Rectification of Landslides in Sri Lankan Road Network - Lessons Learnt

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Content

Introduction

- Sri Lankan landform experience significant changes in elevation from lands at sea level in the coastal regions to the central regions.
- This variation has created many steep slopes all around the central region of the country.
- There is an extensive road network connecting the capital Colombo and all regional cities. The road network traverses through the highly variable terrain in the central region, experience significant variations in the elevations.
- In order to cater the demand of increasing traffic due to the economic development and population growth, it would be necessary to widen the existing roads. Those road widening requires excavation into the slope in the hill terrain.

Introduction (cont…)

- Such road widening was implemented on Avissawella – Hatton - NuwaraEliya Road.
- Ancient landslide at bridge no. 48/2, near Ginigathhena area got reactivated after attempting to cut the slope for said road widening.
- Considering the national importance, Ginigathhena landslide was stabilized under World Bank funded Climate Resilience Improvement Project (CRIP).
- Mitigation measures were focused on three main categories as drainage improvement, ground modification and reinforcement.
- This study was done to identify the importance & effectiveness of the drainage improvement, requirement of combine mitigation measures and necessity of stage construction & correct sequence of landslide mitigation works.

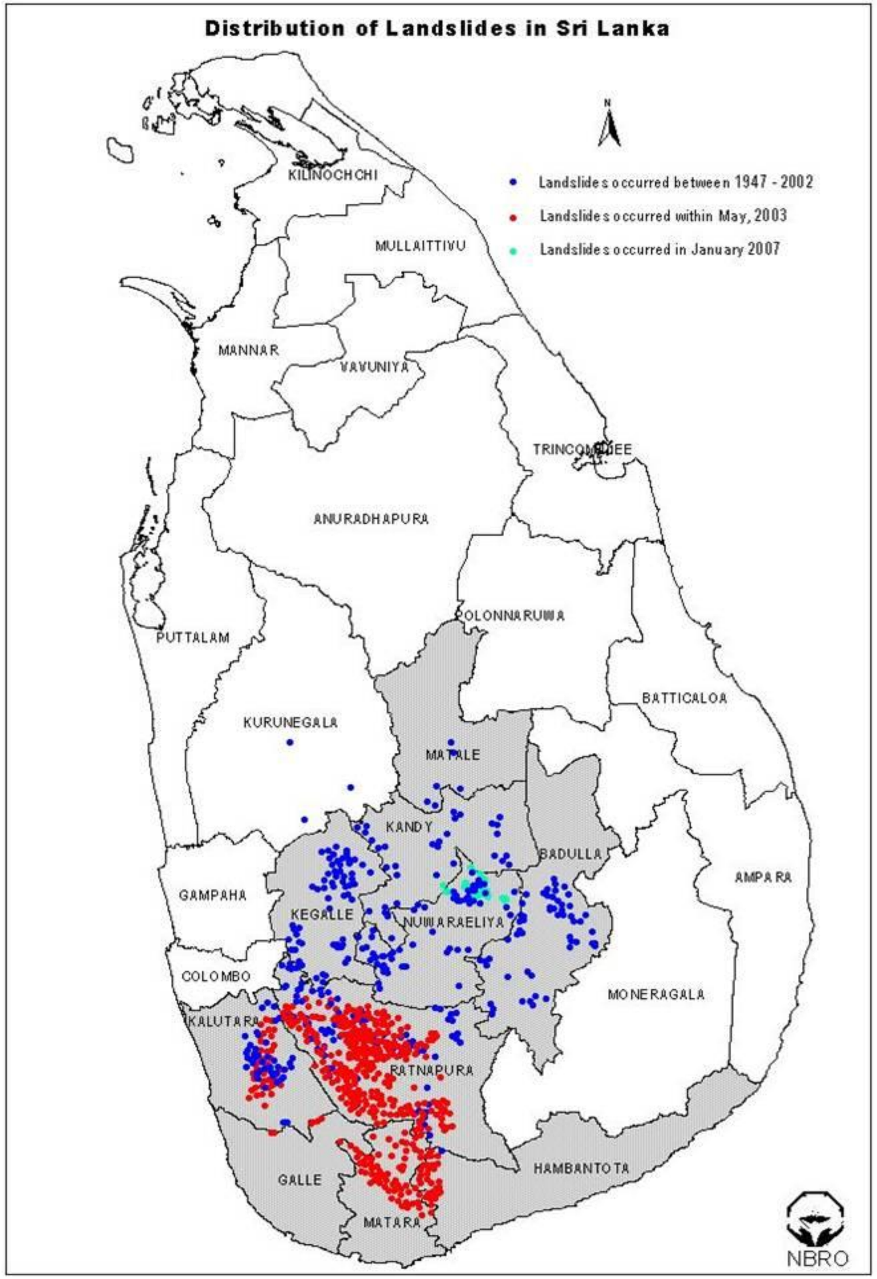
Objectives

- Understanding the behavior of ground water regime with respect to a critical rain fall for different drainage improvement measures.
- Assessment of slope stability with respect to various drainage improvement techniques for the critical rainfall and identify the effectiveness of drainage improvement in slope stability.
- Assessment of stability enhancement by slope reinforcing with soil nailing and economizing the nail design by drainage improvement.
- Confirmation of design outcomes by field monitoring

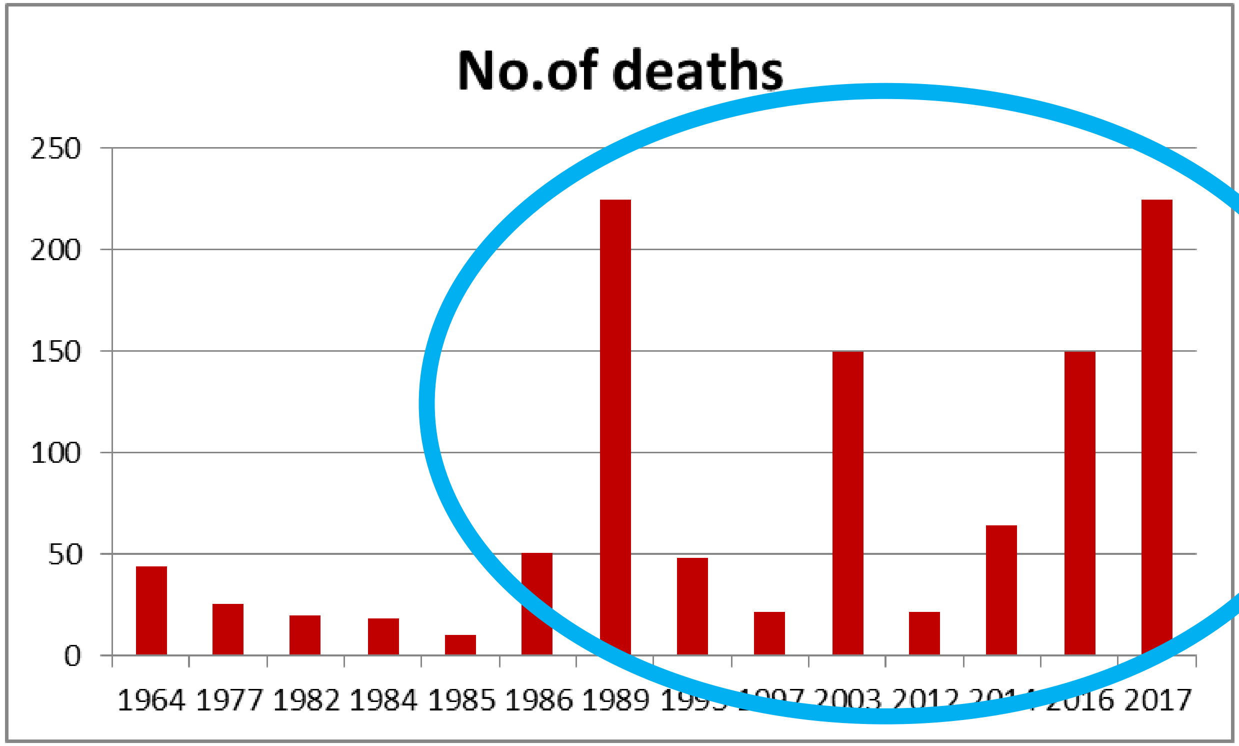
Current Knowledge – *Landslides in Sri Lanka*

- Landslide is defined as "the downward movement of a rock, debris, or earth under gravity" (Cruden, 1991).
- As a tropical country which experiences heavy rainfall with two major monsoons, rainfall is the major triggering factor for landslides in Sri Lanka.
- Rain induced landslides have become a major natural disaster in Sri Lanka during past few decades. Nearly 1,000 human lives were lost while over 300,000 people were made homeless due to cataclysmic landslides events.
- Considering the national importance, many landslide risk reduction projects are conducted all over the landslide prone areas.

Current Knowledge – *Landslides in Sri Lanka*



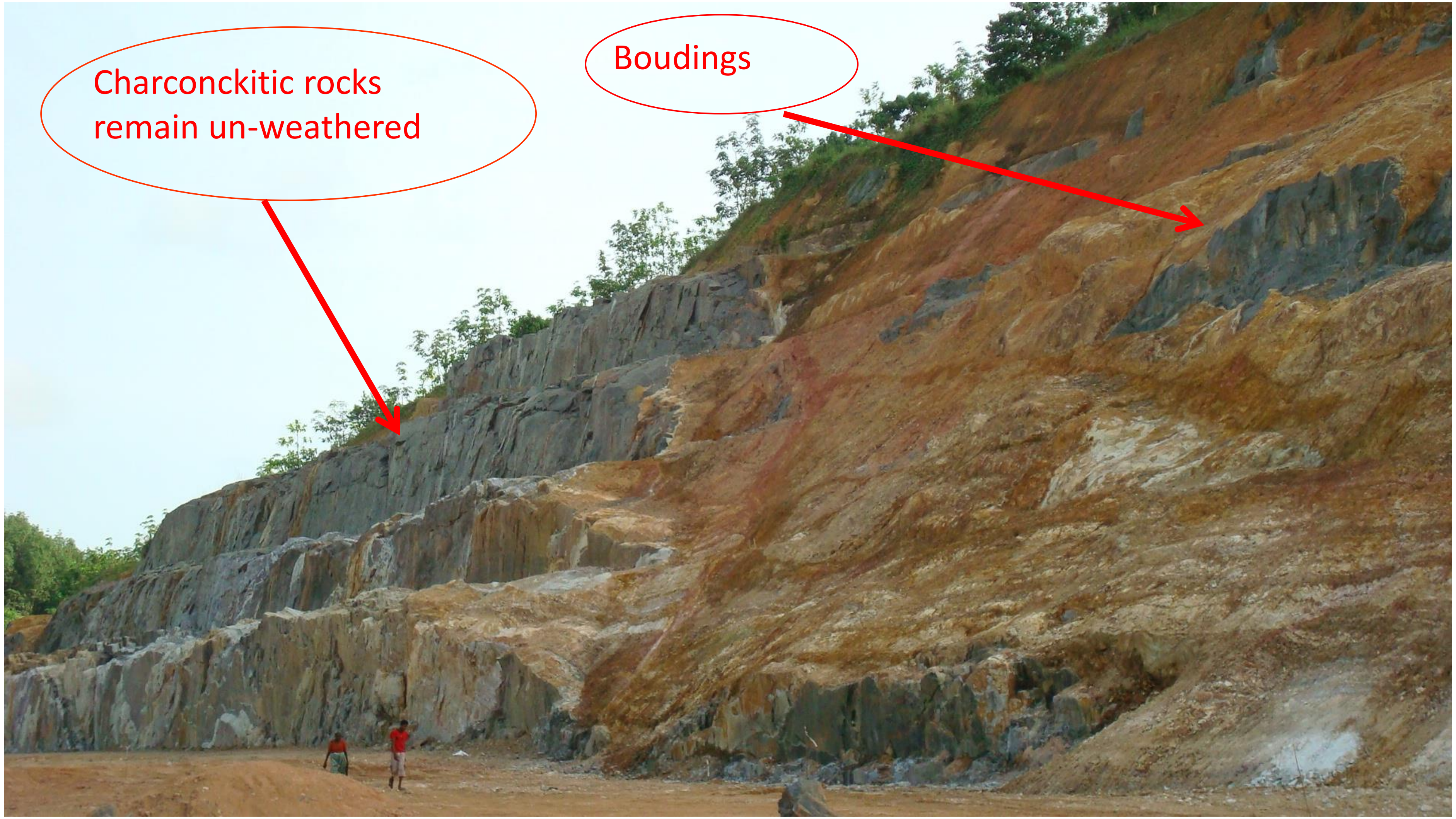
- Landslides are the most pressing natural disaster in the Central Highland which occupies 20 → 30% of the total land area (13,000 → 19,500 km2).
- Spreading over 7→10→13 major districts. Affecting about 30→38% of the total population (6→7.6 million).



Current Knowledge – *Geological Background*

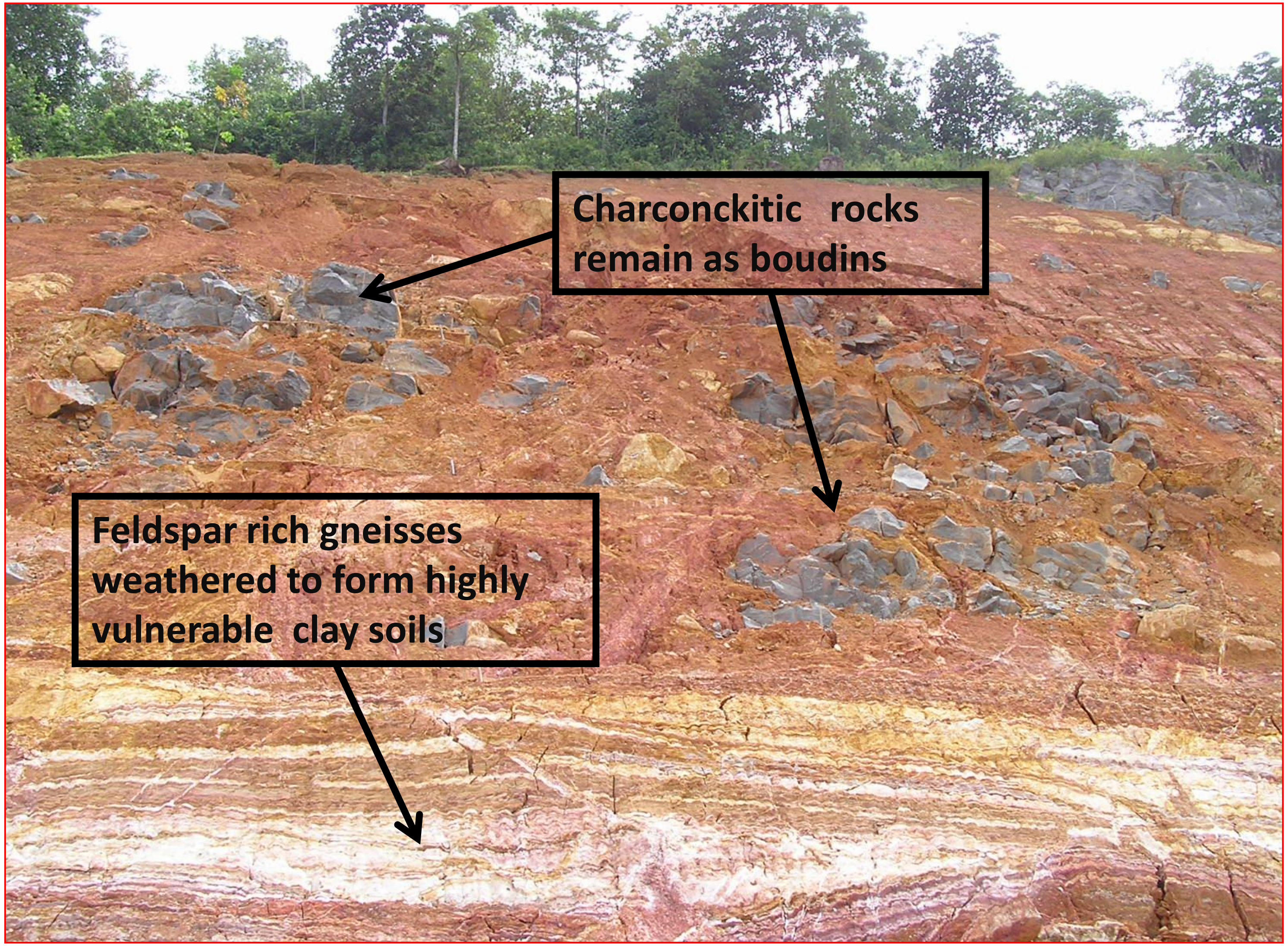
- Sloping grounds in Sri Lanka are formed of; rocks of different levels of weathering, residual soils and colluvial soils.
- Rocks present are mainly Metamorphic. Principal rock types are Gneisses, Charnockites, marble and Quartzite.
- These rocks could have banded structures with one or more joint planes. Joint planes will remain as relict joints in the residual soils.
- Many of these slopes are with a low water table during periods of dry weather. prevailing high martic suctions make them stable.

Current Knowledge – *Geological Background*



- Charconckitic Rocks that have high resistance to weathering Remains un-weathered – known as Boudings

Current Knowledge – *Geological Background*



- Highly heterogeneous - irregular soil/rock profiles due to tropical conditions of weathering and mineralogical changes in parent rock.

Current Knowledge – ***Rain Induced Landslides***

- Near vertical cuts of heights of even 10 m or more would stand safe under these conditions.
- Infiltration of rainwater, loss of matric suctions and perhaps the development of a perched water table condition will make them unstable.
- Failure have taken place in cut slopes and in natural slopes under extreme rainfall conditions

Current Knowledge – *Rain Induced Landslides*

Kegalle Bypass Road

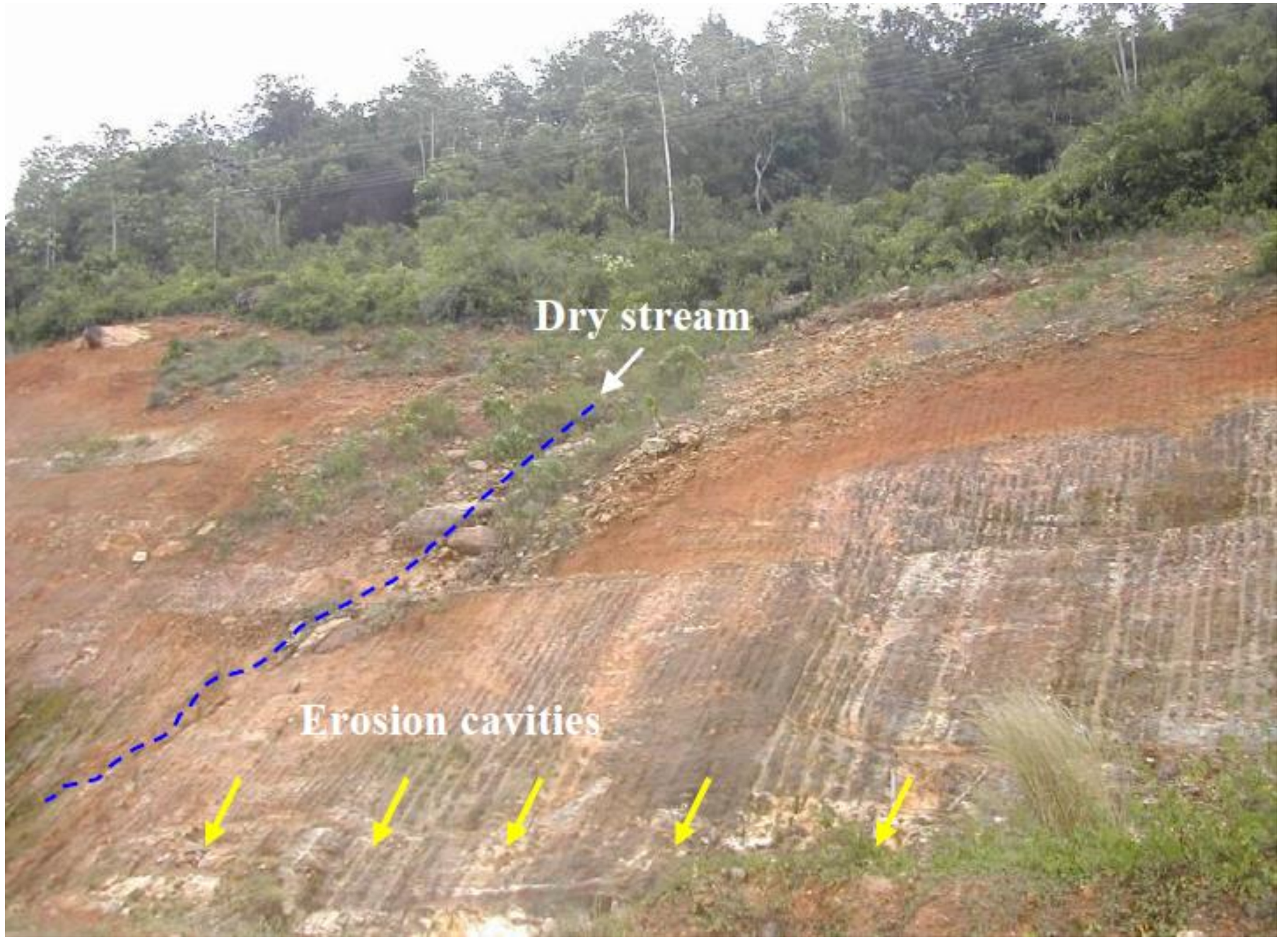
Non Engineering Construction

Immediately after cutting 24-3-2014

Two months later, after the rain 14-5-2014

Current Knowledge – *Rain Induced Landslides*

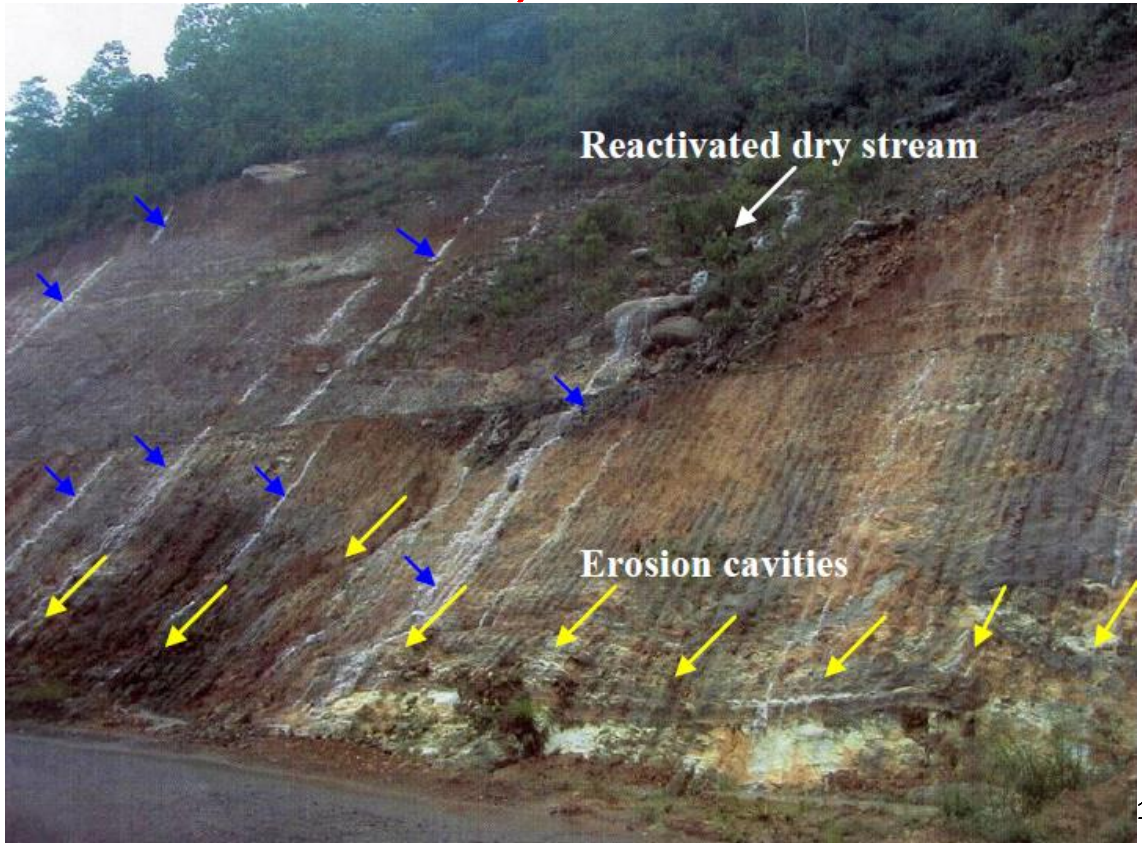
STDP Galle – Matara Section



Slope during a dry period of weather

Slope was cut but drainage measures were not implemented

Uncontrolled flow of water and infiltration during rainy season



Current Knowledge – ***Rain Induced Landslides***

STDP Galle – Matara Section

Ended up as a catastrophic failure

Current Knowledge – *Analysis of Rain Induced Landslides*

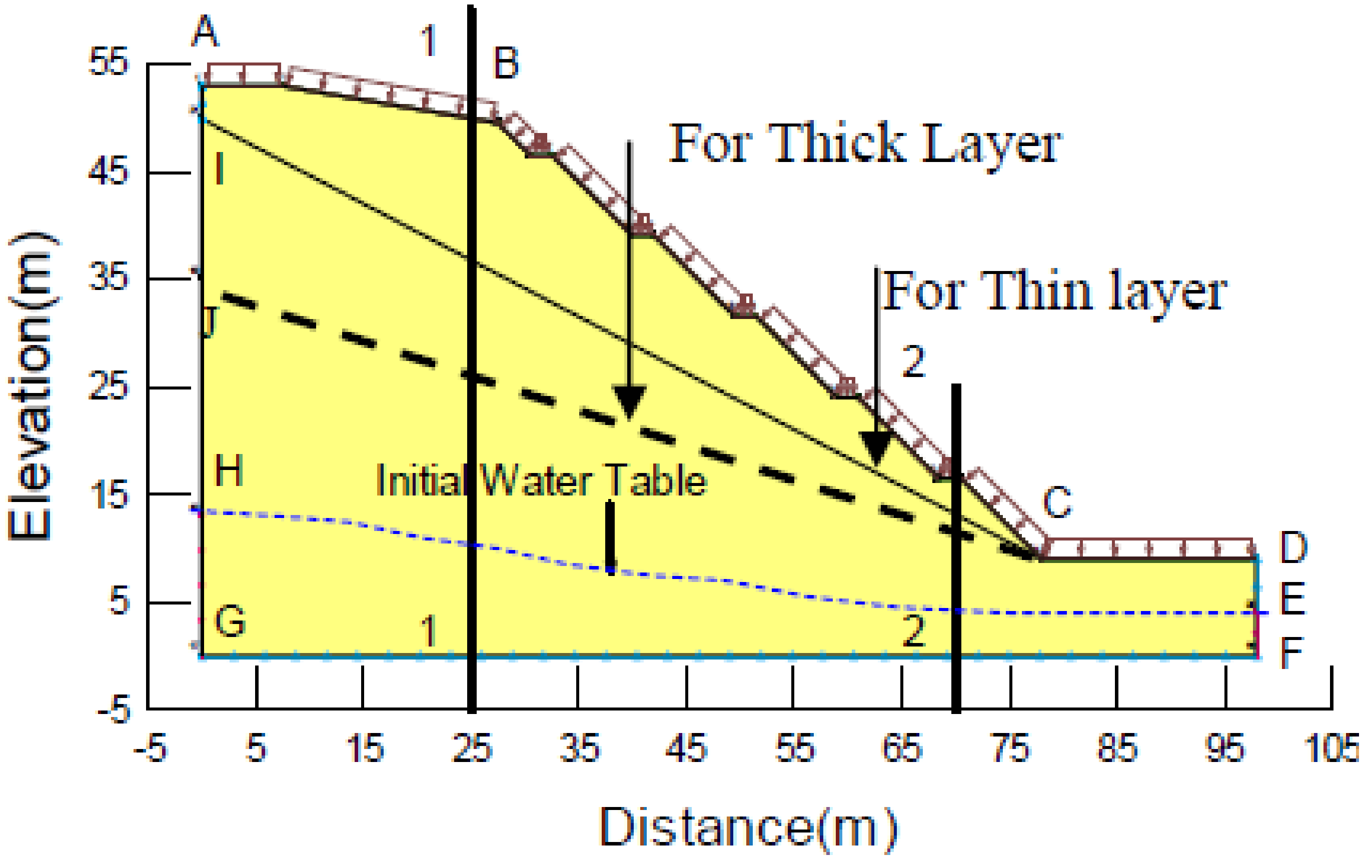
- Seepage analyses base on finite element formulation are performed to understand the effect on the pore pressure regime by the rainwater infiltration. In order to execute reasonably accurate analyses, it is required to have careful idealization of the slope and assignment of appropriate hydraulic characteristics.
- Results from seepage analyses can be incorporated into the stability analyses. Stability analyses are generally done with limit equilibrium approach.

Current Knowledge – *Computer Software for Analysis*

- Seepage & stability analyses are required complex computations and it is difficult to perform those analyses manually.
- Considering the complexity, computer software are used for seepage and stability analysis.
- Commercial software GeoStudio SEEP/W & SLOPE/W are used for seepage & stability analysis respectively.
- The modeling of SEEP/W & SLOPE/W can be combined together and it enables to evaluate the behavior of slopes to rainfall in terms of both change of pore pressures and stability.

Current Knowledge – *Modeling with SEEP/W*

- A transient seepage analysis was done with SEEP/W software for a hypothetical slope rainfall intensities of 5mm/hr and 20mm/hr.



Boundary Conditions

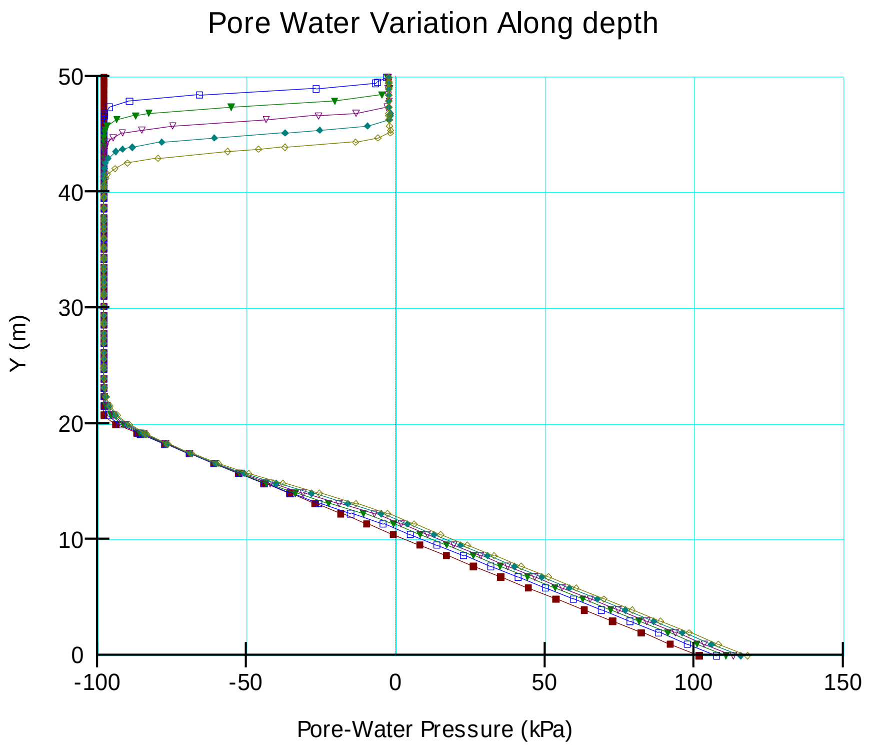
AB, BC, CD= Ir (Rainfall intensity)

AH, DE, FG=Q=0m^3/s (No flow Boundary)

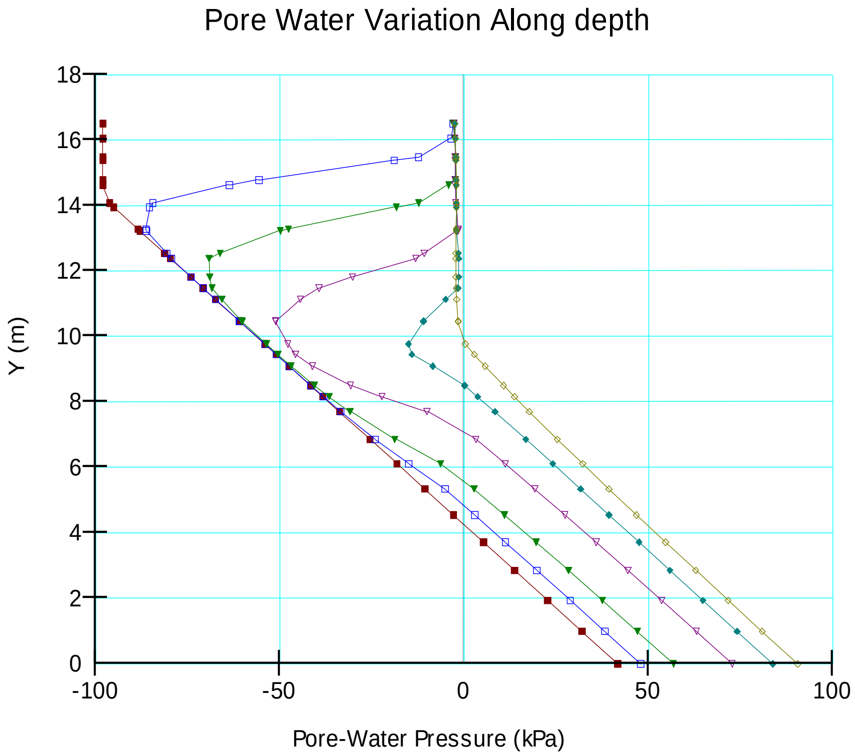
EF, GH=ht (Total head at sides)

Current Knowledge – *Modeling with SEEP/W*

- Resultant variation of pore-pressure for 5mm/hr rainfall in a uniform slope.



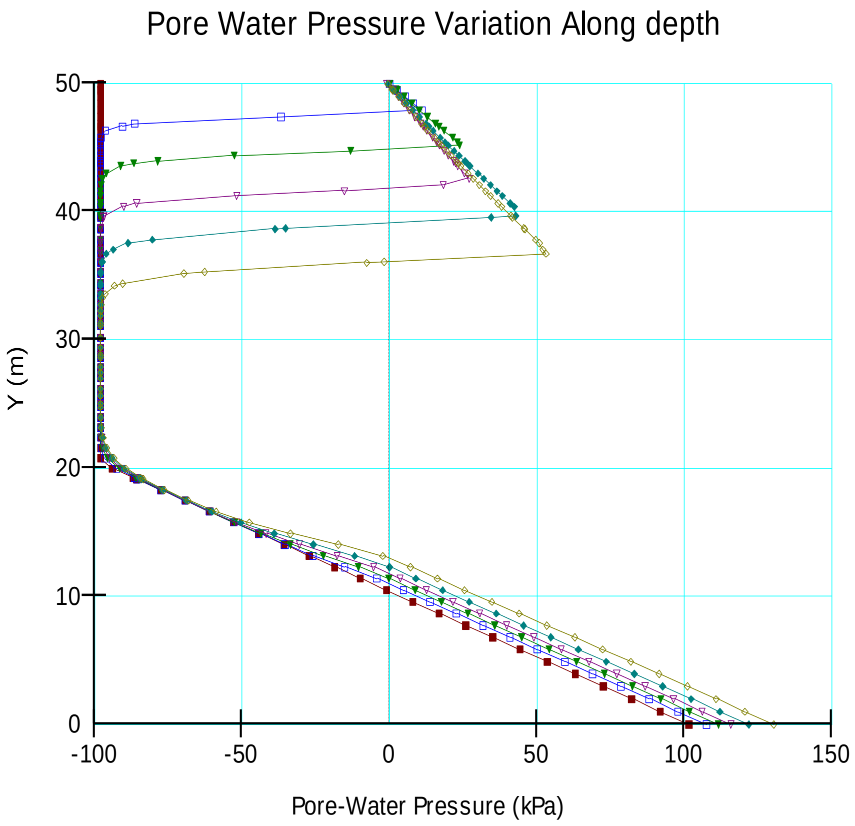
Section 1-1



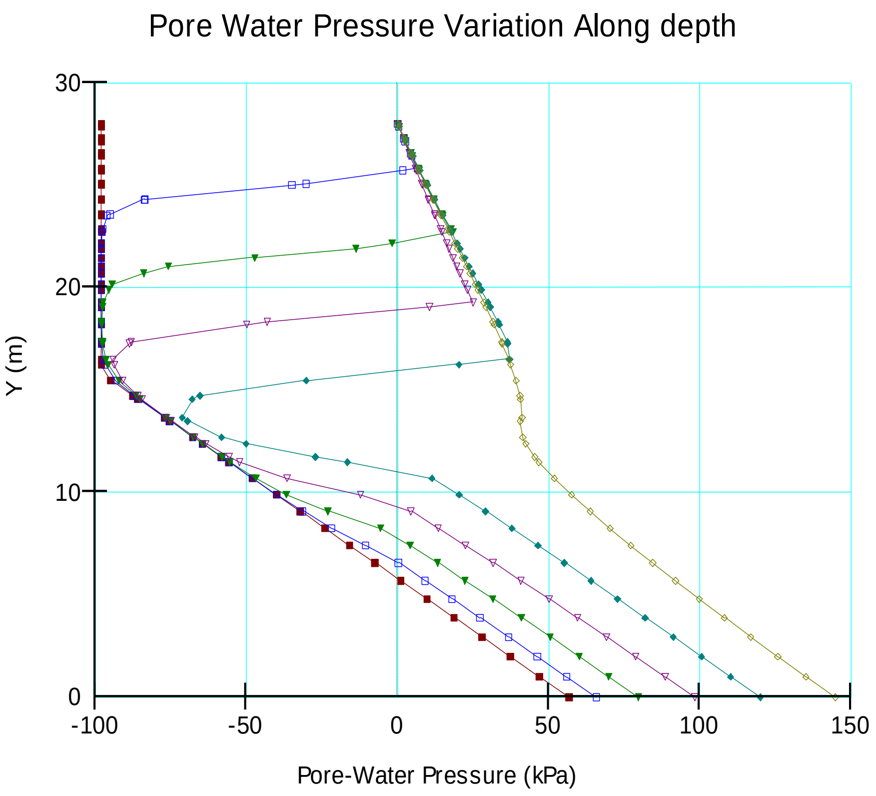
Section 2-2

Current Knowledge – *Modeling with SEEP/W*

- Resultant variation of pore-pressure for 20mm/hr rainfall in a uniform slope.



Section 1-1



Section 2-2

Current Knowledge – *Stability of Slopes & Mitigation*

- "Factor of Safety" (FoS) is used for defining the stability of a slope by stability analysis.

- Different guidelines have different margins for FoS.

- If the FoS of a slope is found to be insufficient under critical conditions, stability of the slope is enhanced by mitigation measures such as;
  - ✓ Surface drainage improvement
  - ✓ Subsurface drainage improvement
  - ✓ Slope modification
  - ✓ Enhancement of shear strength by reinforcing techniques
  - ✓ Earth retaining structures

Current Knowledge – *Mitigation Measures*

- Staged approach is adopted in design of mitigation measures

Surface Drainage Improvement

Considered as the primary and essential mitigation measure which is the cheapest.

Subsurface Drainage Improvement

Some slopes need subsurface drains in addition to surface drains, in order to achieve required safety margins. Can be varied from one directional perforated pipes to pipes in radial directions, directional drilling and wells.

Other Structural Measures

When the required safety margins cannot be achieved by drainage measures only, other structural measures are used. Gravity retaining structures and soil nailing are commonly used.

Current Knowledge – *Case History*

Welipenna Landslide

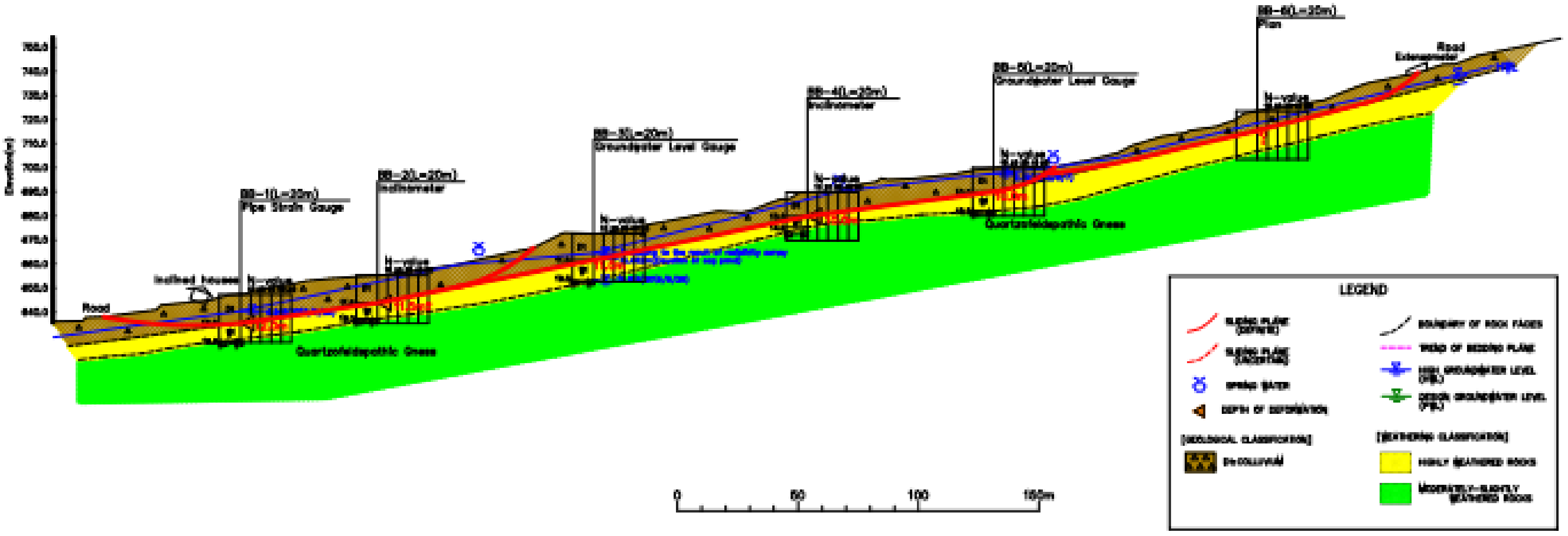
- Mitigation of Welipenna landslide on Southern Expressway is a very good example for landslide mitigation by combination of different measures.
- Drainage improvement, ground modification, reinforcement & toe retuning structure are used for stabilization.
- Most importantly, top down approach was followed in soil nailing. Horizontal drains are installed after grouting the soil nails to prevent cement grout coming to the horizontal drains & blocking them.

Welipenna Mitigation Measures

Current Knowledge – *Case History*

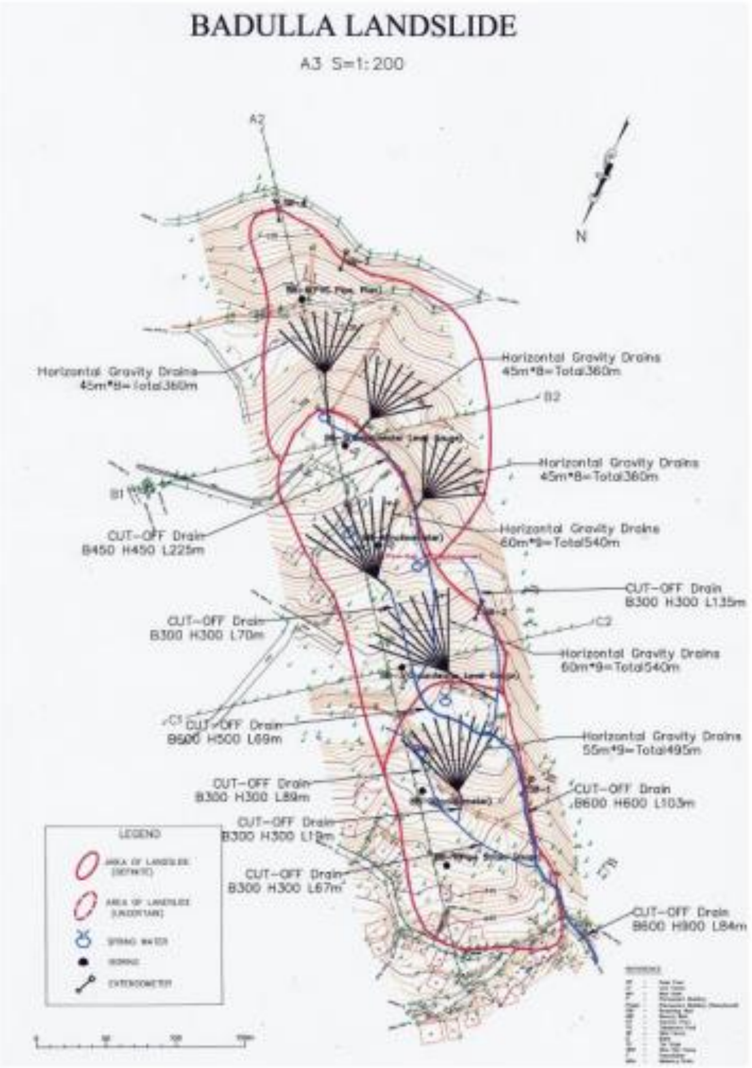
Badulusirigama Landslide

❖ Landslide of long extent in colluvial soil was stabilized with surface drains and sub surface drains in radial directions at different locations (elevations)



Subsoil Profile

Mitigation Measures



Current Knowledge – *Case History*

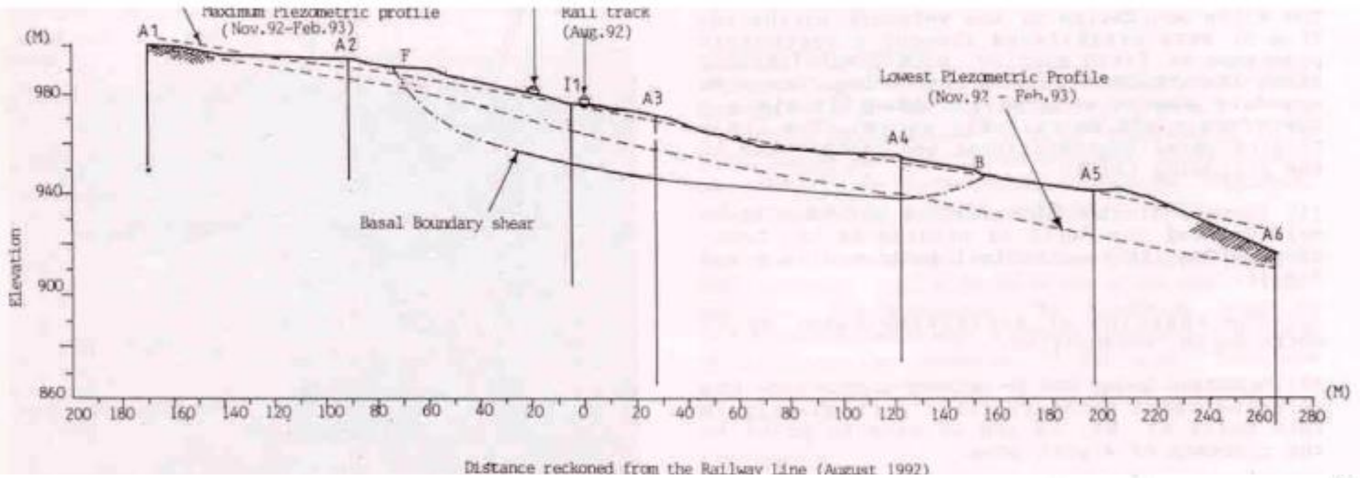
Landslide in STDP

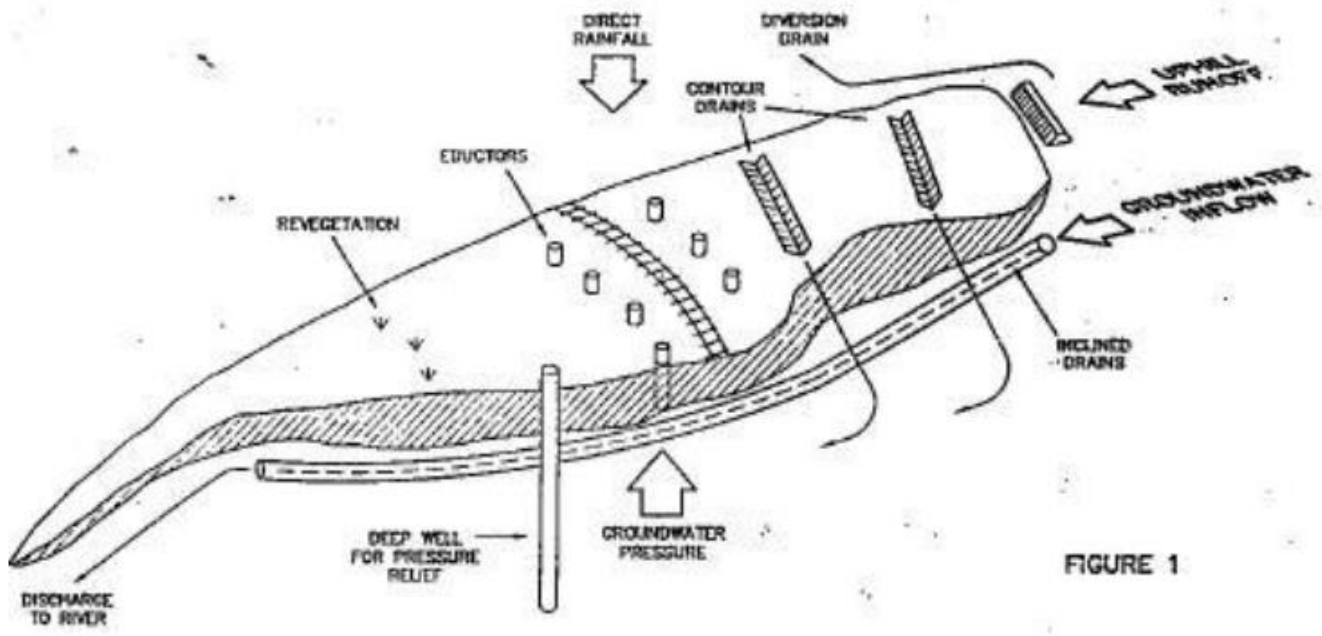
- Stabilized with basin drain, cascade drains, subsurface drains and soil Nailing

Current Knowledge – *Case History*

Watawala Landslide (1994)

- Stabilized with surface and sub directional drains following the failure surface

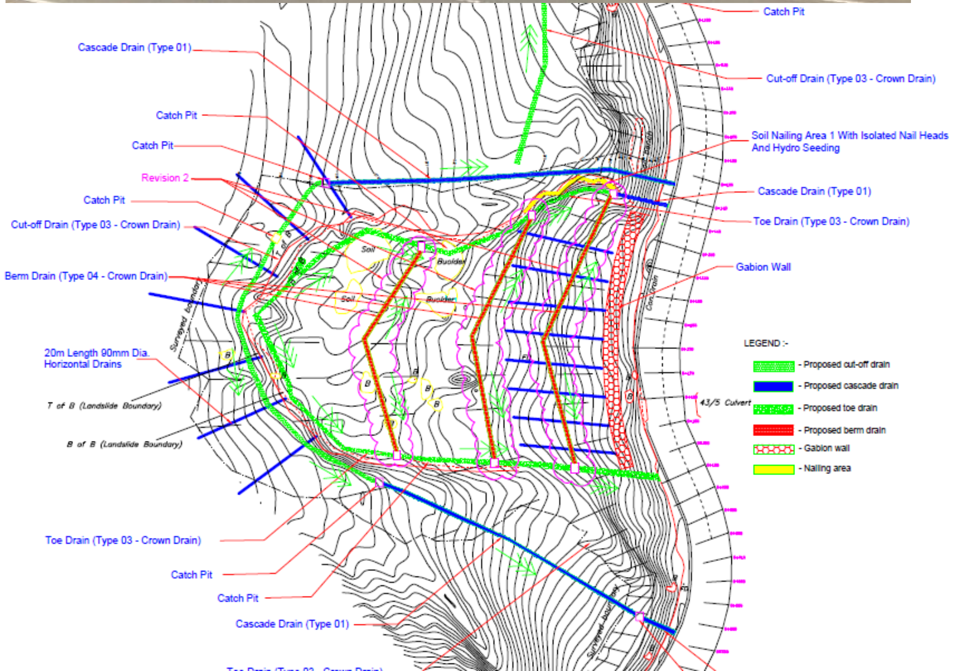




Current Knowledge – *Case History*

Landslide at Kandy-Mahiyangana Road

- Improved by construction of a toe retaining structure –gabion wall, making a gentle slope profile, provision of surface drains, provision of sub surface drains



Current Knowledge – *Case History*

Landslide at Kandy-Mahiyangana Road

- Portion of the slope covered with shotcrete and the nail heads are connected by beams on the other part. In between the beams will be covered with hydro seeding

Ginigathhena Landslide – *Background*

- The ancient landslide at bridge no. 48/2, near Ginigathhena area at Avissawella-Nuwara Eliya road was reactivated by some minor excavation at toe for widening of the bridge and, the failure propagated to upper slope.

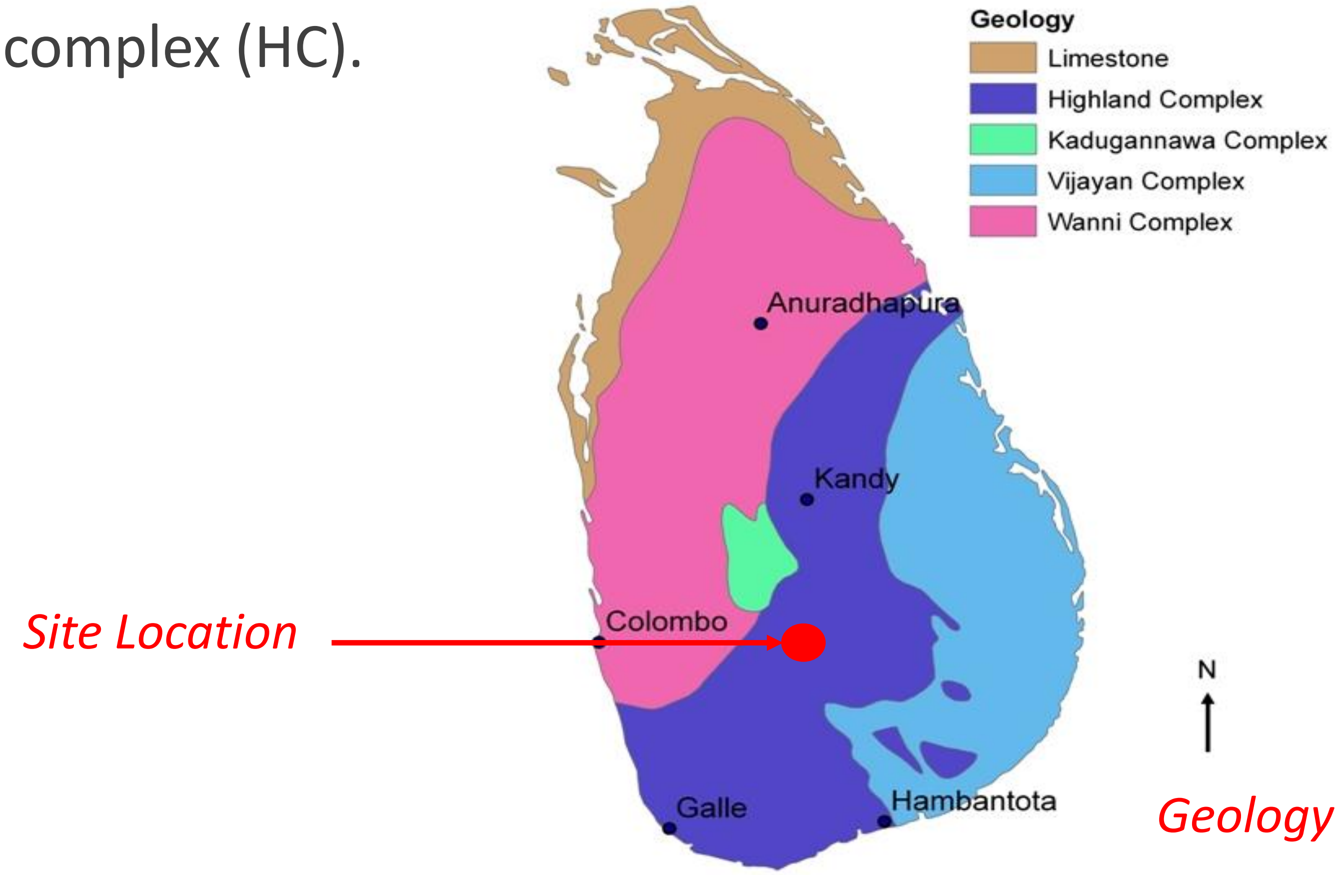
Location Map of the Area

Ginigathhena Landslide

Just after the Failure

Ginigathhena Landslide – *Geology*

- While the major landslide area consists of thick colluvium deposit, some residual soils can be observed at the uppermost slopes.
- The landslide area is generally underlain by highly crystalline metamorphic rock of Highland complex (HC).



Geology Map of Sri Lanka

Ginigathhena Landslide – *Hydrology*

- Immediately above the activated landslide, there is a flat, water logged marshy area which can be identified as a major cause for the high ground water table prevailing in the area.
- Two major streams are flowing into this marshy area from the upper slope and finally come together to flow as one stream through the landslide area. Seepages and high yielding springs are observed in the unstable mass.

Ginigathhena Landslide – *Geology and Hydrology*

Colluvium Soil

Waterlogged Marshy Area at Top

Water Seepage

Stream through LS

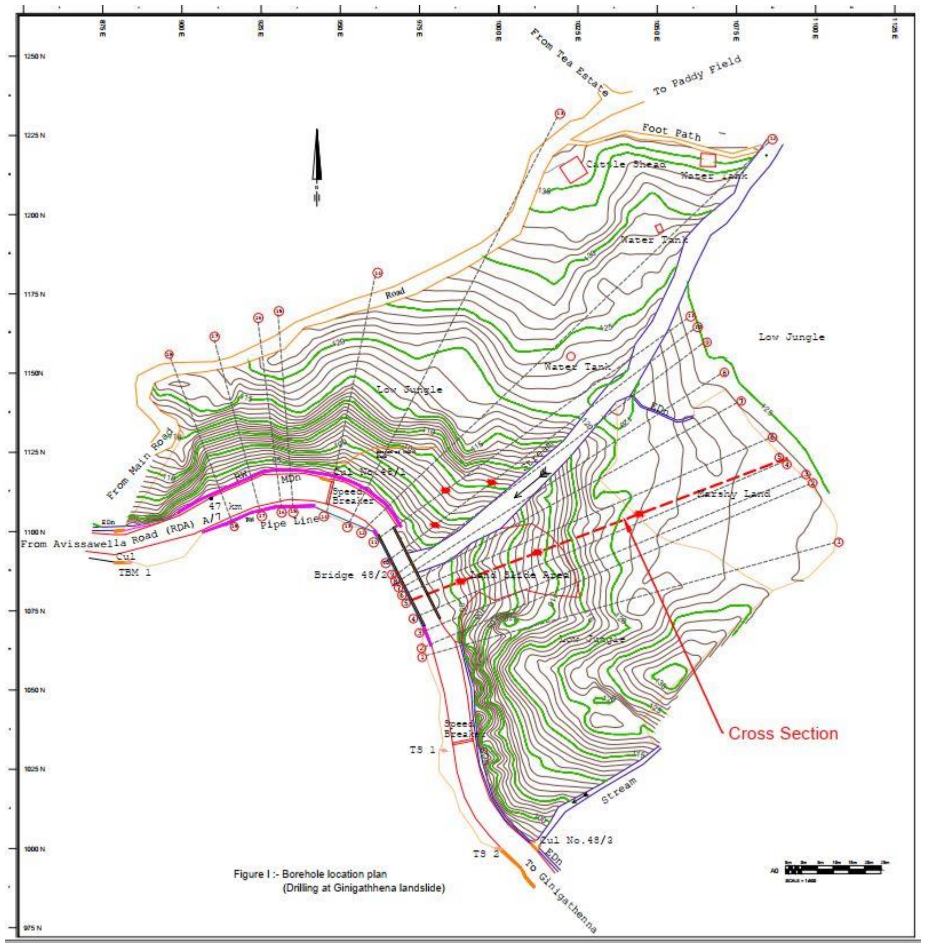
Stream at Top

Ginigathhena Landslide – *Failure & Potential Risk*

- Movement in critically stable mass has been initiated by the removal of toe support and propagated to upper slope. Failure was further activated by rainfall.
- Main Landslide area is a critically stable colluvium mass spreading over an area of $800m^2$ with total potential area of about $3,000\ m^2$.
- This unstable mass could lead to a deep seated failure and a large quantity of soil & rock mass could be released by such failure destructing the bridge and road.
- Also, the widening of the bridge is necessary to cater increasing traffic flow.
- Considering all the above facts and overall impact and the consequences, it was decided to stabilize the slope by mitigation measures.

Ginigathhena Landslide – *Investigation*

- Detailed investigation was carried out to obtaine required information for the detained design and it consists of two parts as;
  - Topographical Survey
  - Geotechnical Investigation
- Contour survey of 1 m interval was done and several cross sections were taken covering the unstable area.
- Three boreholes were advanced with SPTs covering the landslide area as the first part of geotechnical investigation.
- Laboratory testing were done as the second part of the geotechnical investigation to get sub soil properties.



Ginigathhena Landslide – *Investigation*

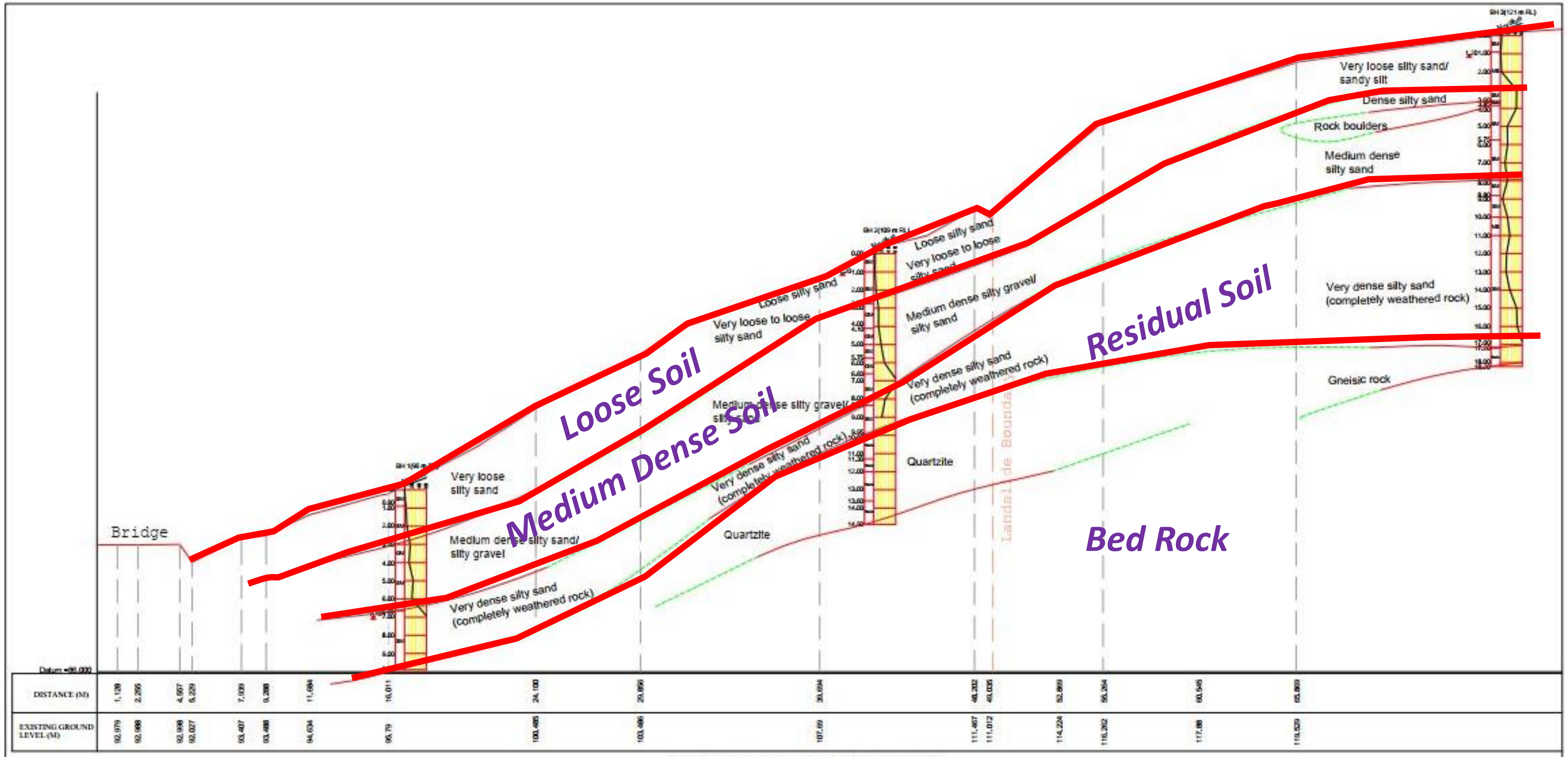


Figure II(c) :- Cross sections at BH1, BH2 and BH3 (Drilling at Ginigathhena landslide)

Subsoil Profile from Investigation

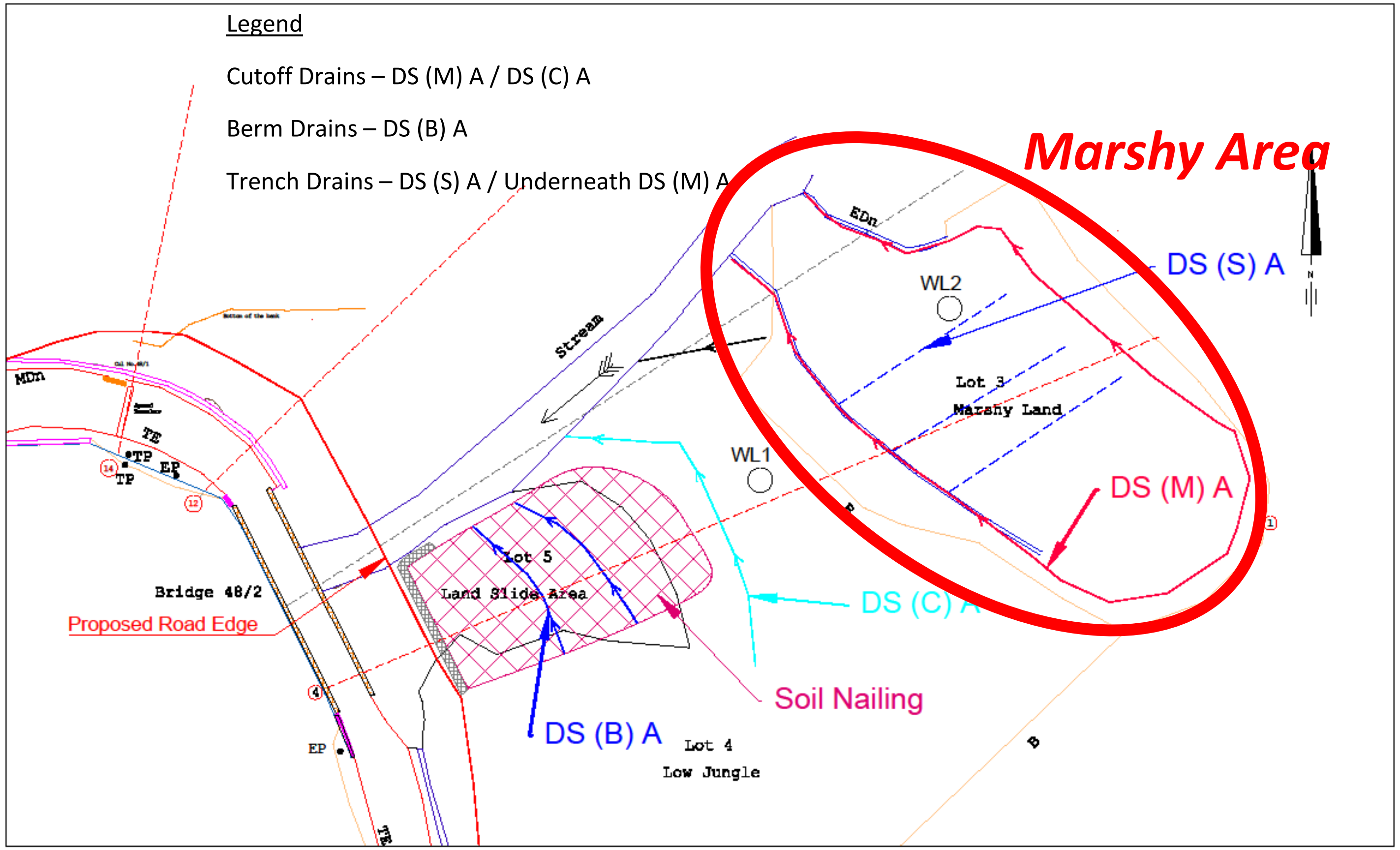
Ginigathhena Landslide – *Mitigation Measures*

- Mitigation measures for the landslide were designed based on the investigation results and there are three major components of mitigation measures as;
    - Drainage Improvement
    - Geometry Modification and,
    - Reinforcing the Slope

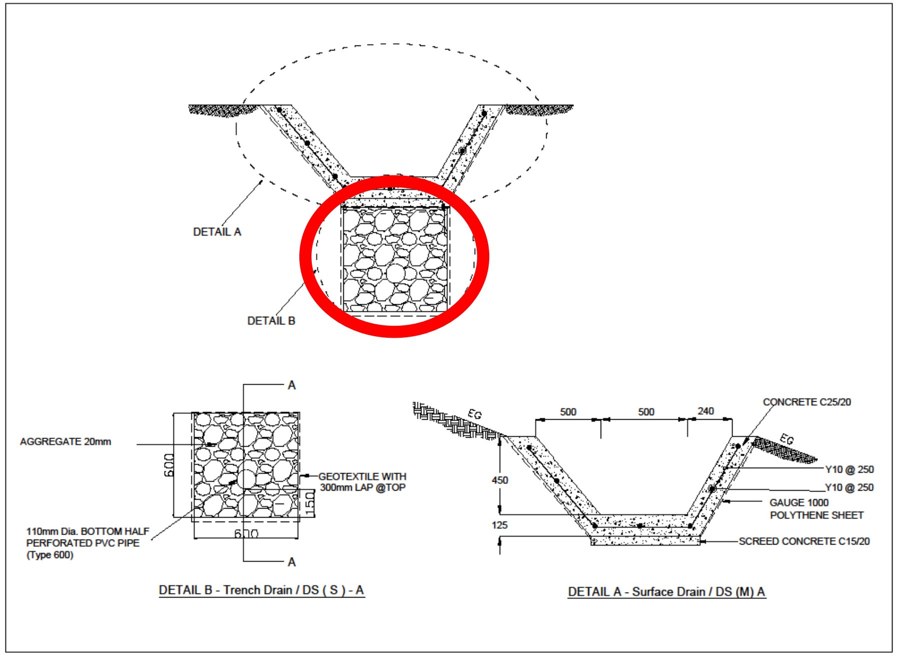
Drainage Improvement

- **Surface drainage improvement** was done to minimize rainwater infiltration with *Cutoff drains, Trench drains, berm drains* and *vegetation* on the excavated slope.
- **Subsurface drainage improvement** was done to dissipate pore pressures inside the landslide body by *Sub horizontal gravity drains* installed at 5 m spacing on every berm.

Ginigathhena Landslide – *Mitigation Measures*



Plan View of Mitigation Measures



Details of Surface Drains

Ginigathhena Landslide – *Mitigation Measures*

Construction of Trench Drains

Surface Drains

Ginigathhena Landslide – *Mitigation Measures*

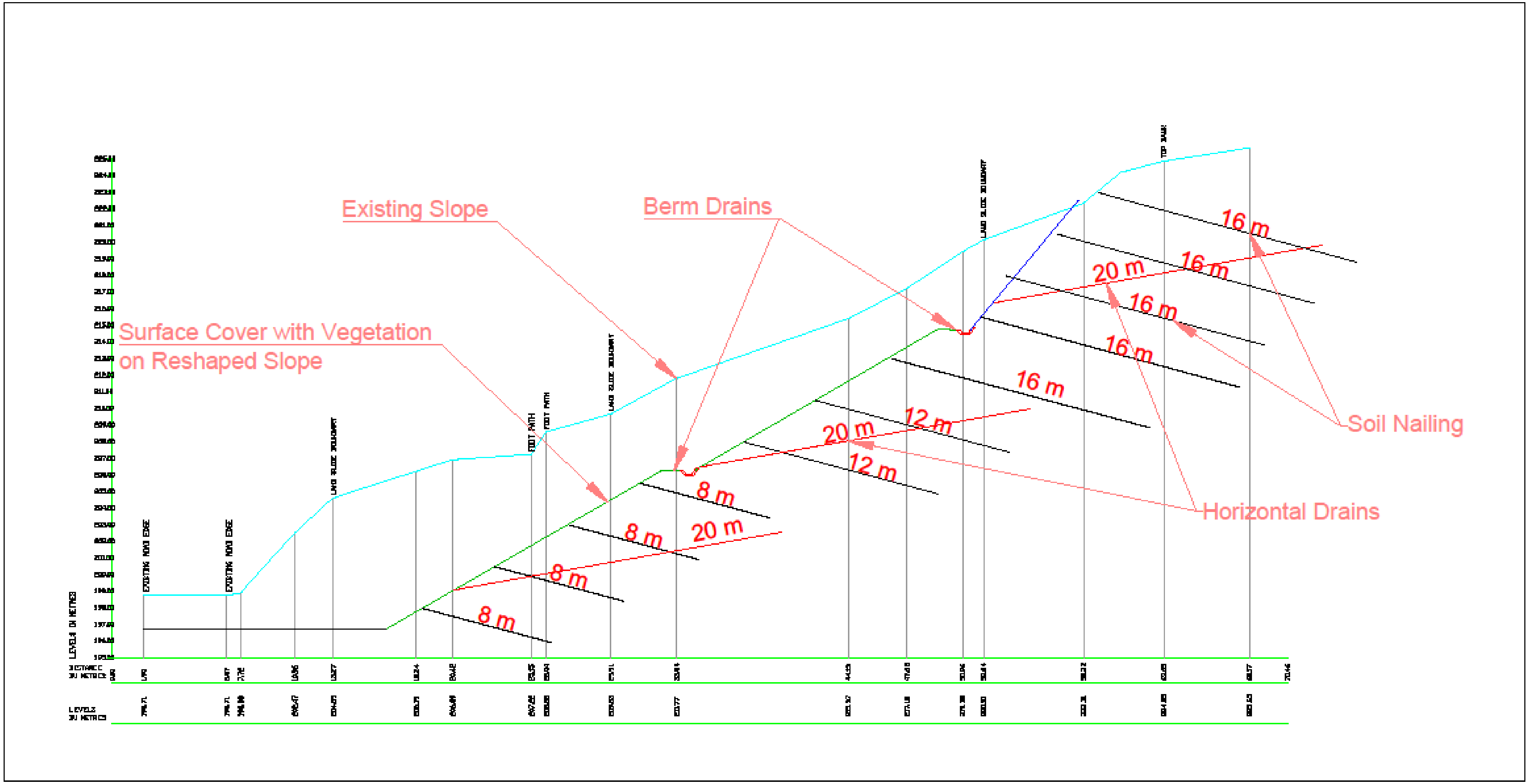
Geometry Modification

- In order to accommodate the proposed widening of the road, excavation at toe region of the slope is required. Slope was cut back to three segments with two berms.
- Since cutting back in to the slope is limited and drainage measures are not adequate to maintain the stability of the slope, it demands reinforcement.

Reinforcement

- 32 mm diameter soil nails installed & grouted in to 125 mm drill holes with 2.0 m horizontal & 2.5 m vertical spacing were used as follows;
  - ✓ Top slope segment – 4 nos. of 16 m long soil nails
  - ✓ Middle slope segment – 1 no. of 16 m long soil nail & 2 nos. of 12 m long soil nails
  - ✓ Bottom slope segment – 4 nos. of 8 m long soil nails

Ginigathhena Landslide – *Mitigation Measures*



Cross Section of Mitigation Measures

Ginigathhena Landslide – *Monitoring*

- Field monitoring programme was established in order to evaluate the slope behavior with mitigation measures. The monitoring scheme consists with;
  - Rainfall monitoring
  - Ground water level monitoring and,
  - Slope movement monitoring

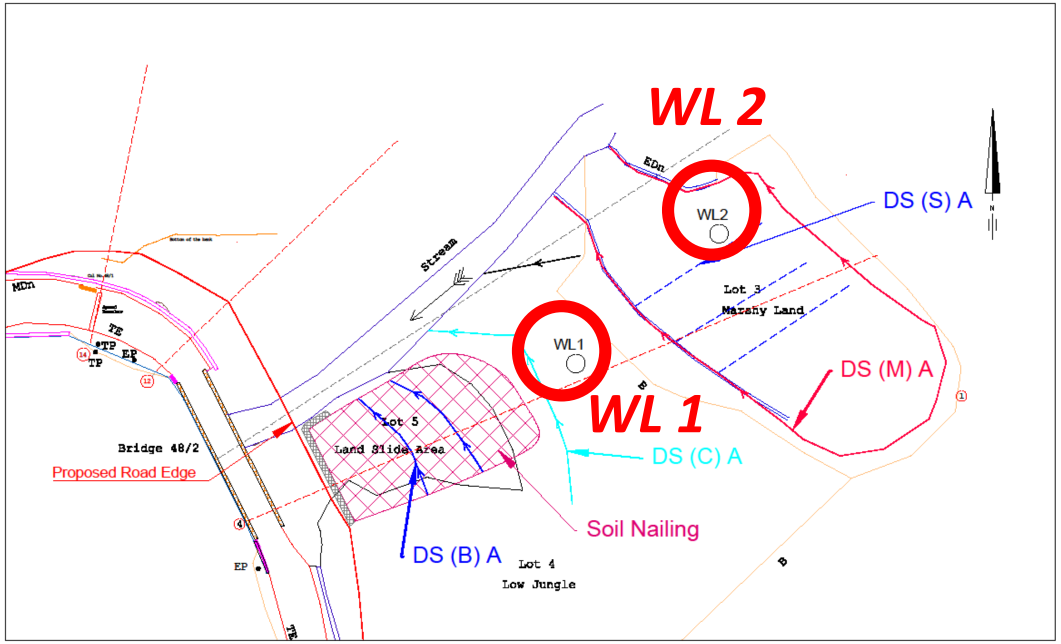
Rainfall Monitoring

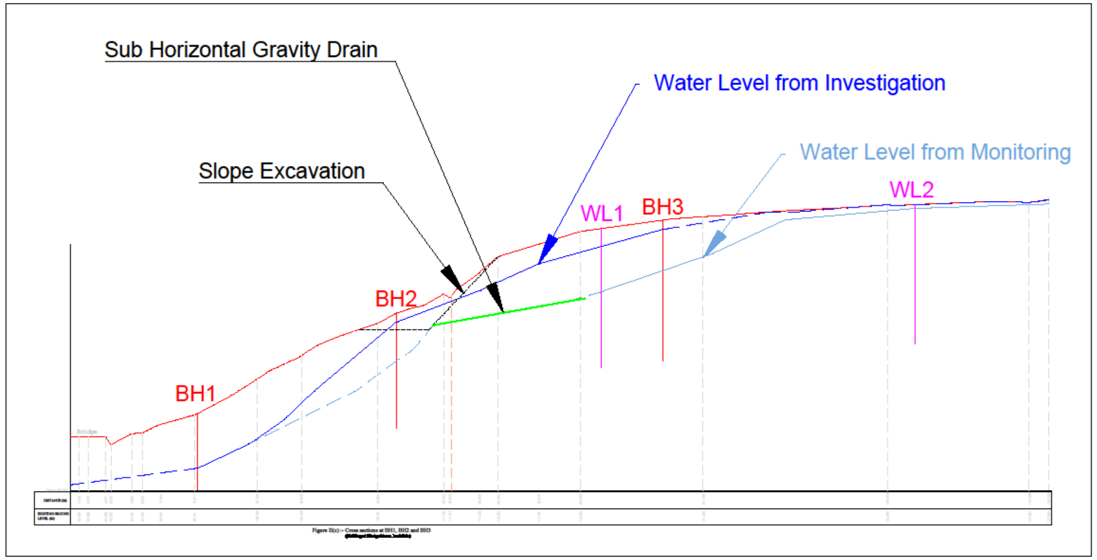
- Rainfall monitoring is done twice a day.
- Manual rain gauge was used.

Ginigathhena Landslide – *Monitoring*

Ground Water Level Monitoring

- Two observation wells (WL1 & WL2) were installed and monitoring was done daily.
- Installation of observation wells were done after excavation of top slope and installation of subsurface drains at top berm level.
- Hence, water table from investigation was lower than the water level from monitoring





Study the Effectiveness of Mitigation

Overview

- This study was carried out in order to evaluate the behavior of the rectified slope under a critical rainfall.
- Effectiveness of drainage improvement in slope stabilization was studied deeply.
- Importance of drainage improvement in soil nailing and economizing of soil nailing by drainage improvement was studied.
- Requirement and significance of stage construction in slope strengthening measures was evaluated.

Study the Effectiveness of Mitigation

- Detail study on effectiveness of mitigation measures in slope stabilization against a critical rainfall event is presented in several sub topics as;
  - ✓ SLOPE/W model
  - ✓ SEEP/W model
  - ✓ Analysis Under Different Conditions
  - ✓ Results
  - ✓ Economizing the Nailing Design

SLOPE/W Model – *Development of the Model*

- SLOPE/W has capacity to perform stability analysis based on many methods of slices approaches. Input data for SLOPE/W model are;

Slope Geometry and Subsoil Profile

- Profile obt…
  fo…

Analysis Type

- Spencer's method

Slip Surface

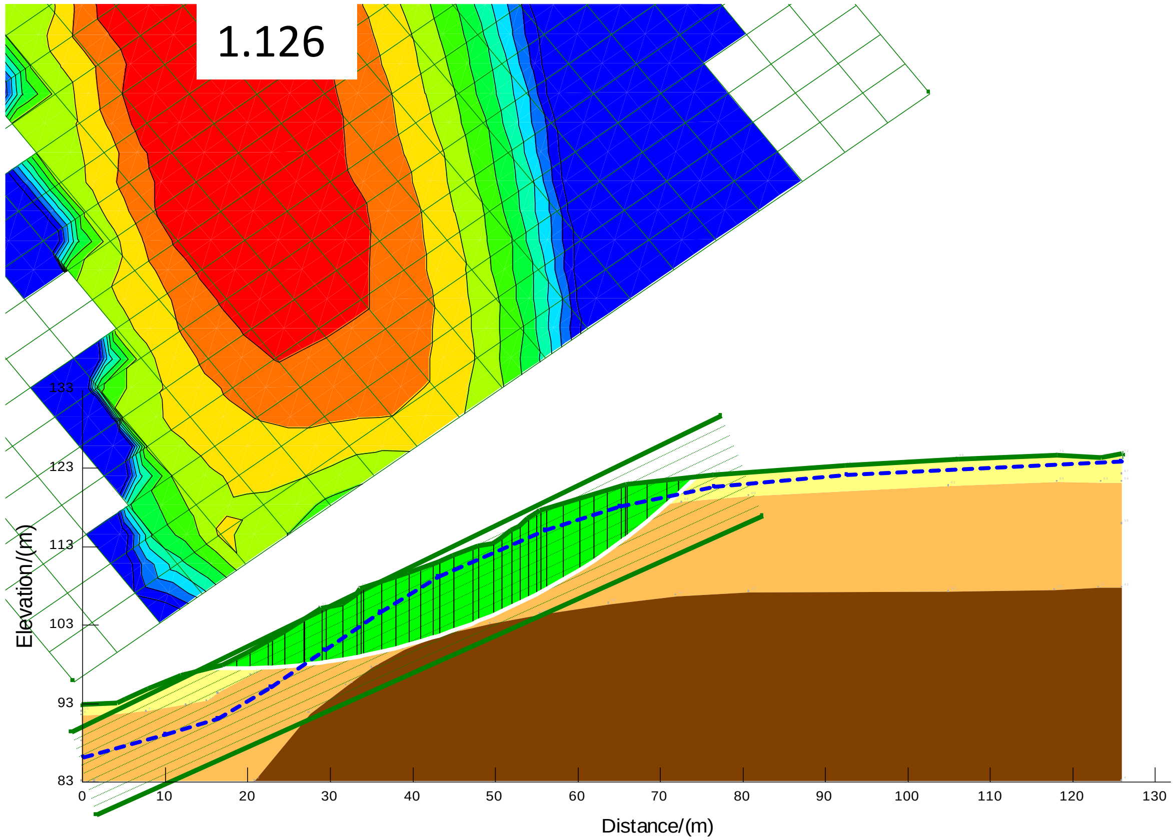
Reinforcement Parameters

- …2 mm bars
- …ill holes
- …nce

SLOPE/W Model

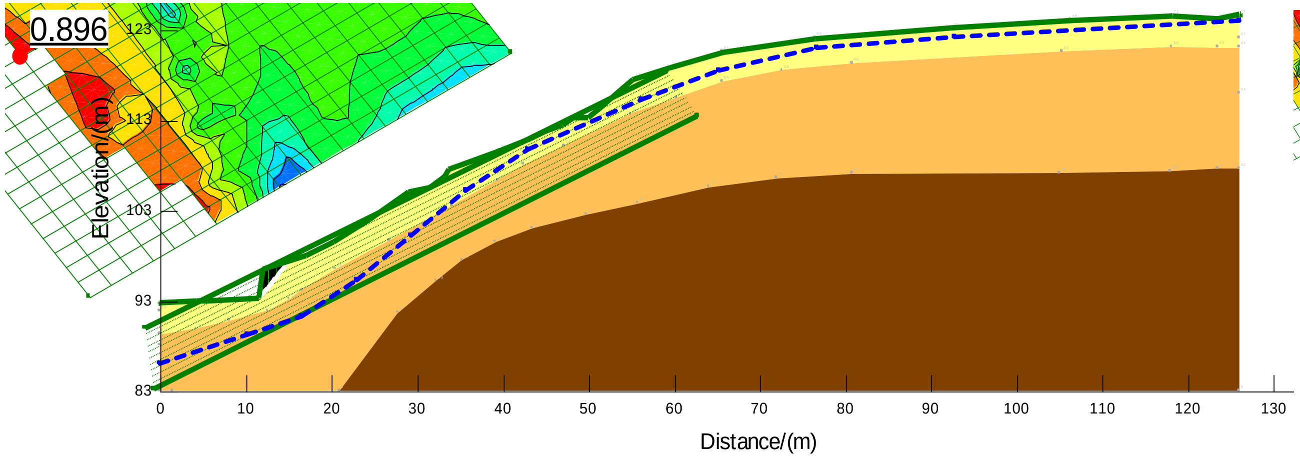
SLOPE/W Model – *Model Verification with Back Analysis*

- Back analysis was done to model the failure occurred with the toe excavation and thereby verification of the model.
- Since there was no rain at the time of failure, no infiltration analysis was done.
- GWT is taken from the results of investigation.
- FoS = 1.126 ➔ critically stable slope.

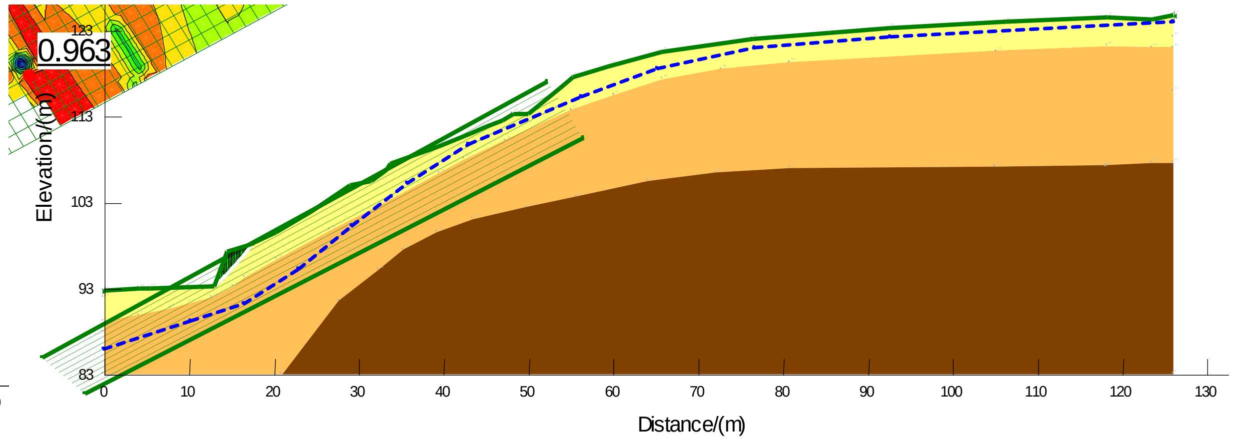


Original Condition

SLOPE/W Model – *Model Verification with Back Analysis*

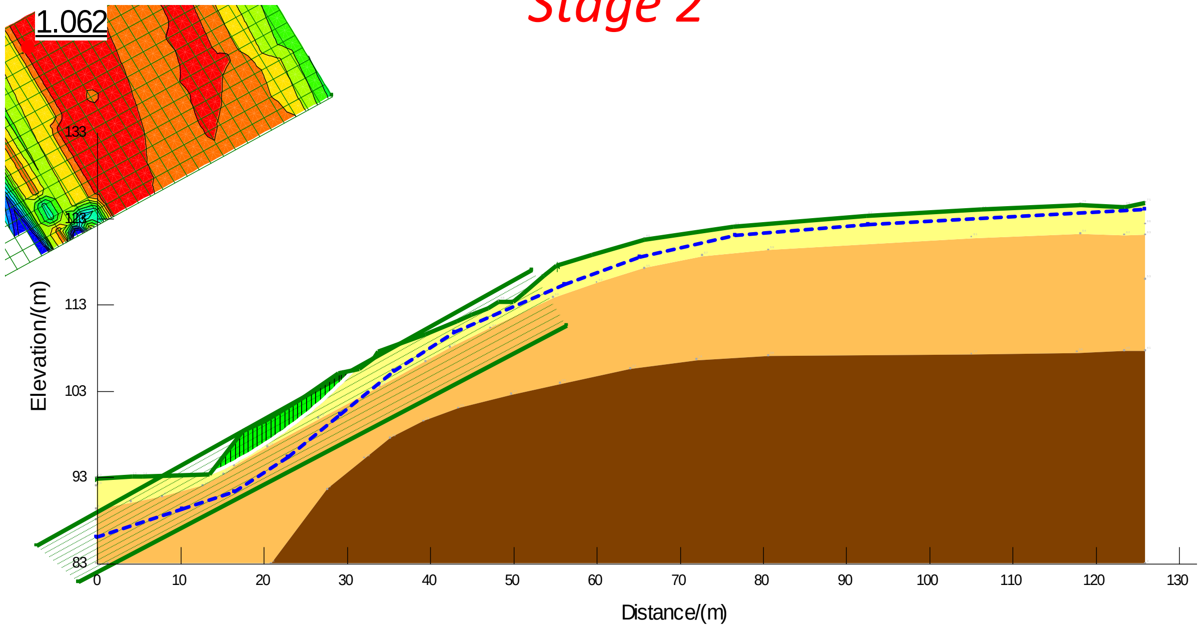


Just After the Excavation (Stage 1)



Stage 2

- FoS = 0.896 ➔ slope failure with excavation
- FoS = 0.963 ➔ propagated failure Stage 2
- FoS = 1.062 ➔ failure will occur with rain
- These low FoS values confirm initial failure, propagation and further activation with rainfall.



Stage 3

SEEP/W Model – *Development of the Model*

- SEEP/W software has a capacity to simulates the movement of liquid water or water vapor through saturated and unsaturated porous media.

Slope Geometry and Subsoil Profile

- Slope geometry and subsoil profile was found by investigation.

Analysis Type

- Transient type analysis was done to simulate the variation of pore pressure regime with time.

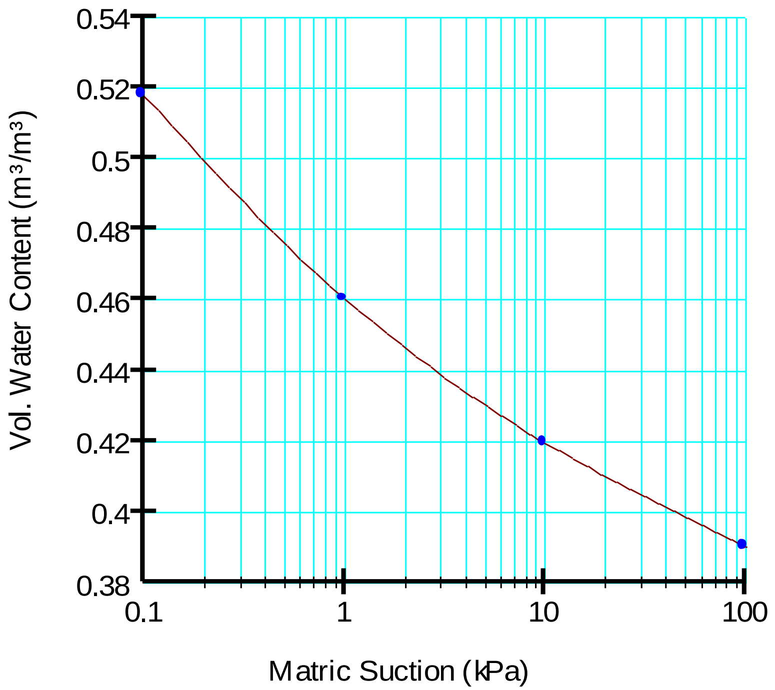
Material Model and Parameters

- Since both saturated & unsaturated conditions are present in the slope, Saturated/Unsaturated soil model was selected for analysis.

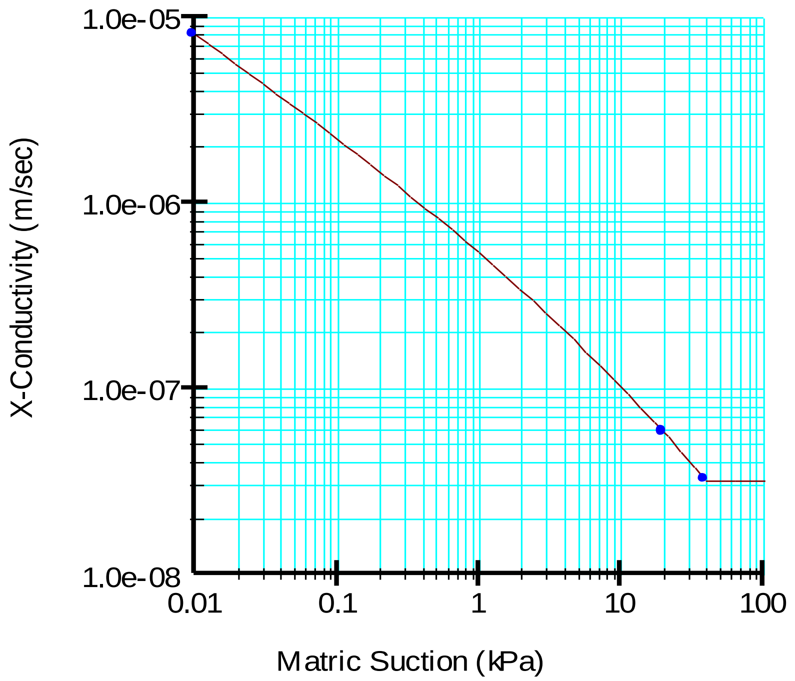
SEEP/W Model – *Development of the Model*

Soil Water Characteristic Curve (SWCC) & Hydraulic Conductivity Function

- Since the research done in Sri Lankan context are limited, results of the study done by Vasanthan (2016) for residual soil was used as the SWCC & Hydraulic Conductivity Function.



SWCC (Vasanthan, 2016)

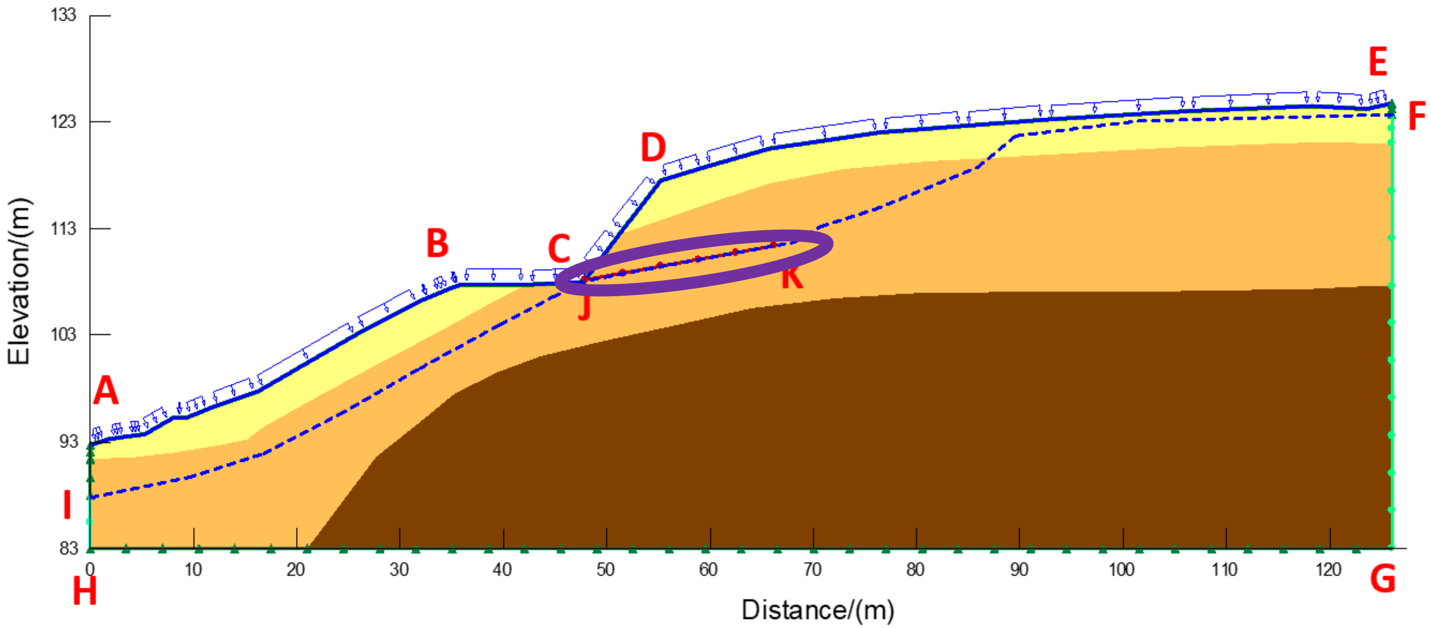


Hydraulic Conductivity Function Modified from (Vasanthan, 2016)

SEEP/W Model – *Development of the Model*

Boundary Conditions

- A-B-C-D-E ➔ Rainfall as Unit Flux
- E-F,A-I ➔ No flow as zero Total Flux
- F-G,I-H ➔ Total heads as Heads
- G-H ➔ No flow as zero Total Flux
- J-K ➔ Zero pressure



- Perforated pipes of sub horizontal gravity drains which were installed at some horizontal spacing was idealized to plain strain condition by zero pressure boundary condition applied to lines with no thickness.

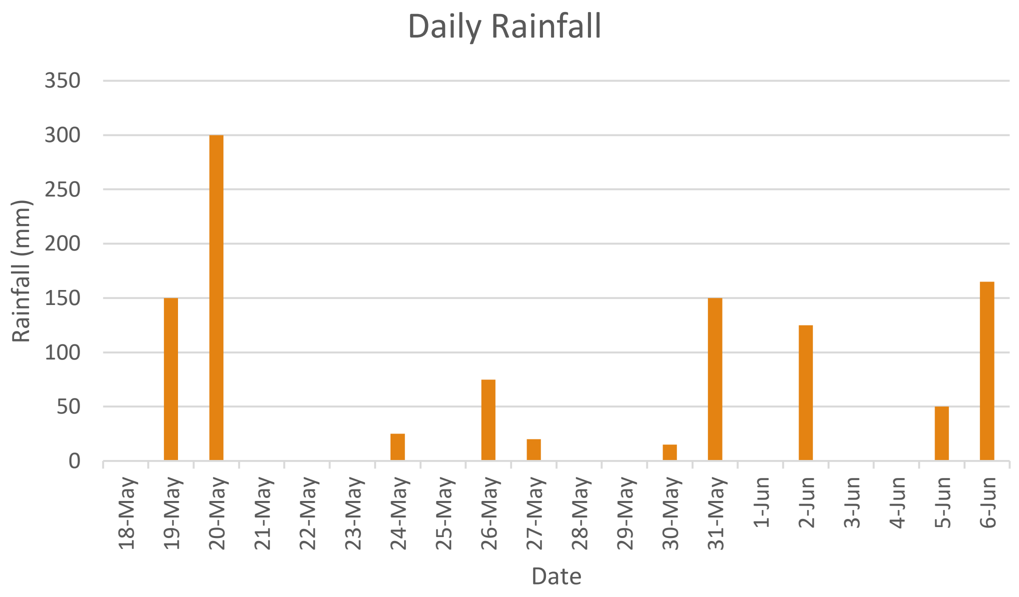
SEEP/W Model – *Development of the Model*

Modeling of Vegetation Cover and Berm Drains

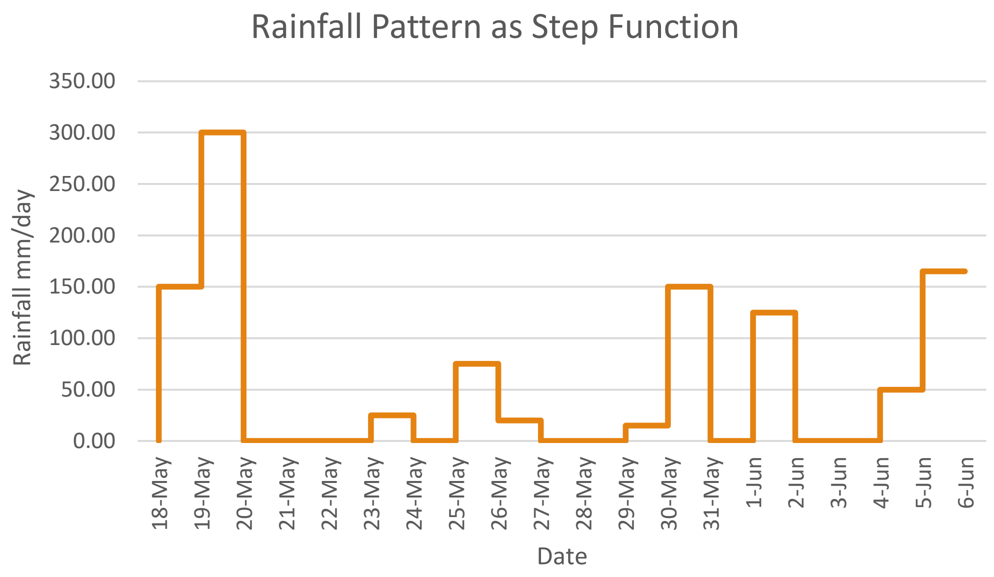
- Kulathilaka & Kumara (2013) has proposed to model the effect of surface drains and vegetation cover by a thin layer of low permeability in the order of 10^{-7} m/s. Therefore, a 100 mm thick layer of permeability of 5×10^{-7} m/s was used.
- Permeability of 1×10^{-20} m/s was assigned for 100 mm thick layer for modeling of berm drains as suggested by Dharmasena & Kulathilaka (2015).

SEEP/W Model – *Model Verification*

- Verification of the SEEP/W model was done simulating a rainfall event and comparing the resultant water level fluctuation with actual water level fluctuation.
- 20 days rainfall cycle including critical rainfall occurred during observation period was simulated.



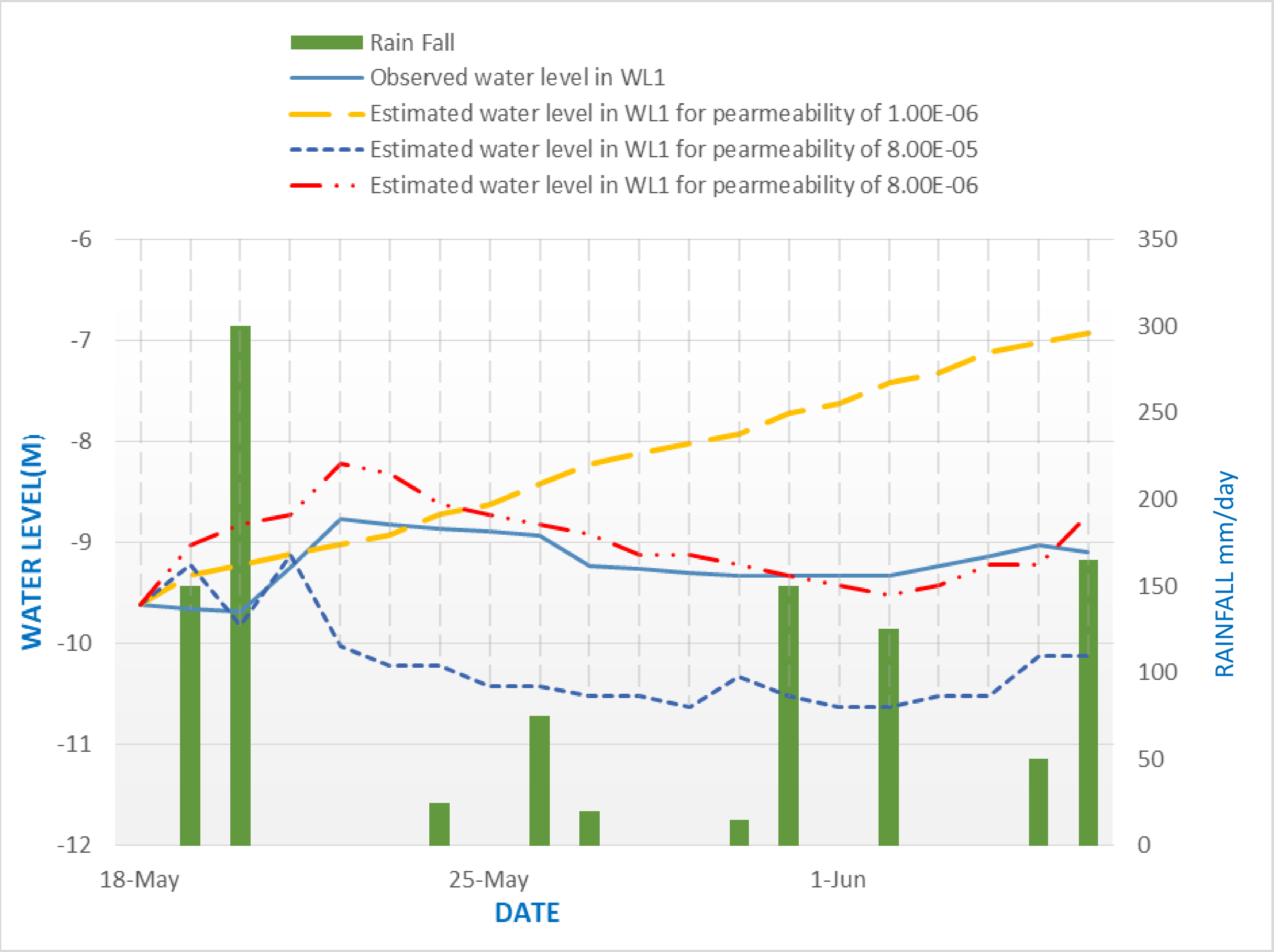
Actual Rainfall Record



Rainfall as Step Function for SEEP/W

SEEP/W Model – *Model Verification*

- Comparison was done for WL1, since fluctuation of the water level is more detectible.
- Permeability varying from 8×10^{-5} m/s to 1×10^{-6} m/s.
- Results of permeability value of 8×10^{-6} m/s comply well with the observations



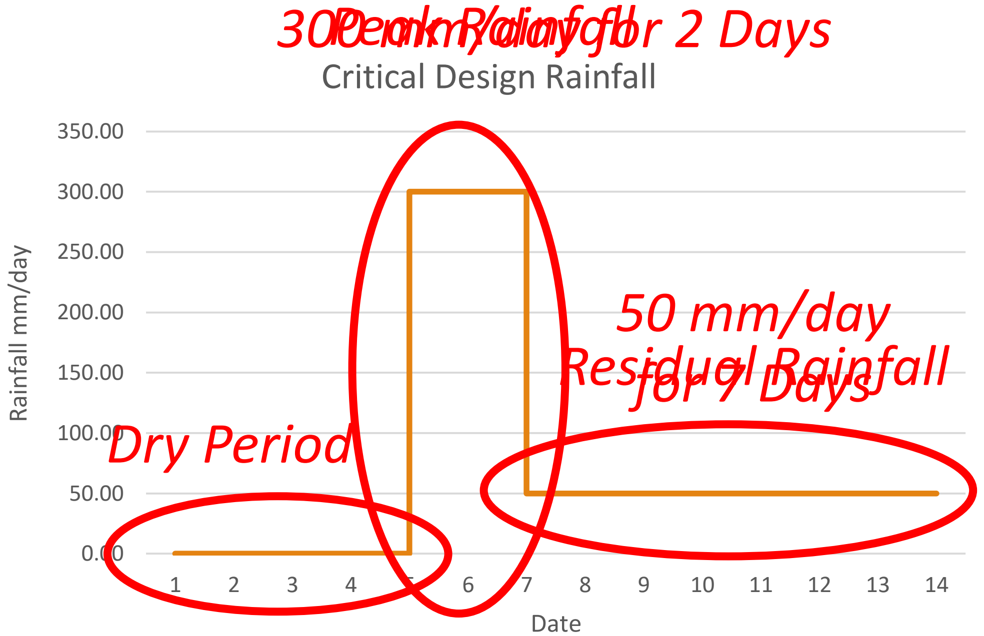
Comparison of Water Levels

Different Conditions – *Critical Design Rainfall*

- Response of the slope to a critical design rainfall event was analyzed under different conditions of drainage improvement and reinforcement.

Critical Design Rainfall

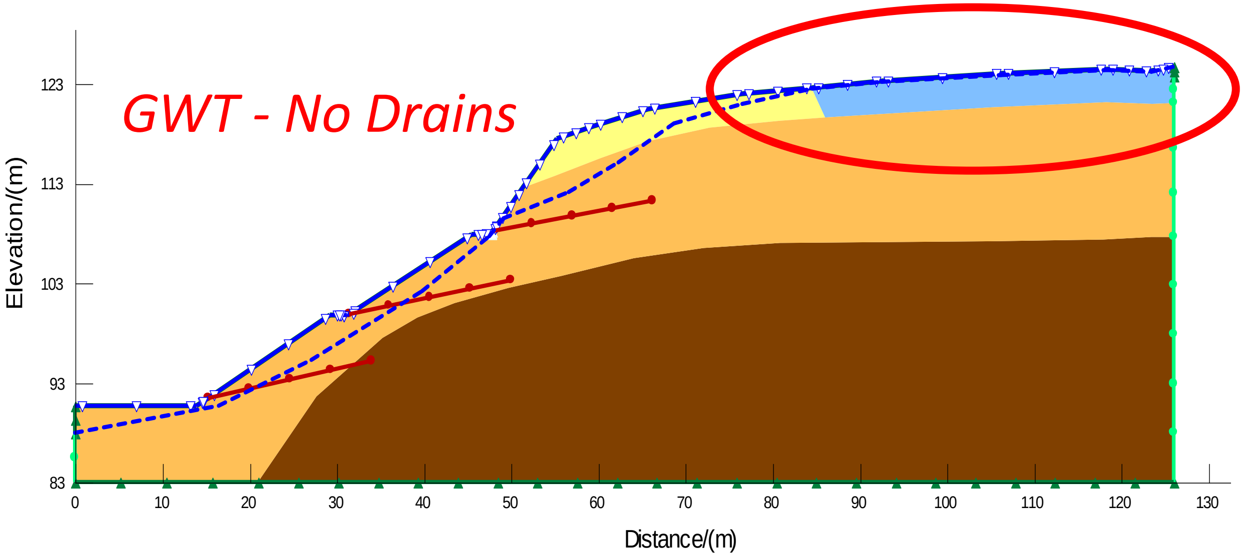
- The critical peak rainfall observed during the monitoring period is 300 mm/day.
- Therefore, critical rainfall was considered as 300 mm/day for two days and 50 mm/day residual rainfall applied for seven days.
- Five days dry period was applied to simulate the GWT lowering from investigation to monitoring stage.

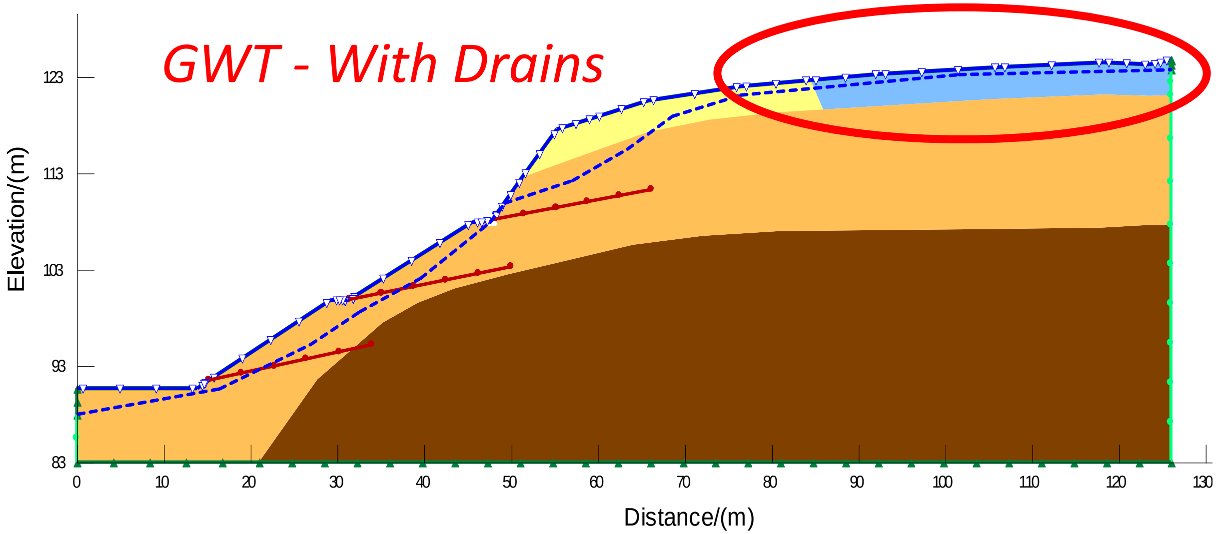


Critical Design Rainfall

Different Conditions – *Drainage Conditions*

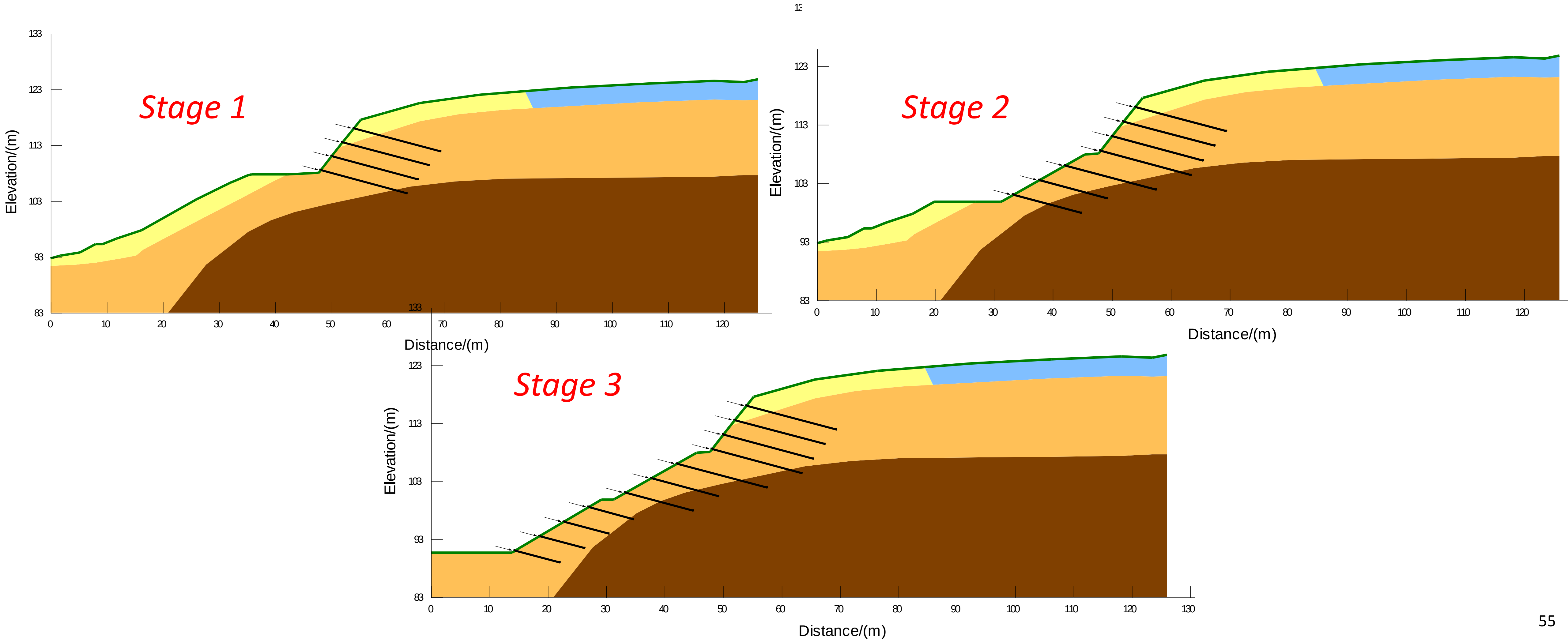
- Following alternative conditions were considered in the analysis.
  - ✓ No drainage improvement ➔ "No Drains"
  - ✓ Surface drainage improvement ➔ "Surface Drains"
  - ✓ Both surface and subsurface drainage improvement➔ "Surface & Subsurface Drains"
- Water table from investigation was taken as initial GWT.
- GWT lowering at marshy area via trench drains were modeled by lowering the initial GWT at crest area for improved drainage analysis.





Different Conditions – *Construction Stages*

- Slope was excavated into three segments with two berms. Stability of each section was studied with & without nails in order to assess the importance of staged construction



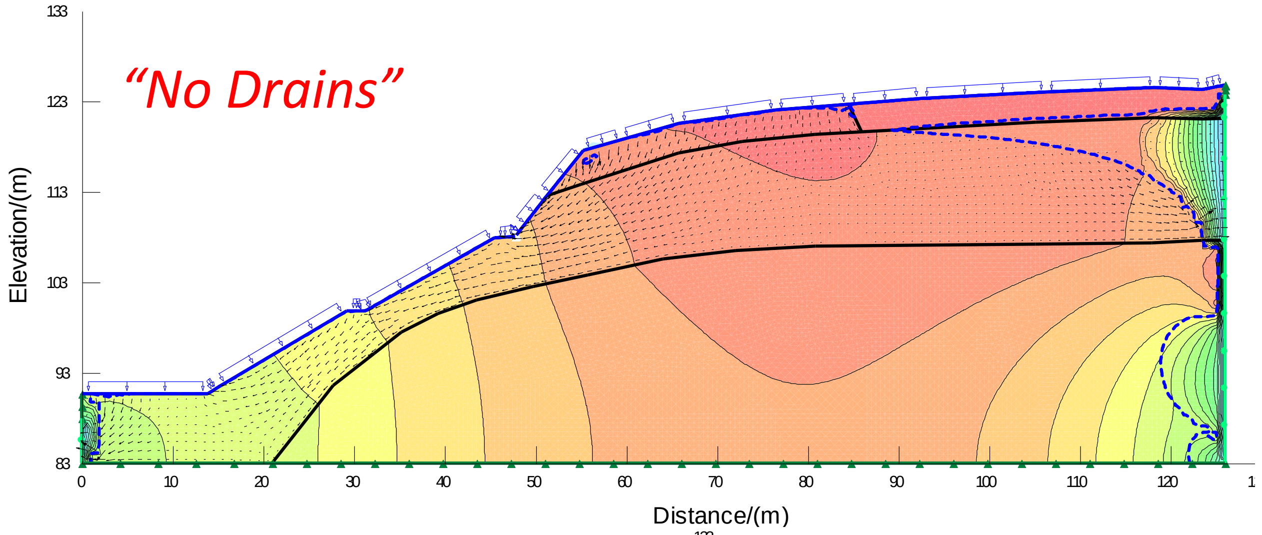
Different Conditions – *All Analysis Types*

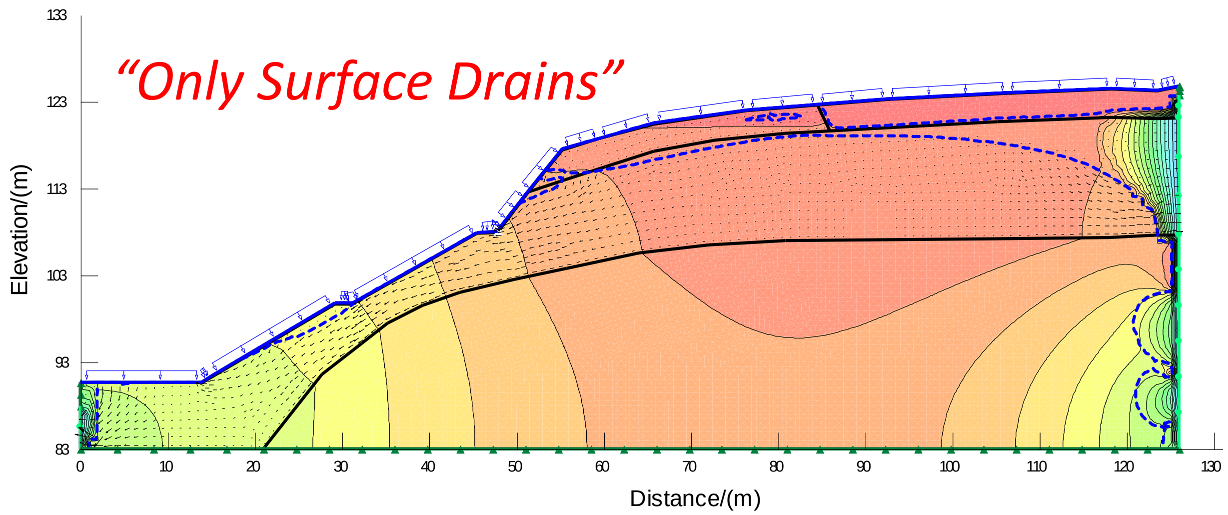
- Different types of analyses done can be summarized as follows.

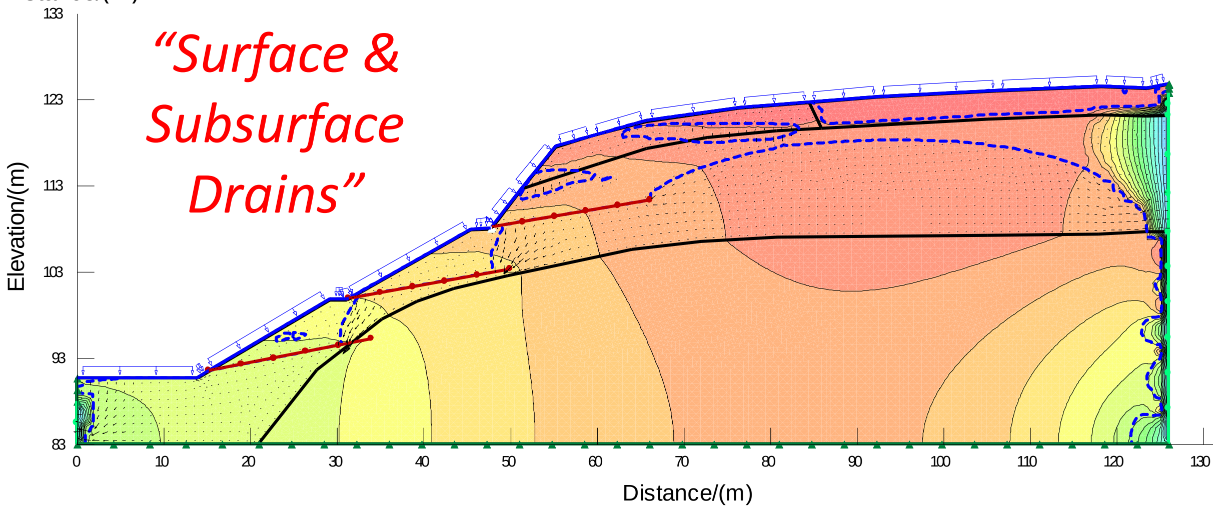
Construction Stage	Without Drainage Improvement		With Surface Drainage Improvement		With Surface and Subsurface Drainage Improvement	
	Without Nailing	With Nailing	Without Nailing	With Nailing	Without Nailing	With Nailing
Stage 1	✓	✓	✓	✓	✓	✓
Stage 2	✓	✓	✓	✓	✓	✓
Stage 3	✓	✓	✓	✓	✓	✓

Results – *Drainage Improvement Effect on Ground Water Regime*

- The pore water pressure contours and ground water level corresponding to different drainage improvements after peak rainfall at Stage 3 (results of SEEP/W) are as follows.



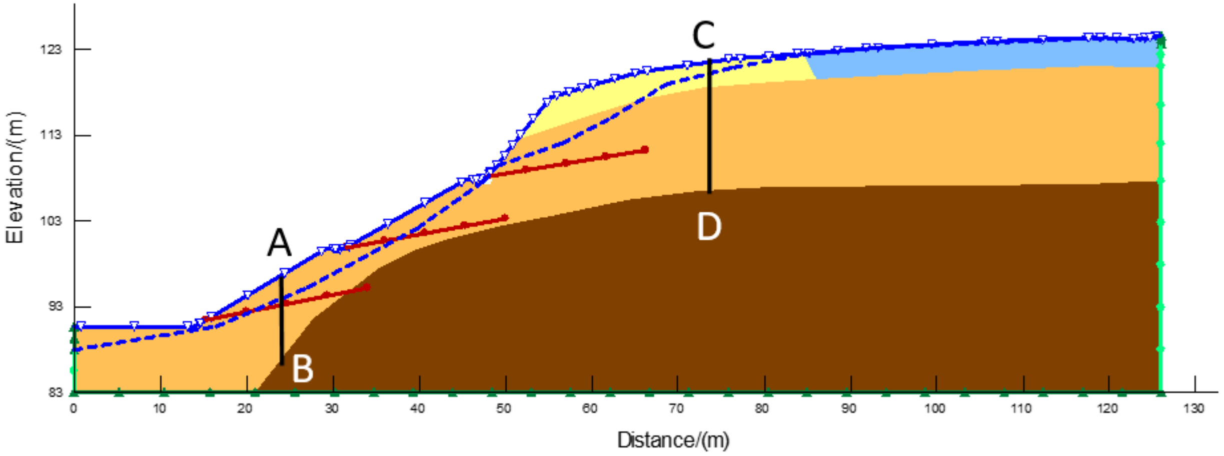


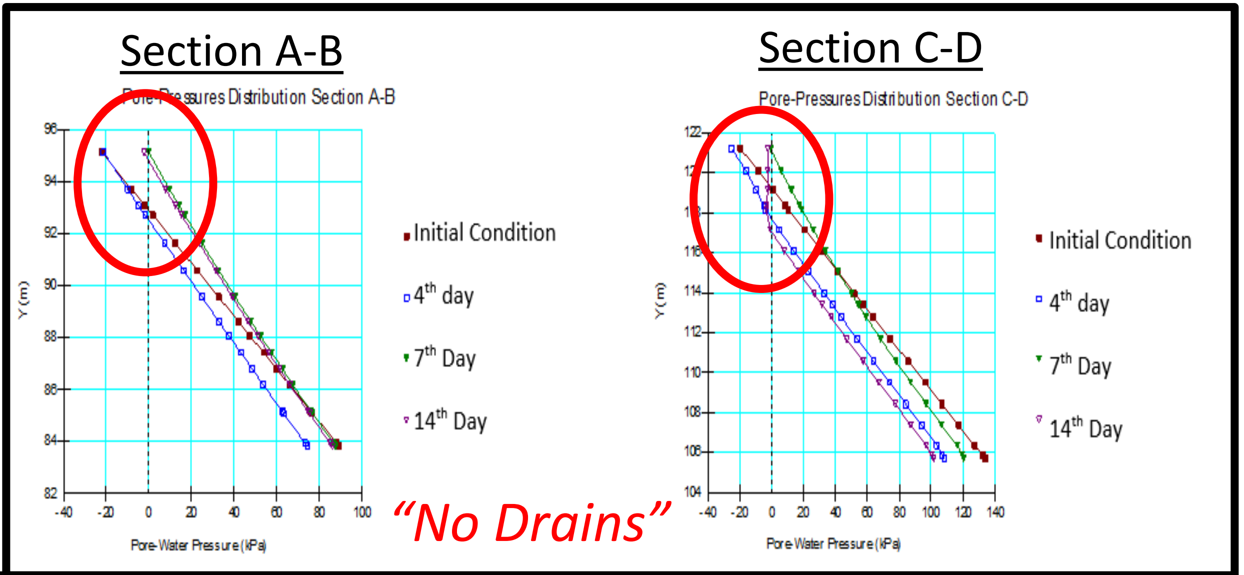


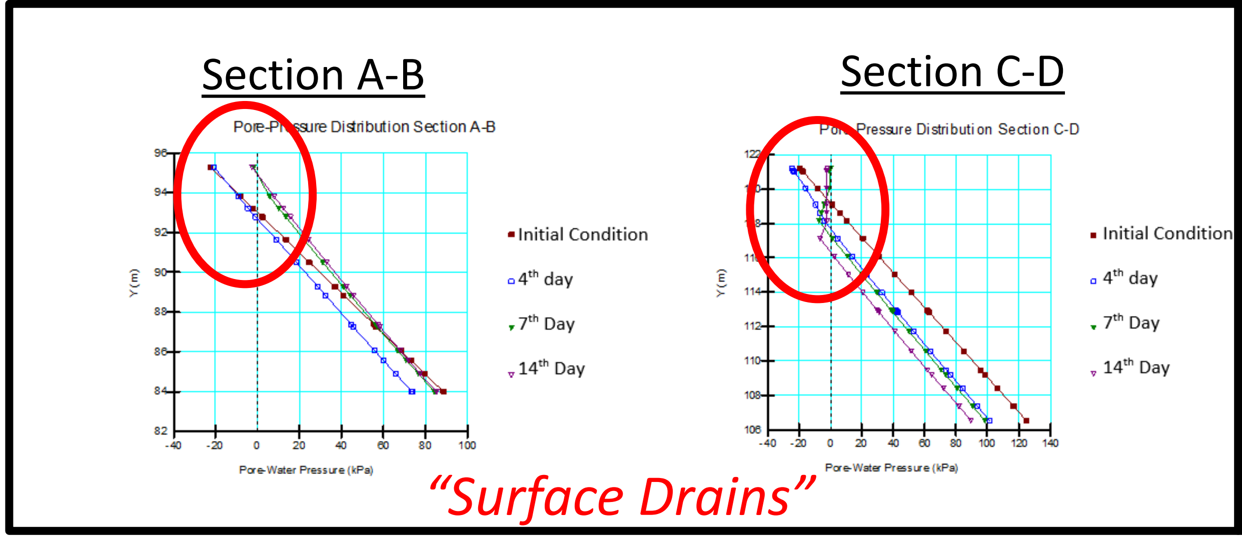
Results – *Drainage Improvement Effect on Ground Water Regime*

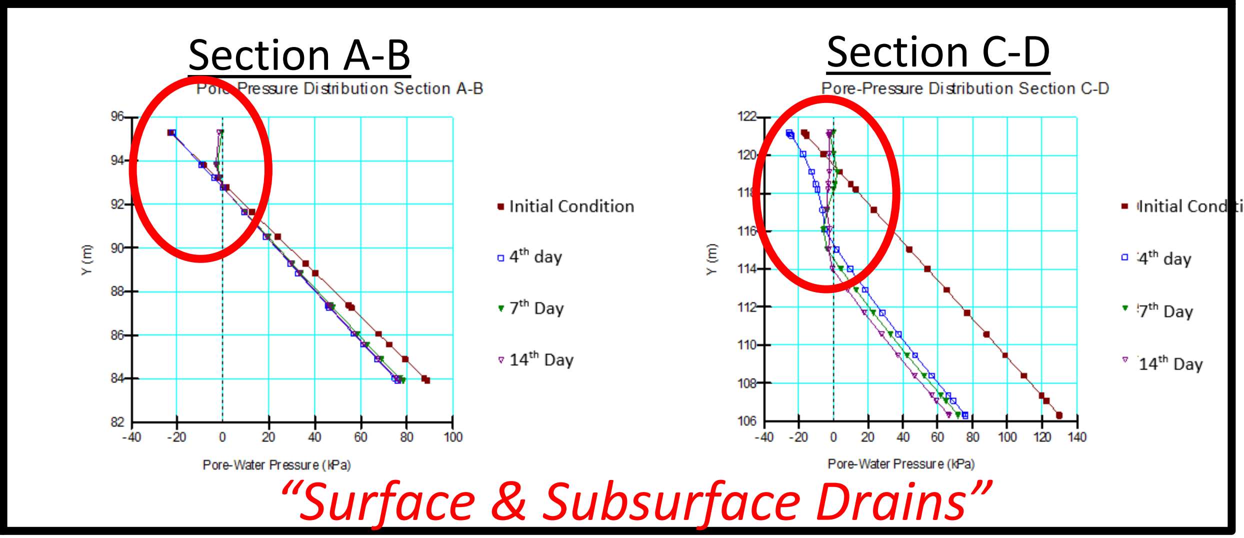
- GWT rise to surface level in "No Drains" condition.
- GWT reduces parallel to the ground surface in "Only Surface Drains" condition.
- GWT further lowered in "Surface & Subsurface Drains" condition. GWT reduces up to the subsurface drain and it takes parabolic shape beyond the edge of the drain.
- Effect on the ground water regime is further studied in terms of pore pressure distribution.

Results – *Drainage Improvement Effect on Ground Water Regime*









Results – *Drainage Improvement Effect on Ground Water Regime*

- Behavior of PWP regime can be summarized as follows.

Section	"No Drains"	"Only Surface Drains"	"Surface and Subsurface Drains"
A-B	• GWT lowered slightly during dry period. • GWT rise close to surface with peak rainfall. • GWT constant during residual rainfall.	• Behavior of GWT is quite similar to "No Drains" Condition.	• GWT lowered during the dry period. • GWT doesn't rise and only loss matric suction with peak rainfall. • PWP doesn't change in residual rainfall.
C-D	• GWT lowered during dry period. • GWT rise close to surface with peak rainfall. • GWT lowered during residual rainfall.	• Behavior of GWT in dry period is quite similar as "No Drains". • GWT doesn't rise and only loss matric suction with peak rainfall. • GWT lowers and matric suction developed with residual rainfall.	• GWT significantly reduce during dry period. • GWT doesn't rise and only loss matric suction with peak rainfall. • GWT lowers and matric suction developed with residual rainfall.

Results – *Drainage Improvement Effect on Ground Water Regime*

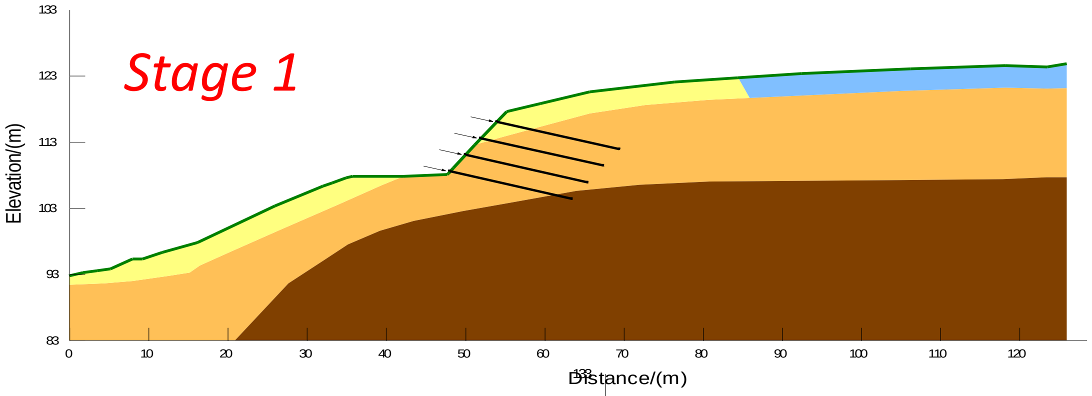
Remarks

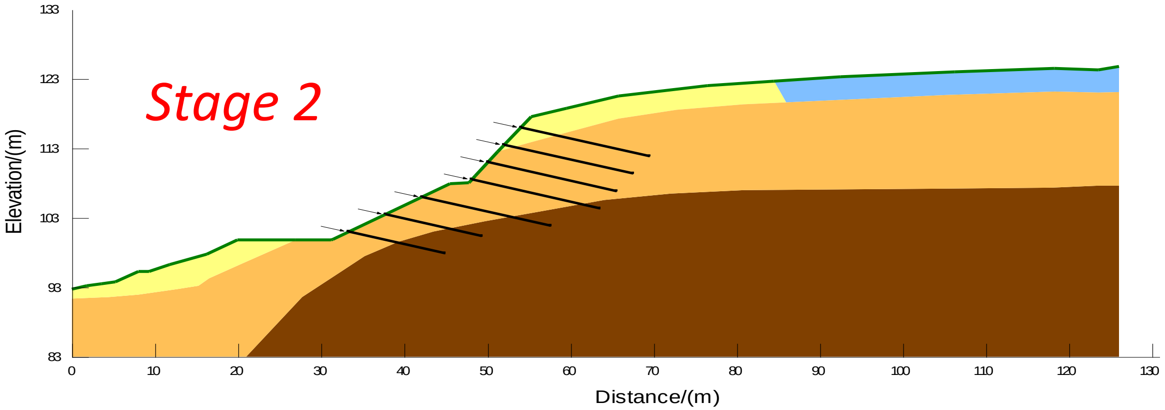
- Surface drains are only effective with rainfall. They cannot influence the ground water movement and only have capability to reduce infiltration.
- Application of subsurface drains influence the ground water directly and thereby lowering the GWT in dry period. In rainy periods, they can rapidly discharge the infiltrated rainwater. However, it occurs when infiltration reaches to the subsurface drains level. Therefore, matric suction up to drain level is lost.
- Application of subsurface drains in addition to surface drains is more effective.

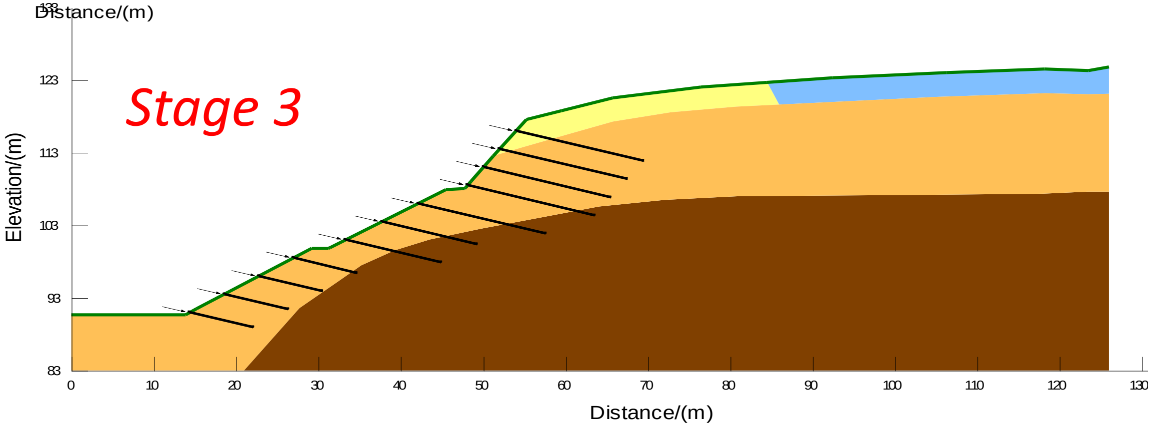
Results – *Drainage & Reinforcement Effect on Stability*

- Results of SEEP/W analysis was incorporated in to SLOPE/W analysis.

- Effect of drainage improvement and reinforcement at each Stage was analyzed against critical design rainfall.







Results – *Drainage & Reinforcement Effect on Stability*

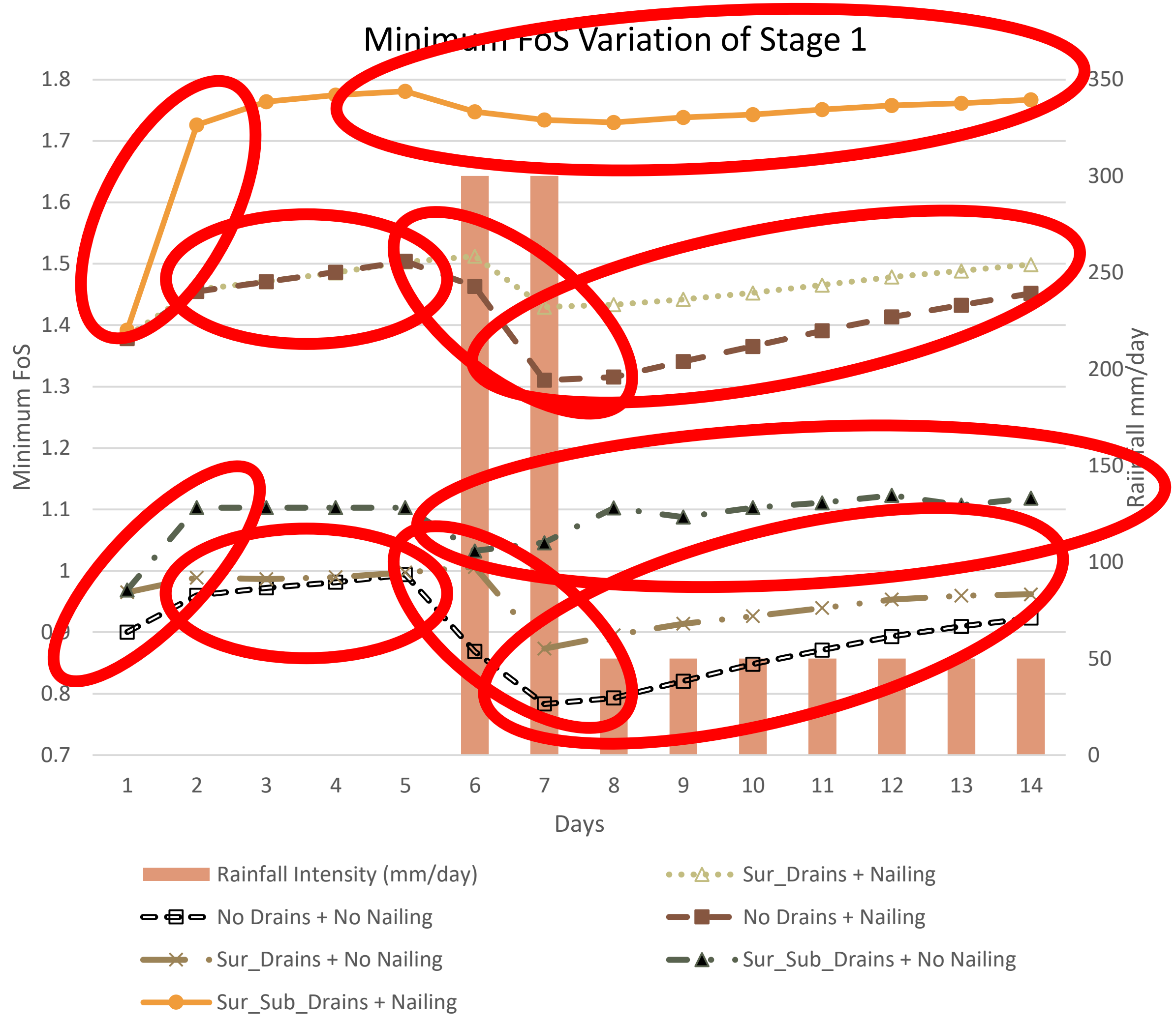
Construction of Stage 1

Results – *Drainage & Reinforcement Effect on Stability*

Stage 1

- Summary of the Variation of minimum FoS for each drainage and reinforcement condition is as follows.

	"No Drains"	"Only Surface Drains"	"Surface and Subsurface Drains"
Dry Weather	FoS increases slightly.	FoS increases slightly as similar to "No Drains" condition.	FoS increase rapidly and maintained at a higher value.
Peak Rainfall	FoS reduces rapidly.	FoS reduces rapidly. Reduction is less than "No Drains" condition and delayed.	FoS reduction is much lesser.
Residual Rainfall	FoS increases.	FoS increases.	FoS gradually increase to peak level.



Results – *Drainage & Reinforcement Effect on Stability*

- Surface drains are effective in directing the rainfall away from the slope minimizing the infiltration. As such, at "no rainfall" condition they will not have any influence.
- FoS with "no drains" and "only surface drains" condition is less than unity when no nails are applied, which implies the slope is unstable.
- Surface drainage improvement slightly increases the FoS and with the combination of subsurface drainage there is a significant improvement of the FoS. Further, application of reinforcement has significantly improved the FoS of all drainage conditions.
- Long term stability is maintained with the application of soil nails for any drainage type.
- Even short term stability cannot be achieved without nailing regardless of drainage.

Results – *Drainage & Reinforcement Effect on Stability*

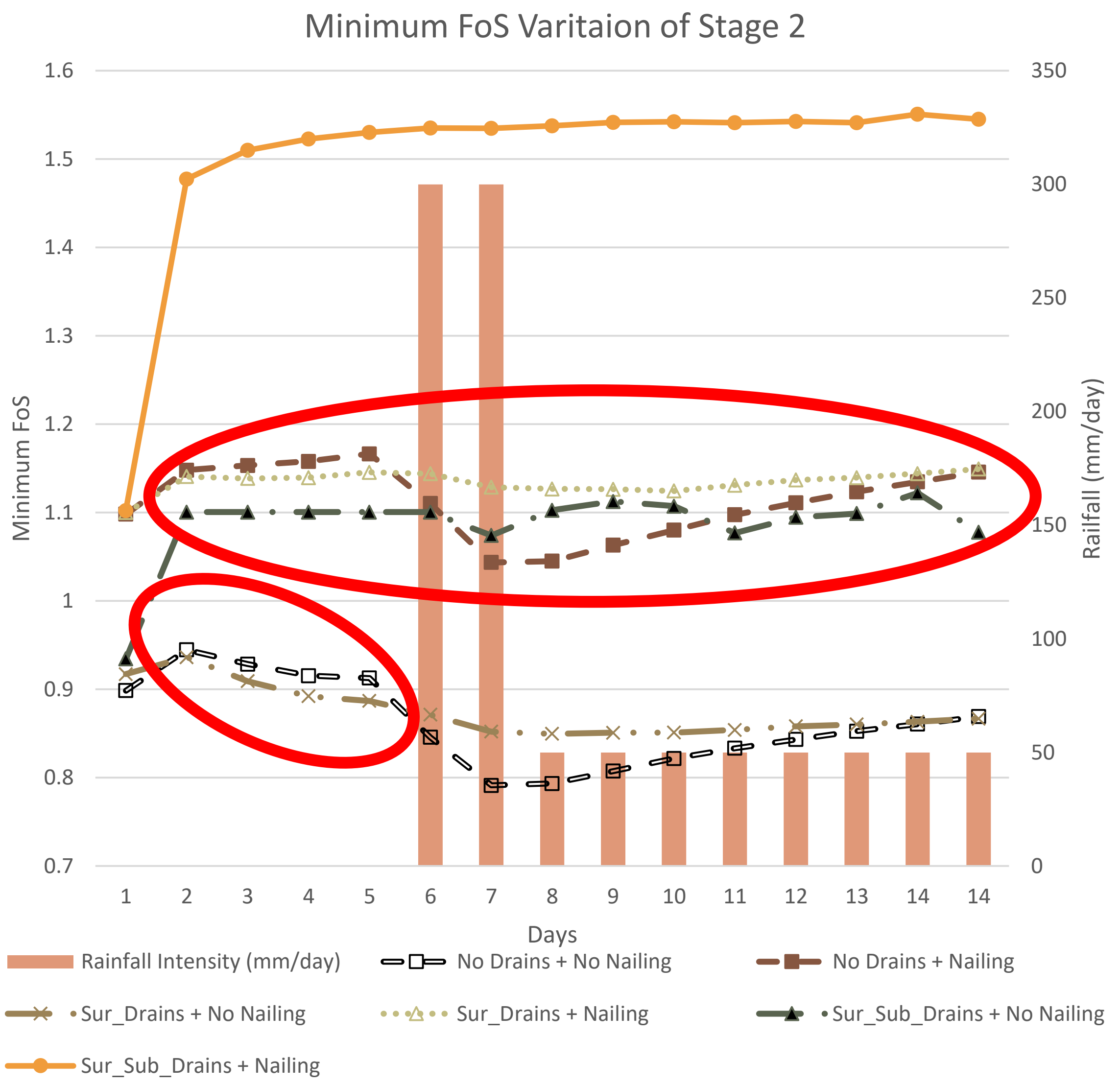
Construction of Stage 2

Results – *Drainage & Reinforcement Effect on Stability*

Stage 2

- Summary of the Variation of minimum FoS for each drainage and reinforcement condition is as follows.

	"No Drains"	"Only Surface Drains"	"Surface and Subsurface Drains"
Dry Weather	FoS reduces slightly @ "No Nails" condition.	FoS reduces slightly @ "No Nails" condition as similar to "No Drains" condition.	FoS increase rapidly and maintained at a higher value.
Peak Rainfall	FoS reduces rapidly.	FoS reduces rapidly. Reduction is less than "No Drains" condition and delayed.	FoS reduction is much lesser.
Residual Rainfall	FoS increases.	FoS increases.	FoS gradually increase to peak level.



Results – *Drainage & Reinforcement Effect on Stability*

- Variation pattern of FoS in Stage 2 is more or less similar that for Stage 1 with several significant features.
- FoS slightly reduces, during the dry period in "no drains" and "only surface drains" condition without nails. Increase of the pore pressures close to toe region due to the downward seepage within the soil even during the dry period, may be the reason.
- FoS is in the same range for both "nailing without subsurface drainage improvement" and "no nailing with subsurface drainage improvement" condition.
- Both drainage measures with nails are required for long term stability.
- Surface drains with nails are required for short term stability.

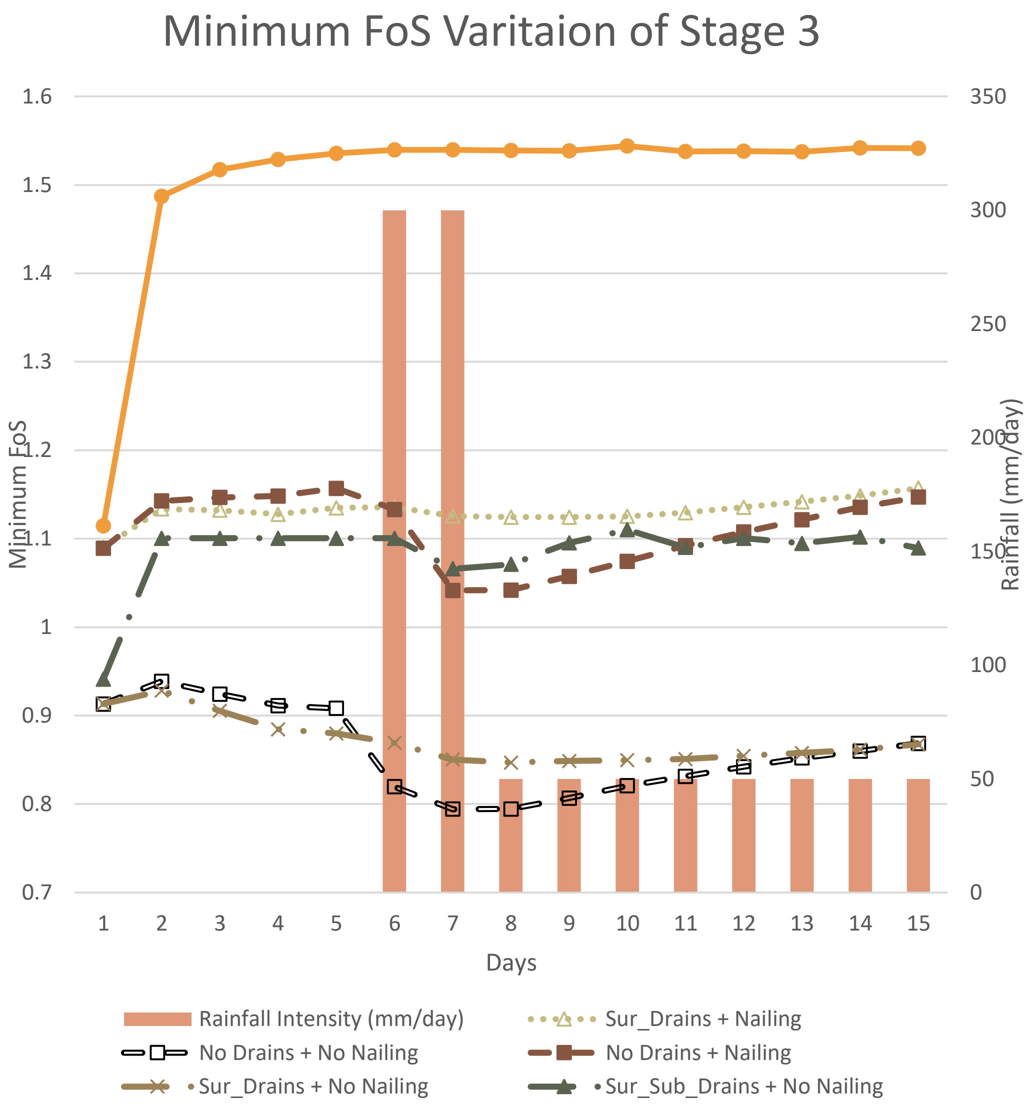
Results – *Drainage & Reinforcement Effect on Stability*

Construction of Stage 3

Results – *Drainage & Reinforcement Effect on Stability*

Stage 3

- Variation of minimum FoS for each drainage and reinforcement condition is presented.
- This variation is almost similar as Stage 2.
- The critical slip surfaces in Stage 2 & 3 are similar because developing the slip surface further downwards in Stage 3 is prevented by the underlain rock layer.



Results – *Drainage & Reinforcement Effect on Stability*

- Summary of the critical FoS after peak rainfall can be summarized as follows.

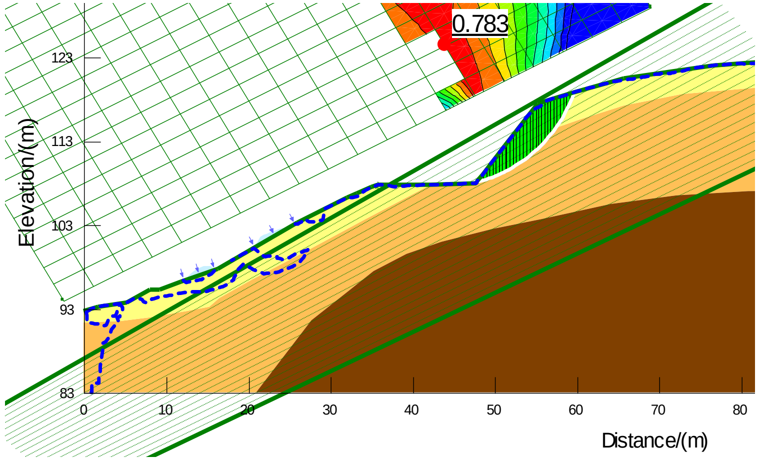
Slope Condition		Stage 1	Stage 2	Stage 3
Drainage	Reinforcement			
No Drains	**No Nailing**	0.783	0.791	0.794
No Drains	**Nailing**	1.310	1.044	1.042
Surface Drains Only	**No Nailing**	0.874	0.850	0.847
Surface Drains Only	**Nailing**	1.430	1.124	1.124
Surface and Subsurface Drains	**No Nailing**	1.046	1.074	1.066
Surface and Subsurface Drains	**Nailing**	1.734	1.535	1.539

Results – *Drainage & Reinforcement Effect on Stability*

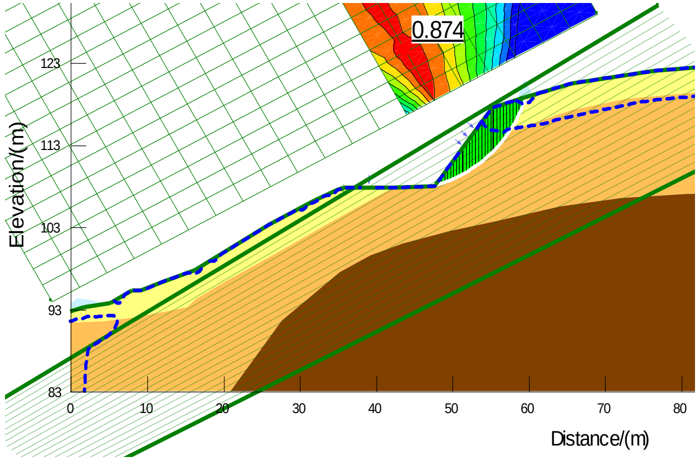
Behavior of Critical Slip Surface

Stage 1

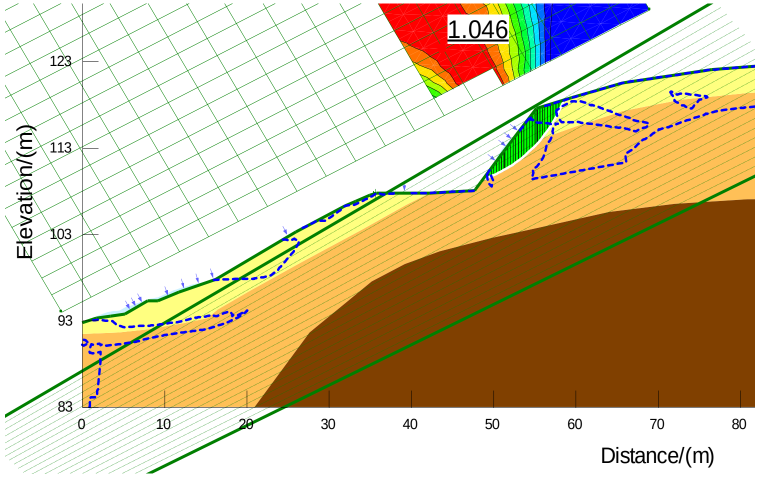
- Critical failure surface is similar for all drainage conditions without nailing.
- Soil nails will move the critical slip surface deeper into the slope and thereby increase the FoS.



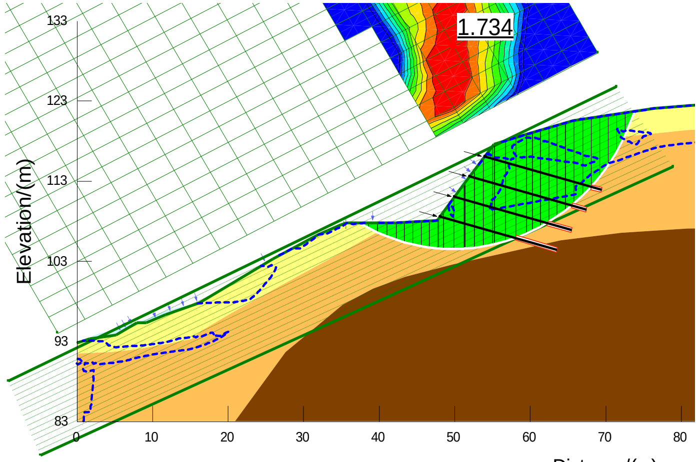
"No Drains"



"Surface Drains"



"Surface & Subsurface Drains"



"With Nails"

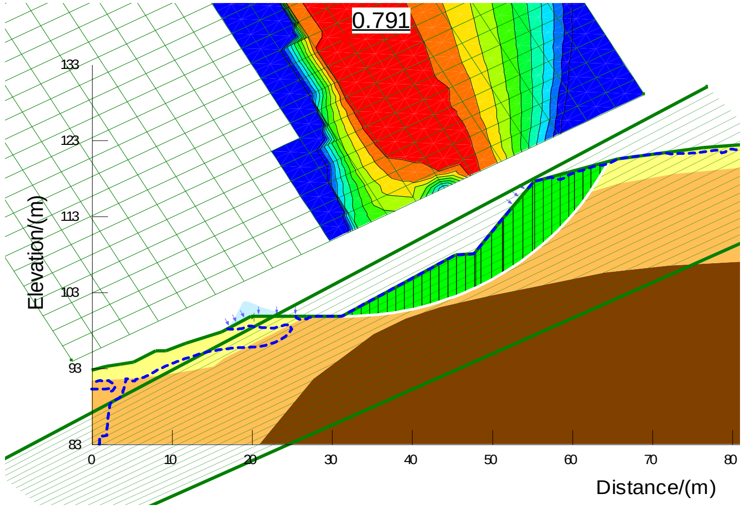
Results – *Drainage & Reinforcement Effect on Stability*

Behavior of Critical Slip Surface

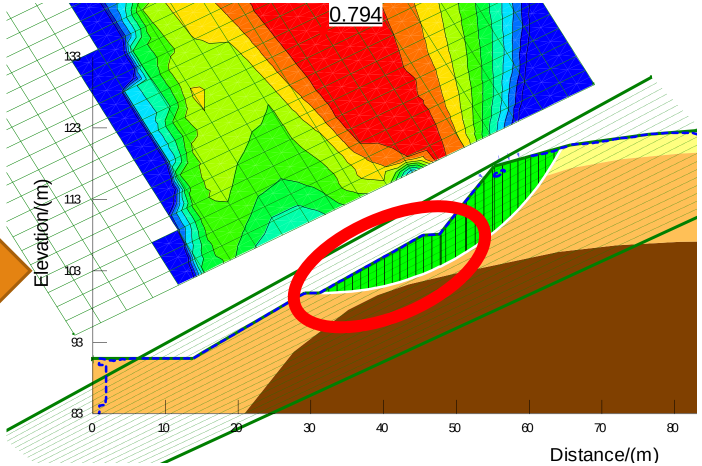
Stage 2 & Stage 3

- Soil nails will move the critical slip surface deeper into the slope and thereby increase the FoS.

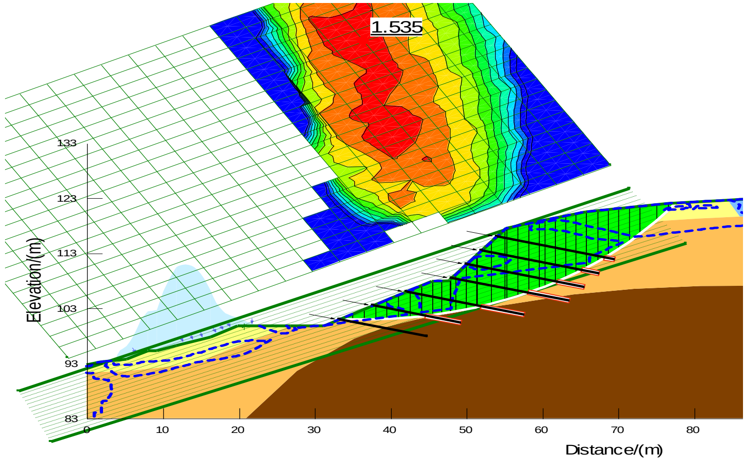
- Critical slip surfaces in Stage 2 & 3 are almost similar because, developing the slip surface further downwards in Stage 3 is prevented by the underlain rock layer.



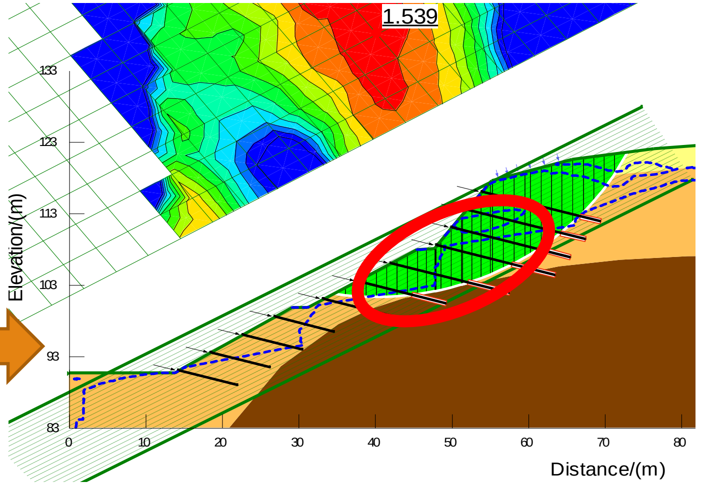
"No Nails" – Stage 2



"No Nails" – Stage 3



"With Nails" – Stage 2



"With Nails" – Stage 3

Economizing the Nailing Design by Drainage

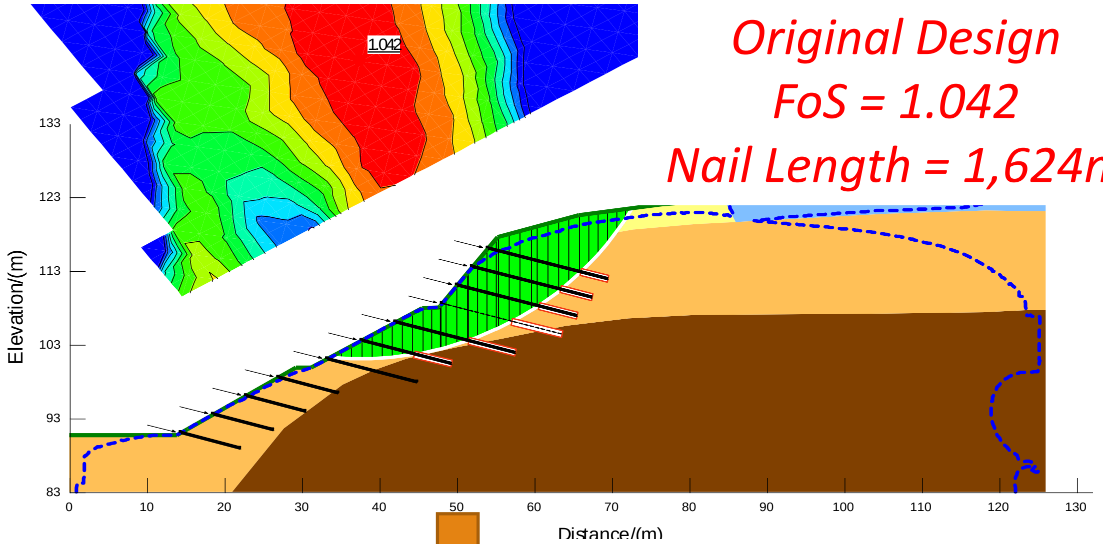
- Implemented design involves both surface & subsurface drains with reinforcement.
- Nailing pattern of implemented design as follows.
  - ✓ 5 nos. of 16 m long nails in 2.0 m horizontal and 2.5 m vertical spacing
  - ✓ 2 nos. of 12 m long nails in 2.0 m horizontal and 2.5 m vertical spacing
  - ✓ 4 nos. of 8 m long nails in 2.0 m horizontal and 2.5 m vertical spacing
- Response of the nailed slope to peak rainfall was studied under "No Drains" and "Only Surface Drains" conditions.
- Additional nailing required to maintain a FoS greater than 1.3 were found under "No Drains" and "Only Surface Drains" conditions.

Economizing the Nailing Design by Drainage

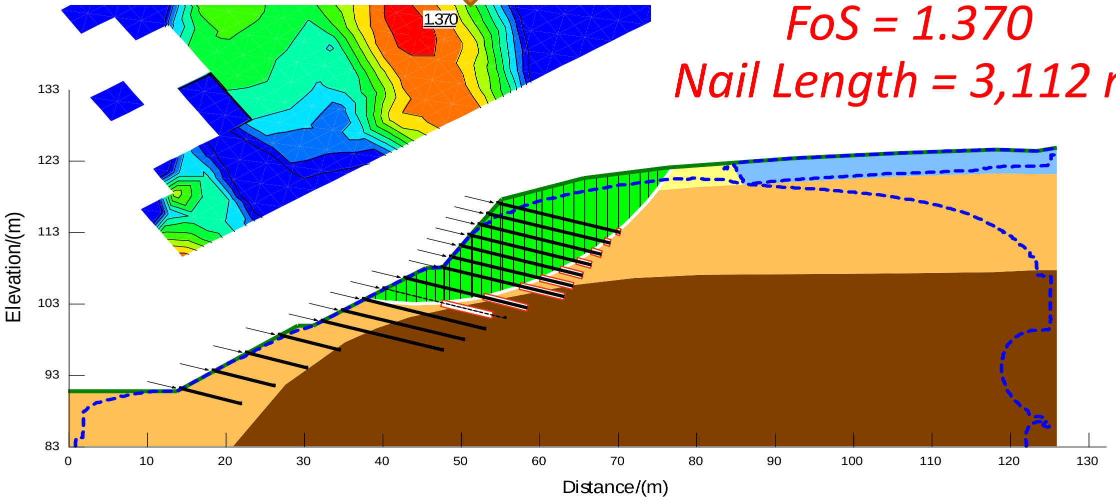
“No Drains” Condition

- Implemented nail pattern have only FoS value of 1.042 for “No Drains” condition, which is not adequate.
- Nailing pattern required to maintain long term stability with peak rainfall as follows.
  - ✓ 12 nos. of 16 m long nails in 1.5 m horizontal and 1.5 m vertical spacing.
  - ✓ 4 nos. of 8 m long nails in 2.0 m horizontal and 2.5 m vertical spacing.

Original Design
FoS = 1.042
Nail Length = 1,624m



New Design
FoS = 1.370
Nail Length = 3,112 m

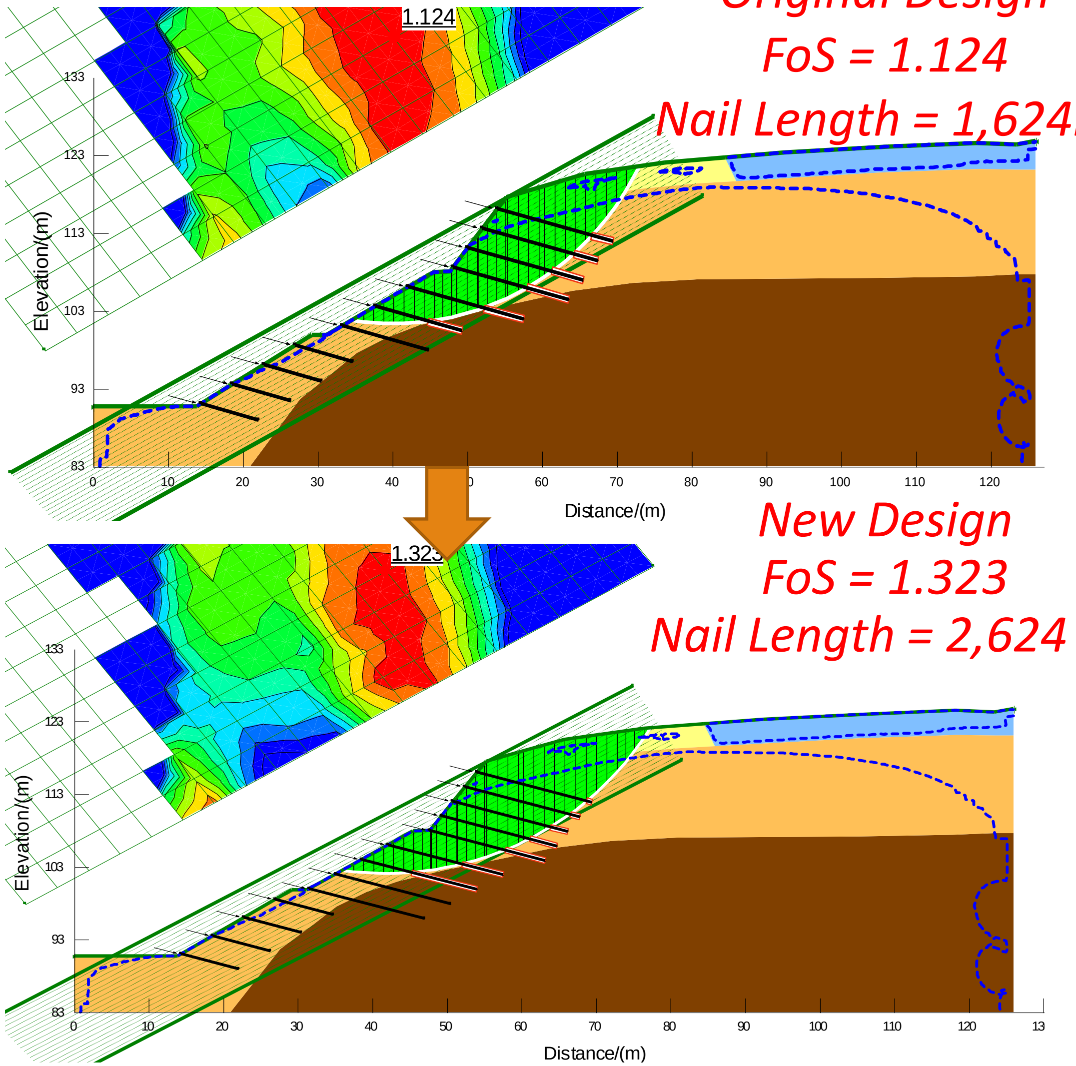


Economizing the Nailing Design by Drainage

“Only Surface Drains” Condition

- Implemented nail pattern have only FoS value of 1.124 for “Only Surface Drains” condition, which is not adequate.
- Nailing pattern required to maintain long term stability with peak rainfall as follows.
  - ✓ 9 nos. of 16 m long nails in 1.5 m horizontal and 2.0 m vertical spacing
  - ✓ 4 nos. of 8 m long nails in 2.0 m horizontal and 2.5 m vertical spacing

Original Design
FoS = 1.124
Nail Length = 1,624m



New Design
FoS = 1.323
Nail Length = 2,624 m

Economizing the Nailing Design by Drainage

- Construction costs for each conditions were calculated based on the average industrial rates.

Drainage Condition	Cost of Nailing and Associated Works (Rs. Mn)	Cost of Drainage Improvement (Rs. Mn)	Cost of Excavation and Other Works (Rs. Mn)	Total Cost (Rs. Mn)	Cost Saving
No Drains	41.6	0	7.4	**49.0**	0.00%
Only Surface Drains	34.9	5.4	7.4	**47.7**	2.65%
Both Surface and Subsurface Drains	25.4	9.1	7.4	**41.9**	14.49%

Conclusion and Recommendations

- During past few decades, rain induced landslides have become a major natural disaster in Sri Lanka.
- In the rain induced landslides, drainage improvement is considered as a mandatory and vital component in mitigation measures and reinforcing can be done when drainage measures are not adequate enough to maintain the stability.
- Understating the effect of drainage improvement in slope stability is important.
- Ginigaththena landslide was trigged by toe excavation, propagated to upper slope and further activated by rainfall.
- Reasonably accurate seepage model can be developed by SEEP/W software to simulate the drainage measures and rainfall infiltration.

Conclusion and Recommendations

- Surface drainage improvement alone does not influence the existing ground water regime significantly. It reduces the amount of infiltration during the rains.
- Subsurface drainage significantly influence the existing ground water regime directly.
- Trench drains were used for lowering the water stagnation at the marshy area at crest.
- Different rectification measures of drainage and reinforcement have different effect on slope stability and should be applied on the correct sequence to ensure that a sufficient safety margins are maintained.
- If only the surface drainage measures are implemented the FoS does not decrease significantly during heavy rains. Combination of surface & subsurface drains is more effective.

Conclusion and Recommendations

- Nailing will apply large tensile forces across potential shallow failure surface and the failure surface will be pushed deeper into the slope.
- Tensile force mobilized by the nails will increase the FoS.
- Properly designed combination of drainage and reinforcement will make the project more economical.
- It is necessary to have appropriate monitoring scheme to evaluate the performance of mitigation measures.
- More accurate results can be obtained if sub horizontal gravity drains are simulated three dimensionally accounting for the horizontal spacing.


CRiP
Thank you