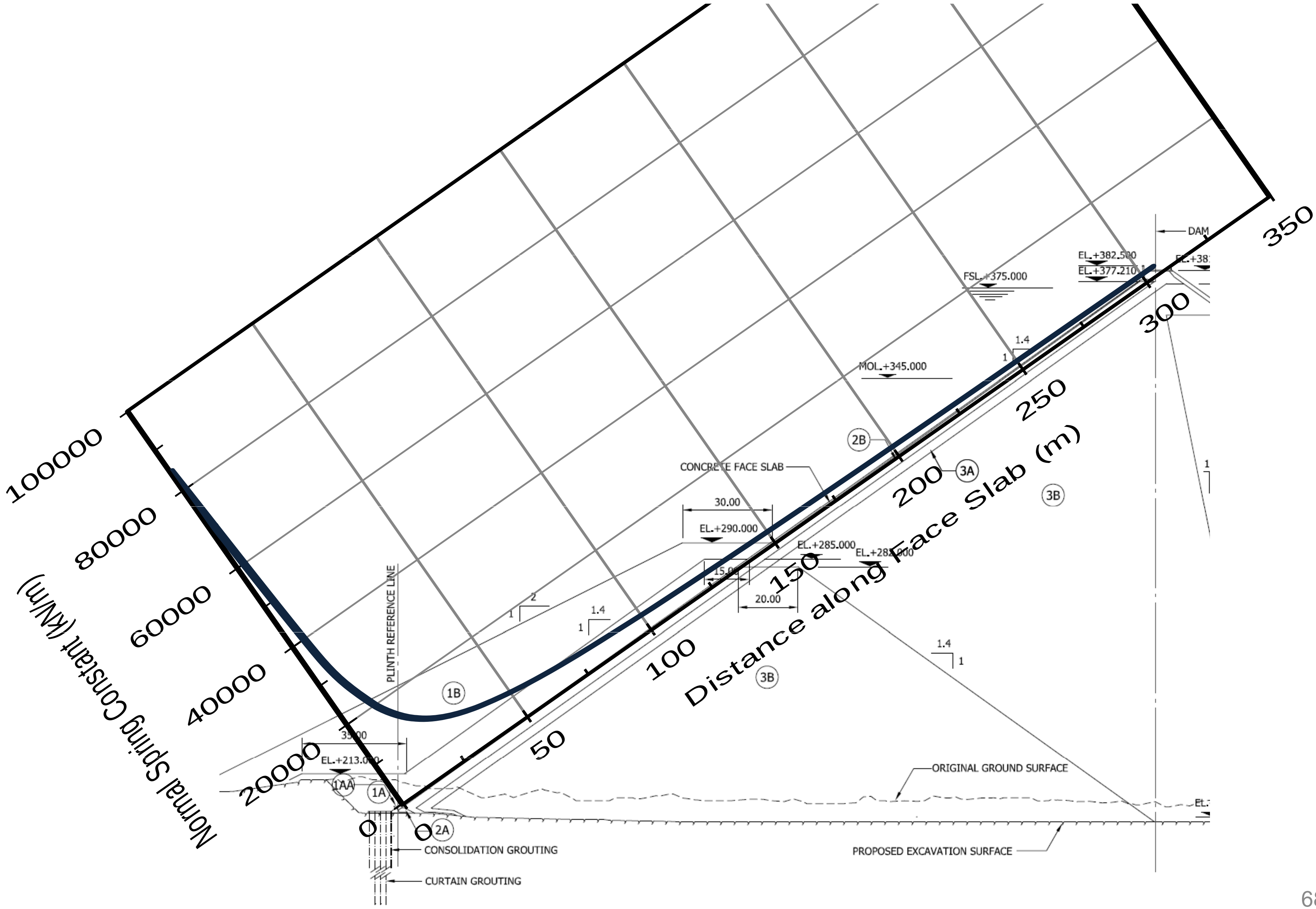


$$K_{rn} = \frac{L}{\frac{l_{r(1)}}{k_{rn(1)}} + \frac{l_{r(2)}}{k_{rn(2)}} + \frac{l_{r(3)}}{k_{rn(3)}} \ldots + \frac{l_{r(m)}}{k_{rn(m)}}}$$

$$k_{rn(i)} = \frac{A_{r(i)} E_{r(i)}}{l_{r(i)}}$$

Spring Constant



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Spring Constant

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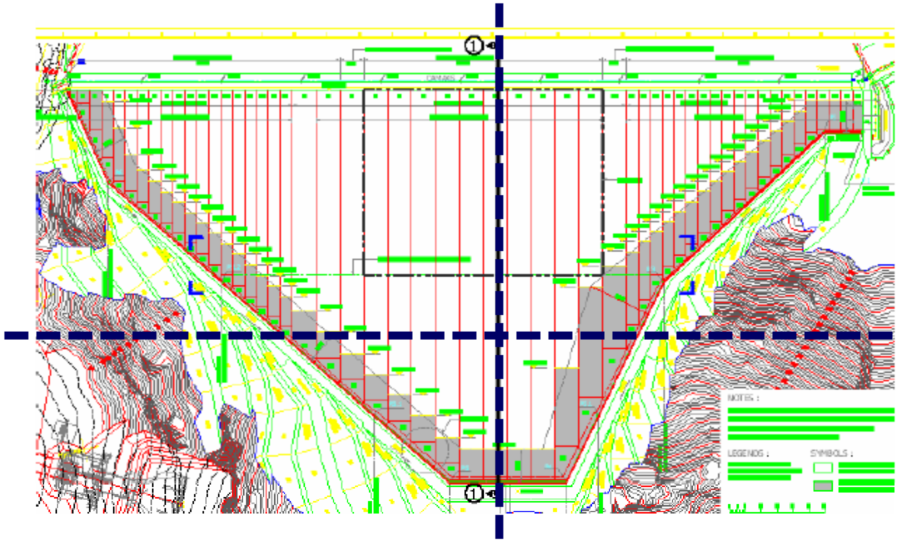
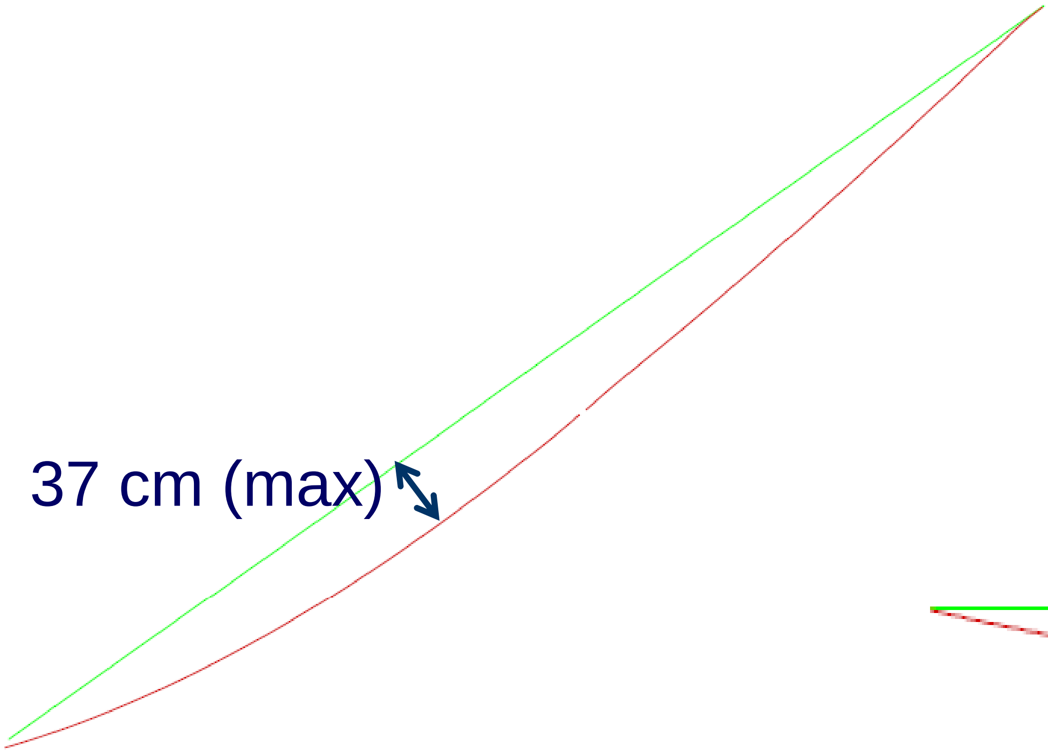
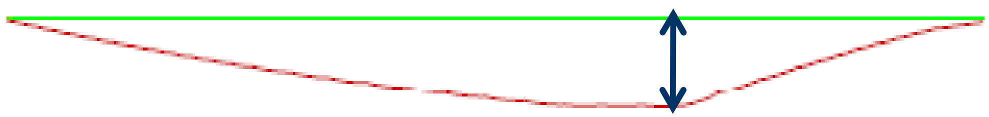


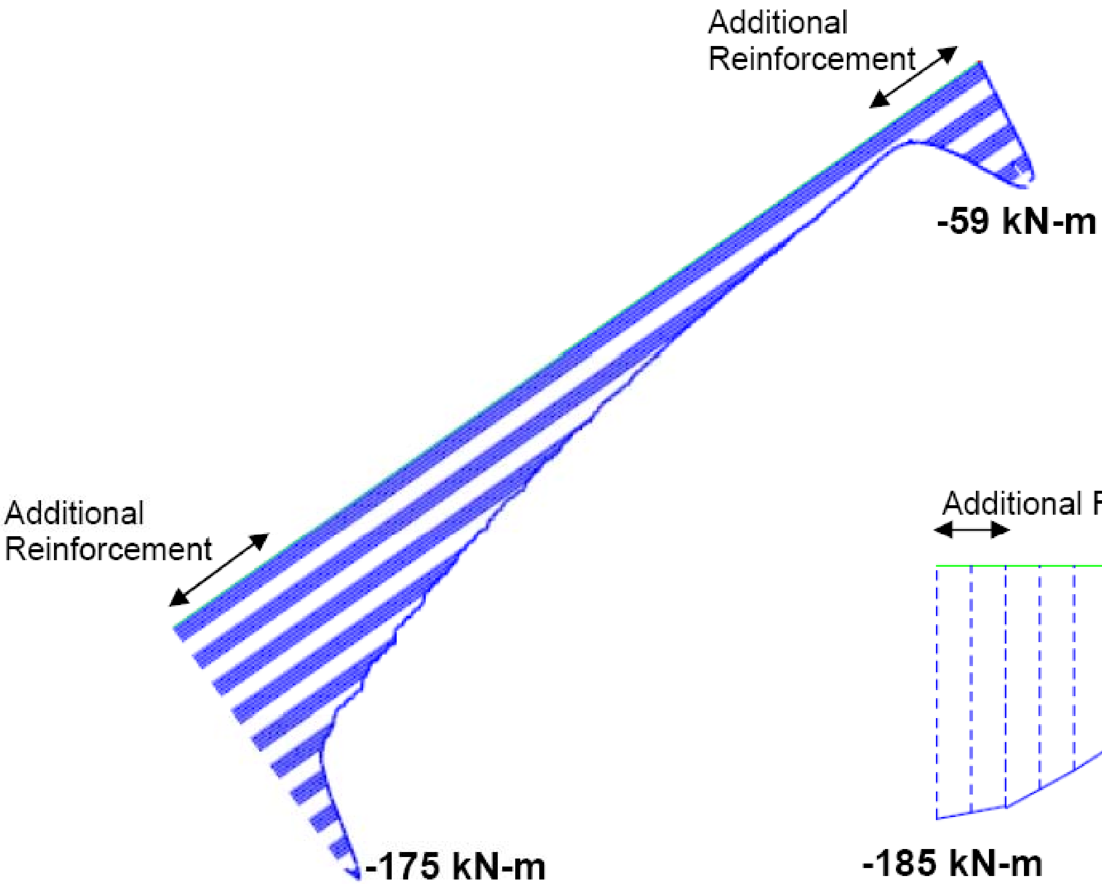


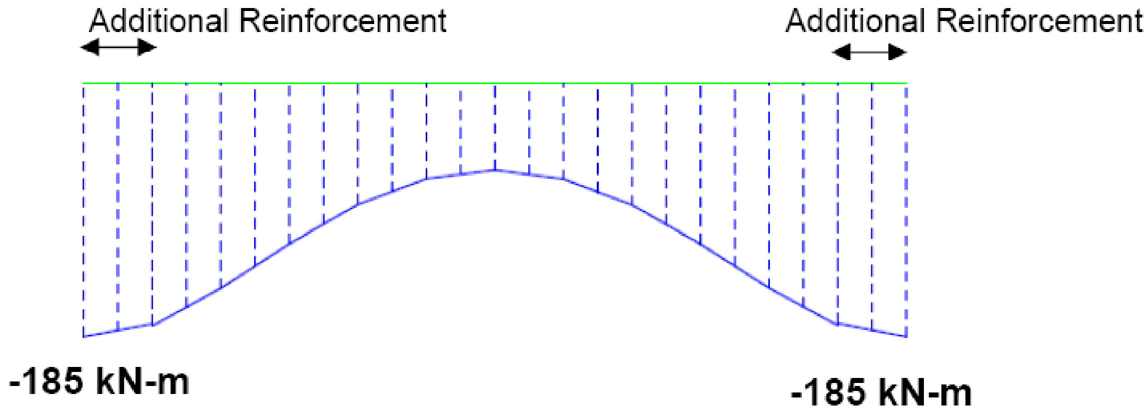
Longitudinal Section



Cross Section

Deformation of Face Slab





Longitudinal Section **Cross Section**

For First Stage Face Slab (Slab No. C9)

Bending Moment Diagram

Design Results

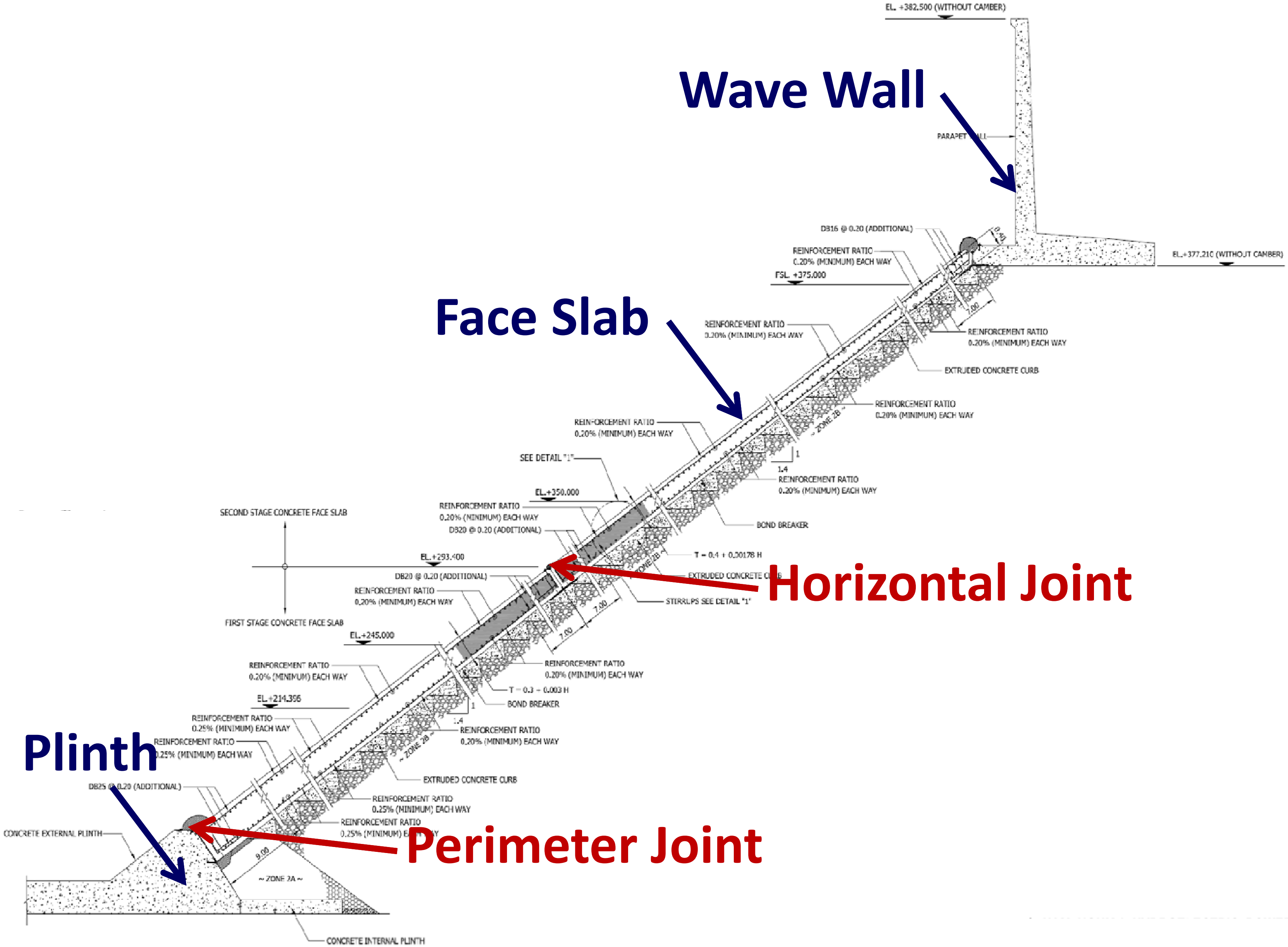
Empirical Considerations

1. Face slab thickness: T(m) = 0.3+0.003H
2. Reinforcement: 0.4% of gross sectional area
3. Slab width: 7.5m for abutments, 15.0m for riverbed section
4. Pre-cutting in the extruded curb along the vertical joint to separate the face slab behaviour individually
5. Joint systems: Perimeter, Vertical and Horizontal joints

Design Results

Numerical Considerations

1. Increase face slab thickness: T(m) = 0.4+0.0018H in second stage face slab in riverbed section
2. Reinforcement: 0.5% of gross sectional area in the area close to the plinth
3. Stirrups against buckling are provided in the central area of face slab
4. Two layers of reinforcements (top and bottom layers) in both directions
5. Additional reinforcement at the face slab rims



Face Slab Reinforcement

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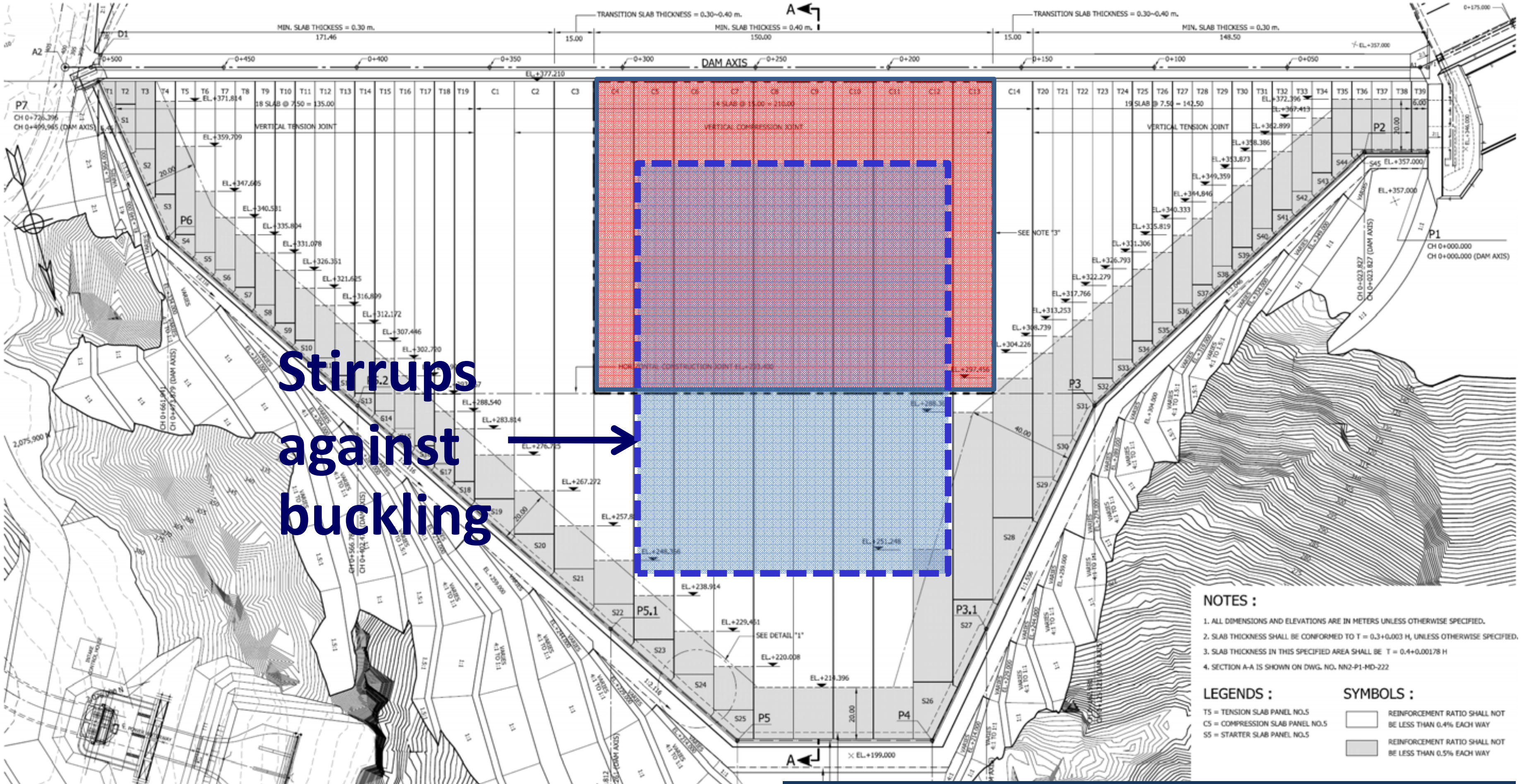


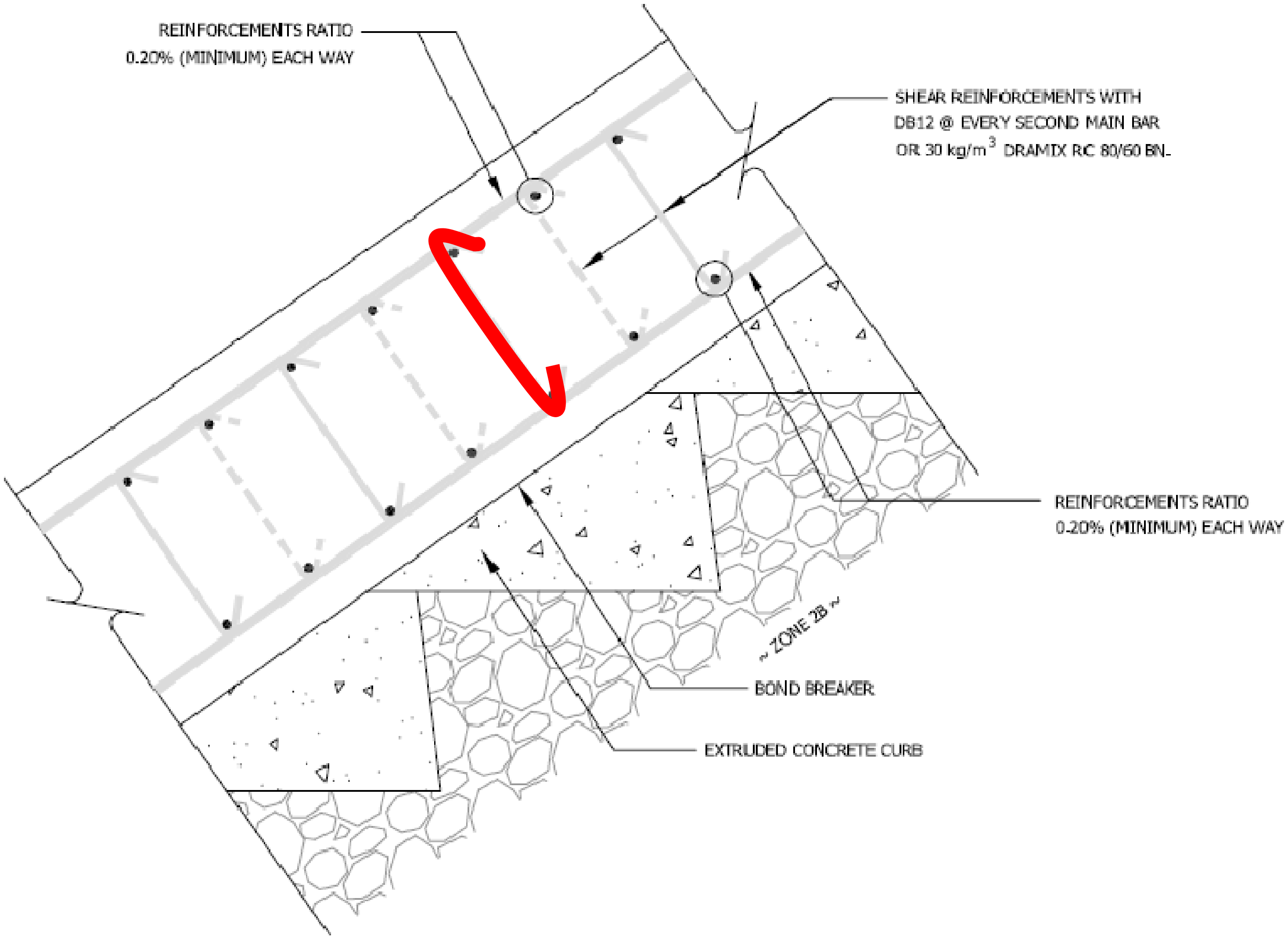
T (m) = 0.3+0.003H

T (m) = 0.4+0.0018H

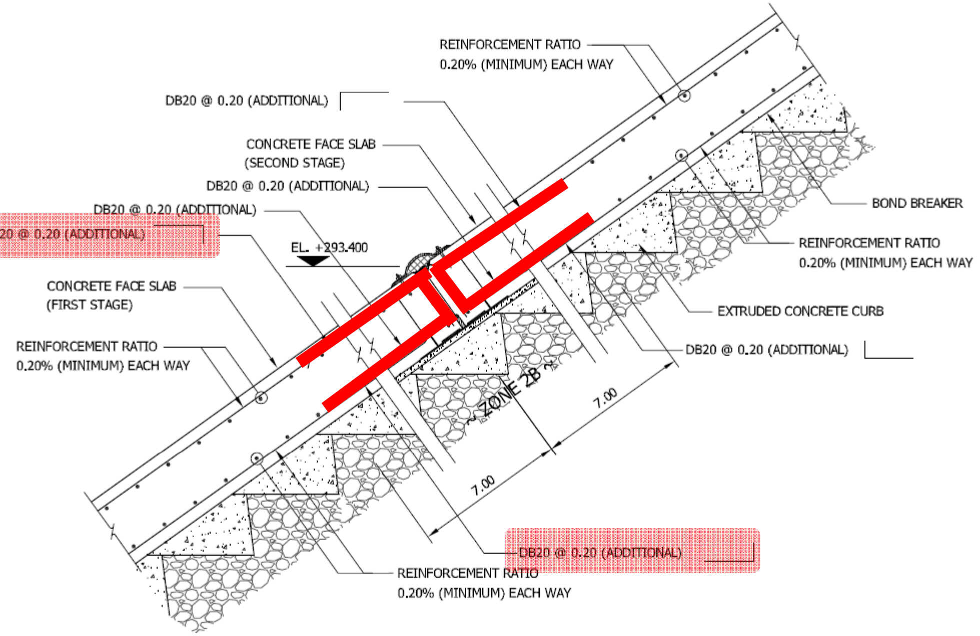
B = 7.5 m at Abutments

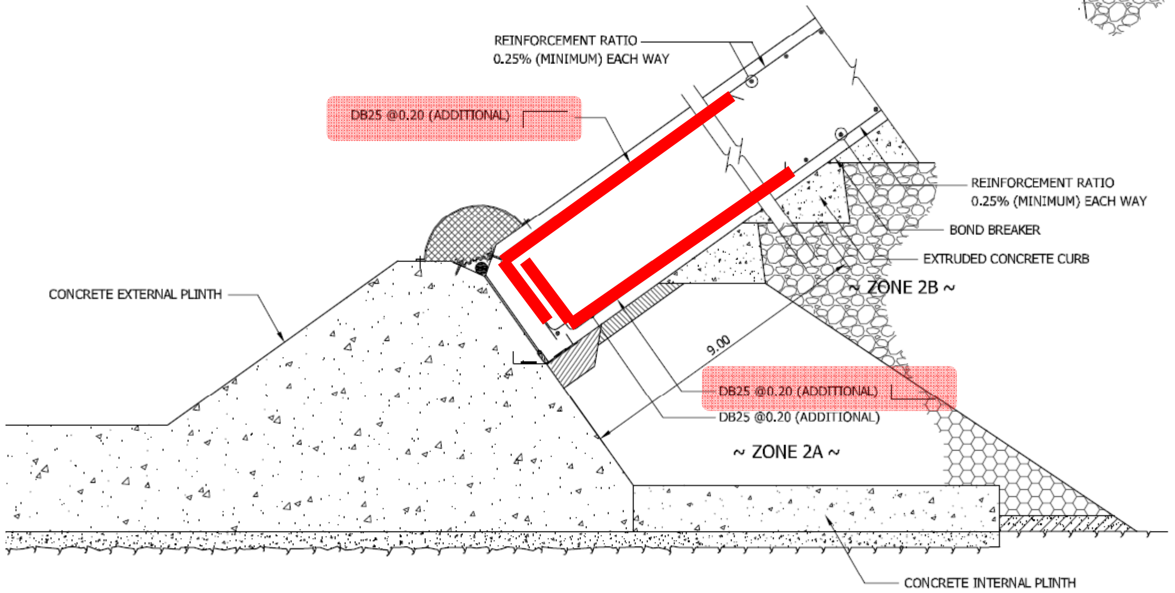
B = 15 m for Riverbed Area

Face Slab Dimensions

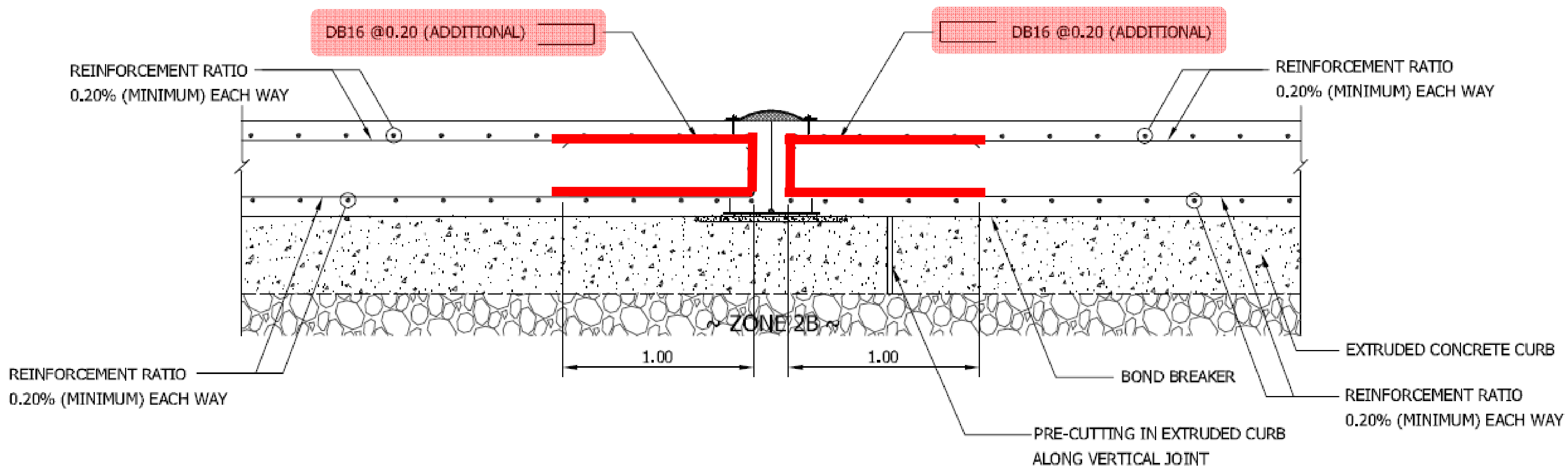


Stirrup Against Buckling





Additional Reinforcement



Additional Reinforcement

Measures Adopted to Prevent Rupture of Face Slab

1. Increase the thickness of the 10 central panels in second staged face slab.

2. The reinforcement is separated into two layers, top and bottom, in both directions as opposed to the usual location in the center of the slab. The stirrups against reinforcement buckling are provided at the high compression area.

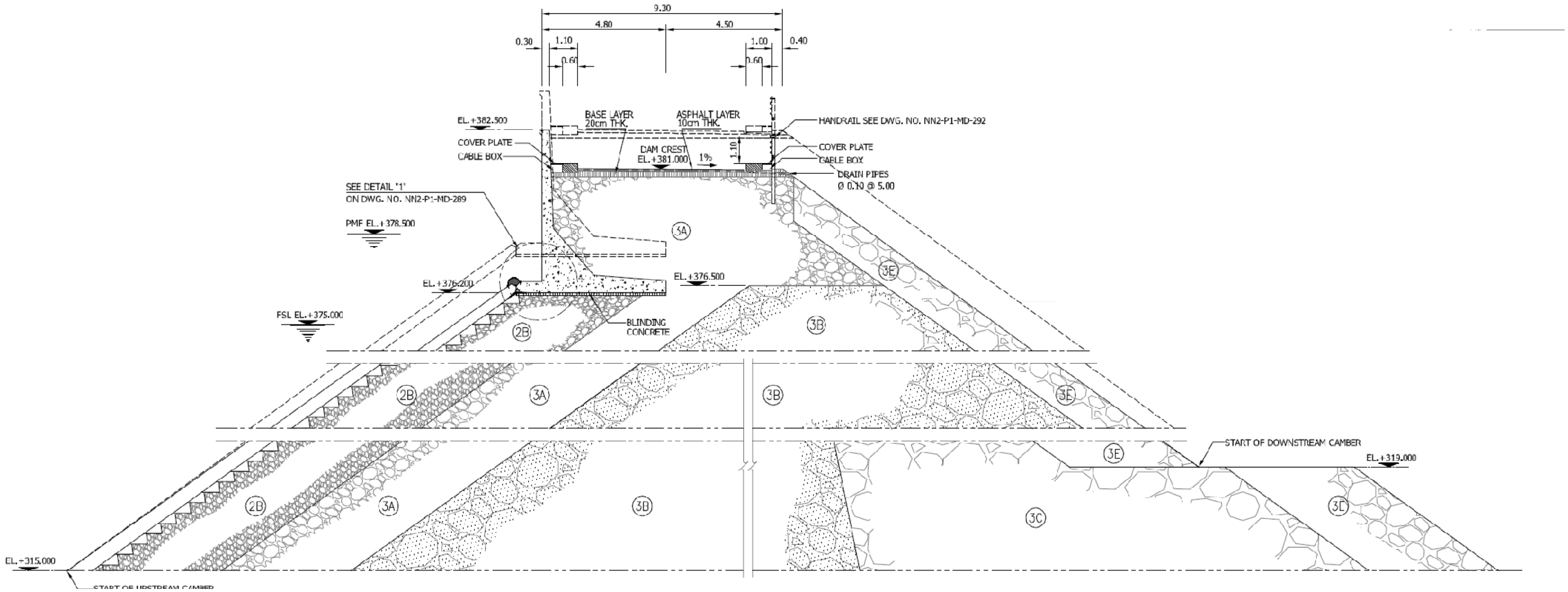
3. The additional reinforcements are employed for anti-spalling and bending stress resistant at the face slab rims.

4. Increase the face slab protection zone, Zones 1A and 1B to EL +298.4 masl, which is about 50% of the dam height.

Design of Dam Crest

Dam Crest Dimension

- Camber: 1.5 m
- Height of Parapet Wall: 5.8 m
- Crest Width: 9.3 m



Dam Crest Detail

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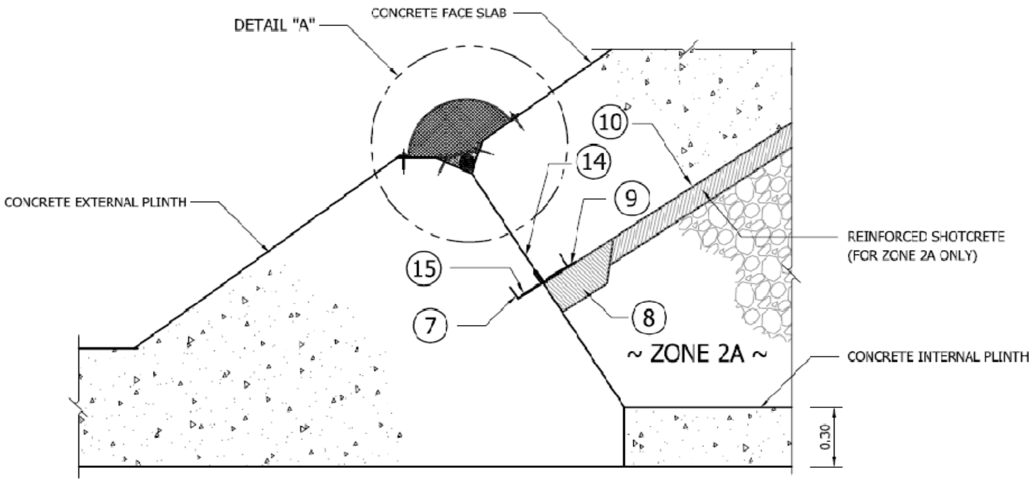
Design of Joints and Waterstops

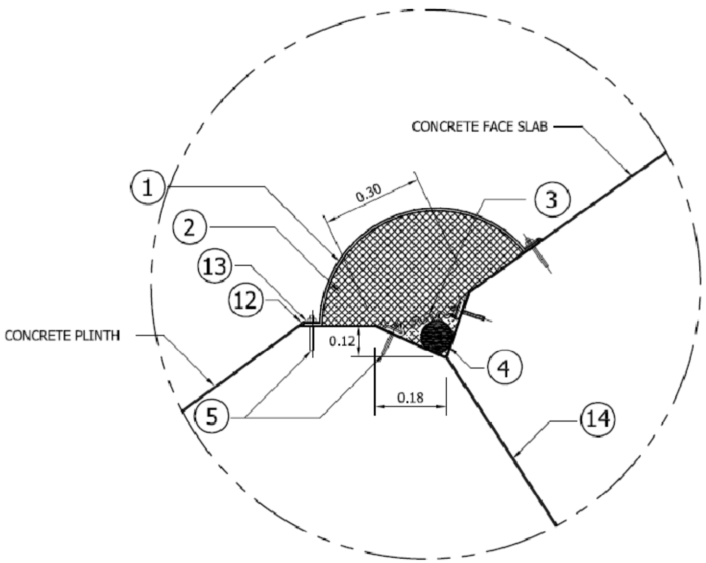
Joints on Face Slab

- Perimeter Joint
- Vertical Joint
- Horizontal Joint



Two Barrier Waterstop System

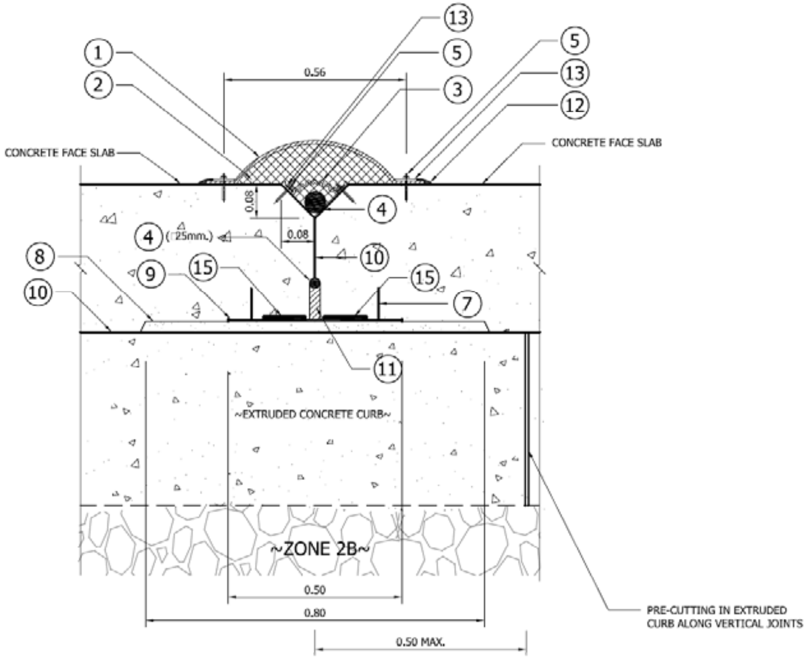
1. Copper waterstop 1.2mm thk.
2. GB filler and GB corrugated rubber waterstop covered by GB-NR-EDPM cover



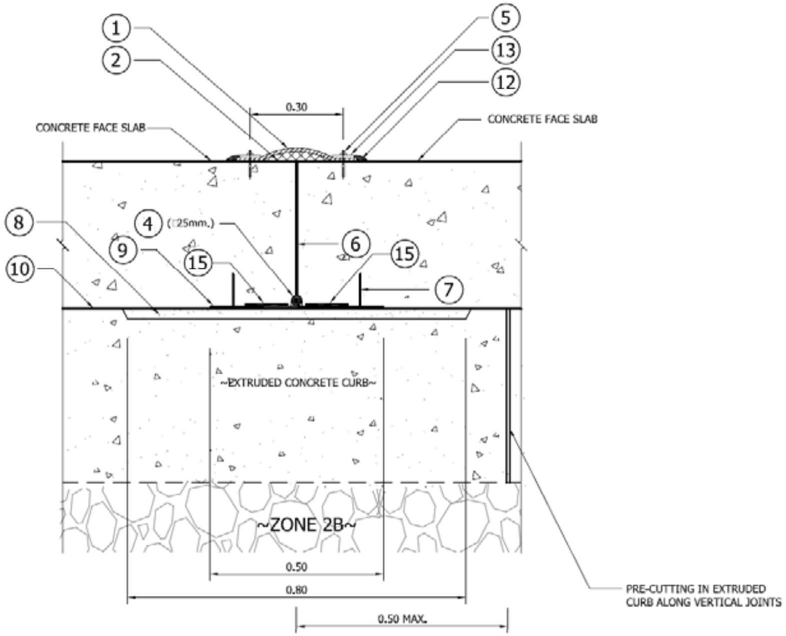
DETAIL "A"

LEGEND:

1. GB-NR-EPDM COVER
2. GB FILLER
3. GB CORRUGATED RUBBER WATERSTOP
4. PVC STICK
5. M10 HOT-DIP GALVANIZED EXPANSION BOLT @ 0.20-0.25 m. SPACING
6. COMPRESSIBLE FILLER (HARD RUBBER 15 mm. THICK) FOR VERTICAL COMPRESSION JOINTS
7. COPPER WATERSTOP 1.2 mm. THICK
8. MORTAR JOINT PAD MIN. 30 mm. THICK
9. RUBBER CUSHION
10. BOND BREAKER
11. POLYVINYL CHLORIDE FOAM
12. SK SEALING AGENT
13. 5x50 mm. HOT-DIP GALVANIZED FLAT STEEL
14. PVC BOARD (15 mm. THICK) FOR PERIMETER JOINTS WITH CONCRETE PLINTH
15. GB SEALANT 100x6 mm.

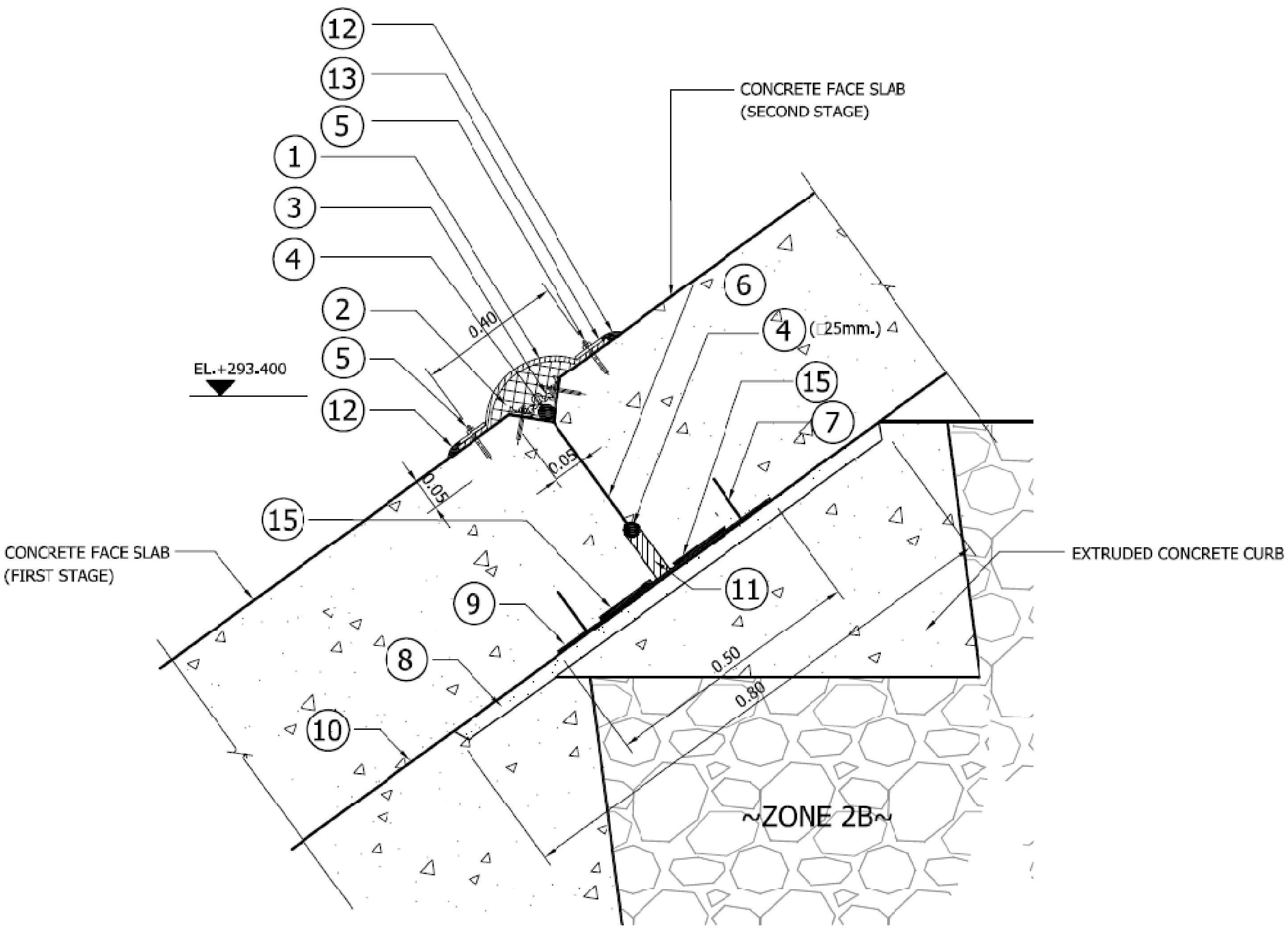


(a) Vertical tension joint



(b) Vertical compression joint

Vertical Joint



Horizontal Joint

Measures Adopted to Prevent Rupture of Face Slab

1. The copper waterstops and mortar pad is outside the theoretical thickness of face slab at compression joints.
2. The height of the central loop of the copper waterstop is reduced to keep the theoretical slab thickness at compression joints.
3. Increase the compressible filler thickness from 10mm to 20mm at compression joints.
4. Increase the compressible filler thickness for five central panels to be 30mm. (During construction)
5. The conventional V-notch at the top of the face slab is eliminated at compression joints.

Design of Instrumentations

Behaviour to be Measured

- Movements: Vertical, Horizontal and Total
- Joint Displacement
- Stress and Strain
- Seepage and Water Pressure
- Dynamic Response

Instrumentations	Behavior Measured						
	Vertical Movement	Horizontal Movement	Total Movement	Joint Displacement	Stress and Strain	Seepage and Water Pressure	Dynamic Response
1. Hydrostatic Settlement Cell	●	×	×	×	×	×	×
2. Electro Level	×	×	●	×	×	×	×
3. Fixed Embankment Extensometer	●	●	×	×	×	×	×
4. Probe Inclinometer and Settlement Gauge	●	●	×	×	×	×	×
5. Probe Inclinometer	×	×	●	×	×	×	×
6. Vibrating Wire Piezometer	×	×	×	×	×	●	×
7. Strong Motion Accelerometer	×	×	×	×	×	×	●
8. Surface Settlement Points	●	×	×	×	×	×	×
9. 3-D Joint Meter	×	×	×	●	×	×	×
10. 1-D Joint Meter	×	×	×	●	×	×	×
11. Open Standpipe Piezometer	×	×	×	×	×	●	×
12. Seepage Flow Meter	×	×	×	×	×	●	×
13. Stain Gauges • Reinforcement • Concrete Face Slab • Non Stress	×	×	×	×	●	×	×
14. Distributed Fiber–Optic Temperature (DFOT)	×	×	×	×	×	●	×
15. Total Pressure Cell	×	×	×	×	●	×	×

Location	Instrumentation	Quantity
Rockfill	Vibrating Wire Piezometer	35
	Total Earth Pressure Cell	3
	Probe inclinometer & Magnetic Settlement Gauge	3 sets
	Distributed Fiber Optic Temperature (DFOT)	900 m.
	Weather Station	1 set
	Hydrostatic Settlement Cell	22
	Fixed Embankment Extensometer	111
	V-notch Measuring Weir	1
	Strong Motion Accelerometer	1
	Gauge House	5
	Open Standpipe Piezometer	7
Face slab	Probe Inclinometer on Faceslab	1
	1 Dimensional Joint Meter	4
	2 Dimensional Joint Meter	10
	3 Dimensional Joint Meter	13
	Electro Level (Tilt Meter)	23
	3D Concrete Strain Gauge	27
	Rebar Strain Gauge	27
	Non Stress Strain Meter	7

Proposed Instrumentations

NN2 CFRD: Construction

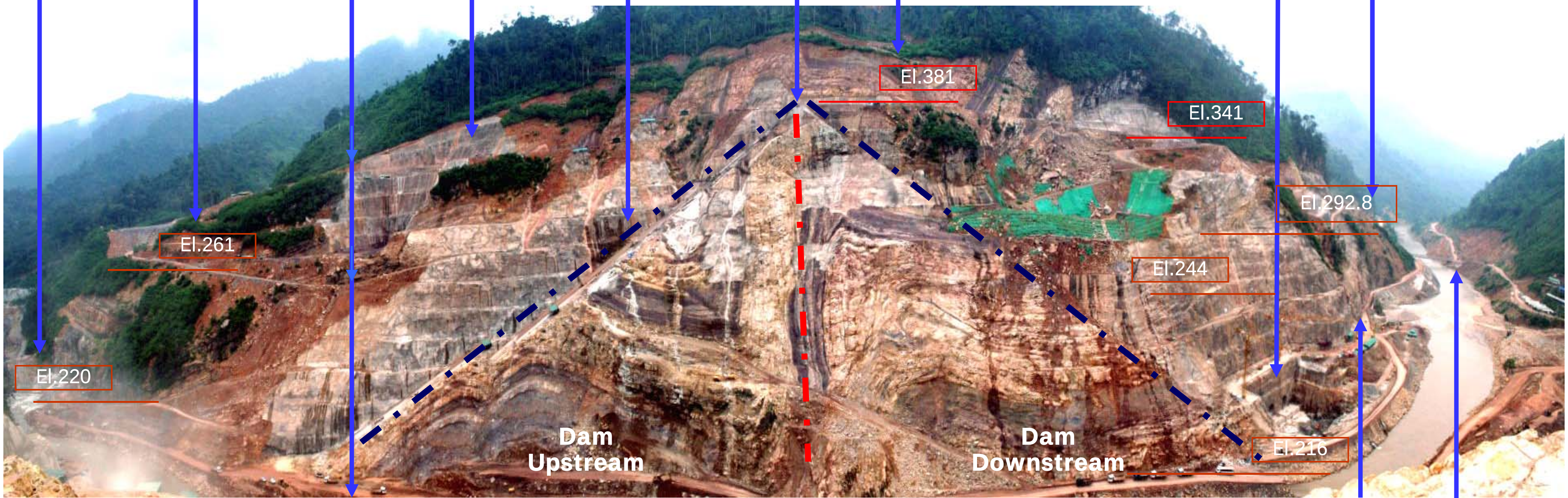
Aerial Photo

Main Dam (CFRD)

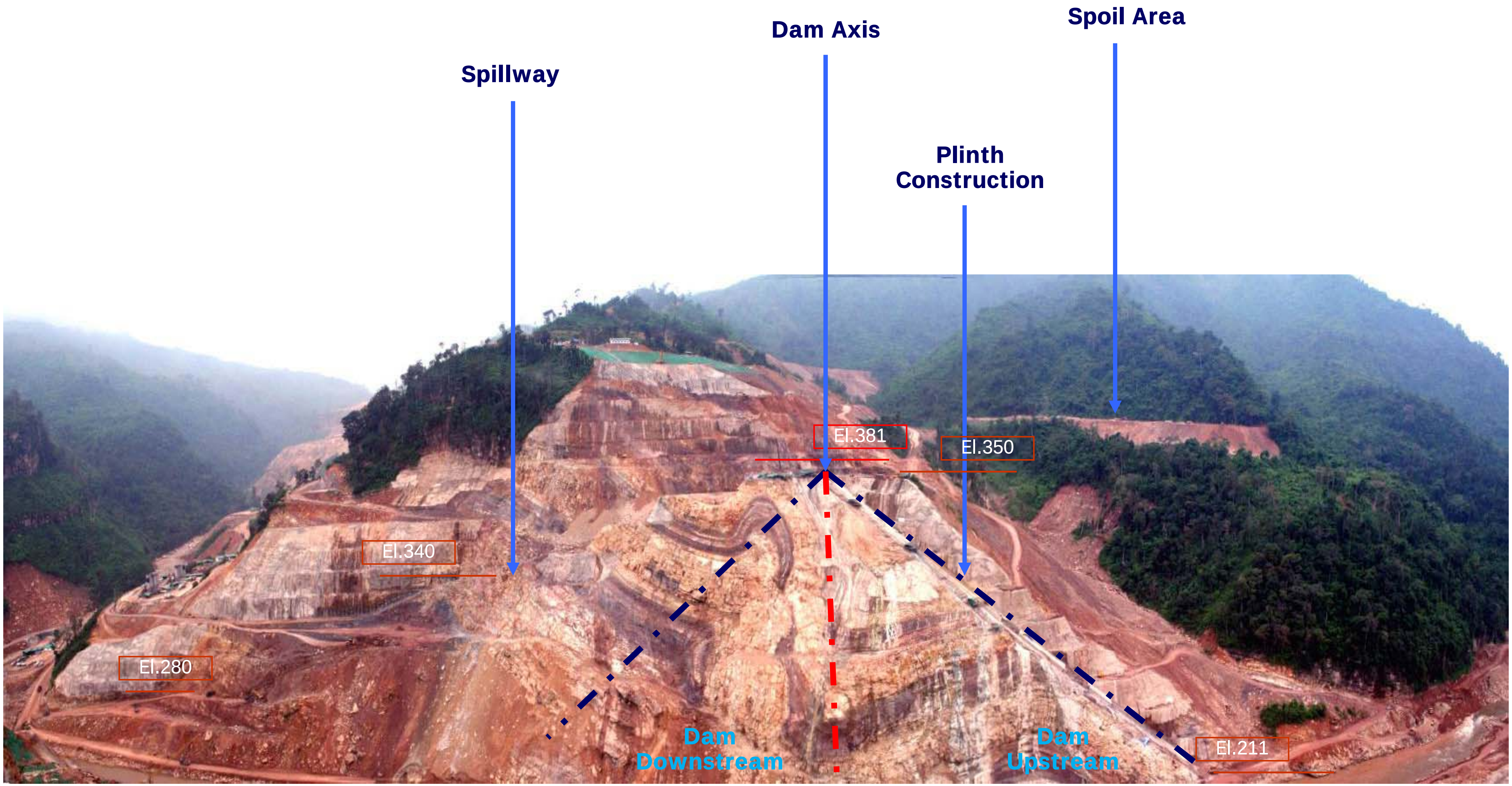
Quantities of Works

Dam Excavation (LB)	= 582,300 m^3
Dam Excavation (RB)	= 520,850 m^3
Dam Embankment	= 9,900,000 m^3
Concrete Face Slab	= 44,800 m^3
Concrete Dam Plinth	= 5,100 m^3
Concrete Wave Wall	= 2,200 m^3
Reinforcement	= 4,100 tons

DAM Left-Abutment Excavation



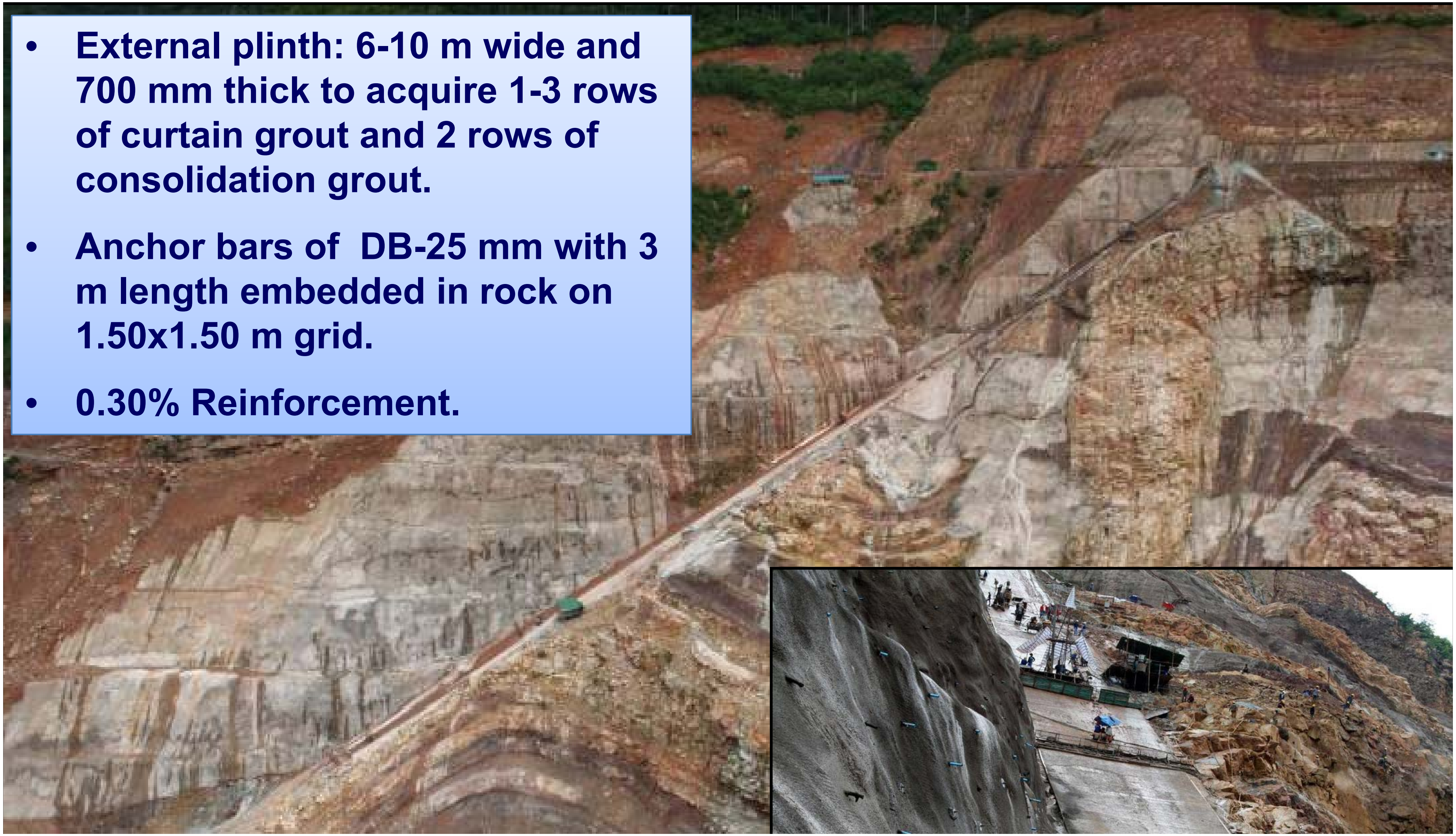
DAM Right-Abutment Excavation



DAM Left Abutment (Upstream)

Plinth Construction

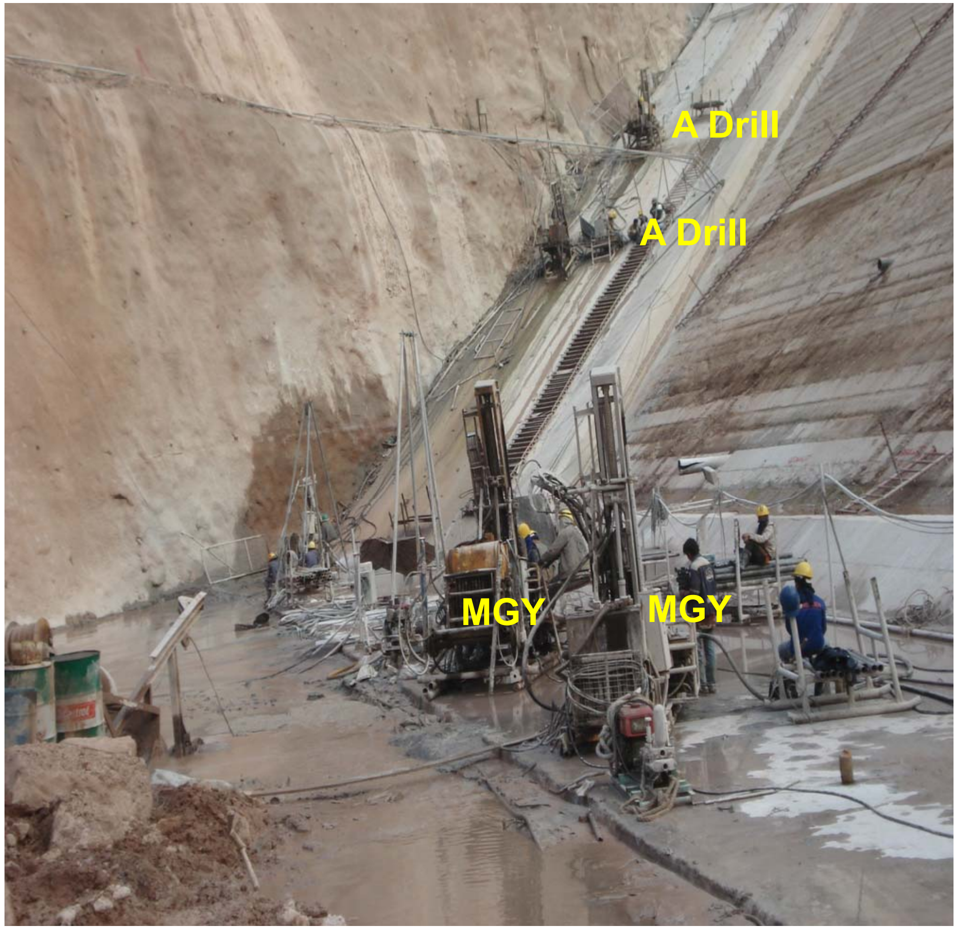
- External plinth: 6-10 m wide and 700 mm thick to acquire 1-3 rows of curtain grout and 2 rows of consolidation grout.
- Anchor bars of DB-25 mm with 3 m length embedded in rock on 1.50x1.50 m grid.
- 0.30% Reinforcement.



DAM Right Abutment (Upstream)

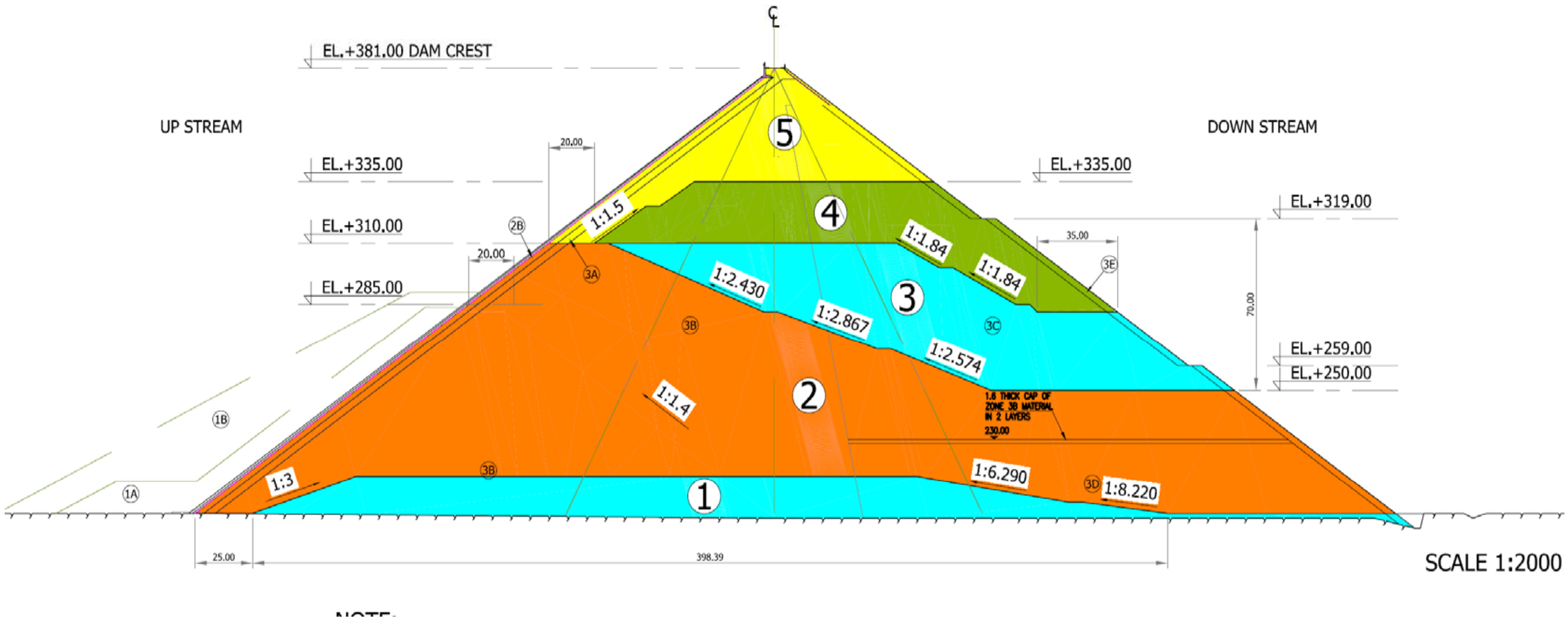
Plinth Construction

Sleeve Grout Pipe Installation

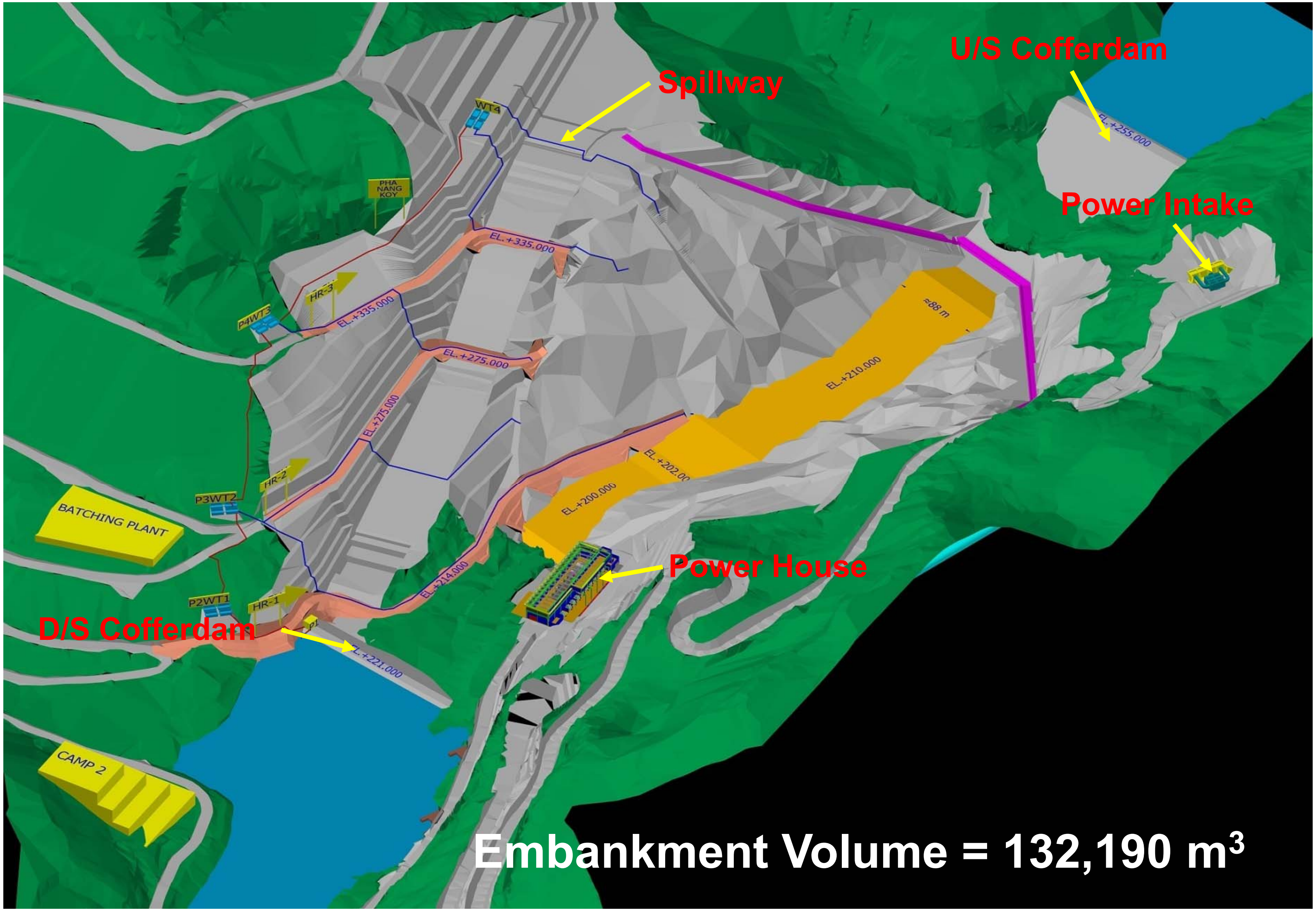


Left Corner (P5)

Right Corner (P4)



Dam Embankment Construction Sequence



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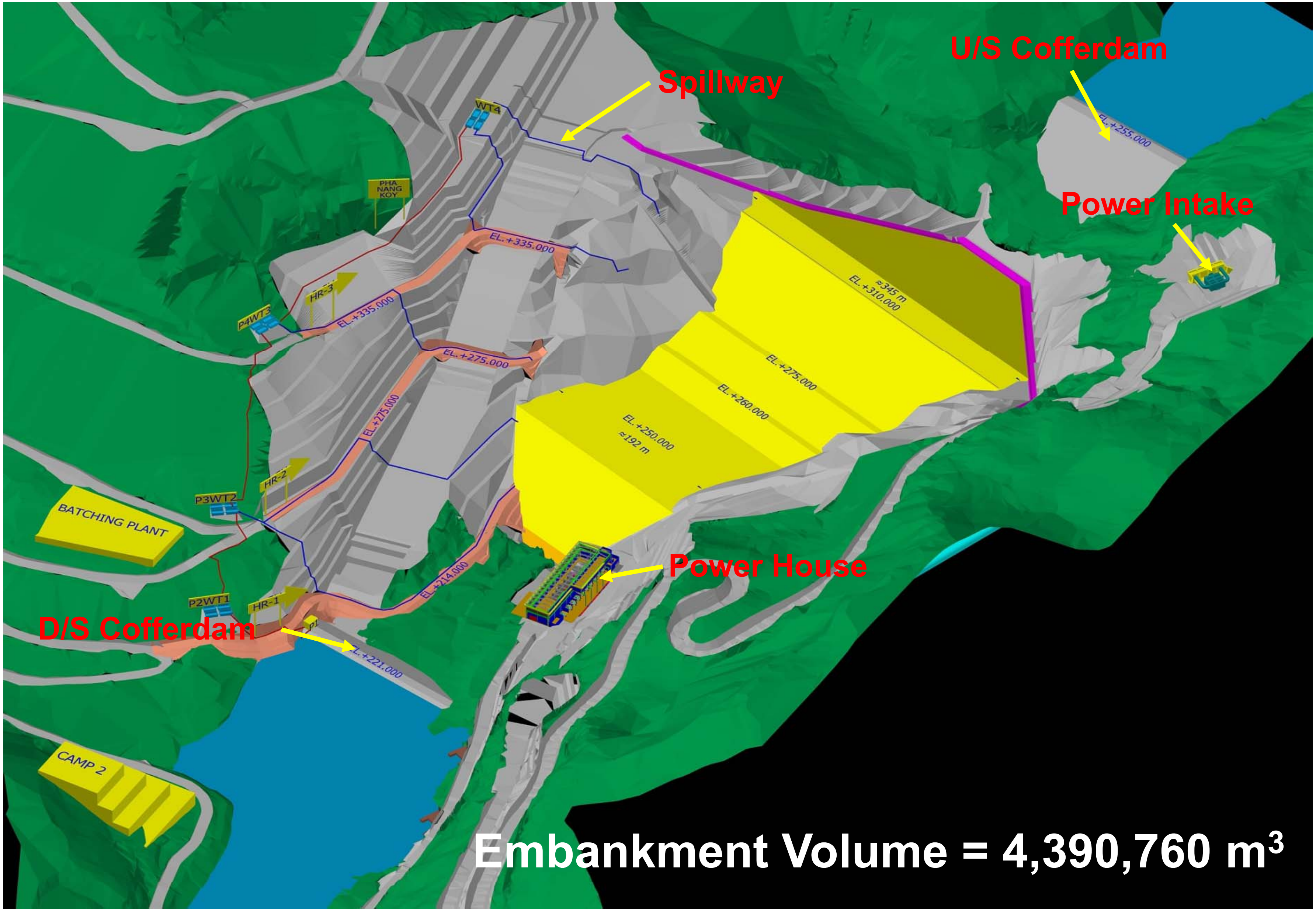
Dam Construction Sequence (Stage 1)

A Member of TEAM GROUP



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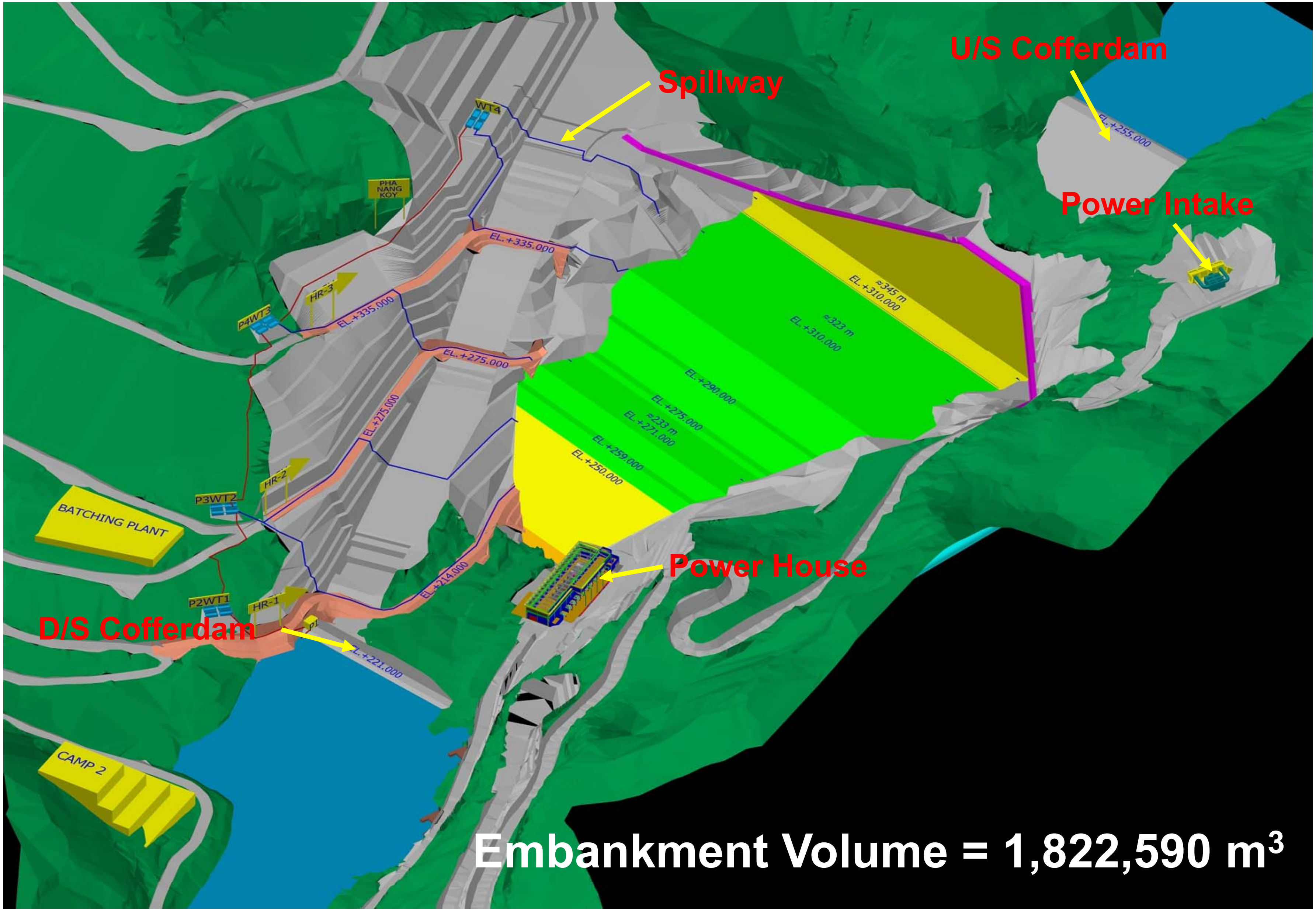
Dam Construction Sequence (Stage 2)

A Member of TEAM GROUP



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Dam Construction Sequence (Stage 3)

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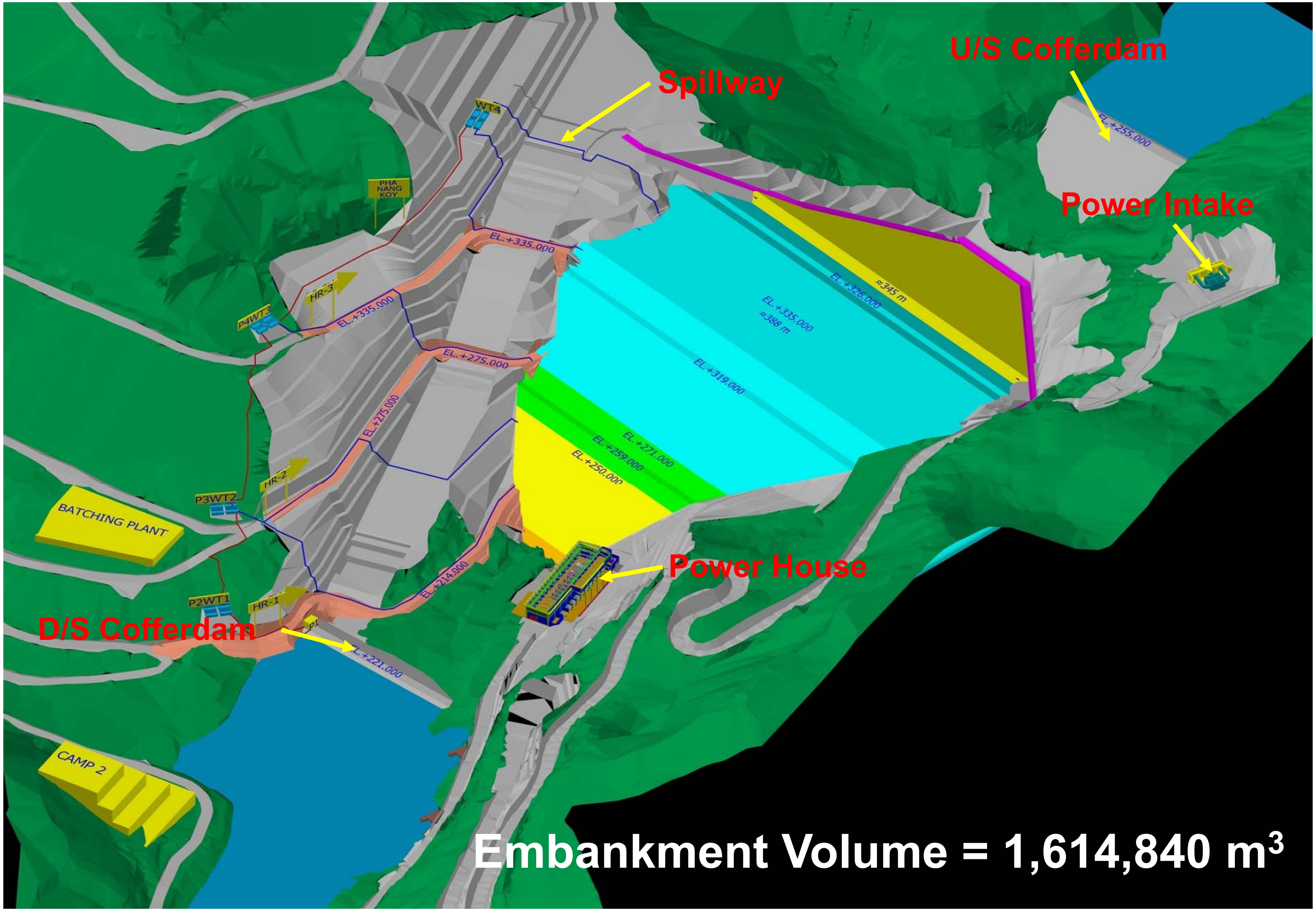

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Dam Construction Sequence (Stage 4)

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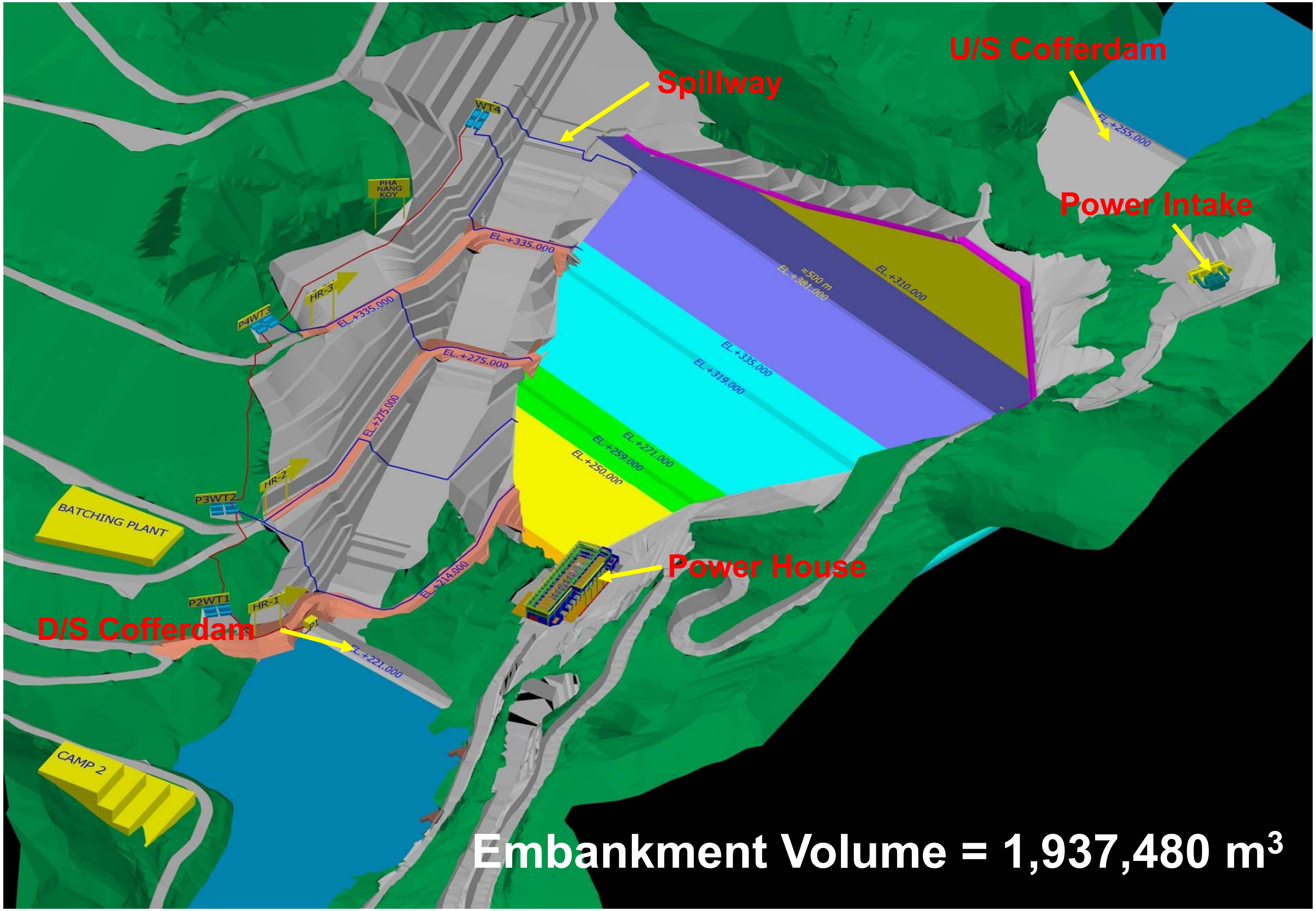

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Dam Construction Sequence (Stage 5)

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- 15 tons vibrating roller
- Unit Weight: 21.5~22.5 kN/m^3
- Zone 3B: 0.80m lift thickness with 8 passes
- Zone 3C: 1.20 m. lift thickness with 6 passes
- Intensive compaction at both steep abutments
- Water Sluicing: 150-200 liters/m^3

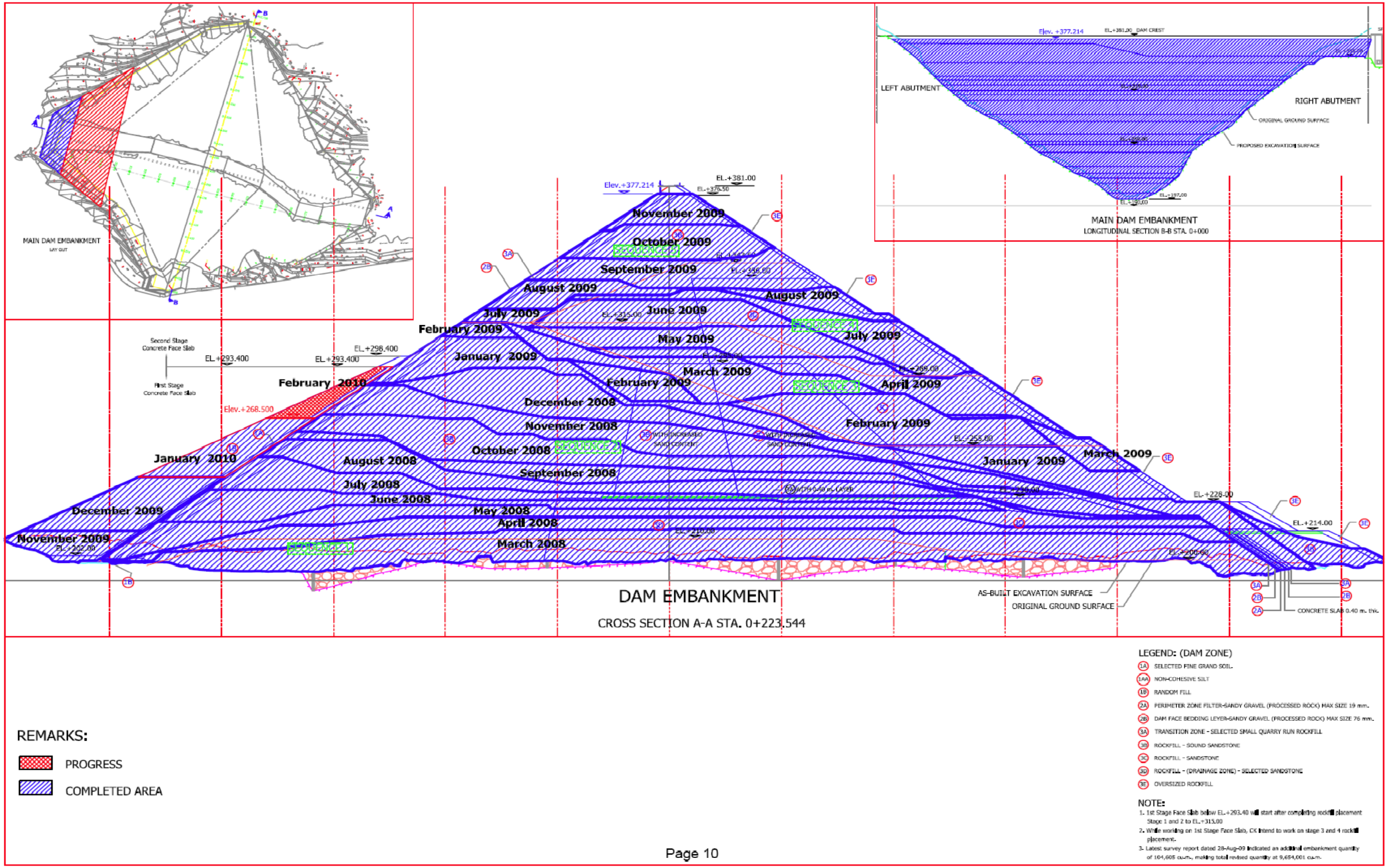
Dam Embankment Construction

Early Start Dam Embankment View from Downsteam

Early Start Dam Embankment View from Upstream

Copper Waterstop Installation

Extruded Curb Construction



Dam Embankment Construction

- **Settlement: less than 5 mm/month.**
- **Concrete: C25/38**
- **Slipform speed: 2 m/hr.**
- **Curing: Curing compound and running water.**

U/S View

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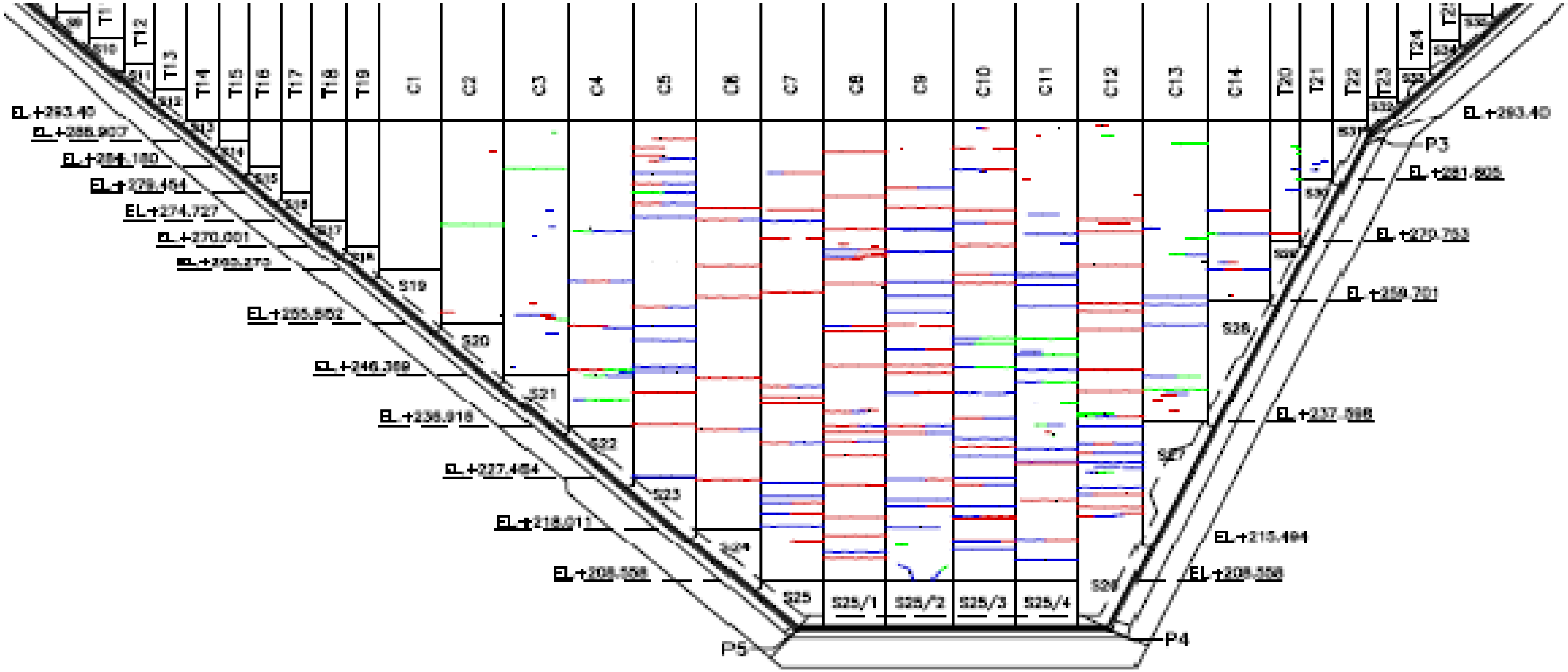
D/S View

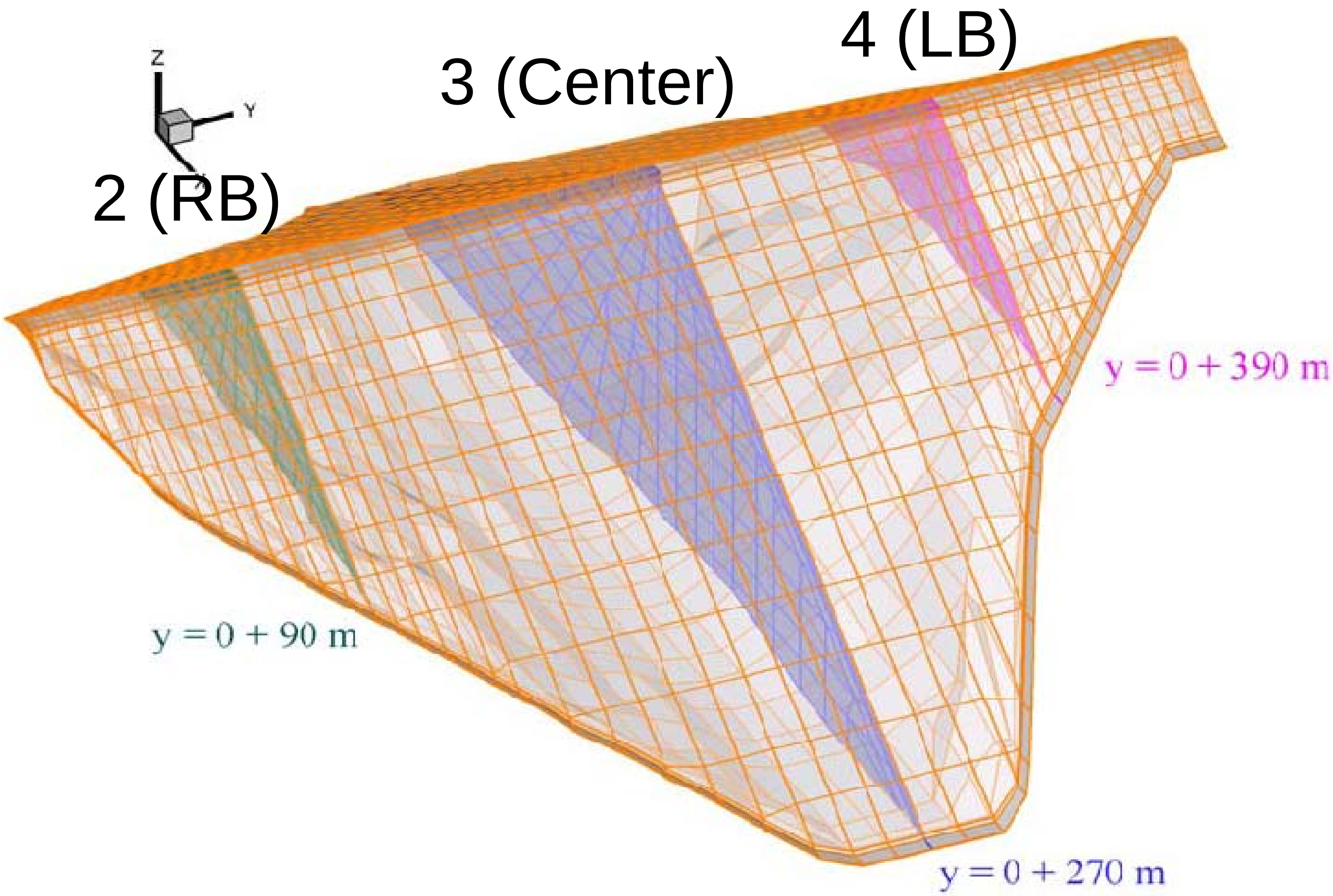
Observed Cracks on First Stage Face Slab



- Numerous horizontal cracks.
- Crack width: between 0.30-0.40 mm
- Cause: Concrete shrinkage

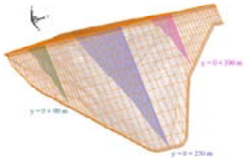
NN2 CFRD: Performance

Location	Instrumentation	Quantity
Rockfill	Vibrating Wire Piezometer	35
	Total Earth Pressure Cell	3
	Probe inclinometer & Magnetic Settlement Gauge	3 sets
	Distributed Fiber Optic Temperature (DFOT)	900 m.
	Weather Station	1 set
	Hydrostatic Settlement Cell	22
	Fixed Embankment Extensometer	111
	V-notch Measuring Weir	1
	Strong Motion Accelerometer	1
	Gauge House	5
	Open Standpipe Piezometer	7
Face slab	Probe Inclinometer on Faceslab	1
	1 Dimensional Joint Meter	4
	2 Dimensional Joint Meter	10
	3 Dimensional Joint Meter	13
	Electro Level (Tilt Meter)	23
	3D Concrete Strain Gauge	27
	Rebar Strain Gauge	27
	Non Stress Strain Meter	7

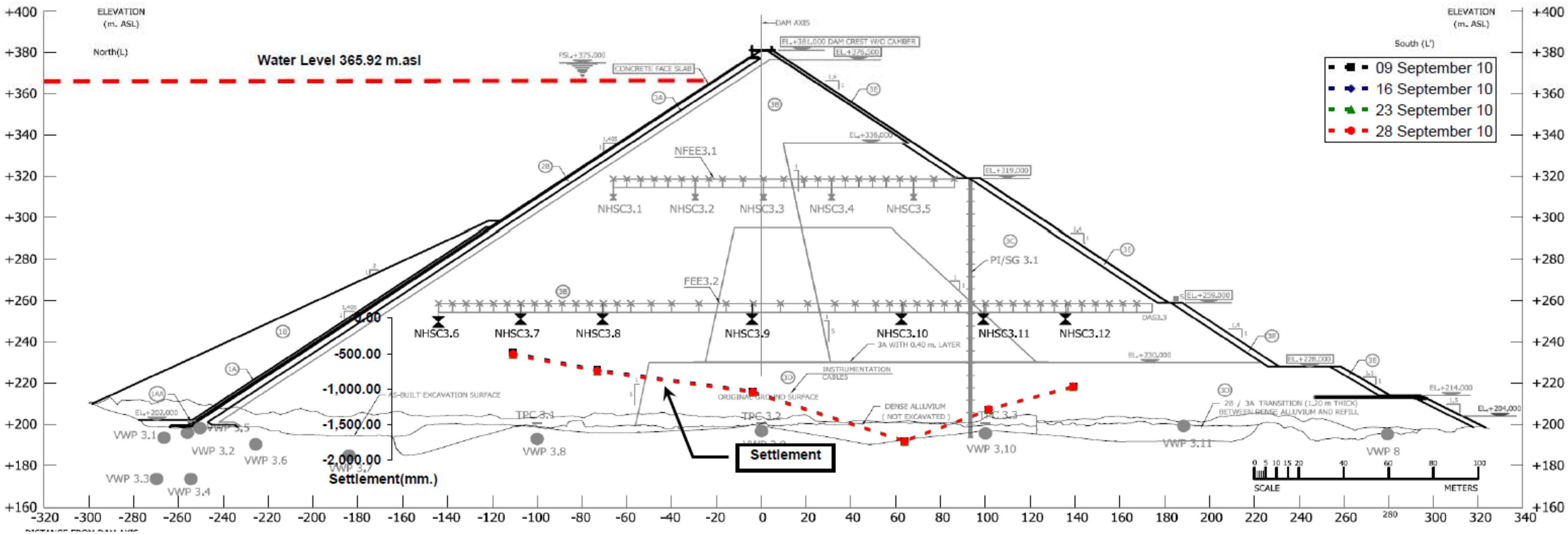


Observed Settlement Section

As of September 30, 2010



Hydrostatic Settlement Cell Section 3 (EL +259.0 m asl)



HSC 3.10

1680 mm (22 Mar 10) End of Construction

1734 mm (30 Sep 10) During Impounding

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Observed Settlement (Center)

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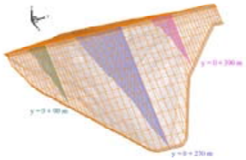
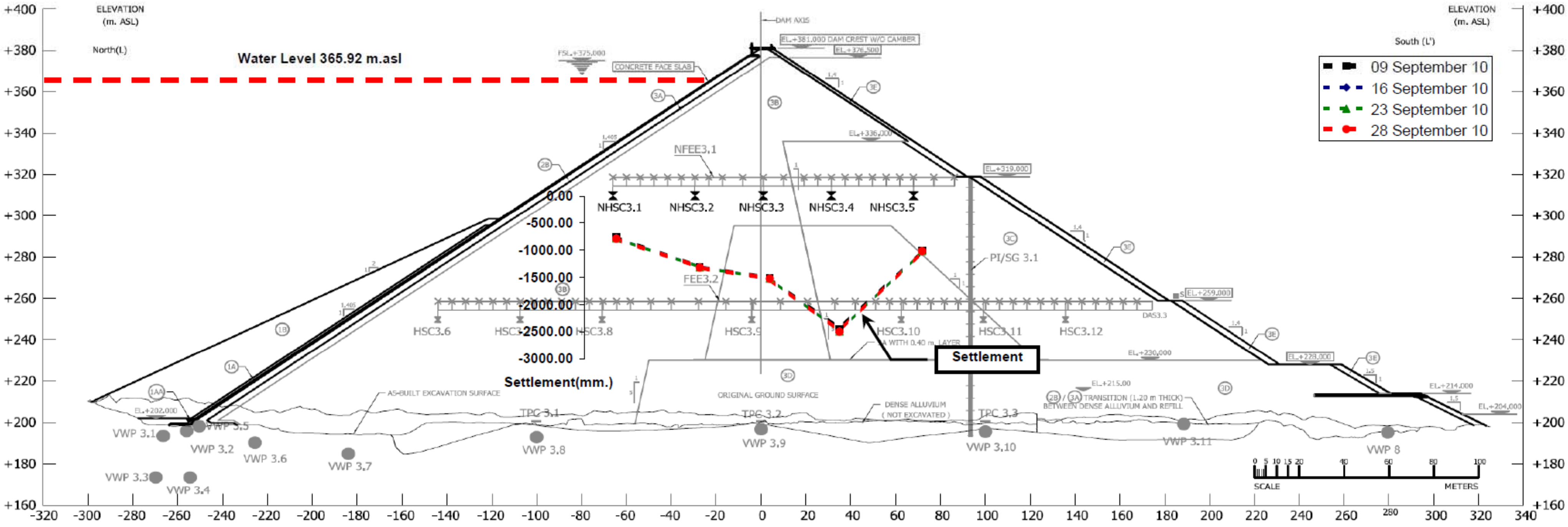
As of September 30, 2010



Hydrostatic Settlement Cell Section 3 (EL +319.0 m asl)



HSC 3.4

2130 mm (22 Mar 10) End of Construction

2520 mm (30 Sep 10) During Impounding

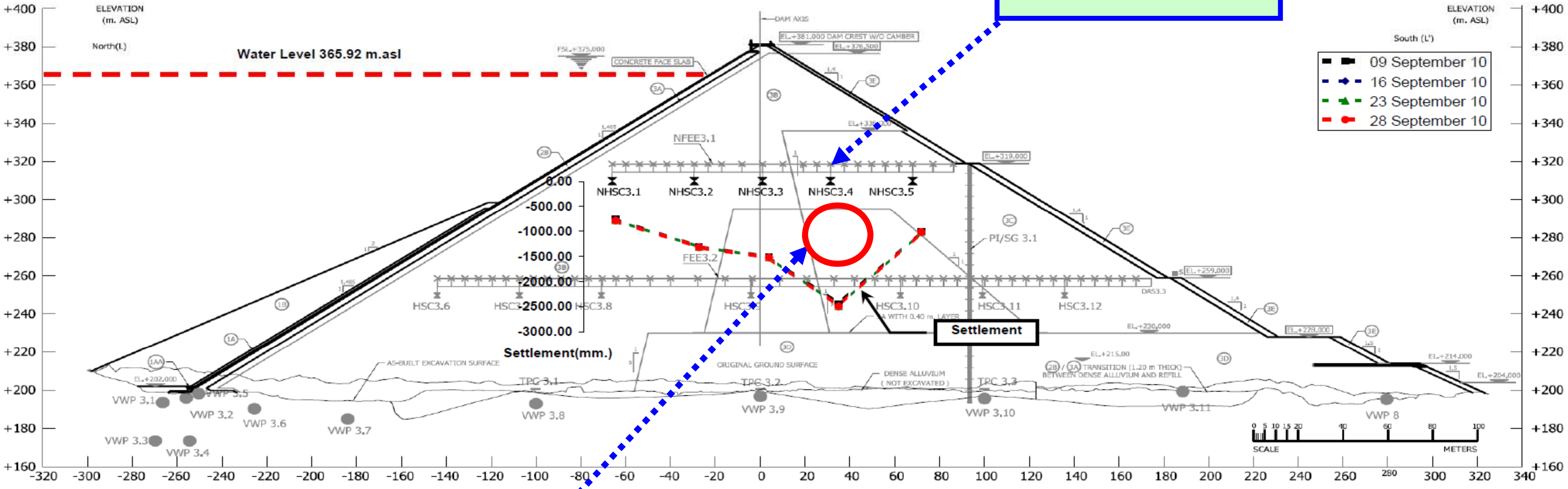
Observed Settlement (Center)

Maximum Settlement Section 3 (EL +319.0 m asl)

HSC 3.4

Max Settlement Observed

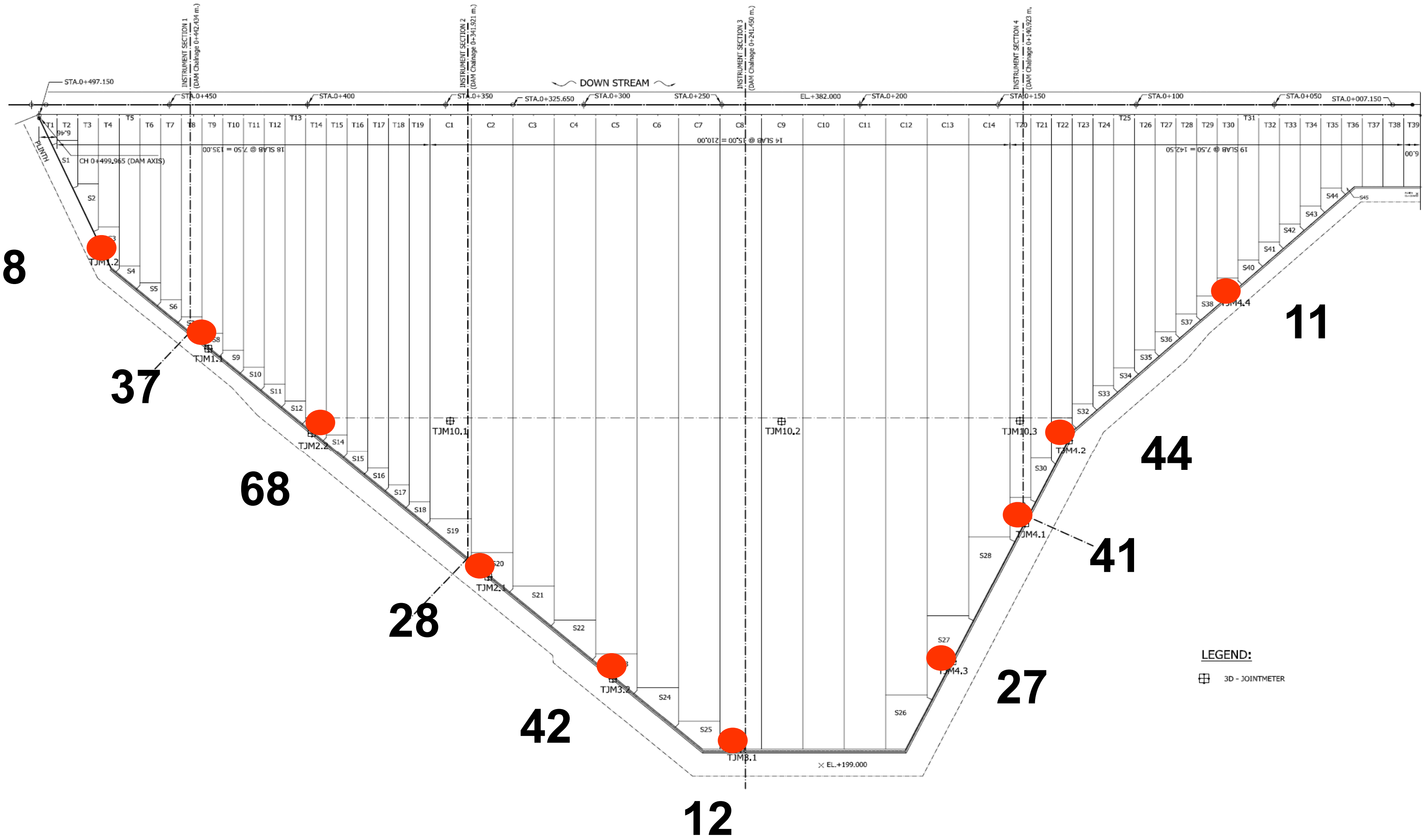
2.52m



Location of Max Settlement Expected

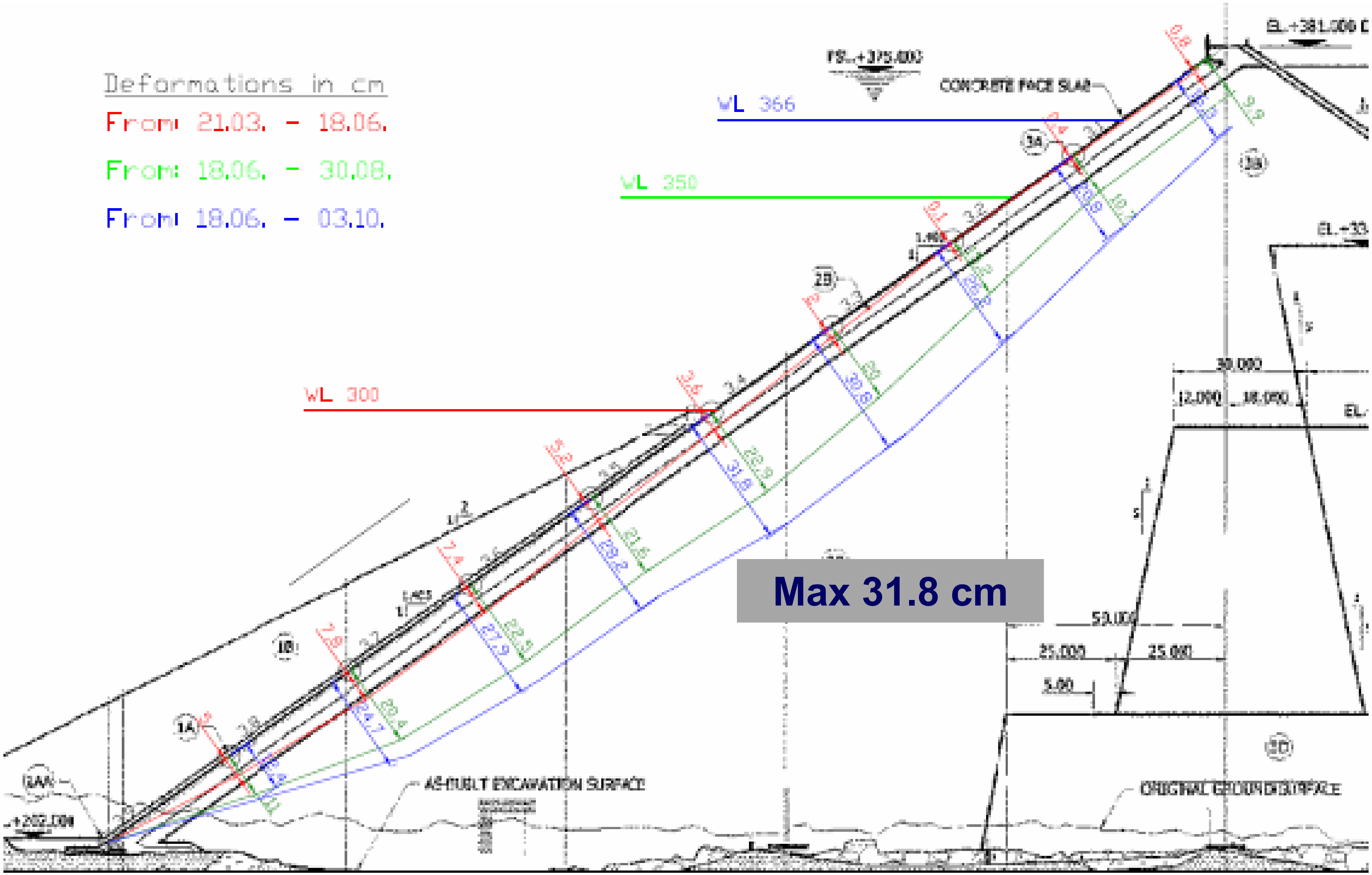
2.8m ?

As of September 30, 2010



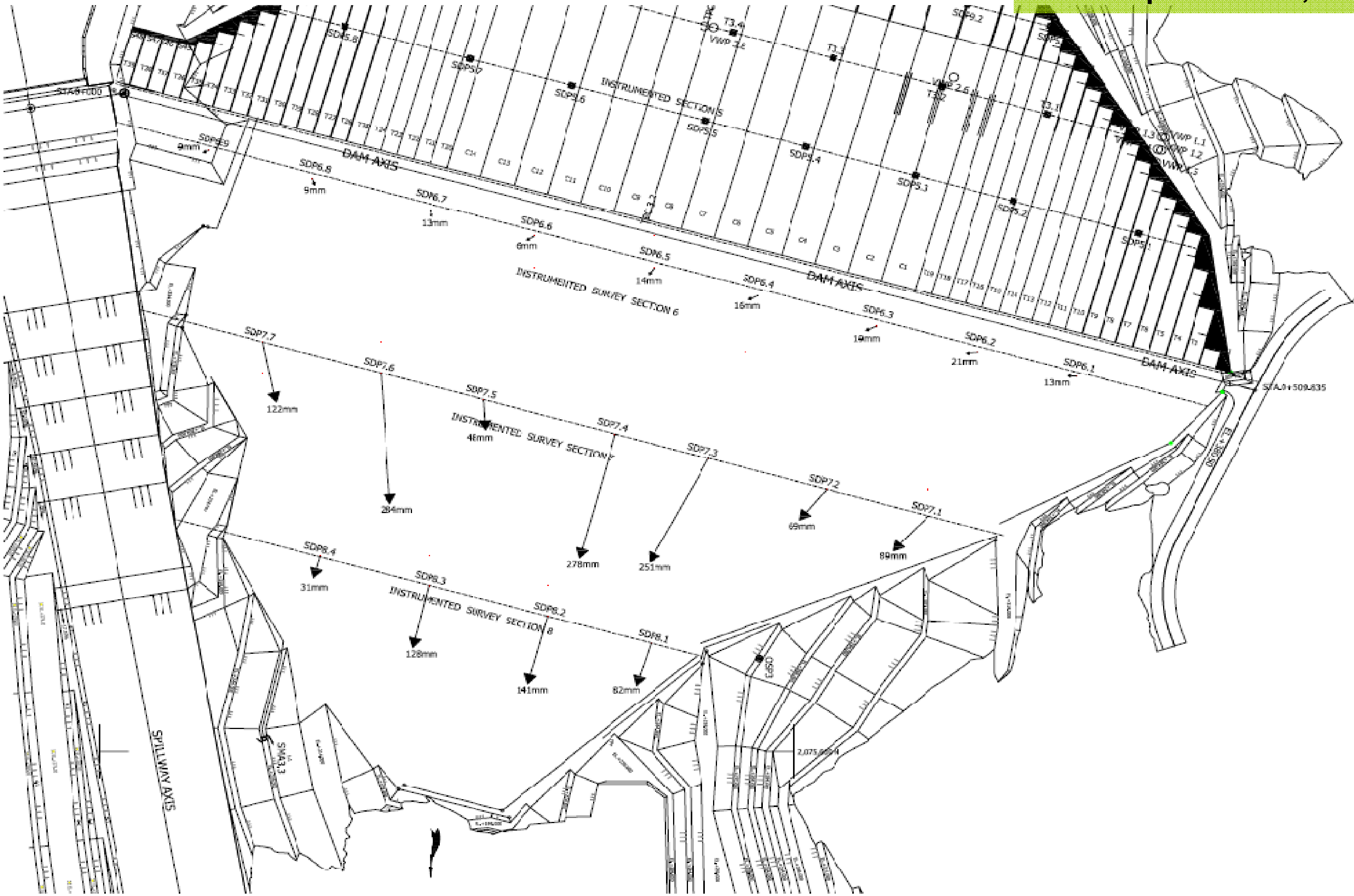
Face Slab Joint Meter (mm)

As of September 30, 2010



Face Slab Deflections (Center)

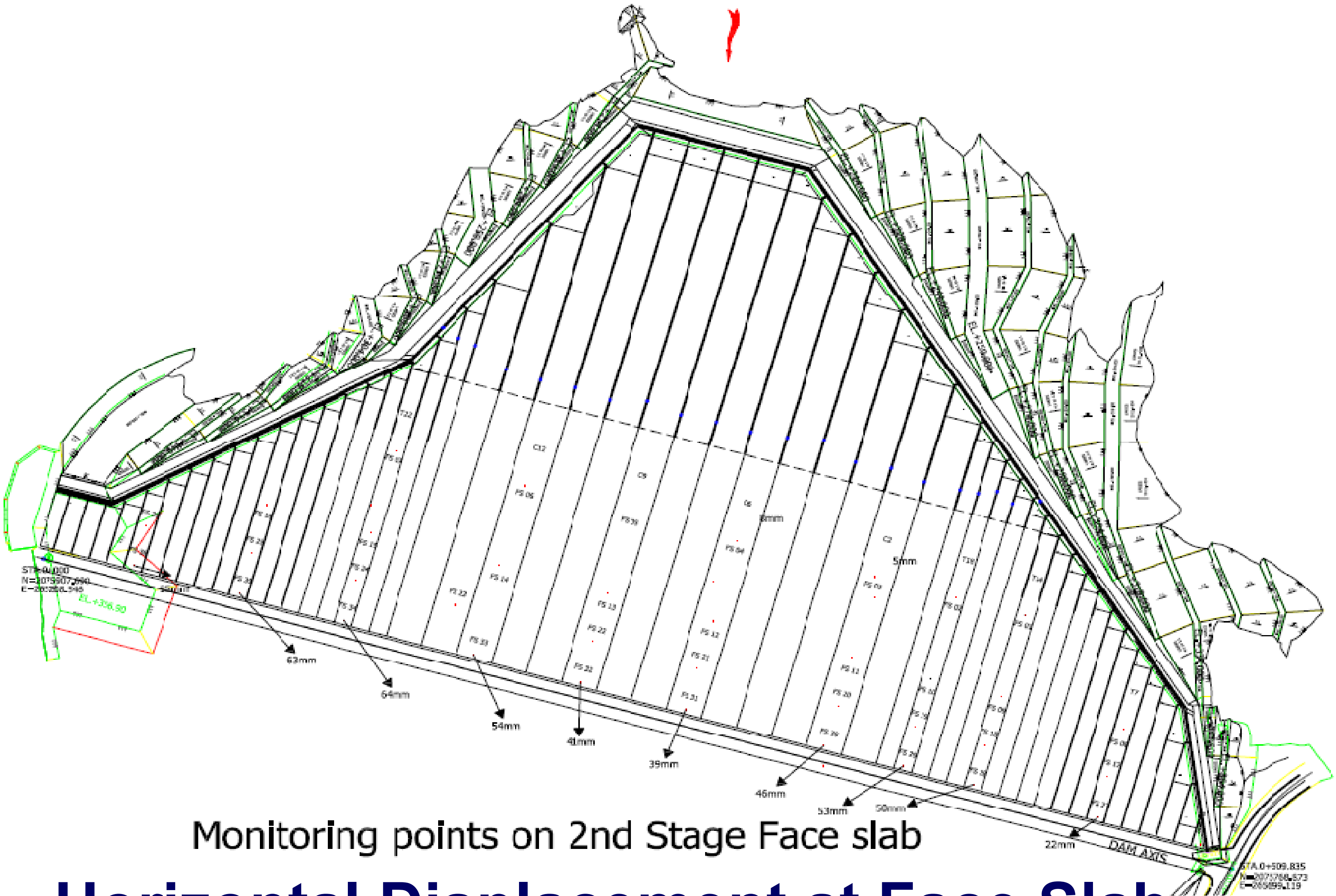
As of September 30, 2010



Horizontal Displacement at D/S Dam Face

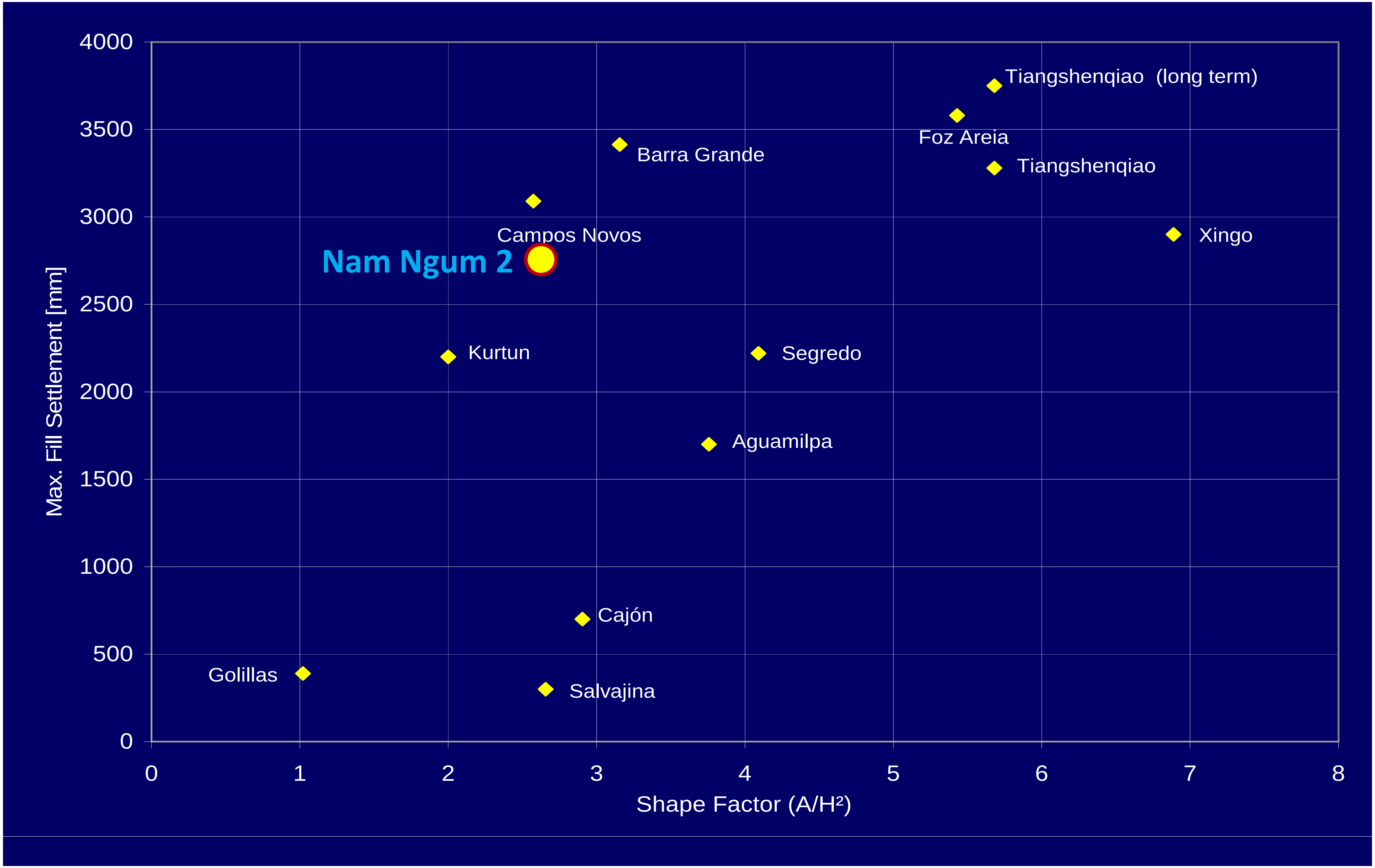
As of September 30, 2010

Monitoring points on Face Slab

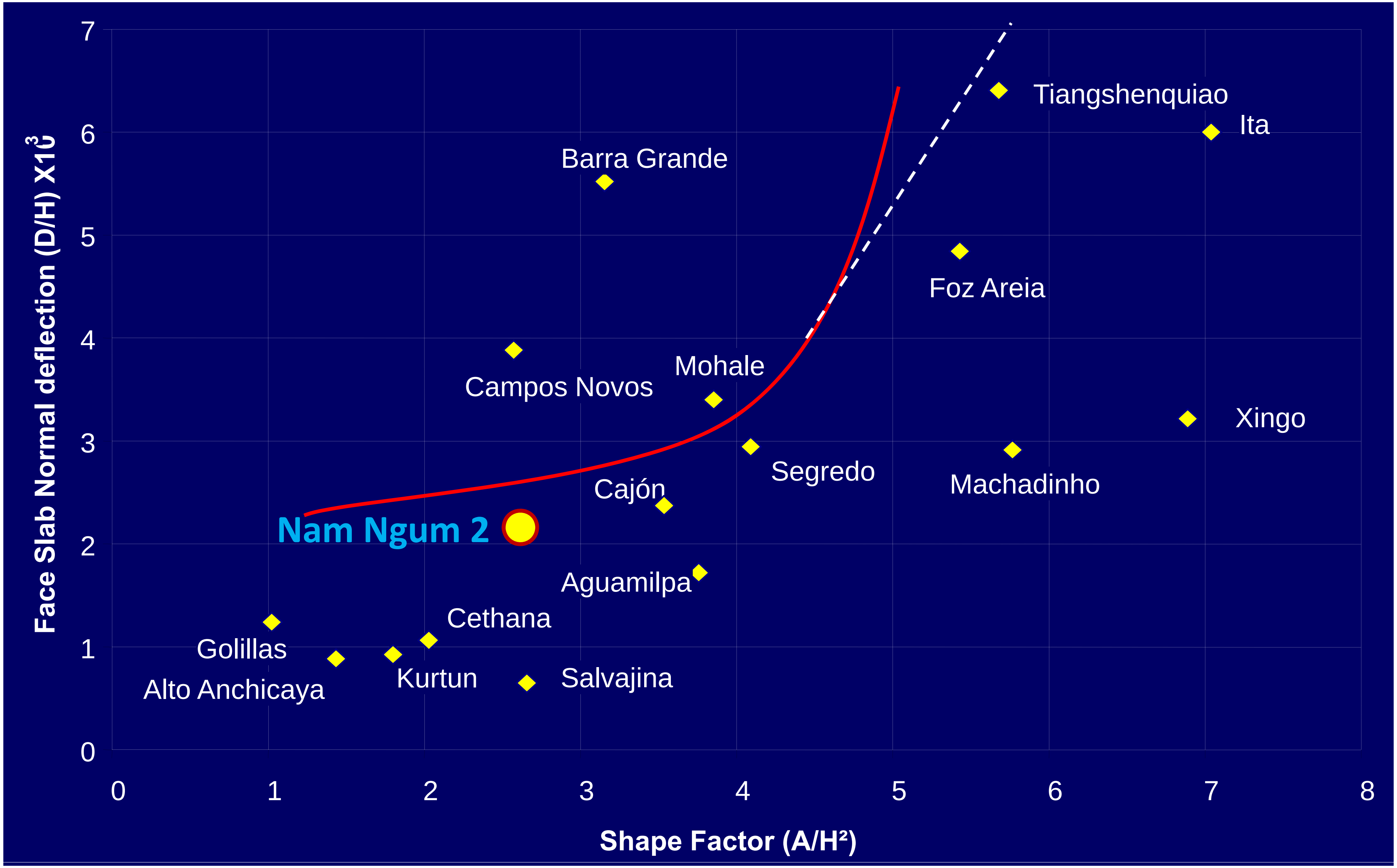


Monitoring points on 2nd Stage Face slab

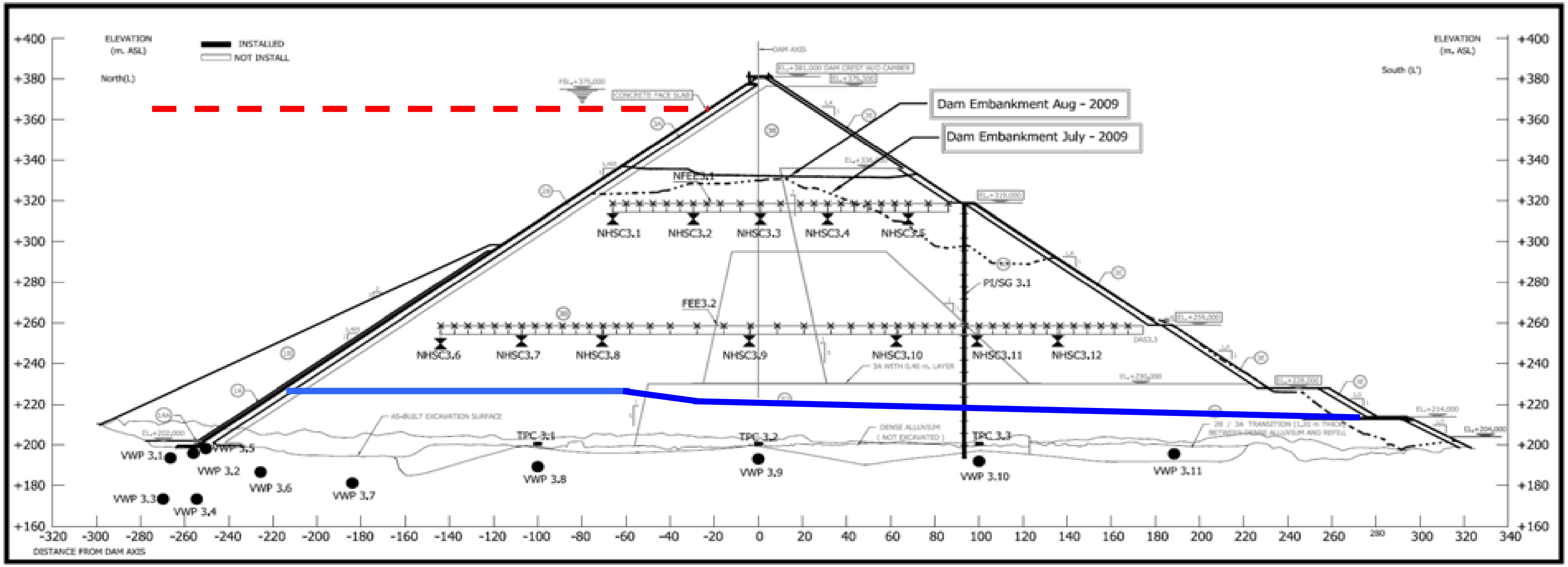
Horizontal Displacement at Face Slab



Settlements During Construction



Face Slab Deflections



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Water Level in Dam

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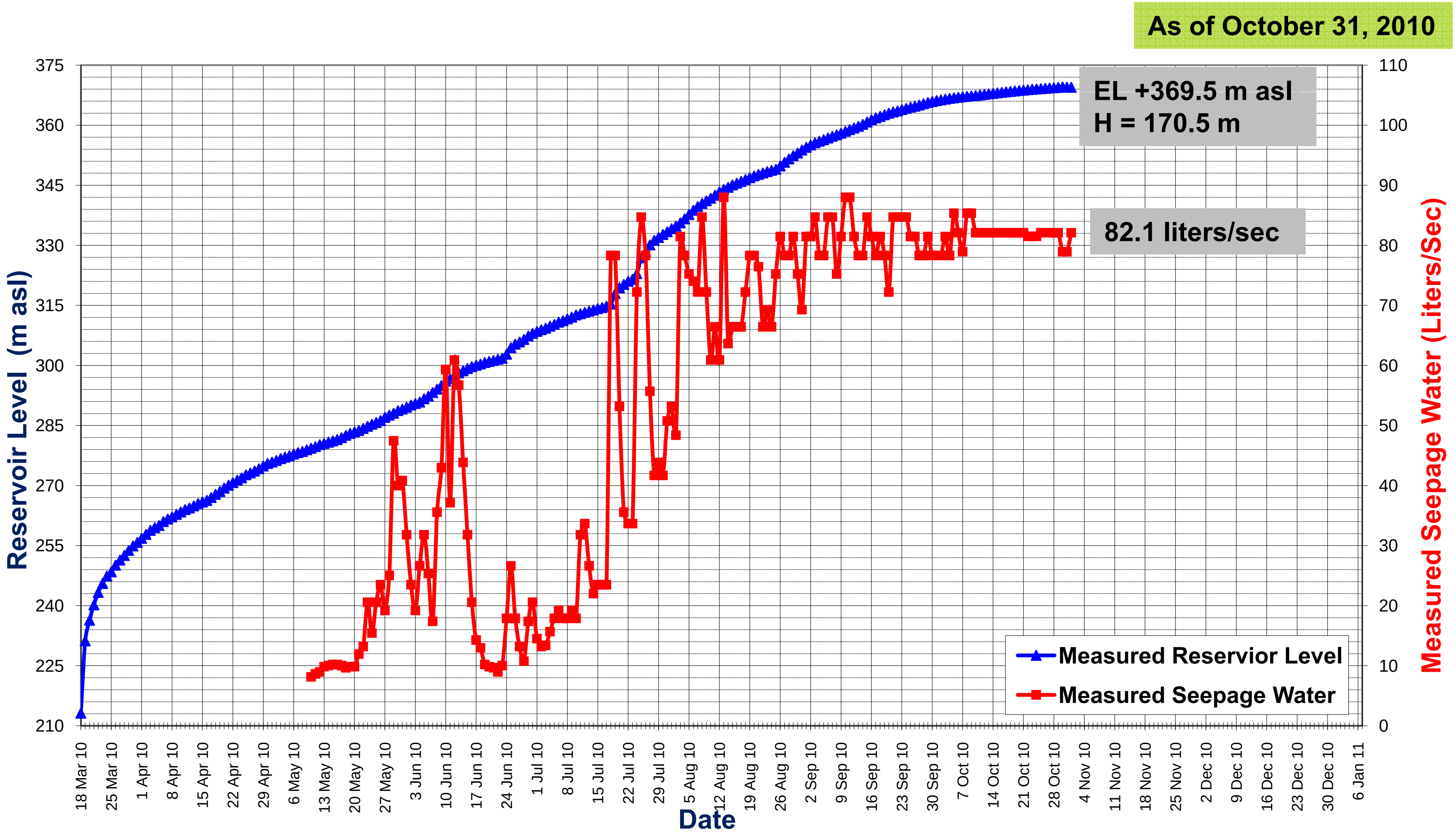
As of March 26, 2010

Reservoir Impounding

As of September 30, 2010

Reservoir Impounding



Reservoir Level and Seepage Water

Summary on Dam Behaviour

- The instrumentation monitoring is satisfactory.
- Deformation behaviour of the dam is acceptable.
- Creep deformation and related structural dam behaviour to be observed.
- Tightness of the dam is satisfactory.
- Seepage monitoring to be improved.
- Visual appearance of the dam is excellent.

Thank You

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