Invited Talk

CE504 Slope Stability and Retaining Structures

IIT Mandi

15 April 2025

Failure of a Marginally Stable Hillslope: A Forensic Investigation

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Landslide at Calcom Cement Plant, Umrangso, Assam

Forensic Geotechnology

A Scientific Approach of Bridging between Comprehension, Intuition and Knowledge Updating to Dig out the Root Cause of an Incident

General Site Conditions

- Lat: N25°31′04″, Long: E92°47‘19.3″, Elevation: +501m MSL
- Climatic conditions: Average Annual Rainfall – 1672 mm (high)

Pre-Reconnaissance Round-Table Discussion

- 2nd November 2015: Meeting with the client
  - *Pictures of damages of the 24-Colony Residential Housing blocks*
    - 2 rows of 12 quarters face-to-face: All extensively damaged
      - Wall and Floor cracking / See through cracks
      - Detachment of plasters
      - Abnormal sounds from cracking
      - Detachment in floors
      - Shifting of soil in plinth area





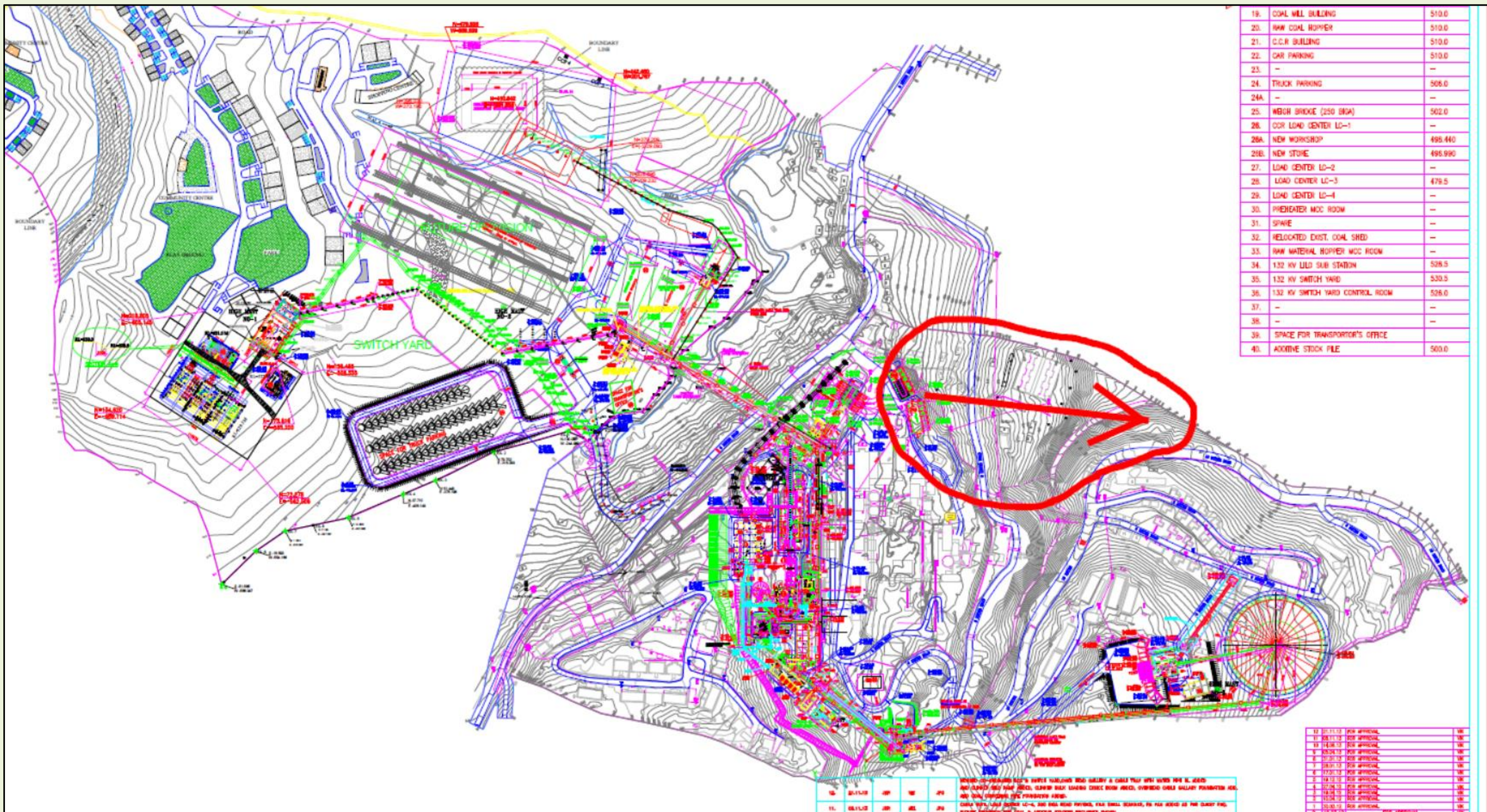


Pre-Reconnaissance Round-Table Discussion

- 2nd November 2015: Meeting with the client, Dalmia Cements
  - *Pictures of damages in the protective retaining and boundary walls*
    - Development of gaps and cracks in the retaining walls
      - Retaining wall 1: Between cement factory (workshop) and 24-Colony
      - Retaining Wall 3: Beside RCL road in front of 24 colony
      - Retaining wall 2: Frontal protection of 24-Colony (3 m)
      - Gaps in old boundary wall
      - Dislodgment of pavement and drains

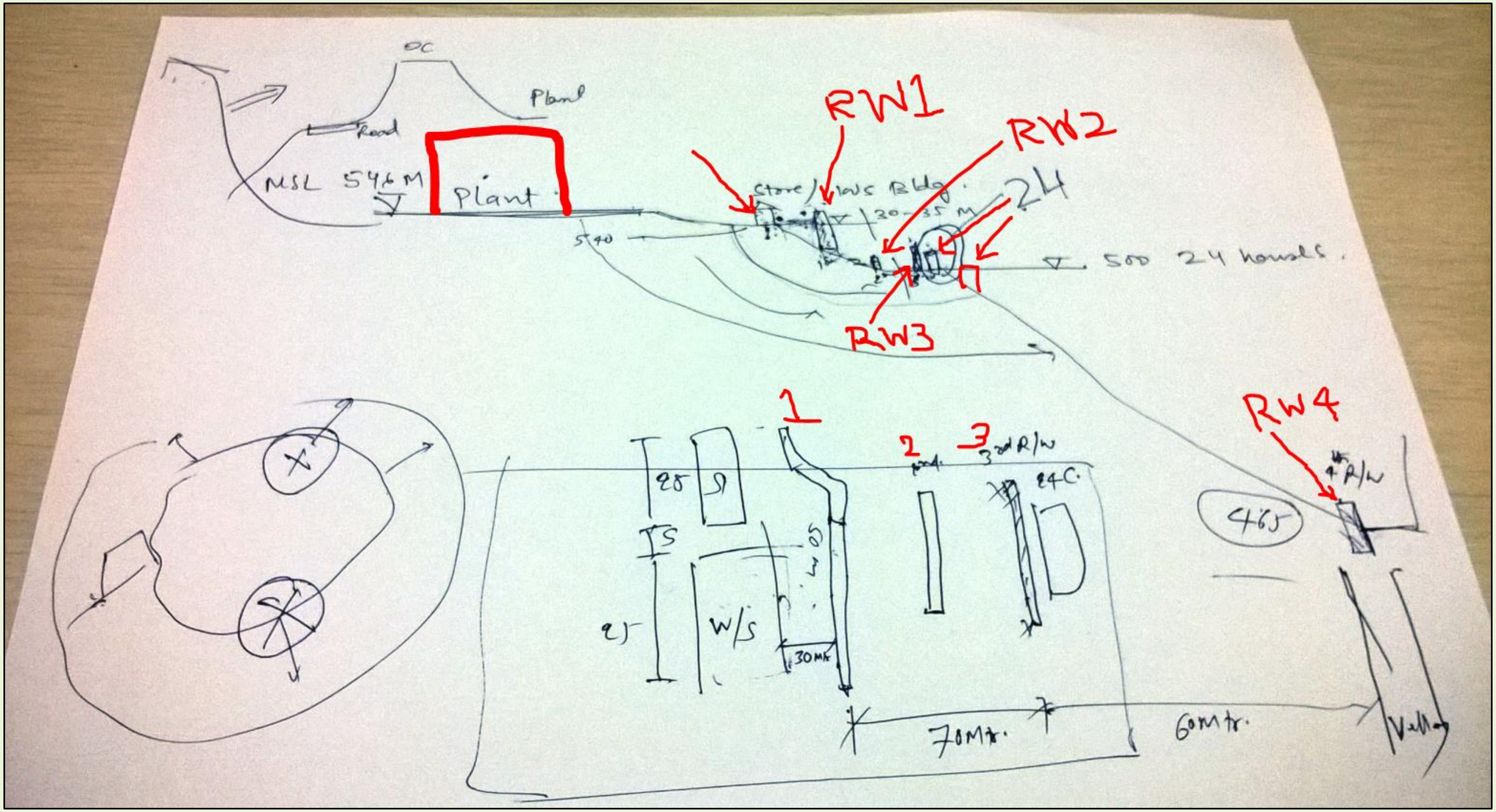
Pre-Reconnaissance Round-Table Discussion

- 2nd November 2015: Meeting with the client, Dalmia Cements
  - ❖ *Contour map of the site*



Pre-Reconnaissance Round-Table Discussion

- 2nd November 2015: Meeting with the client, Dalmia Cements
  - ❖ *Rough sketch of site topography*



Site Visit for Reconnaissance Survey: 3rd Nov 2015

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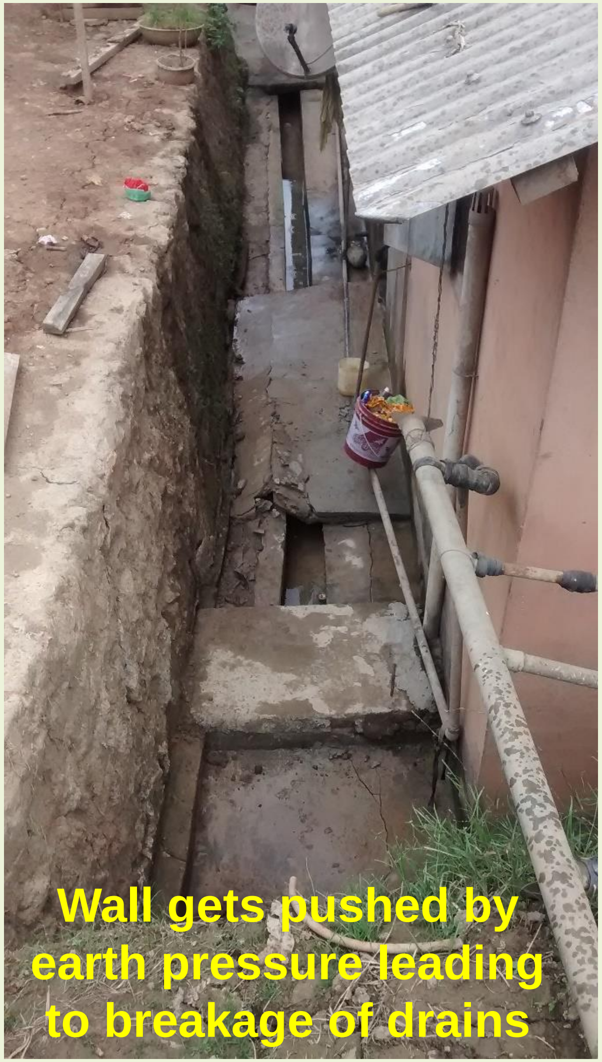


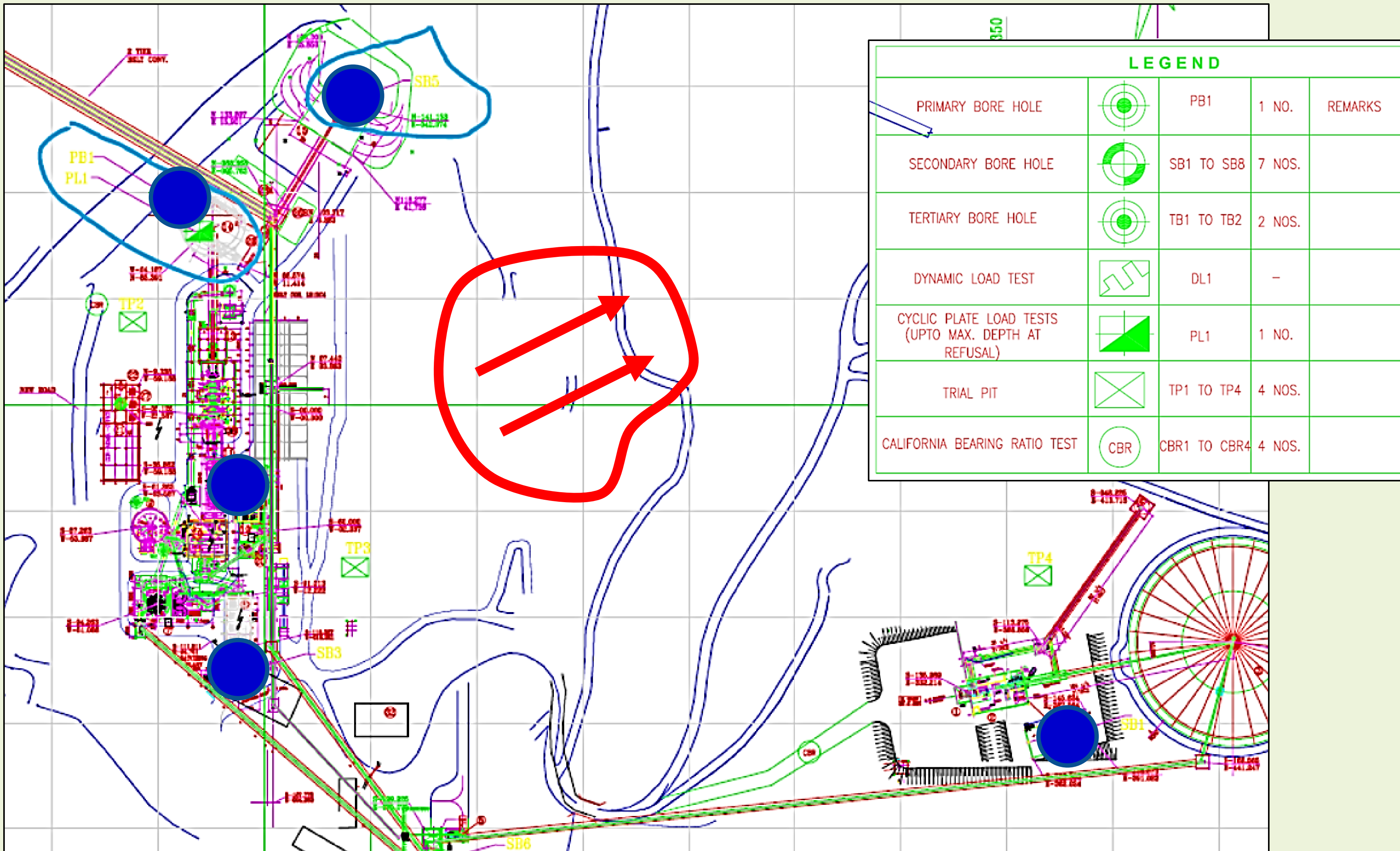
Site Visit for Reconnaissance Survey: 3rd Nov 2015

- Immense mass movement of soil
- Broken boundary wall
- Ejection of seeping water
- Overtopping of retaining wall
- Breakage of downhill protection wall

Extensive damage in the 24-Colony leading to relocation of workers

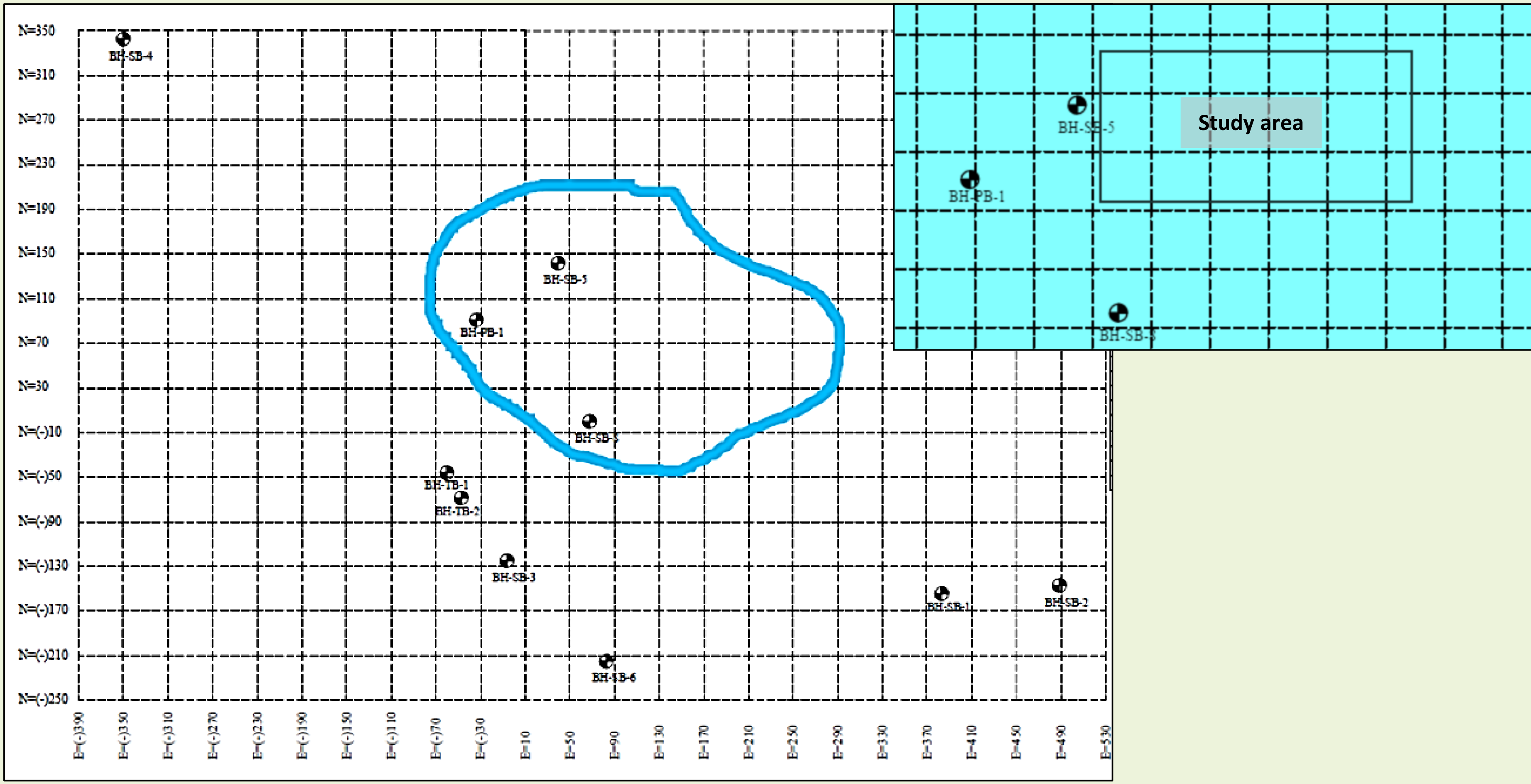
Collection of Information and Data

- Geotechnical investigation locations at the site



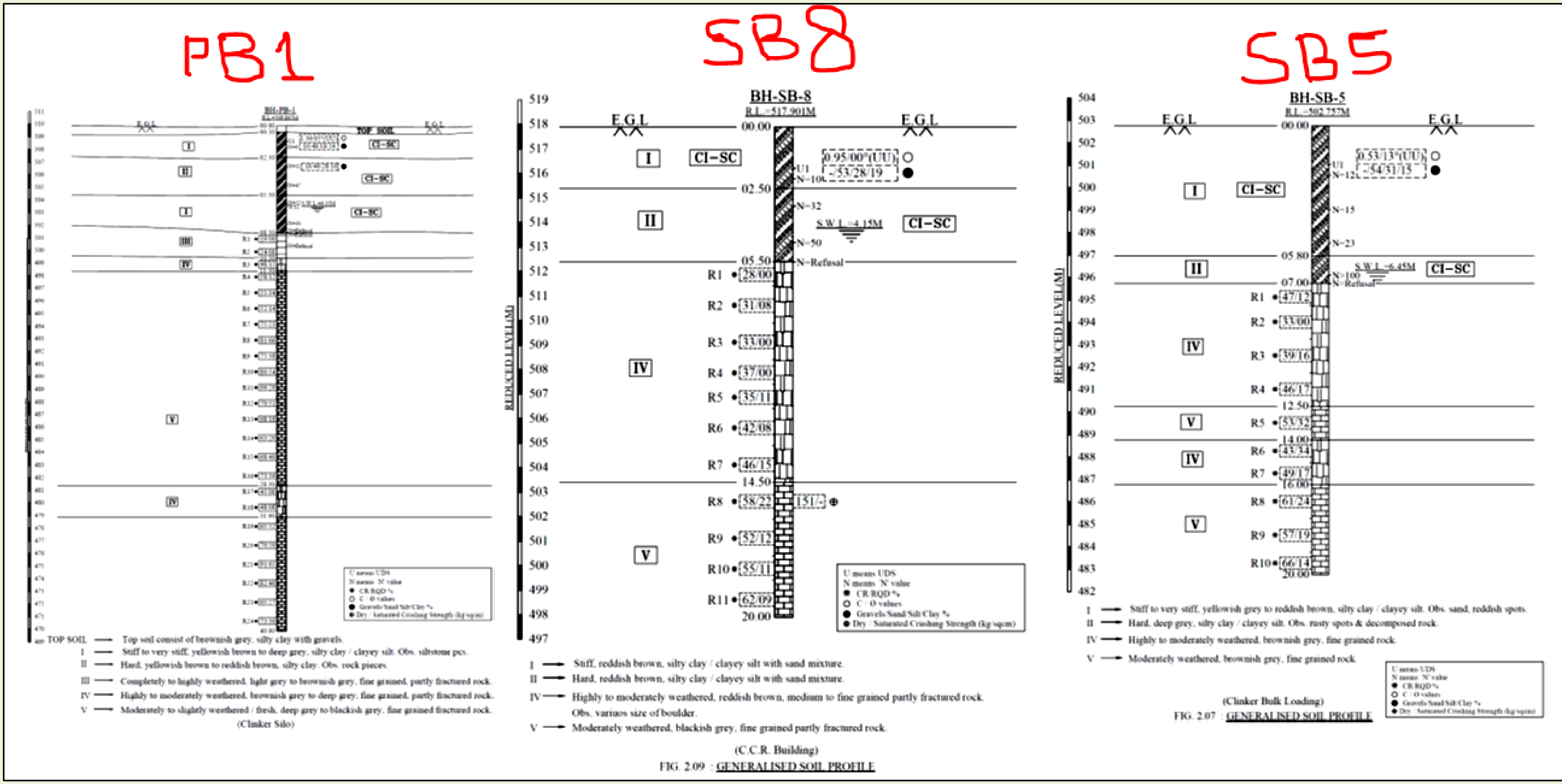
Collection of Information and Data

- Borehole locations at the site
  - *No boreholes present exactly at the failure site*



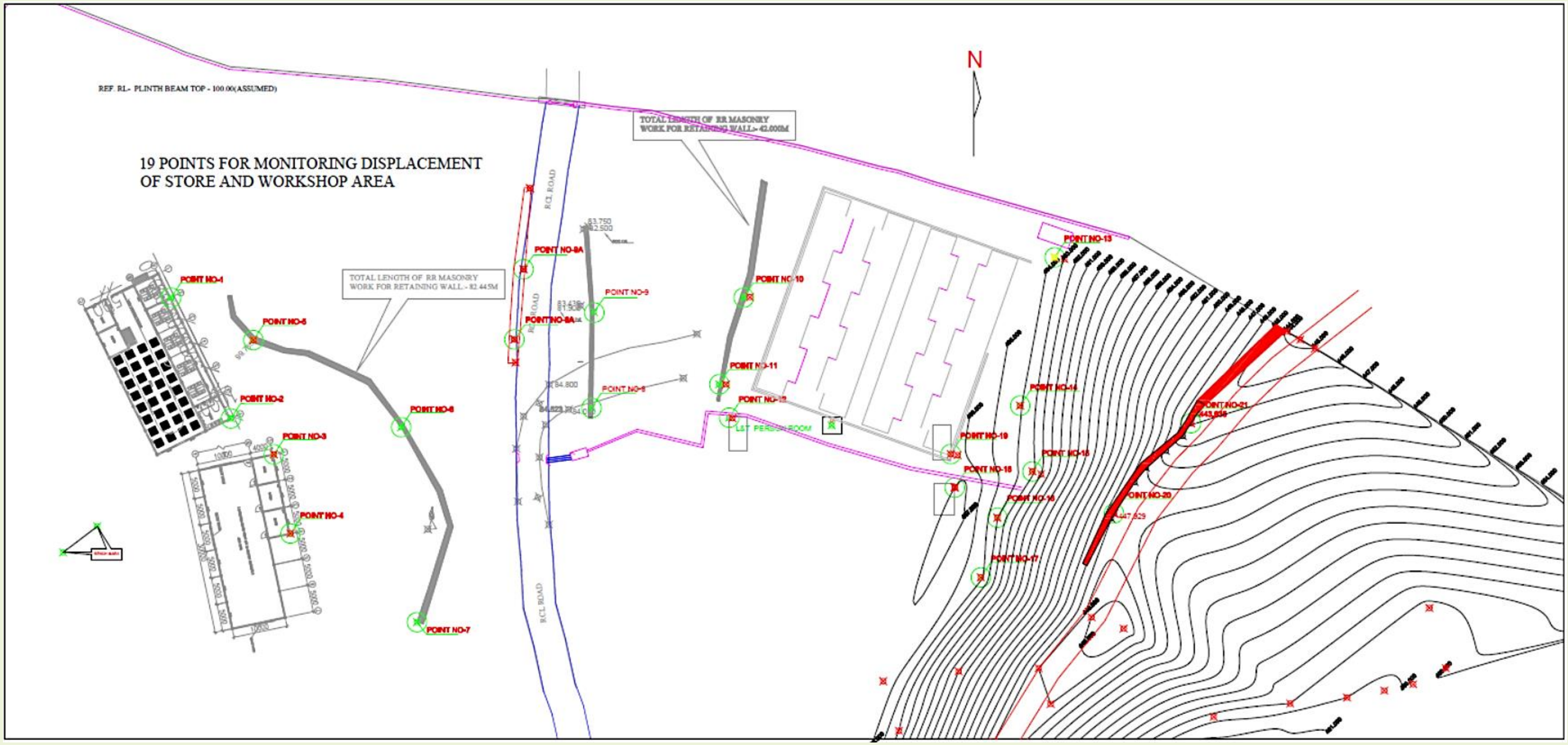
Collection of Information and Data

- Utilize information from nearby borehole to create soil profile



Measurement and Monitoring

- Displacement monitoring stations – 19 locations
  - *Till December 2015*



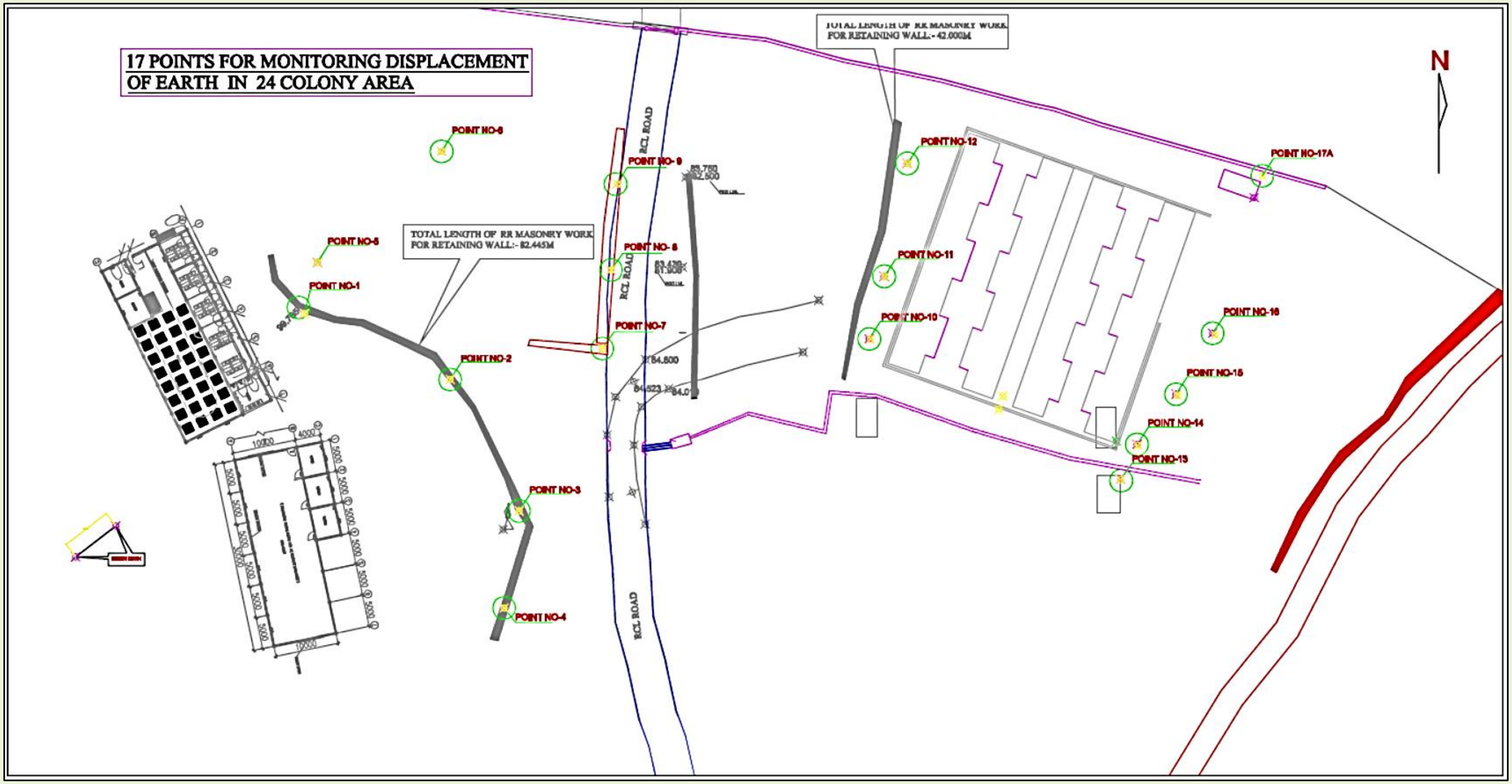
Measurement and Monitoring

- Typical lateral and vertical displacement monitoring data
  - ❖ *Some monitoring points were destroyed due to extreme displacement*

MONITORING REPORT OF EARTH DISPLACEMENT BEHIND STORE AND WORK SHOP																
SL NO	AREA	BASE COORDINATE AND LVL 28/10/2015				12-09-2015					12-11-2015					
						READING TAKEN		DIFFRENCE			SITE READING TAKEN			DIFFRENCE		
		EASTING	NORTHING	RL	STN	NORTHING	RL	EASTING	NORTHING	RL	EASTING	NORTHING	RL	EASTING	NORTHING	RL
11		189.804	143.763	78.975	POINT NO-11	143.786	78.64	-1.216	-0.023	0.335	191.021	143.798	78.591	-1.217	-0.035	0.384
12	REHAB QTRS	191.629	137.583	77.403	POINT NO-12	137.522	77.184	-0.602	0.061	0.219	192.235	137.538	77.179	-0.606	0.045	0.224
13	24 COLONY	251.861	167.28	67.727	POINT NO-13	166.988	67.473	-1.777	0.292	0.254	253.671	166.976	67.441	-1.81	0.304	0.286
14		245.488	139.819	68.046	POINT NO-14	POINT DESTROYED					POINT DESTROYED					
15		247.749	127.621	67.319	POINT NO-15	127.129	66.94	-1.609	0.492	0.379	249.421	127.108	66.831	-1.672	0.513	0.488
16		241.257	119.051	67.986	POINT NO-16	POINT DESTROYED					POINT DESTROYED					
17		238.211	108.001	69.271	POINT NO-17											
18		233.373	124.629	71.882	POINT NO-18	124.816	70.604	0.012	-0.187	1.278	233.358	124.821	70.588	0.015	-0.192	1.294
19		232.621	130.84	70.441	POINT NO-19	130.662	68.995	-1.268	0.178	1.446	233.897	130.65	68.965	-1.276	0.190	1.476
20	DRAIN ALONG RCL ROAD	151.875	152.097	86.317	POINT 8A	152.097	86.317	0.001	0	0	151.876	152.095	86.316	-0.001	0.002	0.001
21		153.562	165.089	86.679	POINT 9A	165.089	86.68	0	0	-0.001	153.561	165.087	86.68	0.001	0.002	-0.001
22	NALA BEHIND 24 COLONY	262.832	119.858	53.89	POINT NO-20	119.858	53.889	-0.001	0	0.001	262.831	119.859	53.88	0.001	-0.001	0.01
23		277.088	136.566	49.881	POINT NO-21	136.566	49.881	-0.001	0	0	277.089	136.567	49.88	-0.001	-0.001	0.001

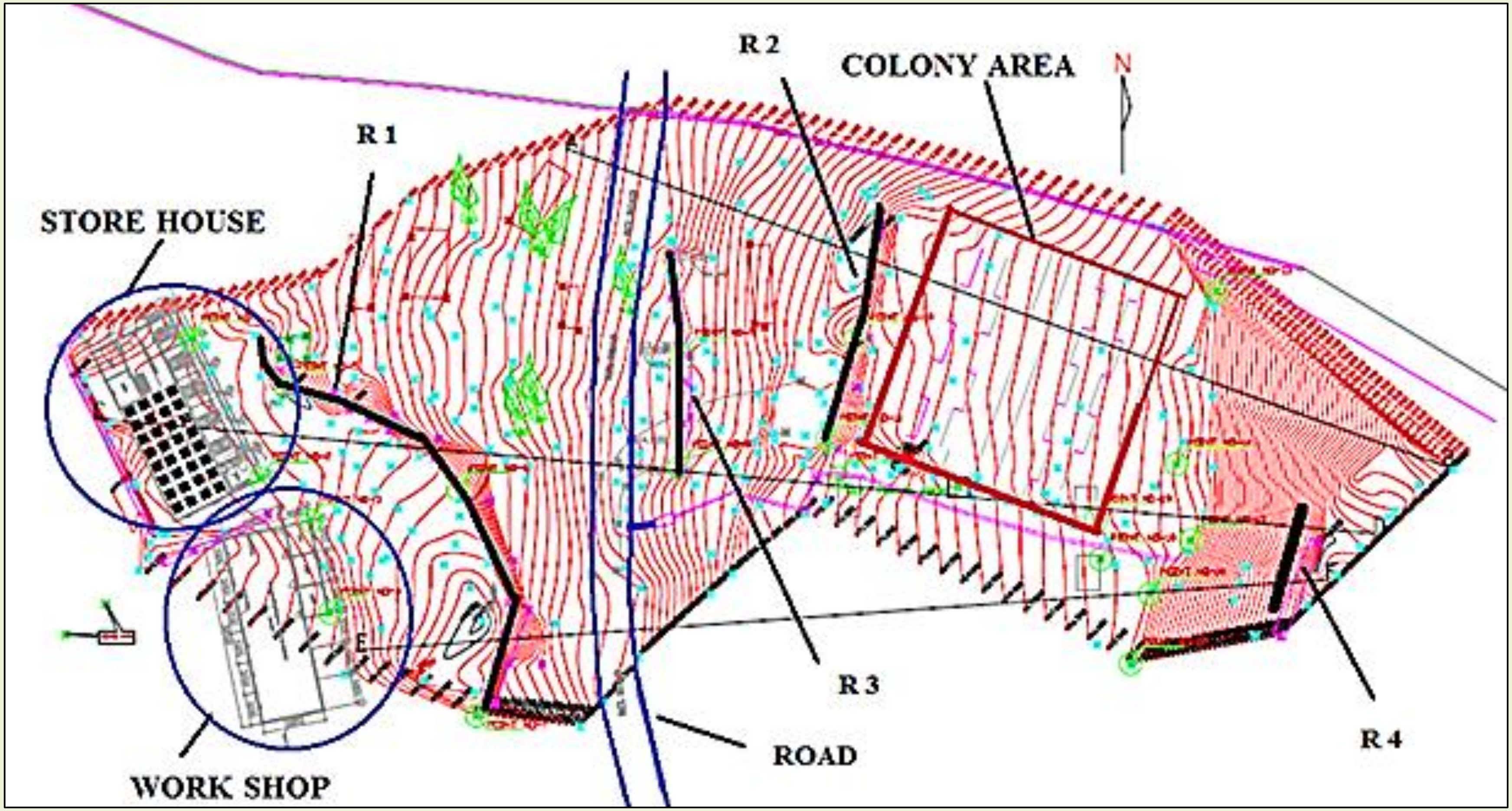
Measurement and Monitoring

- Displacement monitoring stations – 17 new locations
  - *From March 2016 (due to collapse of earlier stations)*



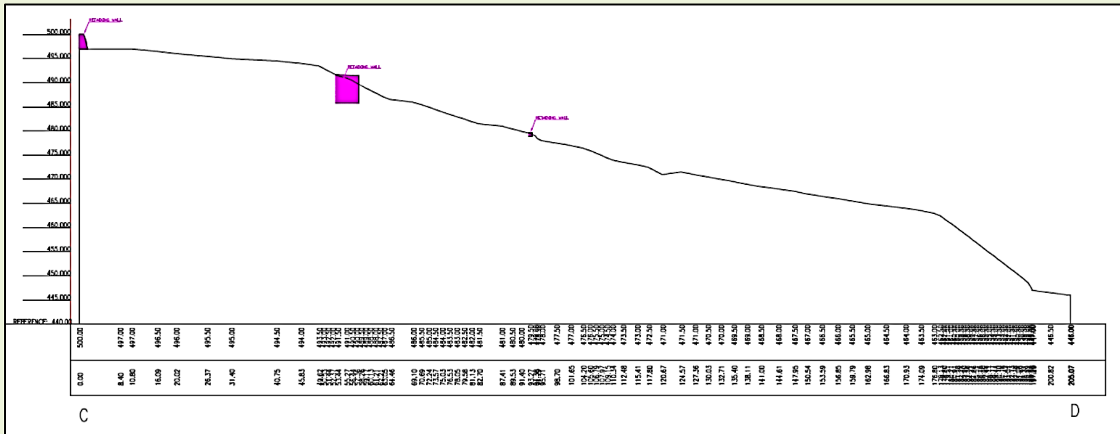
Deciphering Chronological Events

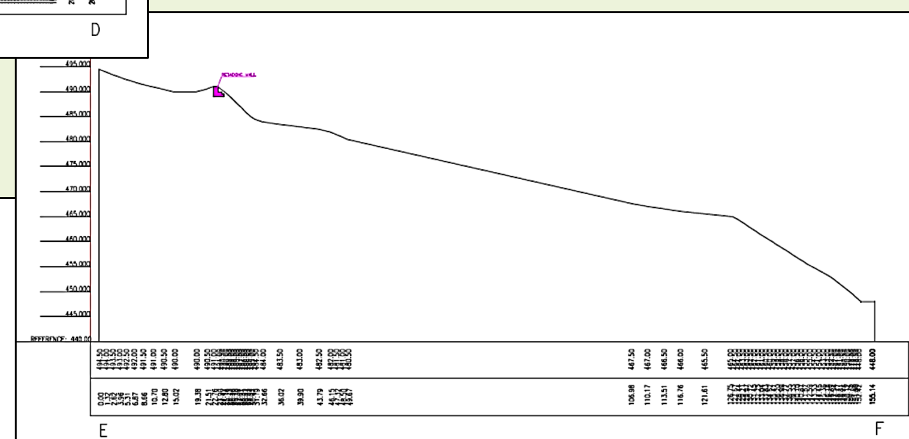
- Contour and Profile of failure site
  - *Sequence of construction of protection retaining walls*

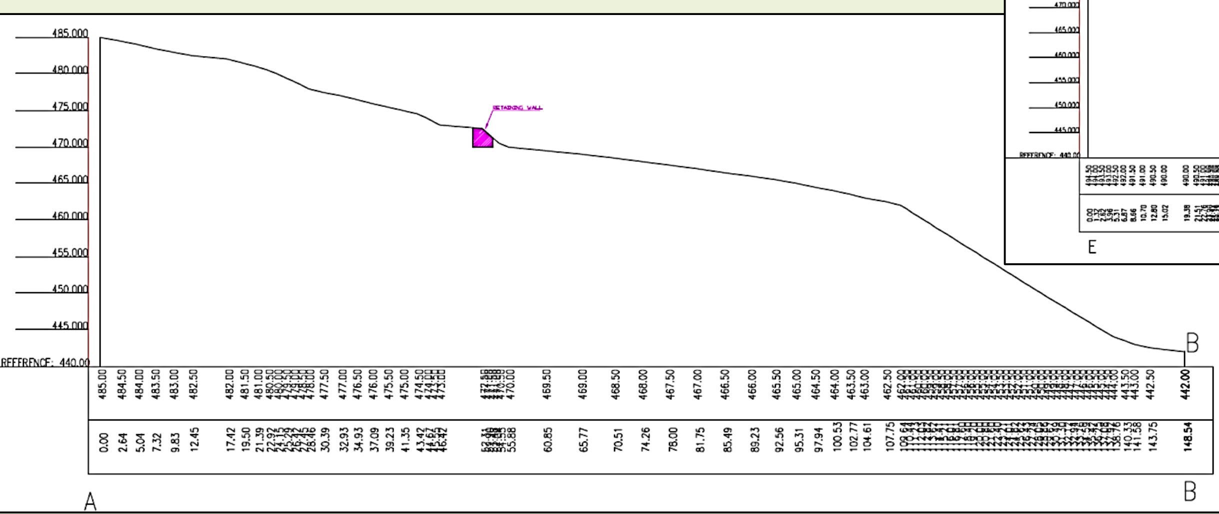


Deciphering Chronological Events

- Hillslope topography along different sections

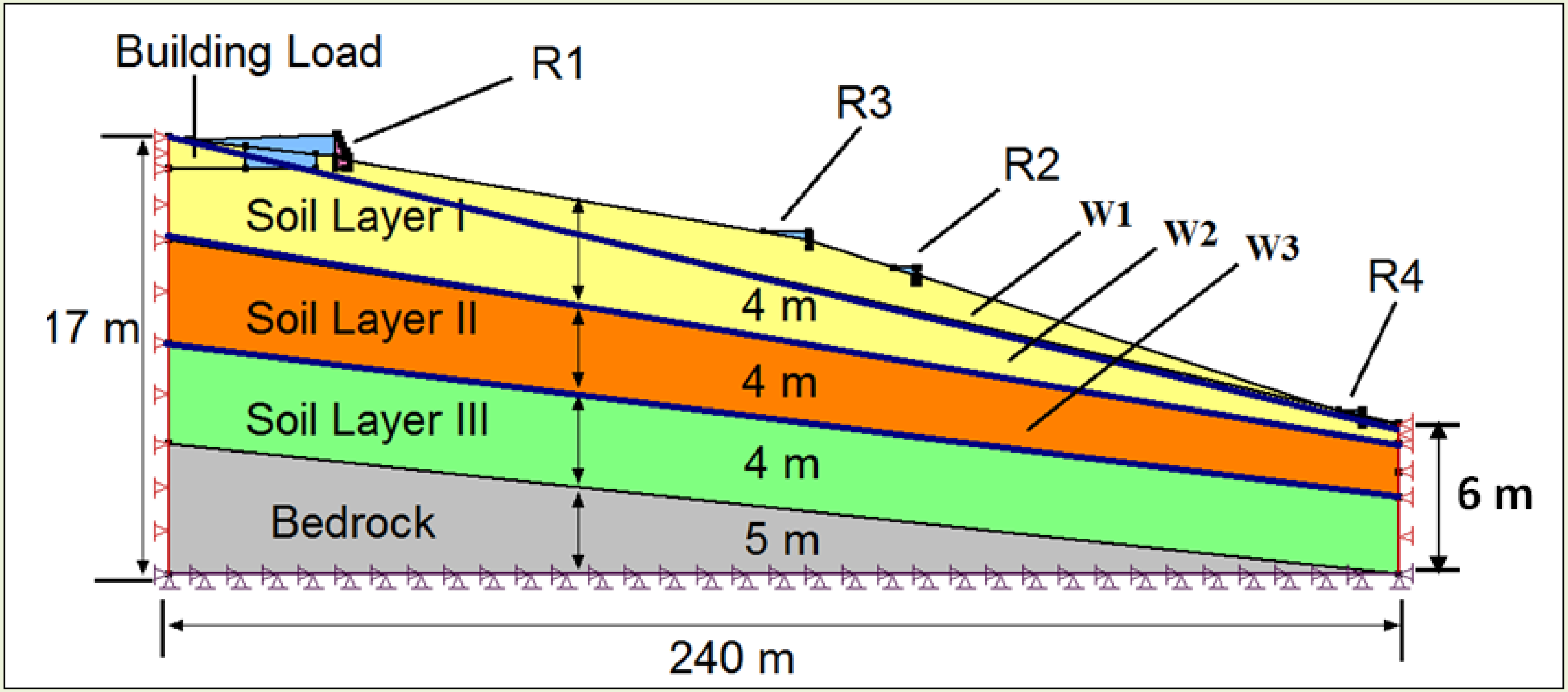






Preliminary Models and Failure Analysis

- Forensic study of hillslope failure using Geostudio
  - ❖ *Soil layering done on the basis of nearby borehole stratigraphies*
    - Assumptive inclination of soil layers somewhat following the terrain
  - ❖ *Depth of water table - Unknown*



Preliminary Models and Failure Analysis

- Forensic study of hillslope failure
  - ❖ *Material properties used in the model for the numerical simulation*

Material properties of the Primary model PM

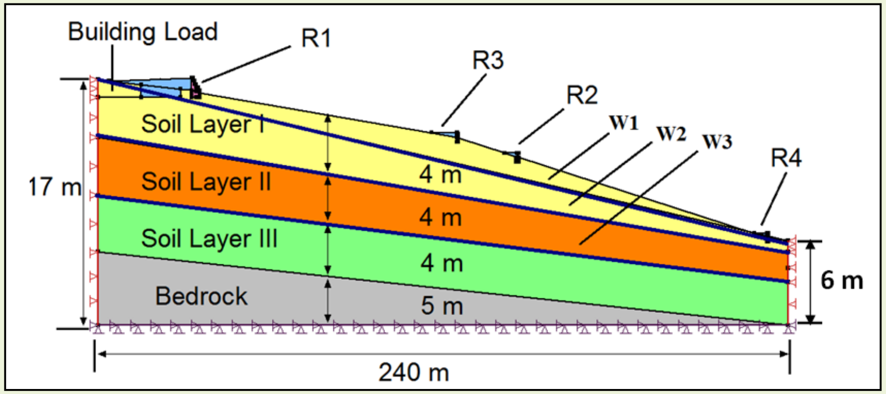
Layer	Undrained Strength Parameters			Drained Strength Parameters			Unit weight (kN/m^3)	Saturated permeability K_{sat} (m/s)	Saturated volumetric water content Θ_{sat} (m^3/m^3)
	c_u (kPa)	φ_u (°)	E (MPa)	c' (kPa)	φ' (°)	E' (MPa)			
Soil layer I	18.5	4	4.7	12.33	4	4.2	19	$3x10^{-8}$	0.425
Soil layer II	18.5	4	4.7	12.33	4	4.2	19	$3x10^{-8}$	0.425
Soil layer III	18.5	4	4.7	12.33	4	4.2	19	$3x10^{-8}$	0.425
Rock	-	-	683	-	-	610.4	24.1	$2x10^{-10}$	0.087
Retaining wall	-	-	17000	-	-	15194	29	$3x10^{-13}$	0.33

Material properties of the secondary model SM

Layer	Undrained Strength Parameters			Drained Strength Parameters			Unit weight (kN/m^3)	Saturated Permeability K_{sat} (m/s)	Saturated Volumetric water content Θ_{sat} (m^3/m^3)
	c_u (kPa)	φ_u (°)	E (MPa)	c' (kPa)	φ' (°)	E' (MPa)			
Soil layer I	18.5	4	4.7	12.33	4	4.2	19	$3x10^{-8}$	0.425
Soil layer II	18.5	4	4.7	12.33	4	4.2	19	$3x10^{-8}$	0.425
Soil layer III	94	4	90.65	62.66	4	81	19	$3x10^{-8}$	0.425
Rock	-	-	683	-	-	610.4	24.1	$2x10^{-10}$	0.087
Retaining wall	-	-	17000	-	-	15194	29	$3x10^{-13}$	0.33

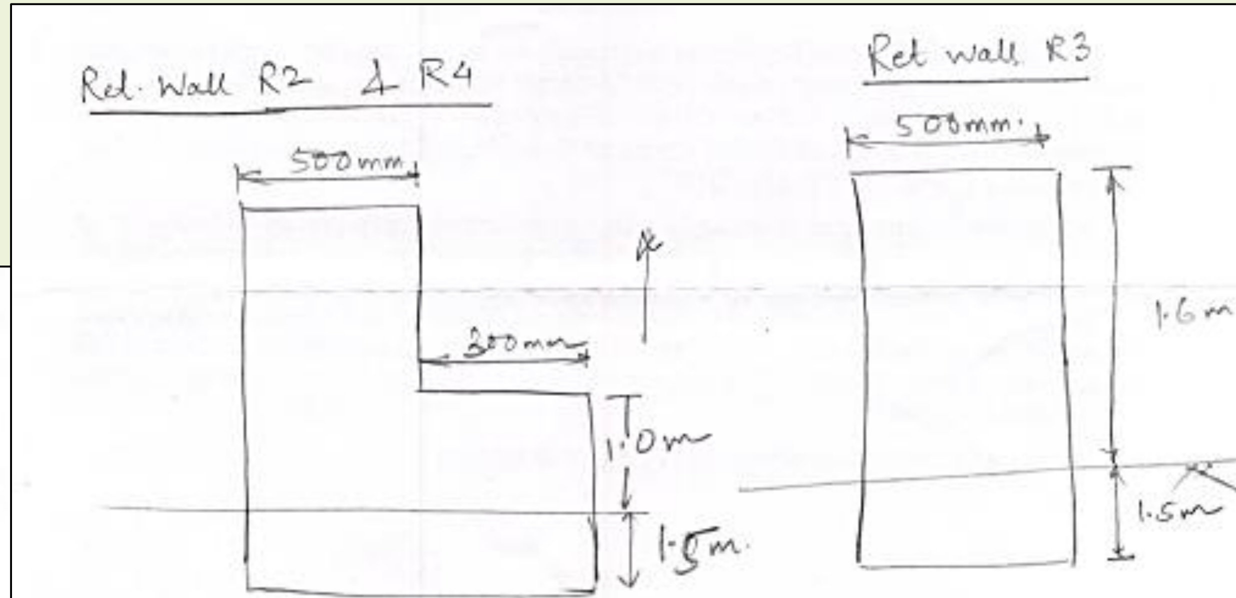
Material properties of the tertiary model TM

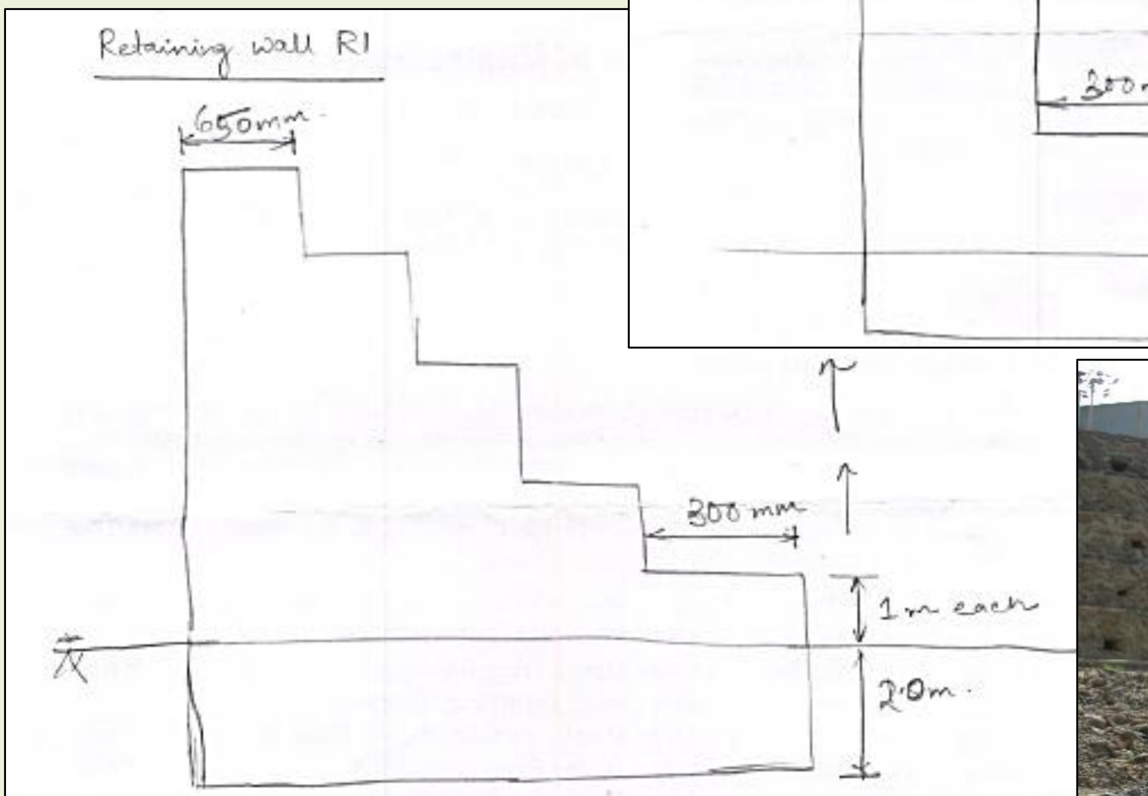
Layer	Undrained Strength Parameters			Drained Strength Parameters			Unit weight (kN/m^3)	Saturated Permeability K_{sat} (m/s)	Saturated Volumetric water content Θ_{sat} (m^3/m^3)
	c_u (kPa)	φ_u (°)	E (MPa)	c' (kPa)	φ' (°)	E' (MPa)			
Soil layer I	18.5	4	4.7	12.33	4	4.2	19	$3x10^{-8}$	0.425
Soil layer II	94	4	90.65	62.66	4	81	19	$3x10^{-8}$	0.425
Soil layer III	94	4	90.65	62.66	4	81	19	$3x10^{-8}$	0.425
Rock	-	-	683	-	-	610.4	24.1	$2x10^{-10}$	0.087
Retaining wall	-	-	17000	-	-	15194	29	$3x10^{-13}$	0.33



Schematic Section of Retaining Walls

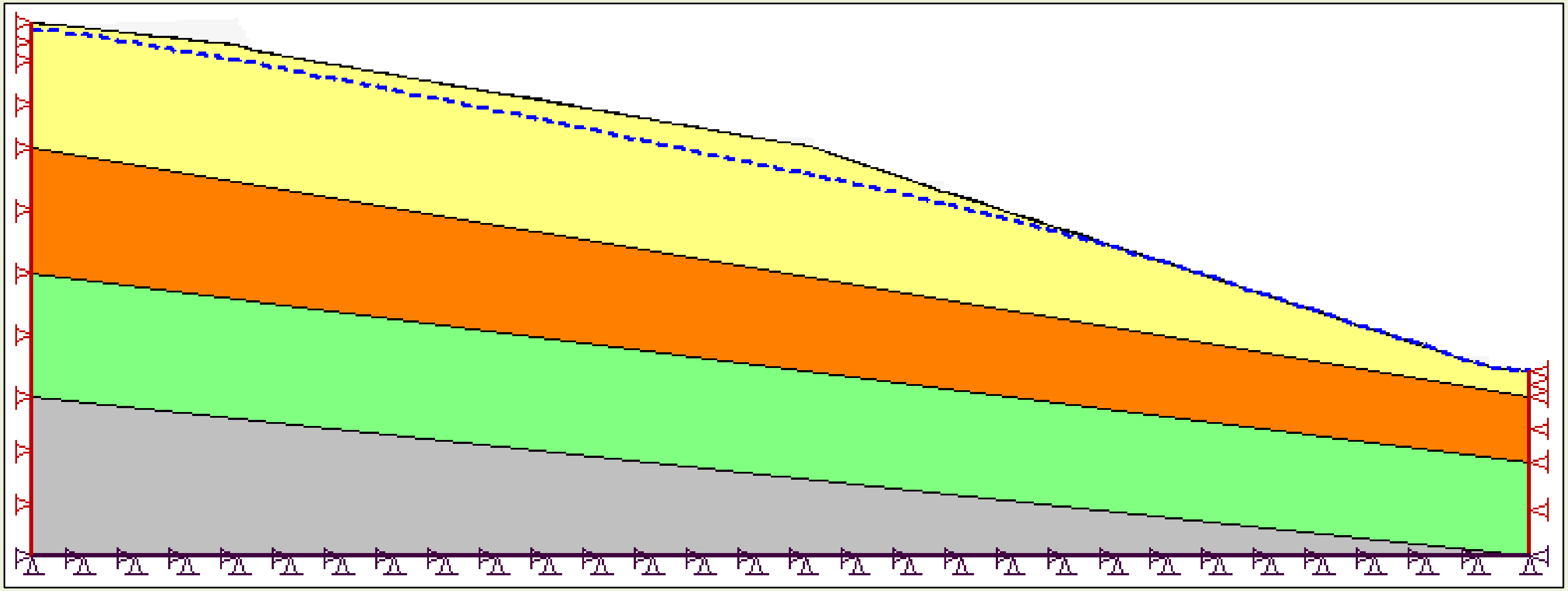
- Modelling the retaining wall





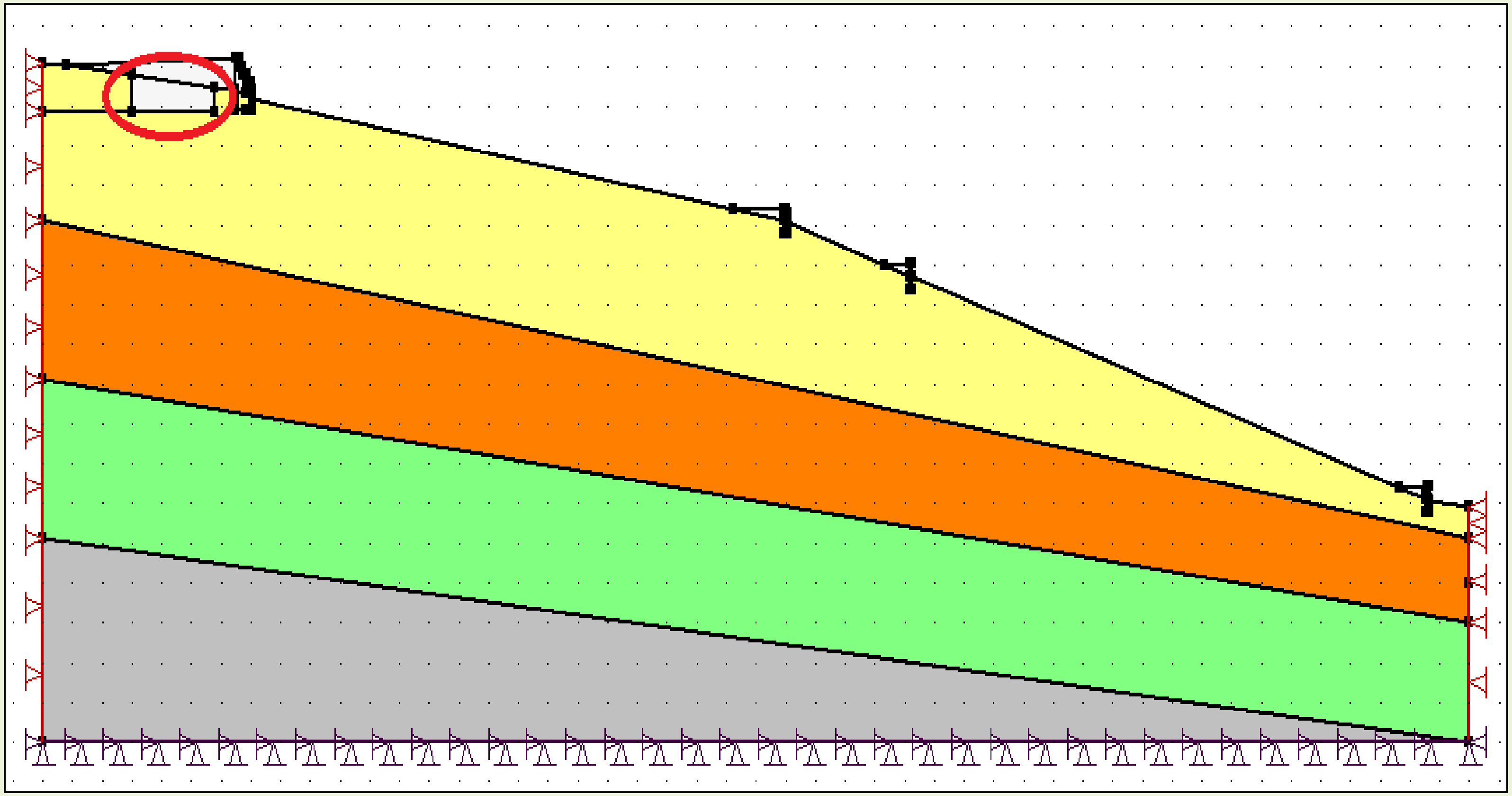
Preliminary Models and Failure Analysis

- Forensic analysis of hillslope failure
  - *Sequential anthropogenic intervention at the site (Stages of construction)*
    - **Stage 1**: In-situ analysis to assess the stability of the virgin slope before human intervention



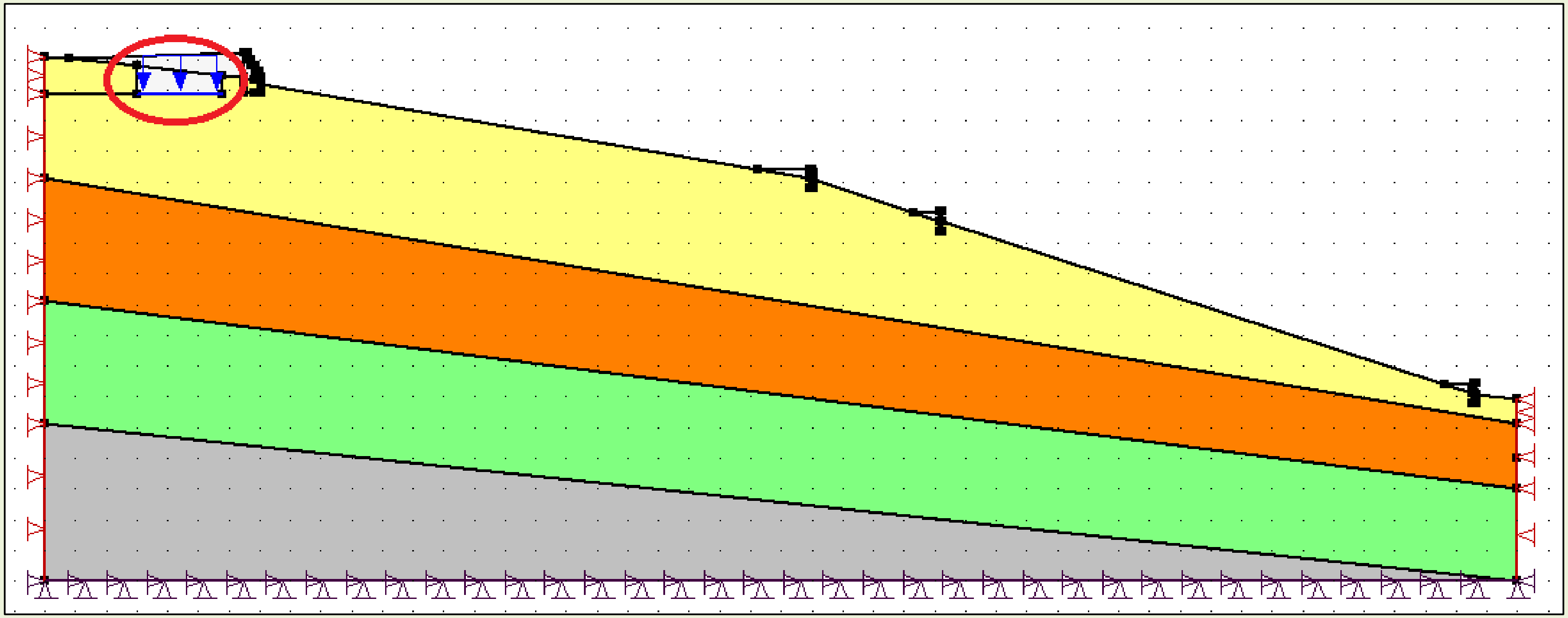
Preliminary Models and Failure Analysis

- Forensic analysis of hillslope failure
  - *Sequential anthropogenic intervention at the site (Stages of construction)*
    - **Stage 2**: Excavation of foundation of building



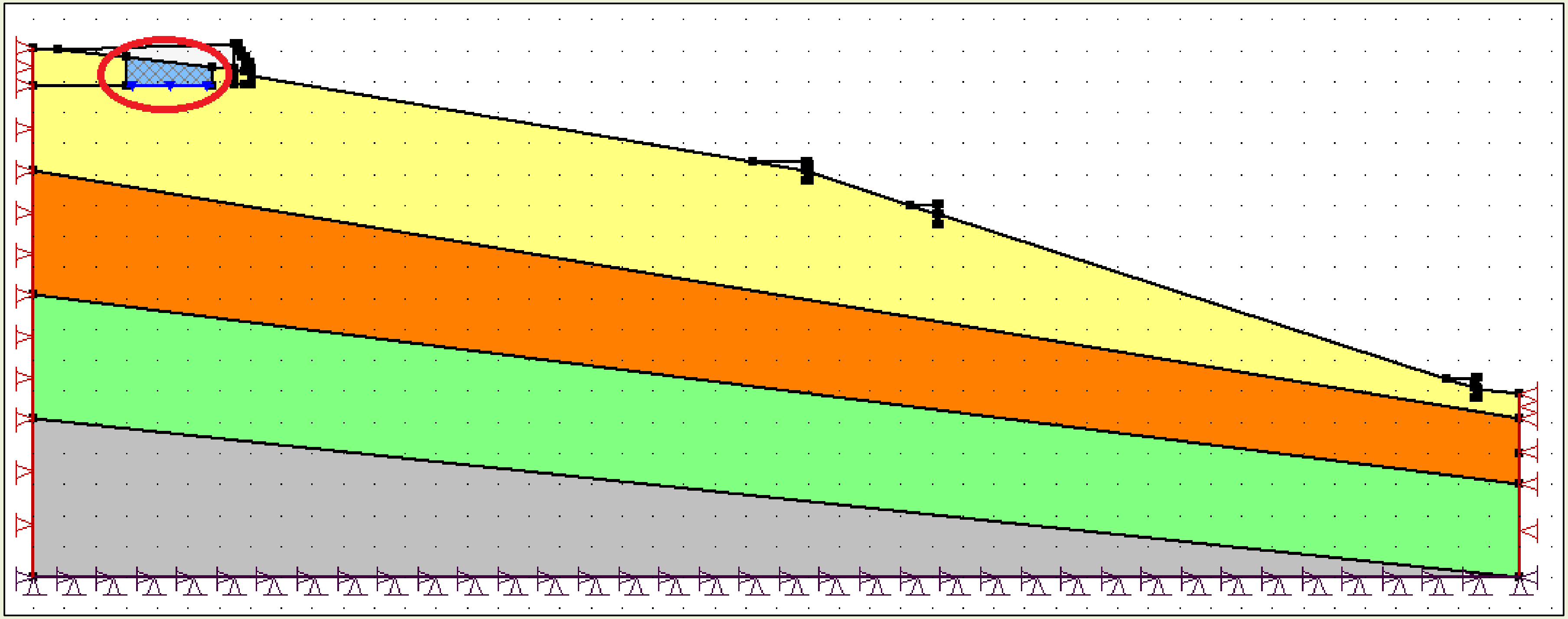
Preliminary Models and Failure Analysis

- Forensic analysis of hillslope failure
  - ❖ *Sequential anthropogenic intervention at the site (Stages of construction)*
    - **Stage 3**: Imposition of building load at the site due to the construction of the building (Calculated from structural data)



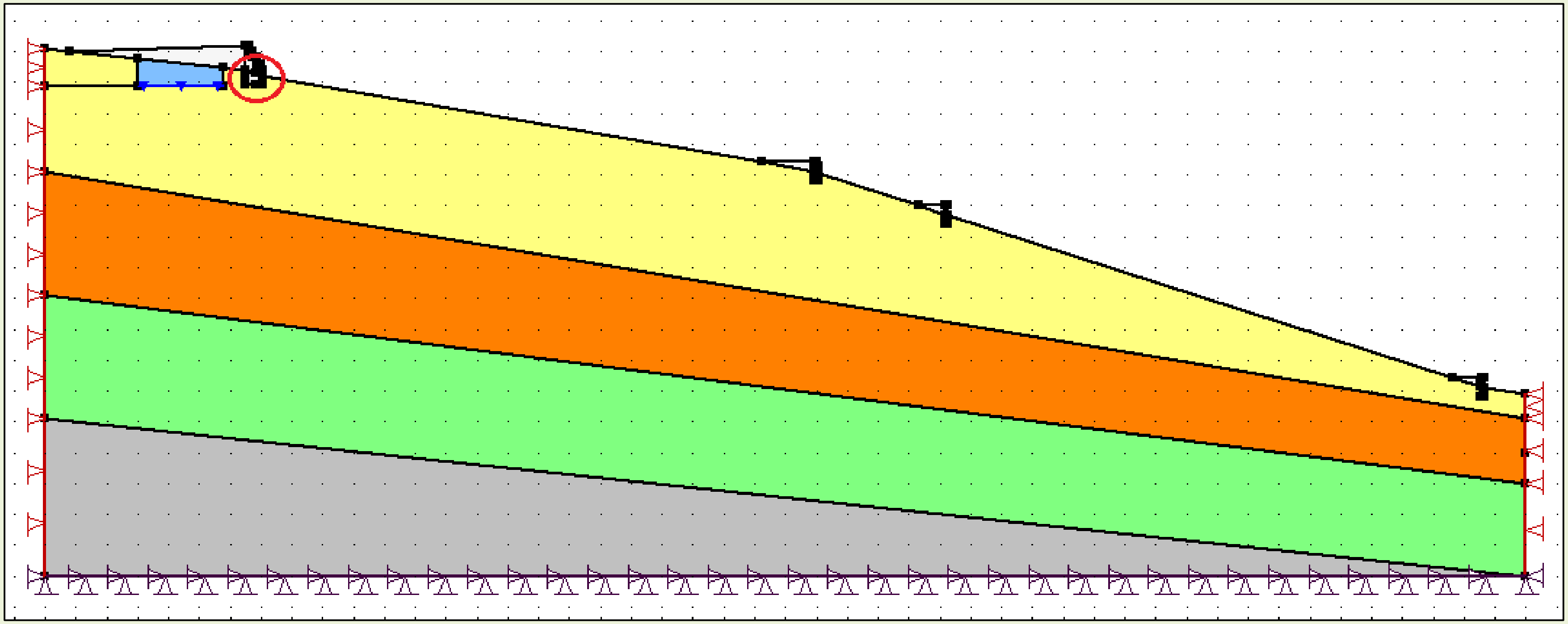
Preliminary Models and Failure Analysis

- Forensic analysis of hillslope failure
  - ❖ *Sequential anthropogenic intervention at the site (Stages of construction)*
    - ▪ **Stage 4**: Filling back and embedment of the shallow footings (Stages 3 and 4 are done simultaneously in the field)



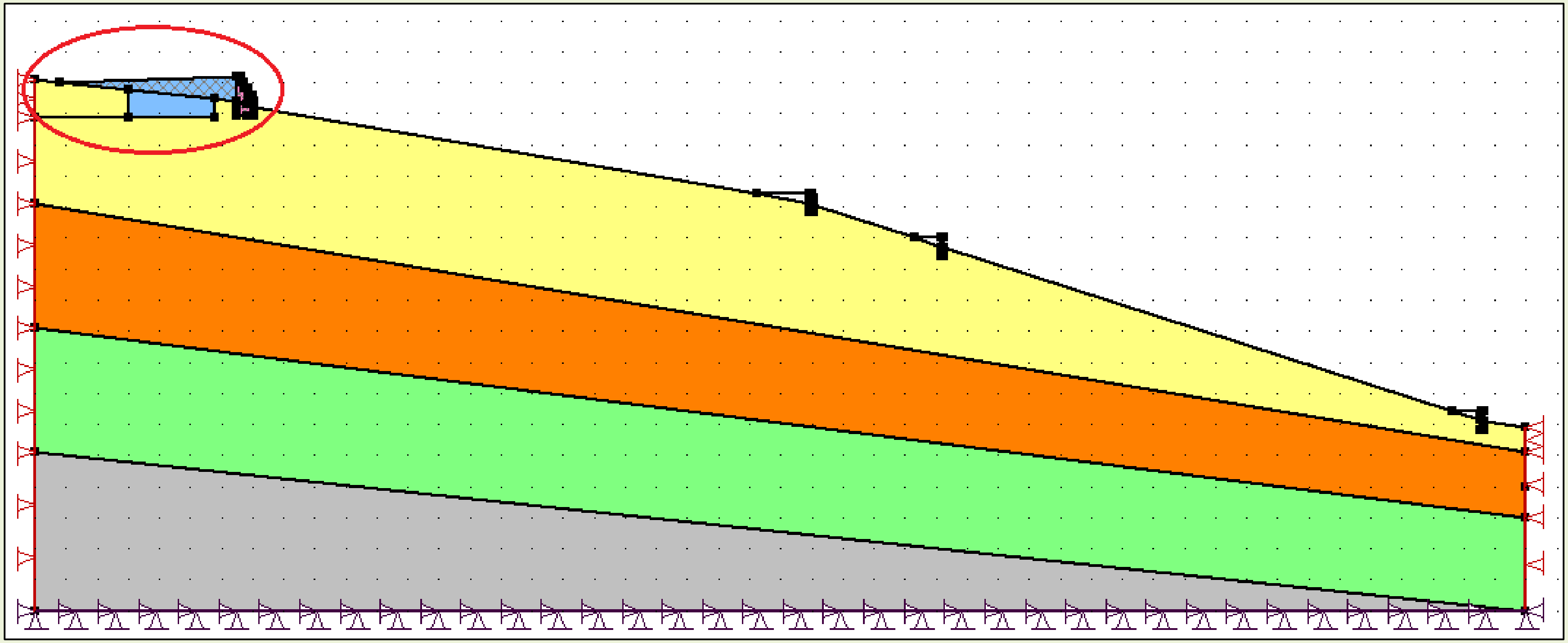
Preliminary Models and Failure Analysis

- Forensic analysis of hillslope failure
  - *Sequential anthropogenic intervention at the site (Stages of construction)*
    - **Stage 5**: Excavation of the foundation of the retaining wall R1



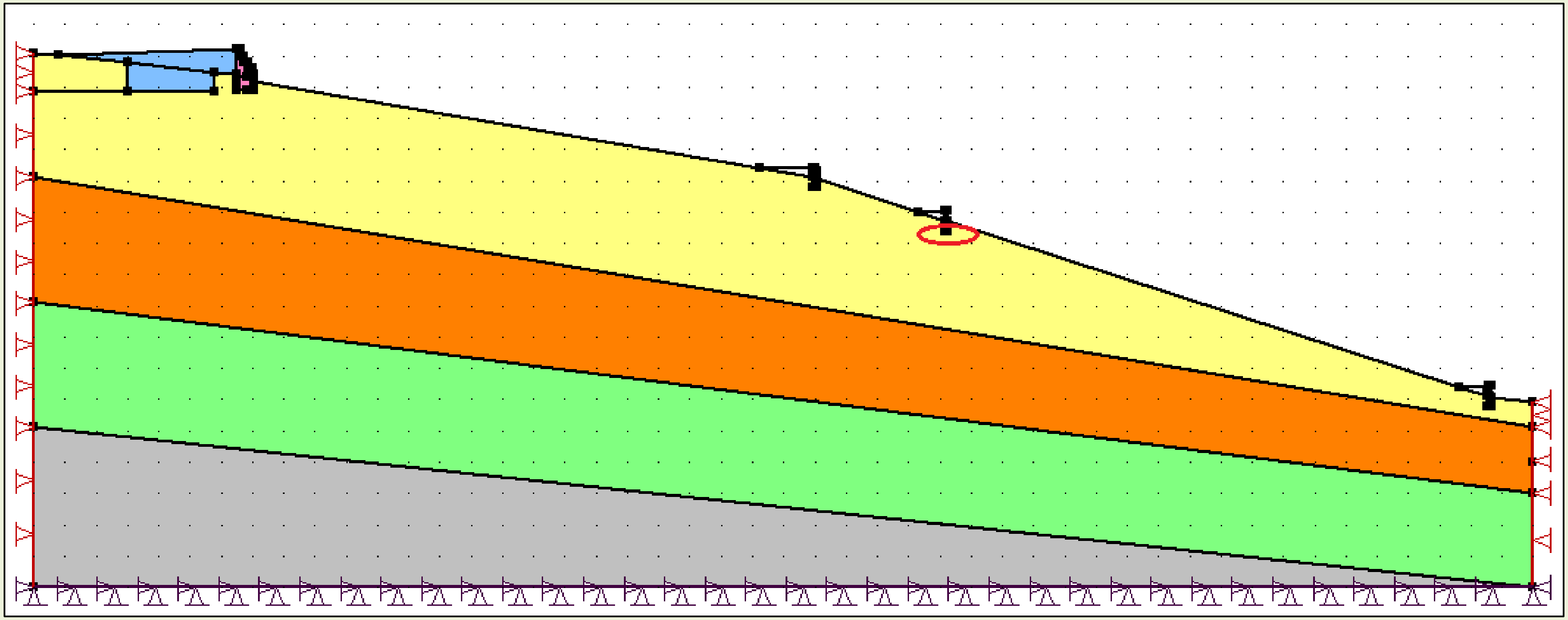
Preliminary Models and Failure Analysis

- Forensic analysis of hillslope failure
    - ❖ *Sequential anthropogenic intervention at the site (Stages of construction)*
        - **Stage 6**: Construction of R1 and simultaneous back-filing



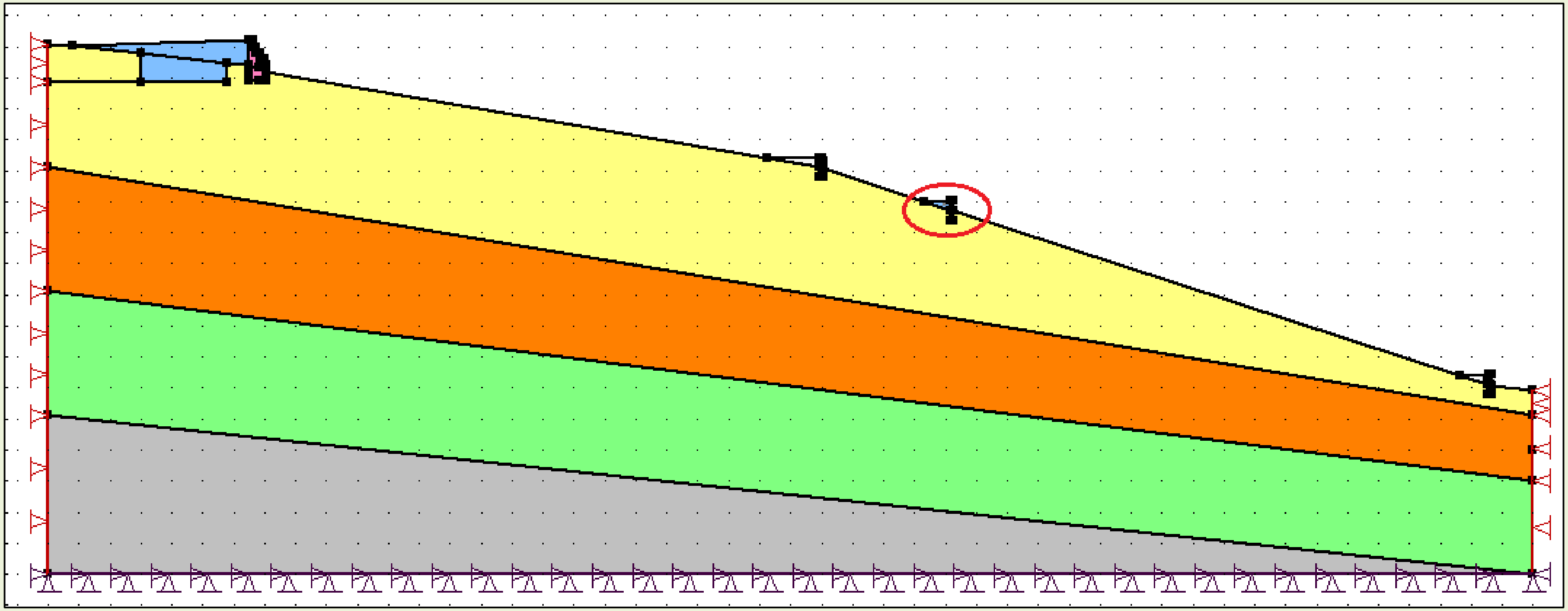
Preliminary Models and Failure Analysis

- Forensic analysis of hillslope failure
  - ❖ *Sequential anthropogenic intervention at the site (Stages of construction)*
    - **Stage 7**: Excavation of the foundation of the retaining wall R2



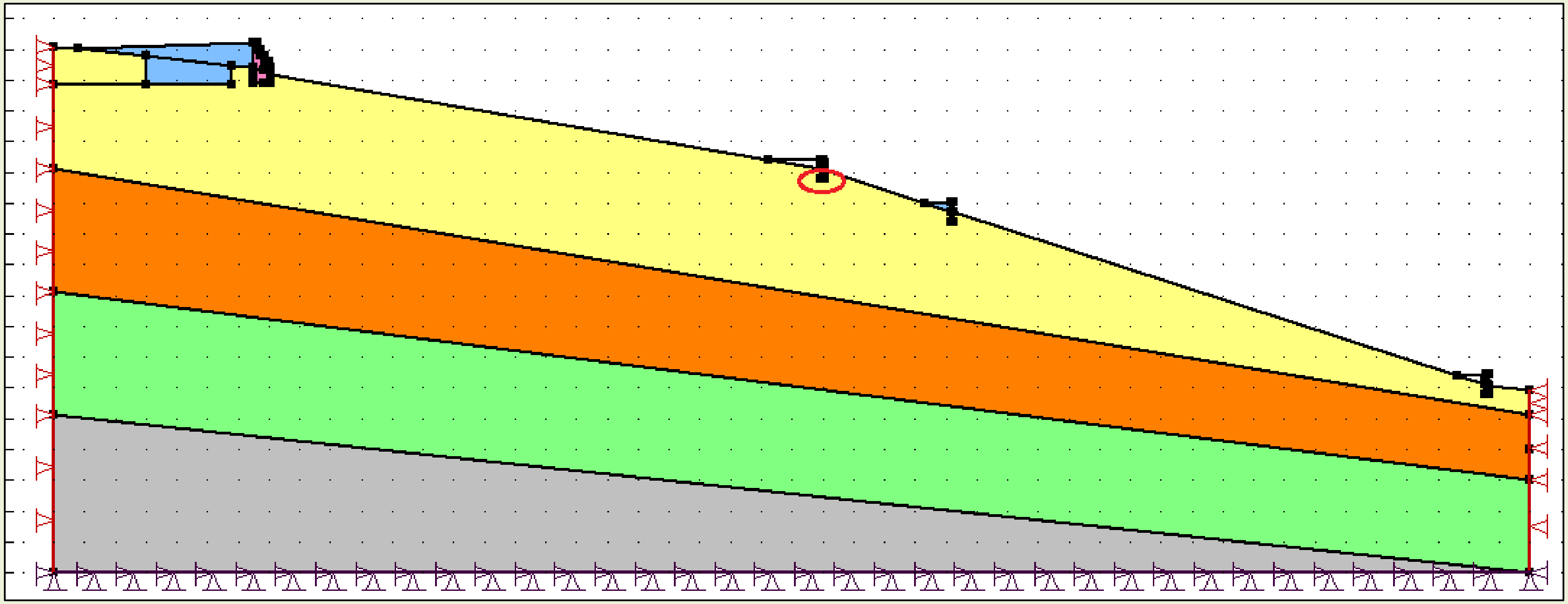
Preliminary Models and Failure Analysis

- Forensic analysis of hillslope failure
  - ❖ *Sequential anthropogenic intervention at the site (Stages of construction)*
    - **Stage 8**: Construction of R2 and simultaneous back-filing



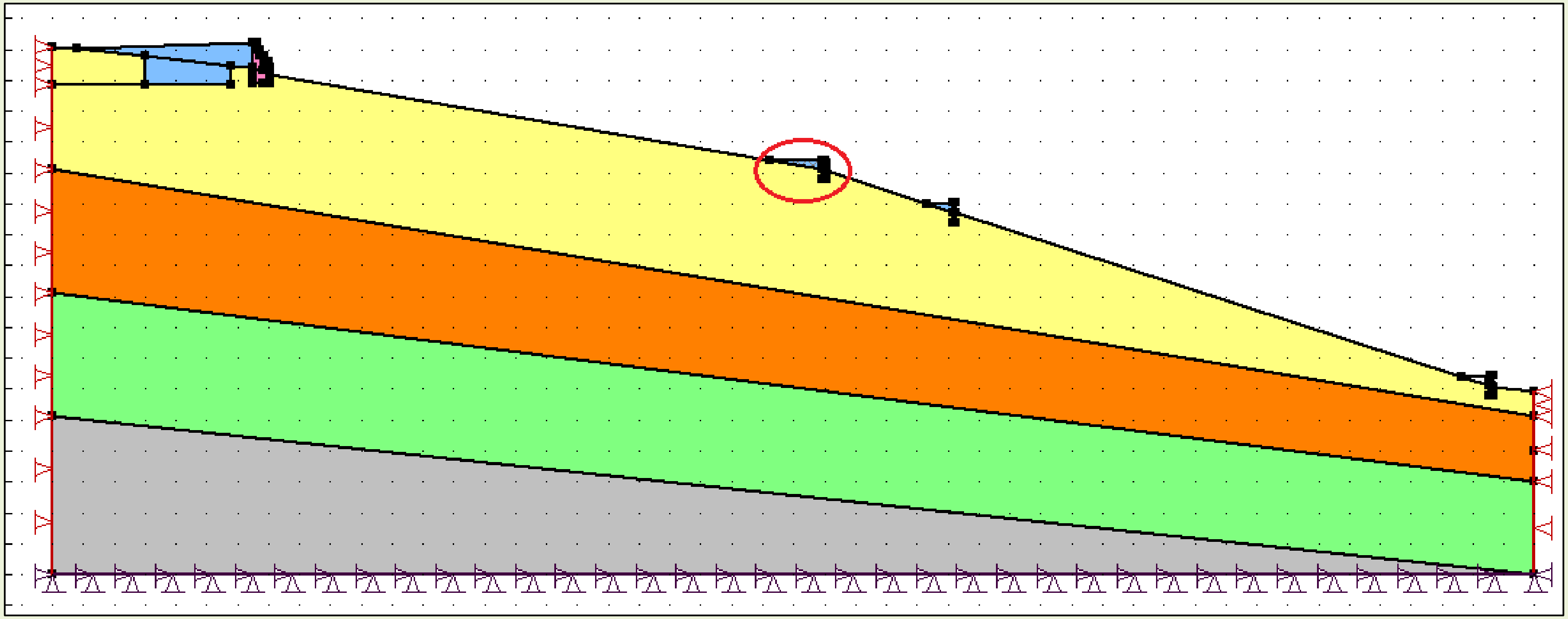
Preliminary Models and Failure Analysis

- Forensic analysis of hillslope failure
  - *Sequential anthropogenic intervention at the site (Stages of construction)*
    - **Stage 9**: Excavation of the foundation of the retaining wall R3



Preliminary Models and Failure Analysis

- Forensic analysis of hillslope failure
  - ❖ *Sequential anthropogenic intervention at the site (Stages of construction)*
    - **Stage 10**: Construction of R3 and simultaneous back-filing



Preliminary Models and Failure Analysis

- Forensic analysis of hillslope failure
  - *Application of Parent-Child concept to amalgamate various modules*
    - SEEP/W → SIGMA/W → SLOPE/W (Applied in sequence)

- SEEP/W → Finite element based steady-state seepage analysis to generate the pore-water pressures under a given WT

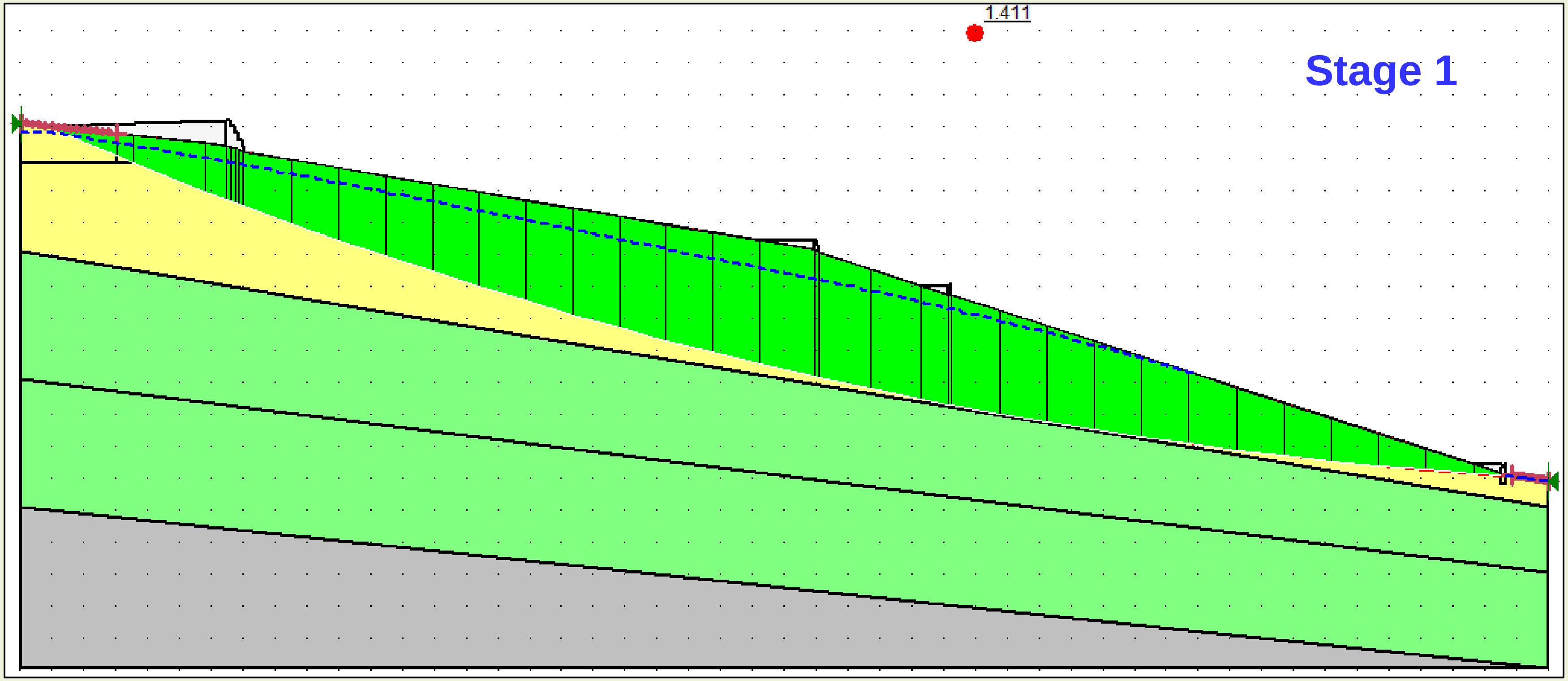
  → FE-based transient seepage analysis to identify the steady state WT due to a rainfall based infiltration and development of transient pore-water pressures

- SIGMA/W → Finite element based load-deformation analysis conducted by incorporating the steady-state WT and pore-water pressures generated from the preceding SEEP/W analysis

- SLOPE/W → Limit Equilibrium based slope stability analysis to identify the critical slip surface and the Factor of Safety values, by incorporating the results from the preceding SIGMA/W analysis

Preliminary Models and Failure Analysis

- Slope stability analysis using Slope/W
  - *Morgenstern-Price Method for analysis*
  - *Entry-Exit method for slip surface definition*



Preliminary Models and Failure Analysis

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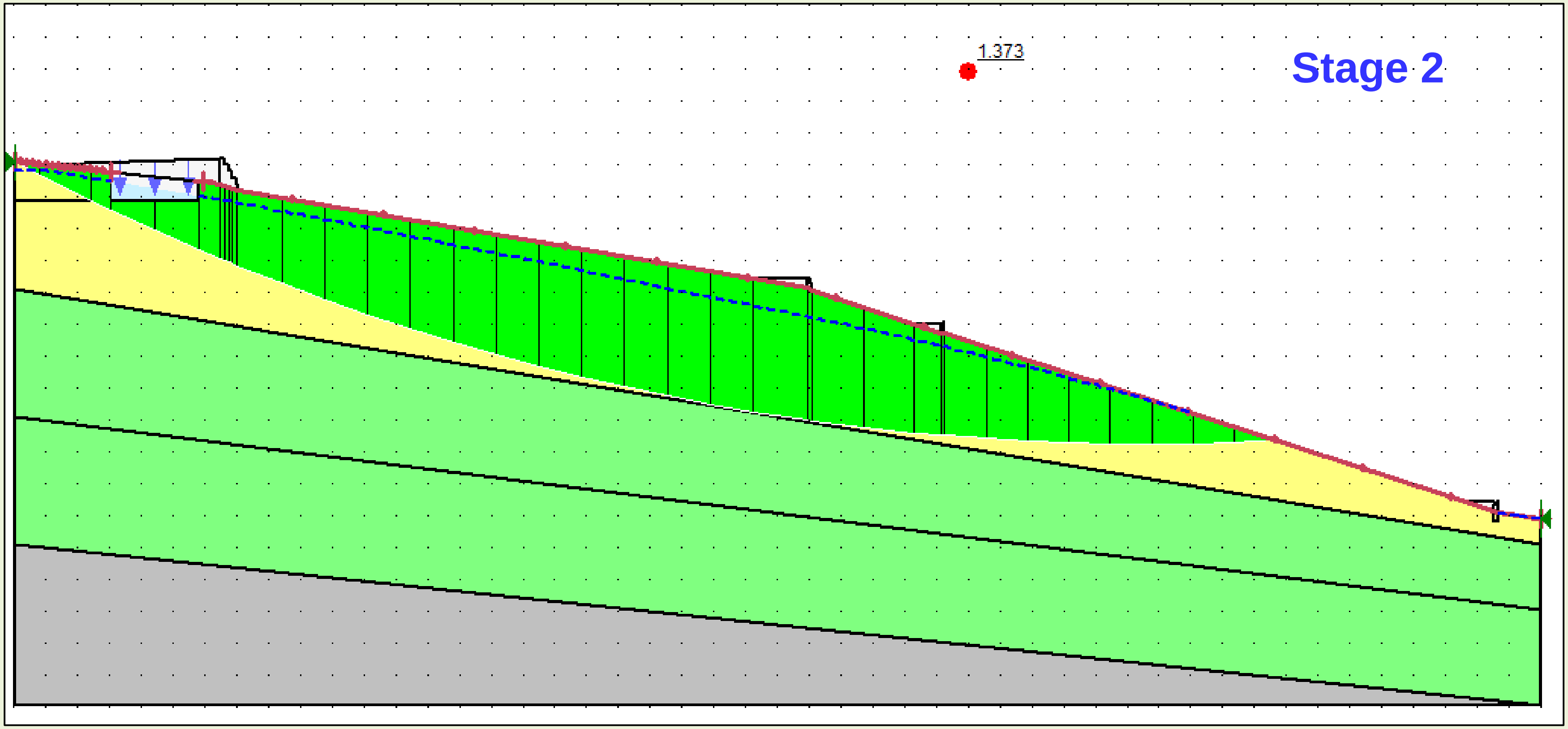

Preliminary Models and Failure Analysis

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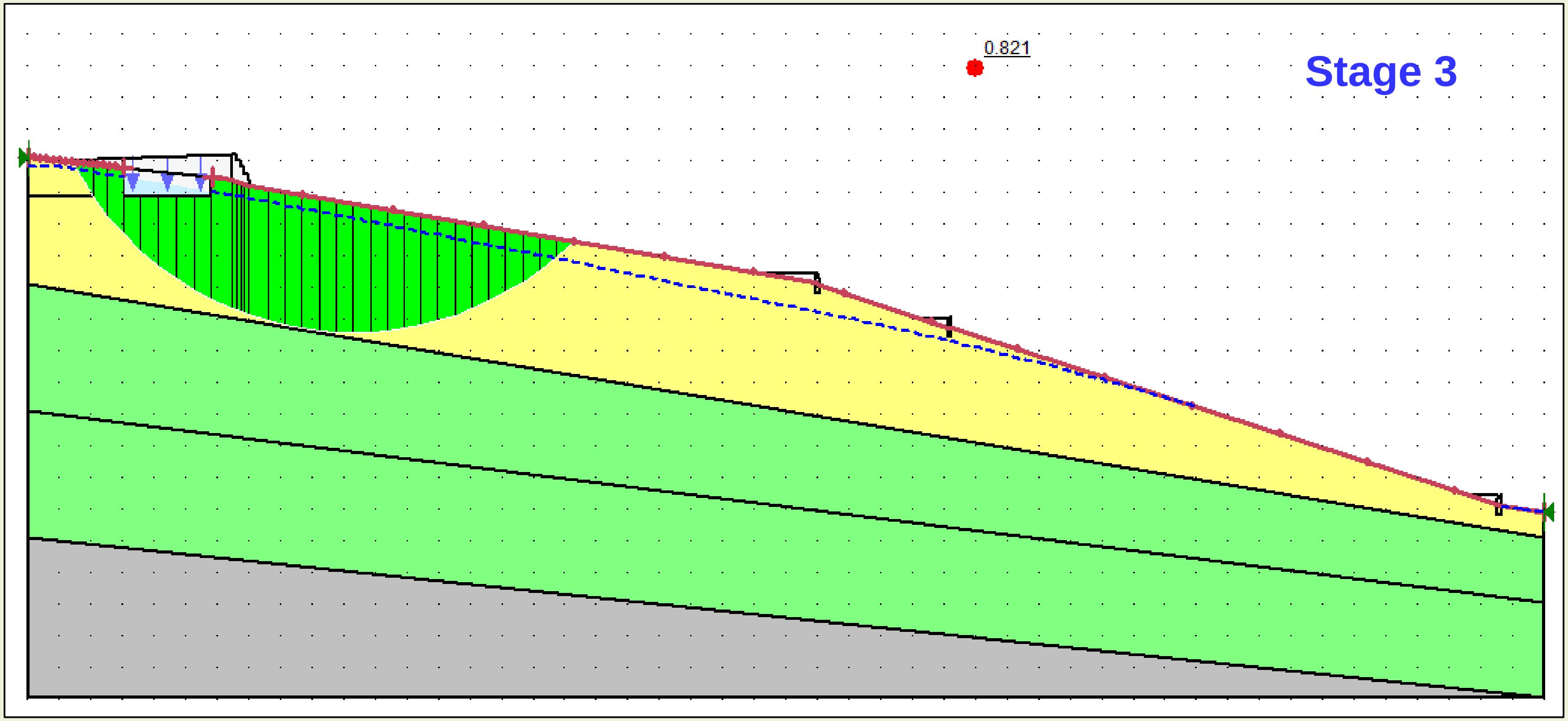

Preliminary Models and Failure Analysis

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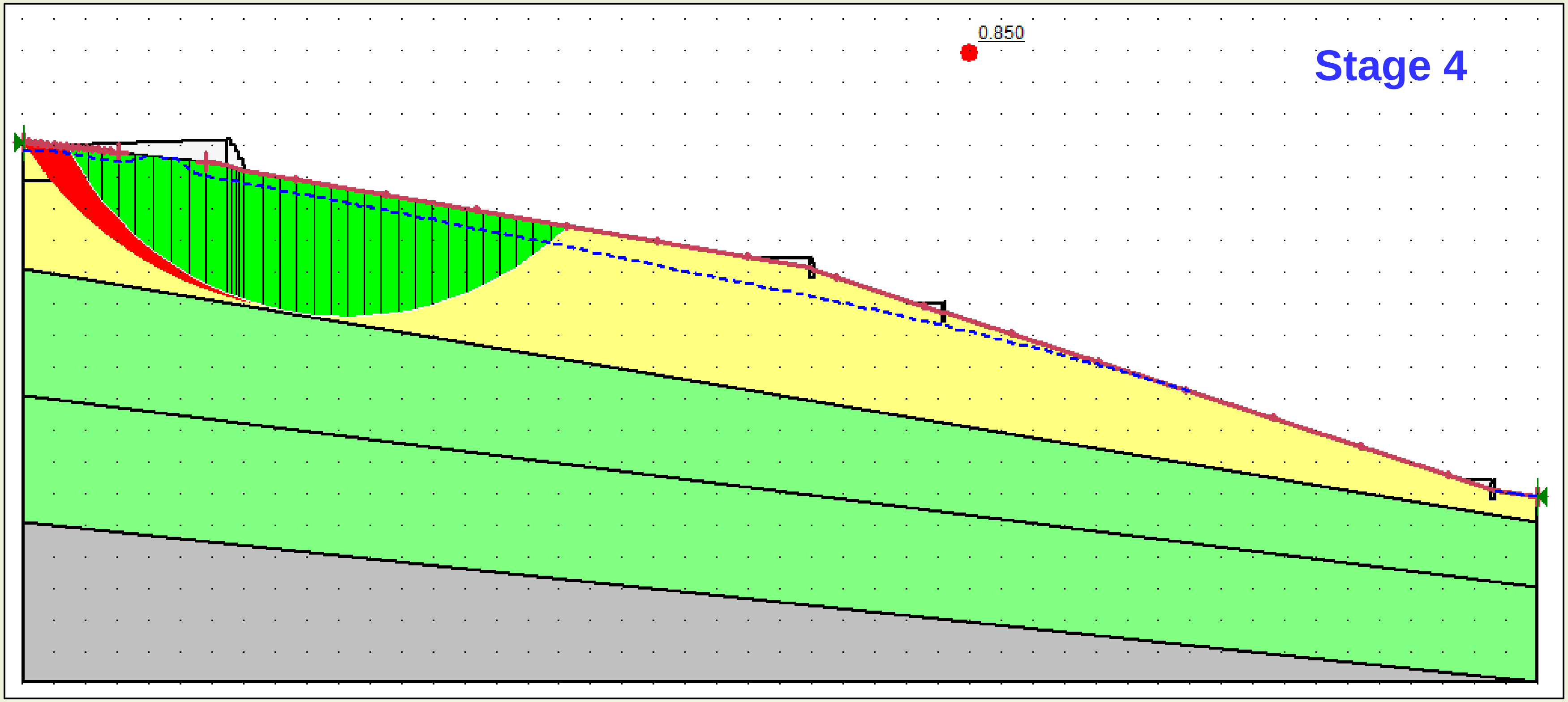

Preliminary Models and Failure Analysis

- Slope stability analysis using Slope/W
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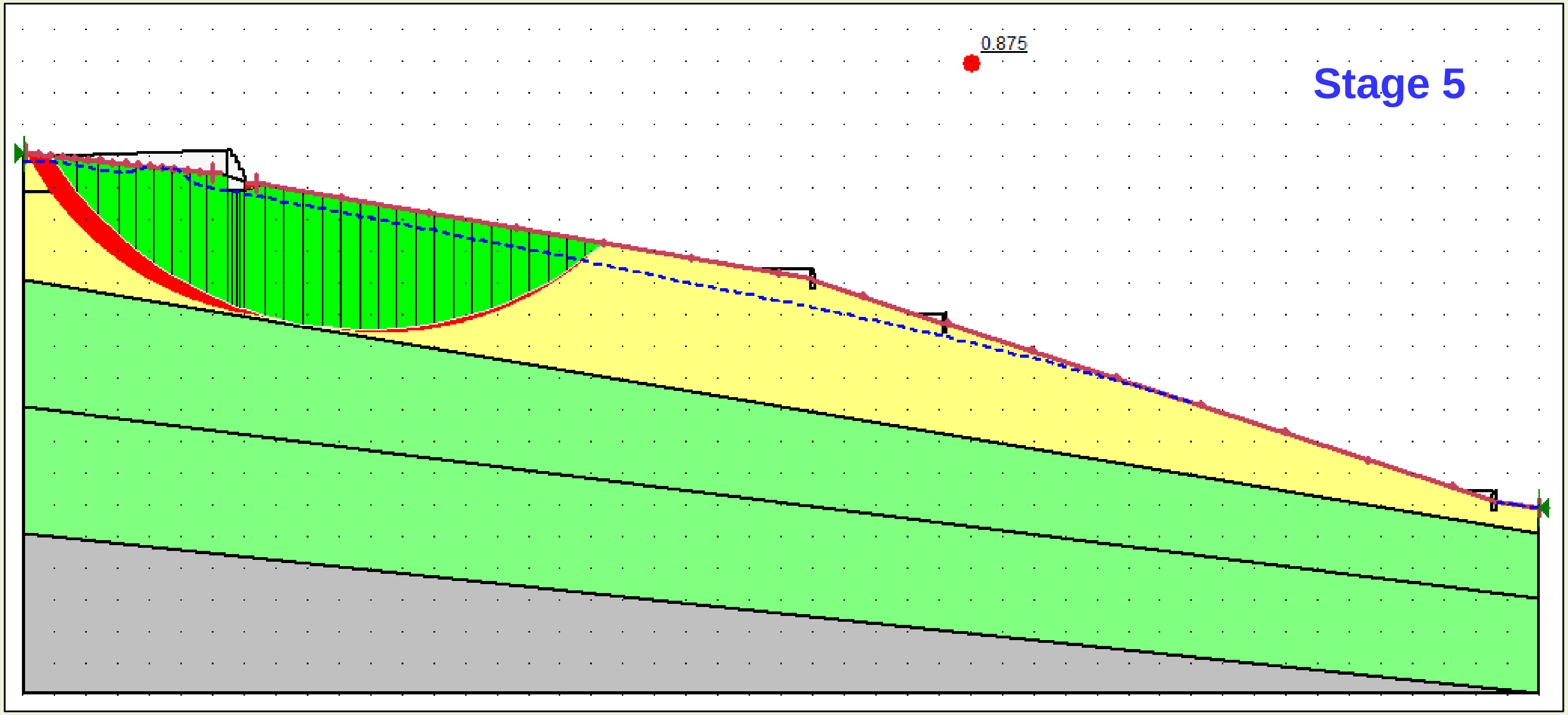

Preliminary Models and Failure Analysis

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  - *Morgenstern-Price Method for analysis*
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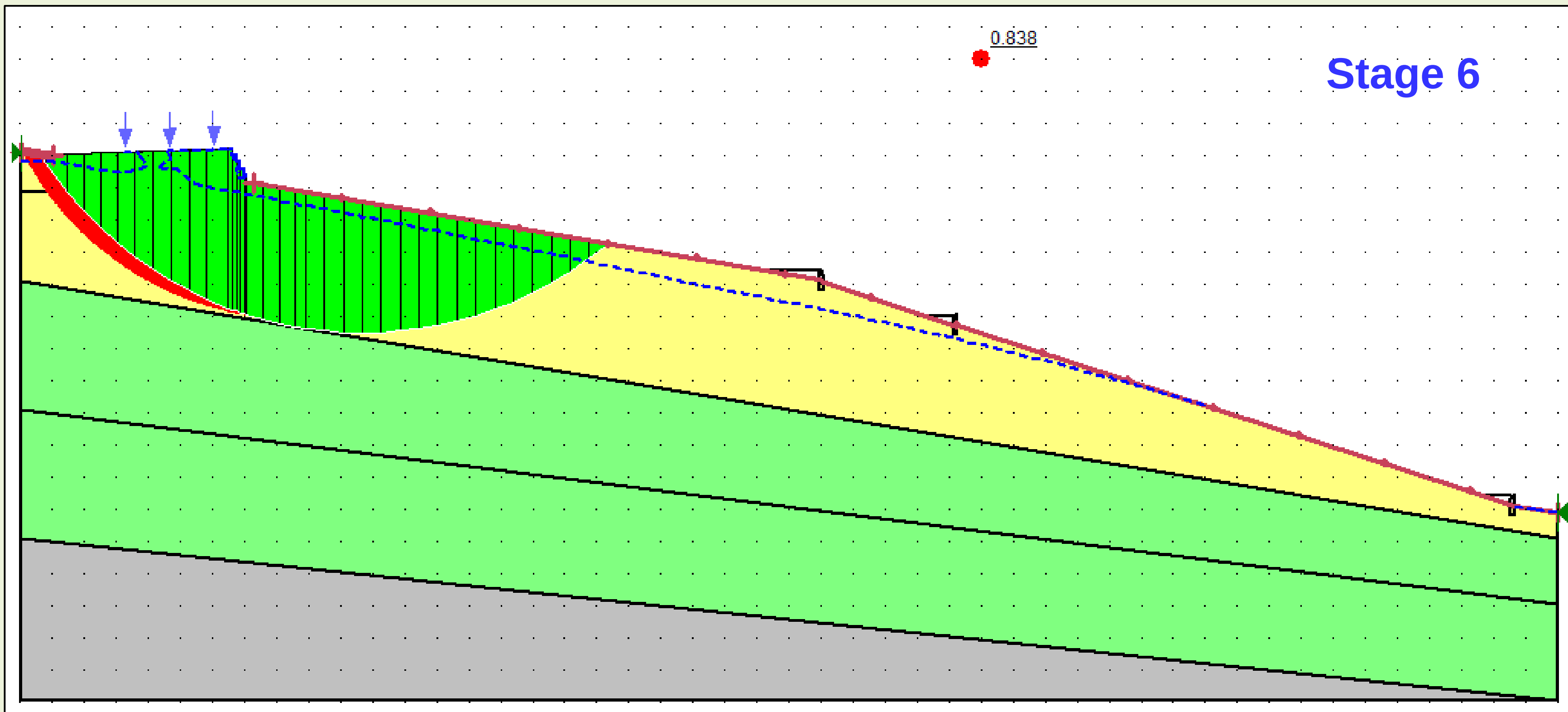

Preliminary Models and Failure Analysis

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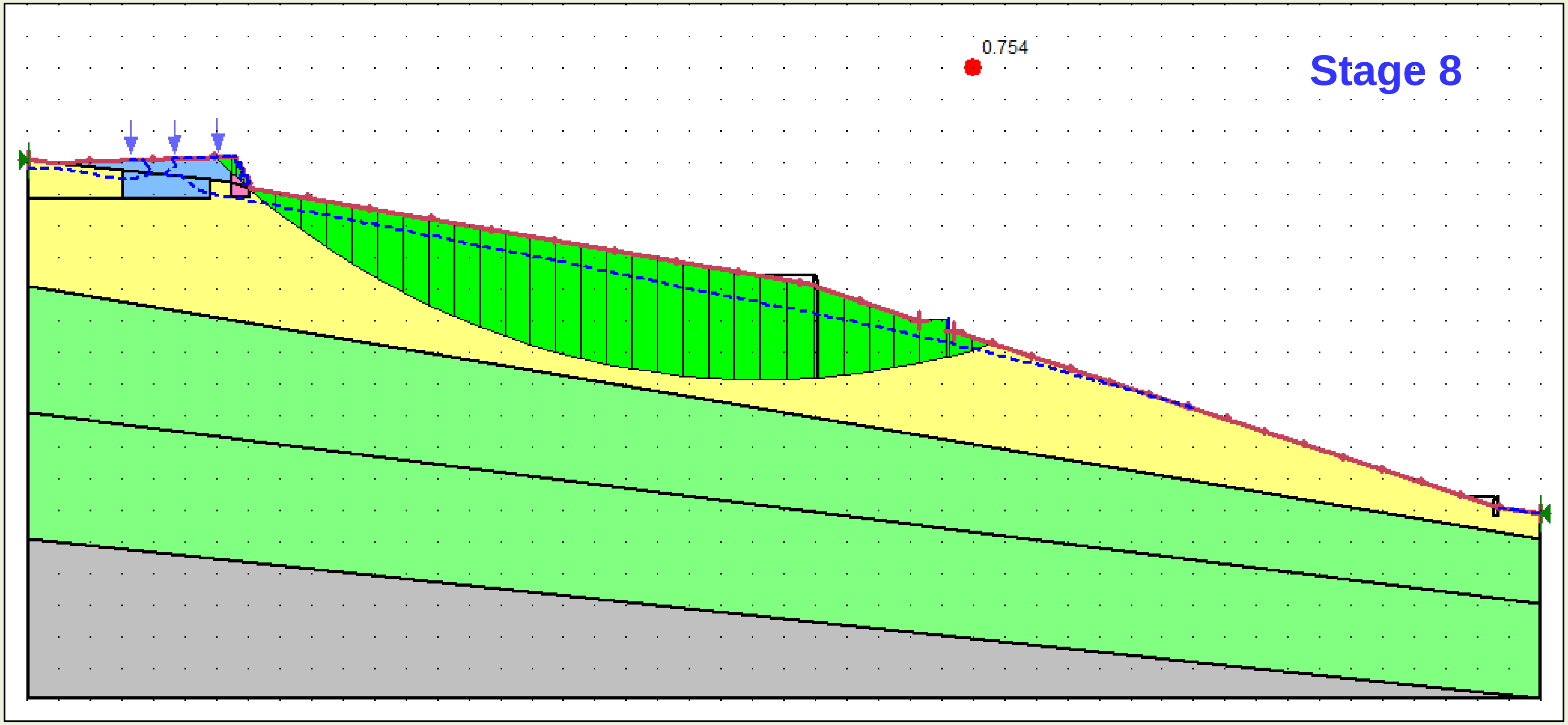
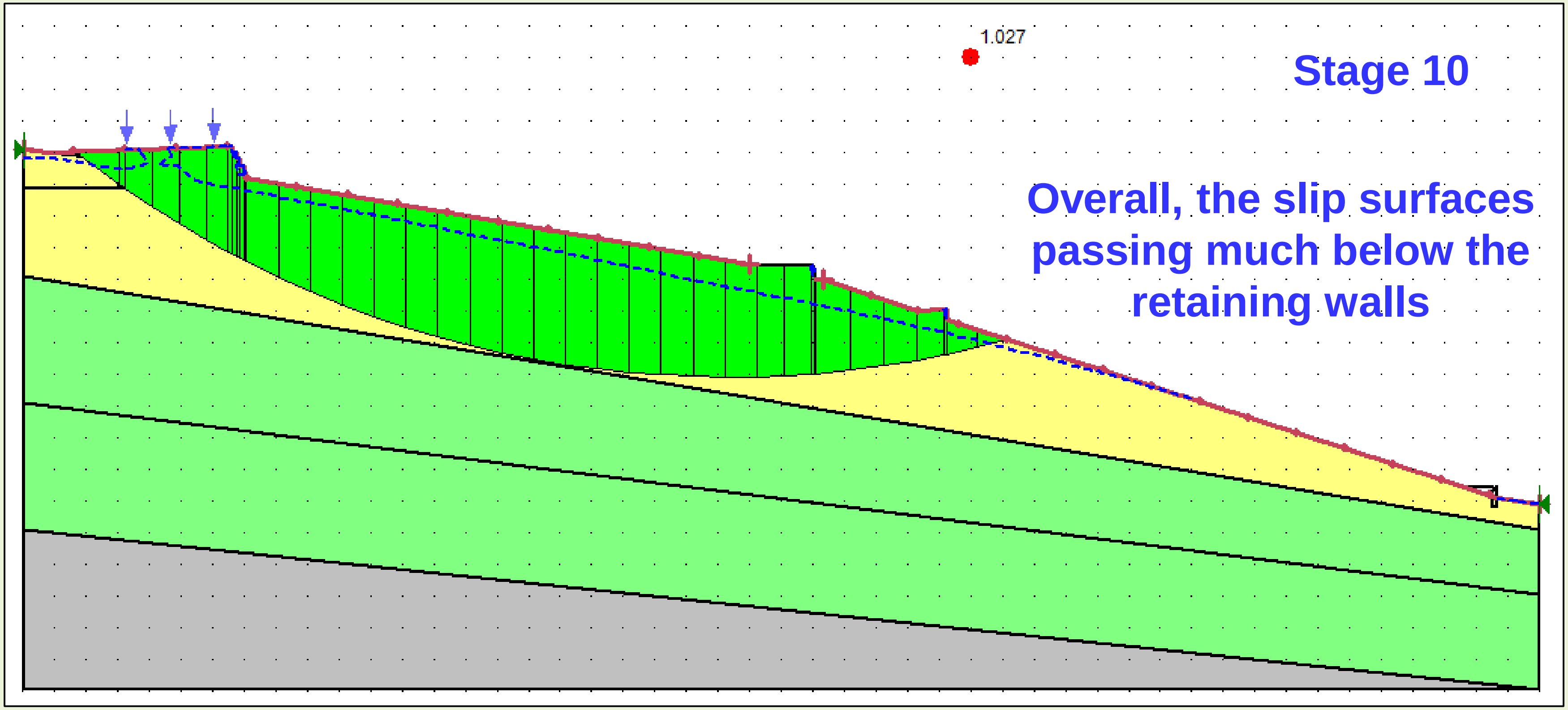


Preliminary Models and Failure Analysis

- Slope stability analysis using Slope/W
  - ❖ *Morgenstern-Price Method for analysis*
  - ❖ *Entry-Exit method for slip surface definition*

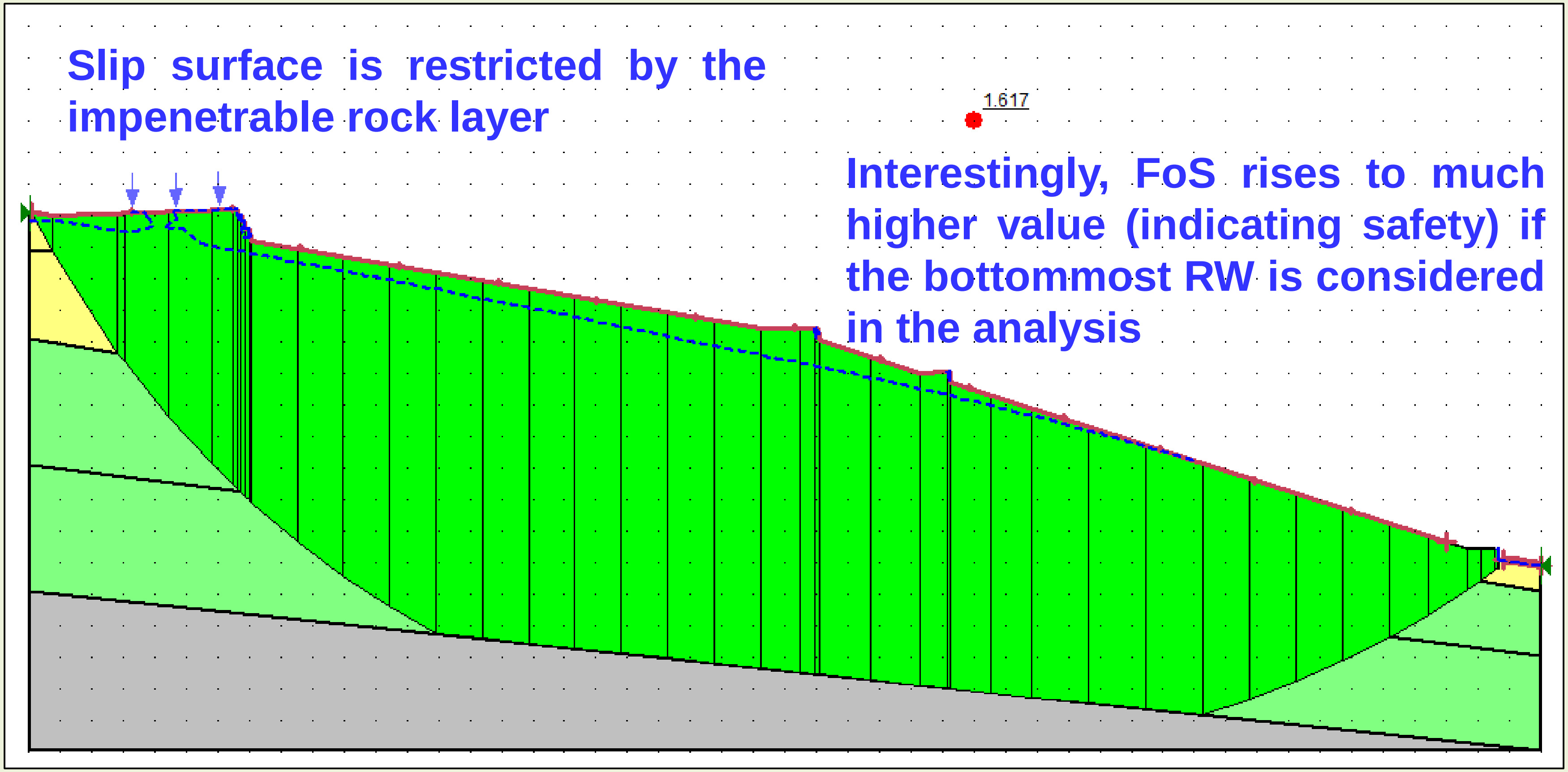
Retaining walls and backfills simply kept on adding weight to the system leading to more destabilization



Preliminary Models and Failure Analysis

- Slope stability analysis using Slope/W
  - ❖ *Morgenstern-Price Method for analysis*
  - ❖ *Entry-Exit method for slip surface definition*

This did not happen in the field, RW4 was overtopped by mud and water → Necessity for further investigation



Preliminary Models and Failure Analysis

- Identification of the most feasible soil stratigraphy
  - ❖ *Based on stability analysis of various stages (Slope/W Module)*
    - PM and SM fails under the presence of any WT condition even in the in-situ condition (landslide in natural hillslope was not recognized at site)

Stage of construction	Dry	Water level at a depth of 1 m (W1)	Water level at a depth of 4 m (W2)	Water level at a depth of 8 m (W3)
Primary Model (PM)				
(1)	1.106	0.693	0.765	0.821
(2)	1.156	0.882	0.886	0.919
(3)	0.928	0.692	0.694	0.717
(4)	0.937	0.765	0.736	0.778
(5)	0.947	0.777	0.750	0.792
(6)	0.930	0.765	0.736	0.778
(7)	0.928	0.764	0.743	0.776
(8)	0.929	0.764	0.744	0.777
(9)	0.940	0.77	0.758	0.779
(10)	0.928	0.764	0.744	0.777

Stage of construction	Dry	Water level at a depth of 1 m (W1)	Water level at a depth of 4 m (W2)	Water level at a depth of 8 m (W3)
Secondary Model (SM)				
(1)	1.416	0.920	1.029	1.054
(2)	1.388	0.952	1.025	1.053
(3)	1.038	0.489	0.609	0.854
(4)	1.078	0.975	0.976	0.88
(5)	1.076	0.989	0.975	0.875
(6)	1.064	1.038	1.038	0.919
(7)	1.087	1.146	1.077	0.935
(8)	1.083	1.151	1.097	0.936
(9)	1.071	1.080	1.083	0.931
(10)	1.081	1.066	1.060	0.924

Stage of construction	Dry	Water level at a depth of 1 m (W1)	Water level at a depth of 4 m (W2)	Water level at a depth of 8 m (W3)
Tertiary Model (TM)				
(1)	2.112	1.411	1.588	1.511
(2)	2.100	1.373	1.577	1.513
(3)	0.976	0.821	0.793	0.769
(4)	0.967	0.850	0.802	0.774
(5)	1.015	0.875	0.825	0.805
(6)	0.985	0.838	0.798	0.785
(7)	1.373	0.817	1.065	1.025
(8)	1.344	0.752	0.967	1.007
(9)	1.288	1.029	1.035	0.975
(10)	1.294	1.024	0.984	0.959

Tertiary model indicates that imposition of building load (Stage 3) induced the marginal stability in the natural hillslope

Preliminary Models and Failure Analysis

- Influence of WT depth on the Tertiary Model
  - ❖ *Attempt to identify the location of the Water Table*
    - In dry condition, the imposition of building load (Stage 3) might have initiated some creep instability, which was arrested by constructed RWs
    - WT assumed at any depth (W1, W2 or W3) showed similar instability after Stage 3
      - However, under such scenarios, no water seepage is expected in the hillslope
      - The possible location of initial WT yet remains unsolved from this aspect

Stage of construction	Dry	Water level at a depth of 1 m (W_1)	Water level at a depth of 4 m (W_2)	Water level at a depth of 8 m (W_3)
Tertiary Model (TM)				
(1)	2.112	1.411	1.588	1.511
(2)	2.100	1.373	1.577	1.513
(3)	0.976	0.821	0.793	0.769
(4)	0.967	0.850	0.802	0.774
(5)	1.015	0.875	0.825	0.805
(6)	0.985	0.838	0.798	0.785
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(9)	1.288	1.029	1.035	0.975
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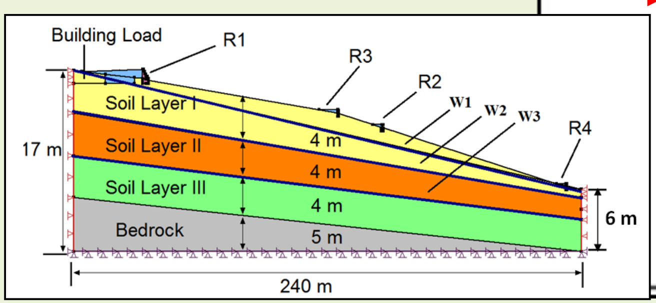
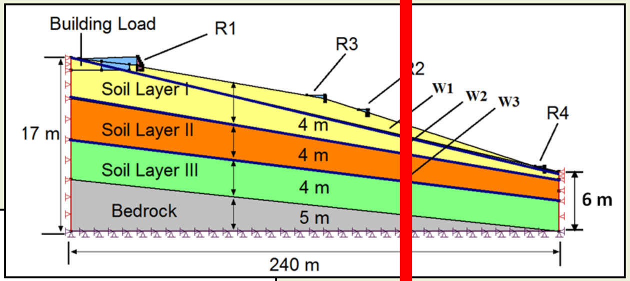


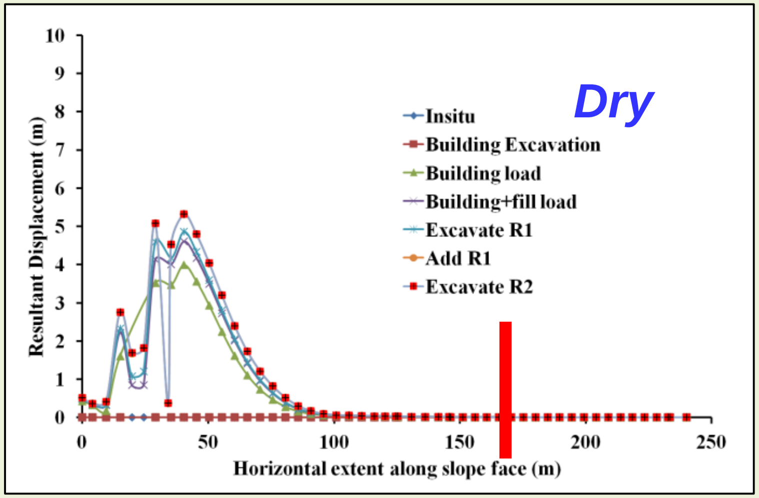
Preliminary Models and Failure Analysis

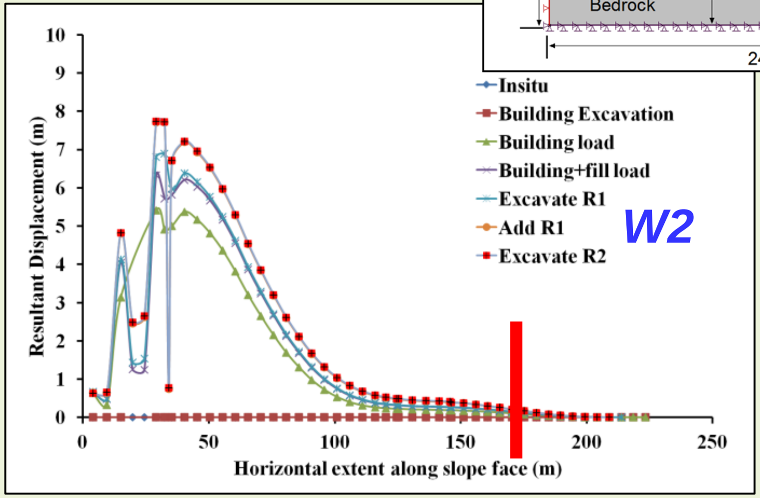
- Displacement along the hillslope
  - ❖ *From SIGMA/W analysis*

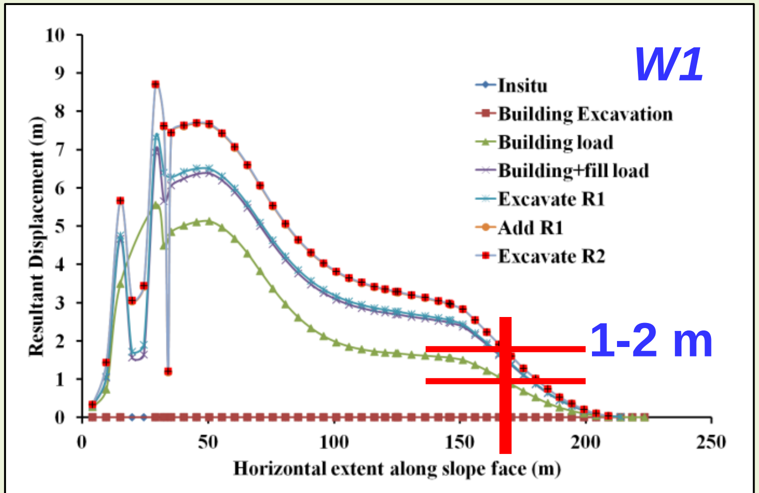


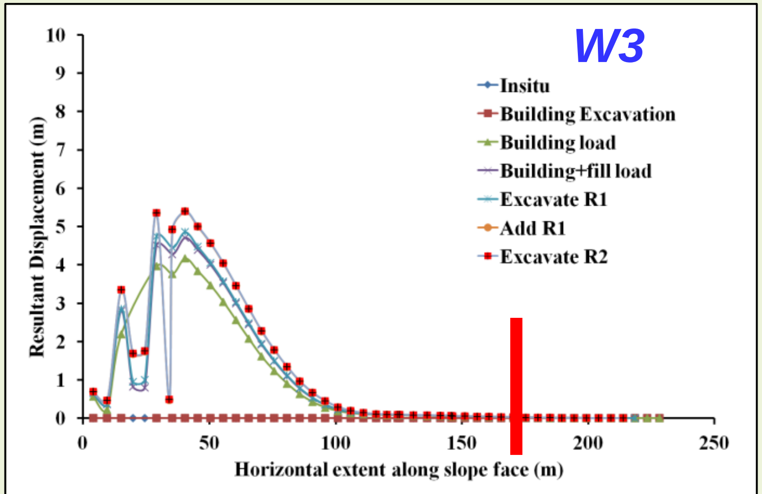
24-Colony Location

170 m from Workshop building





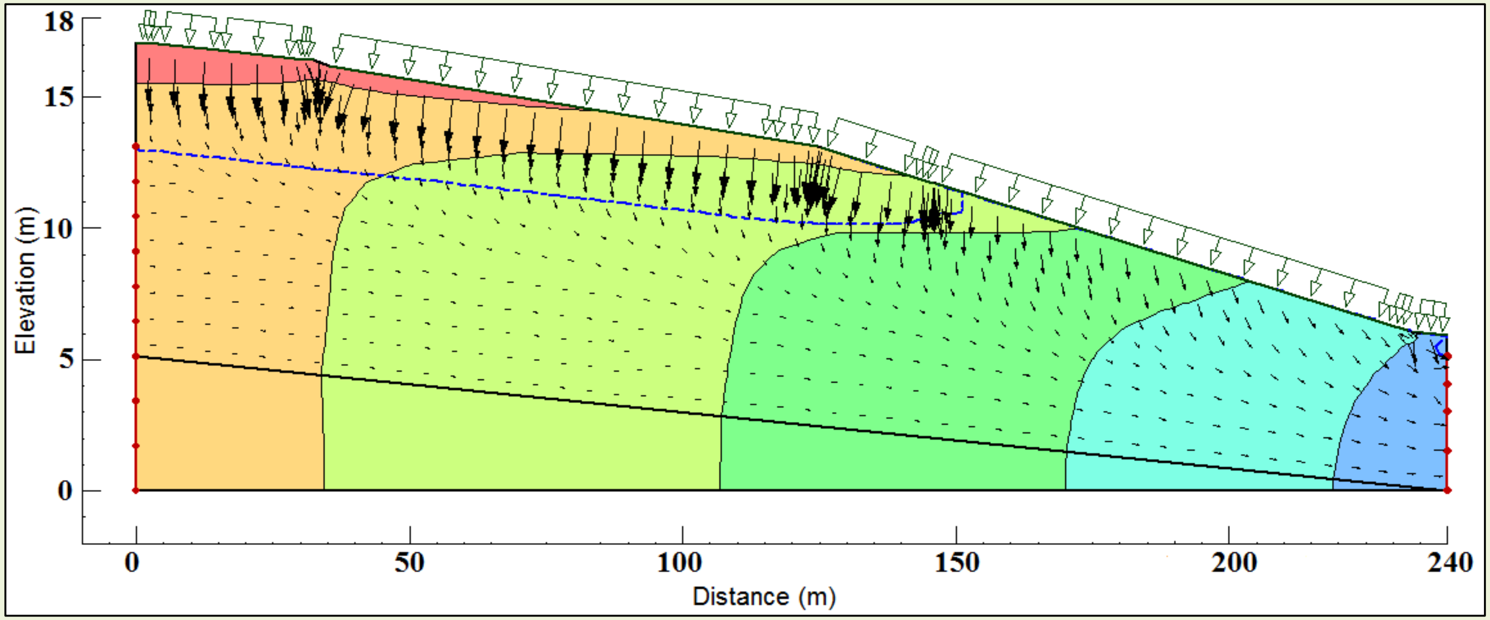




W1 seems to be the most probable WT location, given that it produces some deformation around 24 colony

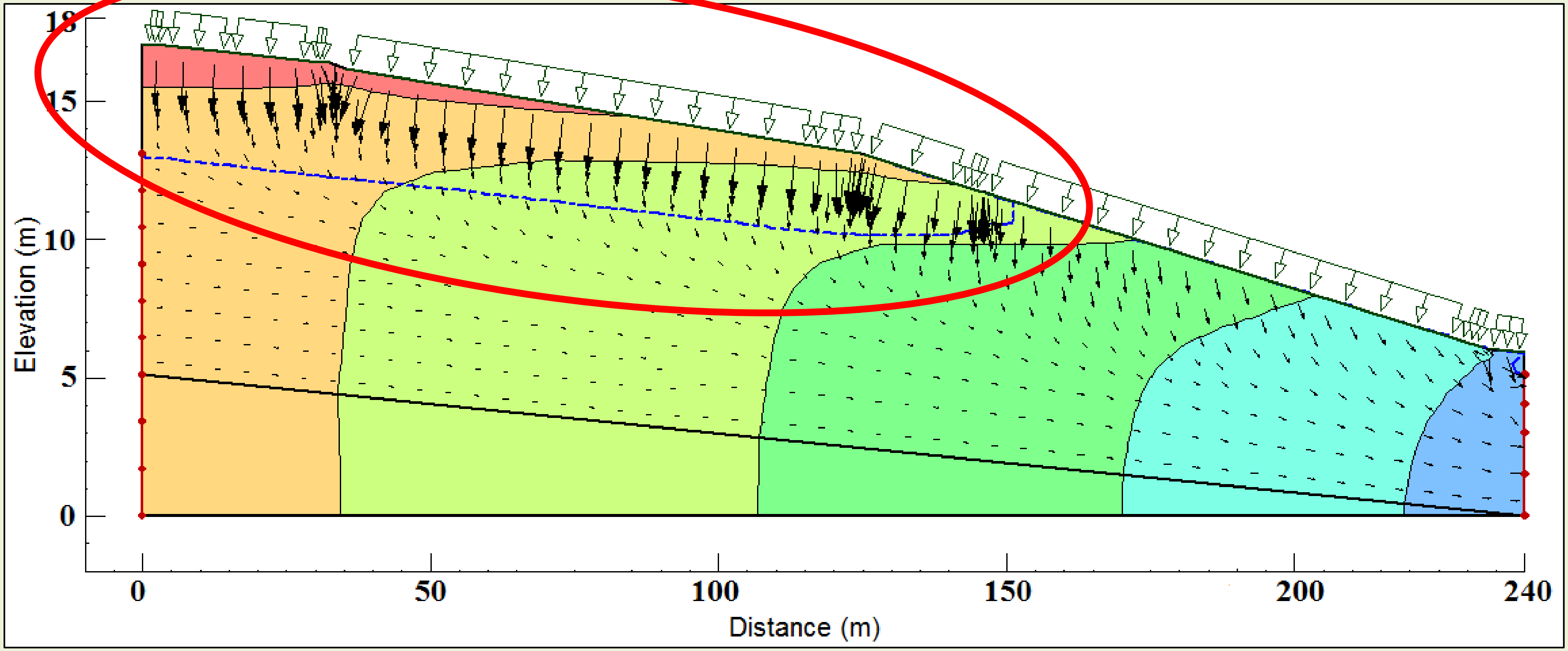
Preliminary Models and Failure Analysis

- What happened to water seeping out from slope face behind the 24 colony → Question still looms !
- Inclusion of rainfall and rainwater infiltration in the SEEP/W analysis
  - ❖ *Prevalent infiltration during the monsoons*
    - 5.4×10^{-8} m/s (estimated from climatic and meteorological data)
  - ❖ *Modeled as constant head of water over the entire slope*



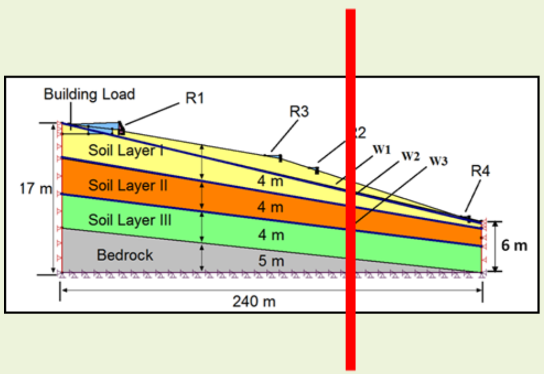
Preliminary Models and Failure Analysis

- Interesting inferences !!!
  - *Infiltration leads to the rise of the WT*
    - WT, upon rising, intersects the slope face near the 24 colony

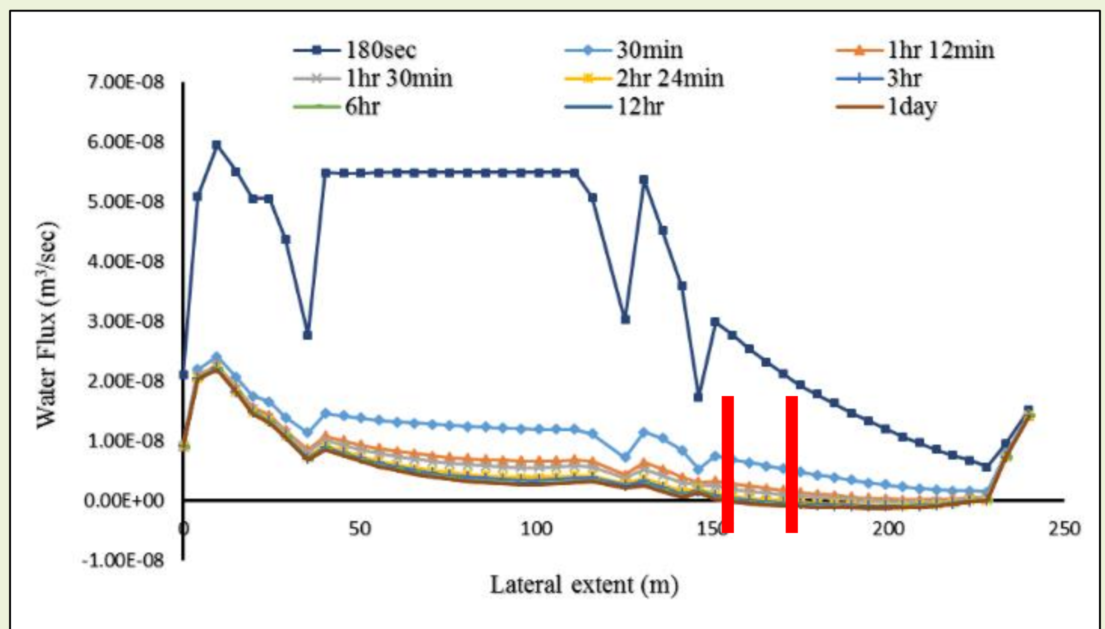


Preliminary Models and Failure Analysis

- Interesting inferences !!!
  - ❖ *Intersection of WT at the slope face near the 24 colony (160-180 m from left)*
    - Denoted by achievement of zero or negative water flux at the slope face
      - Water comes out of the slope face at the prescribed location
    - Time duration of the rise of WT to intersect: Approximately 3-6 h of rain
      - Coincidentally, the same was reported from the field that the first slide behind the colony was noted after an initial 3-4 hr of rainfall around October 2015



24-Colony Location
170 m from Workshop building

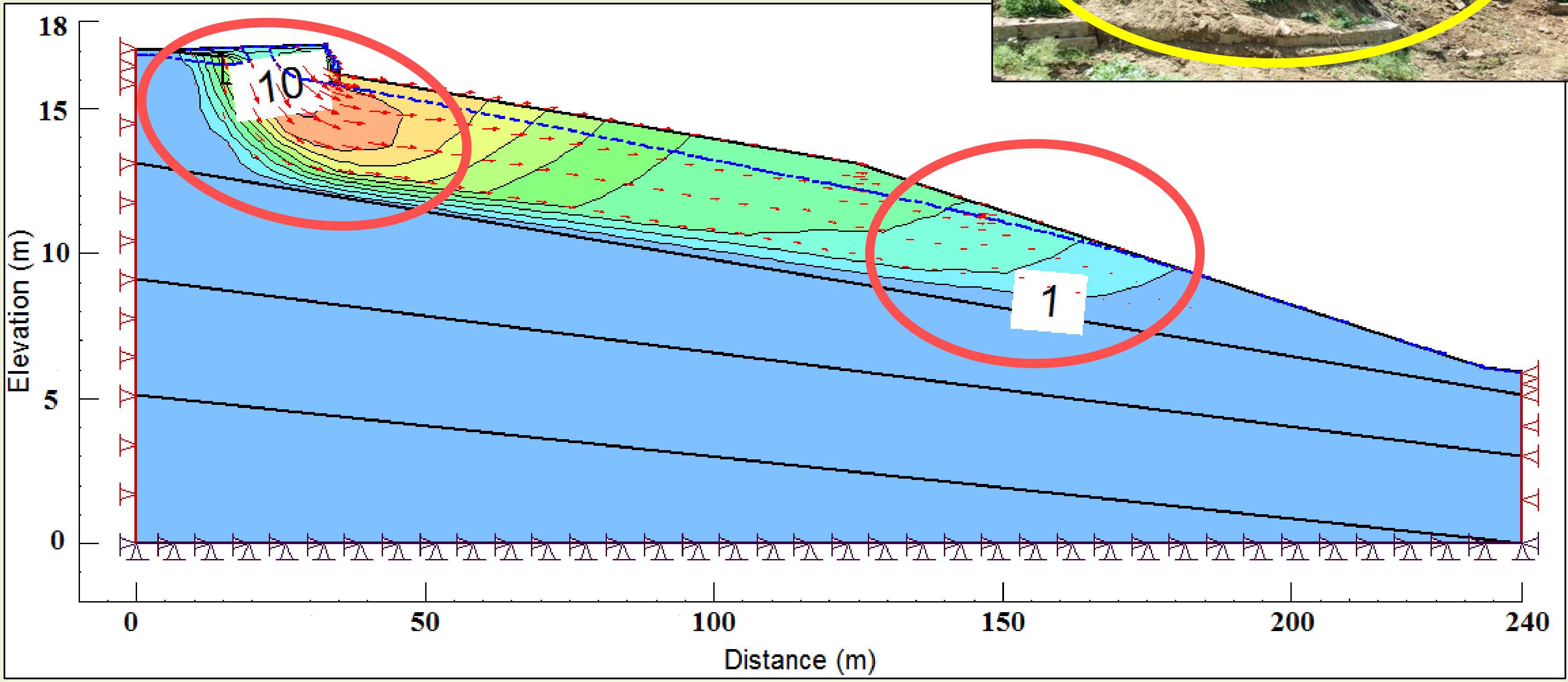


Preliminary Models and Failure Analysis

- Interesting inferences !!!
  - *Intersection of WT at the slope face near the 24 colony (160-180 m from left)*
    - Field observation of water emanating out of the slope face behind 24 colony

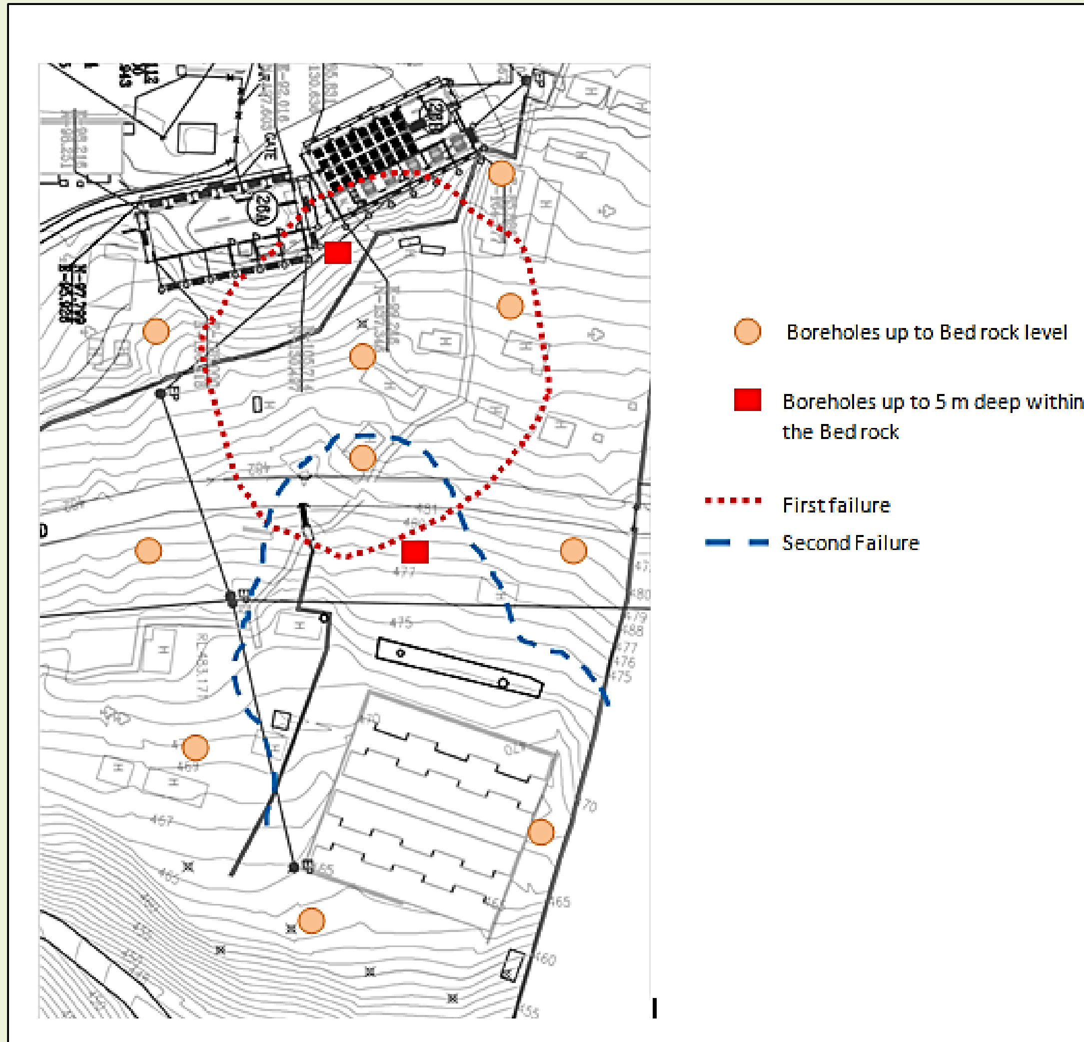
Preliminary Models and Failure Analysis

- Still, we were unhappy !!! ☹
  - *Why so less displacement behind the 24 colony, while the field displacement was maximum at that location !?*
    - Max displacement around building???



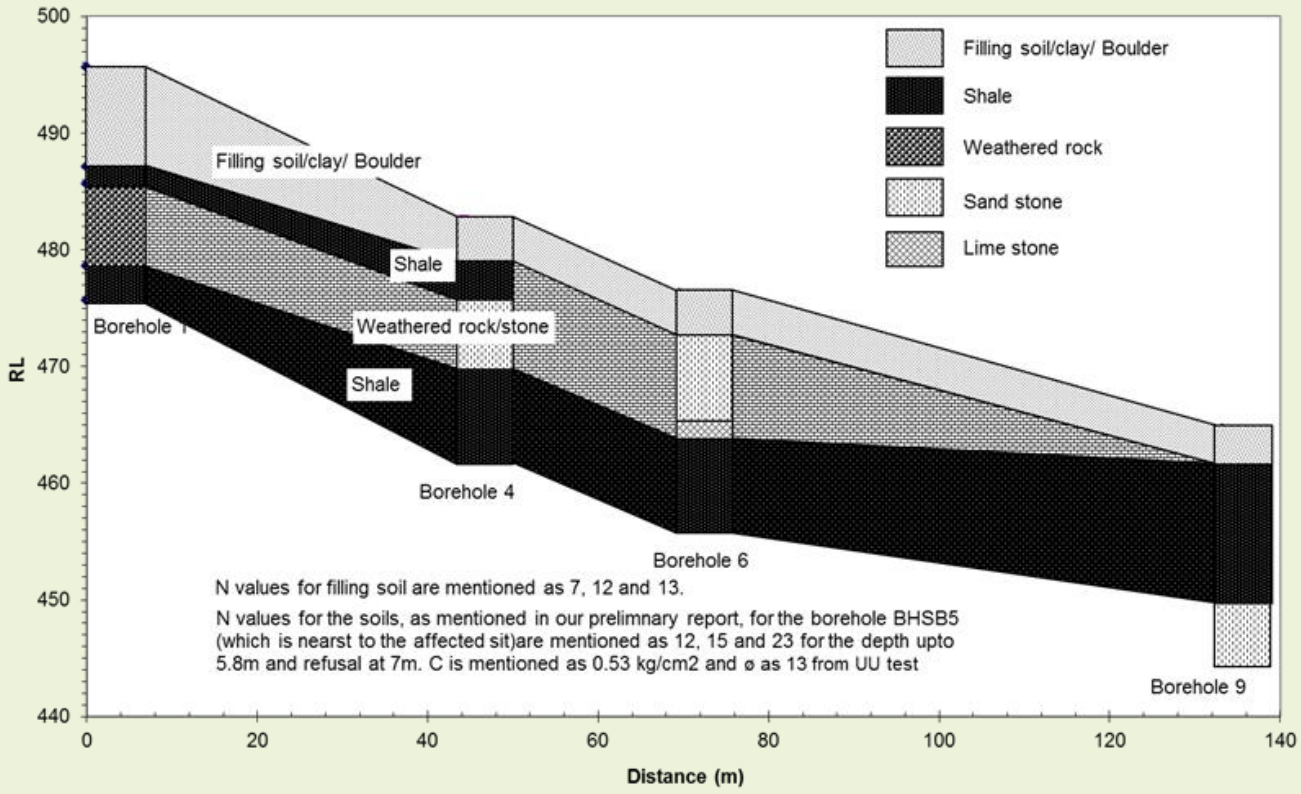
Model Updating from Further Field Studies

- What did we miss earlier???
  - ❖ *Is it the boreholes and stratigraphy??*
    - Yes !! They were not really from failure site
      - It is possible that our assumption of soil stratigraphy and even some of the soil parameters are incorrect ☹
  - ❖ *Prescription*
    - Conduct few more borehole surveys at the landslide site itself
      - Site was accessible? – Yes !!



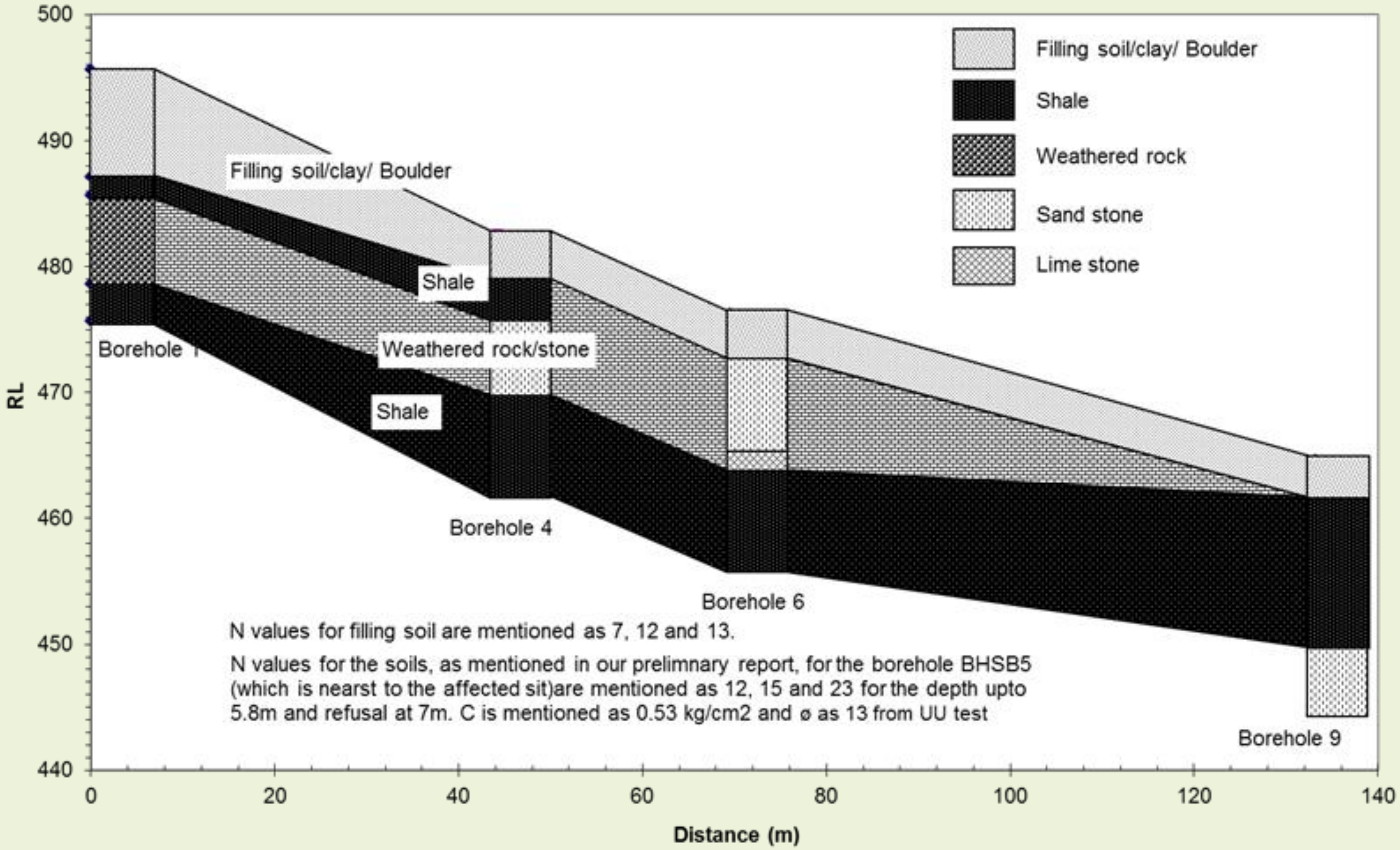
Model Updating from Further Field Studies

- A new understanding of the failure site
  - ❖ *Presence of thick cover of loosely deposited fill soil*
    - Deposited during construction of workshop and store
      - This information was completely missing in earlier discussions



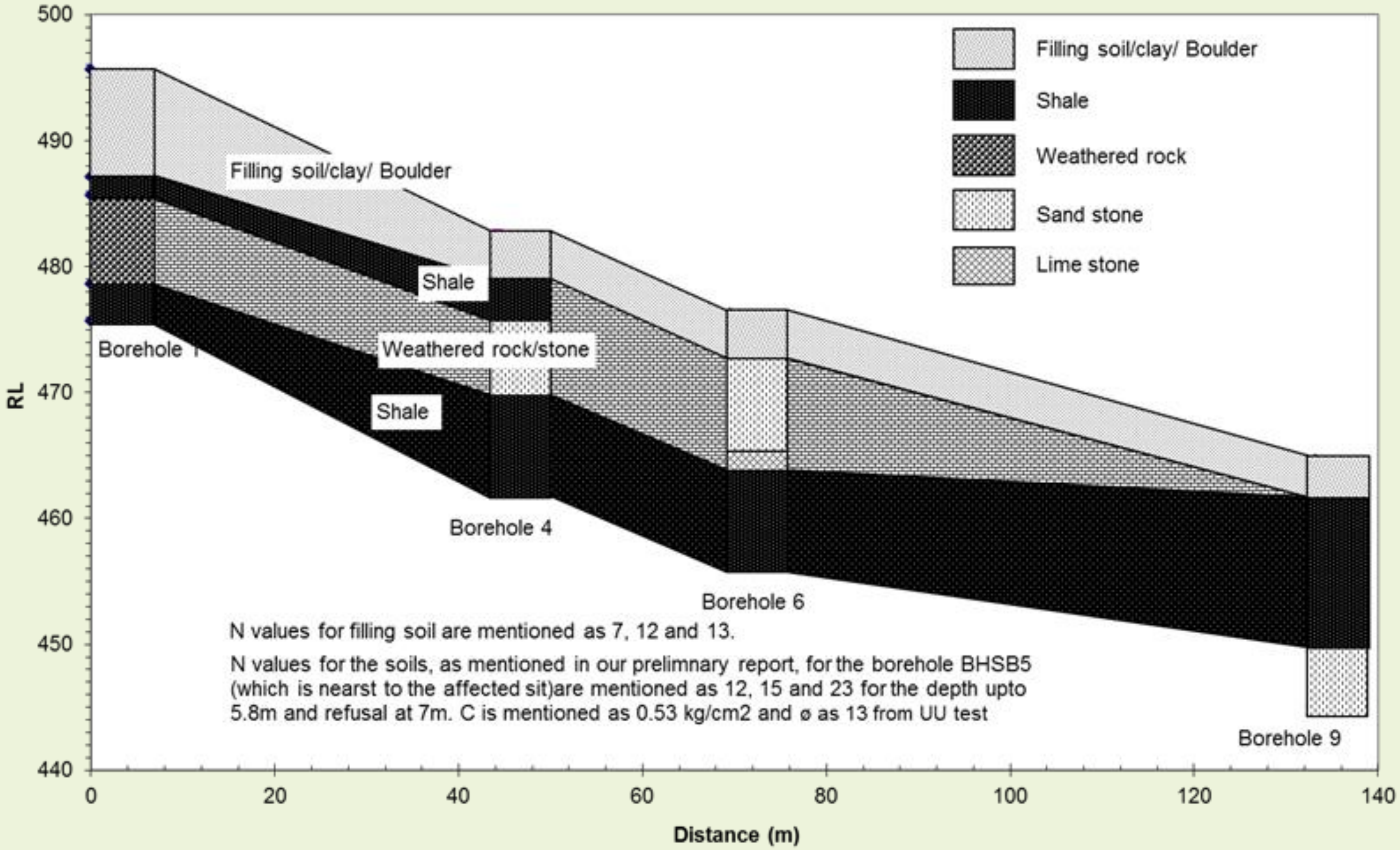
Model Updating from Further Field Studies

- A new understanding of the failure site
  - *Presence of shale pockets*
    - Offers shear surface when get wet due to infiltration and percolation of water



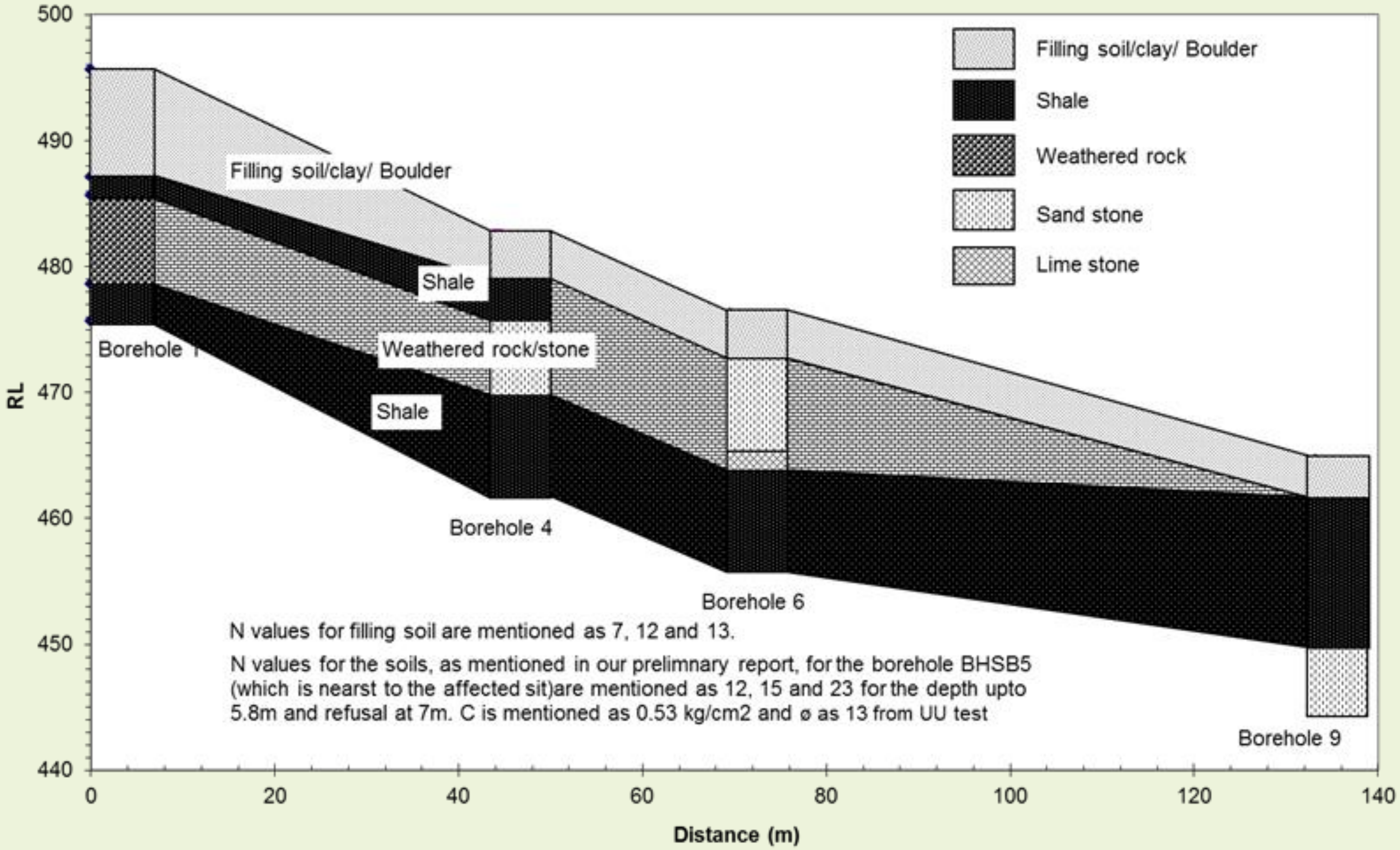
Model Updating from Further Field Studies

- A new understanding of the failure site
  - ❖ *Presence of weathered rock/stone*
    - Allows easy gradient-based migration of water beneath the slope surface



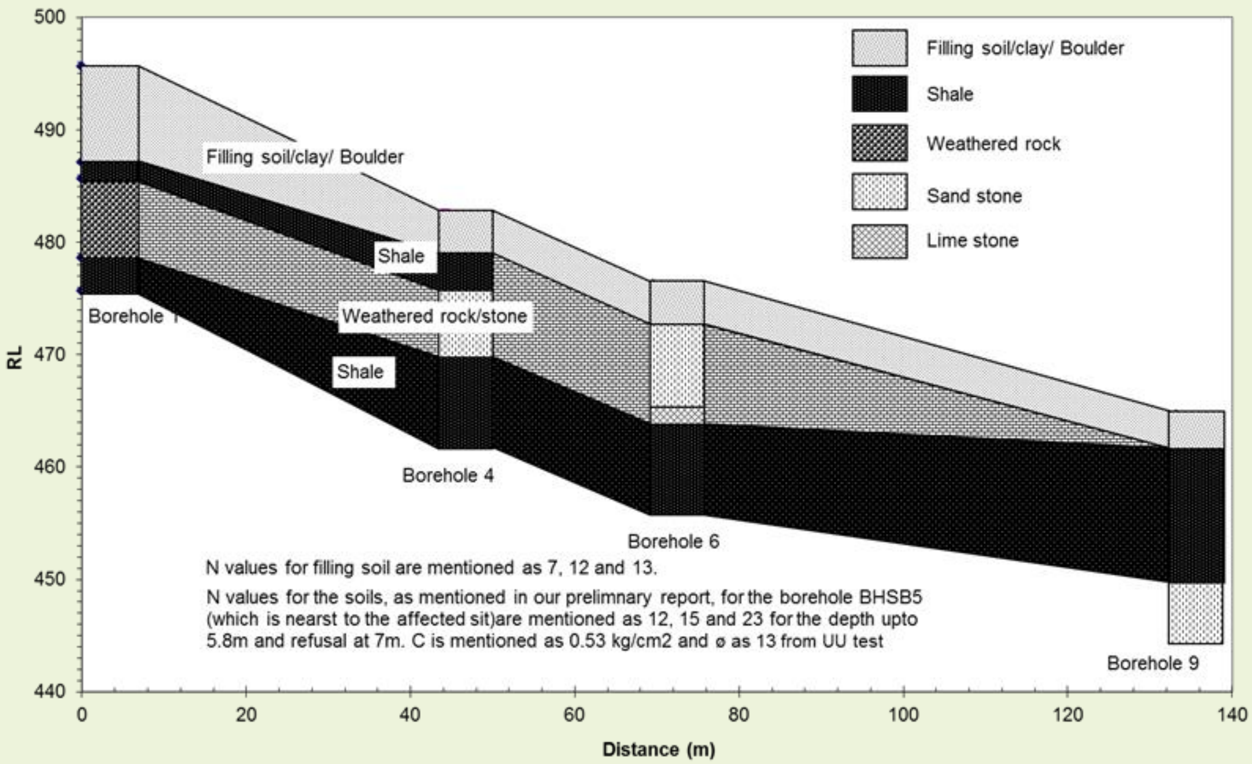
Model Updating from Further Field Studies

- A new understanding of the failure site
  - *Presence of thick deposit of shale*
    - May act either as bedrock when dry, or offer sliding surface when wet



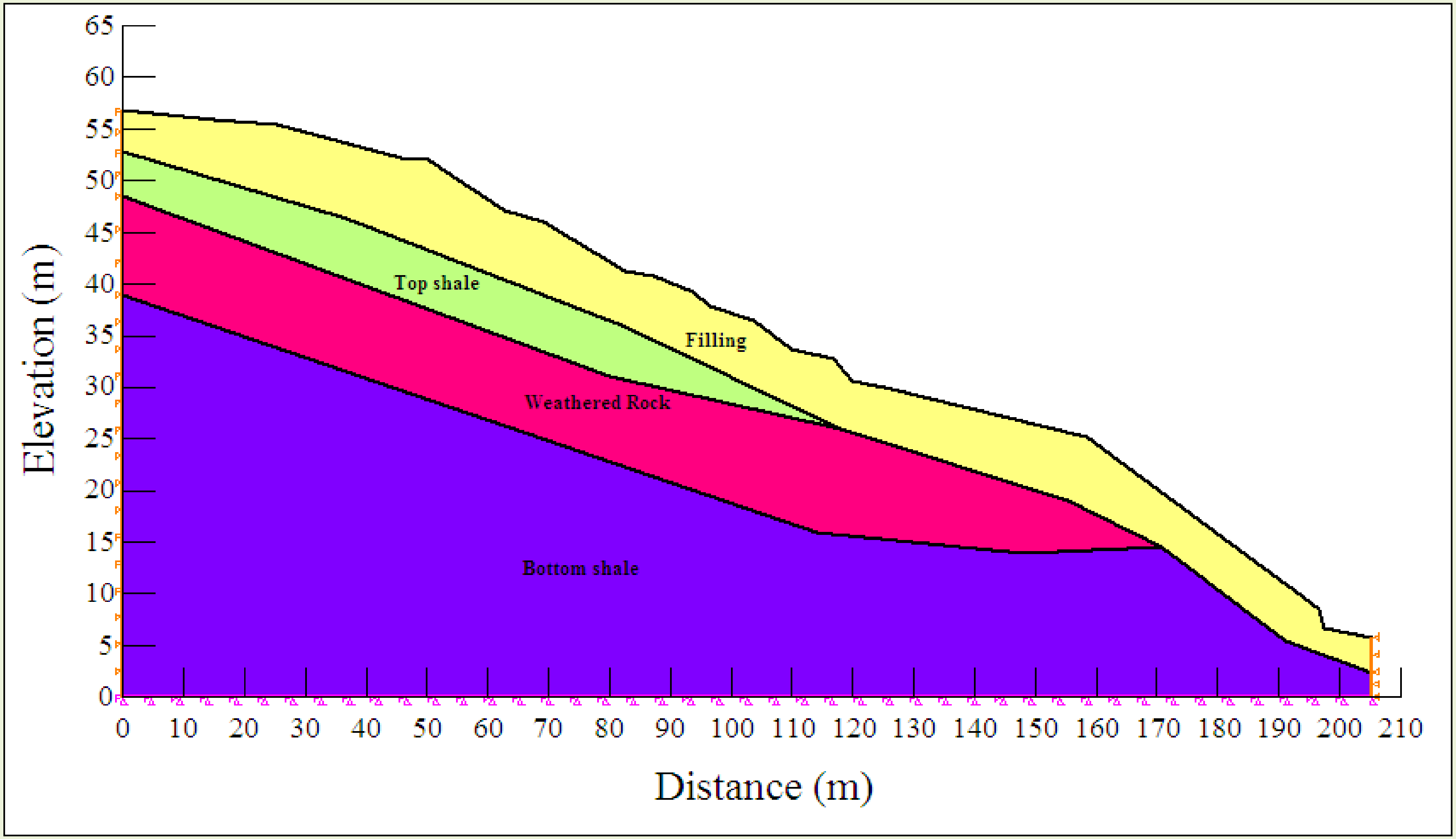
Model Updating from Further Field Studies

- A new understanding of the failure site
  - *A strong intuition developed that the failure is actually shallow slide due to the movement of the loose deposit itself*
    - All the retaining walls and workers colony were simply resting on the loose deposit



Model Updating from Further Field Studies

- A new numerical model is developed



Model Updating from Further Field Studies

- Model parameters are chosen from the new set of experimental investigations (from both field and lab)

SIGMA/W and SLOPE/W

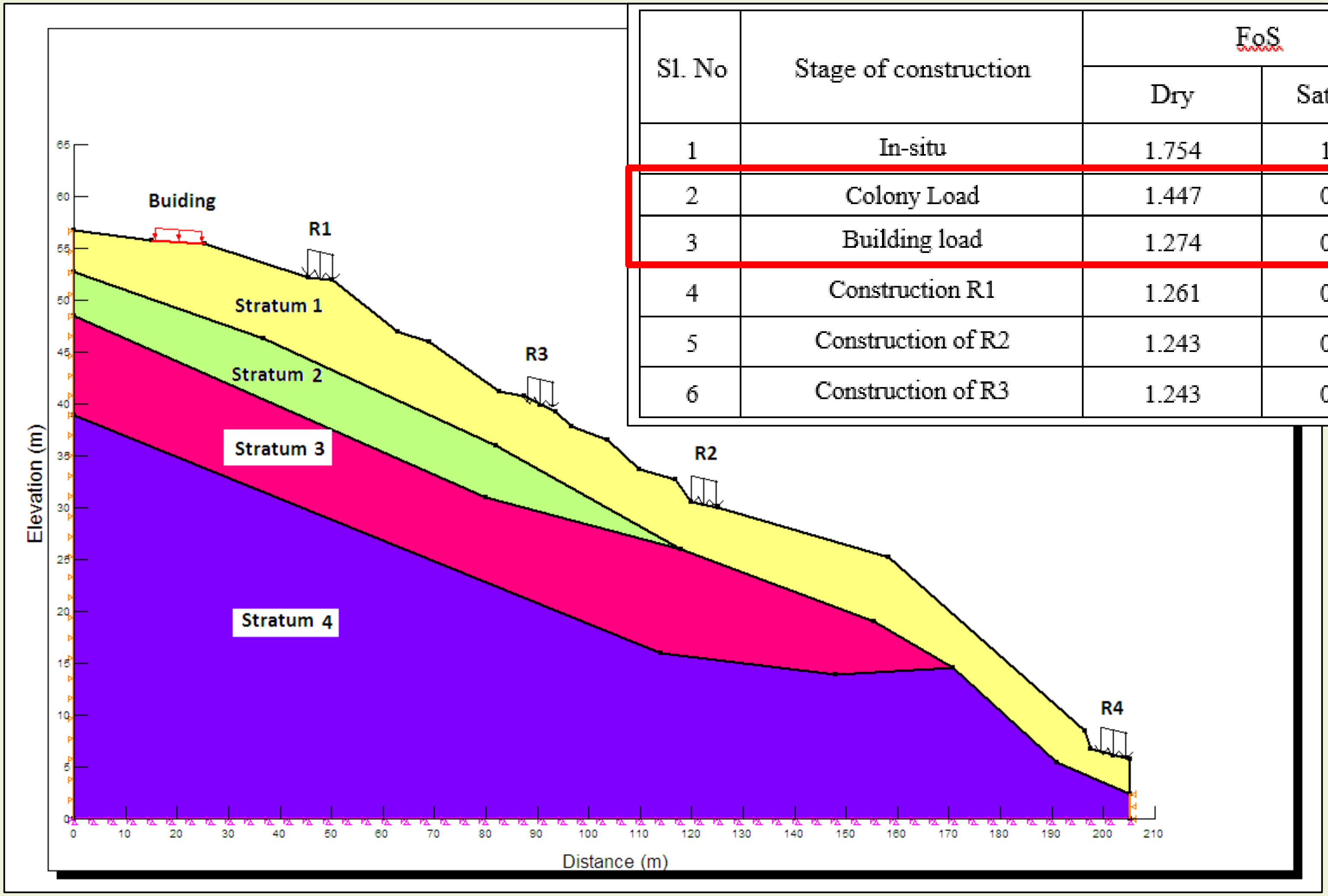
Layer	Type of soil	Material model (in Sigma/W)	Material model (in Slope/W)	Total stress parameter s_u (kPa)		E (MPa)	Unit weight (kN/m^3)
				Dry	Saturated		
1	Filling	Elastic plastic	Undrained $\phi = 0$	42	22	4.08	15
2	Moderately stiff Shale	Linear Elastic	Impenetrable bedrock	-	-	860	22
3	Weathered Rock	Linear Elastic	Impenetrable bedrock	-	-	860	22
4	Hard Shale	Linear Elastic	Impenetrable bedrock	-	-	860	22

Layer	Type of soil	Material model (in SEEP/W)	Saturated hydraulic conductivity (m/sec)	Saturated volumetric water content (m^3/m^3) obtained from porosity
1	Filling	Saturated Only	3×10^{-8}	0.425
2	Moderately stiff Shale	Saturated Only	2×10^{-10}	0.087
3	Weathered Rock	Saturated Only	2×10^{-10}	0.087
4	Hard Shale	Saturated Only	2×10^{-10}	0.087

SEEP/W

Results from Updated Analysis

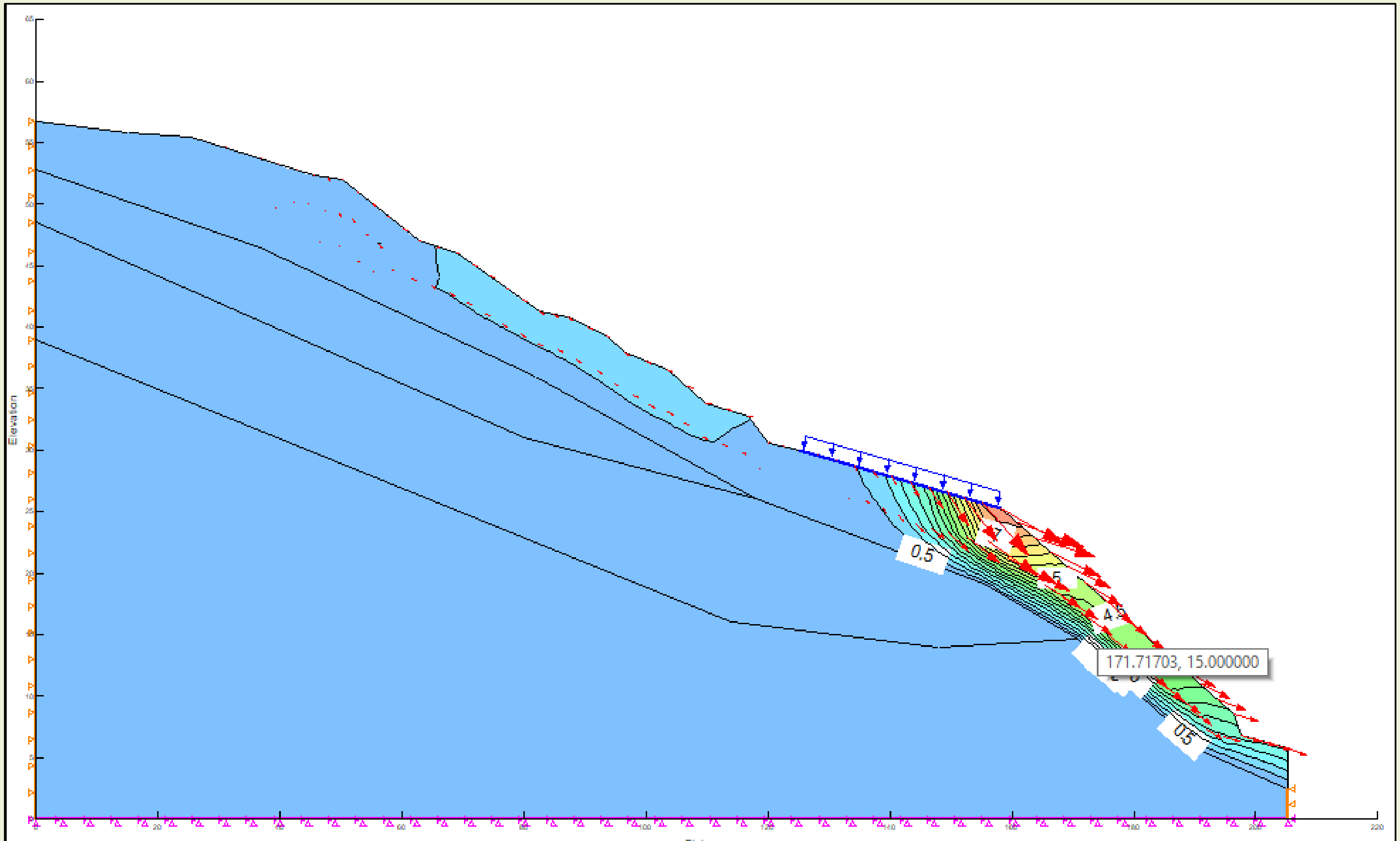
- Application of various loads in stages (as earlier)



Sl. No	Stage of construction	FoS	
		Dry	Saturated
1	In-situ	1.754	1.014
2	Colony Load	1.447	0.970
3	Building load	1.274	0.645
4	Construction R1	1.261	0.669
5	Construction of R2	1.243	0.669
6	Construction of R3	1.243	0.671

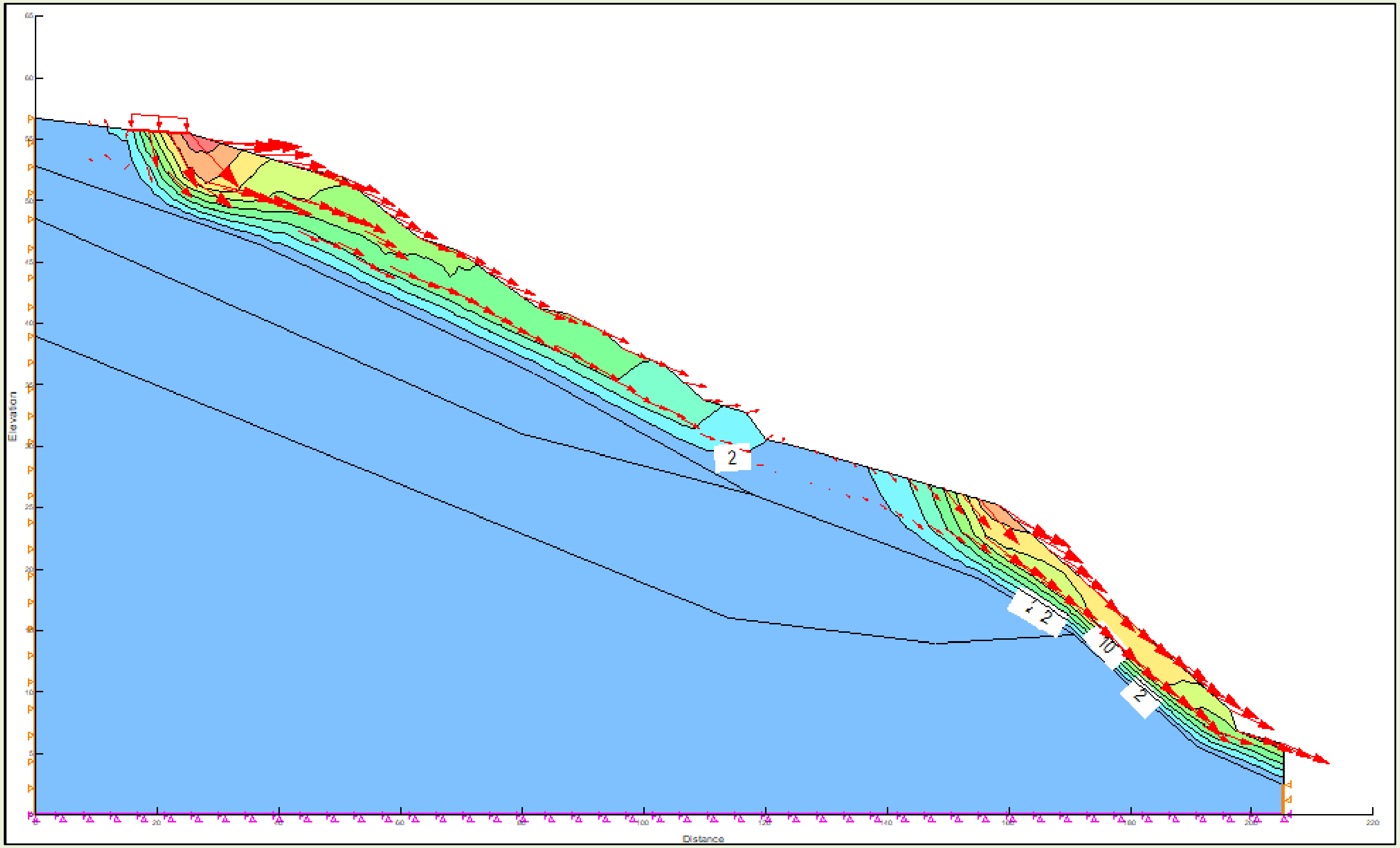
Displacement Results from Updated Analysis

- Application of colony load
  - ❖ *Invokes sufficient displacement in saturated stage*



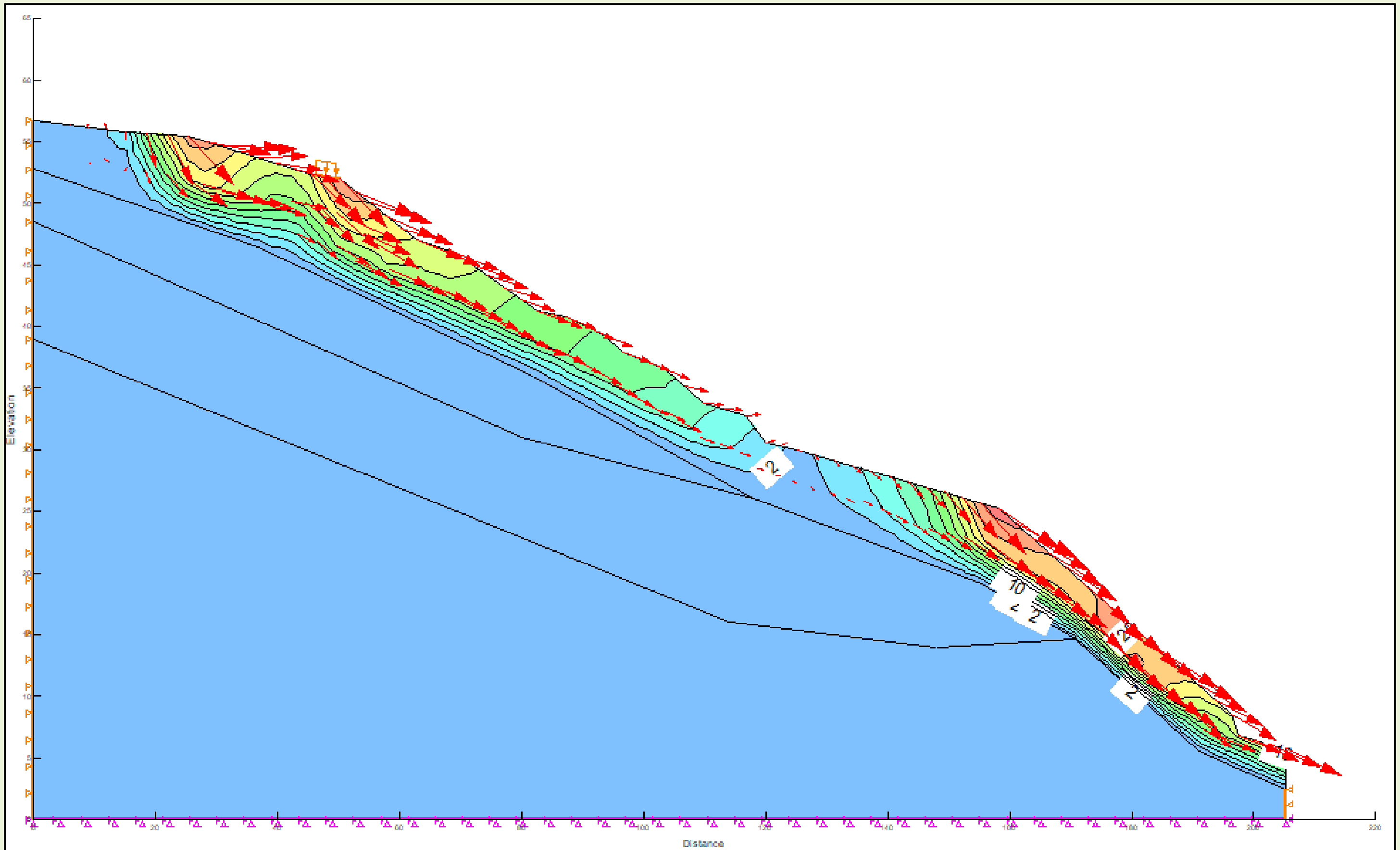
Displacement Results from Updated Analysis

- Application of building load
  - ❖ *Another slip deformation zone is initiated*



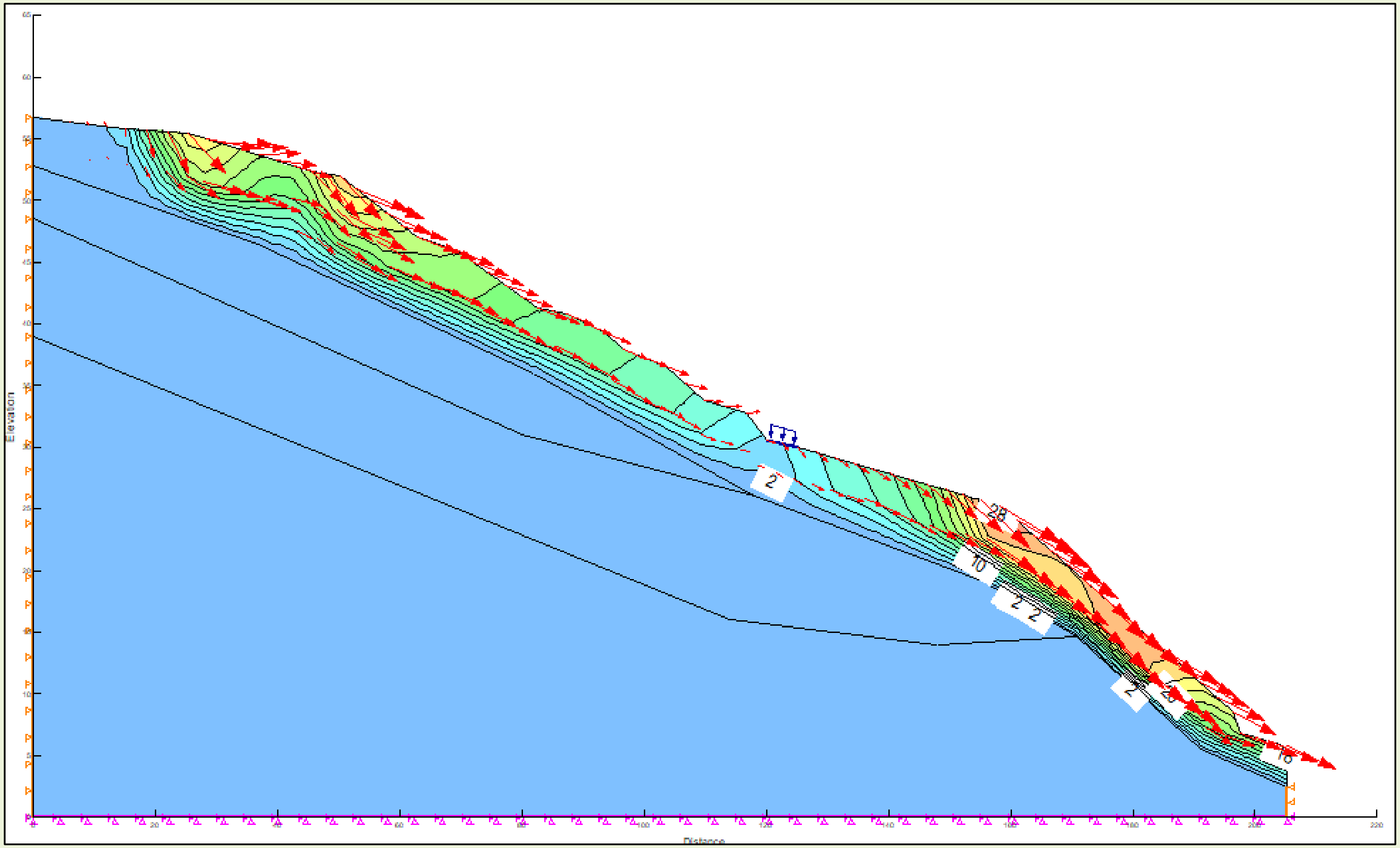
Displacement Results from Updated Analysis

- Application of RW1
  - *RW1 placed on loose deposit*
    - Didn’t help → Added more load to invoke enhancement of deformation zone



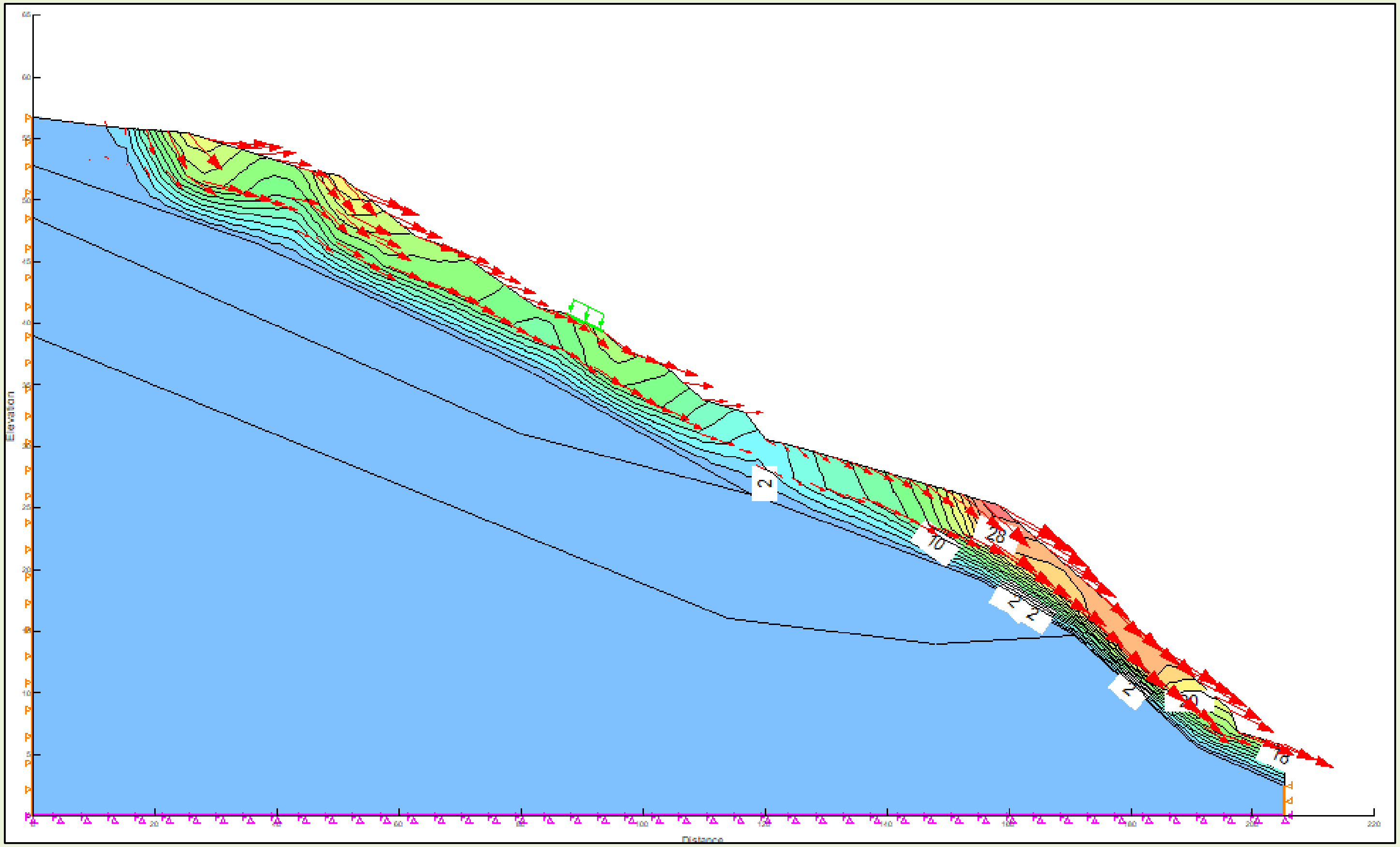
Displacement Results from Updated Analysis

- Application of RW2
  - ❖ *RW2 placed on loose deposit → Deformation zones start overlapping*



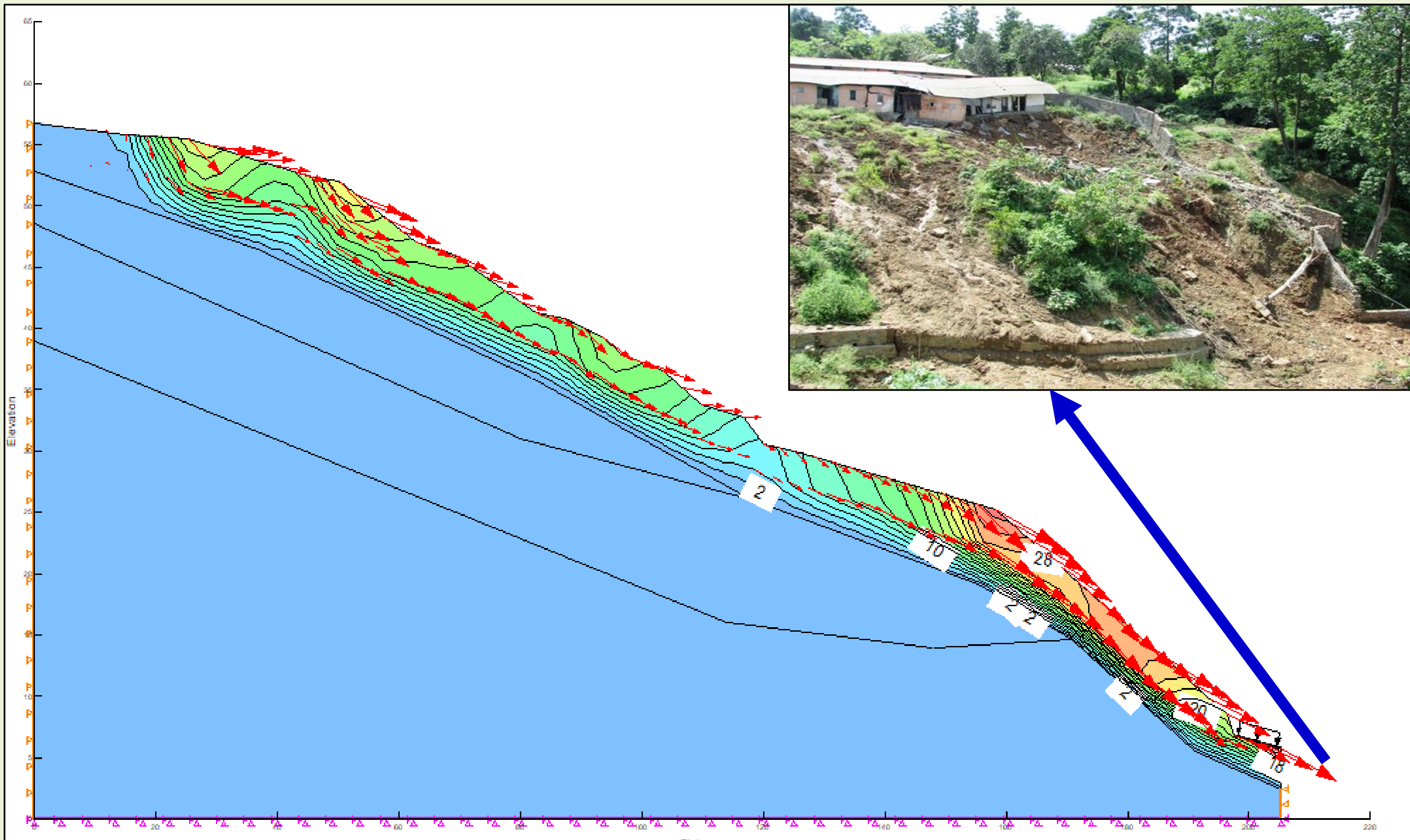
Displacement Results from Updated Analysis

- Application of RW3
  - *RW3 placed on loose deposit → Deformation zones completely overlaps*
    - MASS MOVEMENT OF SOIL towards complete failure



Displacement Results from Updated Analysis

- Application of RW4
  - ❖ *The bottommost barrier gets overtopped by excessively displacing soil*



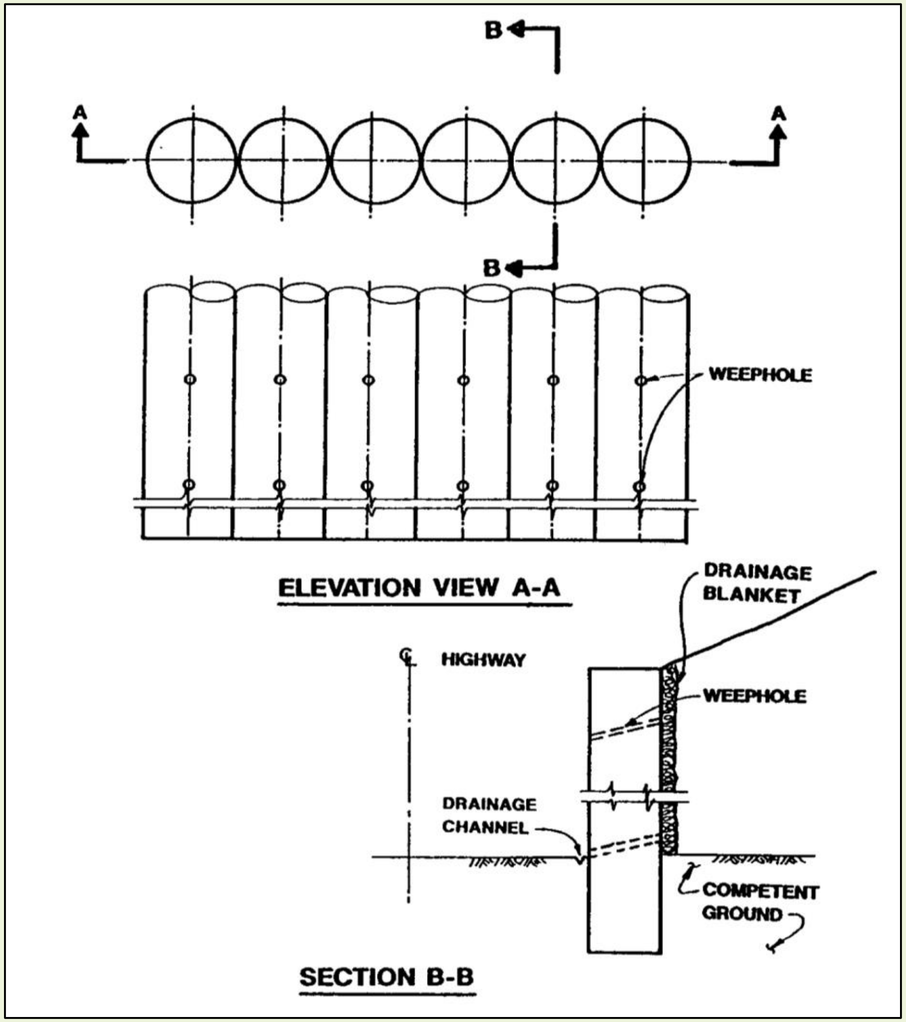
OUTCOME OF FORENSIC ANALYSIS

☺ Happy to identify the background reasons of cause, triggers and subsequent failure

☺ Matched well with the several observations made during field reconnaissance

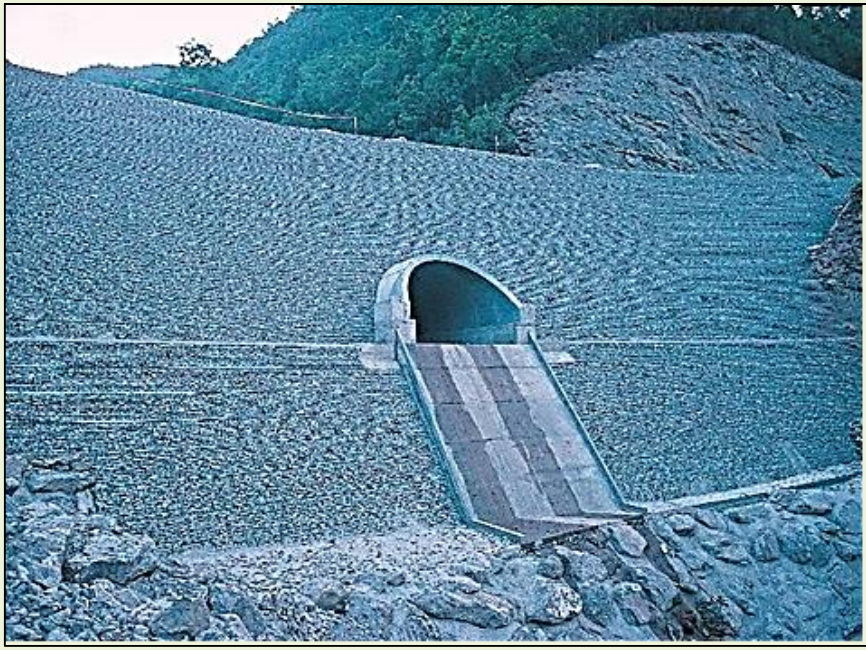
Stabilization Schemes

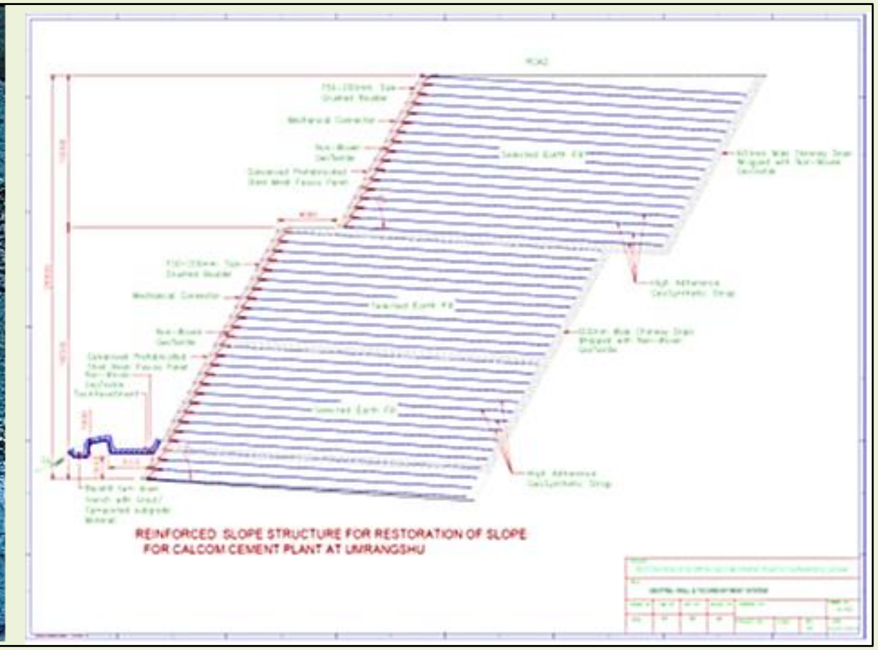
- Several stabilization schemes were proposed
  - *Tie-back walls*



Stabilization Schemes

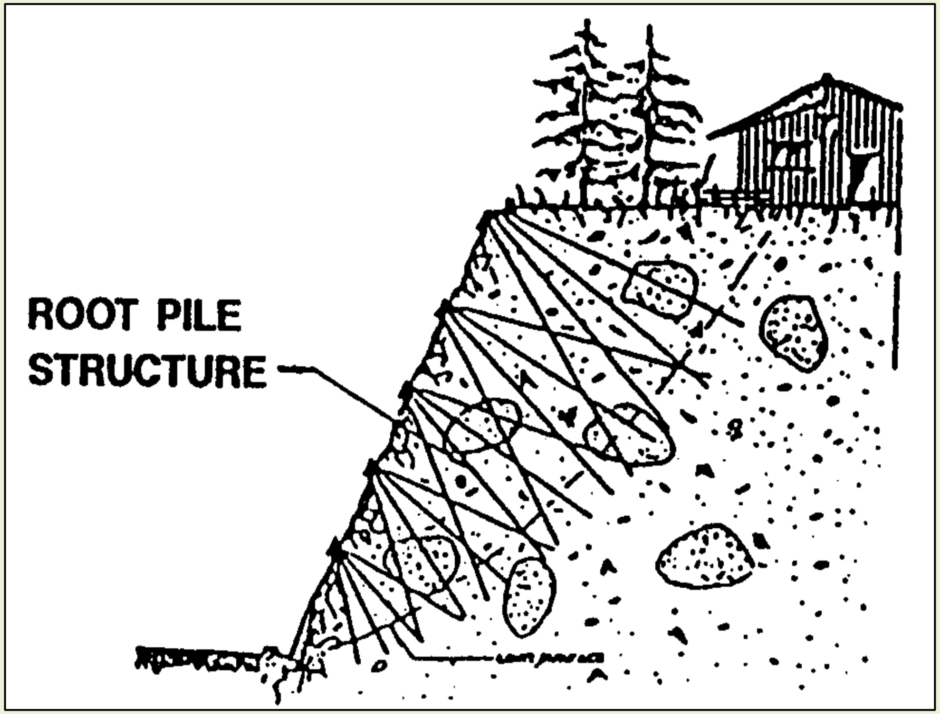
- Several stabilization schemes were proposed
  - *Reinforced Earth Walls*





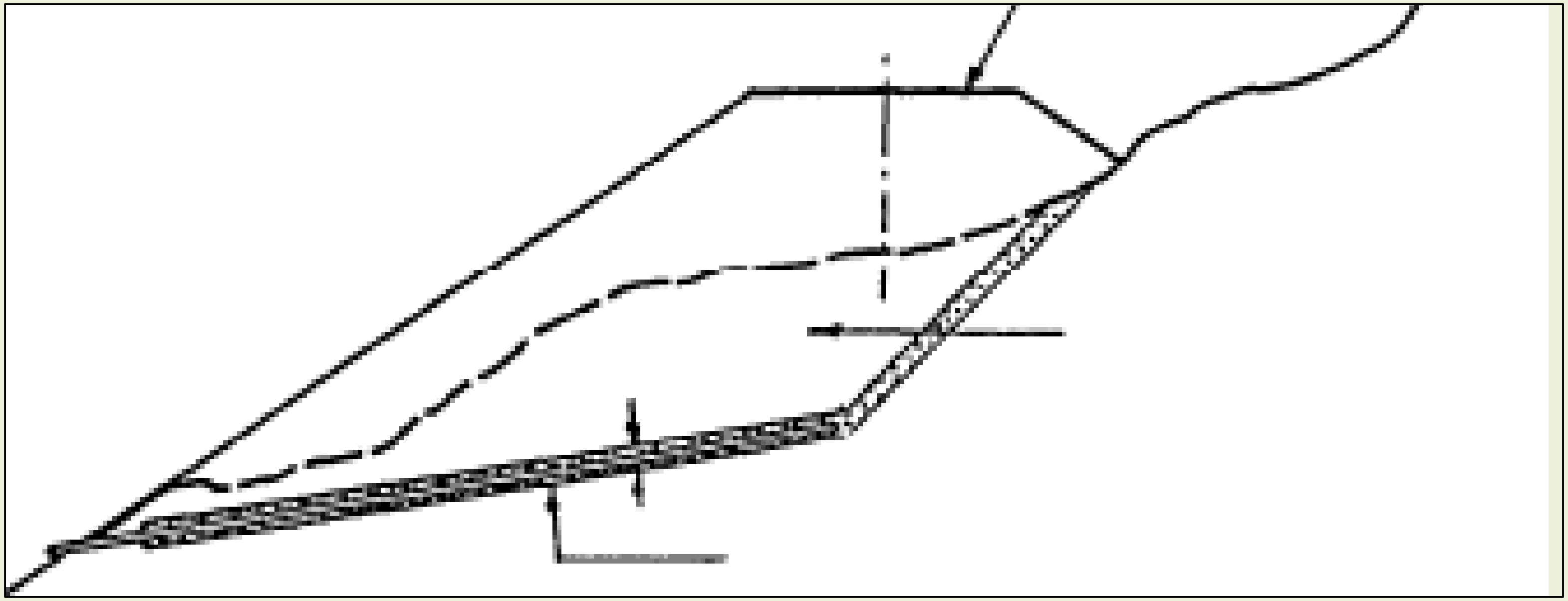
Stabilization Schemes

- Several stabilization schemes were proposed
  - ❖ *Reticulated Micropiles*



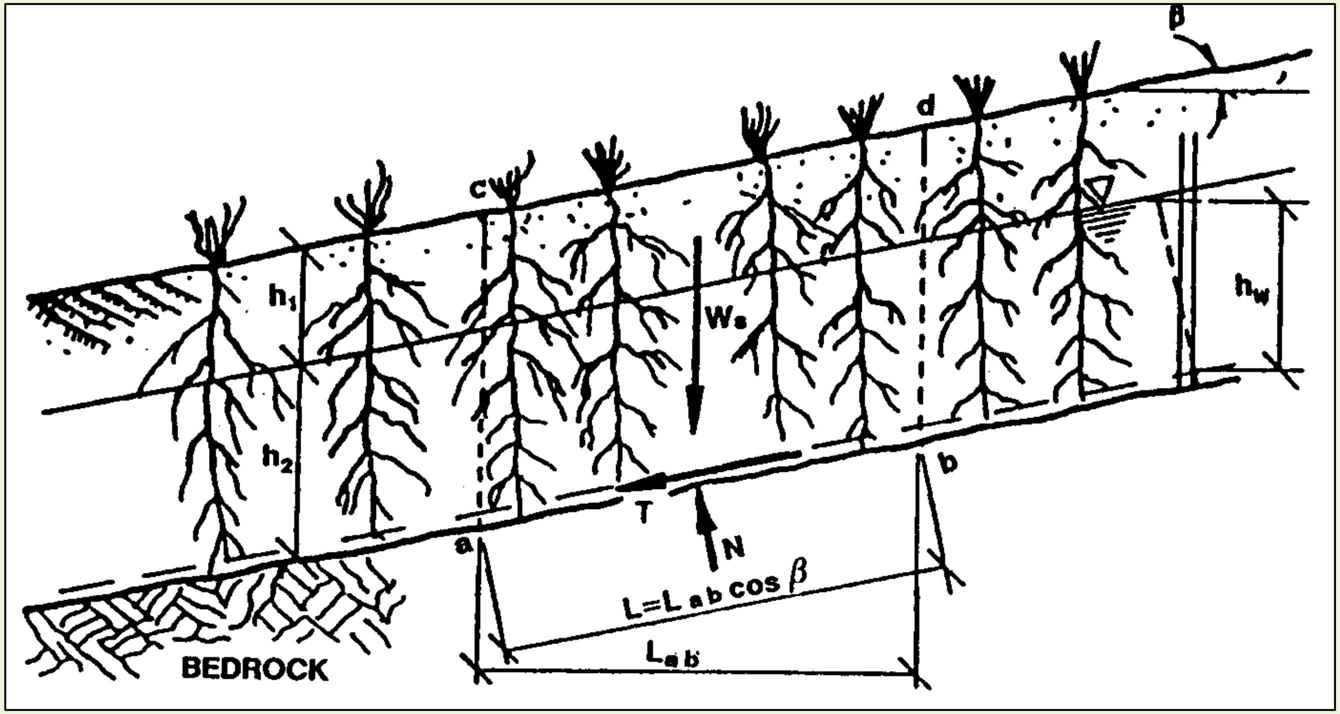
Stabilization Schemes

- Several stabilization schemes were proposed
  - ❖ *Proper Drainage (Surface and Subsurface)*



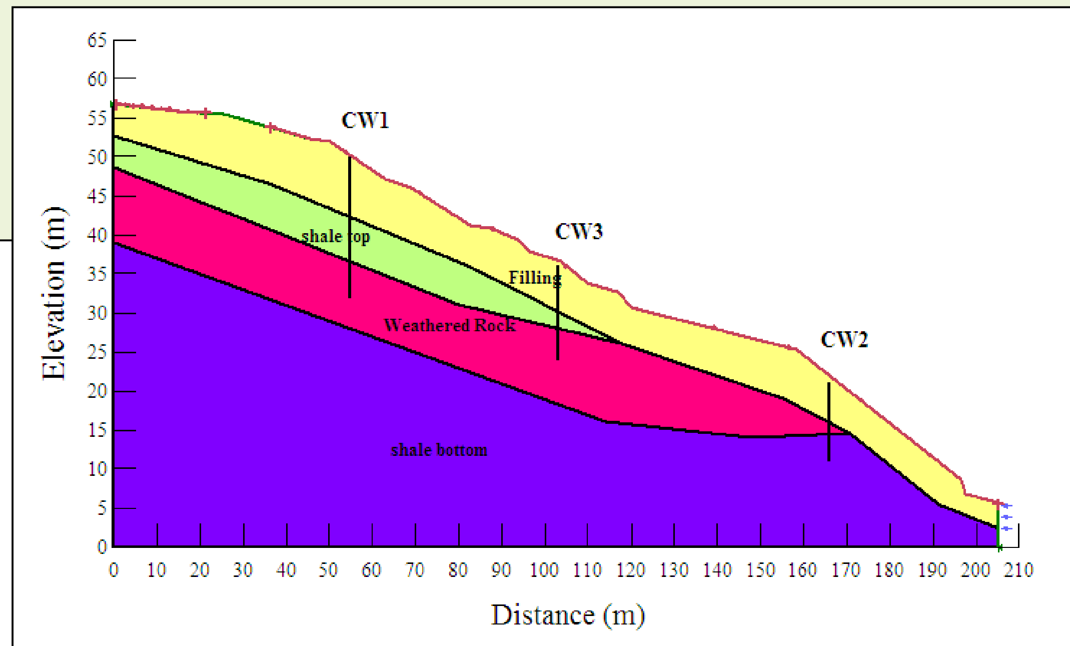
Stabilization Schemes

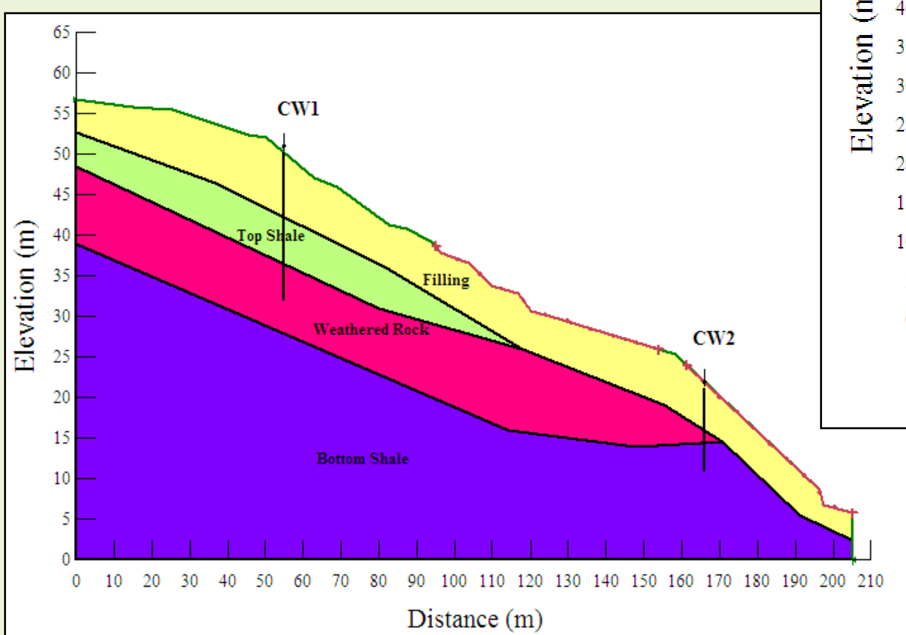
- Several stabilization schemes were proposed
  - ❖ *Stabilization by vegetative cover*



Adopted Stabilization Scheme

- Cut-off Sheet Pile Wall with adequate drainage
  - *Sheet pile walls to be pushed and embedded in the weathered rock layer*
    - 2-sheet pile row / 3-sheet pile row strategies





Cut-off wall	Location (Surface coordinates)	Height (m)
CW1	X = 55 m, Y = 50 m	18
CW2	X = 166 m, Y = 21 m	10
CW3	X = 103 m, Y = 36 m	12

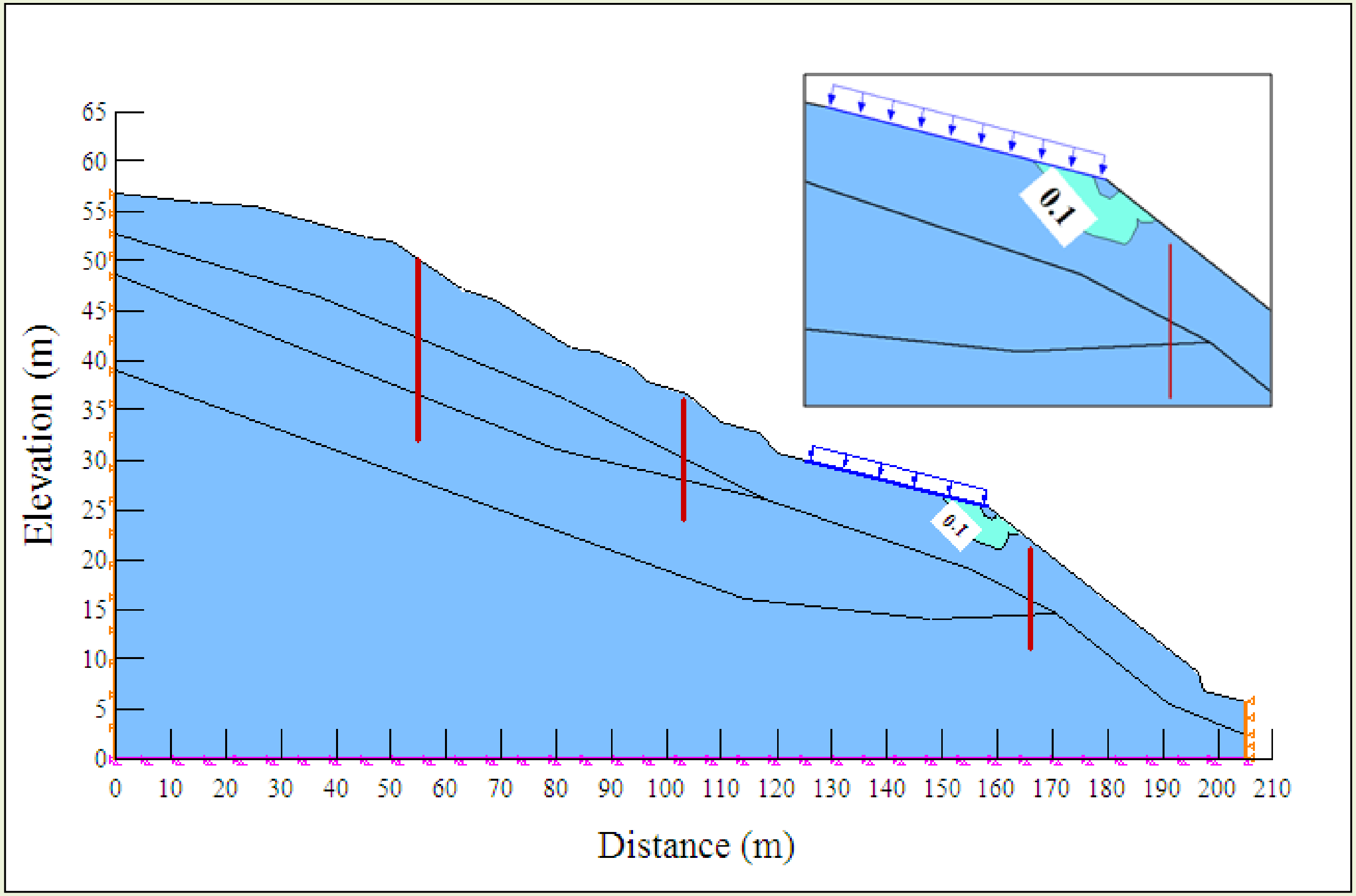
Adopted Stabilization Scheme

- Cut-off Sheet Pile Wall with adequate drainage
  - *A successful stabilization scheme was noted from stability analysis*

Sl. No	Stage of construction	FoS		
		Before Stabilization	After Stabilization (3 rows of cutoff wall)	After Stabilization (2 rows of cutoff wall)
1	In-situ	1.014	2.212	1.589
2	Colony Load	0.970	1.710	1.5
3	Building load	0.645	2.244	1.615
4	Construction R1	0.669	2.205	1.611
5	Construction of R2	0.669	2.132	1.606
6	Construction of R3	0.671	2.249	1.641

Adopted Stabilization Scheme

- Cut-off Sheet Pile Wall with adequate drainage
  - ❖ *Large displacement behind the colony were well arrested*



Final Remarks

- Domain of Forensic Geotechnical Engineering
  - ***Understanding of the failure after the incident has occurred***
    - Pre-reconnaissance round-table discussion
    - Reconnaissance for data collection (Collection of evidences)
      - Incident scene inspection
      - Interview with eye-witness and specimen collection
      - Measurement and monitoring data
    - Deciphering the chronological events
    - Development of preliminary models and failure analysis
      - May be based on several preliminary unknown assumptions
      - Examining cause-effect and triggers
    - Updating models based on observations and experimental investigations (laboratory / field)
    - Development of remedial measures (if scope permits)

Umrangsho Falls: A True Beauty

Acknowledgements

Acknowledgements

Priyanka Talukdar

- Talukdar, P., Bora, R. and Dey, A. (2016) "**Forensic investigation of the failure of a marginally stable hill slope**" *5th International Conference on Forensic Geotechnical Engineering*, Bangalore, India, pp. 389-400.
- Talukdar, P., Bora, R. and Dey, A. (2018) "**Numerical investigation of hill slope instability due to seepage and anthropogenic activities**" *Indian Geotechnical Journal* (Springer), Vol. 48, Iss. 3, pp. 585-594. (DOI: 10.1007/s40098-017-0272-4)

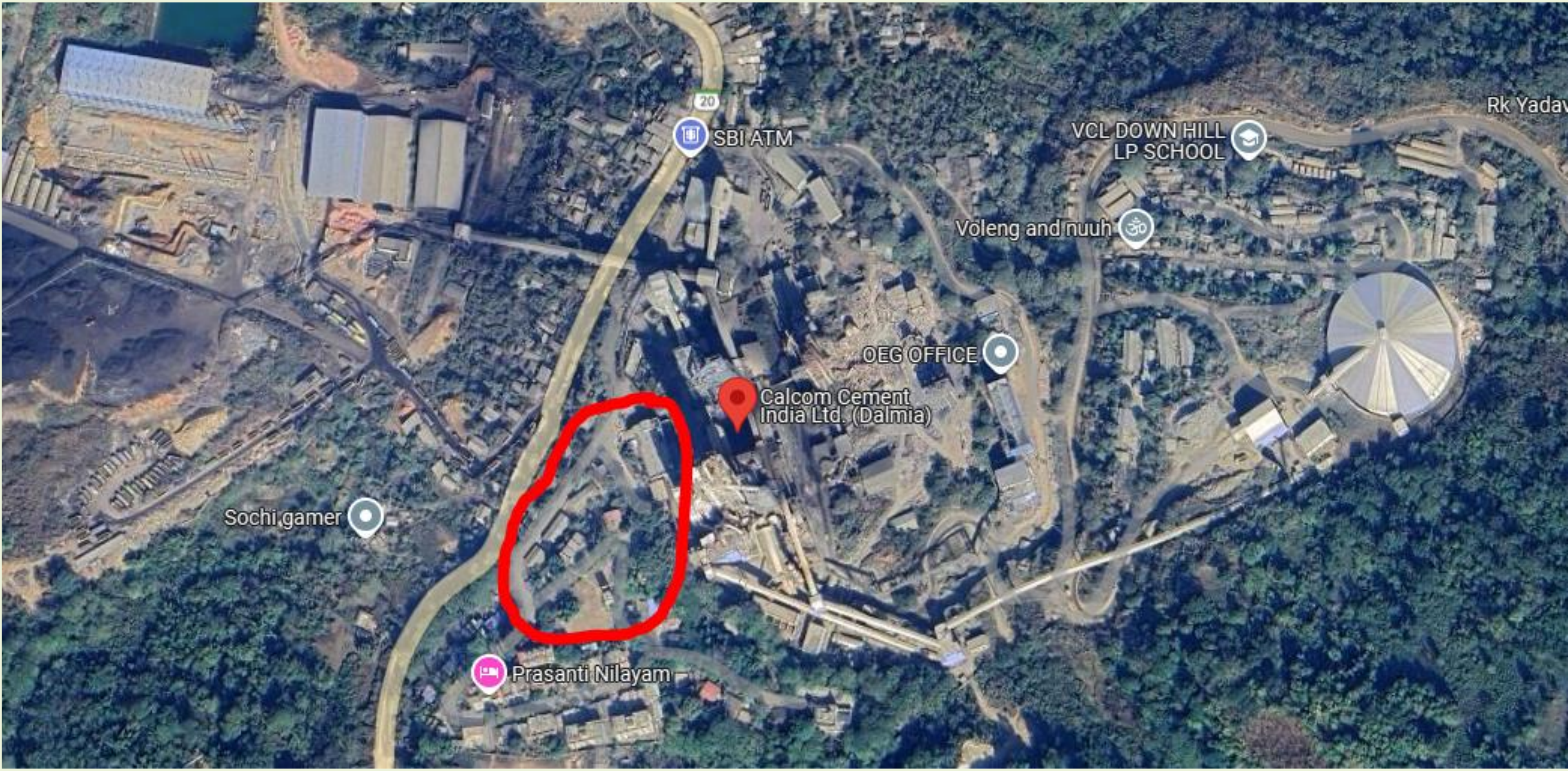
❖ **Project: Geotechnical Analysis of Landsliding and Stability of the Plant Area at Umrangsho** (2015-17) [Principal Consultants: Dr. Anil Kumar Mishra, Dr. A. Dey, Dr. A. Murali Krishna, Dr. T V Bharat] [**Funded by: Calcom Cement India Ltd., Umrangshu**].

Ruplekha Bora

http://www.iitg.ac.in/arindam.dey/homepage/index.html#

https://www.researchgate.net/profile/Arindam_Dey11

Current Day Visuals



Current Day Visuals

Thank You for Patient Hearing