National Workshop on
Importance of Disaster Risk Reduction and Resilience

Mizoram University, 10 April 2023

Recent Advances in Geotechnical Engineering
Learning through Case Studies

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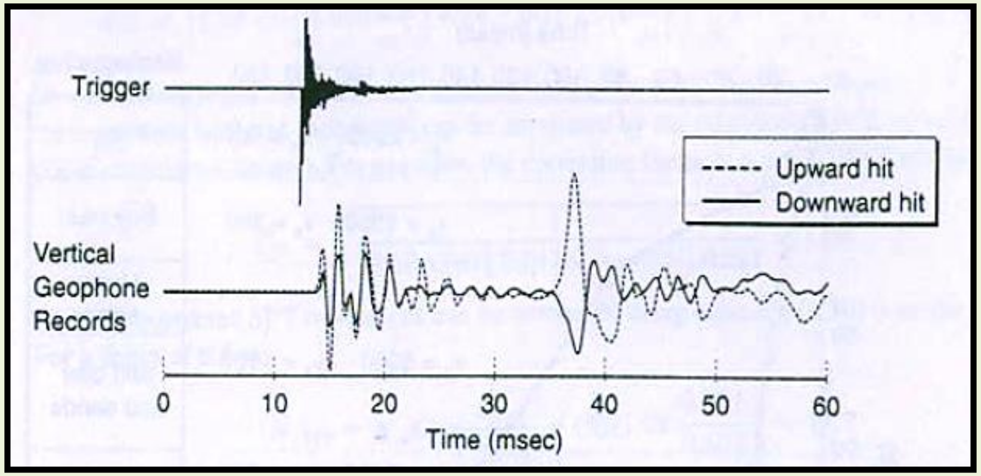
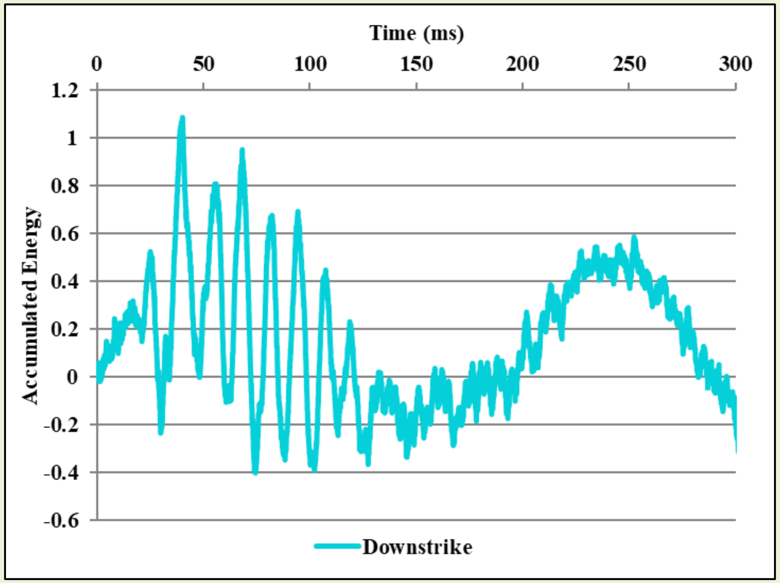
Hillslope Profiling at NEEPCO Hydel Plant, Saiphum, Mizoram

Geophysical Prospecting – Crosshole Survey





THEORY v/s PRACTICE

Theory vs Practice: Tuirial Project, Mizoram

- **Location of site**: Tuirial, Saiphum, Mizoram
- **Client**: NEEPCO
- **Project**: Diversion of Tuirial River, Construction of dam and reservoir, Development of Hydro-Electric Power Plant
- **Calamity**: Seismic failure of a large hill-slope geopardizing the power-distribution unit located at the same foot-hill
- **Background information**: GSI report states only about static stability of the slope, no dynamic analysis
- **Objective**: Geophysical prospecting of the subsurface
- **Hindrance**: The site slope is already subjected to stabilization, so no scope/chance of getting soil samples
- **Tests conducted**: Seismic Crosshole Survey and MASW

Tuirial Project, Mizoram

Tuirial Project, Mizoram

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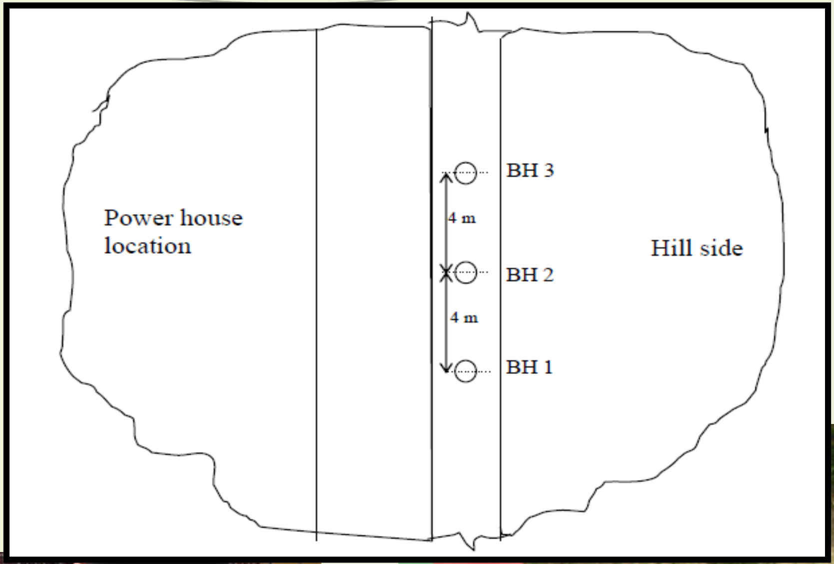
Tuirial Project, Mizoram

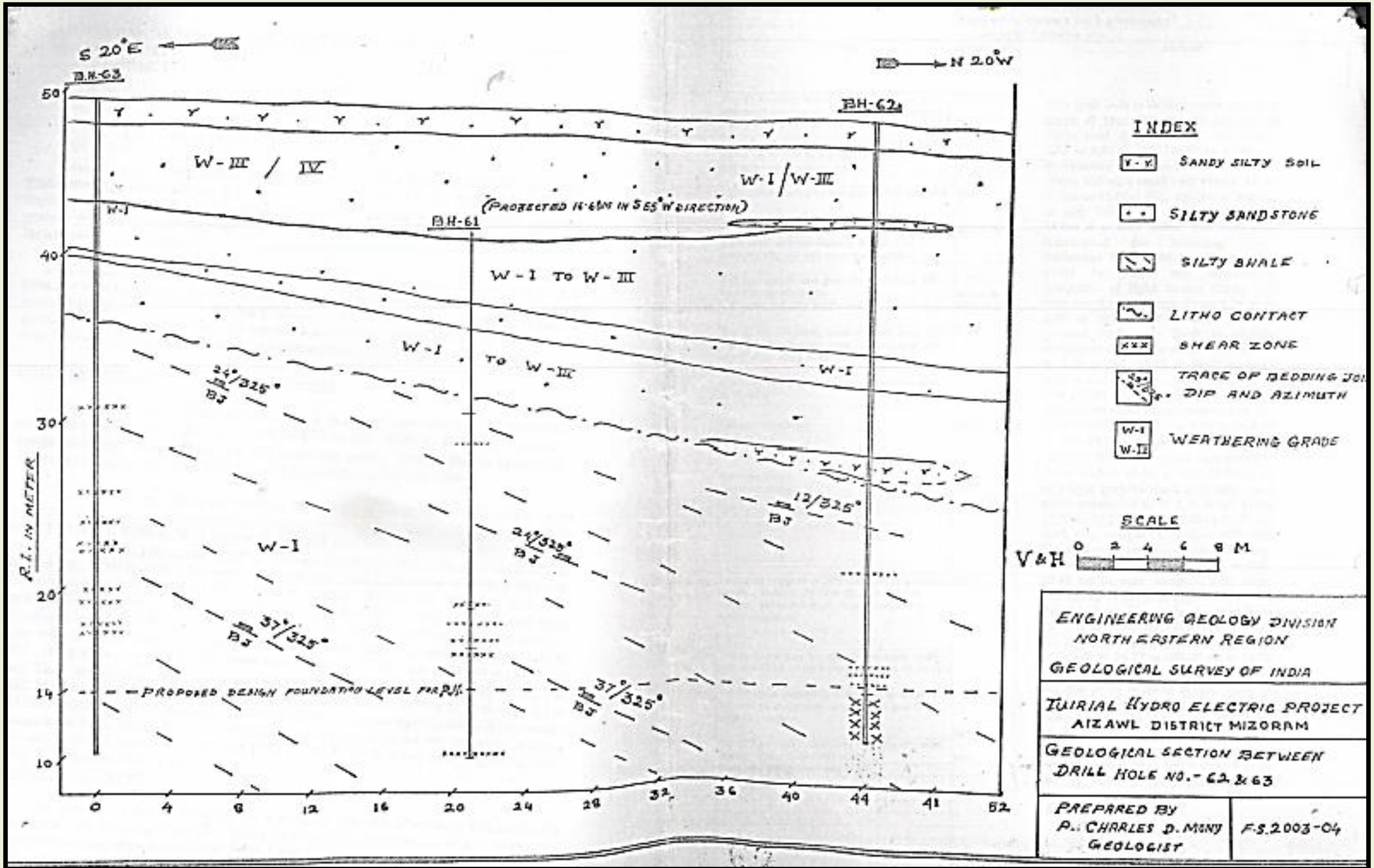
Instruments

Instruments

- Ballard Shock Wave Generator
- 5D Geophone Receiver array
  - *1 Vertical and 4 Horizontal*



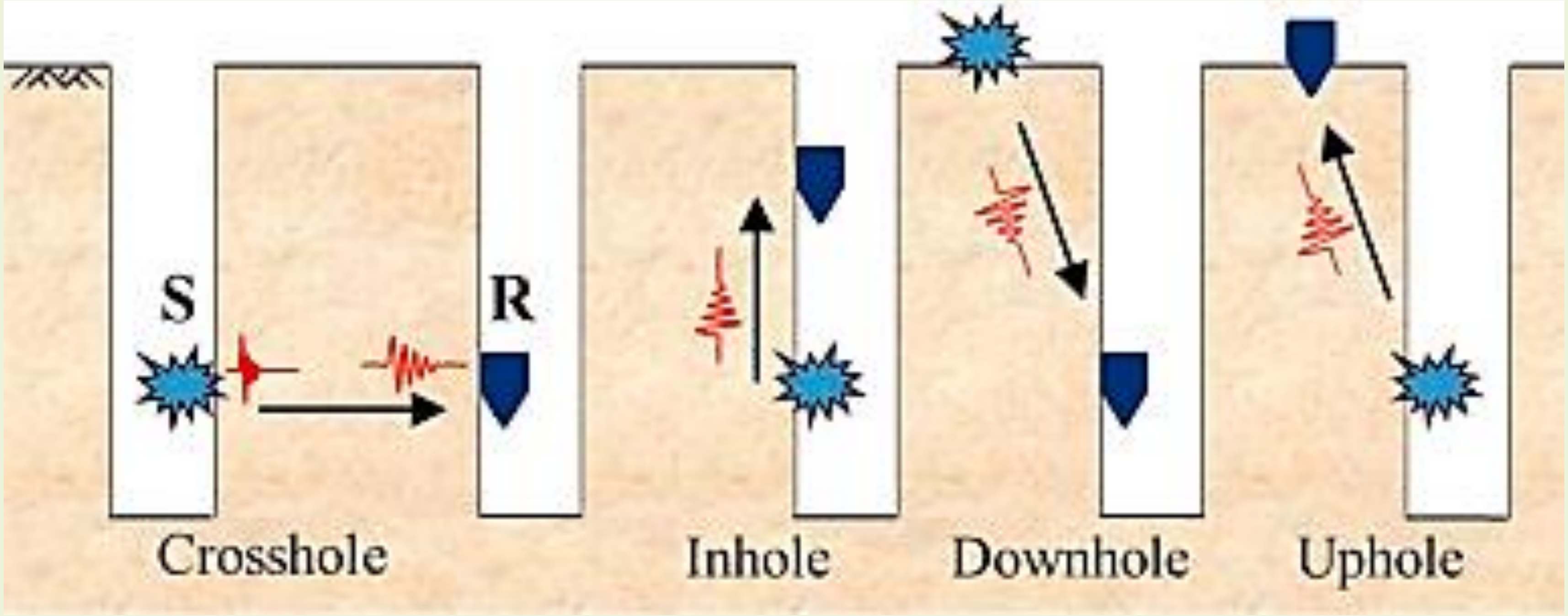
Geological Investigation Report from GSI



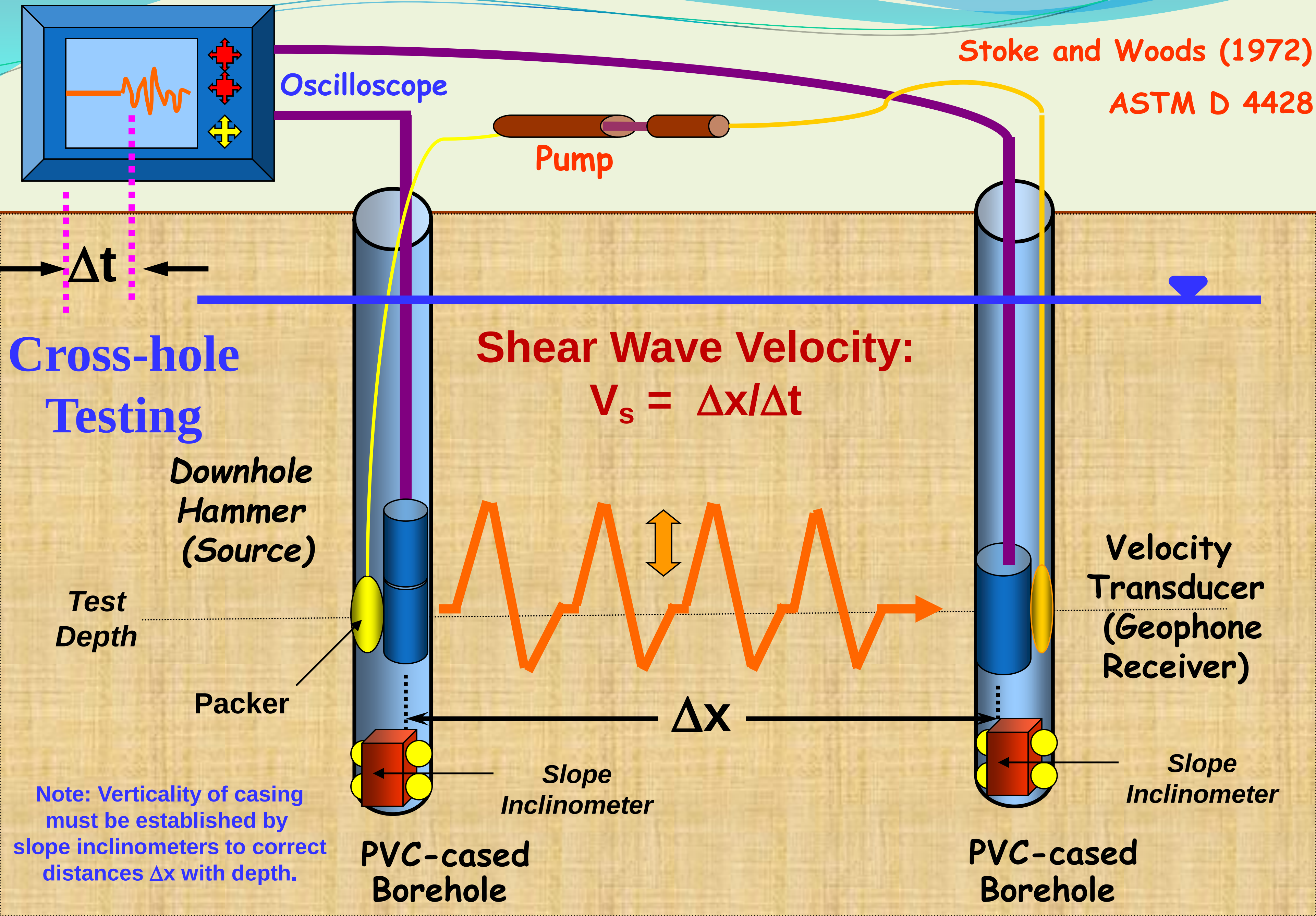
Geophysical Prospecting

- Identification of the subsurface information through the applications of wave propagation through soil/rock media

Seismic Borehole Surveys



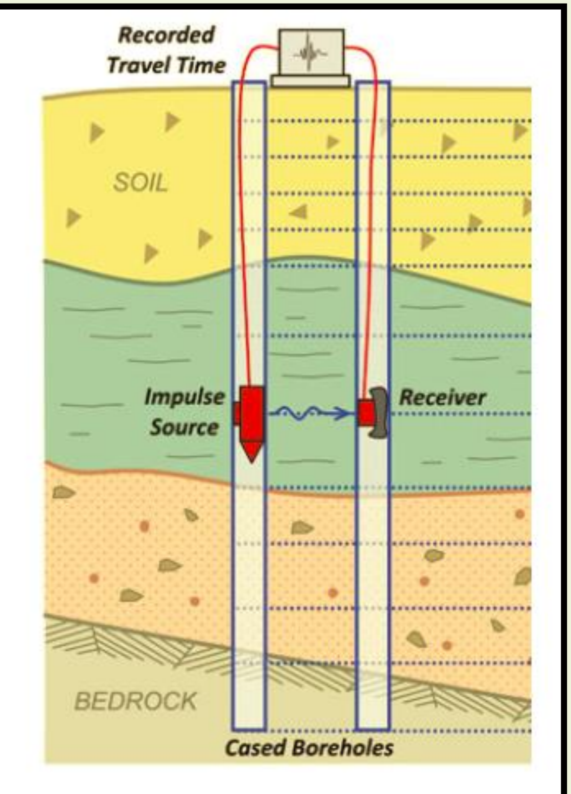
Cross-hole Testing

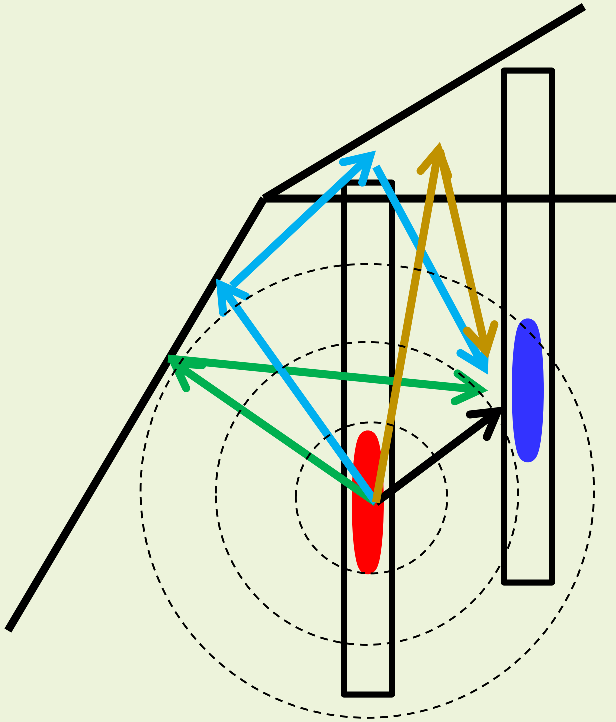


Note: Verticality of casing must be established by slope inclinometers to correct distances Δx with depth.

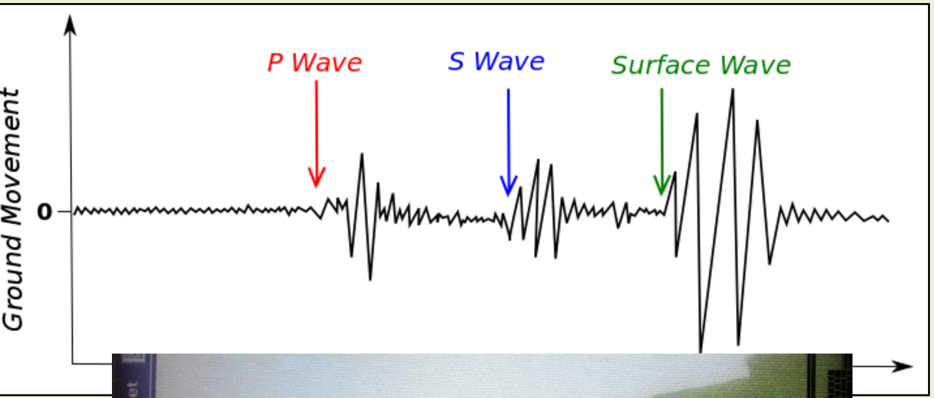
Expectation vs Reality

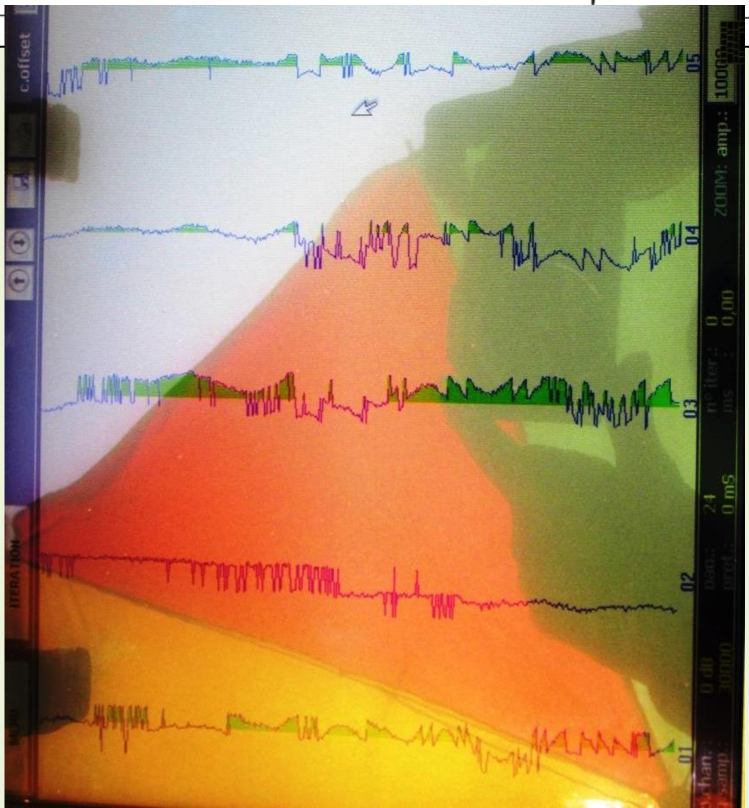
- Multidirectional sensors in ideal ground
  - *Each sensor should record the effect of the desired wave*
- Heterogeneity in the soil creates record adulteration
  - *Reflection from boundary and soil interface*

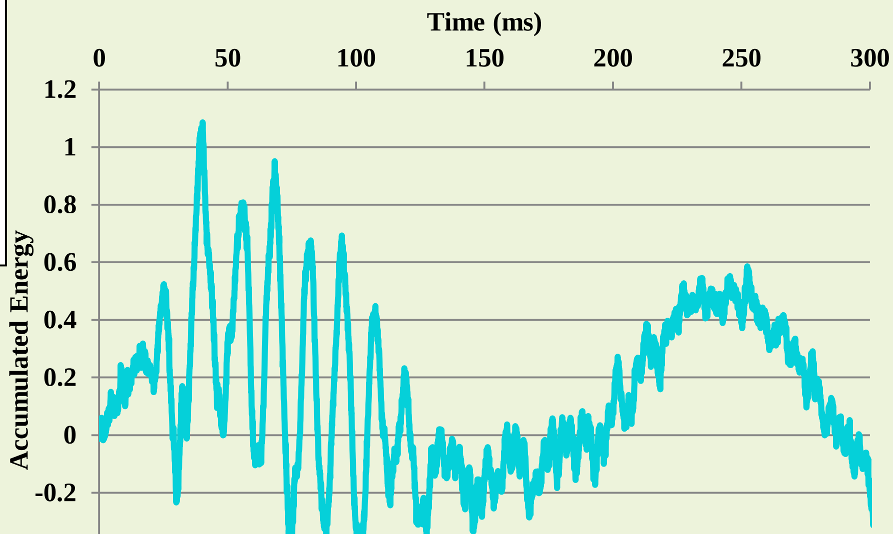




Signals: Theoretical and Field Observation



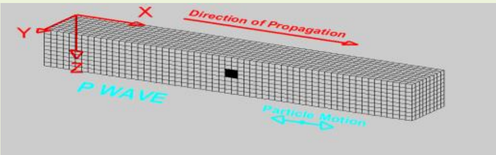




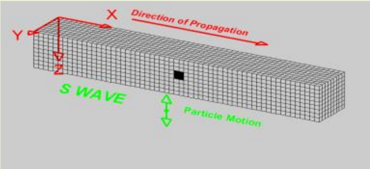
Depth = 3 m

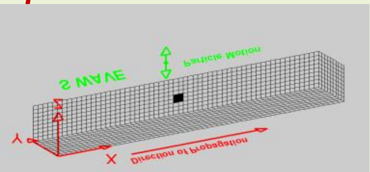
Arrival of S-wave

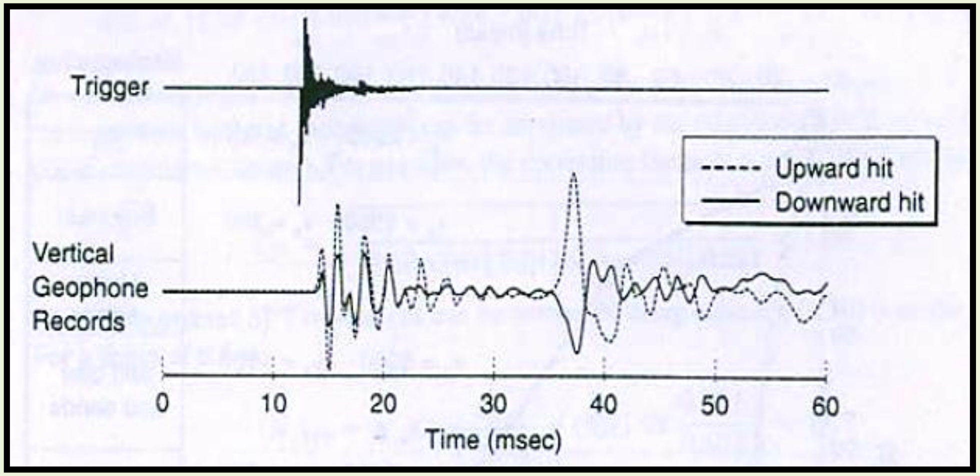
- Concept of Polarity Reversal
  - ❖ *P-wave particle movement are in the same polarity independent of the direction of Ballard strike*

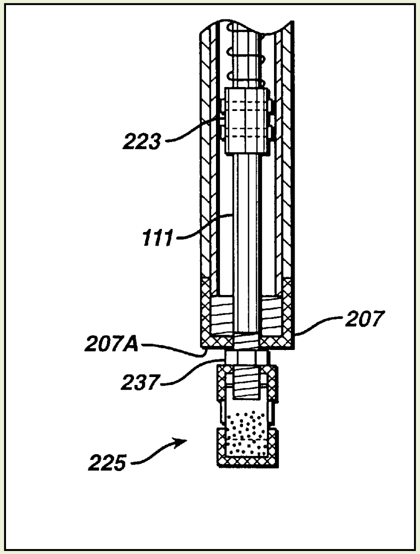


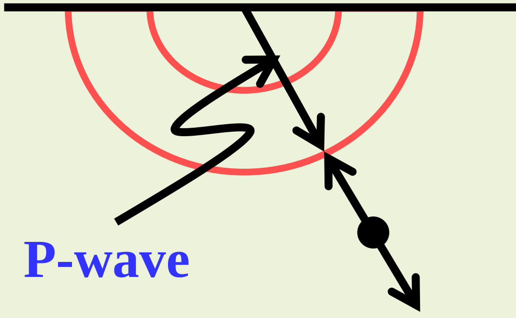
  - ❖ *S-wave particle movement changes the polarity depending on the direction of Ballard strike*

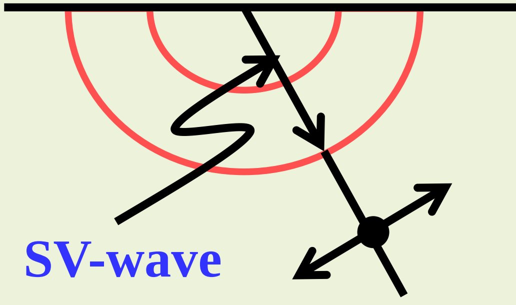












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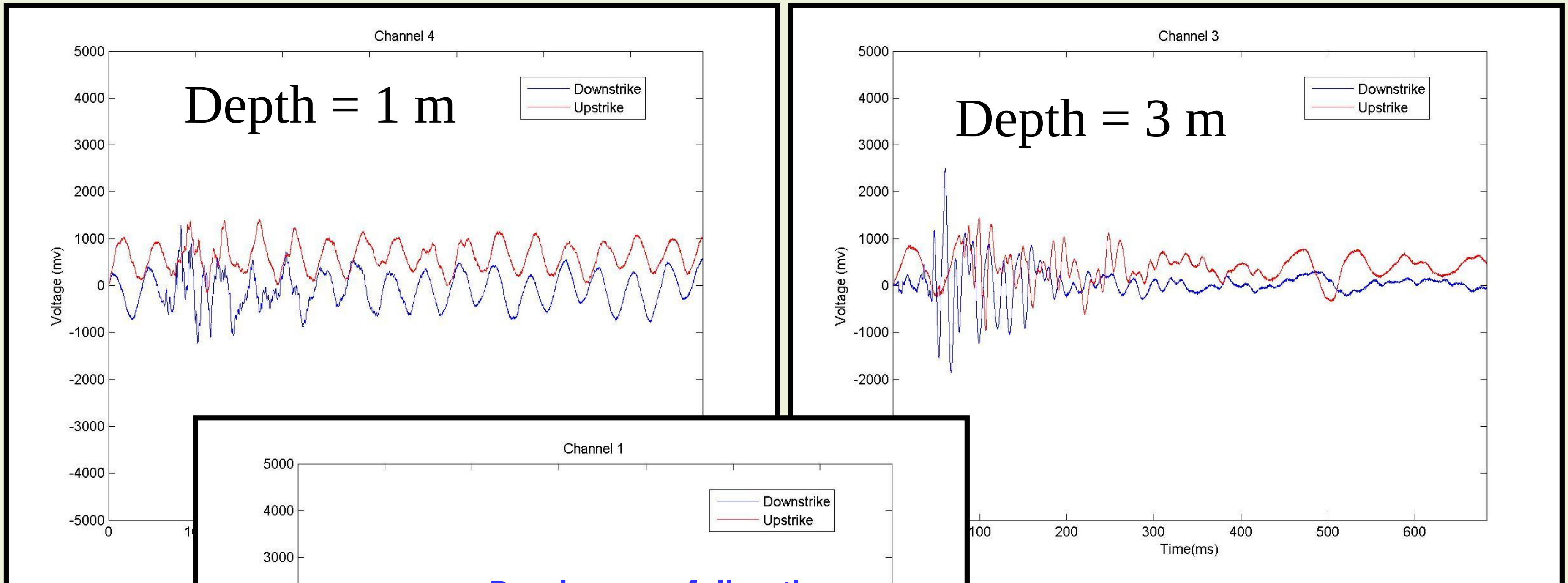
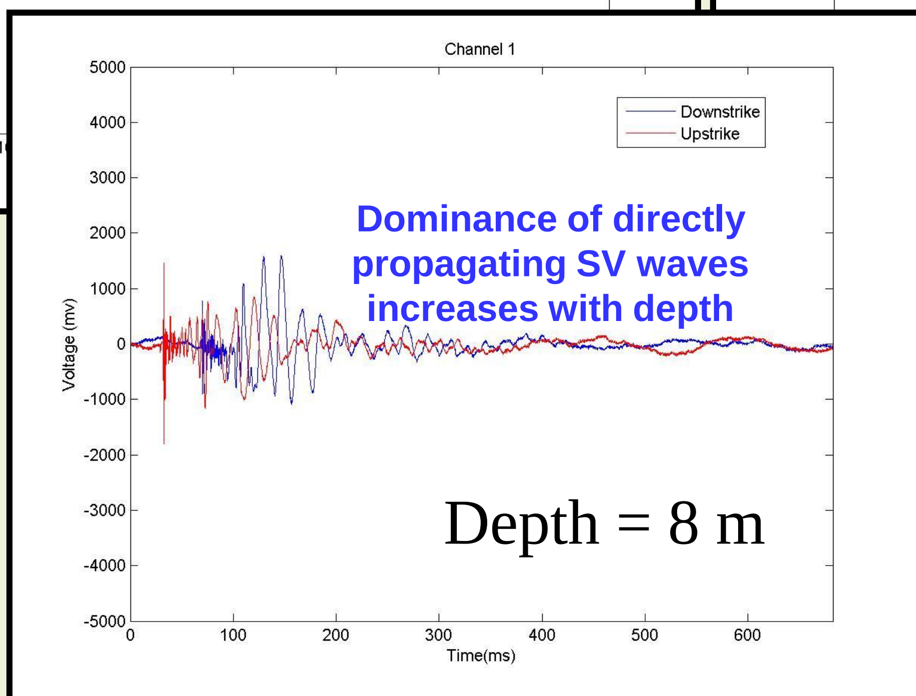
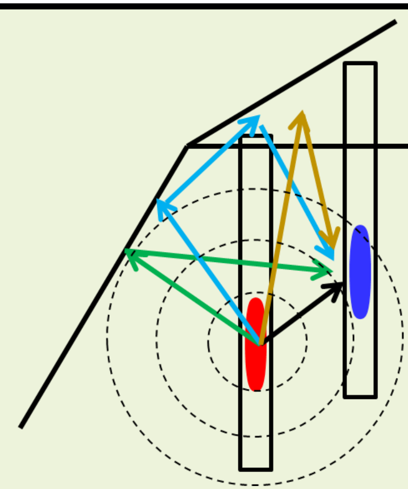
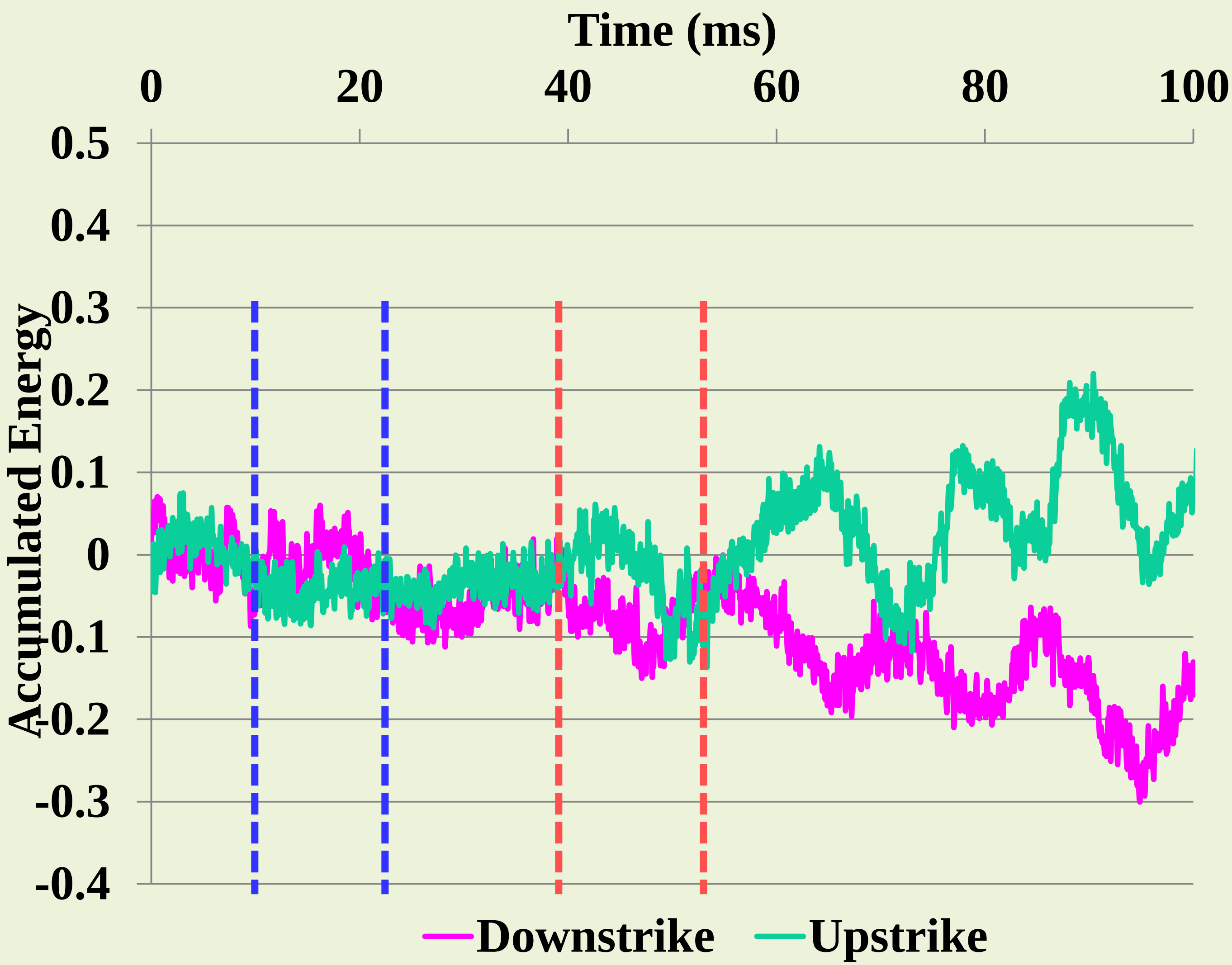




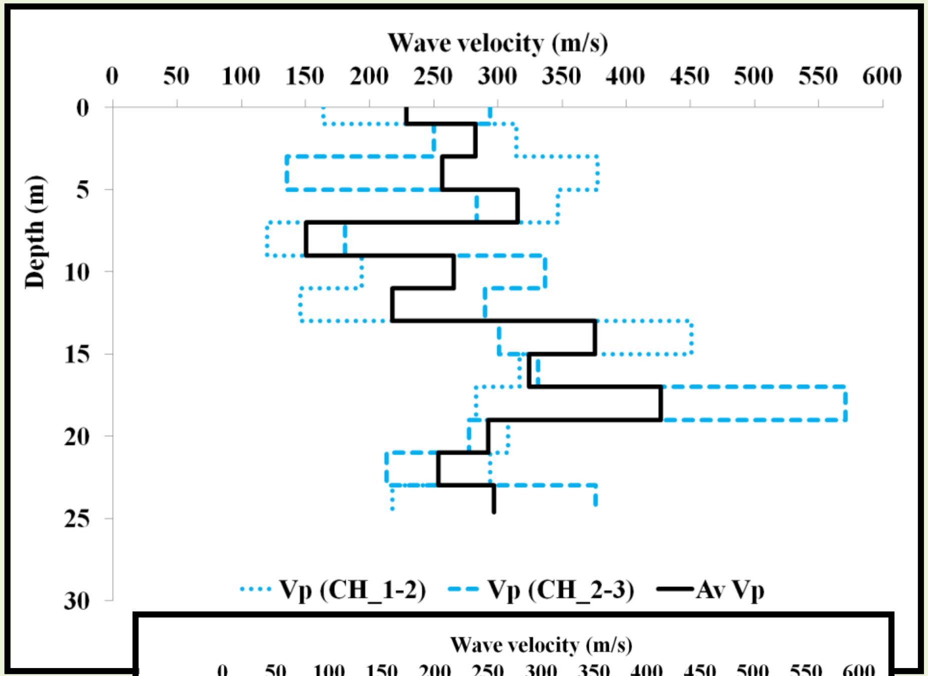
Dominance of directly propagating SV waves increases with depth

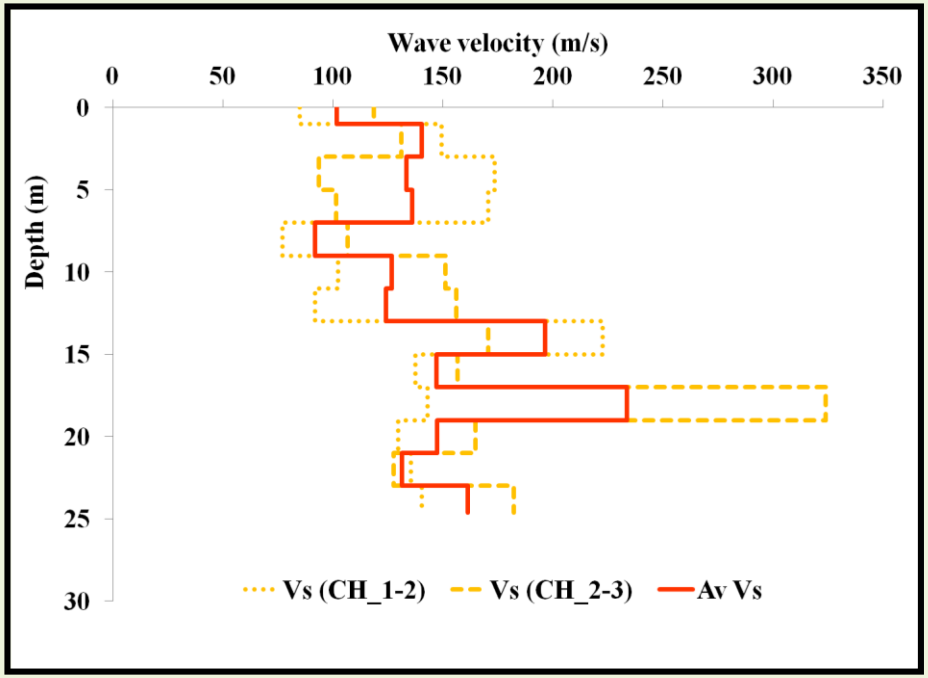


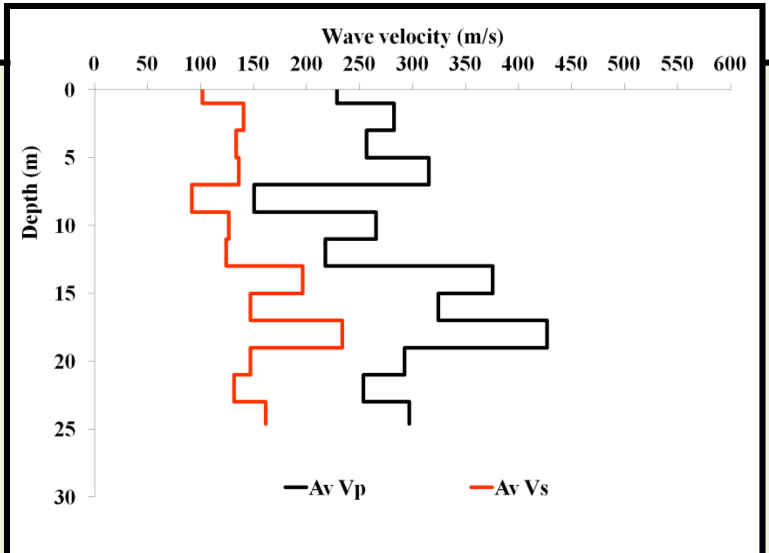
Arrival of S-wave



Subsurface Velocity Profile







$$V_p / V_s = 1.6\text{-}2.2$$

Landslide at Calcom Cement Plant, Umrangso, Assam

Forensic Geotechnology

Why is it important to conduct exploratory borings at PROPER LOCATION???

General Site Conditions

- Lat: $N25^{\circ}31'04''$, Long: $E92^{\circ}47'19.3''$, 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 raft





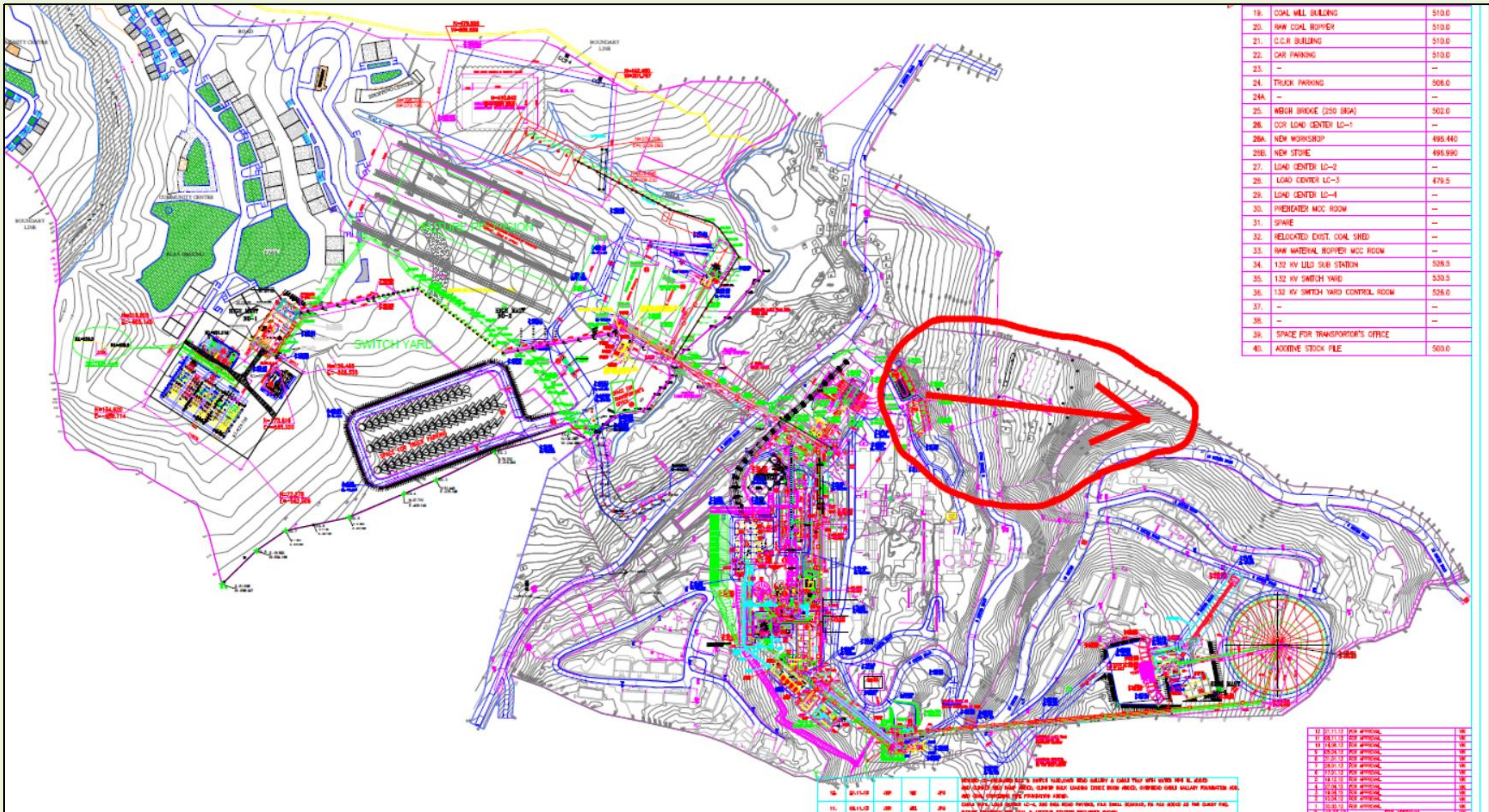


Pre-Reconnaissance Round-Table Discussion

- 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

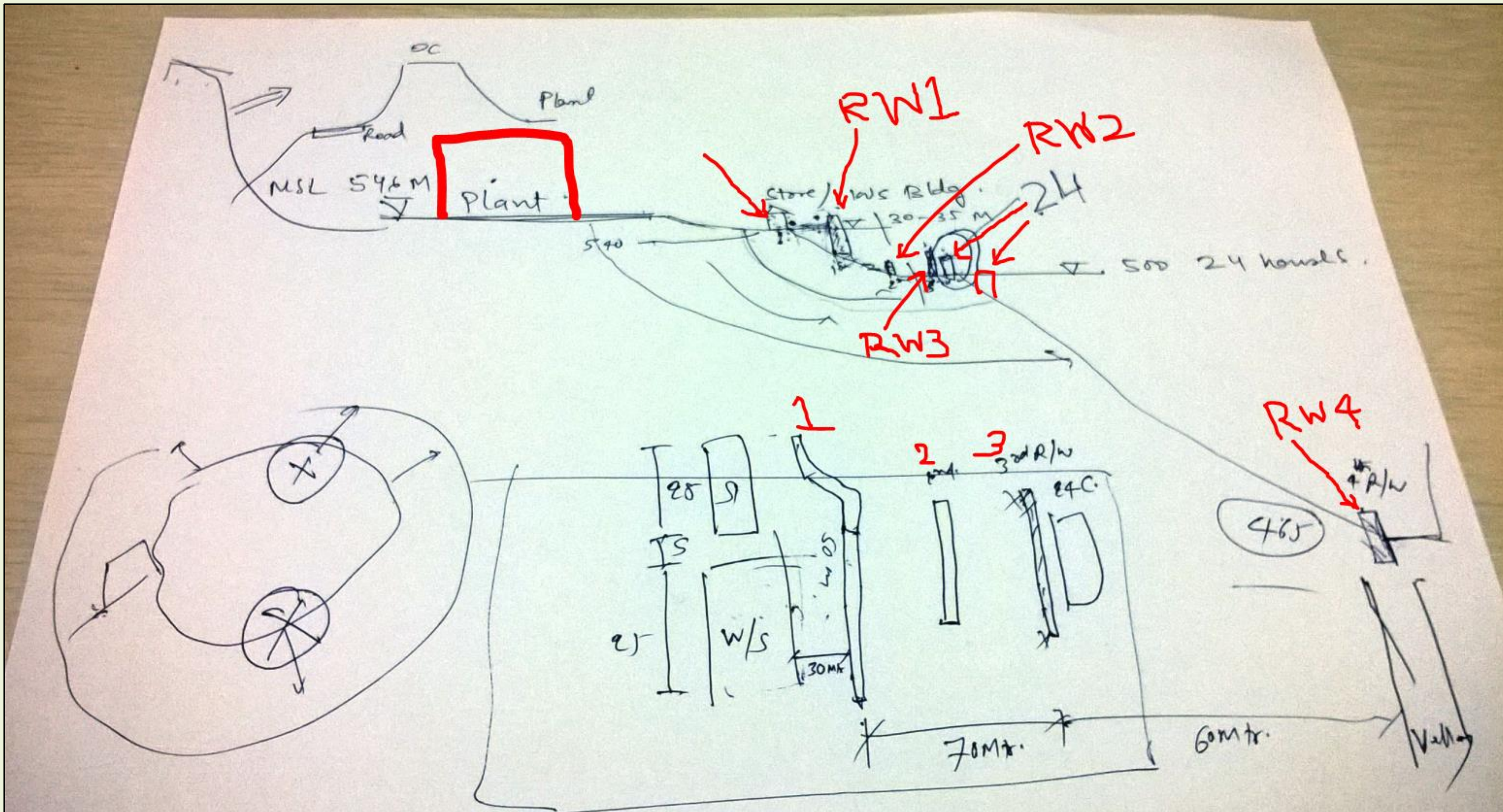
Pre-Reconnaissance Round-Table Discussion

- 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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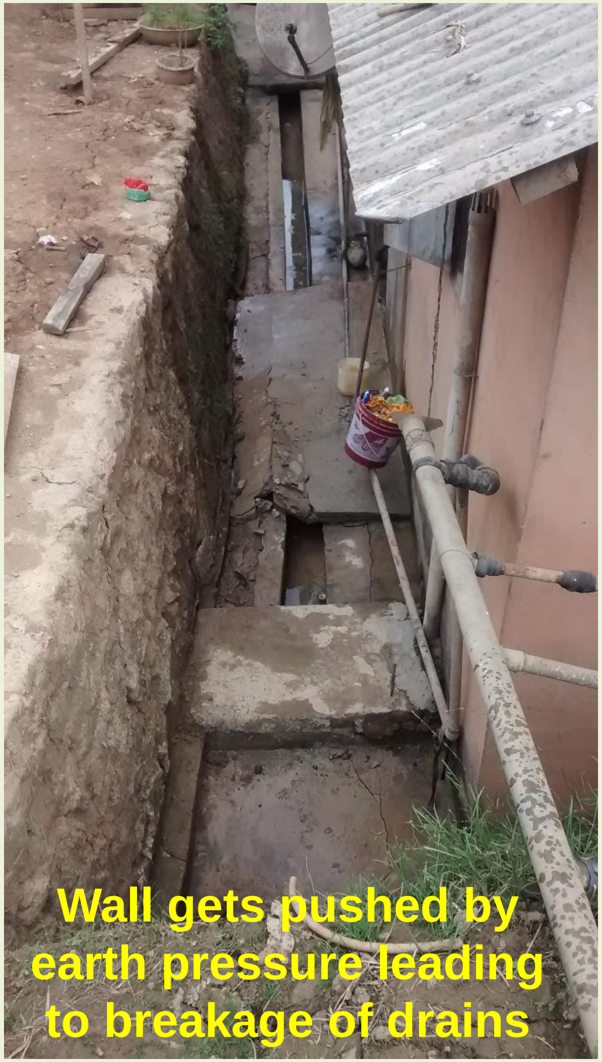


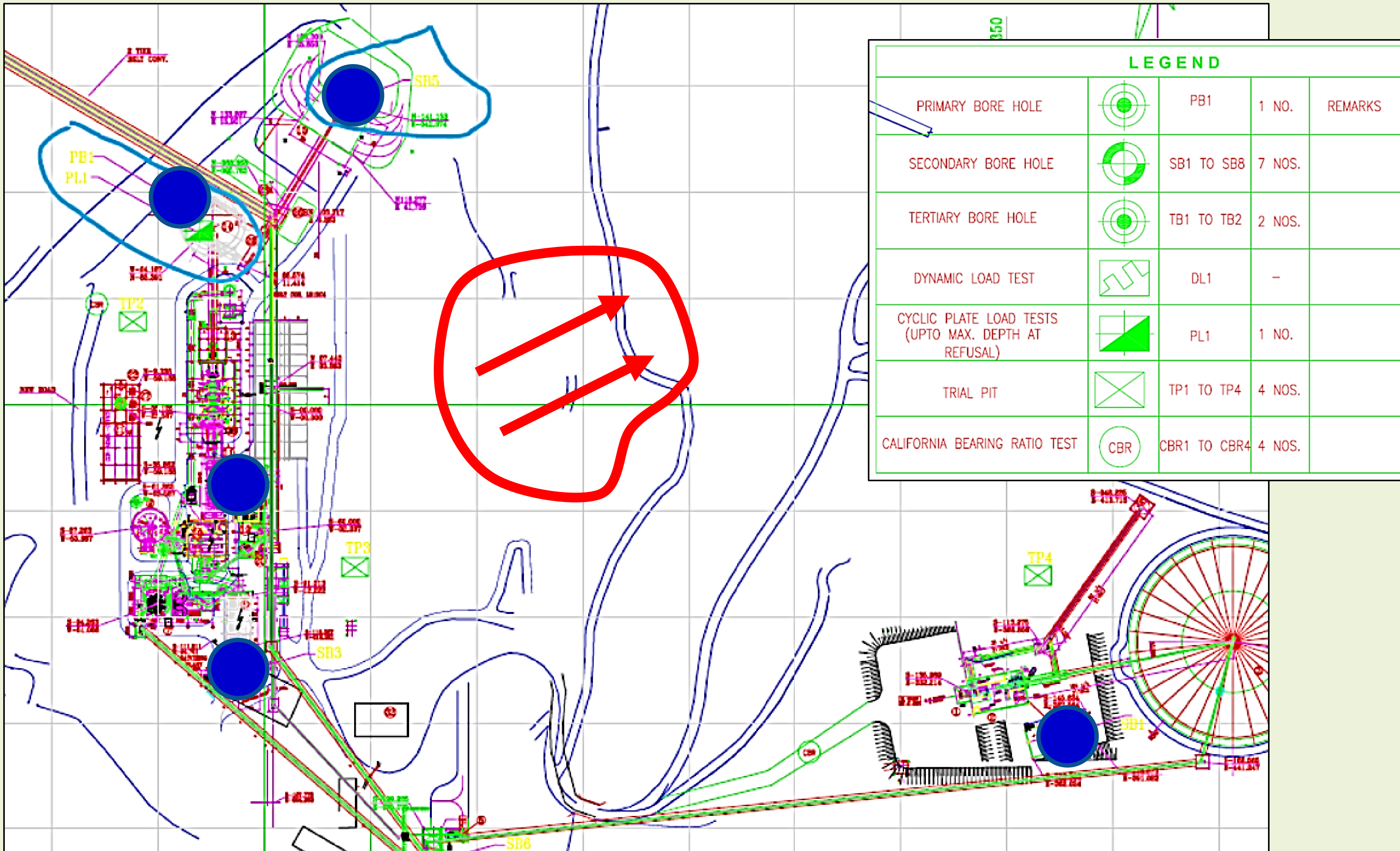
Site Visit for Reconnaissance Survey: 3rd Nov 2015

- 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

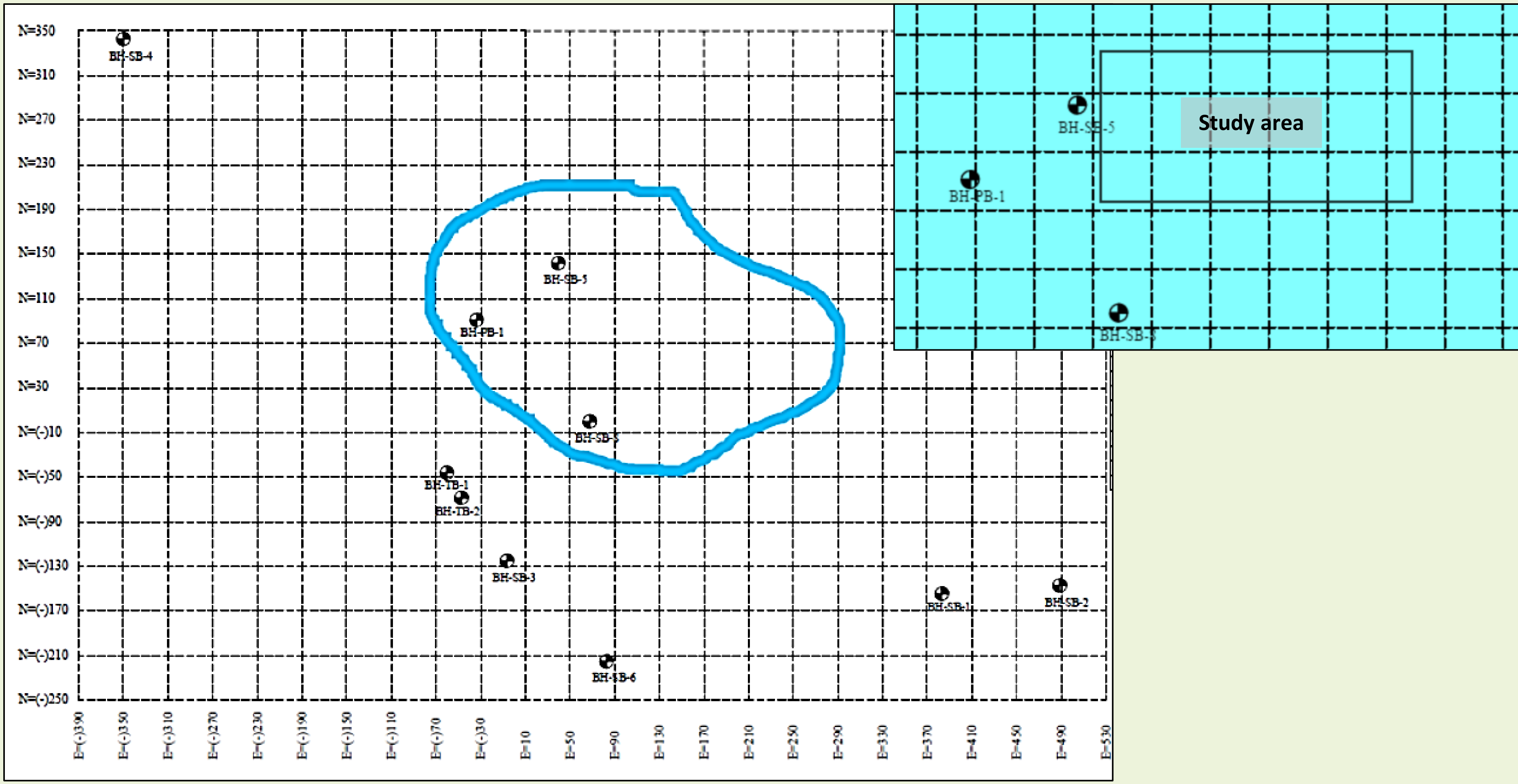
Collection of Information and Data

- Geotechnical Investigation locations at the site



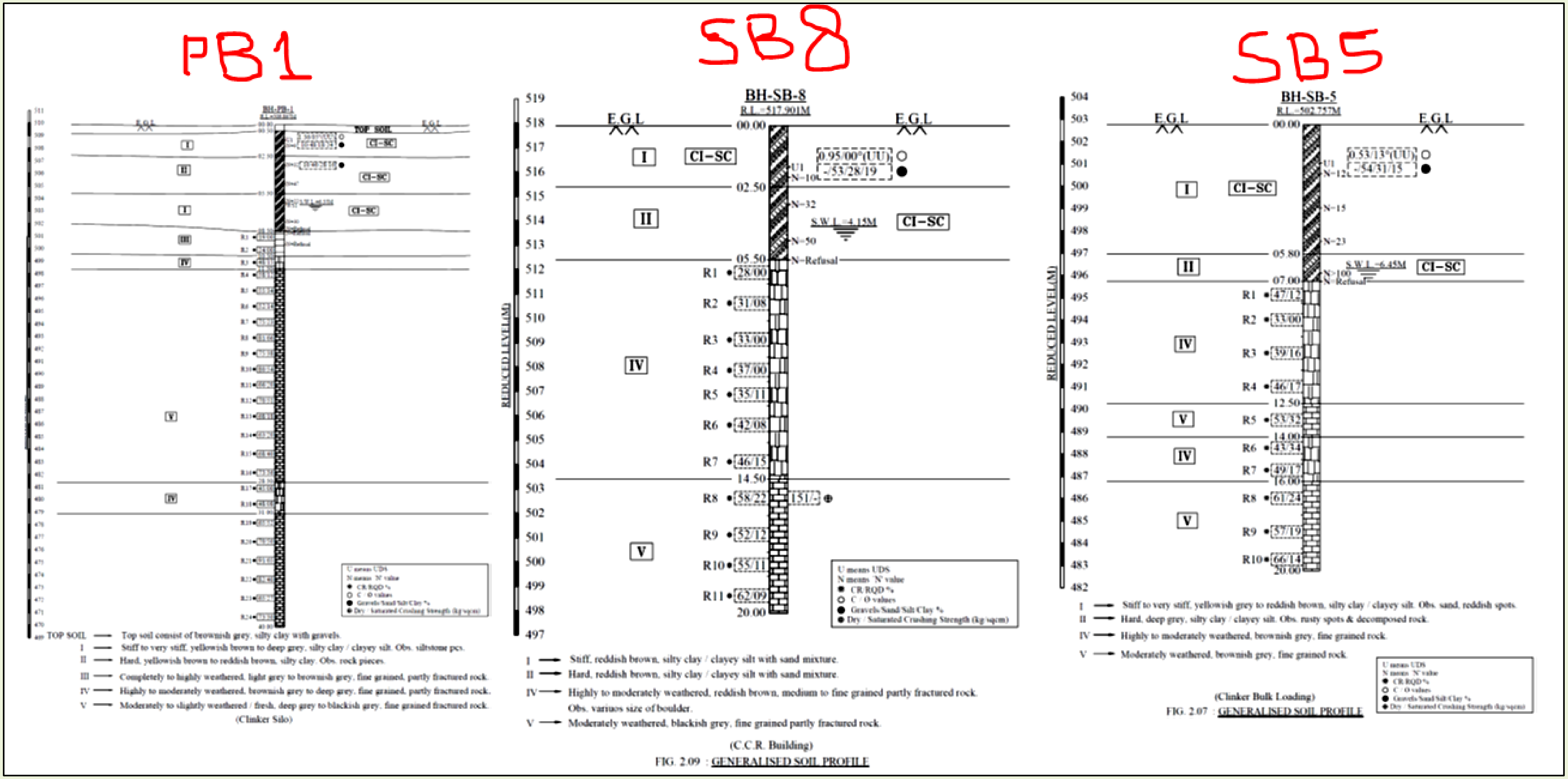
Collection of Information and Data

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



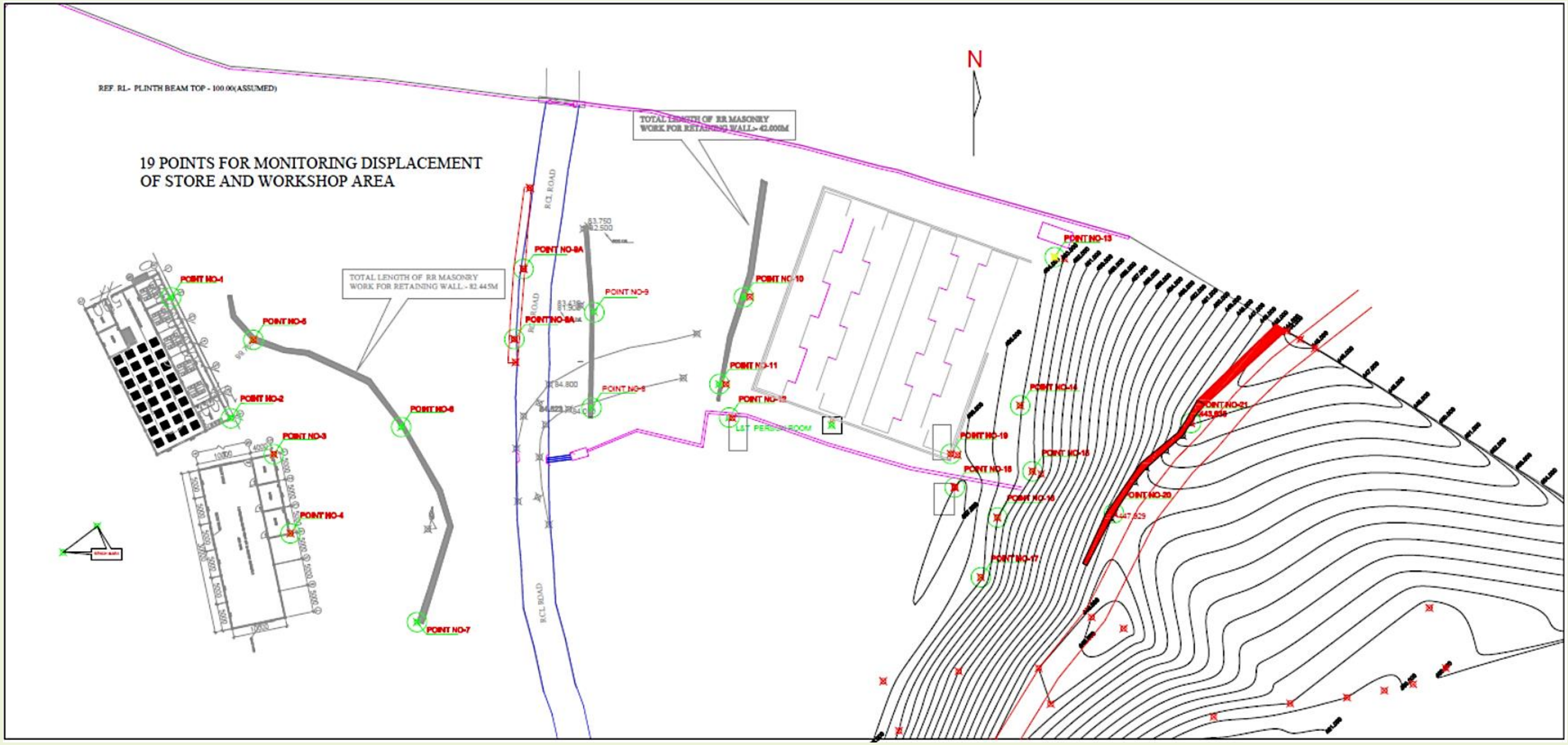
Collection of Information and Data

- Utilize information from nearby borehole to create soil profile



Measurement and Monitoring

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



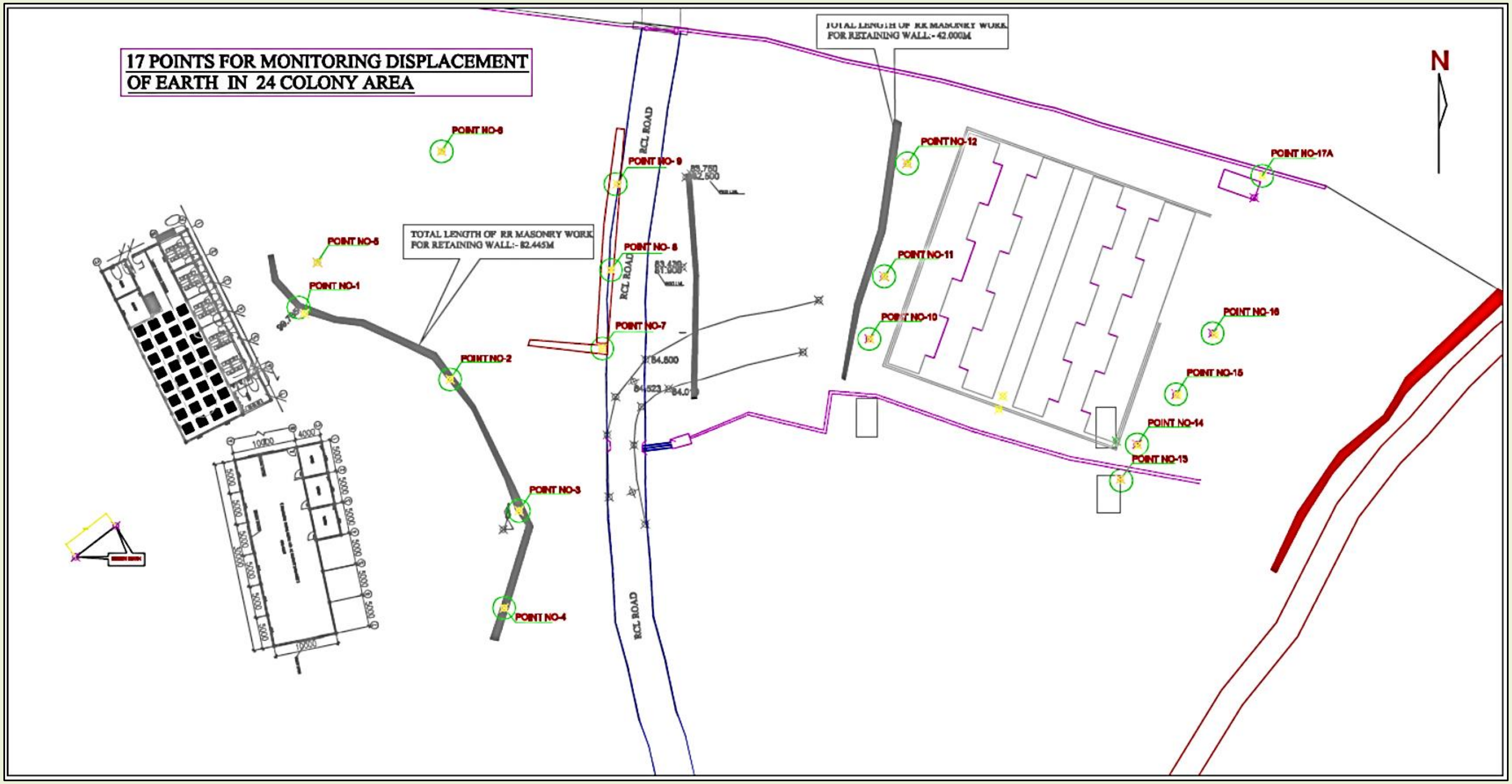
Measurement and Monitoring

- 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

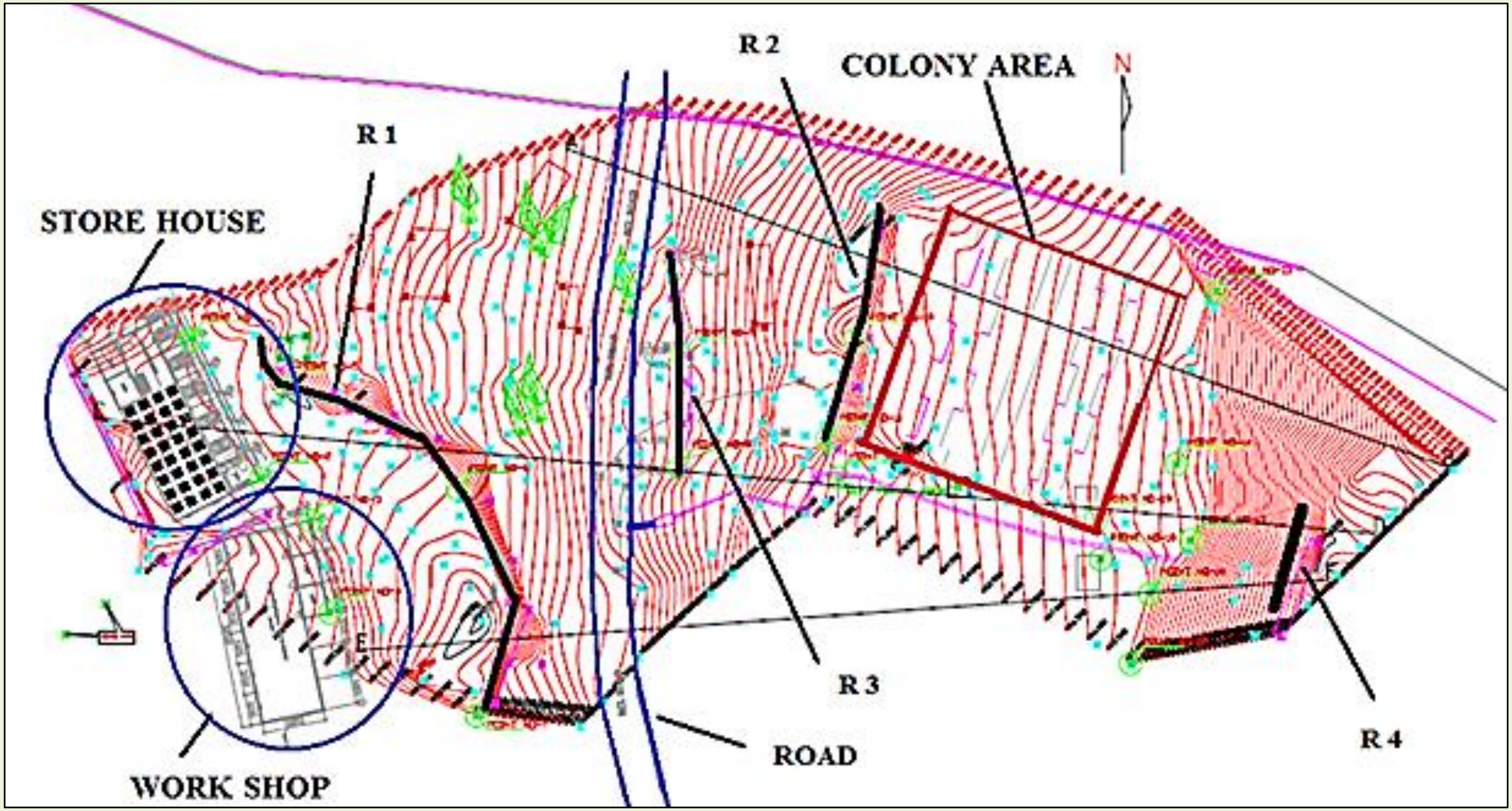
Measurement and Monitoring

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



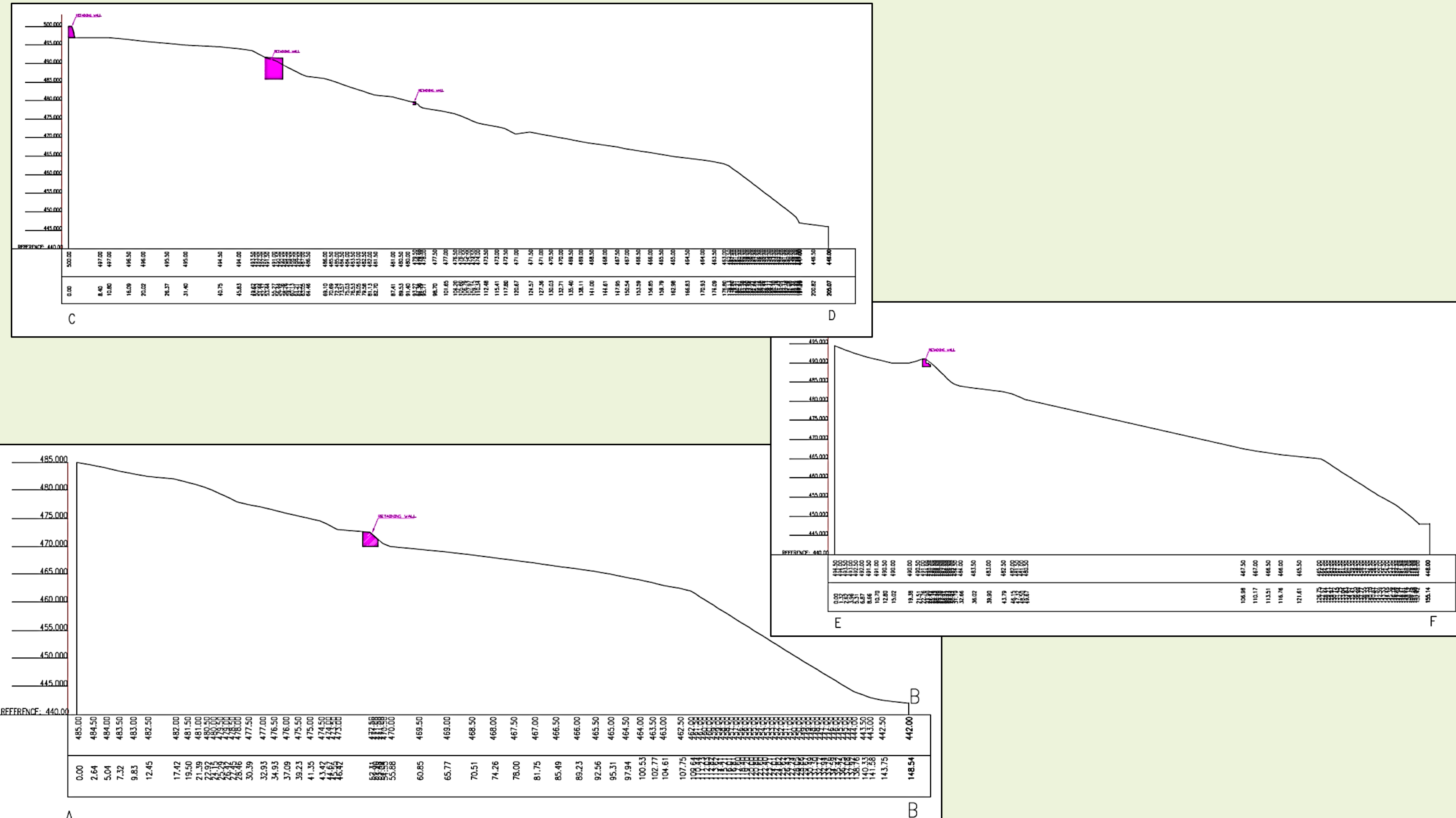
Deciphering Chronological Events

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



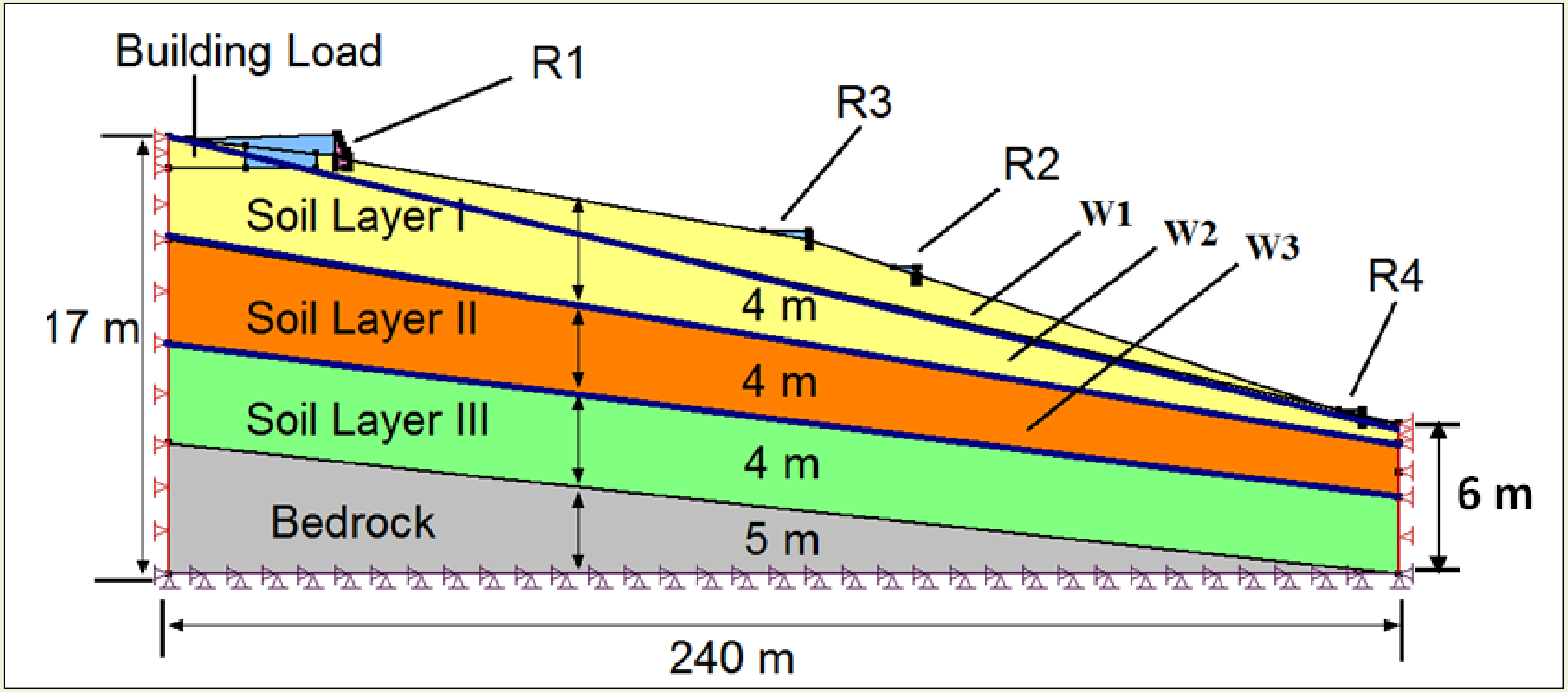
Deciphering Chronological Events

- 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*
  - *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

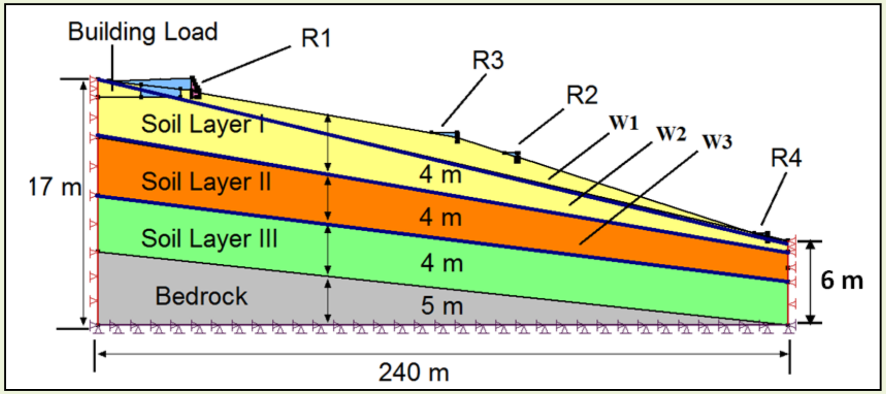
Layer	Undrained Strength Parameters			Drained Strength Parameters			Unit weight (kN/m^3)	Saturated permeability K_{sat} (m/s)	Saturated volumetric water content Θ_{sat} (m^3/m^3)
	c_u (kPa)	φ_u (°)	E (MPa)	c' (kPa)	φ' (°)	E' (MPa)			
Soil layer I	18.5	4	4.7	12.33	4	4.2	19	3x10^{-8}	0.425
Soil layer II	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

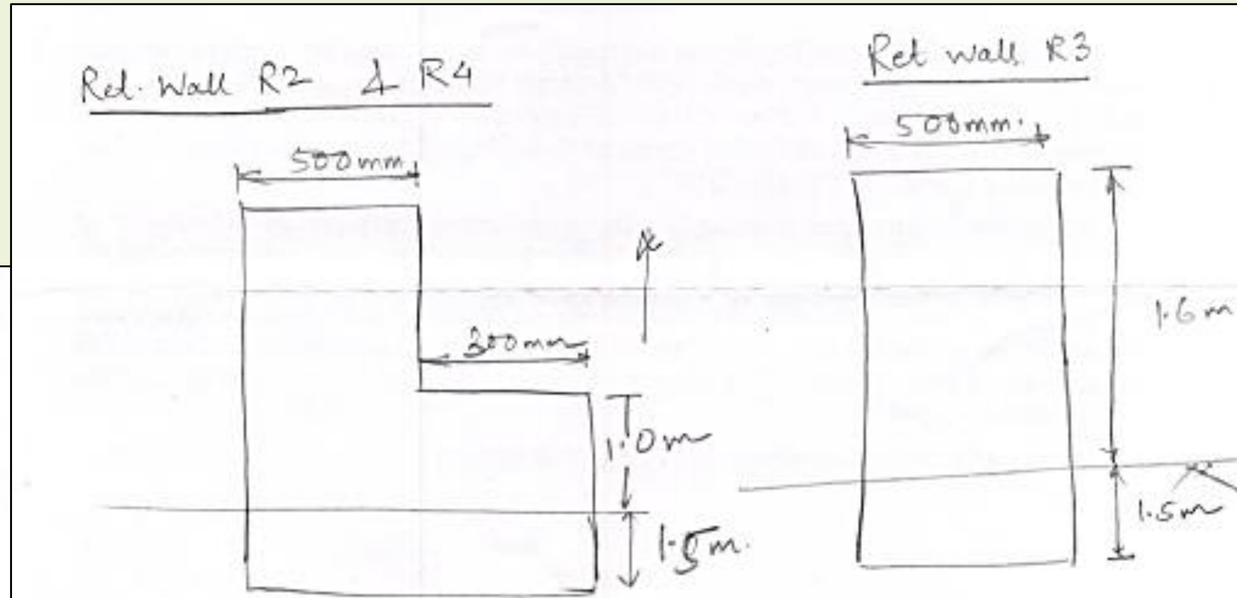
Material properties of the tertiary model TM

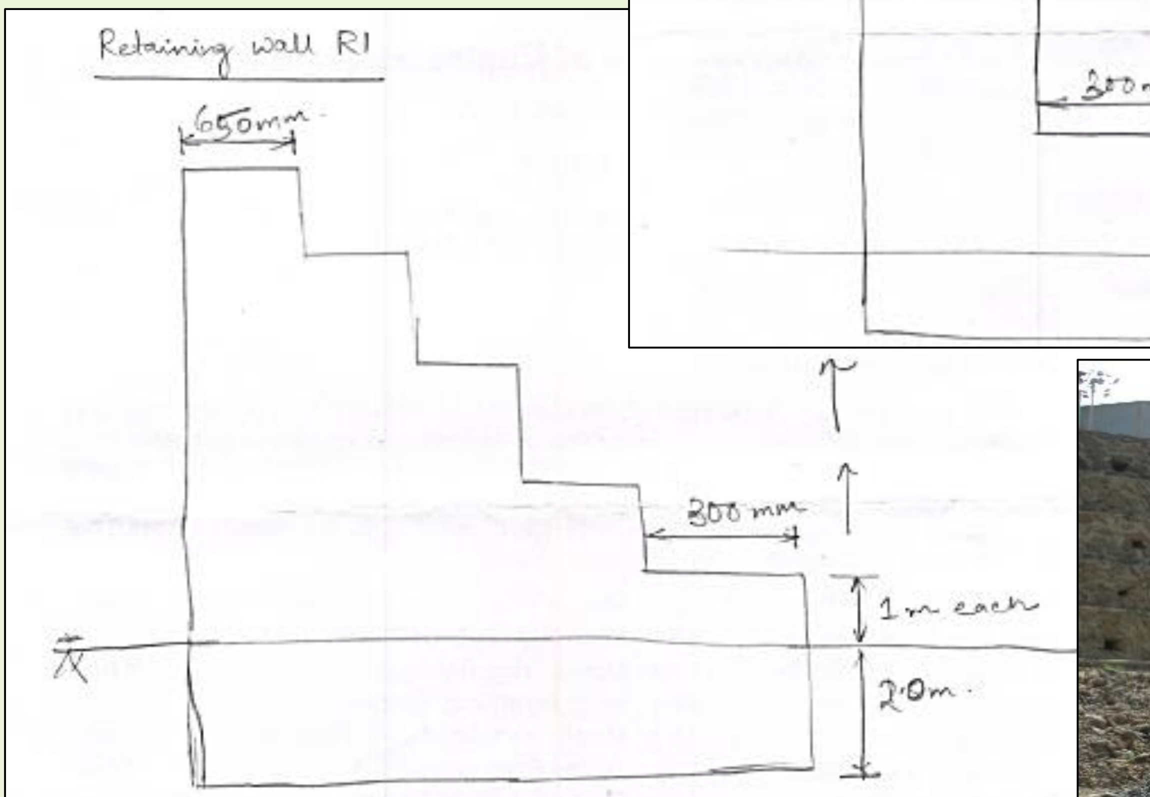
Layer	Undrained Strength Parameters			Drained Strength Parameters			Unit weight (kN/m^3)	Saturated Permeability K_{sat} (m/s)	Saturated Volumetric water content Θ_{sat} (m^3/m^3)
	c_u (kPa)	φ_u (°)	E (MPa)	c' (kPa)	φ' (°)	E' (MPa)			
Soil layer I	18.5	4	4.7	12.33	4	4.2	19	3x10^{-8}	0.425
Soil layer II	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

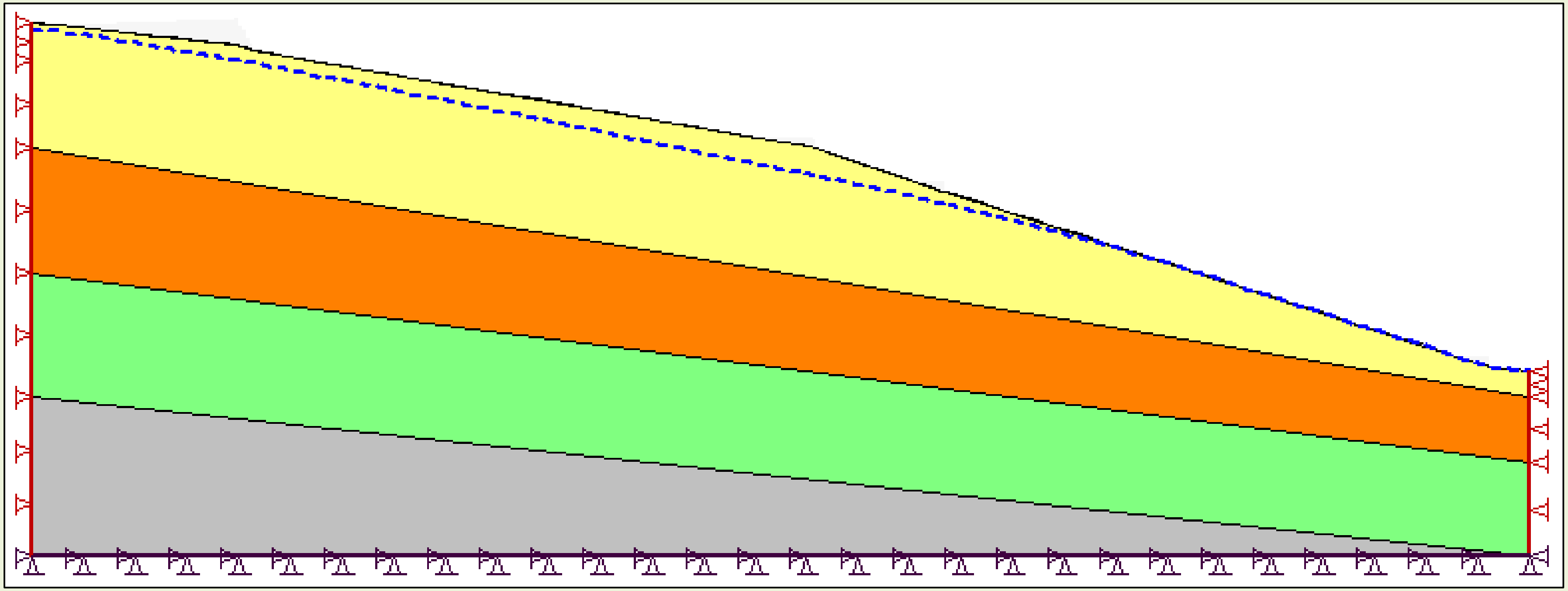
- Modelling the retaining wall





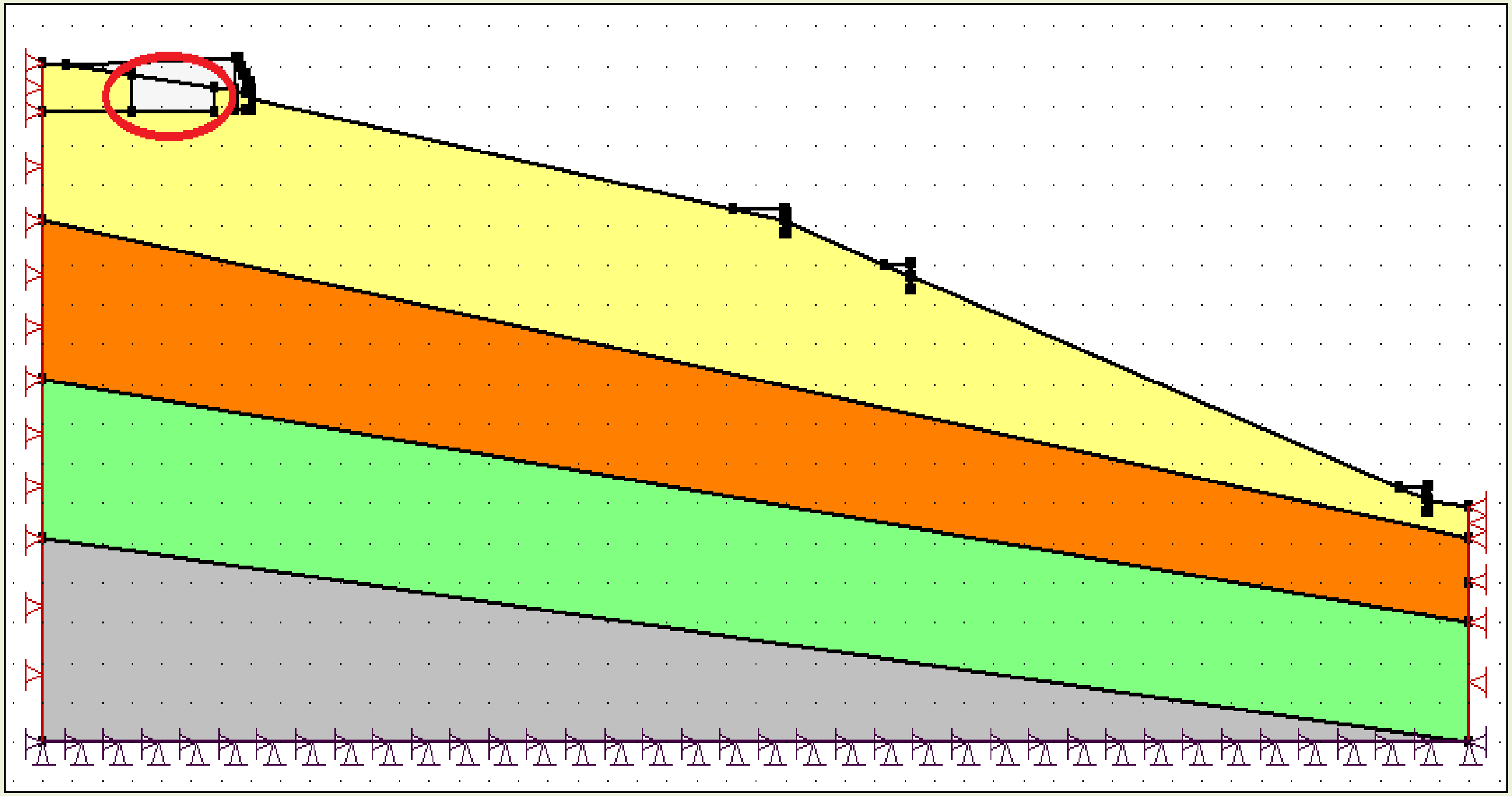
Preliminary Models and Failure Analysis

- 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



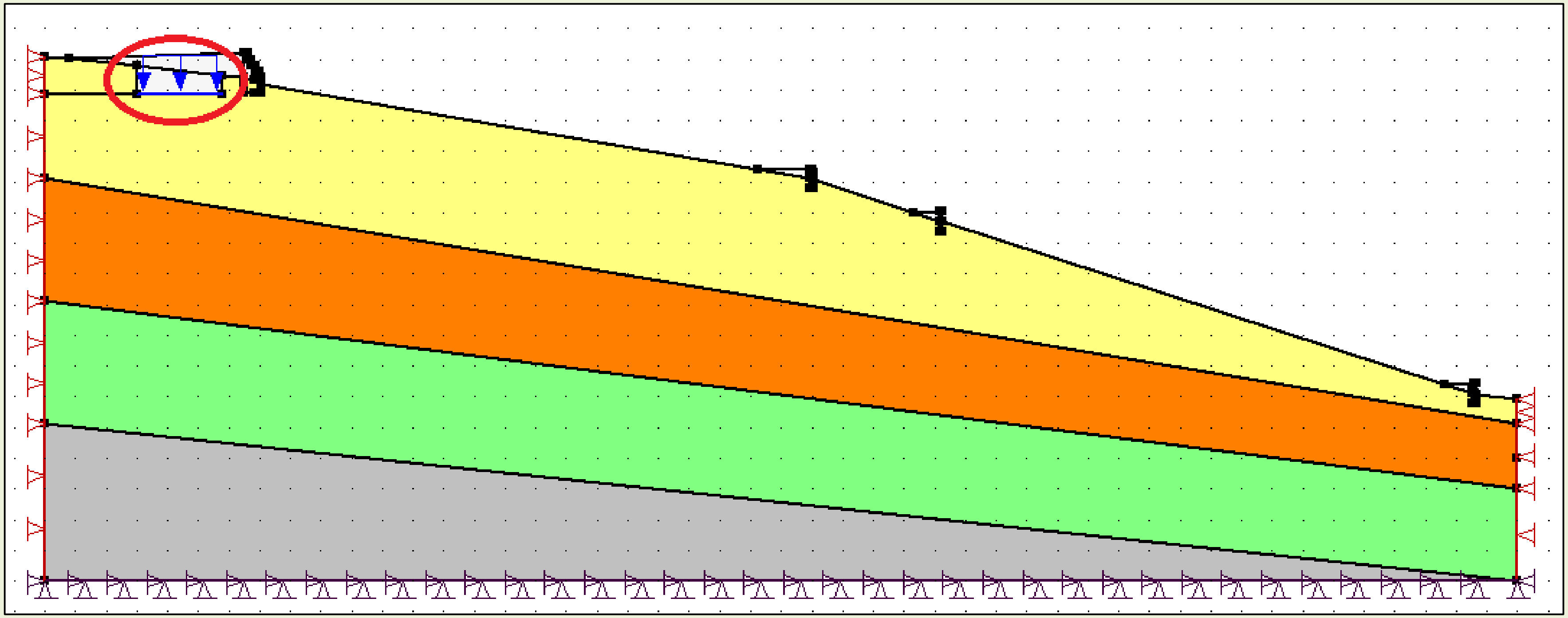
Preliminary Models and Failure Analysis

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



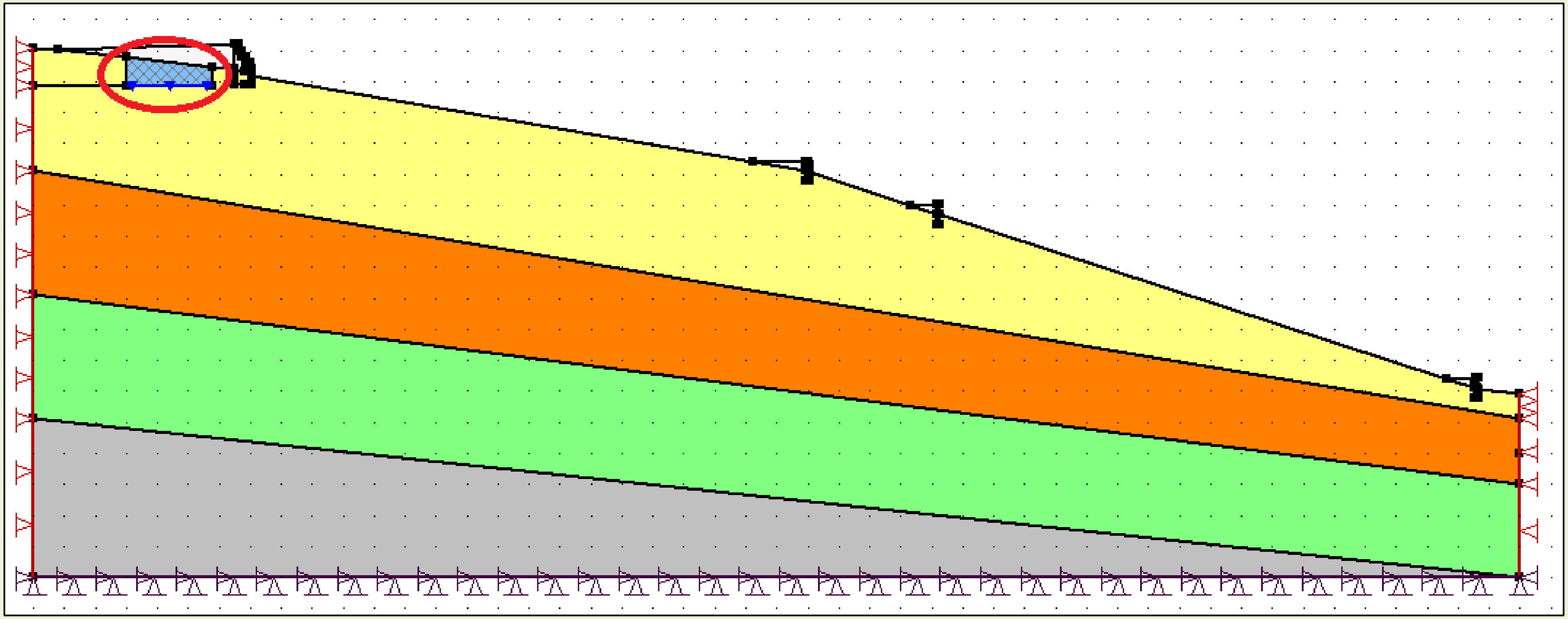
Preliminary Models and Failure Analysis

- 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)



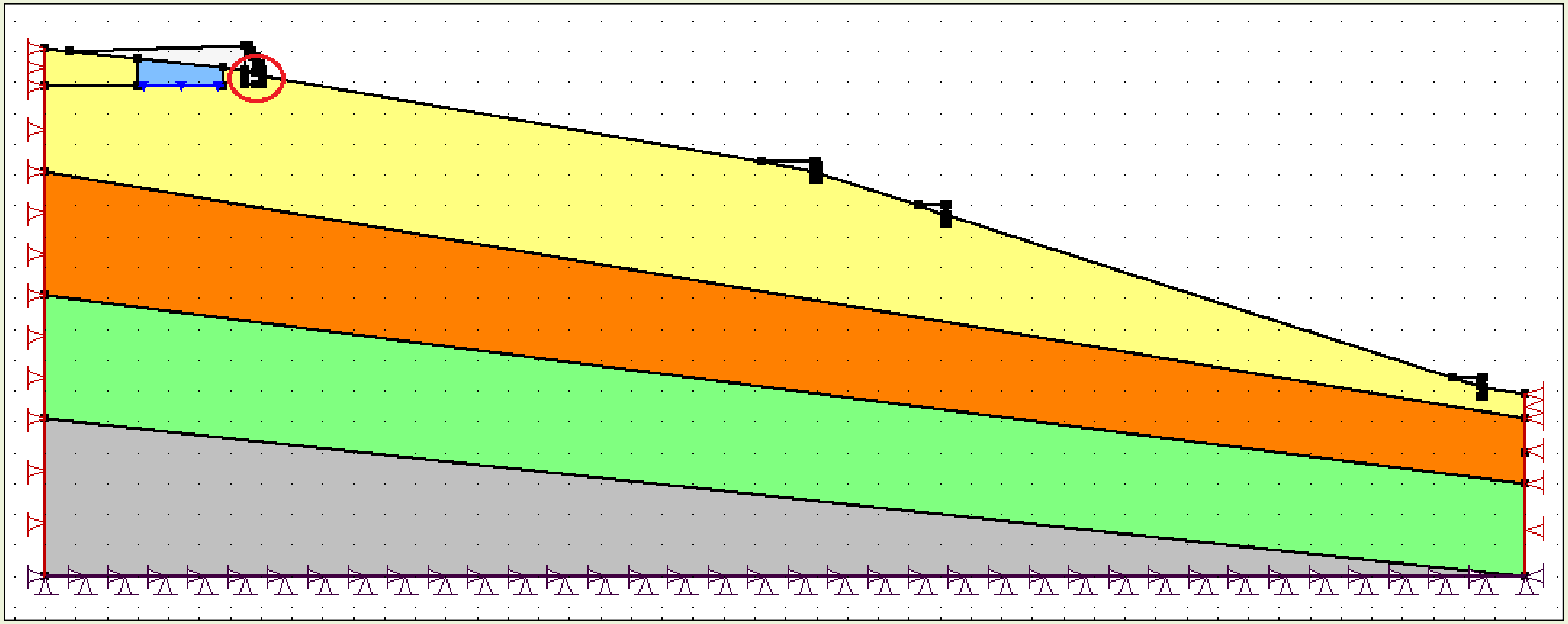
Preliminary Models and Failure Analysis

- 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)



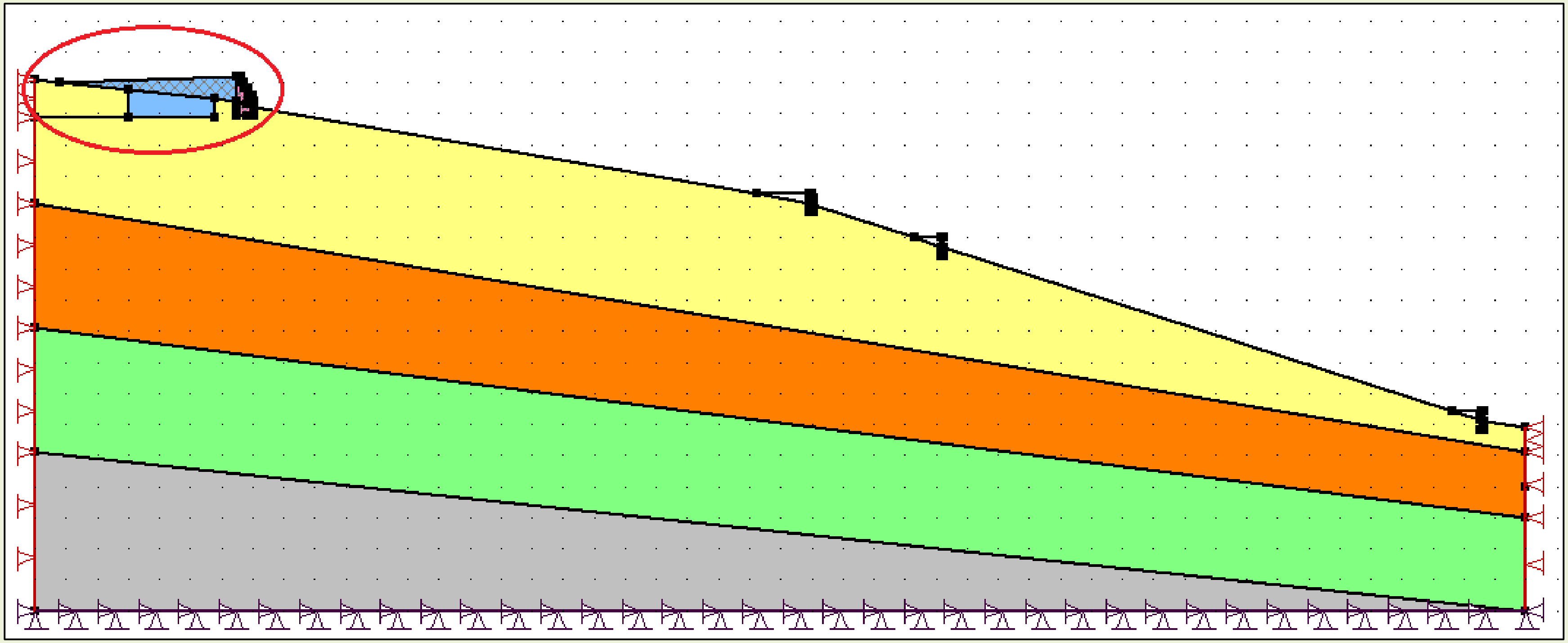
Preliminary Models and Failure Analysis

- 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



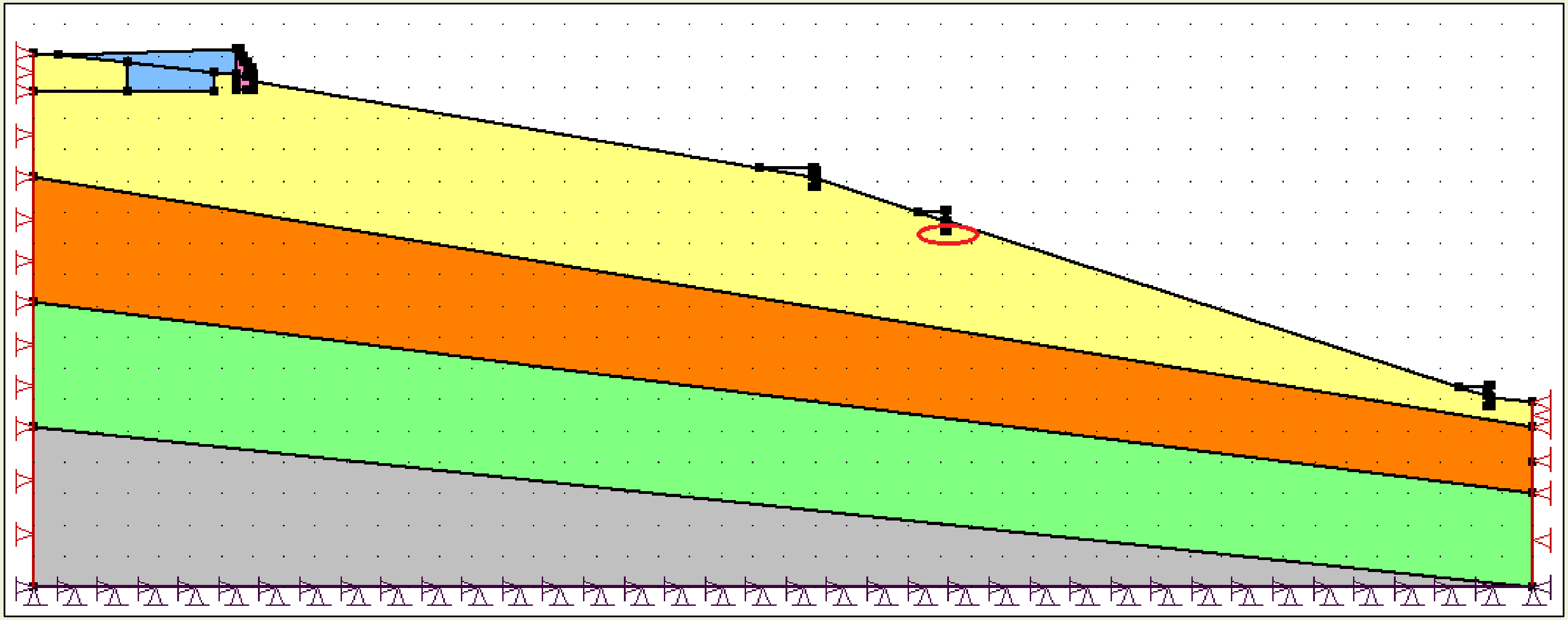
Preliminary Models and Failure Analysis

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



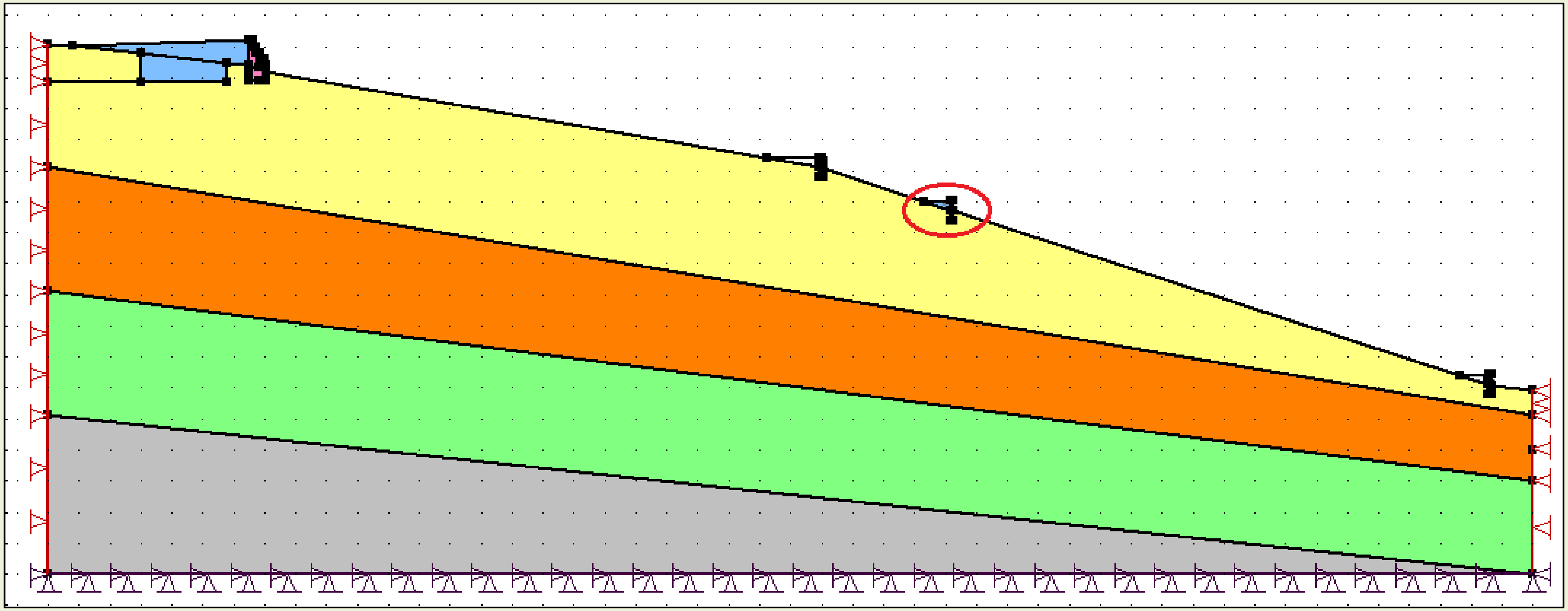
Preliminary Models and Failure Analysis

- 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



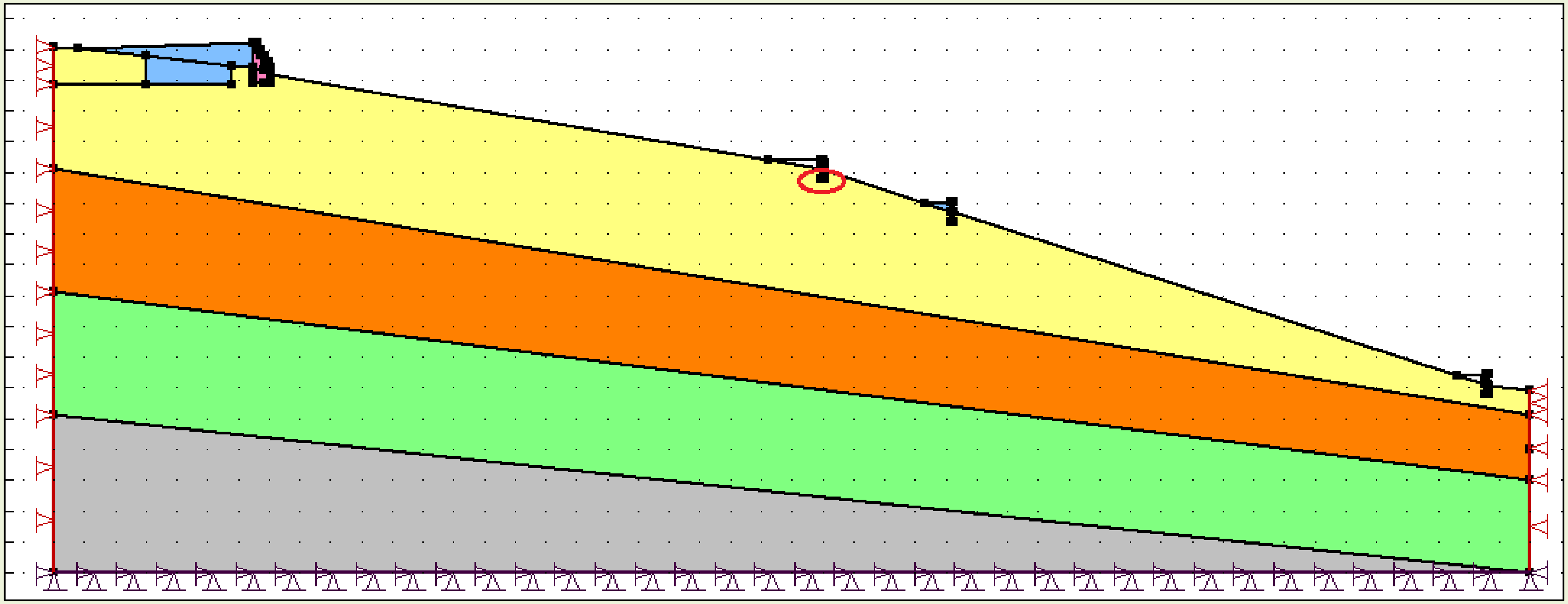
Preliminary Models and Failure Analysis

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



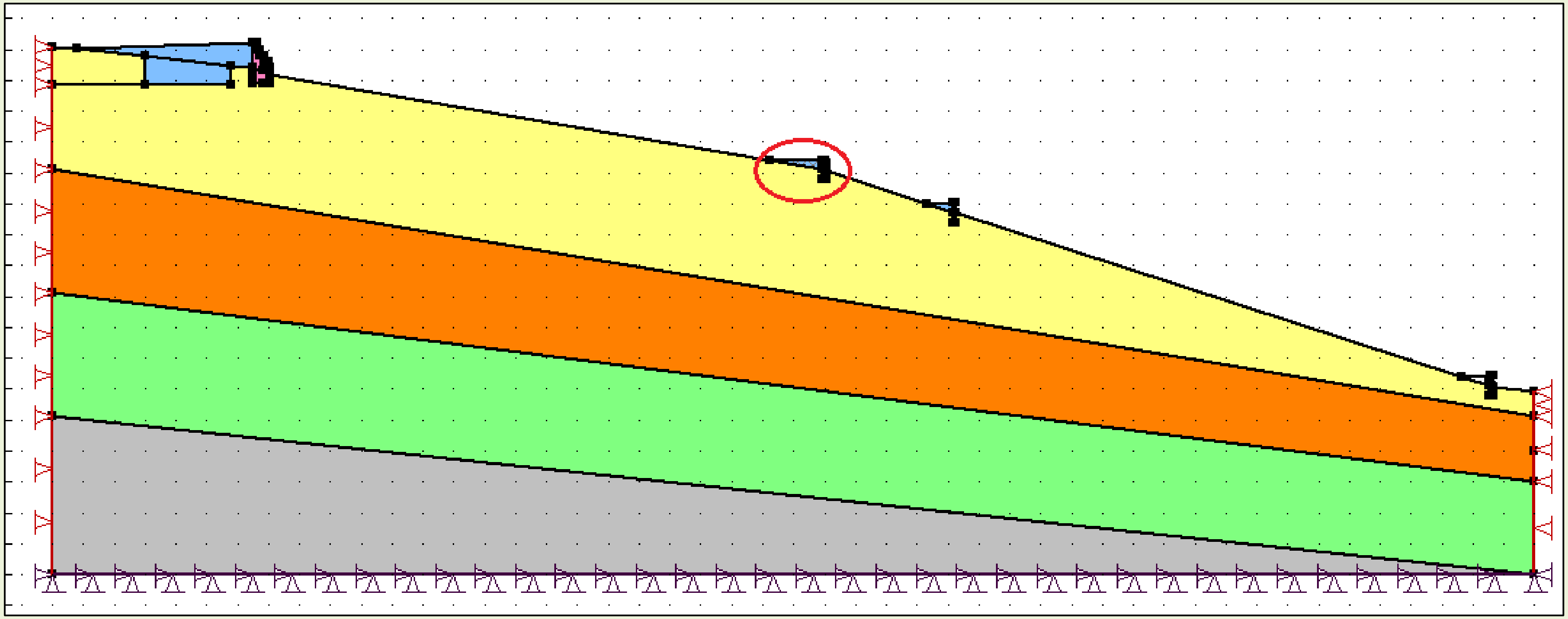
Preliminary Models and Failure Analysis

- 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

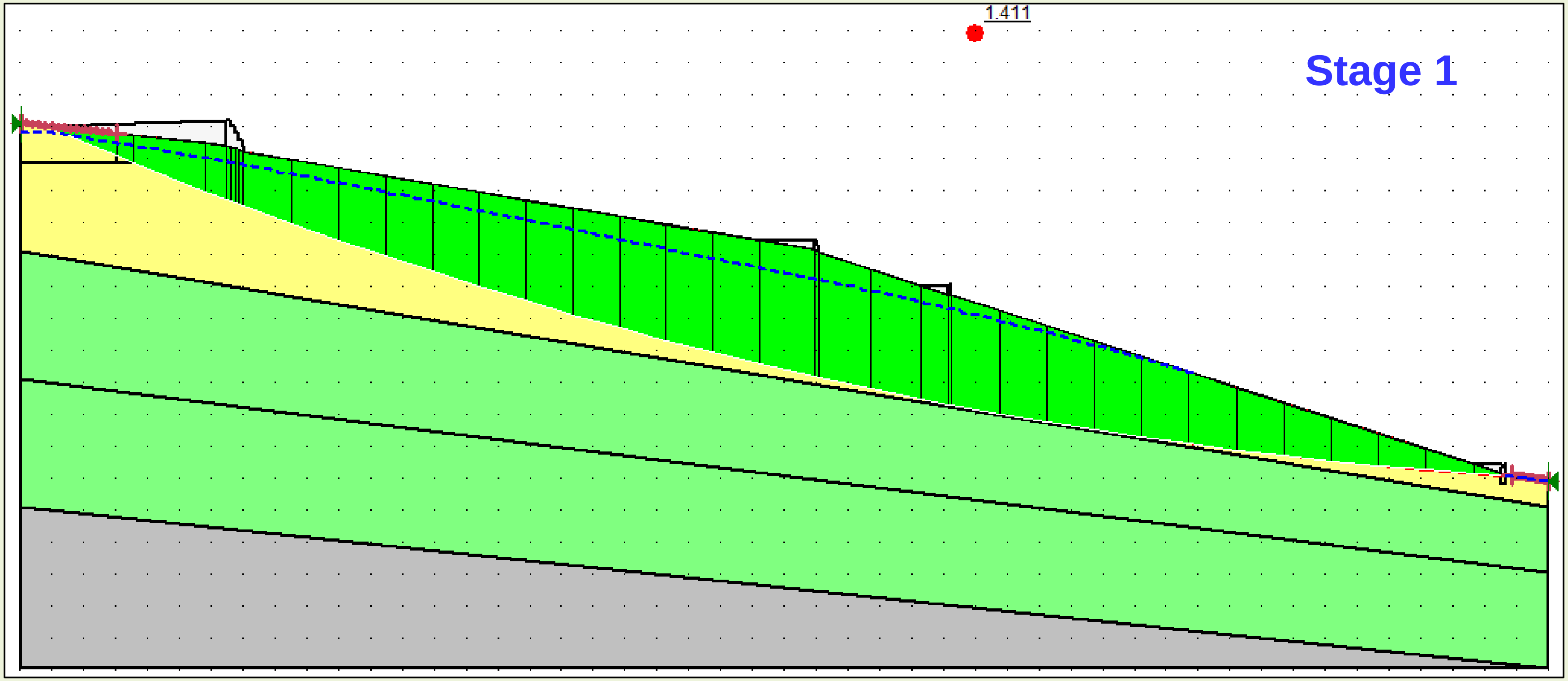
  → FE-based transient seepage analysis to identify the steady state WT due to a rainfall based infiltration and development of transient pore-water pressures

- 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

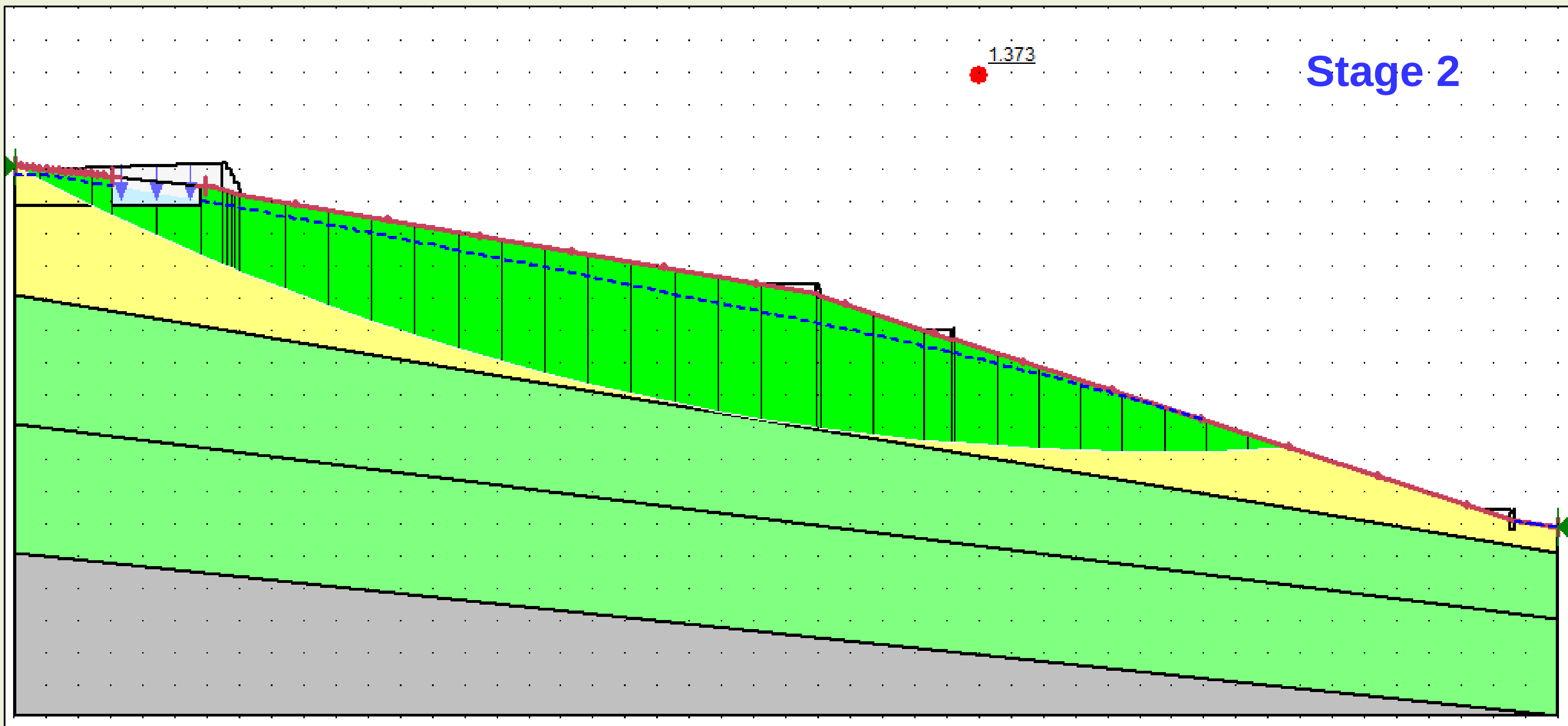
Preliminary Models and Failure Analysis

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



Preliminary Models and Failure Analysis

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



Preliminary Models and Failure Analysis

- Slope stability analysis using Slope/W
  - *Morgenstern-Price Method for analysis*
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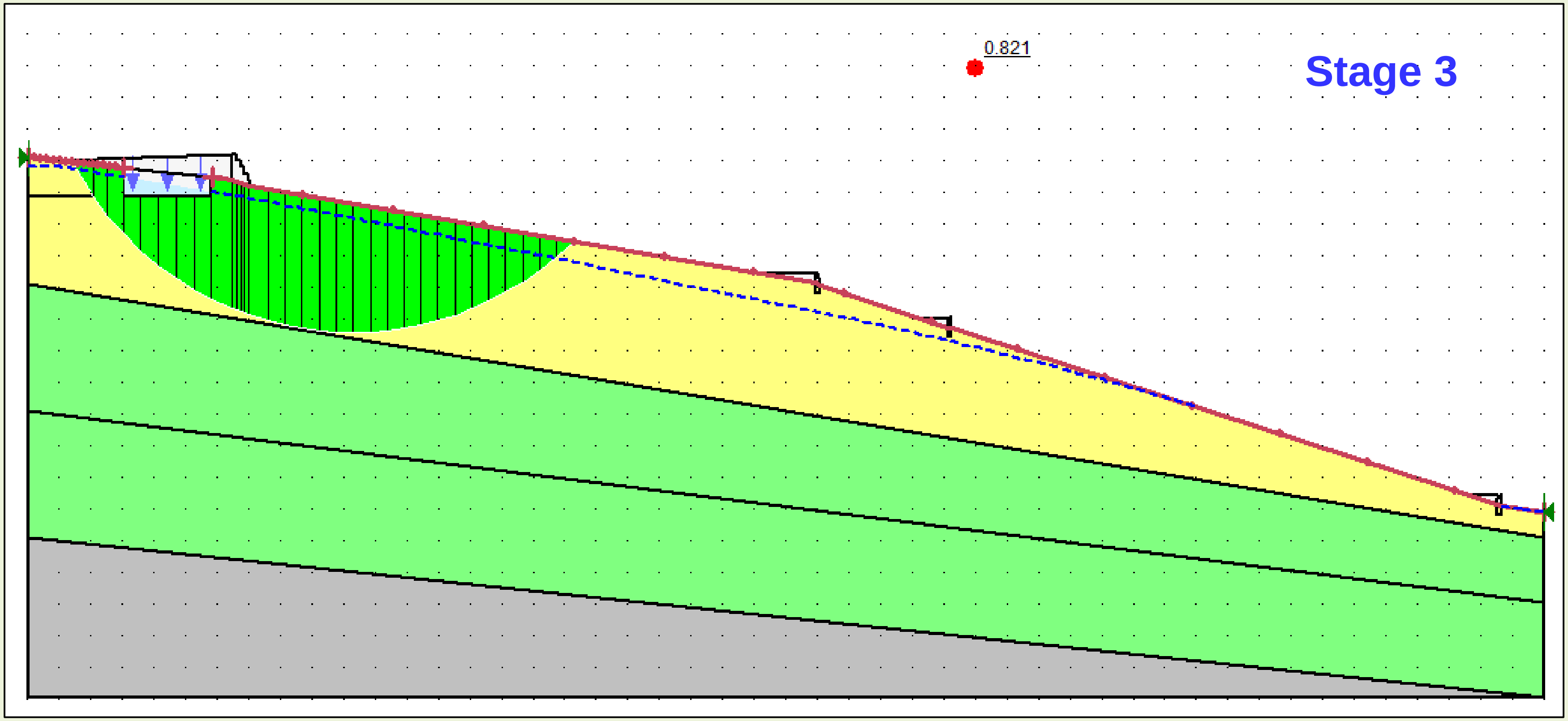
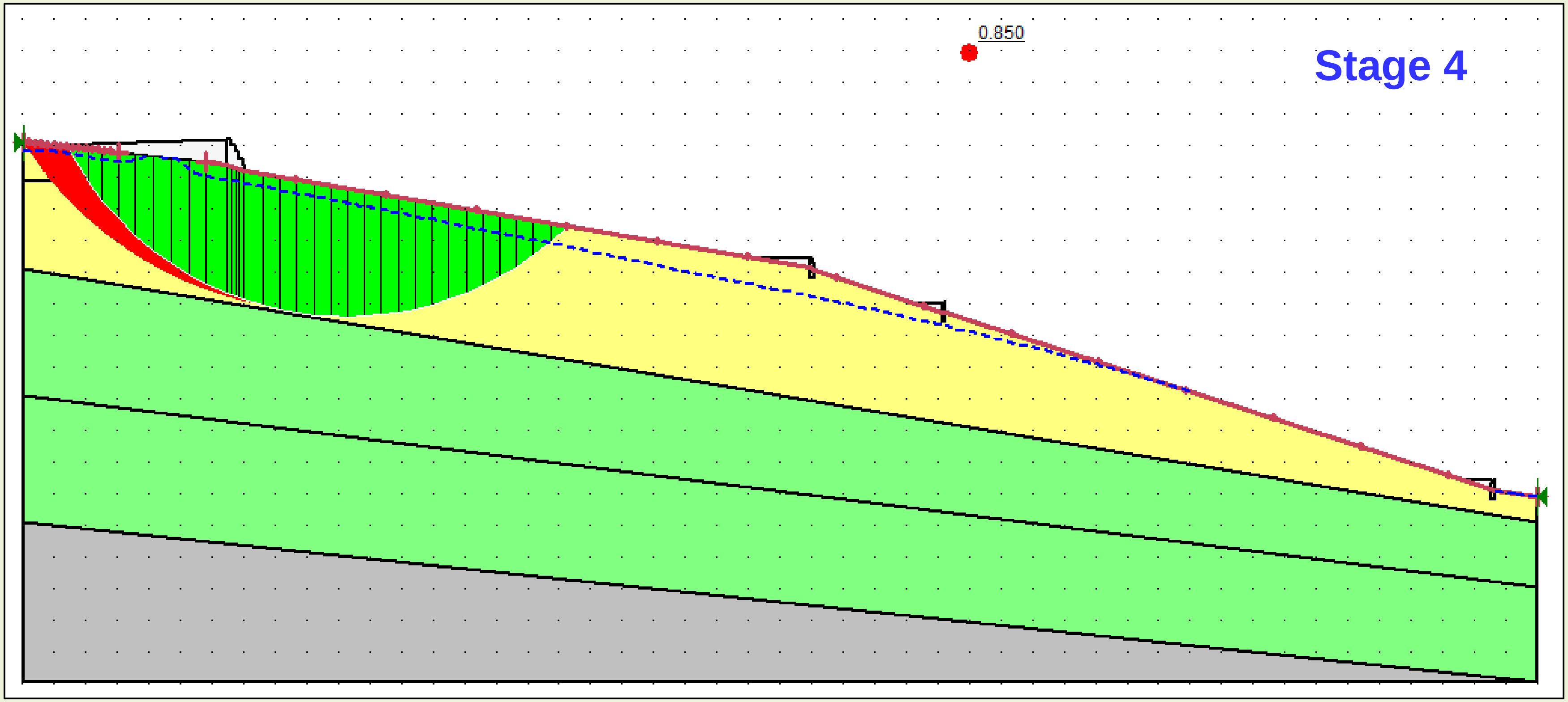


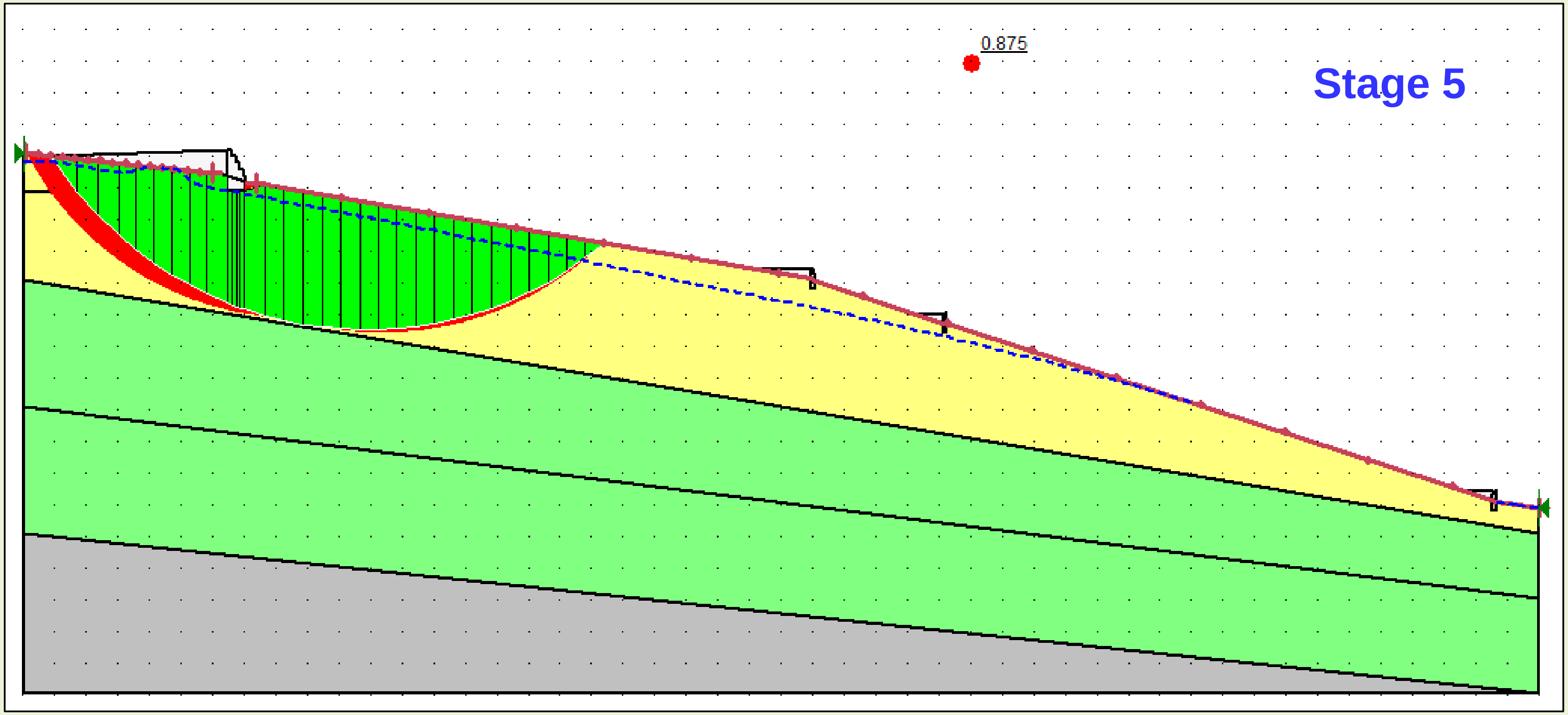
Preliminary Models and Failure Analysis

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



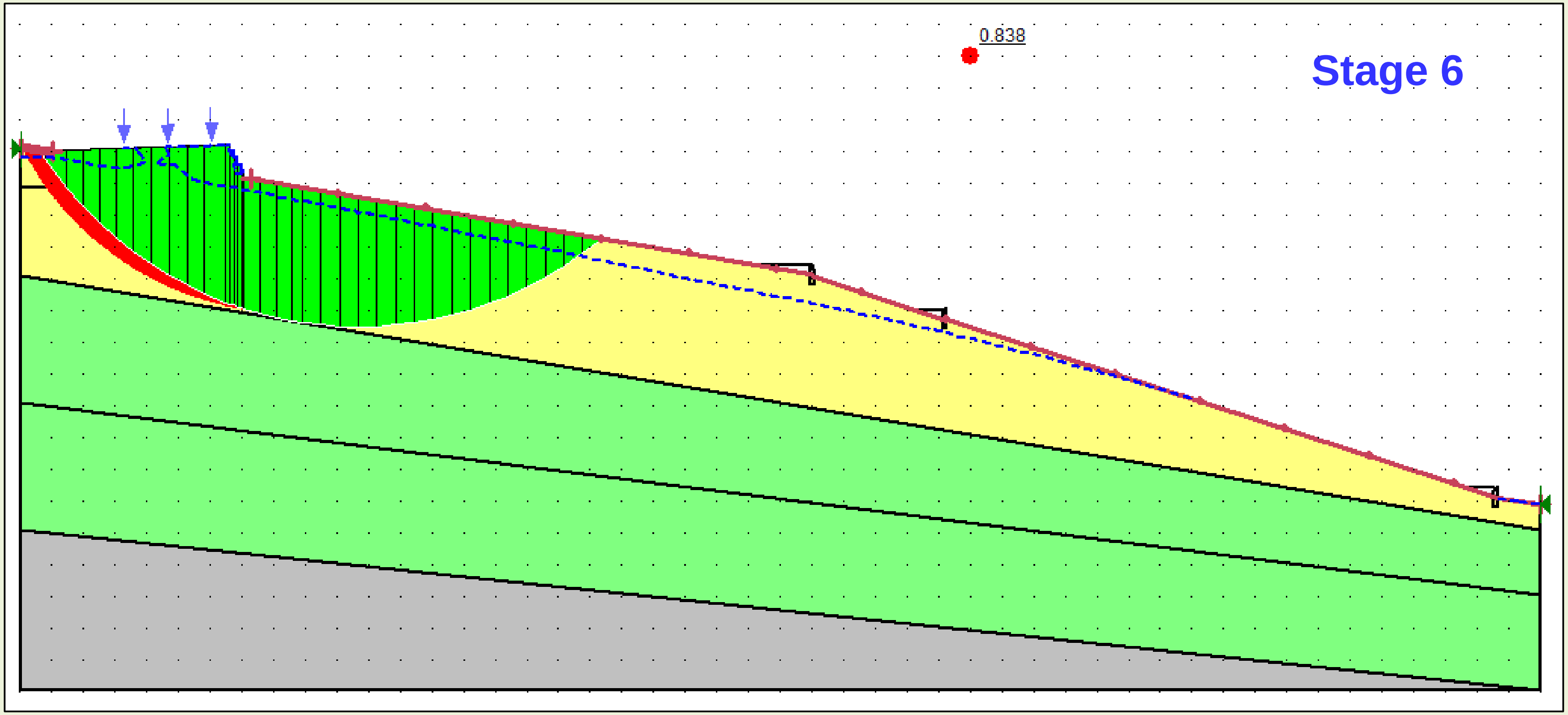
Preliminary Models and Failure Analysis

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



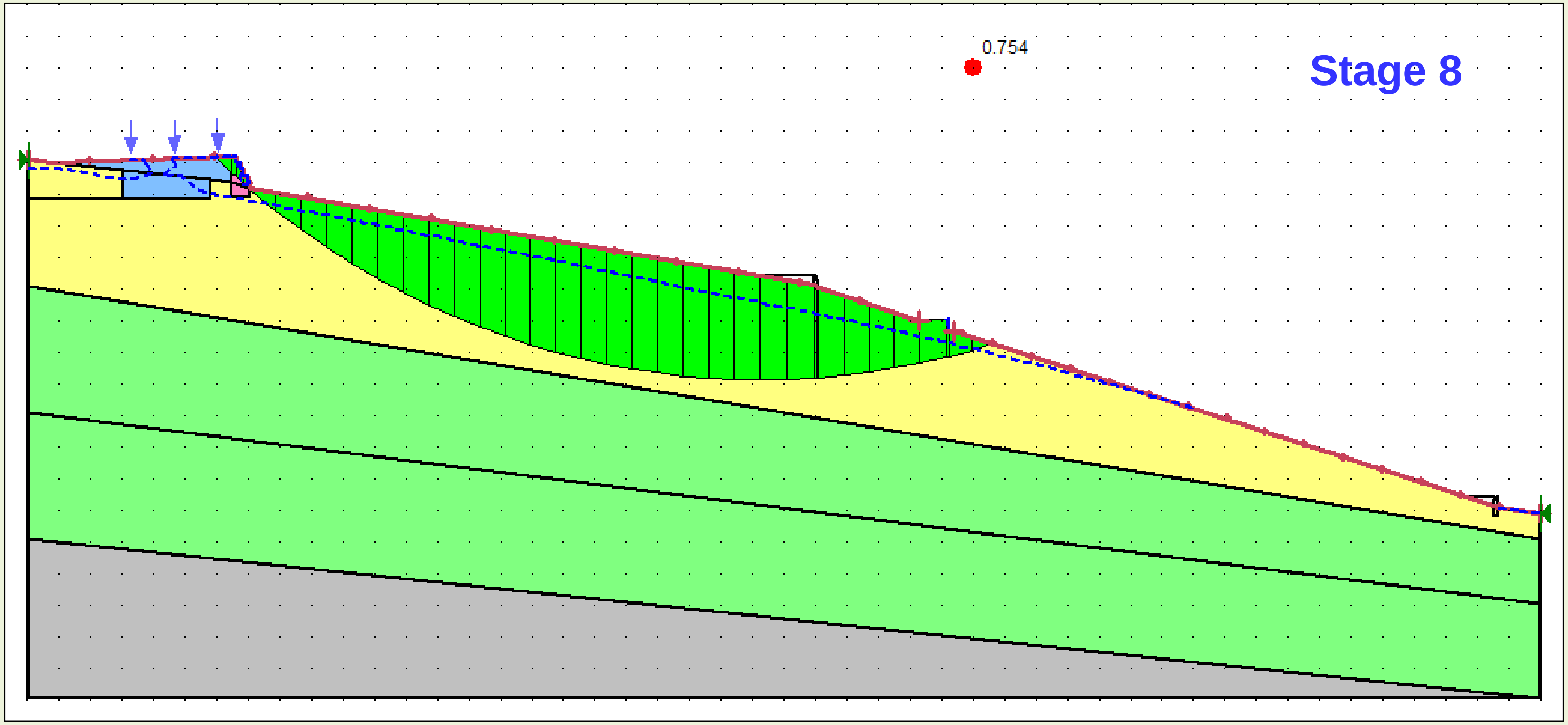
Preliminary Models and Failure Analysis

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



Preliminary Models and Failure Analysis

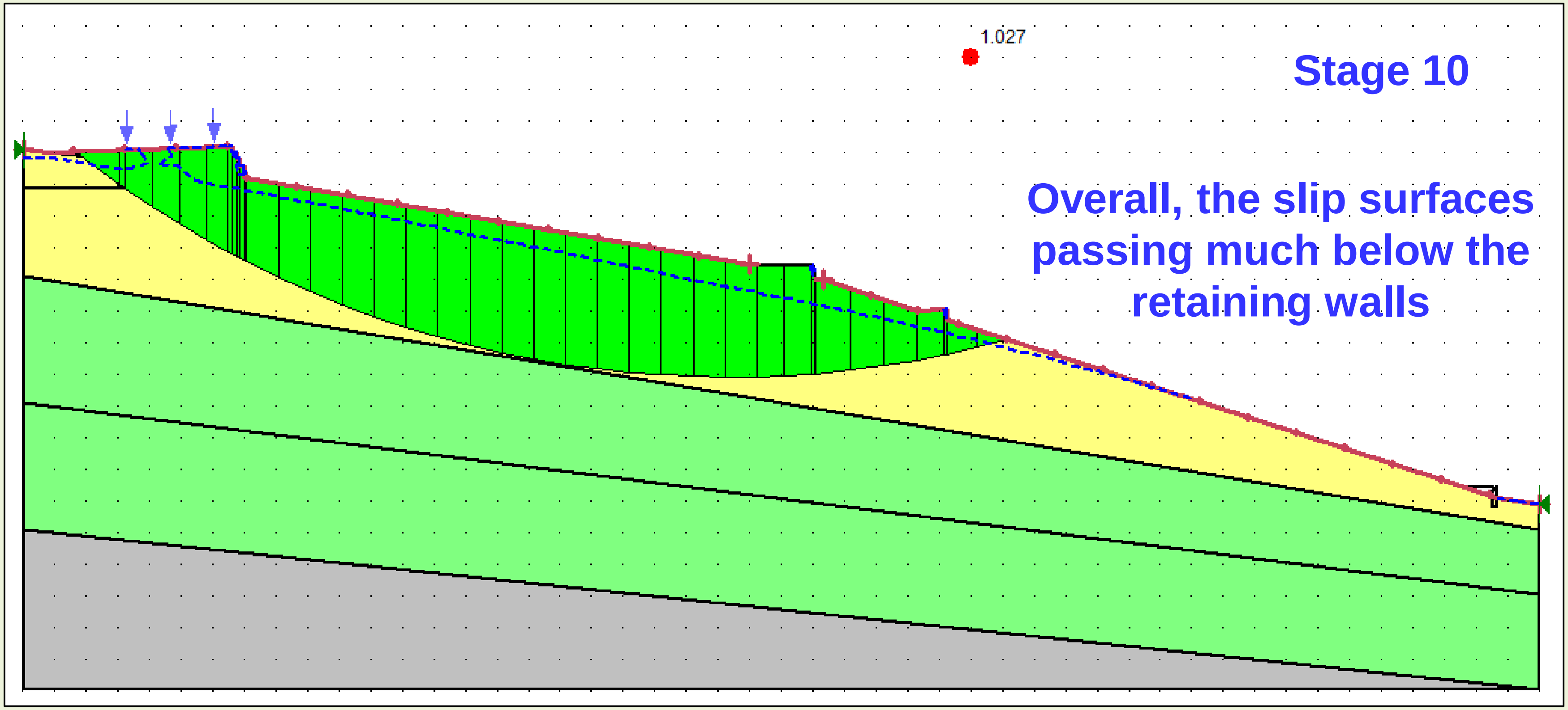
- Slope stability analysis using Slope/W
  - *Morgenstern-Price Method for analysis*
  - *Entry-Exit method for slip surface definition*



Preliminary Models and Failure Analysis

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

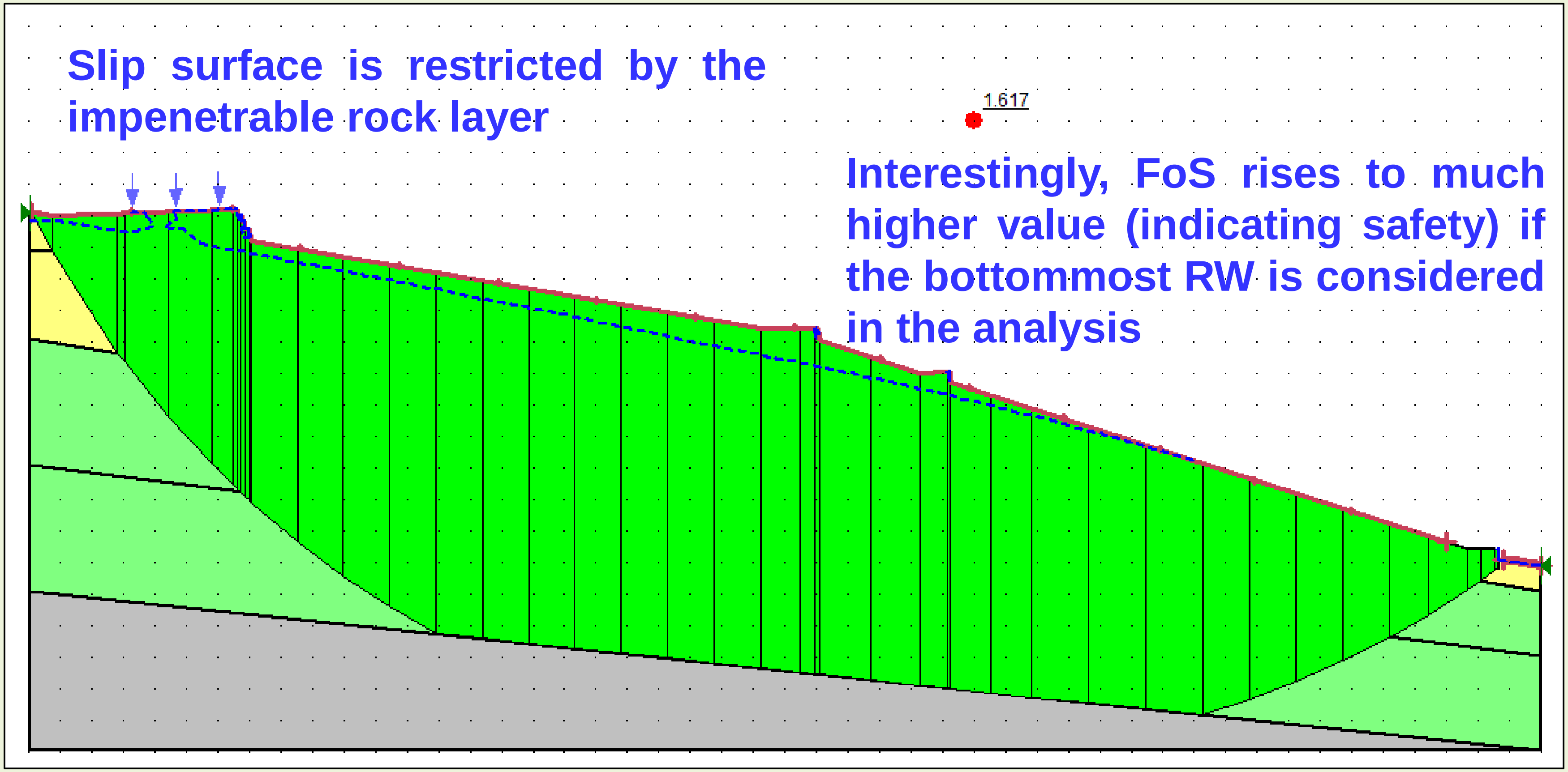
Retaining walls and backfills simply kept on adding weight to the system leading to more destabilization



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 (W_1)	Water level at a depth of 4 m (W_2)	Water level at a depth of 8 m (W_3)
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 (W_1)	Water level at a depth of 4 m (W_2)	Water level at a depth of 8 m (W_3)
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 (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
(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 (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
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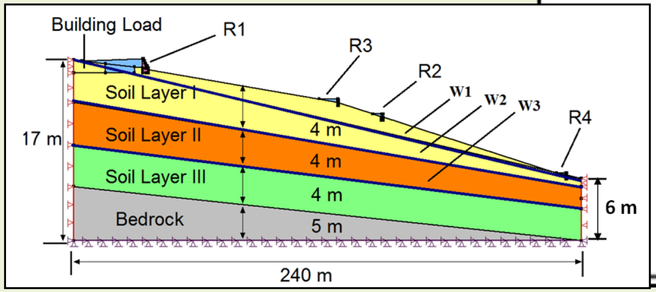
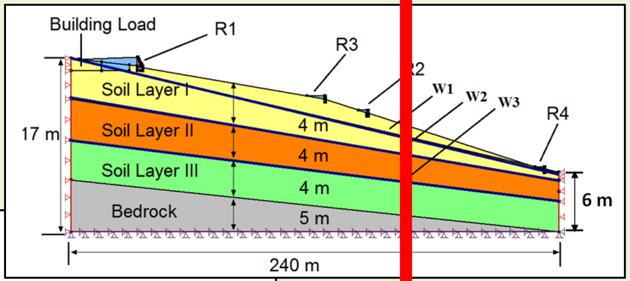
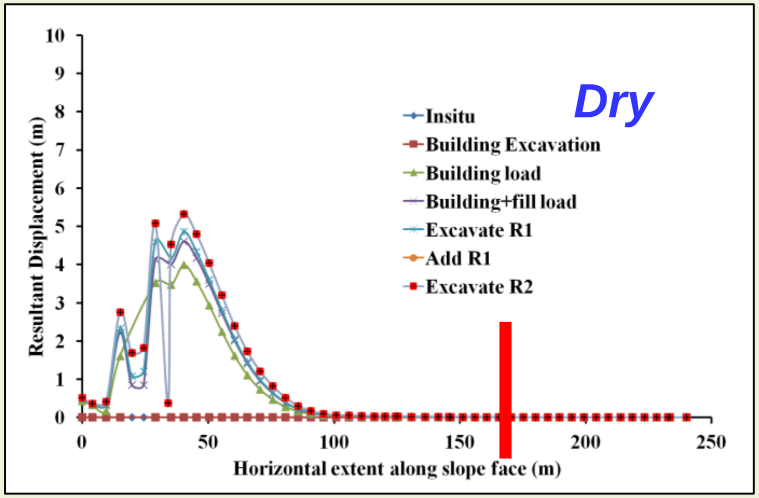
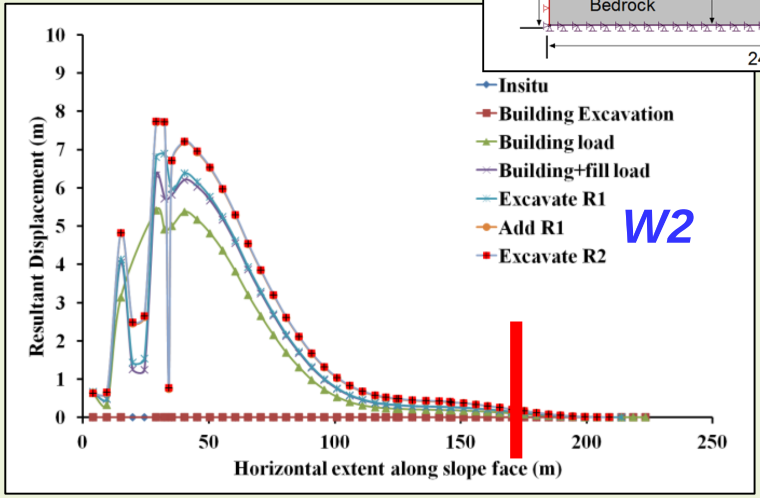


Preliminary Models and Failure Analysis

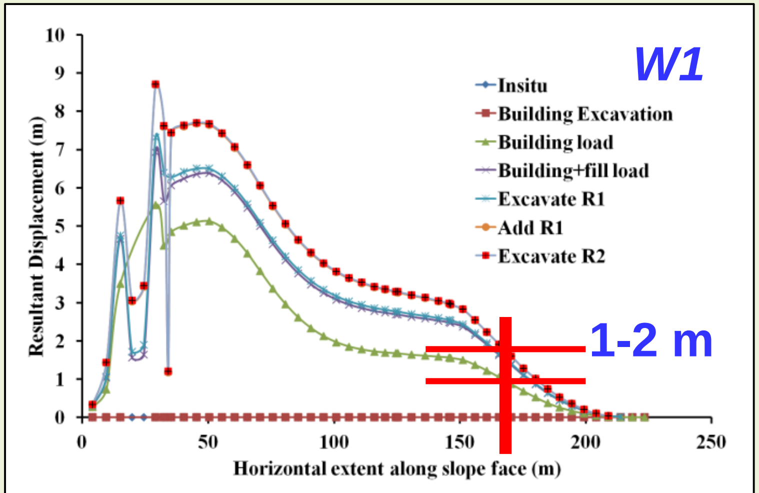
- Displacement along the hillslope
  - *From SIGMA/W analysis*

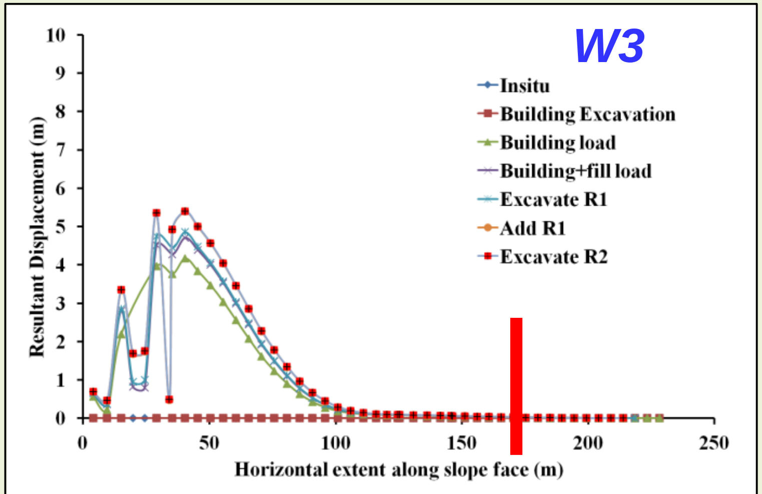






24-Colony Location
170 m from Workshop building

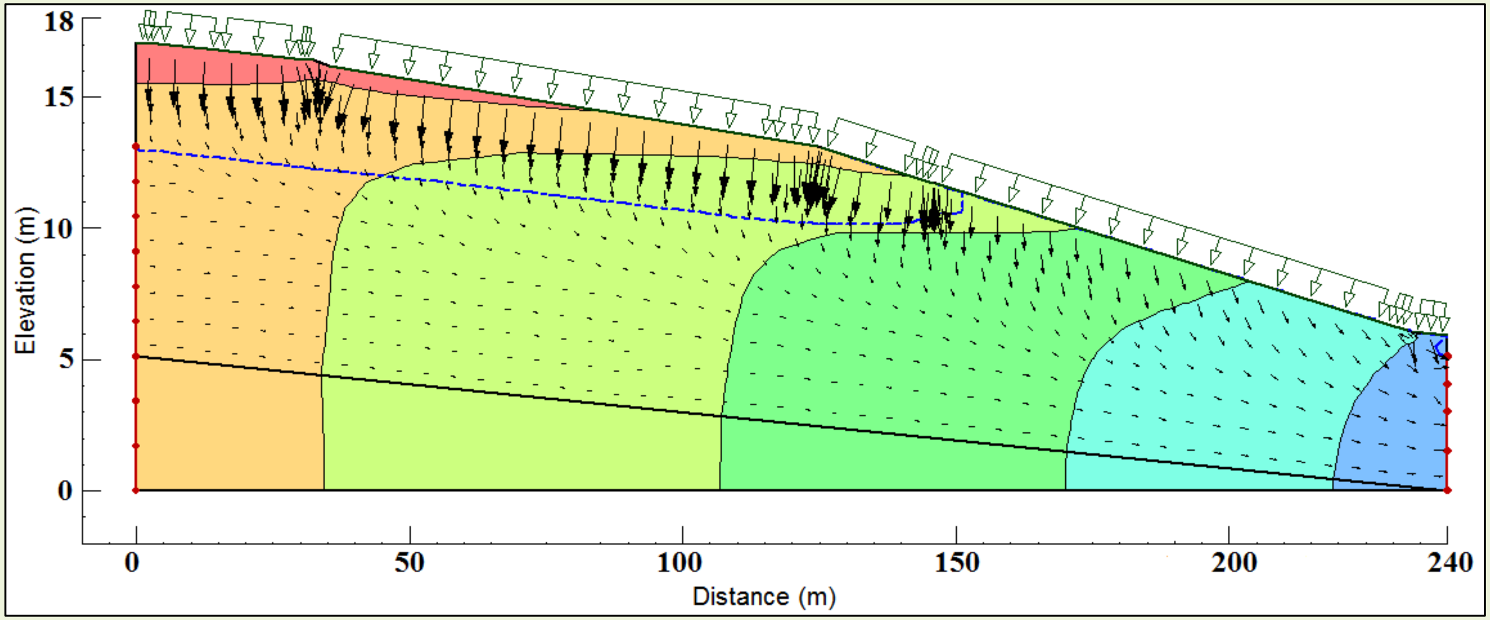




W1 seems to be the most probable WT location, given that it produces some deformation around 24 colony

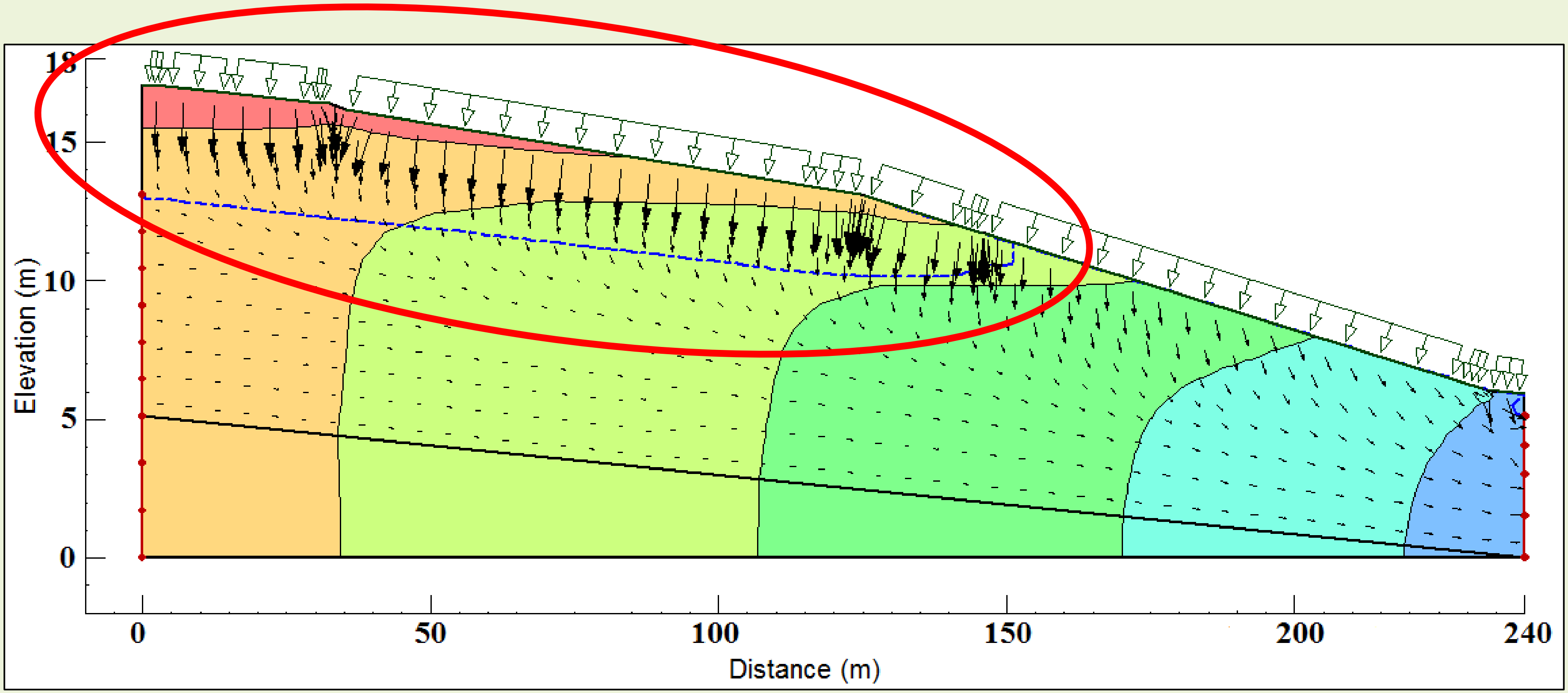
Preliminary Models and Failure Analysis

- 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 x 10^{-8} m/s (estimated from climatic and meteorological data)*
  - ❖ *Modeled as constant head of water over the entire slope*



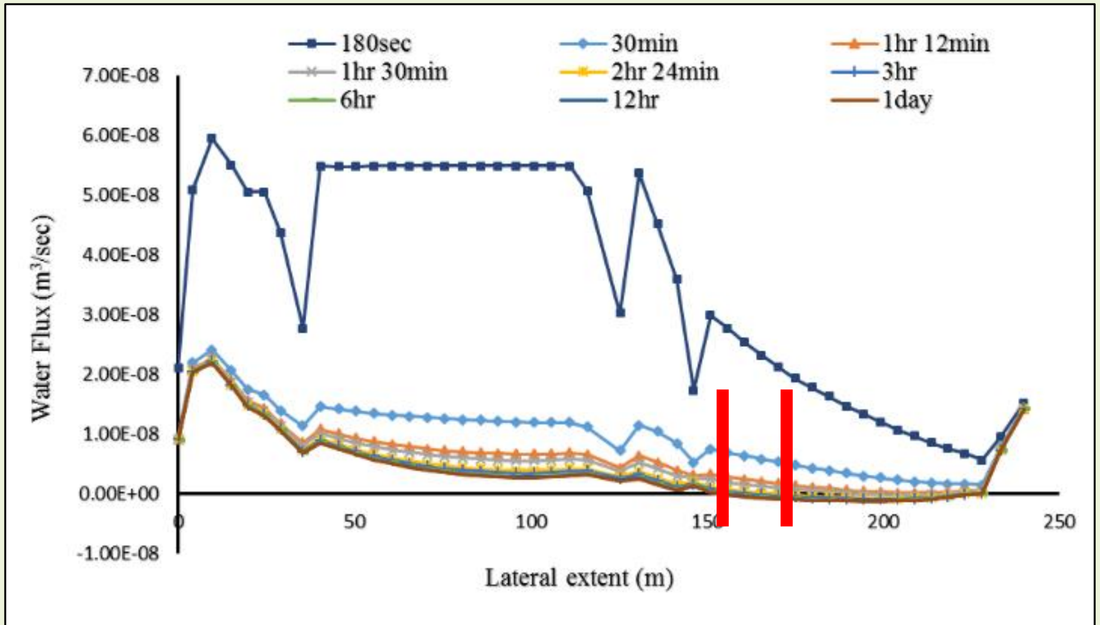
Preliminary Models and Failure Analysis

- 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

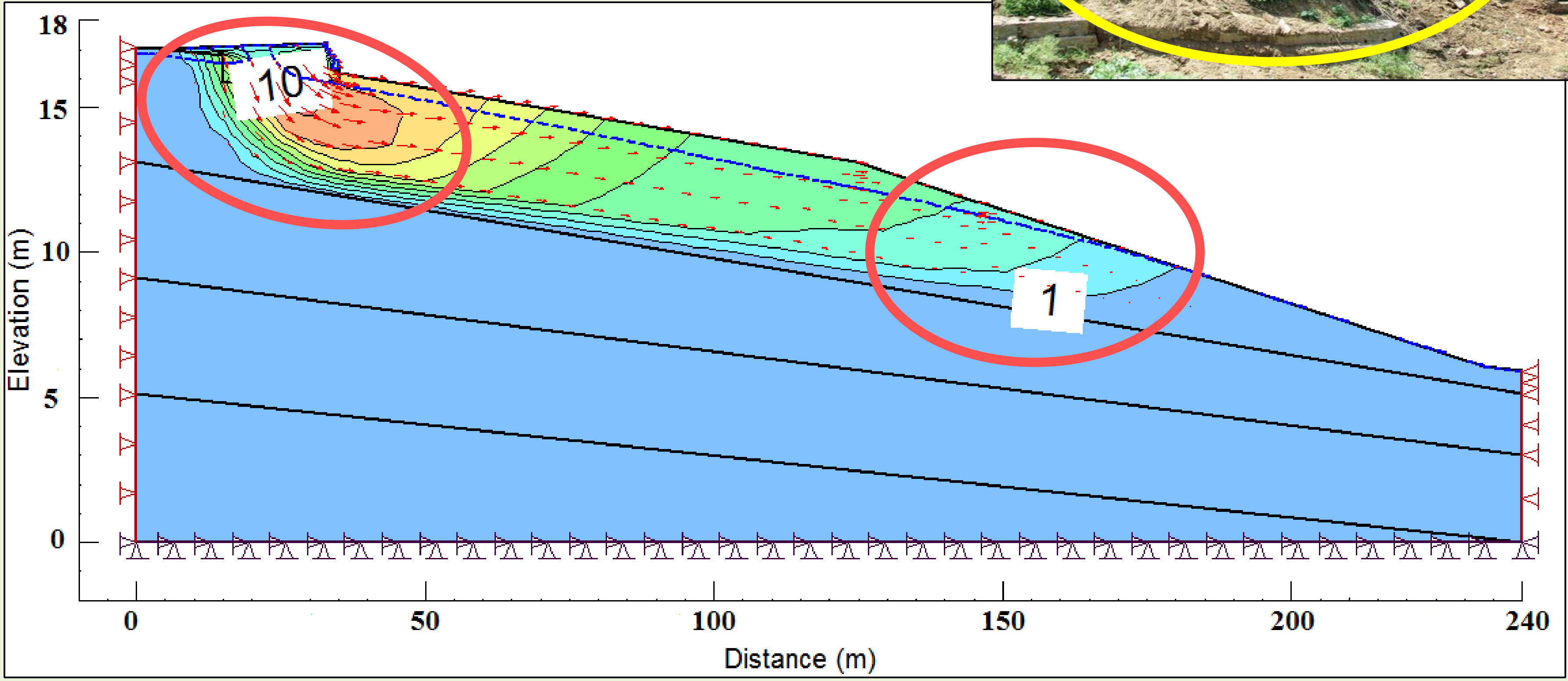


Preliminary Models and Failure Analysis

- 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

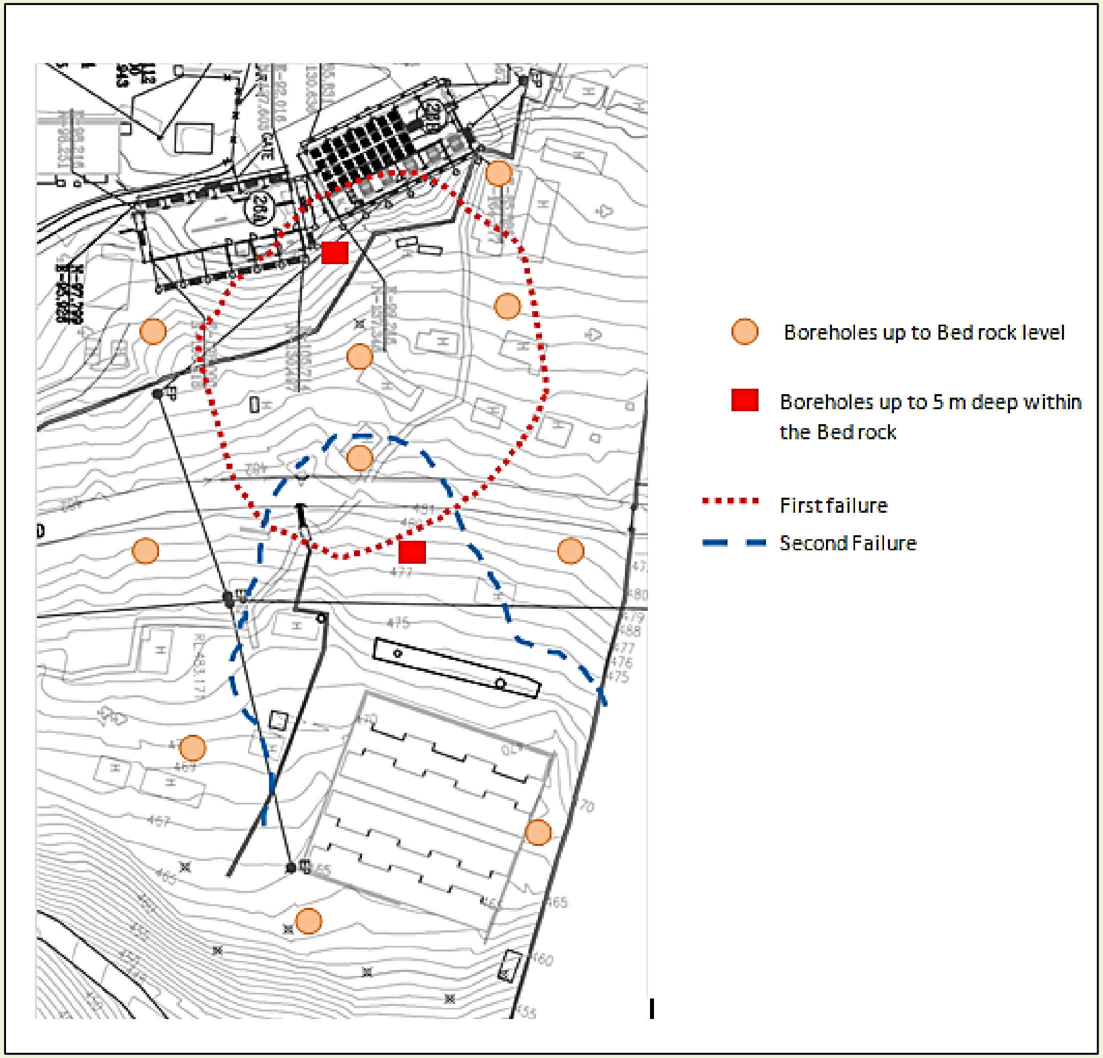
Preliminary Models and Failure Analysis

- 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???



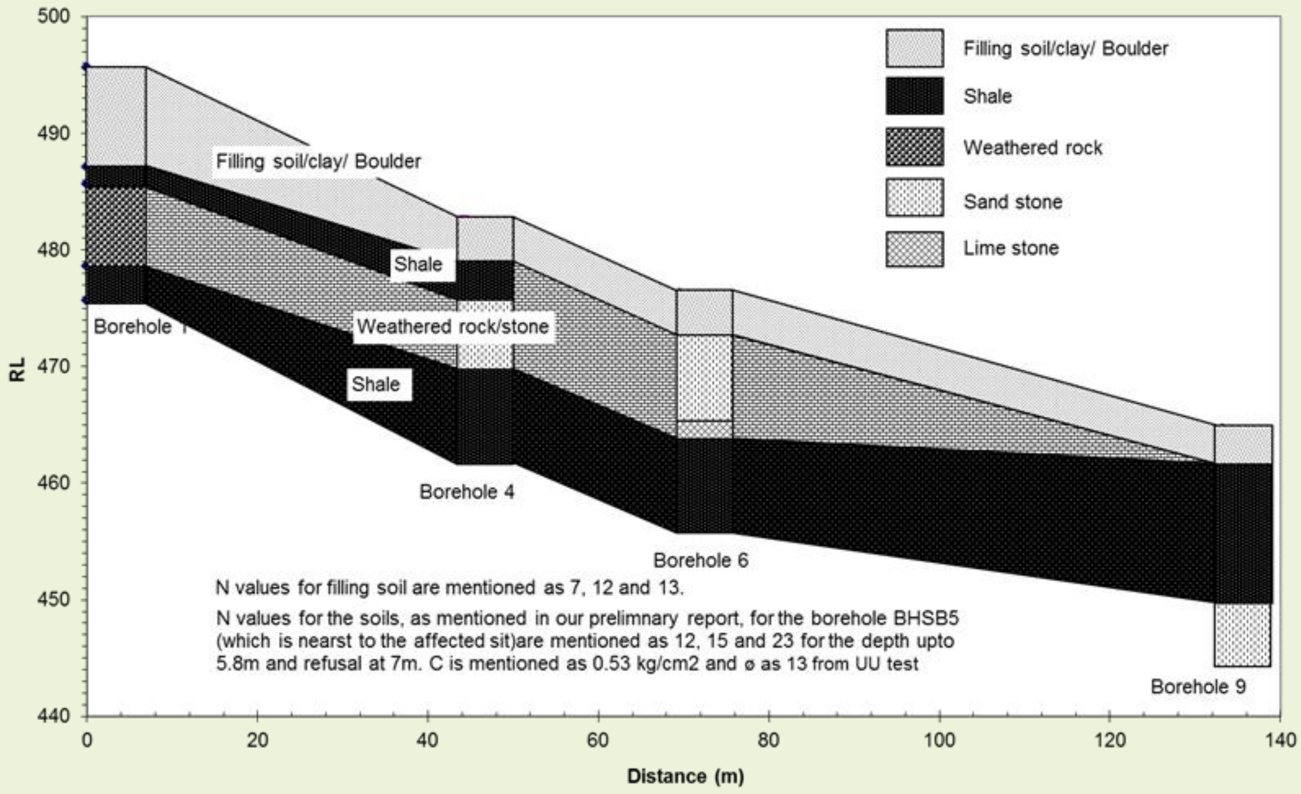
Model Updating from Further Field Studies

- 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 !!



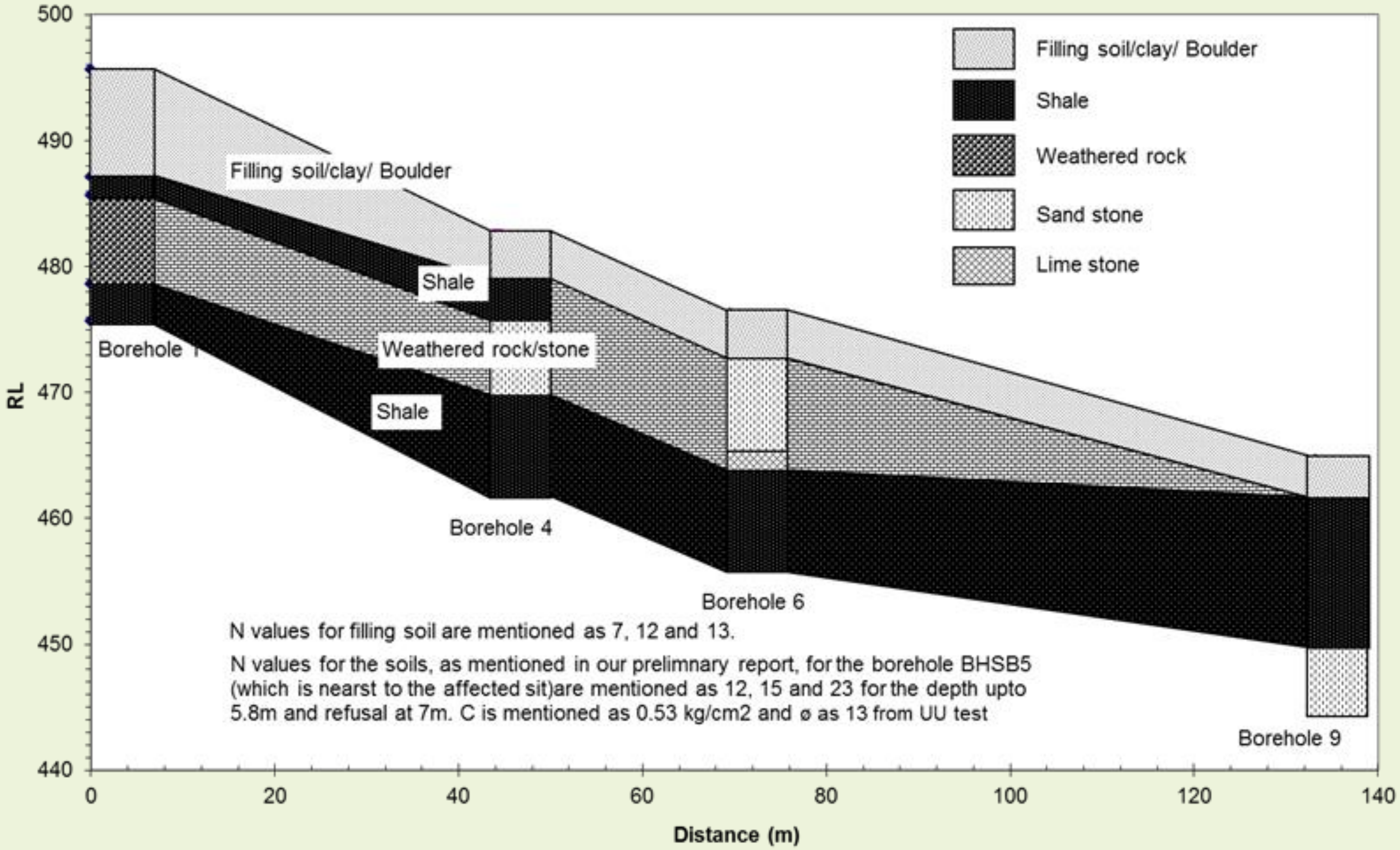
Model Updating from Further Field Studies

- 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



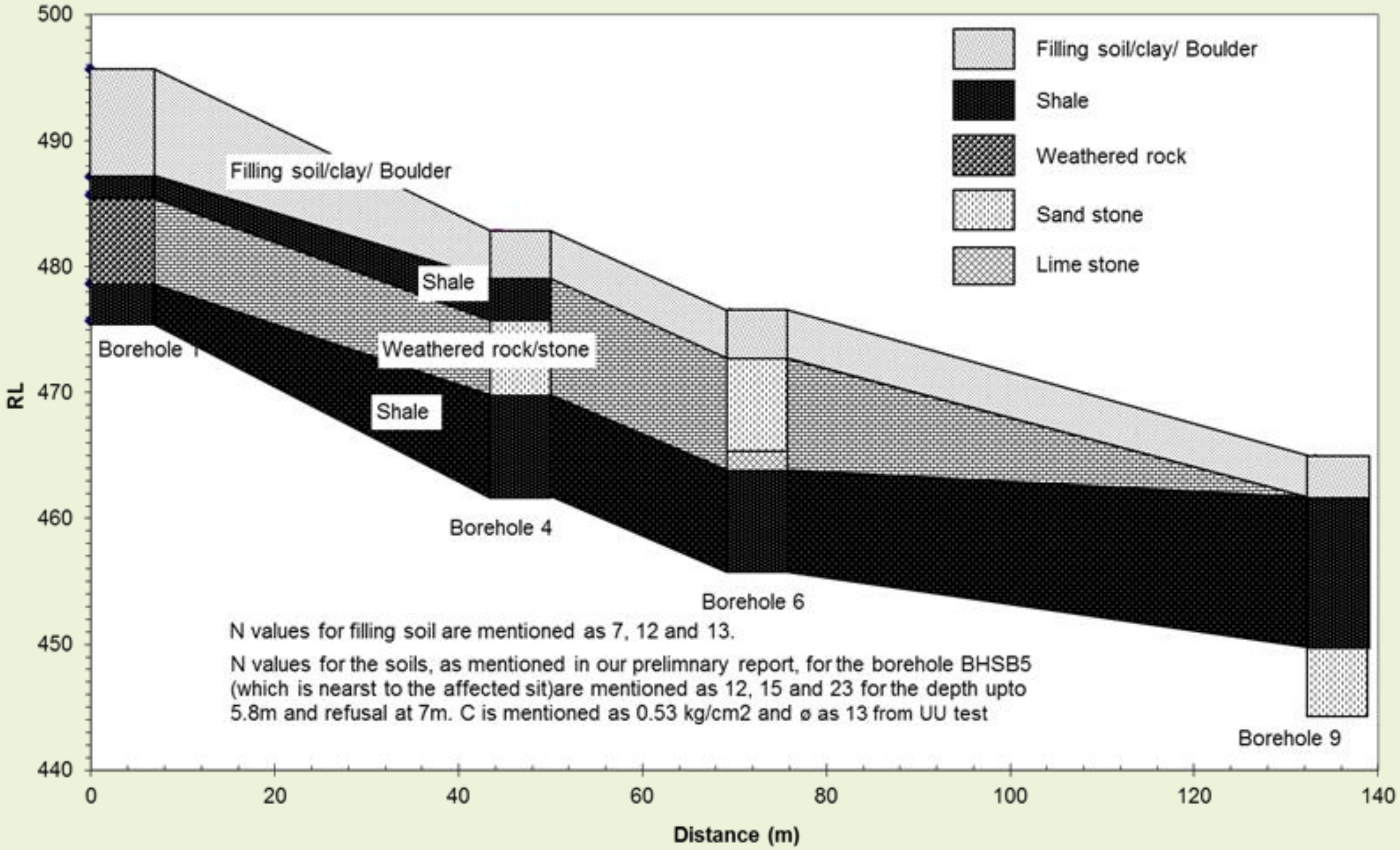
Model Updating from Further Field Studies

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



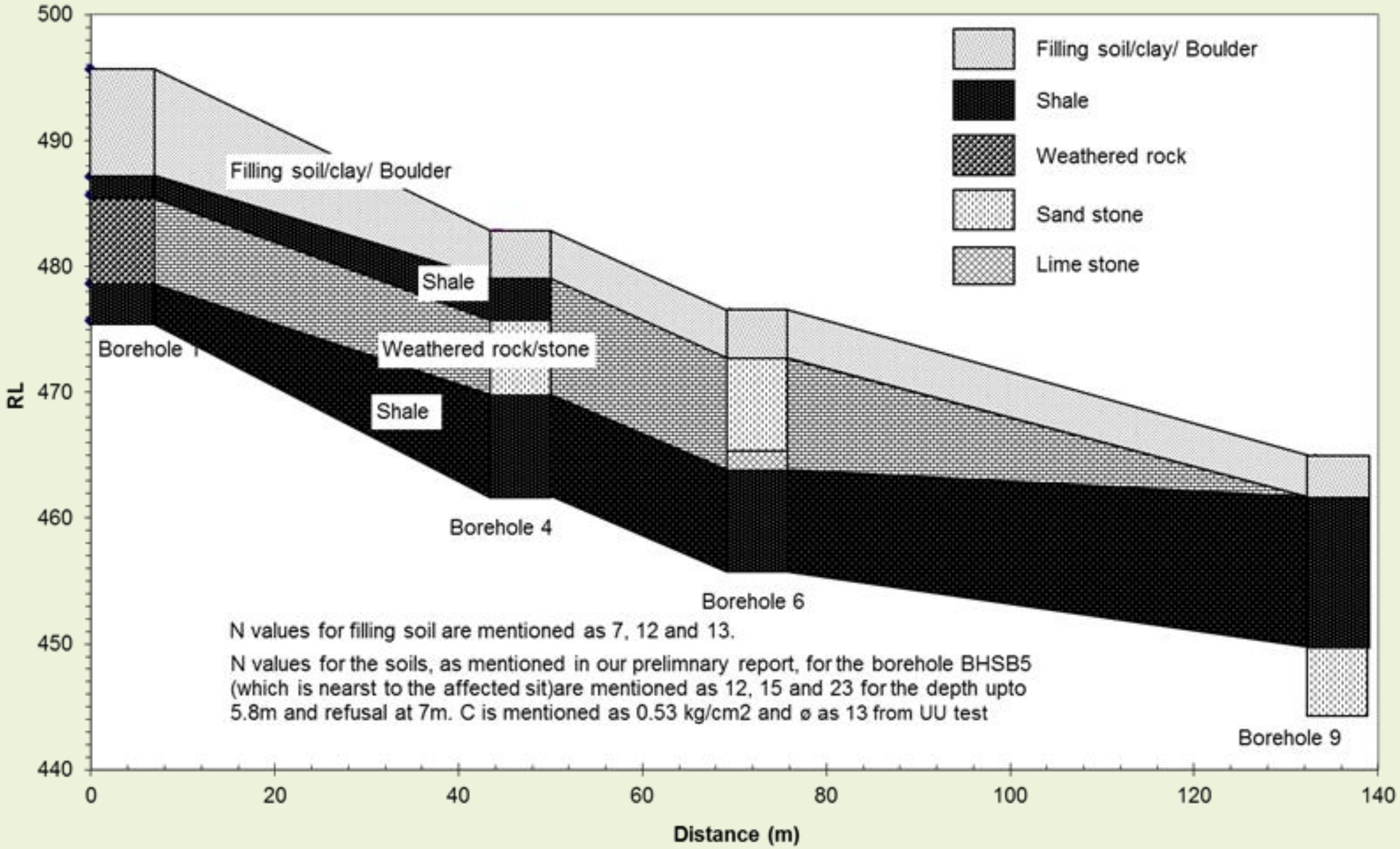
Model Updating from Further Field Studies

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



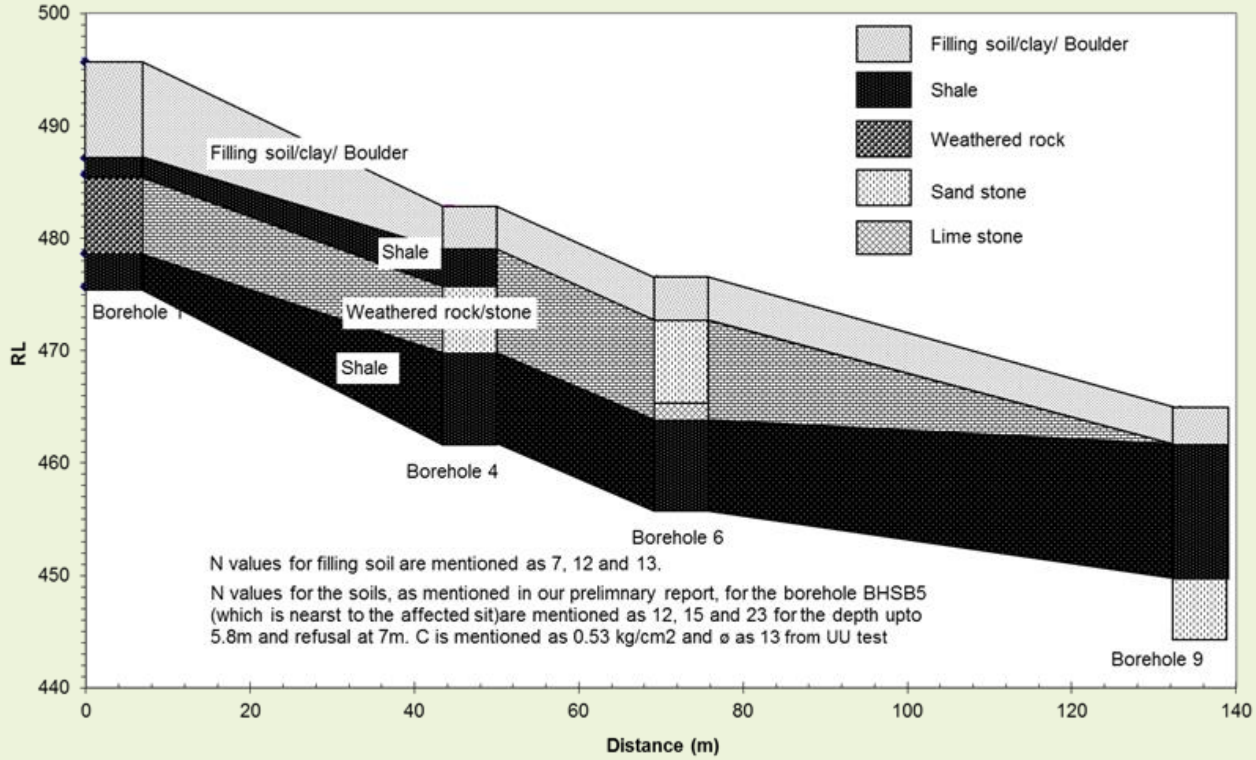
Model Updating from Further Field Studies

- 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



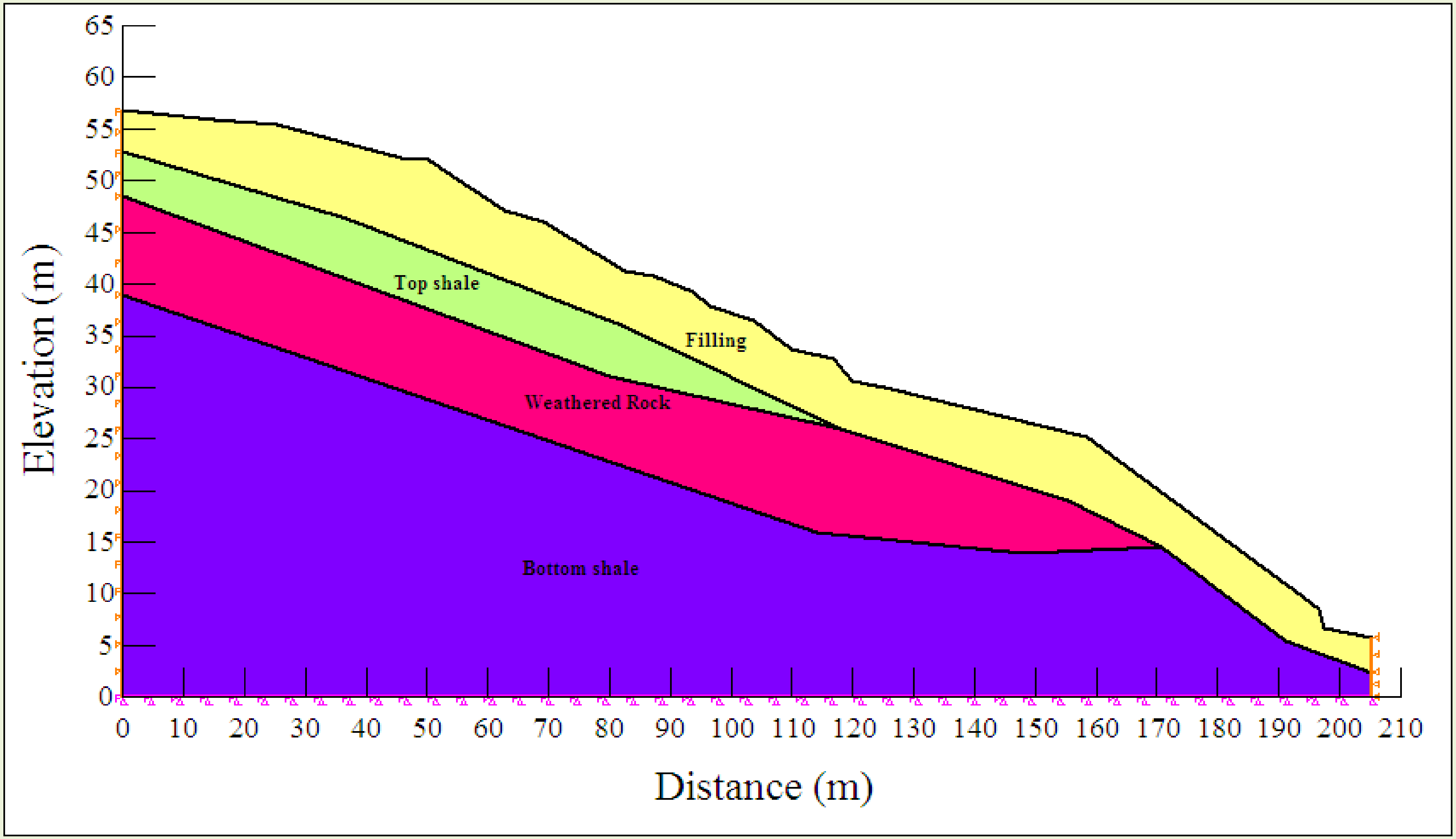
Model Updating from Further Field Studies

- 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

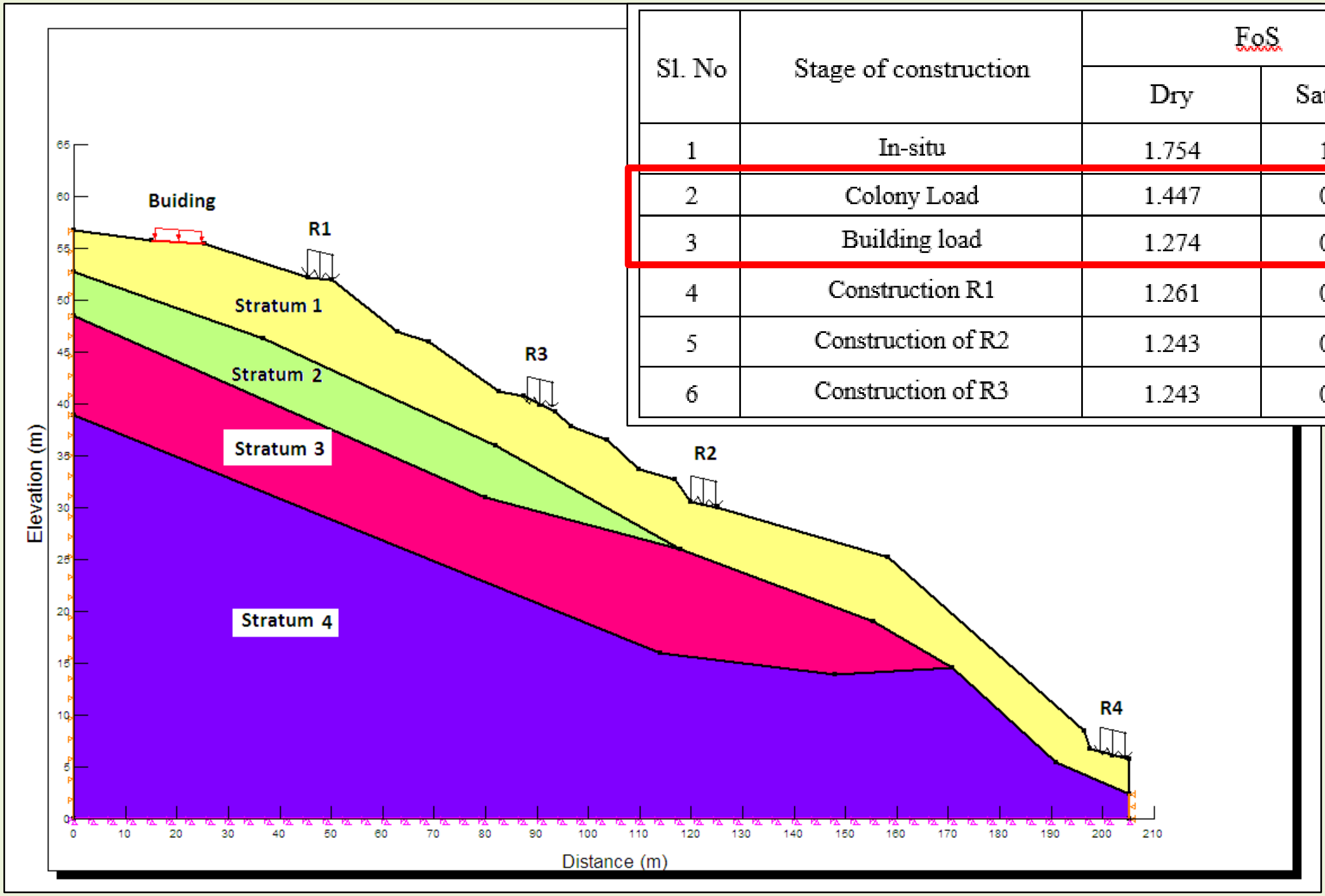
Layer	Type of soil	Material model (in Sigma/W)	Material model (in Slope/W)	Total stress parameter s_u (kPa)		E (MPa)	Unit weight (kN/m^3)
				Dry	Saturated		
1	Filling	Elastic plastic	Undrained $\phi = 0$	42	22	4.08	15
2	Moderately stiff Shale	Linear Elastic	Impenetrable bedrock	-	-	860	22
3	Weathered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

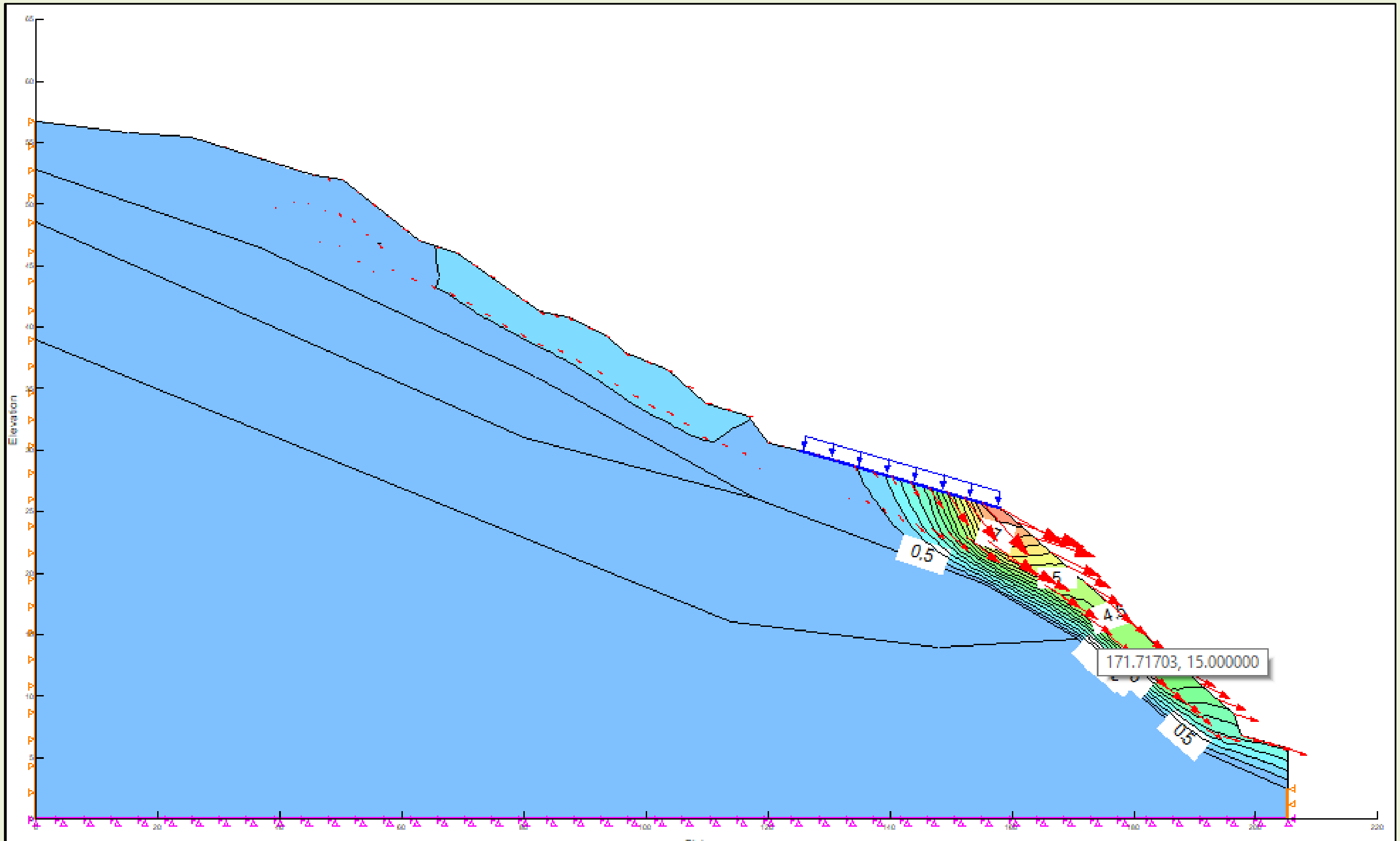
- Application of various loads in stages (as earlier)



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

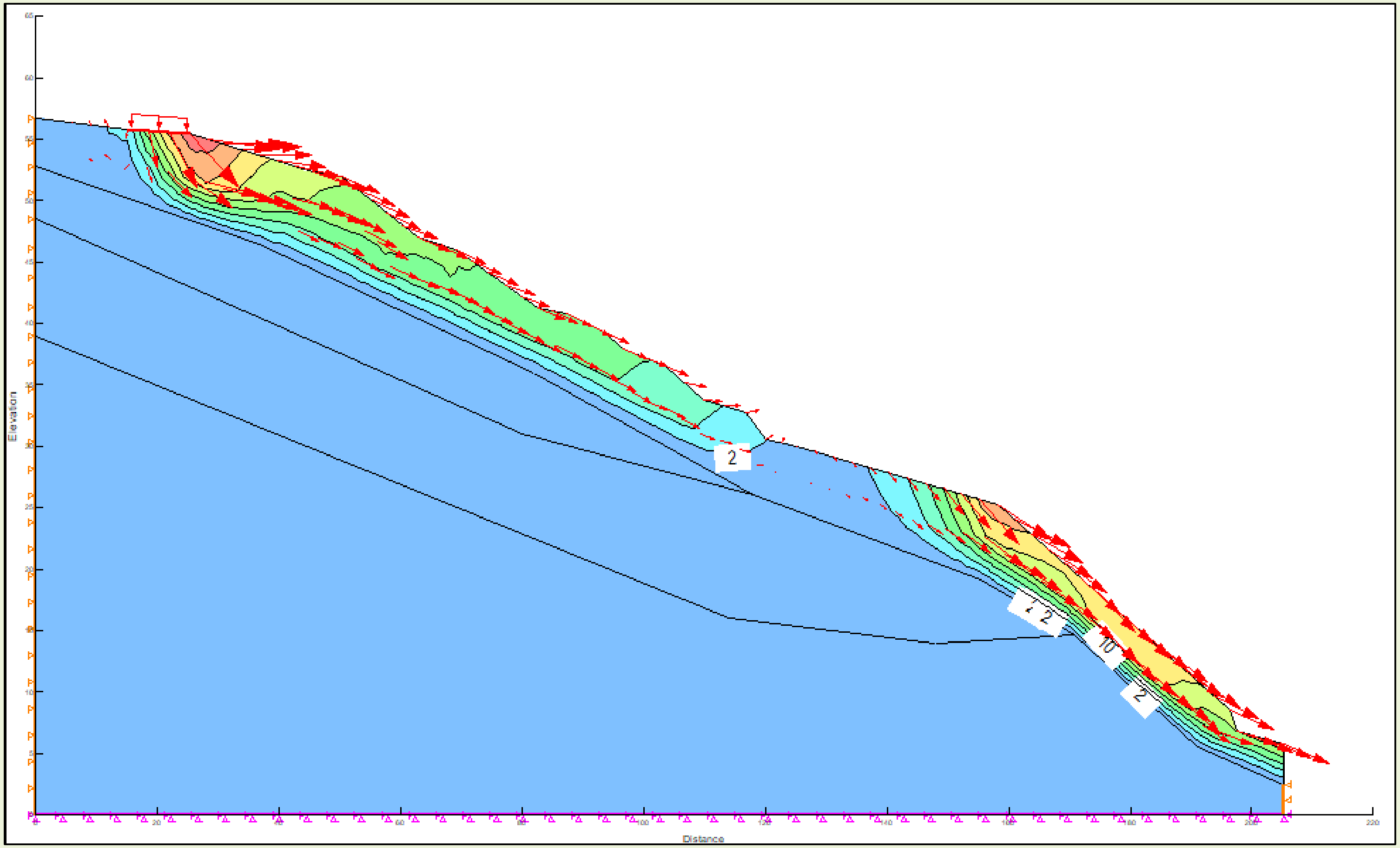
Displacement Results from Updated Analysis

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



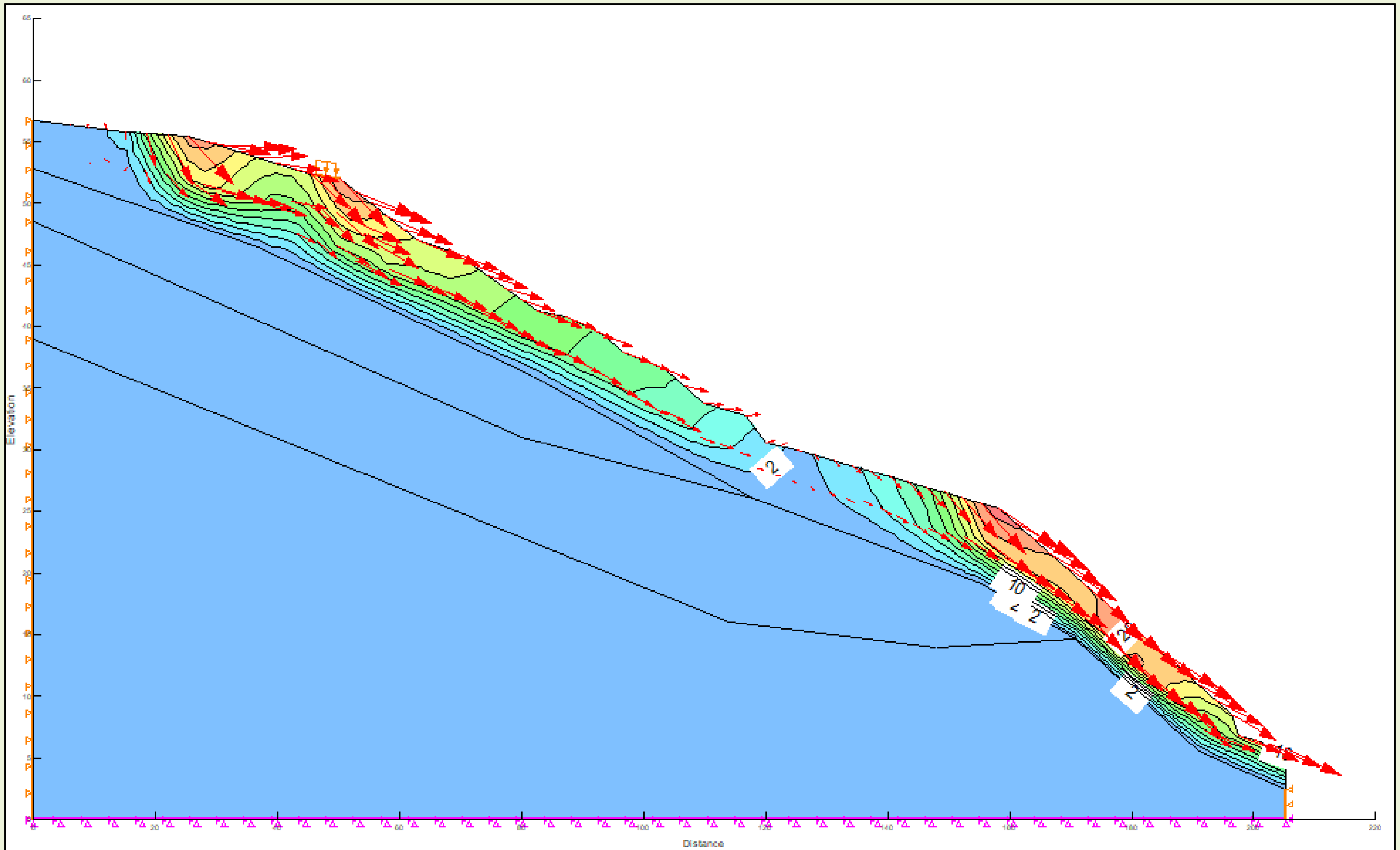
Displacement Results from Updated Analysis

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



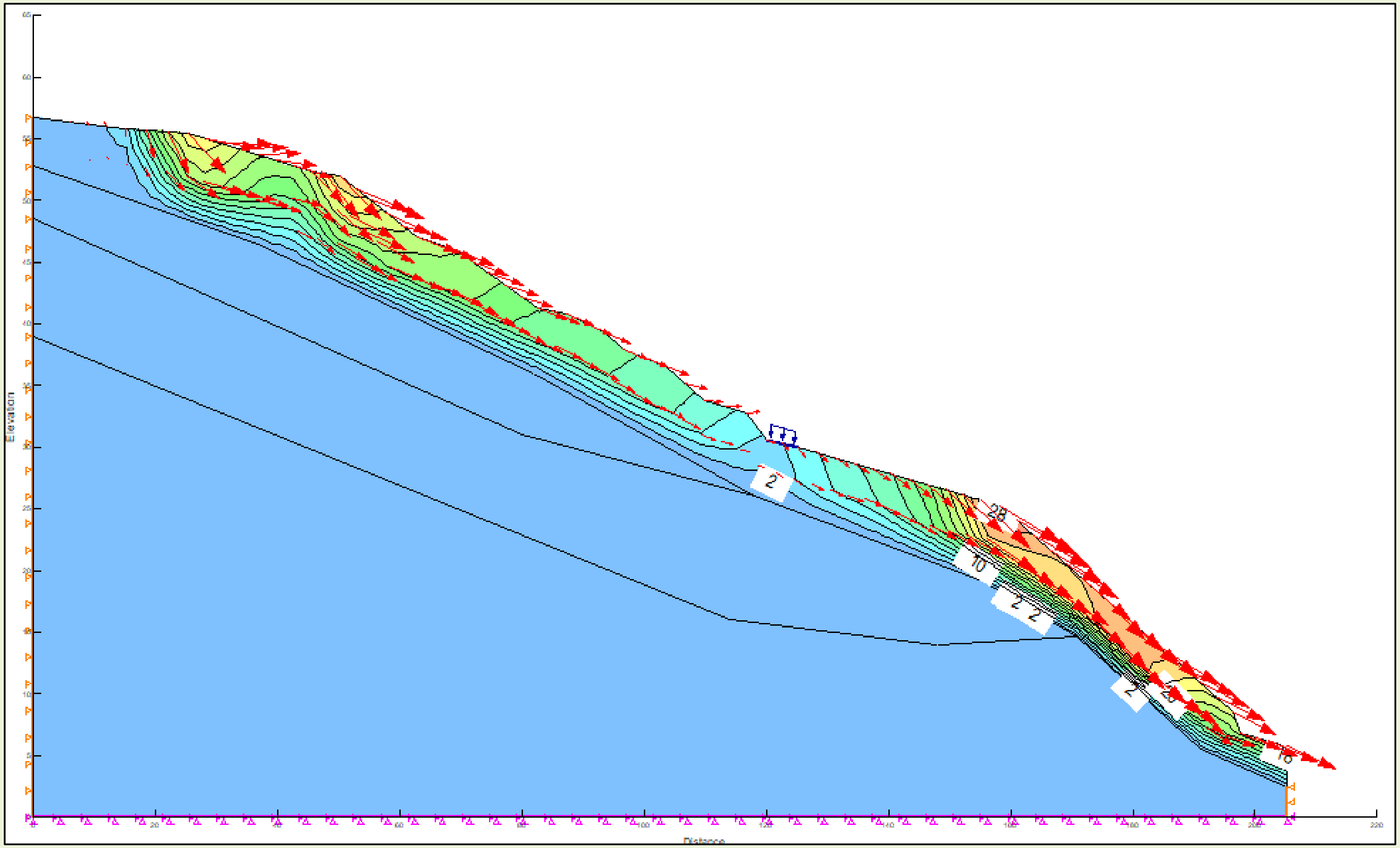
Displacement Results from Updated Analysis

- Application of RW1
  - *RW1 placed on loose deposit→ Doesn't help → Adds more load to invoke wider spread deformation zone*



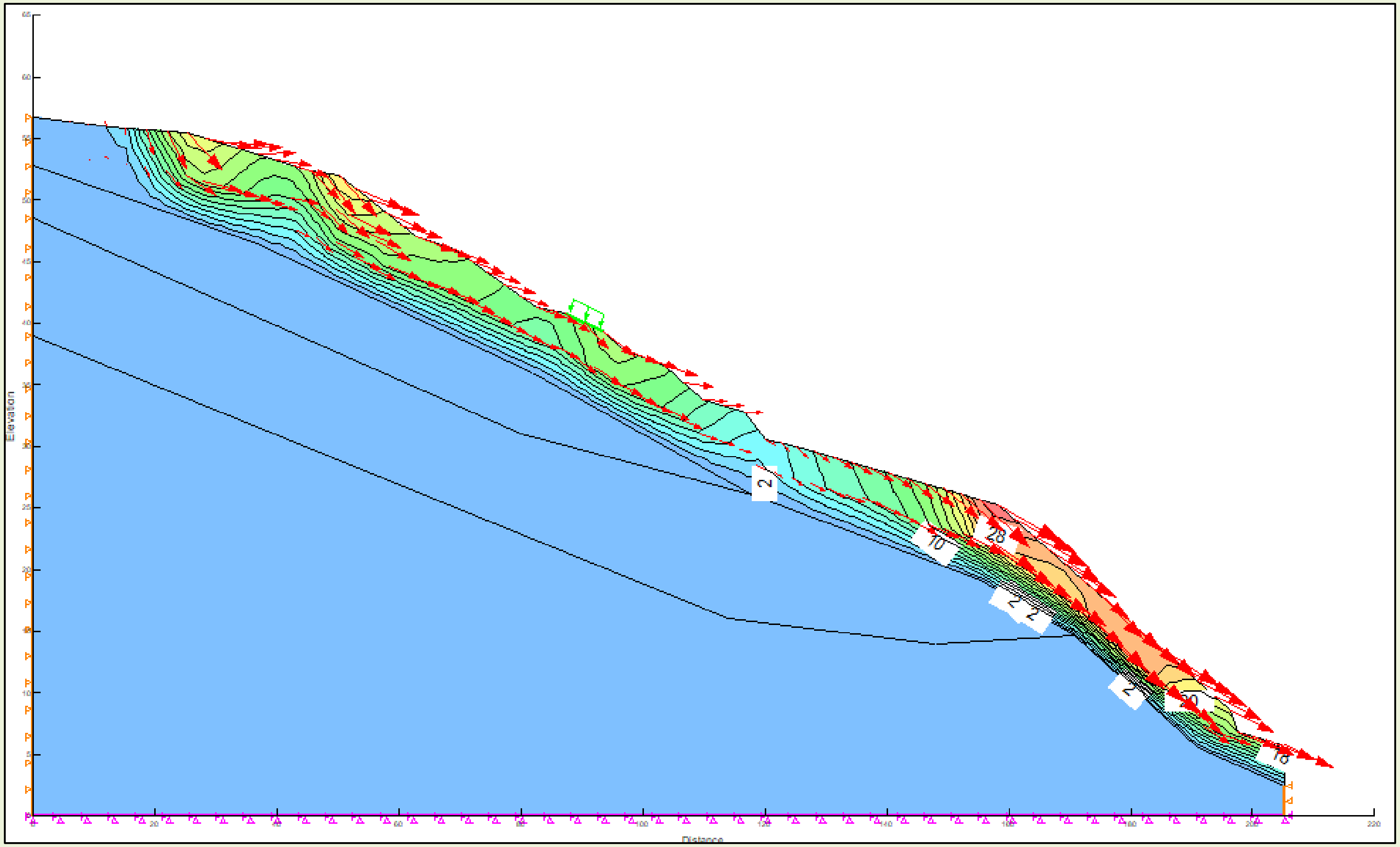
Displacement Results from Updated Analysis

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



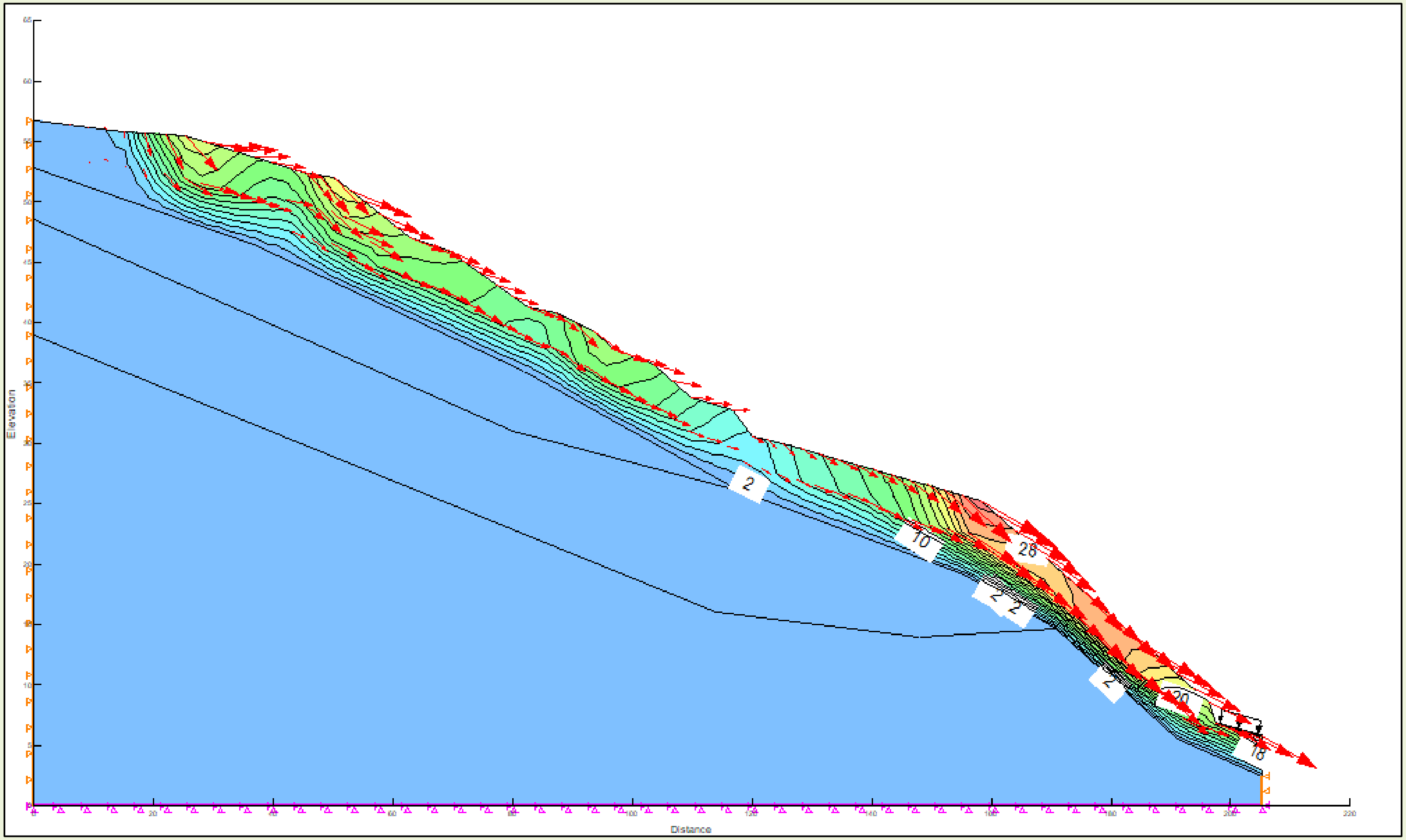
Displacement Results from Updated Analysis

- 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*



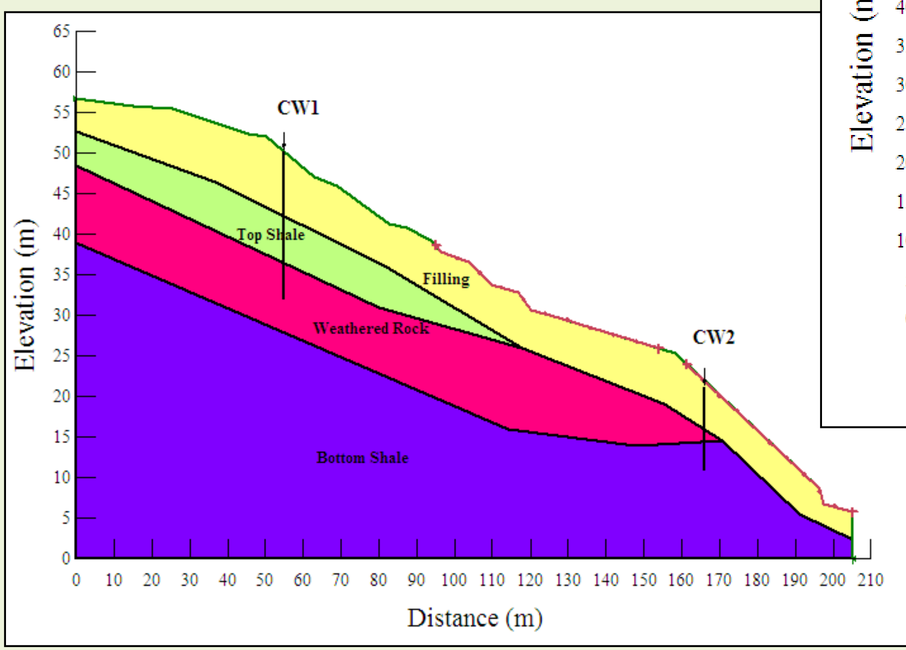
OUTCOME OF FORENSIC ANALYSIS

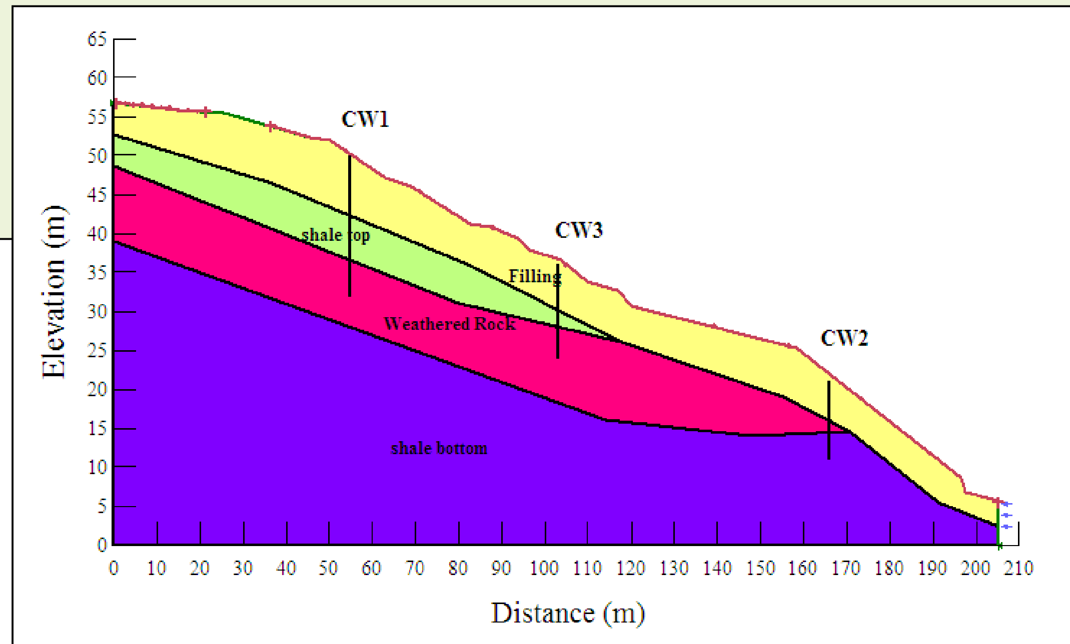
☺ Happy to identify the background reasons of cause, triggers and subsequent failure

☺ Matched well with the several observations made during field reconnaissance

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

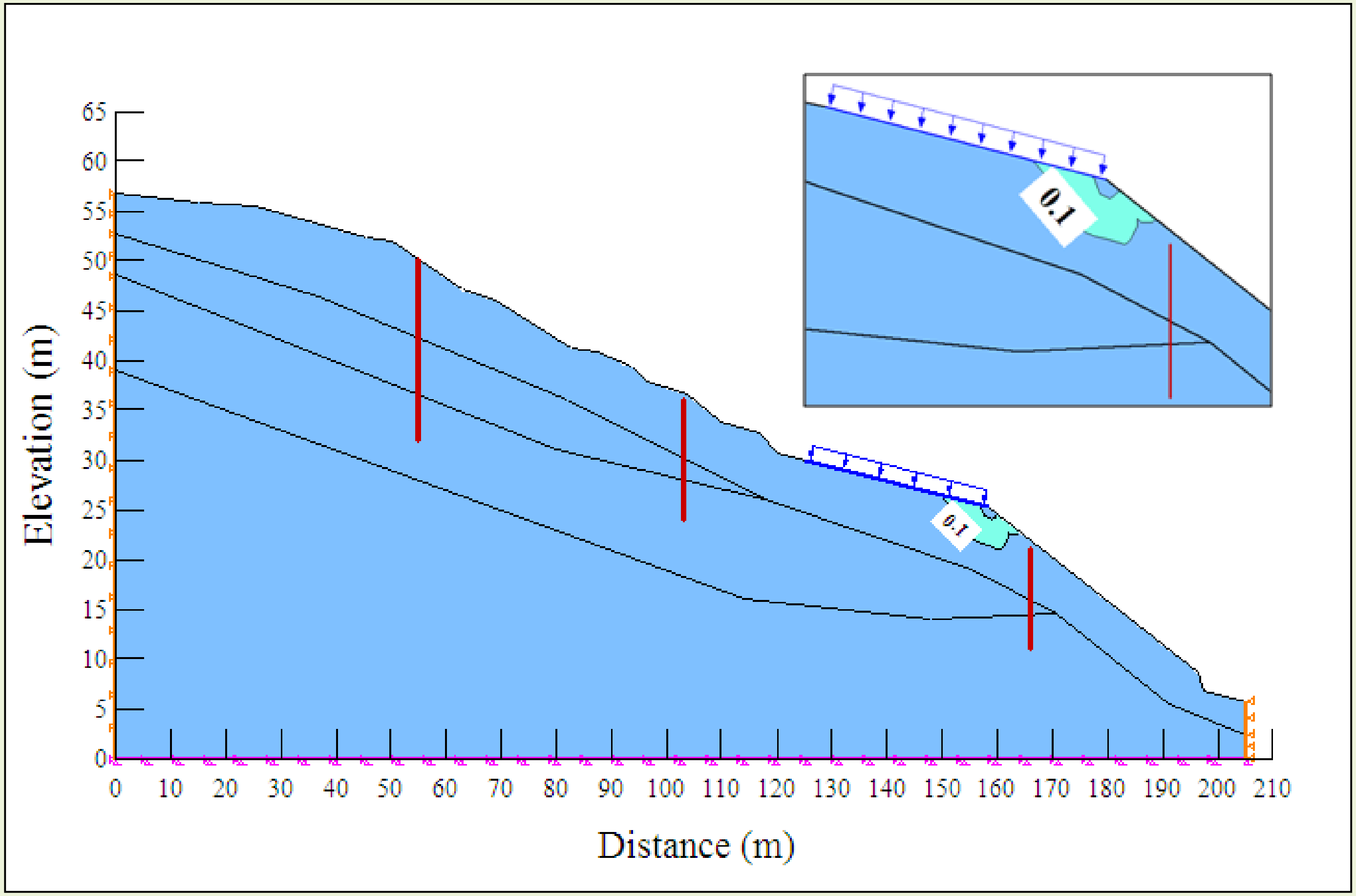
Adopted Stabilization Scheme

- 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*



Heritage Railway Station at Udaipur, Agartala, Tripura

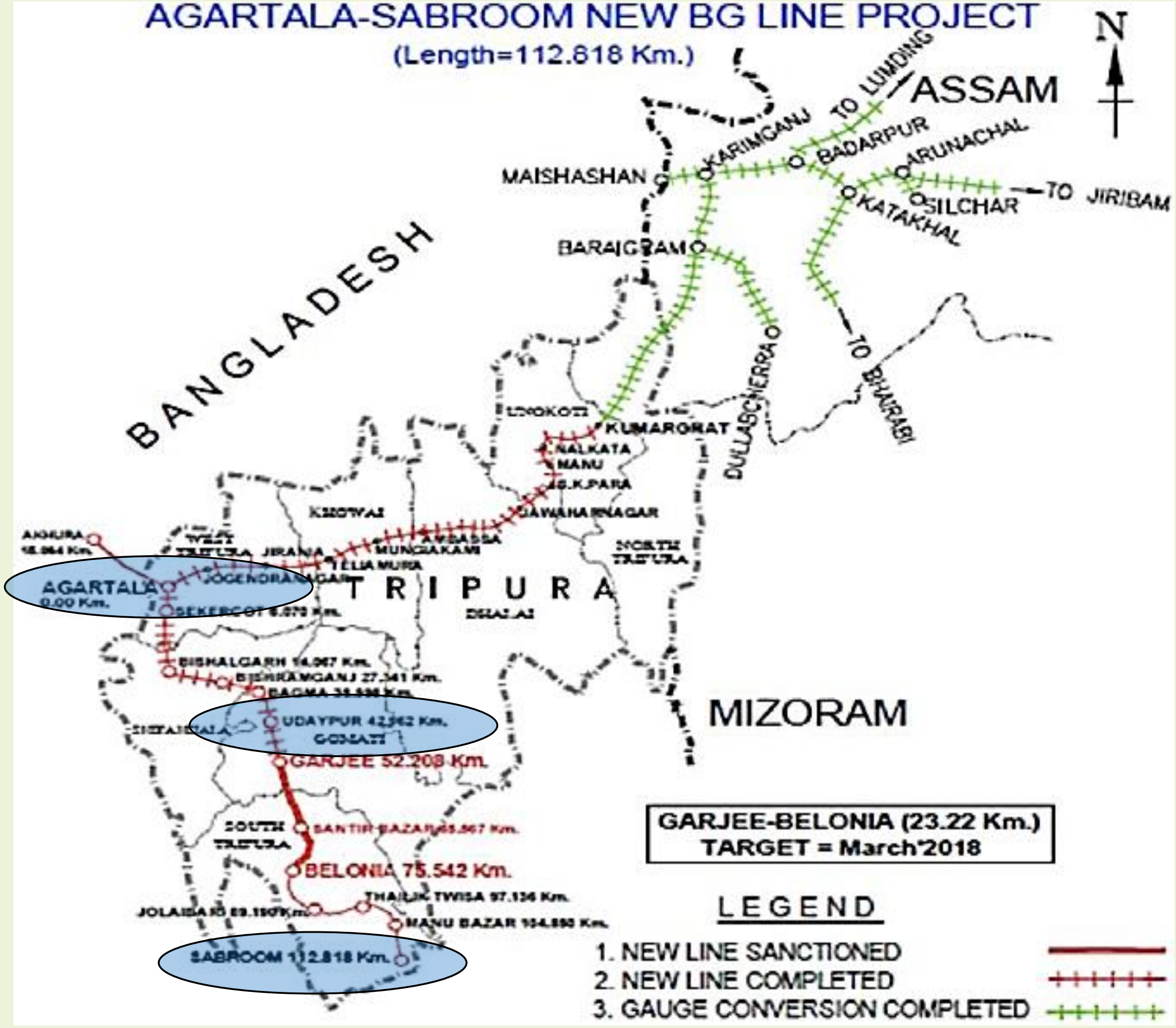
Construction in Very Difficult Subsoil

Ground Improvement Methodology

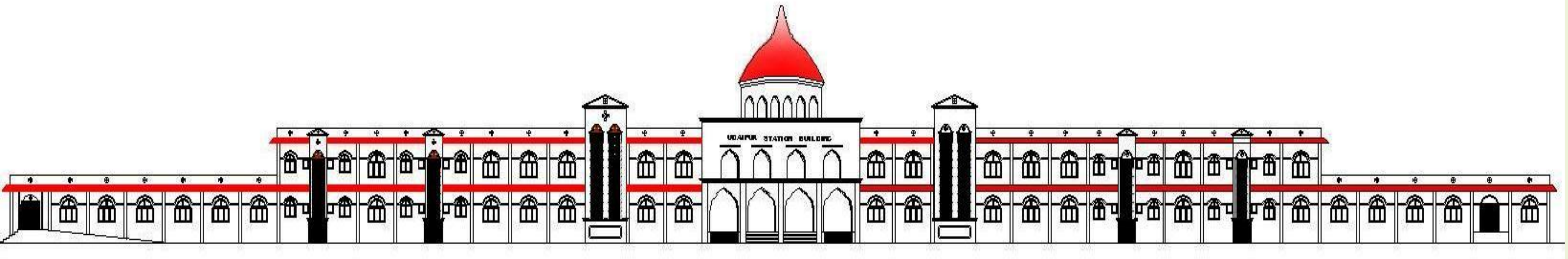
Project Walkthrough

- Udaipur railway station of Agartala-Sabroom New BG Line Project is situated between Km. 42.2 to 43.3 (Km. 0.00 at Agartala) in the state of Tripura.
- Station is situated in the Sukhsagar Lake of Udaipur.
  - *Water logged and marshy soil.*
  - *Existence of soft soil (Silty Clay) up to 13.3-20 m depth at various locations.*
  - *Out of 13.3 m, top 8 m is mixed with decomposed trees & wooden logs.*
- During construction of building differential settlement of piles.

Rail Links of Tripura (Proposed and Existing)



- Planned Developments
  - Railway station building and associated facilities
  - Railway line over embankment
  - Station Yard…



Chronology of the Problem

- Formation in station yard:
  - *Construction started in Dec' 2010.*
  - *Excessive settlement in the range of 1-2 m was noticed in Oct' 2011 when constructed embankment height reached 3 m.*
  - *The work continued & reached to a height of 5 m.*
  - *Huge Settlement, Cracks and Heaving of adjacent ground beyond toe (up to 25m on both sides of embankment).*
- Station building:
  - *Earth filling started in Nov' 2011.*
  - *Pile foundation started in Dec' 2011.*
  - *Pile foundation completed by Nov' 2012.*
  - *Differential settlement observed in Pile cap No. 13, 14 and 35 in May 2012*
  - *Cracks noticed in plinth beam and grade beams connected to above mentioned pile caps.*
  - *Brickwork for wall done in Jan' 2014 and differential settlement increased further.*


JCB
LIFTALL

3-Stage Remedial Measures

- Ground improvement of the adjoining area by Pre-fabricated Vertical Drain (PVD) for accelerating consolidation of soft soil.
  - *Arresting long-term settlement*

- Sheet piling of adequate retaining capacity around the station building before stripping off the existing surrounding embankment for PVD installation.
  - *Preventing the movement of embankment soil*

- Retrofitting of the station building by providing additional pile raft system and Carbon Fibre Reinforced Polymer (CFRP).
  - *Distribution of building load and Strengthening the building*

Embankments on Soft Soils

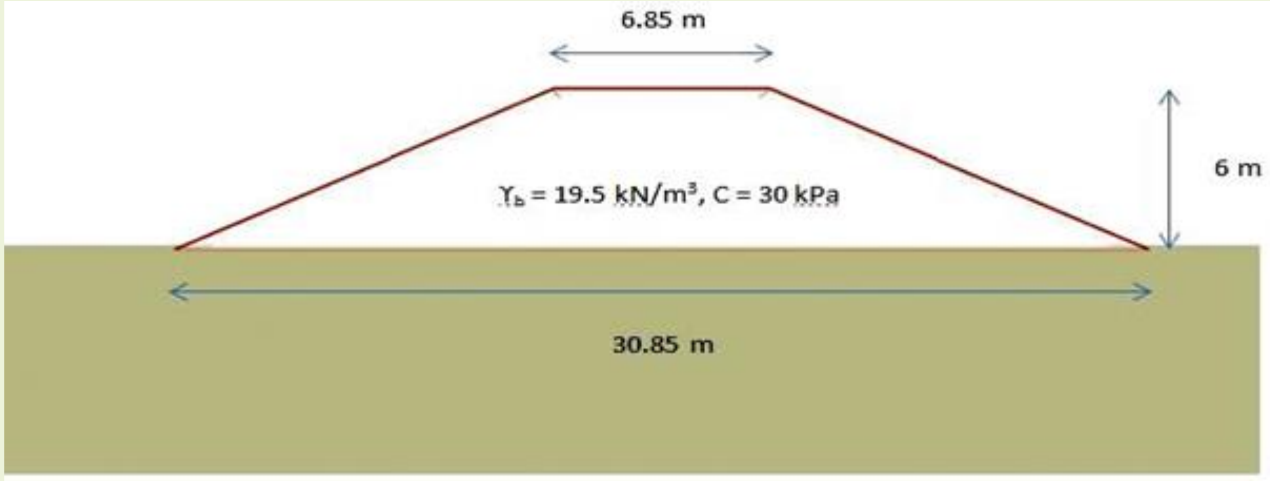
- Embankment constructions are required for highways, railways
  - *Lengths are in many kms*
- Many times the foundation soils are found to be of soft soils
  - *Low shear strength*
    - May not have sufficient bearing capacity
  - *High compressibility*
    - Undergo higher settlement
    - Resulting large differential settlements
- The design and construction of embankments over soft soil has always been a challenging task for engineers
  - *Proper engineered attention required during initial planning stage with proper ground improvement techniques*

Problems Faced during Embankment Construction

- Height of embankment = 6.2 m
- Embankment construction started in stages: Dec' 2010.
  - *September 2011*
    - First failure noticed at 3.0-3.5 m height:
  - *March 2012*
    - Large settlement of 5-5.2 m
    - Heaving up of ground until 30 m distance from the embankment
- After that further construction stopped

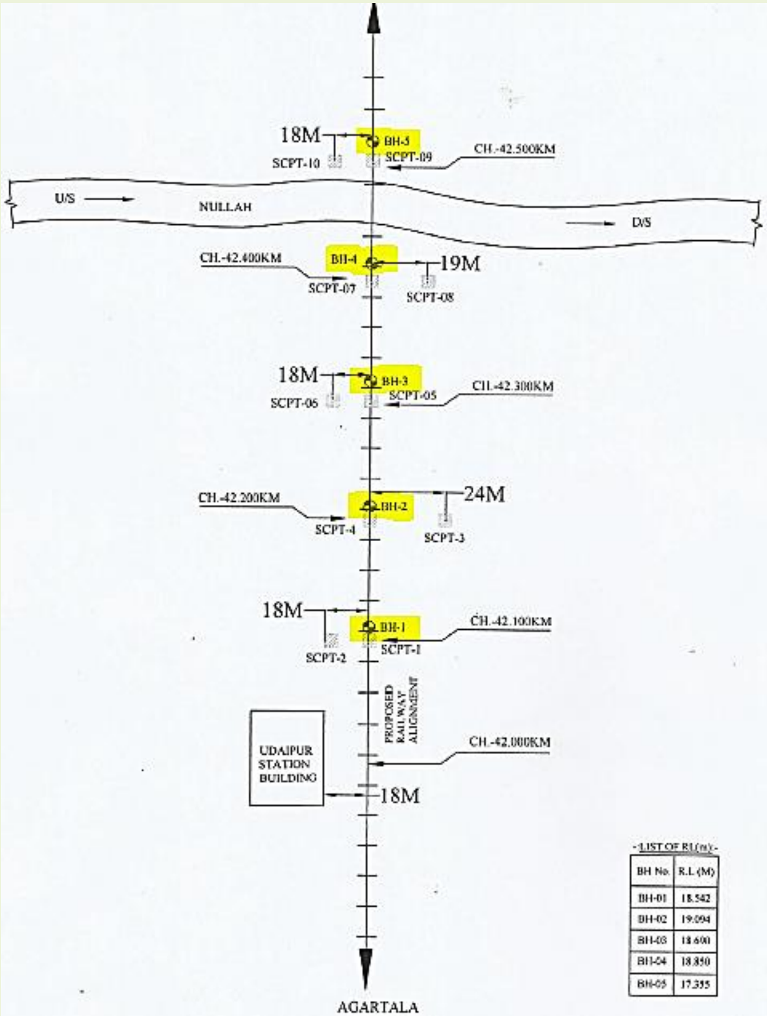
Problem Description

- New broad gauge (BG) railway line project (about 110 km) railway embankments are being constructed



- *The site of interest is in a water logging area*
- *During monsoon, the water level rises approx. to 3 – 4 m above the EGL*
- *The old soil reports available for the site indicate that the subsoil consist of soft soils up to about 12-13 m below EGL.*
- *Construction of the embankment was started during Dec 2010 directly on the natural soil without giving any pre-treatment.*

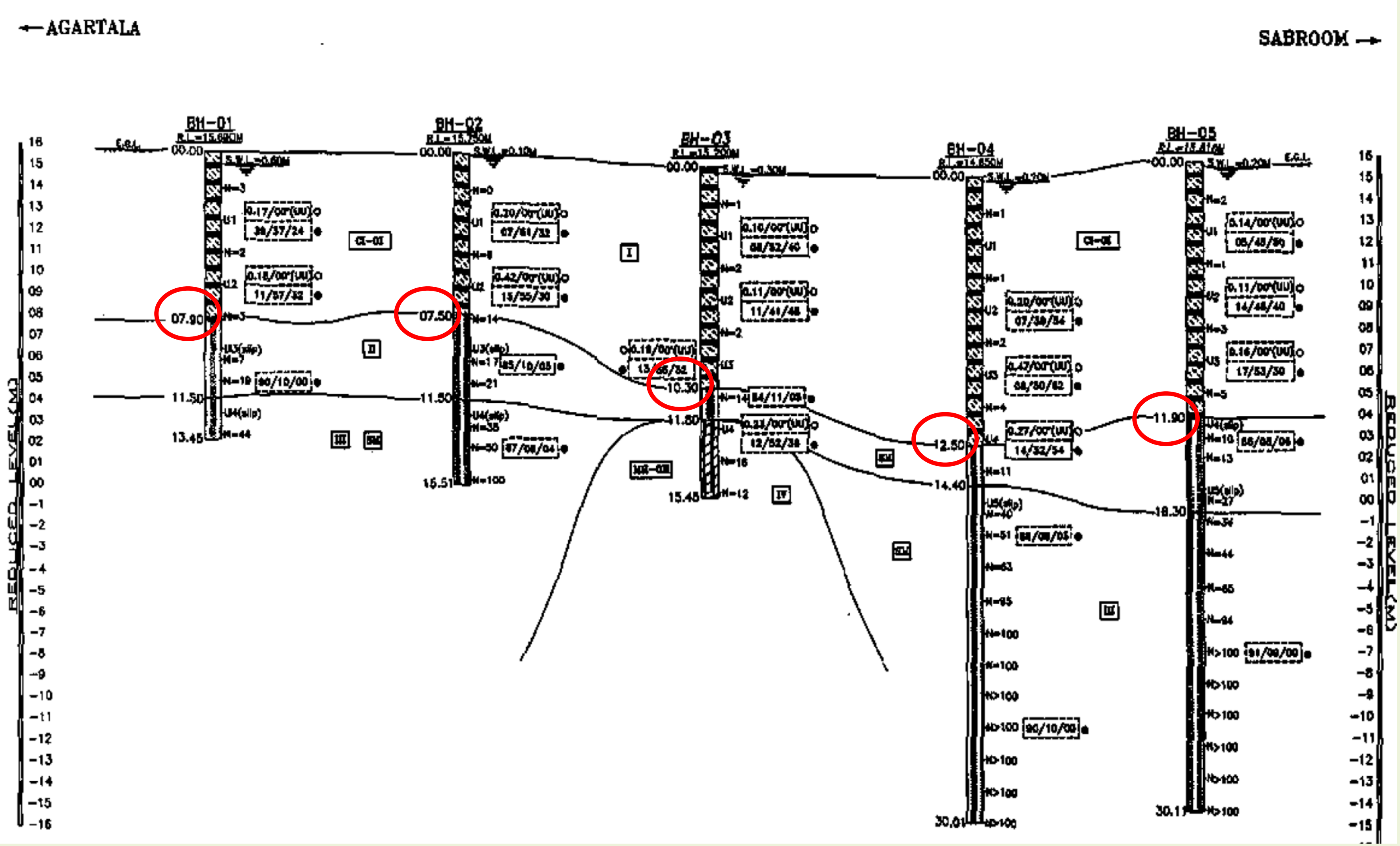
Field Investigation

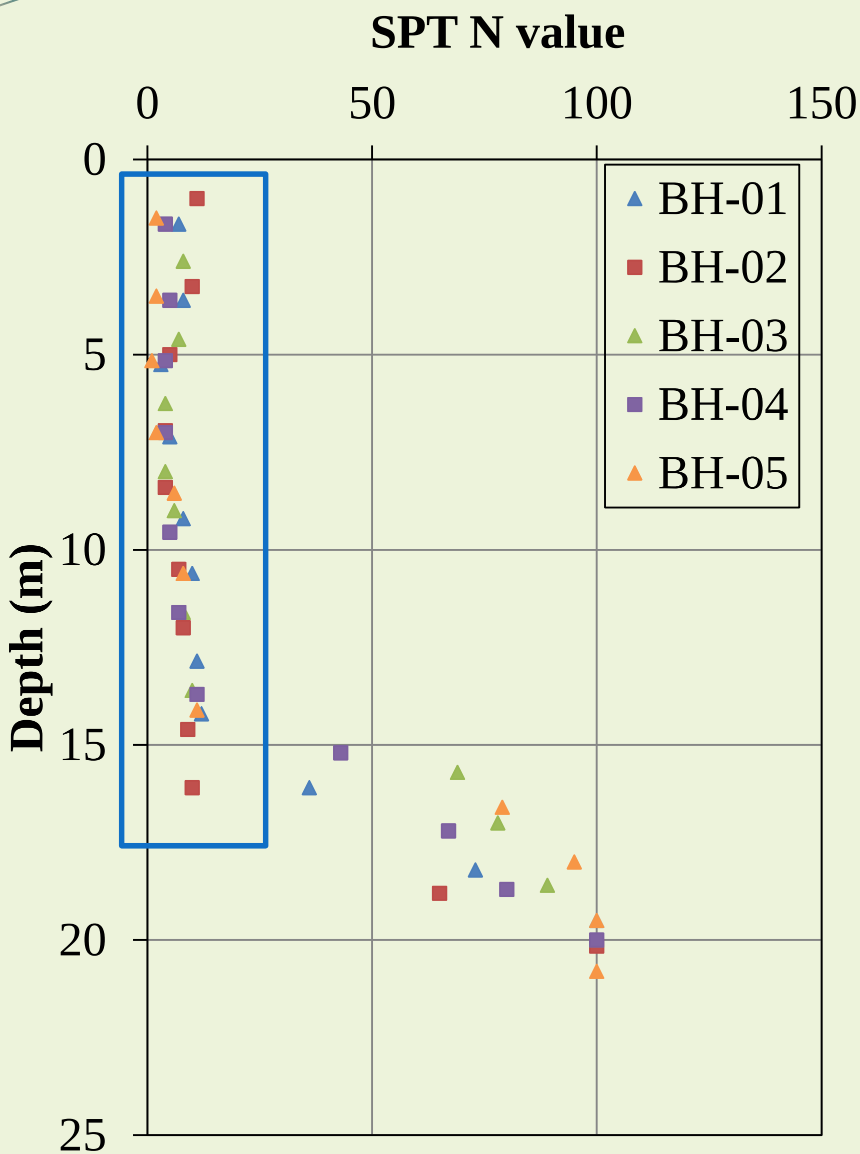


Bore Hole No.	Chainage (km)	G.L. (m)	Terminating Depth (m)	Standing Water Level (m)
BH-01	42.100	18.542	21.37	0.8
BH-02	42.200	19.094	21.87	2.5
BH-03	42.300	18.69	22.18	2.7
BH-04	42.400	18.85	21.48	2.8
BH-05	42.500	17.355	21.15	0.6

Locations of boreholes (CE Testing report, 2013)

Boreholes along the railway line



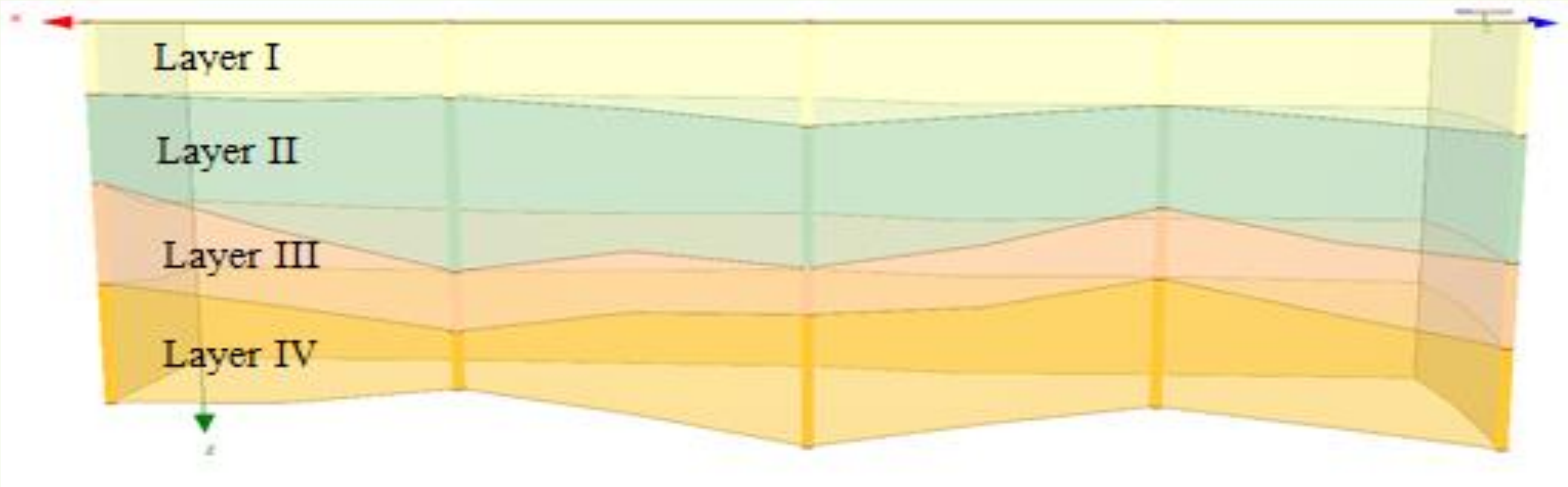


- Stratification of the subsoil

Stratum	SPT N-values	Depth (m)
Layer I	3 - 5	4
Layer II	5 - 10	5
Layer III	10 - 15	4
Layer IV	> 70	5

Tentative Subsurface Profiling

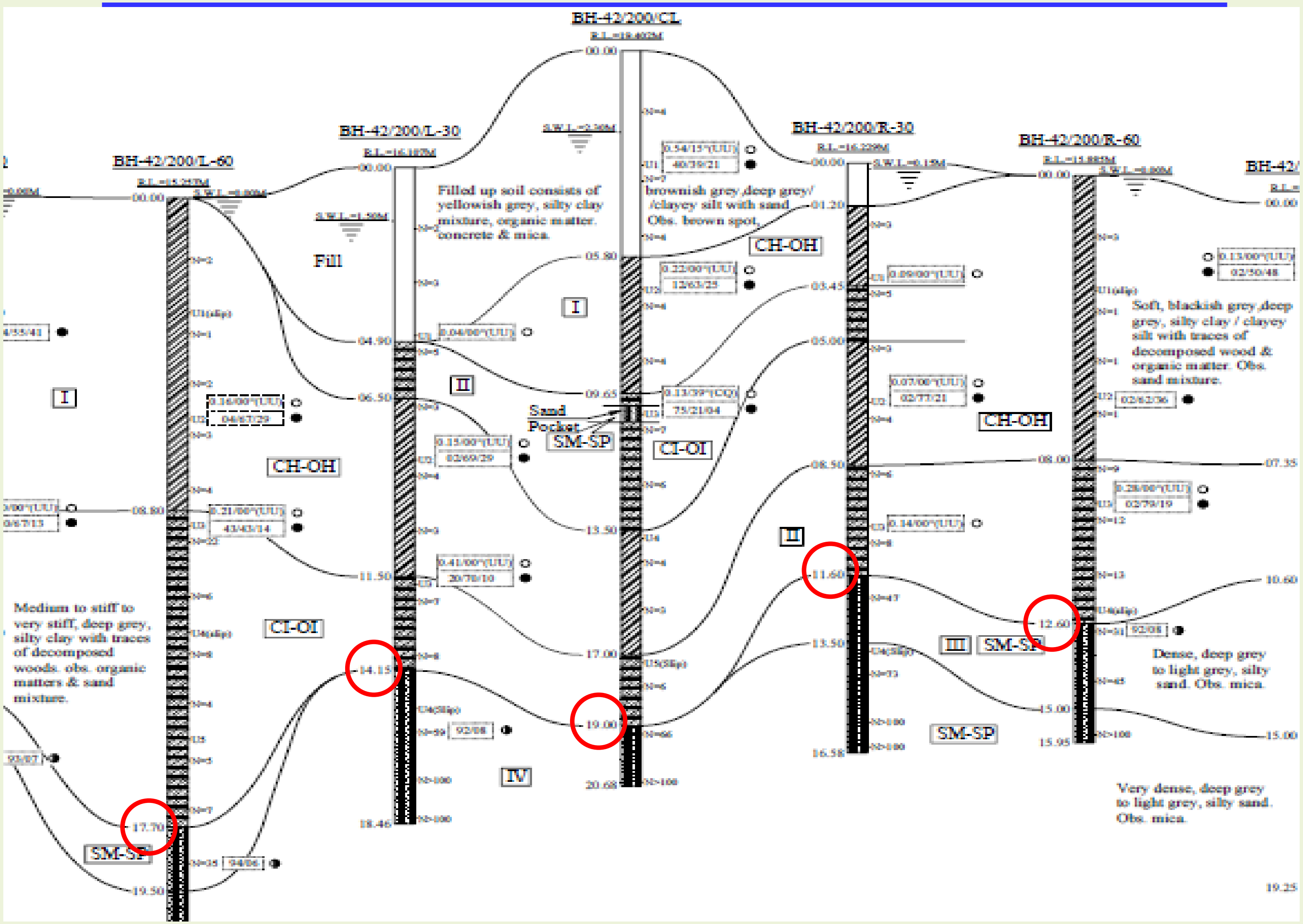
- From available bore log data of 5 boreholes, 4 different layers are identified.
- Depending on the SPT N-values, cohesion and physical appearance of the soil.



Investigations for Forensic Analysis

- New Borelogs in adjacent areas (outer embankment area)
- SPT
- SCPT
- UDS collection and Laboratory tests

Boreholes at the outer side of embankment



Boreholes at the outer side of embankment

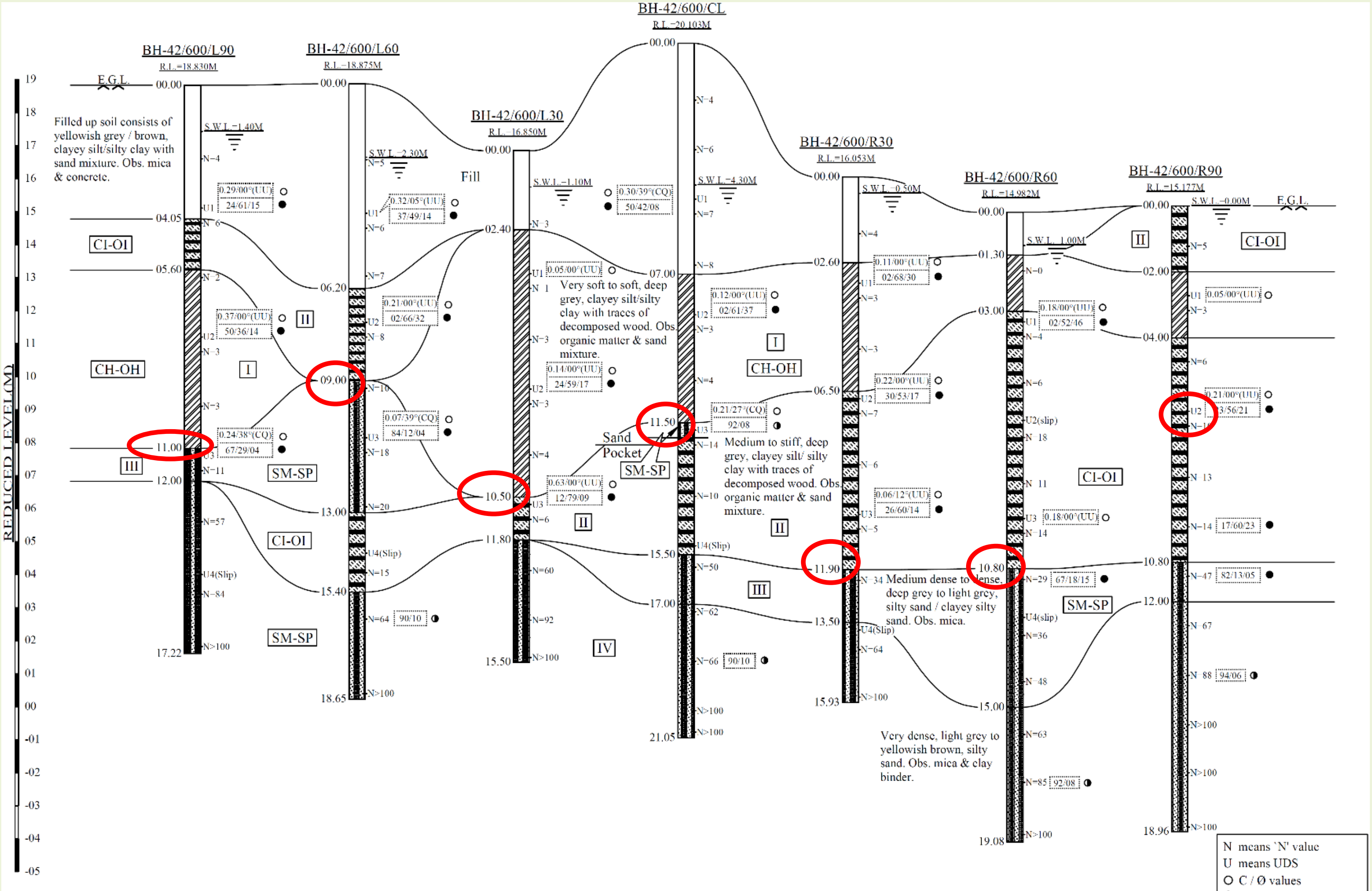
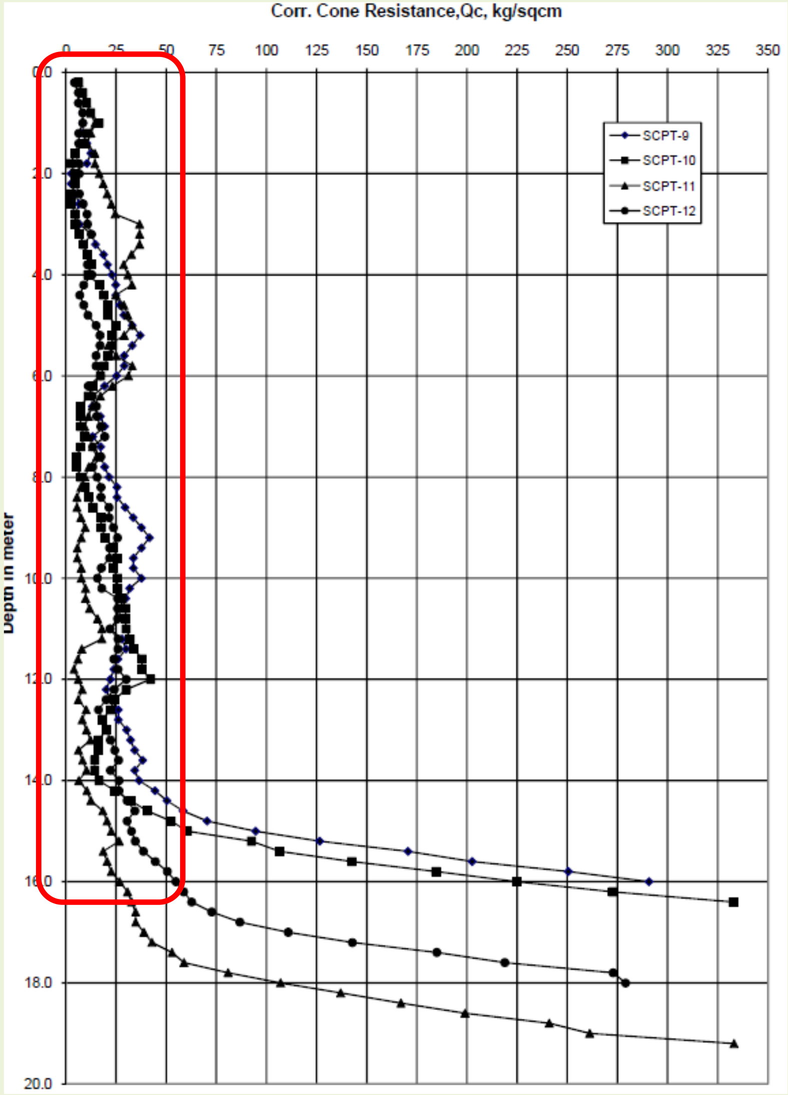
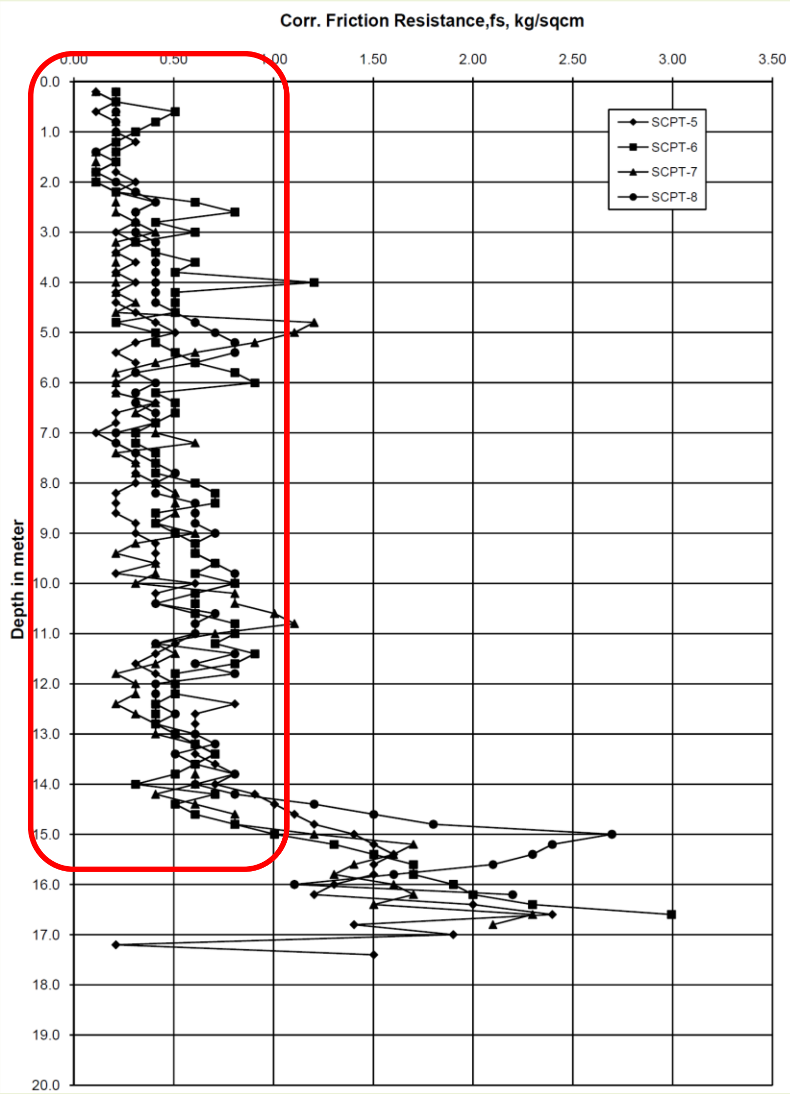


FIG. 2.05 : GENERALISED SOIL PROFILE

Typical SCPT results





Laboratory tests on Undisturbed Soil

- *Proper identification and classification of the sub-soil deposits is required.*
- *Undisturbed samples of 100 mm dia. were collected by means of pushing Shelby tubes.*
- *Index and Engineering properties of the soil were found out.*

Undisturbed sample cores obtained from the site location

Wax Coat

Bore hole details

Index Tests

a) Dry Sieve analysis, b) Hydrometer Analysis, c) Liquid Limit, d) Specific gravity by gravity bottles and e) Plastic Limit

Index Properties

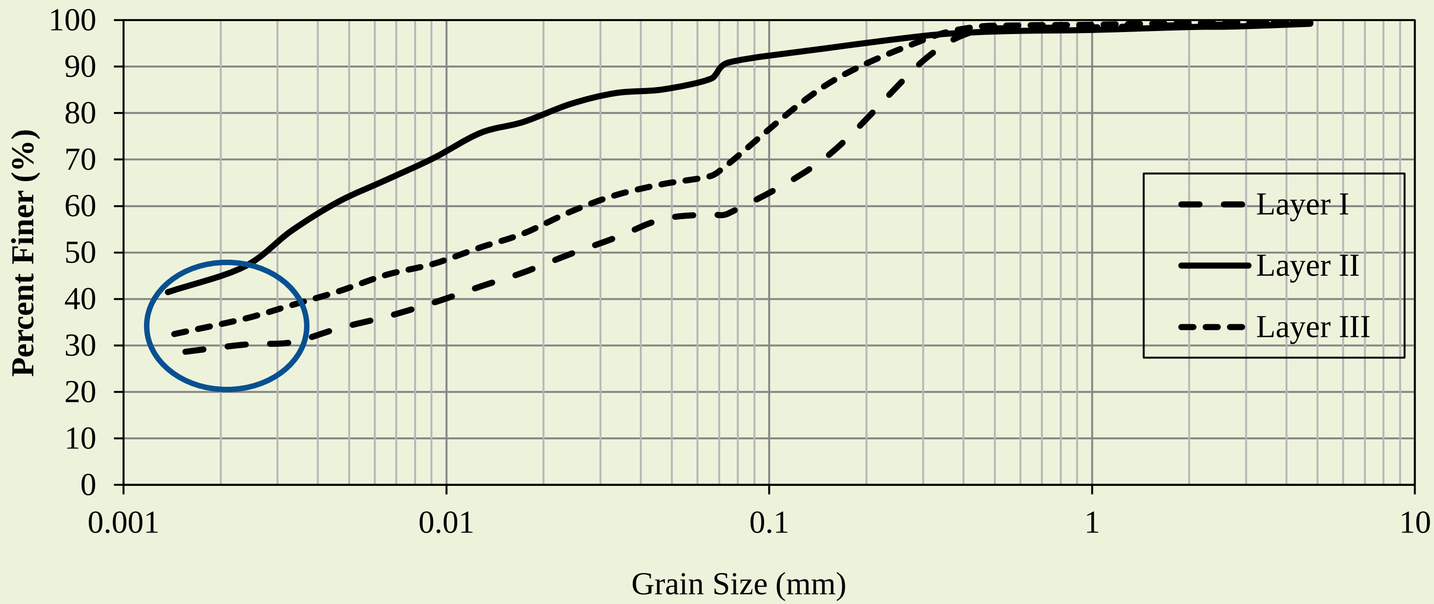
- Summary of index properties and classification of cohesive soil samples

Bore Hole	Sample Number	Depth (m)	Natural Moisture content, %	Specific Gravity	Liquid Limit	Plastic Limit
BH 01	UDS-02	1.65-2.10	28.57	2.511	42.6	-
BH 03	UDS-01	2.00-2.45	26.58	2.601	-	20
BH 01	UDS-04	5.25-5.70	82.52	1.398	55.2	19.04
BH 04	UDS-06	9.55-10.00	23.54	2.335	42.4	20.8
BH 03	UDS-04	6.25-6.70	40.29	2.725	47.6	-
BH 05	UDS-04	5.15-5.60	80	2.257	48.8	-

Particle size Distribution

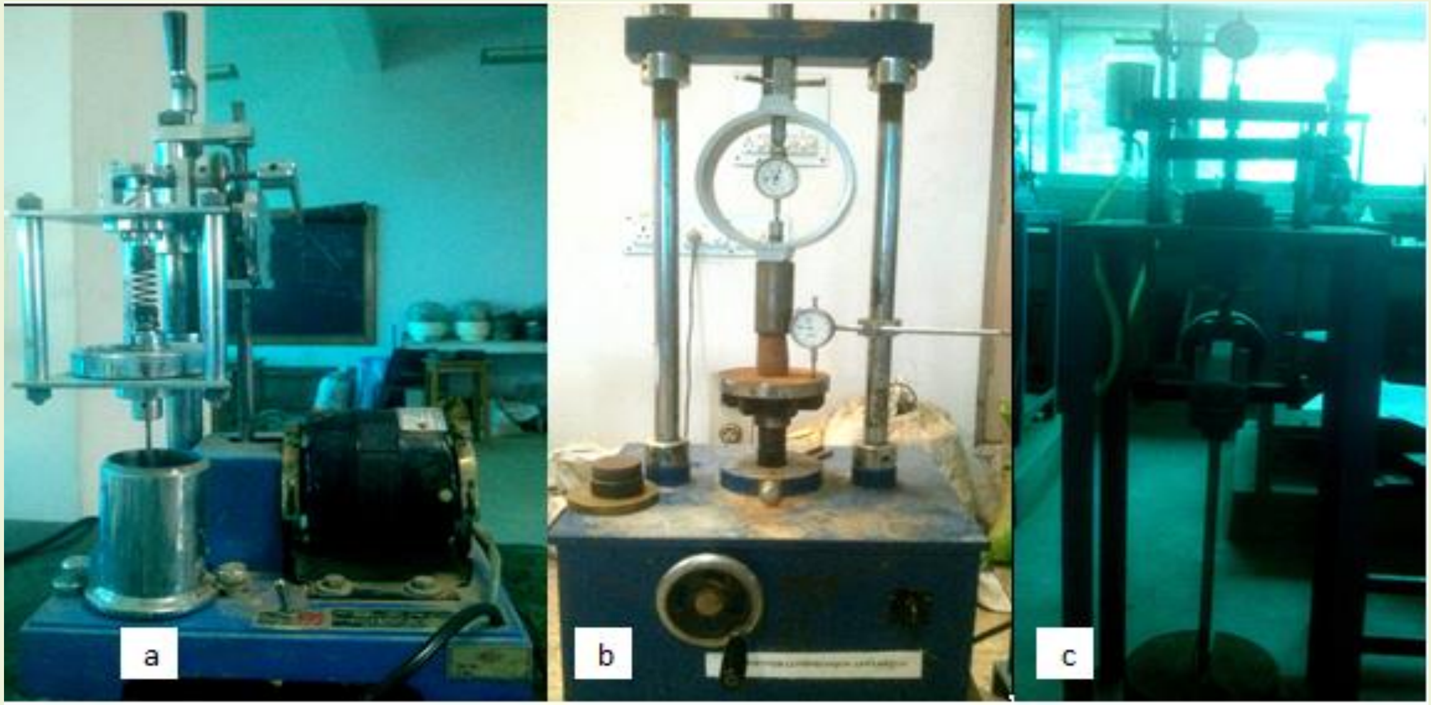
Particle size	Layer I (%)	Layer II (%)	Layer III (%)
Coarse sand (4.75mm-2mm)	0.5	2	0
Medium sand (2mm-0.425mm)	1.5	0	2
Fine sand (0.425m-0.075mm)	40	7	30
Silt (0. 075mm-0.002mm)	28	47	34
Clay (<0.002mm)	30	44	34

Both wet sieve and hydrometer analysis are conducted to complete particle size distribution of the sub-soil



Engineering Properties of soil

- *Undrained shear strength of the soil is found out from Unconfined Compression test (UCS) and laboratory Vane shear test.*
- *Compressibility and Permeability Parameters are found out from Oedometer test.*



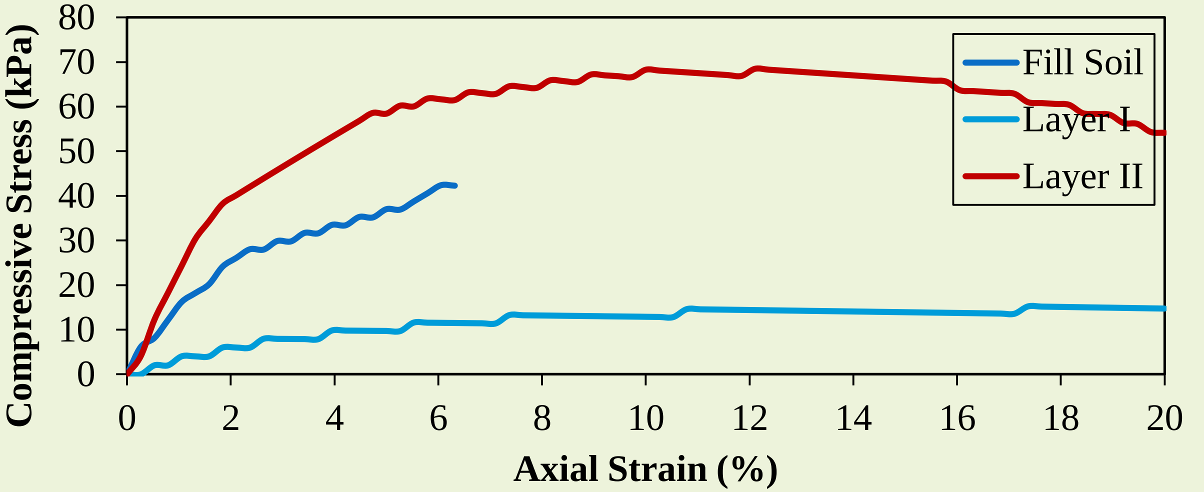
a) Vane Shear test b) Uniaxial compression test and c) Oedometer Test

Undrained Shear Strength

Bore Hole	Sample Number	Depth (m)	UCS		Vane Shear		Consistency
			Moisture Content, %	c_u (kPa)	Moisture Content, %	c_u (kPa)	
BH 01	UDS-02	1.65-2.10	28.57	26.48	30.21	34.3	Soft
BH 01	UDS-04	5.25-5.70	75.23	12.17	82.52	7.775	Very Soft
BH 01	UDS-10	16.10-16.55	-	7.03	-	-	Very Soft
BH 03	UDS-01	2.00-2.45	26.58	55.69		16.01	Very Soft
BH 03	UDS-04	6.25-6.70	30.92	28.61	40.29	44.36	Medium
BH 04	UDS-04	5.15-5.60	-	-	21.58	105.2	Stiff
BH 04	UDS-06	9.55-10.00	27.67	41.87	23.54	53.97	Medium
BH 05	UDS-02	1.50-1.95	15.16	54.11	20.36	25.61	Stiff
BH 05	UDS-04	5.15-5.60	-	-	80	14.17	Soft
BH 05	UDS-08	12.5-12.6	34.54	22.5	24.4	54.88	Soft

Distribution of undrained shear strength is very erratic (mostly soft) – conducive of large differential settlements

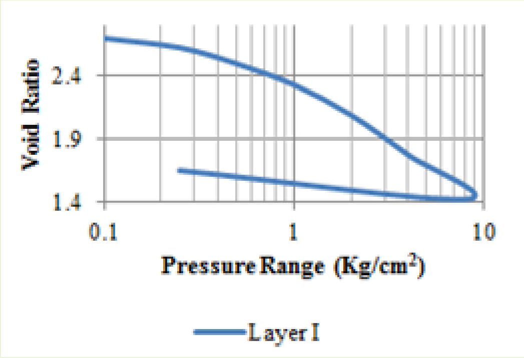
Modes of failure

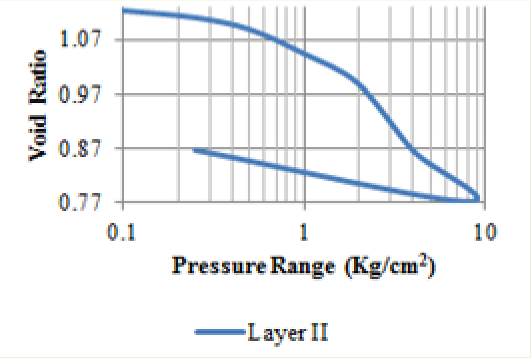


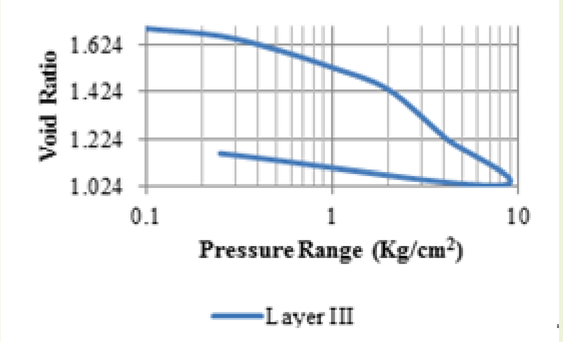
Stress strain response of different layers under unconfined compression

Consolidation Tests

- Typical void ratio against effective stress for different layers of the soil are drawn from the readings of consolidation test.
- C_c and C_v values are calculated from the graphs.







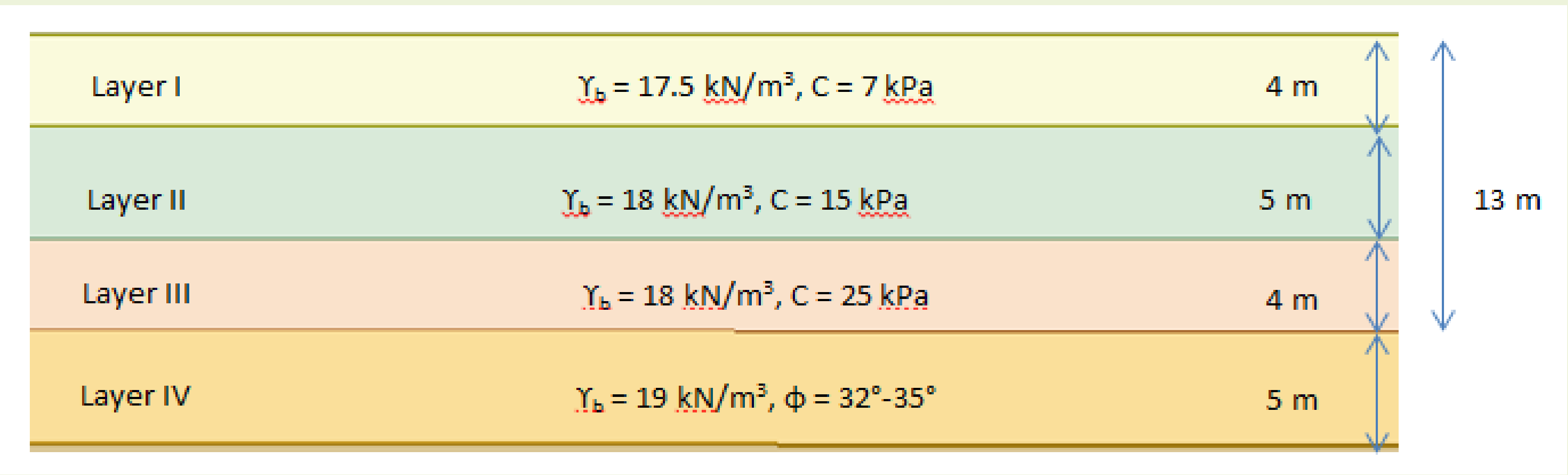
Borehole	Depth (m)	Moisture Content, w%	Initial Void Ratio, e_0	C_c	C_v (cm^2/sec)	k_v (cm/sec)
UDS-04	10.65-11.10	40.8	1.126	0.365	0.000576	1.57×10^{-08}
UDS-03	9.0-9.45	61	1.702	0.664	0.001369	5.05×10^{-08}
UDS-03	10.0-10.45	87.9	2.719	1.079	0.000838	6.04×10^{-08}

Subsoil Parameters

Stratum	Fill	Layer I	Layer II	Layer III	Layer IV
Unit Weight (kN/m^3)	19.5	17.5	18	18	19
Specific Gravity	2.45	2.2	2.34	-	-
Cohesion (kPa)	30	7	15	25	0
Angle of Internal Friction, φ °	-	-	-	-	32-35
Natural Moisture content	24%	48%	23.54%	34.54%	-
Liquid Limit	42%	50%	42.40%	-	-
Plastic Limit	20%	19%	20.80%	-	-
Plasticity Index	22%	31%	21.60%	-	-
Compression Index, C_c	-	1.079	0.365	0.664	-
Coefficient of Consolidation, C_v (cm^2/sec)		0.000838	0.000576	0.001369	
Permeability (cm/sec), k_v	-	8.76×10^{-9}	1.57×10^{-8}	5.05×10^{-8}	-
Initial void ratio, e_0	-	2.719	1.126	1.702	-

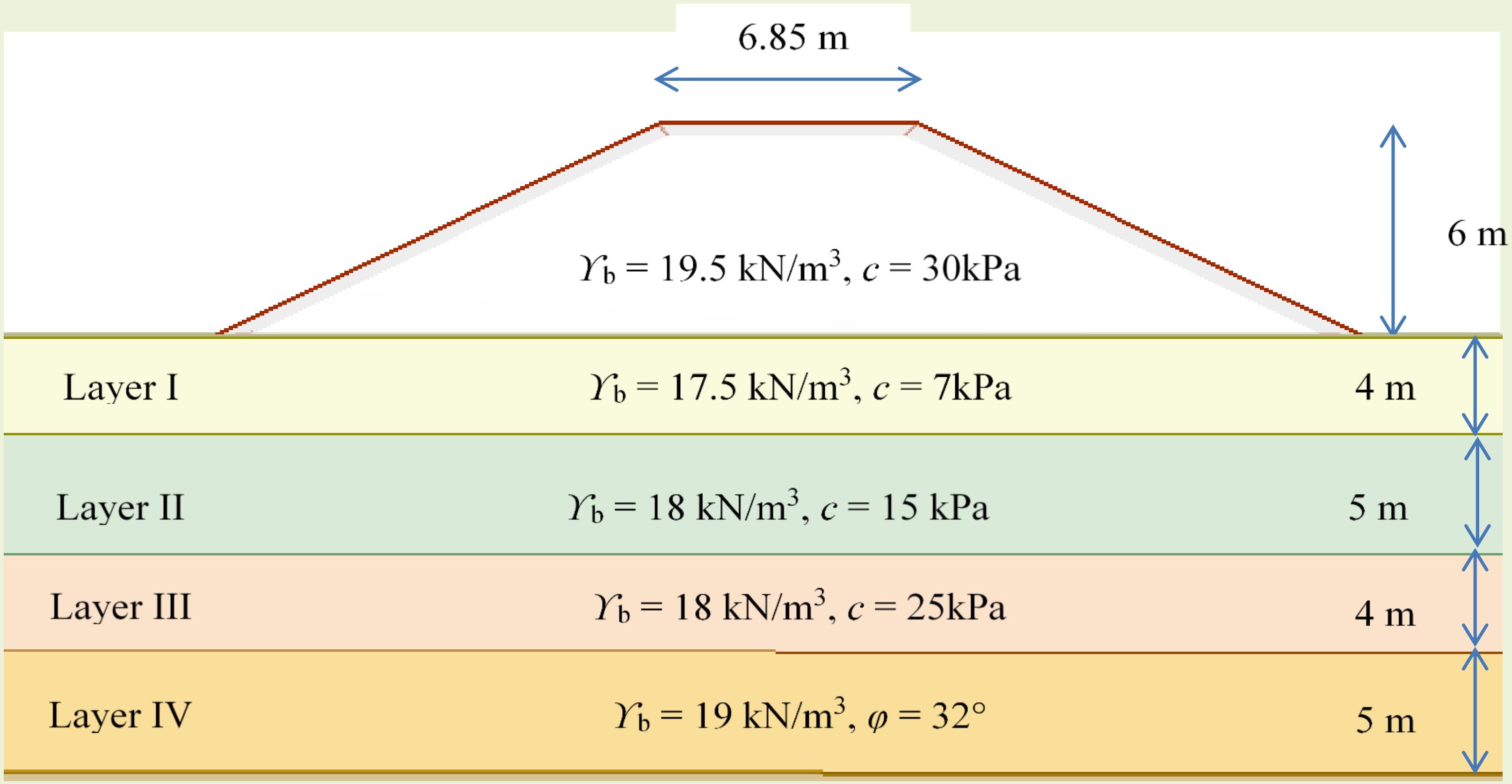
Sub-soil Profile with properties

- The ultimate soil profile with parameters found out from the laboratory tests.
- These properties will be used in modeling in Settle3D software.



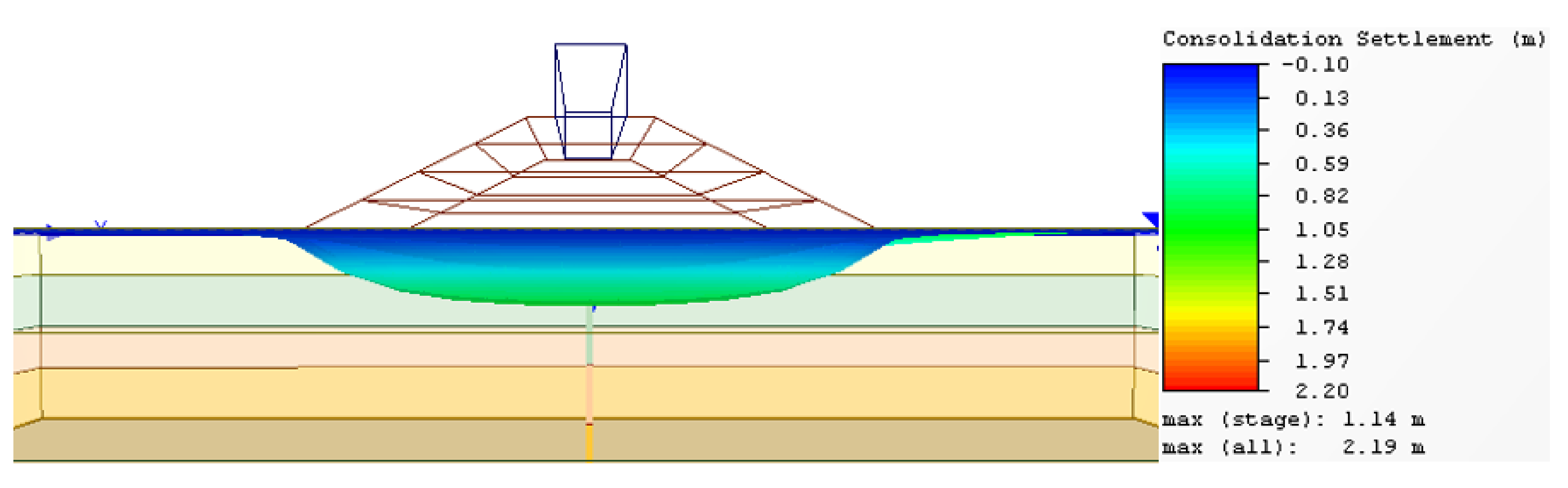
Railway Embankment Resting on Soft Soil

Soil profile considered for the analysis



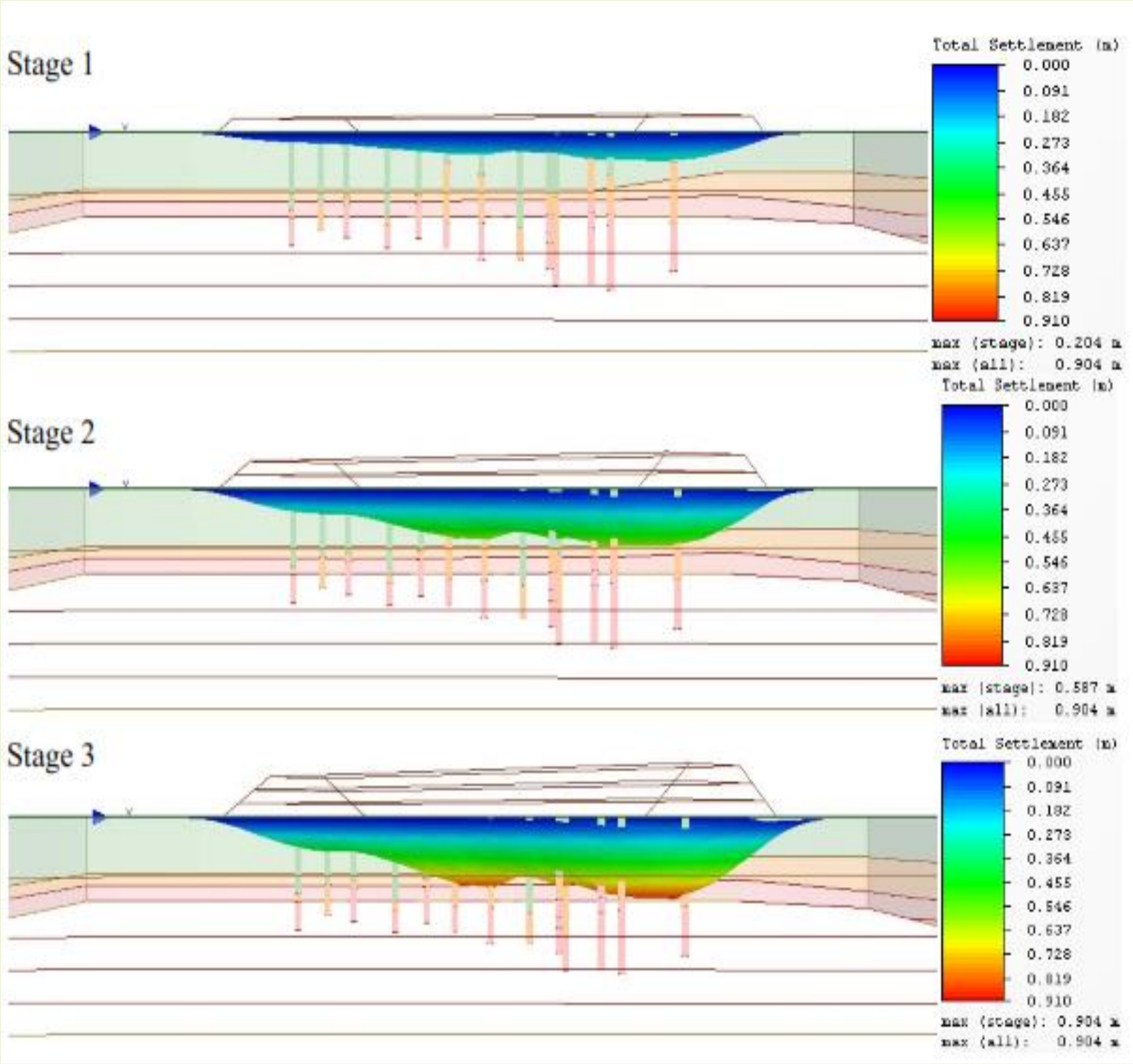
Analysis of Embankment stability

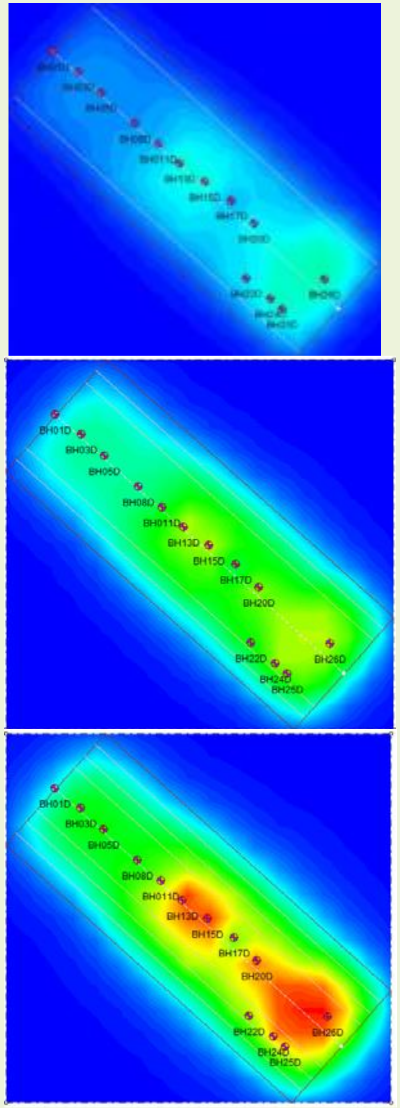
- Using SETTLE3D software (Rocscience 2014)
  - *The primary consolidation settlement of 0.505 m, 0.755 m, and 0.951 m after 3.14 m, 4.64 m, and 6 m embankment heights were observed.*



- Numerical study confirms large deformations observed in the field
- Warrants for ground improvement

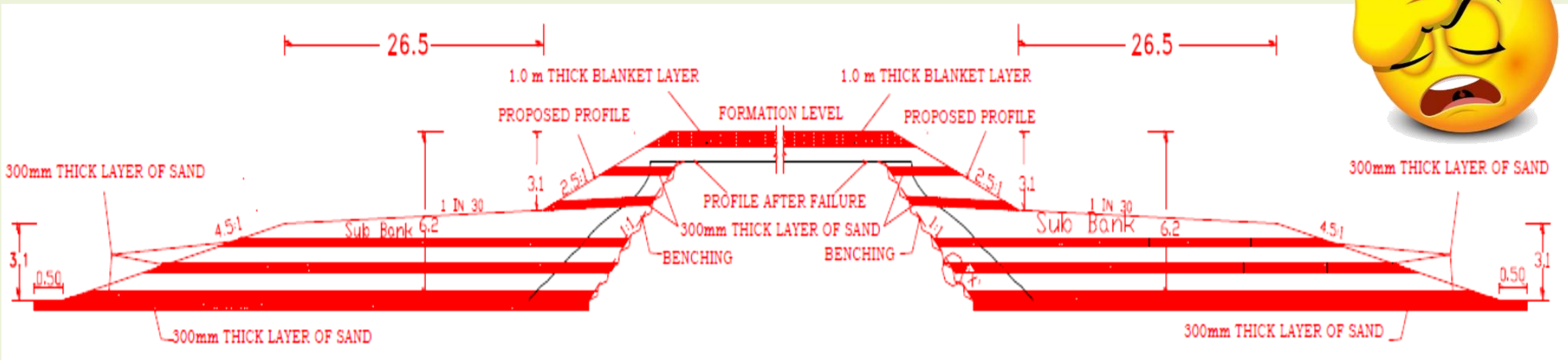
Large Differential Settlements along the Embankment





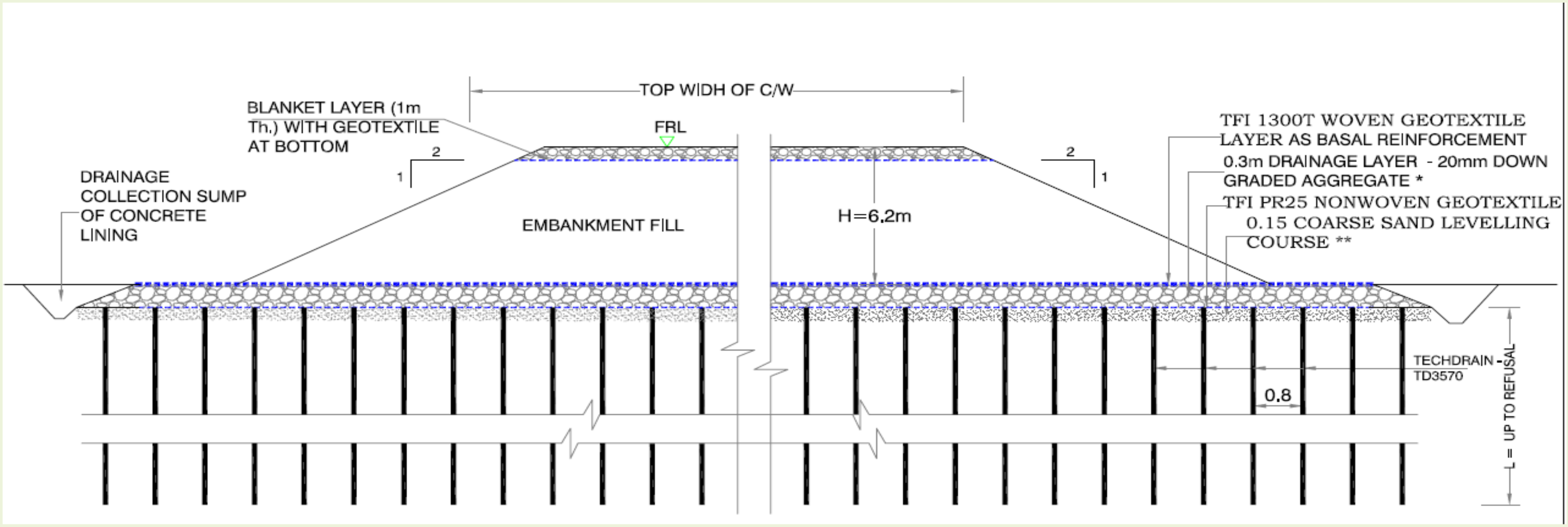
Initial Recommendation

- Construction of widened embankment encompassing failed one
  - *Having slope of 4.5:1 for 3.1 m height from GL and slope of 2.5:1 for rest 3.1m height of embankment with 26.5 m wider sub bank at 3.1m from top.*
  - *Stage Construction with measurement settlement & pore pressure.*
- Requirement of Additional land.
- Requirement of more time for stage construction
- Possibility of settlement of central embankment in future



Restoration of embankment

- Prefabricated vertical drains (PVDs) or sand piles with preloading
  - *Owing to the time constraint of the project and unavailability of stone aggregate nearby to the site*



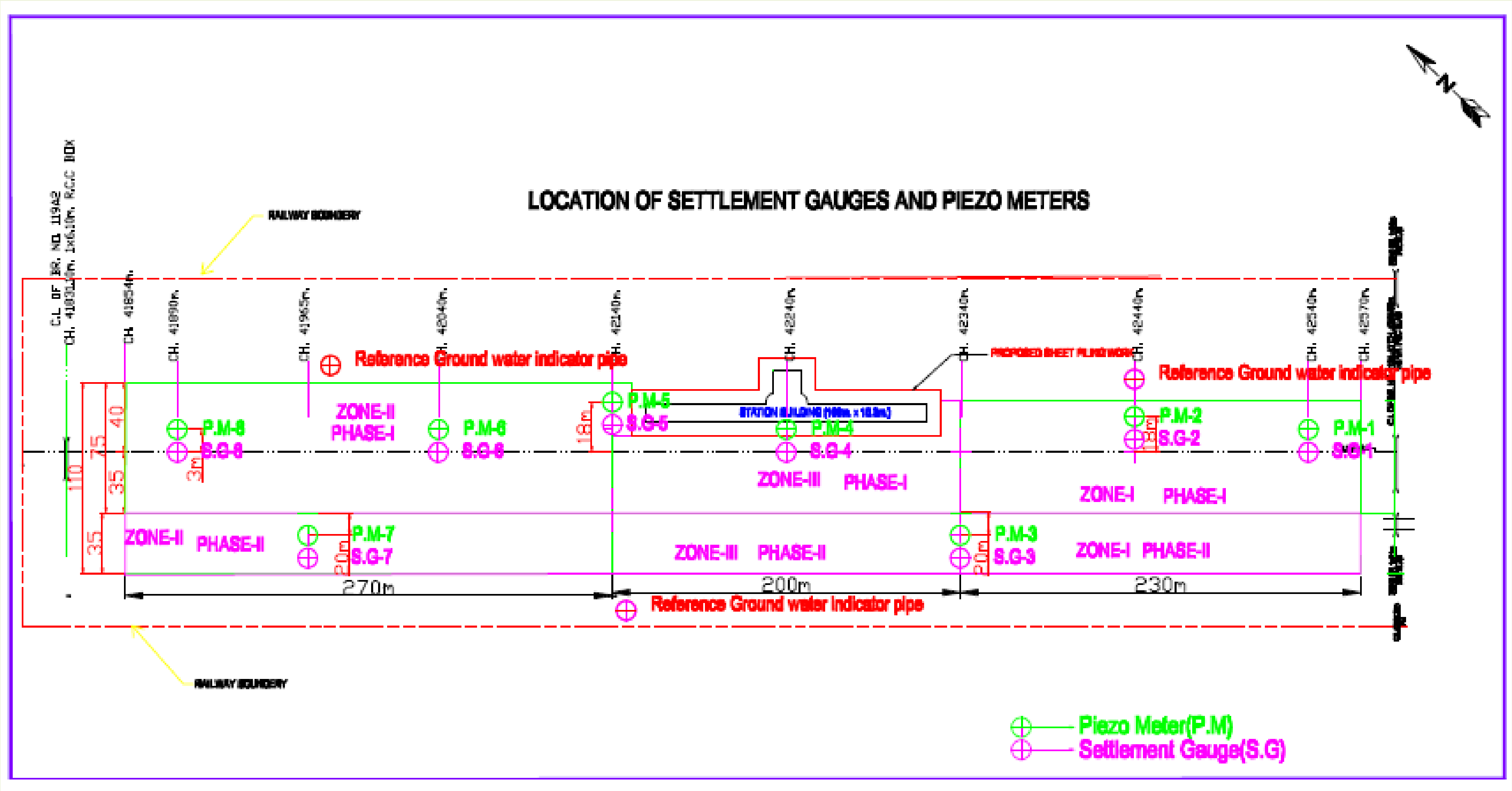
Typical Schematic of Railway Embankment on PVD


L&T-KOMATSU

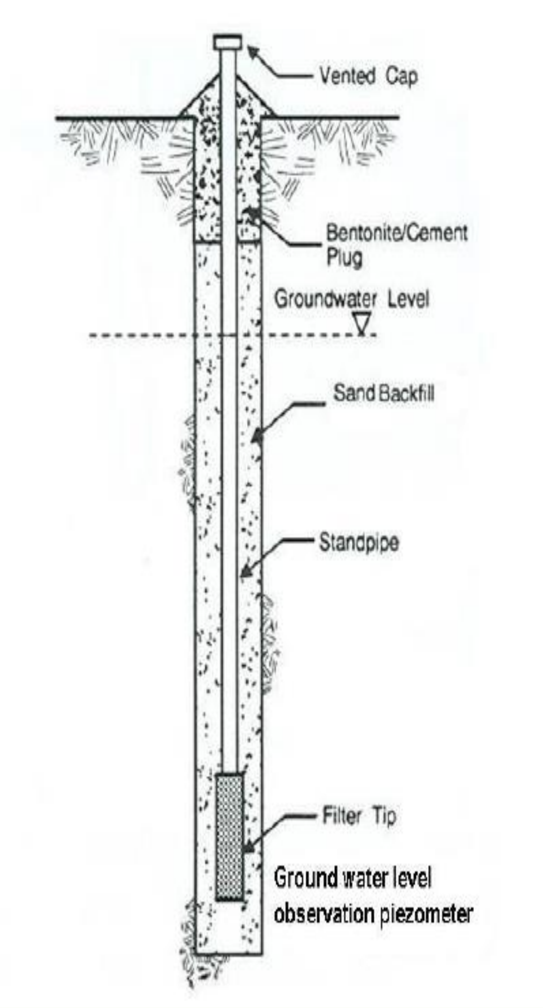
a) Laying of Coarse sand, b) Laying of Non-Woven Geo-textile, c) Laying of Granular Blanket.

d) Laying of Woven Geo-textile, e & f) Stage construction of embankment.

Instrumentation



Piezometers & Settlement Gauges



Construction Plan for Embankment at Udaipur

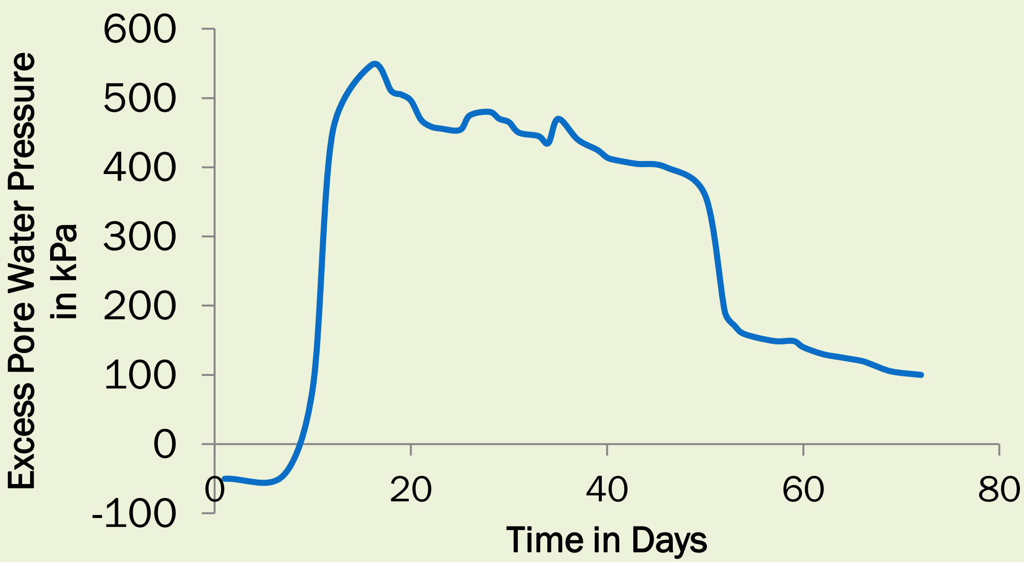
Height of embankment, m	P_0, kPa[H/2*6.53]	δP, kPa [(Δh*19)+24]	No of Days	Settlement due to load with time, mm	Cumulative Settlement, mm	Time* period, days	Uh	Cumulative settlement, m (achievable)	U
0	43.26	0.00	0	0.00	0.00	0	0.00	0.00	0
0.5	43.26	33.50	20	0.488	0.488	20	0.45	0.22	17.75
1	43.26	43.00	20	0.099	0.587	40	0.70	0.42	33.71
1.5	43.26	52.50	20	0.089	0.676	60	0.84	0.56	45.37
2	43.26	62.00	20	0.081	0.756	80	0.91	0.69	55.67
2.5	43.26	71.50	20	0.074	0.831	100	0.95	0.79	63.76
6.2	43.26	141.80		0.407	1.238	**			

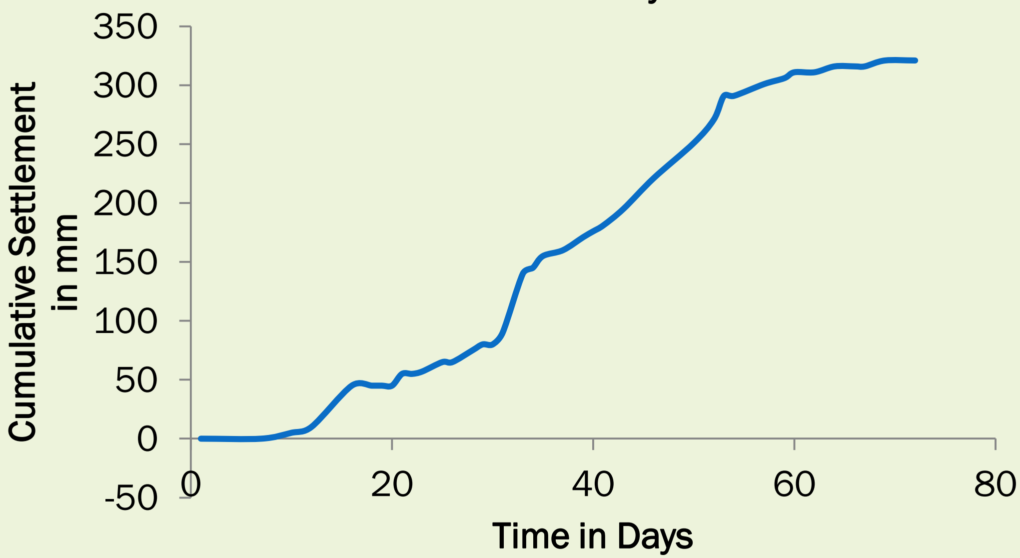
Considering 20 days of time period after execution of each stage of 0.5m height.

Height of embankment (m)	No of Days	Corresponding degree of consolidation	Initial Cohesion (kPa)	Increased pressure δP [due to DL (kPa)]	Gain in Cohesion value	Final Cohesion, kPa	Bearing Capacity of soil, in kN/m^2
0	0	0	4	0	0	4	20.6
0.5	20	45	4	9.5	0.75	4.75	24.4
1	20	71	4	19	2.38	6.38	32.8
1.5	20	83	4	28.5	4.18	8.18	42
2	20	91	4	38	6.11	10.11	51.9
2.5	20	95	4	47.5	7.97	11.97	61.5

Suzuki and Yasuhara, Soils and Foundations, 2007

Record of Pore Water Pressure, Settlement & N-Value





N-Value Before & After Installation of PVDs (Ch: 42.44)			
Depth from OGL	Description of the Soil	Old Bank (May 2014)	New Bank (11 Jan 2016)
2	Soft , deep, grey clayey soil	4	9
3		4	15
4.5	Medium, deep, grey clayey silty soil		16
6		4	11
7	Medium, deep, grey clay silty sand soil	7	16
9		6	25
11	Medium dense silty sand	4	28
12.5		3	29
14.5	Medium to dense sandy soil	6	36
16		66	72
17.5	Very dense sandy soil	100	100
N-Value After 51 days of PVD installation			

Retrofitting of Railway Station Building

USE OF MODERN RETROFITTING TECHNIQUES IN UDAIPUR STATION BUILDING OF AGARTALA-SABROOM NEW LINE PROJECT OF N.F.RAILWAY

By: Harpal Singh, Chief Engineer/Con-8/Maligaon,

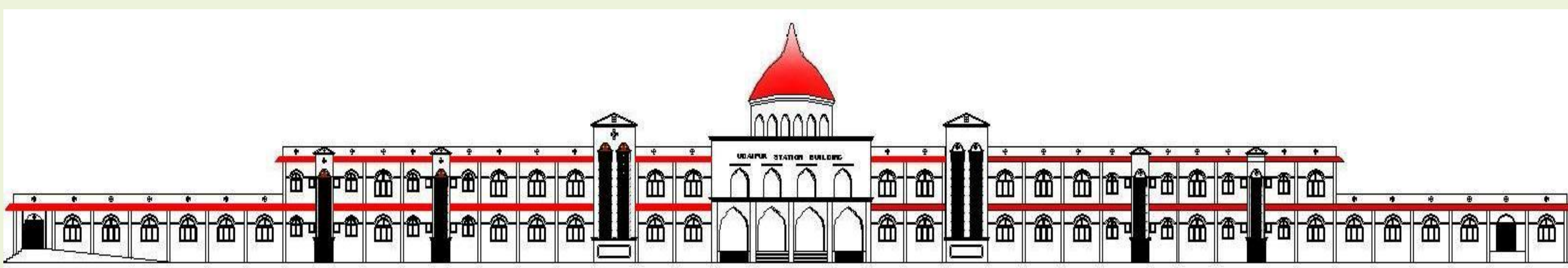
B.N.Bhaskar, Deputy Chief Engineer/Con/Agartala,

Koteshwar Ponnala, Asstt. Executive Engineer/Udaipur

The Institution of Permanent Way Engineers (India)

http://ipweindia.org.in/index.php/books-publications/technical-papers/10-publications

https://drive.google.com/file/d/1b4Xu7lIM6ZykaMArHBwnIlFzDZOqLLaH/view?usp=sharing

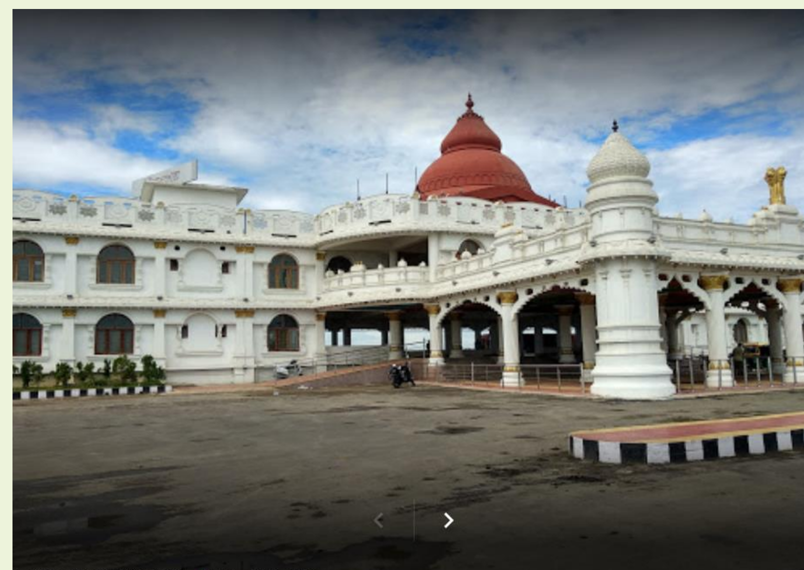


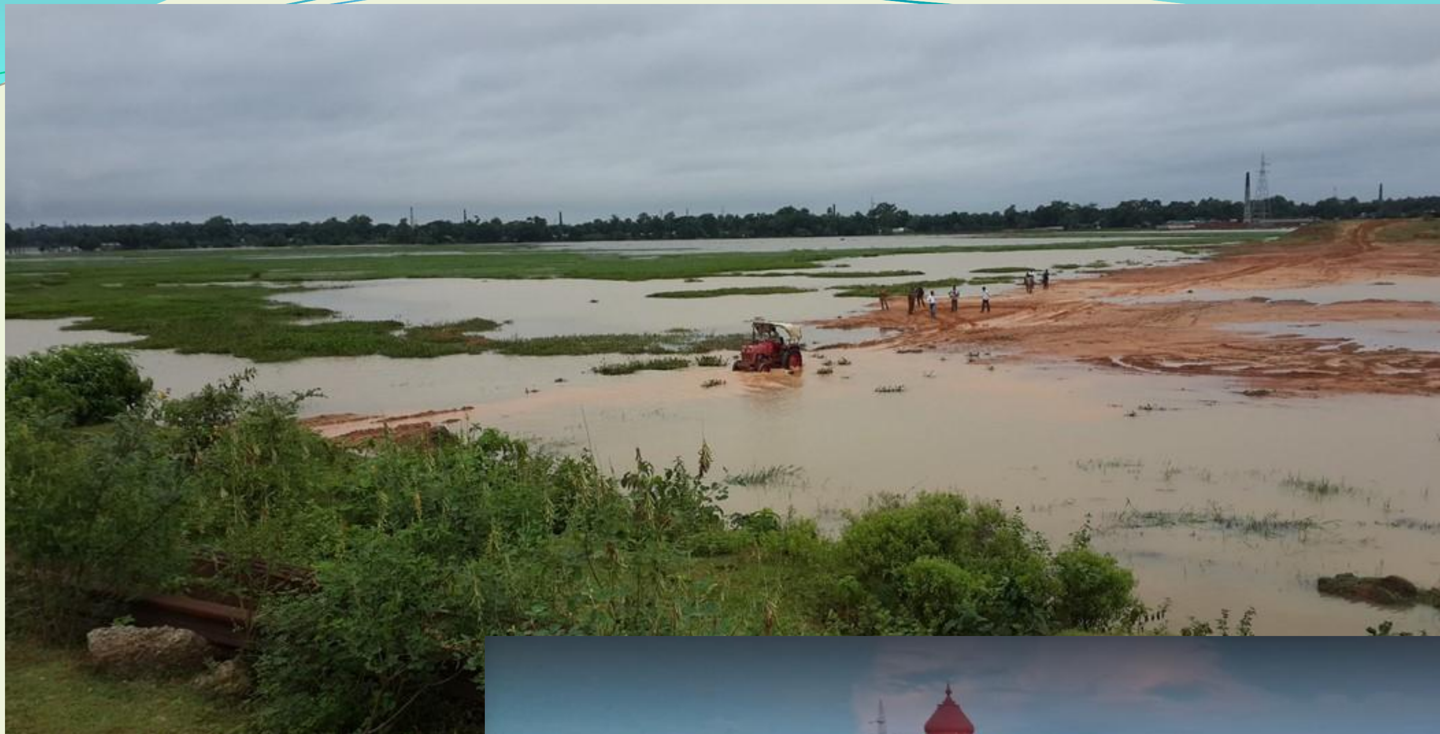

Agartala-Udaipur Section,
First Engine Rolling upto Udaipur,
on 15.03.2016
NORTHEAST FRONTIER RAILWAY
FIRST BROAD GAUGE ENGINE ROLLING
FROM AGARTALA TO UDAIPUR


Footplate inspection
of Agartala-Udaipur Section
by GM/Con/NFR on 17.03.2016
70388

Heritage Railway Station, Udaipur, Agartala

- Application of preloading and PVD for developing of railway yard in a ditch marshland



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UDAIPUR

Thank You for Patient Hearing