ReSSA+
Overview and Instructive Examples

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Federal Highway Administration

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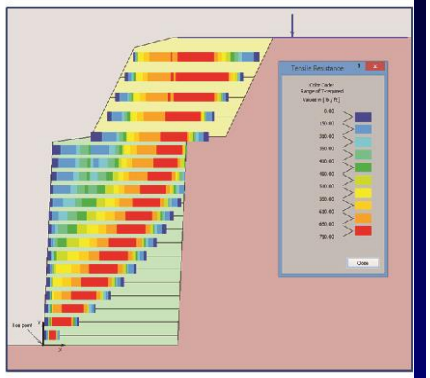

LIMIT EQUILIBRIUM DESIGN FRAMEWORK FOR MSE STRUCTURES WITH EXTENSIBLE REINFORCEMENT

Technical Report Documentation Page

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16. Abstract

Current design of reinforced soil structures in the U.S. distinguishes between slopes and walls using the batter angle as a criterion. Using a unified approach in limit state design of reinforced 'walls' and 'slopes' should diminish confusion while enabling a wide and consistent usage in solving geotechnical problems such as complex geometries and soil profiles. Limit equilibrium (LE) analysis has been used successfully in the design of complex and critical (e.g., tall dams) for many decades. Limit state analysis, including LE, assumes that the *design* strength of the soil is mobilized. Presented is a LE framework, limited to extensible reinforcement, which enables the designer to find the tensile force distribution in each layer required at a limit state. This approach is restricted to Allowable Stress Design (ASD). Three example problems are presented.

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Roadmap of Presentation

- ***Why Limit State analysis is needed?***
- ***Limit Equilibrium Analysis: Global Approach***
- ***The Safety Map Tool***
- ***Limit Equilibrium Analysis: Baseline Solution***
- ***Limit Equilibrium: Design Approach***
- ***Limit Equilibrium: Instructive Examples***
- ***Concluding Remarks***

Why Limit State Check is Needed?

- Limit State failure is a realistic possibility
- Such state is avoided by assigning adequate margins of safety in design
- To quantify such margins, one needs to reliably predict limit state conditions
- Limit State implies that soil strength is fully mobilized anywhere within the reinforced mass; stability then is hinging on the reinforcement tensile resistance
- This state is also called 'Internal Stability'

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Global Limit Equilibrium (LE)

- Simple to use; applicable to complex problems
- Vast experience
- Reinforced soil is subset of slope stability analysis
- Compatibility between dissimilar materials may need to be considered ➔ Consequently, present scope is limited to extensible reinforcement
- Global LE design is half-cooked ➔ Strength of reinforcement is examined globally while the locally <u>required</u> strength, including connections, is overlooked ➔ Potential local overstressing
- It does not deal explicitly with 'Internal Stability' ➔ It provides a narrow design insight

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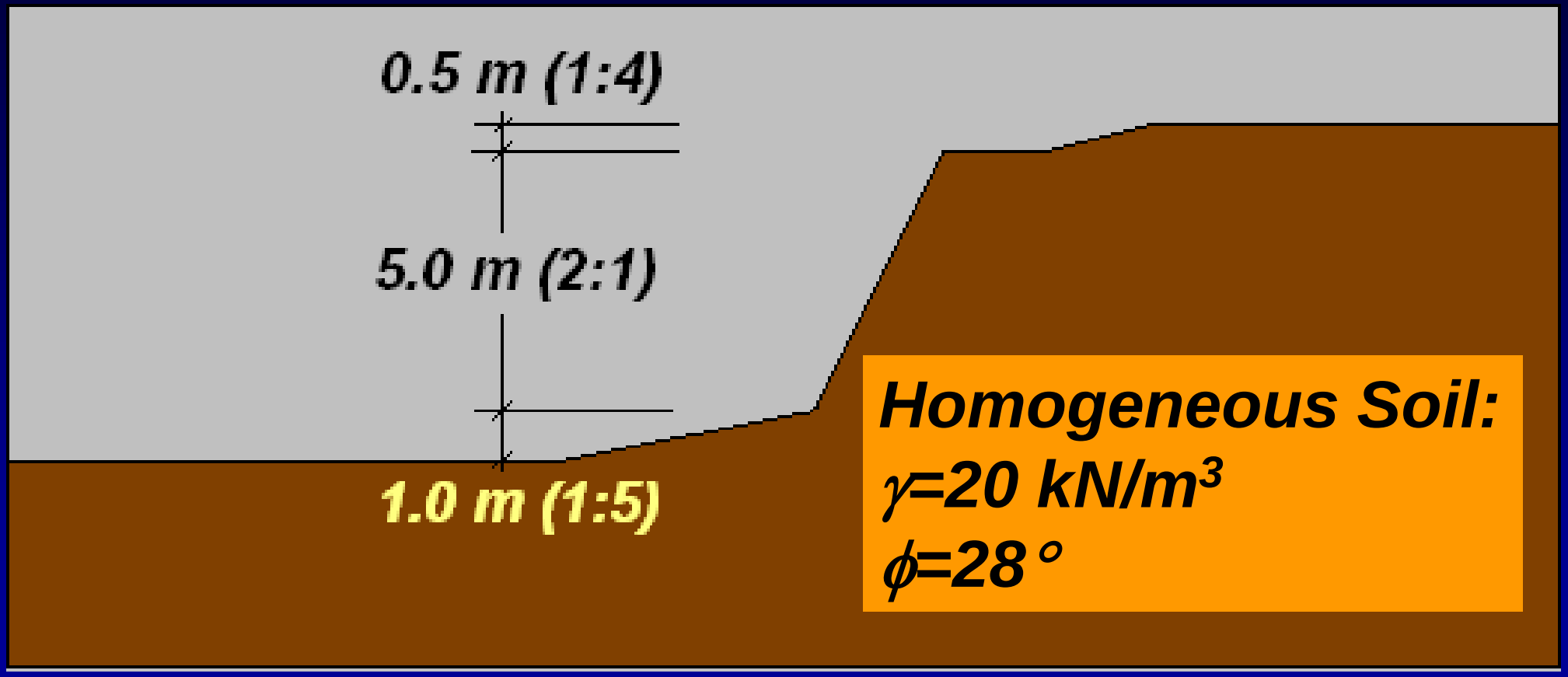
The Safety Map Tool

- Baker and Leshchinsky (2001) introduced the concept of, and coined the term, Safety Map

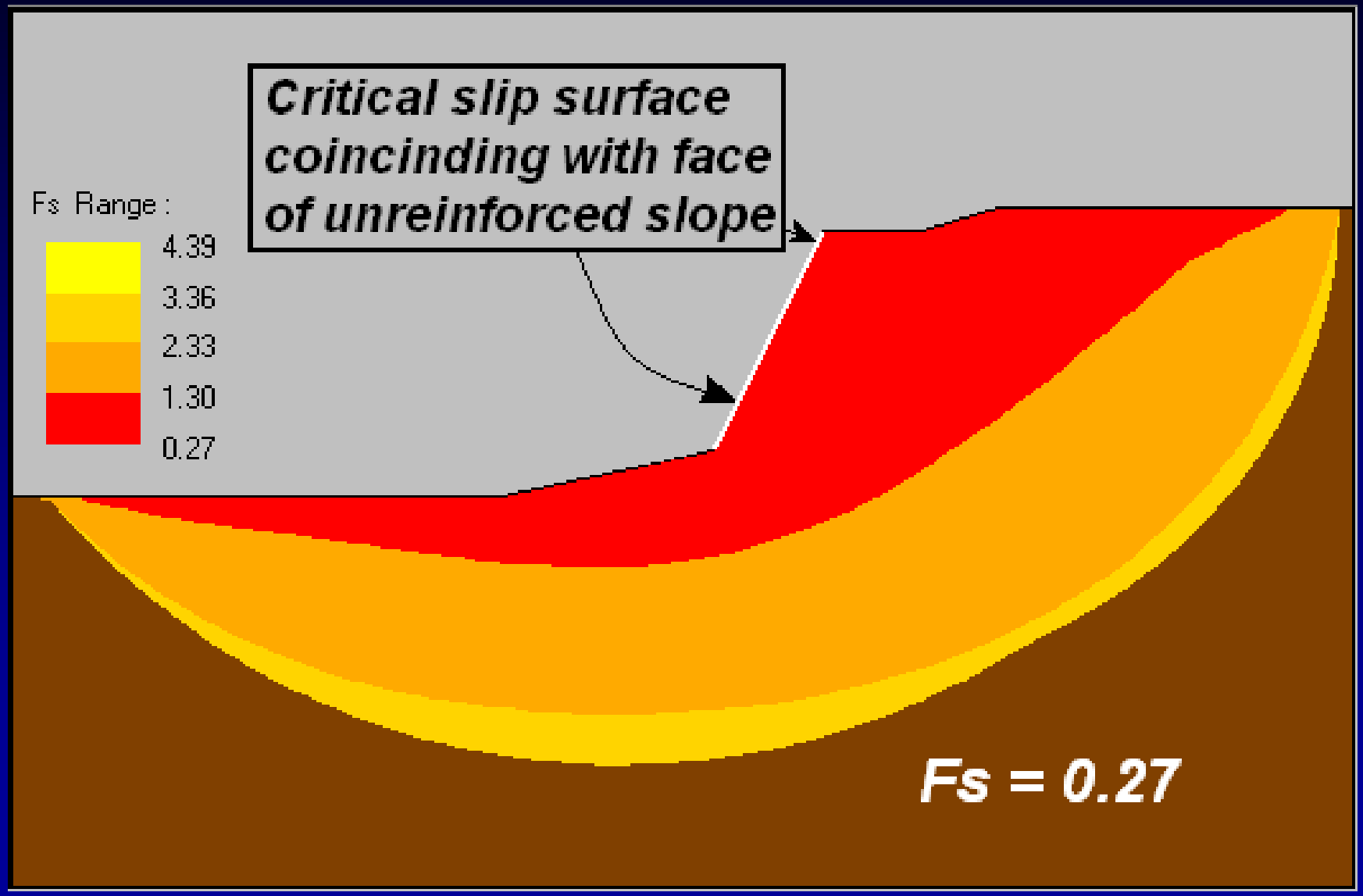
- Safety Map = Visual diagnostic tool for the state of stability of a reinforced mass

- Design Objective: Select strength & layout of reinforcement to produce as uniform safety factors within the reinforced mass as practically possible = Efficiency

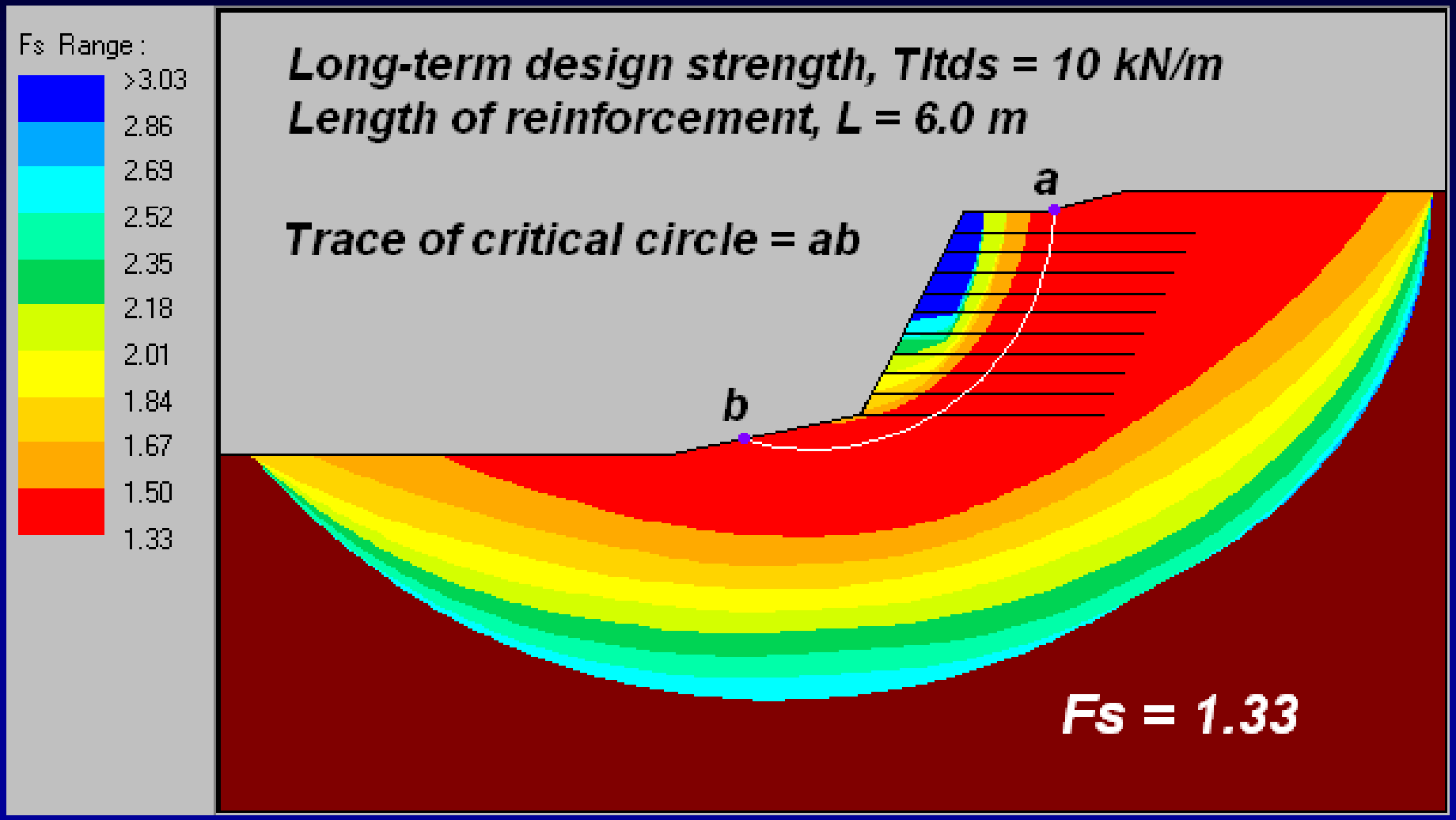
Example Problem: Effects of Water



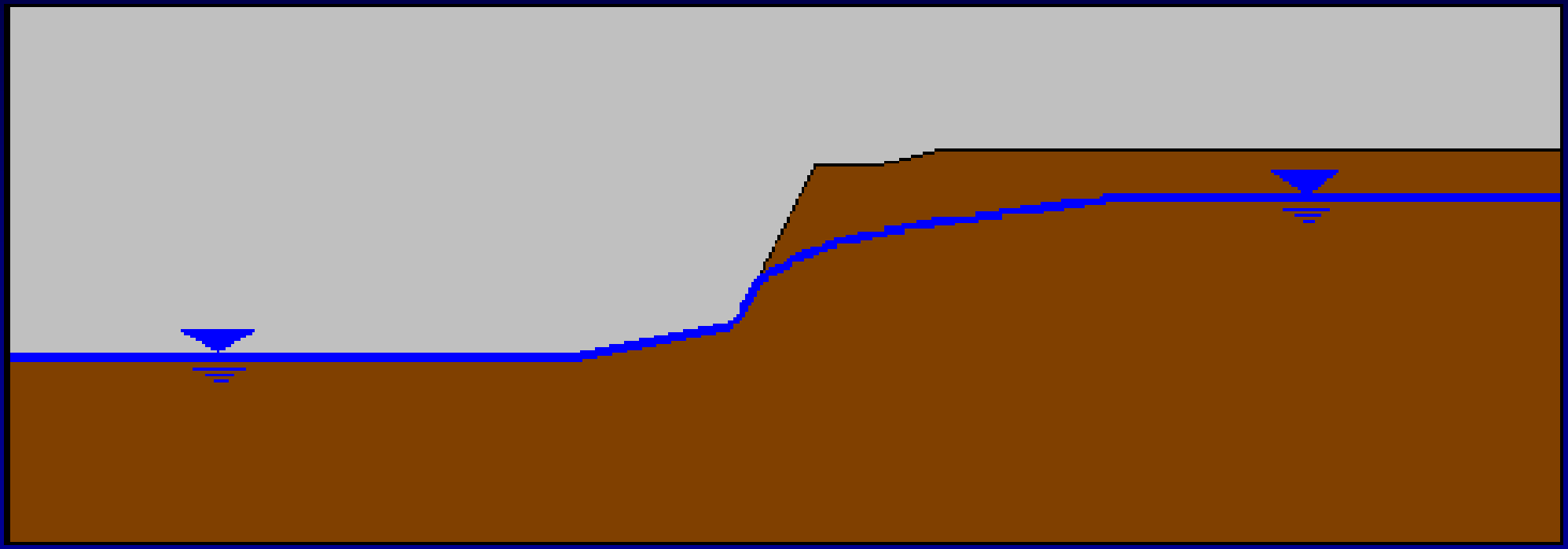
Unreinforced Dry Problem



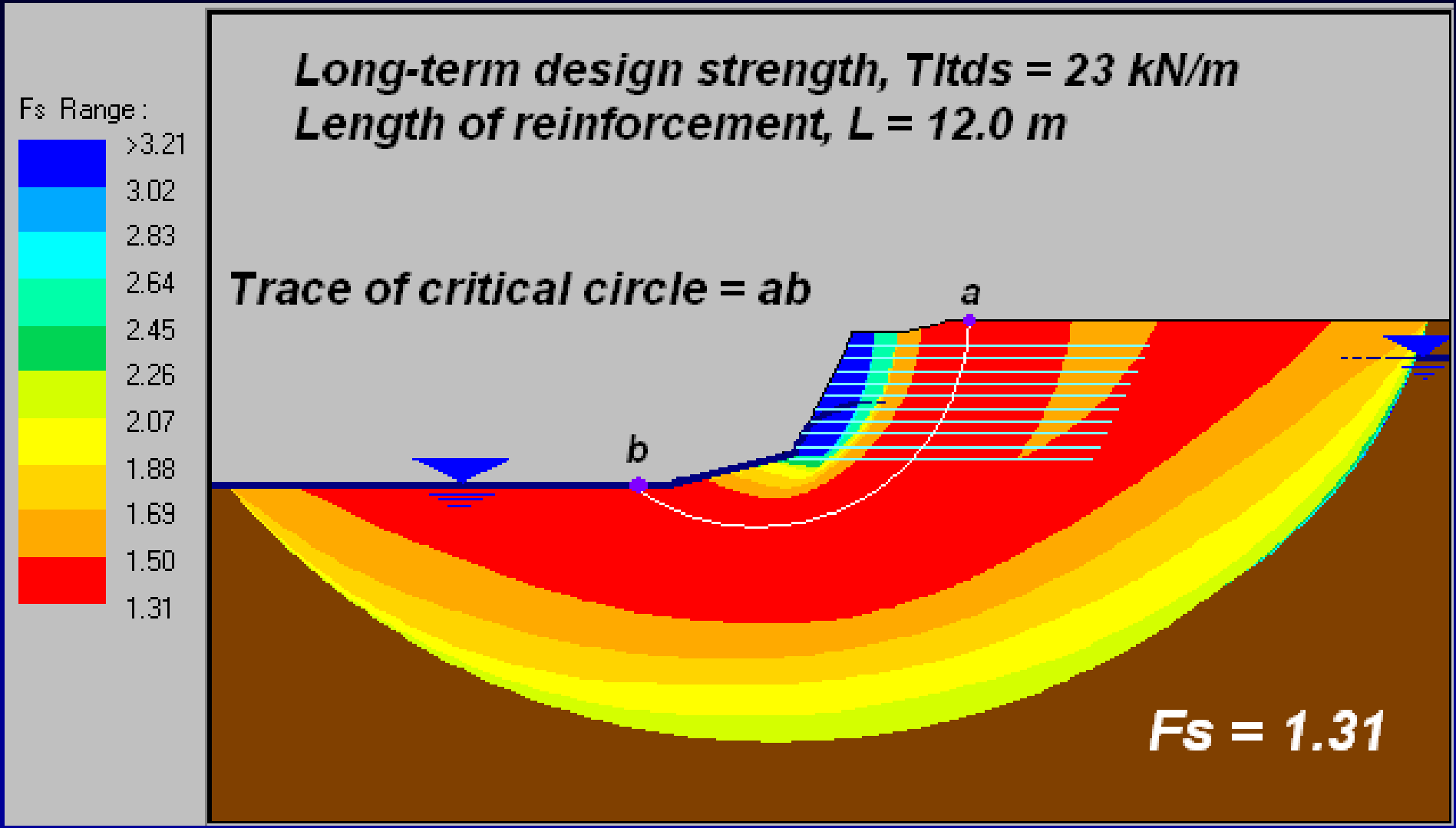
Reinforcement for Dry Problem using Circular Arc (Bishop)



Seepage into Design of Dry Reinforced Slope



Redesigned Reinforcement for Water



Roadmap of Presentation

- *Why Limit State analysis is needed?*
- *Available Limit State Methods of Analysis*
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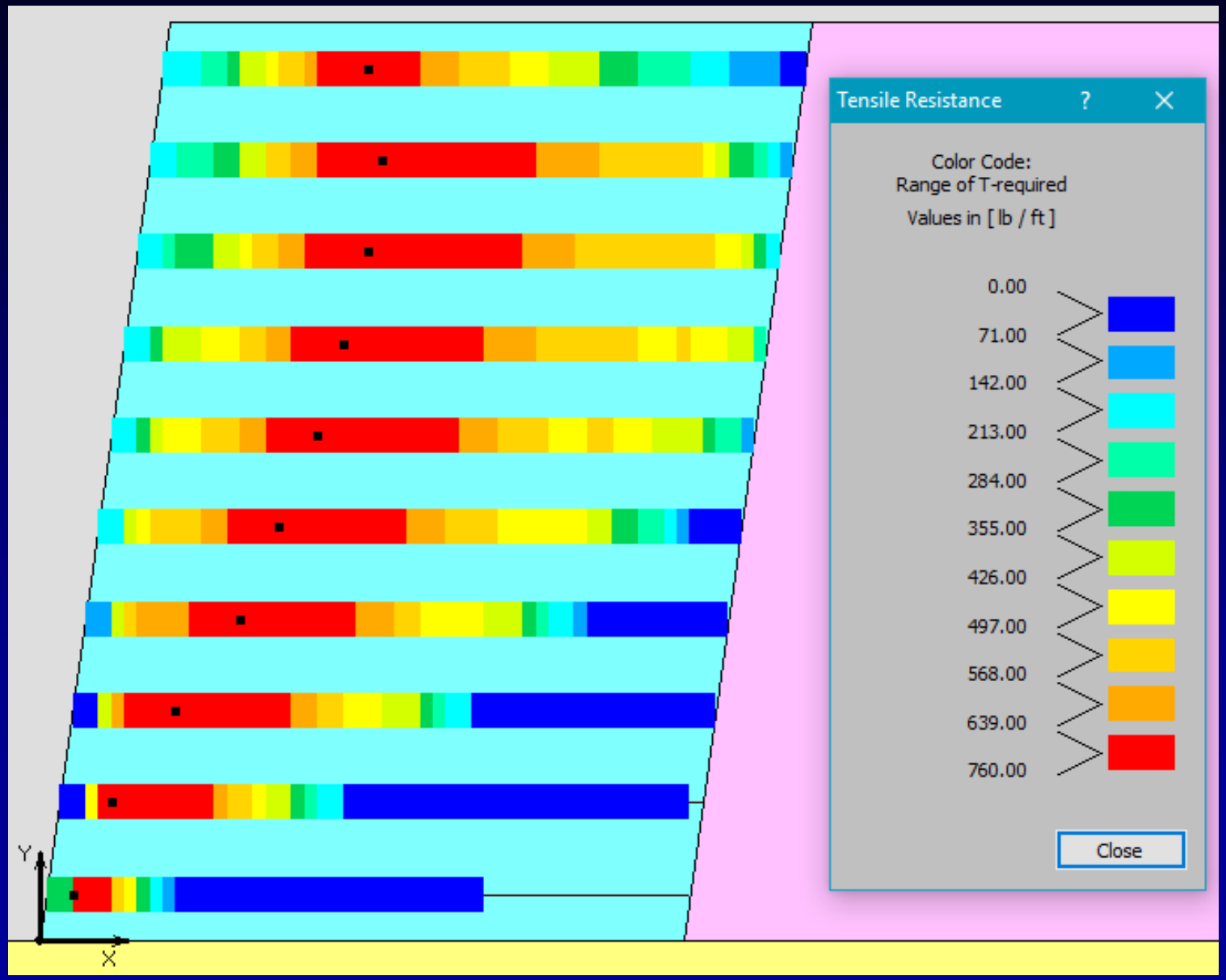
Inverse of Safety Map…

- ***Safety Map finds the spatial distribution of the <u>safety factors</u>, SF, in the reinforced soil problem***
- ***Conversely, the LE Framework (ReSSA+) produces the tensile resistance needed for Fs=SF=1.0 everywhere***

- ***The Framework approach produces the baseline solution: Tension Map, T(x), including T_{max} and T_o for each layer → It leads to a rational and robust selection of reinforcement and facing***

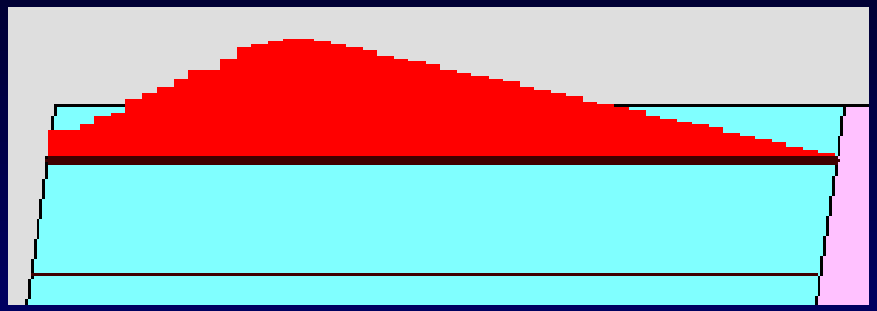
Example of Tension Map: Visualization of T(x)



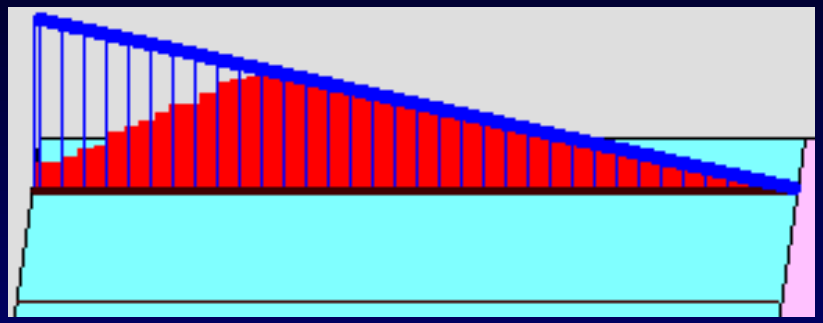
The Framework: Process in Nutshell

- Check numerous test bodies ➔ Set SF=1.0 and calculate T(x) for each layer
- Use a systematic top-down process assessing many surfaces emerging at the slope
- For T(x) failure along any surface is equally likely ➔ T(x) is termed Baseline Solution ➔ Tension Map
- The tension, T(x), may be limited by pullout at the rear and/or front ends

Details: Baseline & Pullout (front and rear pullouts not function of T_{max})

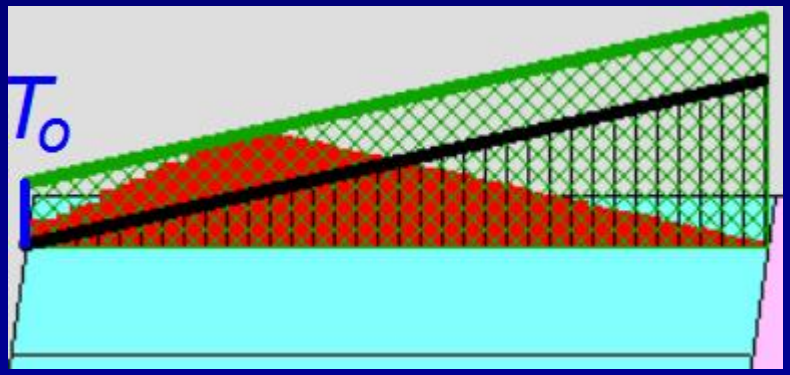


1. $T(x)$



2. Rear pullout constraint

3. Front pullout… oops



4. Adjust front pullout
➔ Upwards shift is T_o

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Advancement of Current Design

- Application of the LE design approach is split into two stages: Internal Stability and Global Stability
- Internal stability considers the distribution of tensile loading in all reinforcements
- Unlike previous design, this enables direct consideration of geometry, loading conditions, reinforcement layout, pullout resistance, etc.
- Global stability is consistent with current design

Stage 1: 'Internal Stability'

- Select SF=Fs=1.0 on soil strength
- Use framework to find T(x) including T_{max} & T_o
- Determine max(T_{max}) to select geosynthetic
- LTDS=$F_{s\text{-}strength}$×max($T_{max\text{-}i}$) where $F_{s\text{-}strength}$=1.5
- T_{ult}=LTDS$\times RF_{cr} \times RF_d \times RFid$

- Stage 1 is a rational and robust alternative to existing approaches ➔ Consistent with principles of LE and is <u>not</u> arbitrary

Stage 2: Global Stability

- Select reinforcement and facing following Stage 1
- Conduct global slope stability analysis to ascertain that for the selected facing, layout and strength reinforcement, Fs is greater than, say, 1.30 or 1.50, for all feasible failure geometries
- If needed, increase the length and/or strength of reinforcement to meet the prescribed Fs

Why Two Stages: Stage 1 & Stage 2?

- Stage 1 examines local needs for limit state thus preventing potential overstressing in Stage 2 by adequately selecting reinforcement ➔ Stage 1 provides rational basis for selecting LTDS & Facing to be used in Stage 2
- Stage 2 is standard LE in reinforced soil design ➔ Deals with global stability including sliding and foundation's failure ➔ Along critical slip surface all layers are assumed to carry equal T_{max}, limited by front and back pullout
- Stage 2 alone does not render connection load

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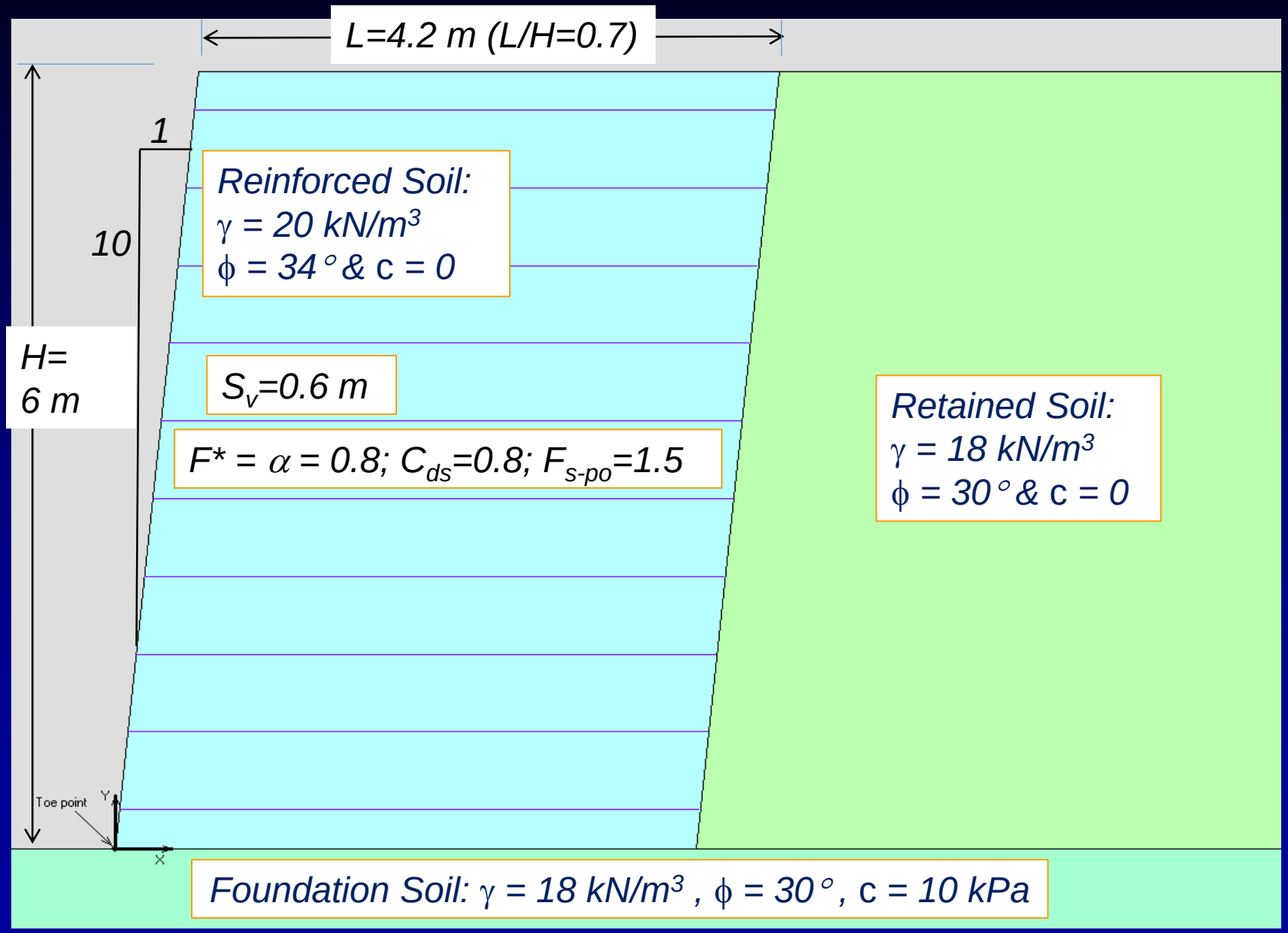
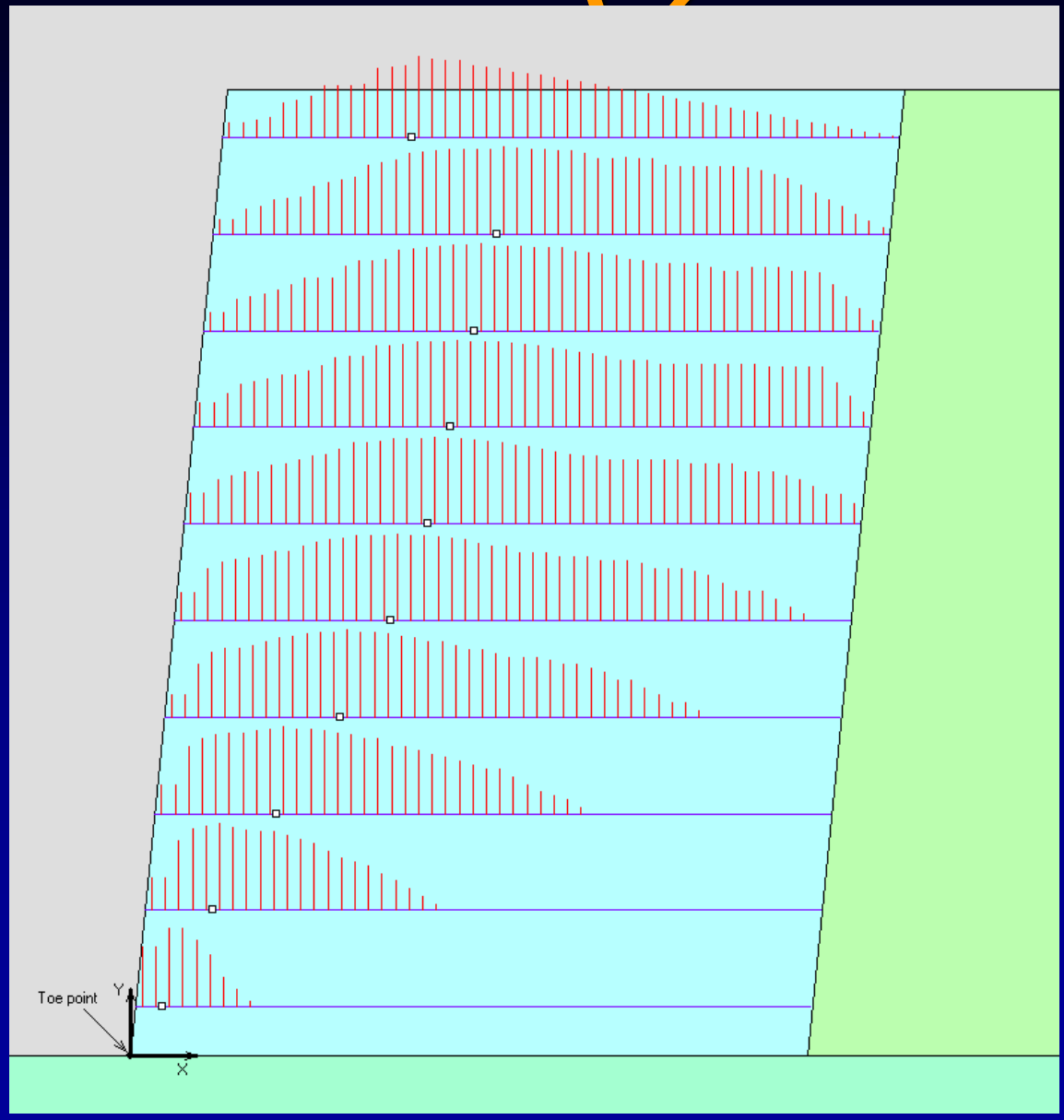
Benchmark Problem



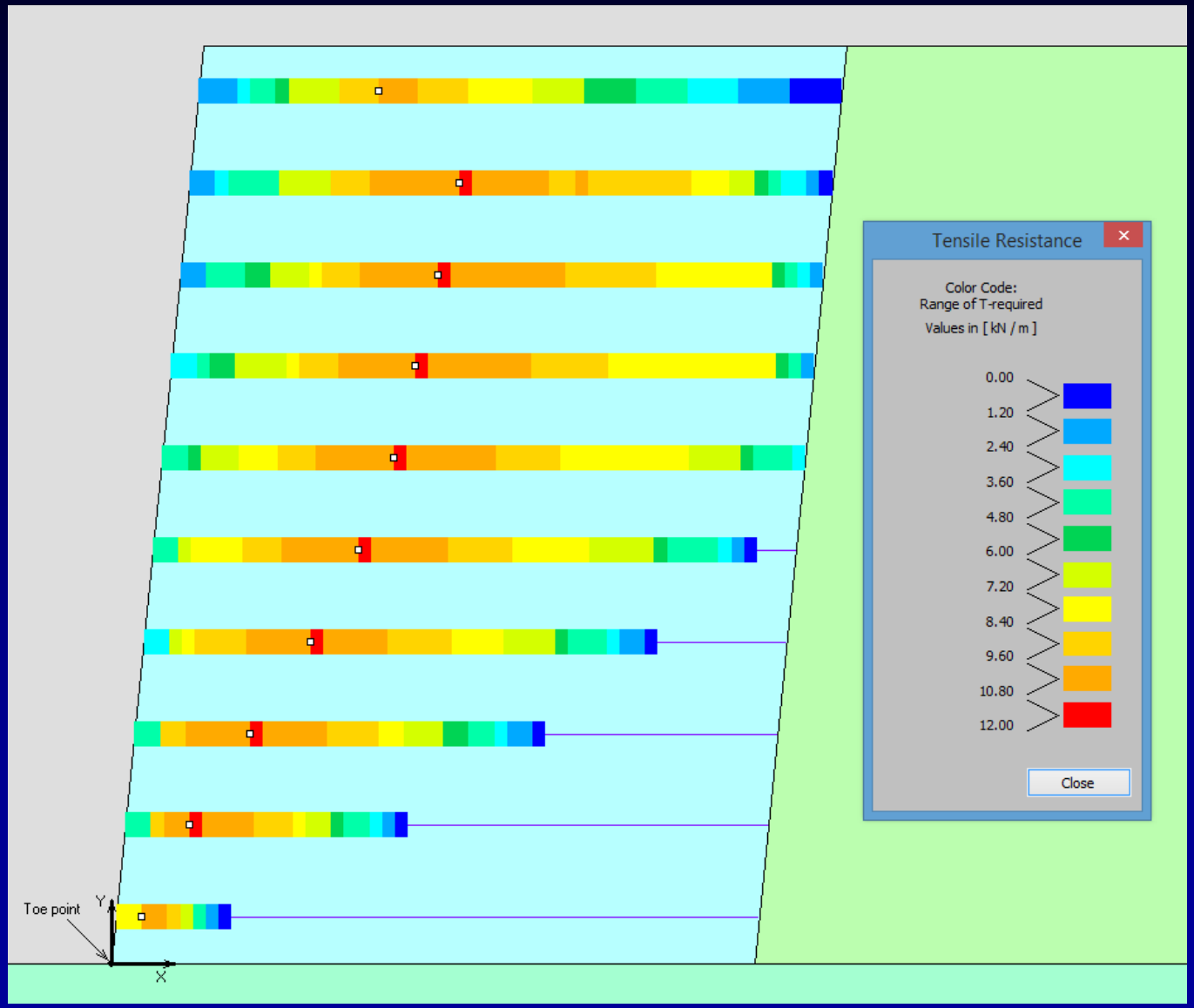
Computed Distribution of T(x)

Unlike assumptions in current design, the locus of T_{max} does not develop along a singular slip surface. It is influenced by pullout resistance and compound failures, both of which are directly accounted for.

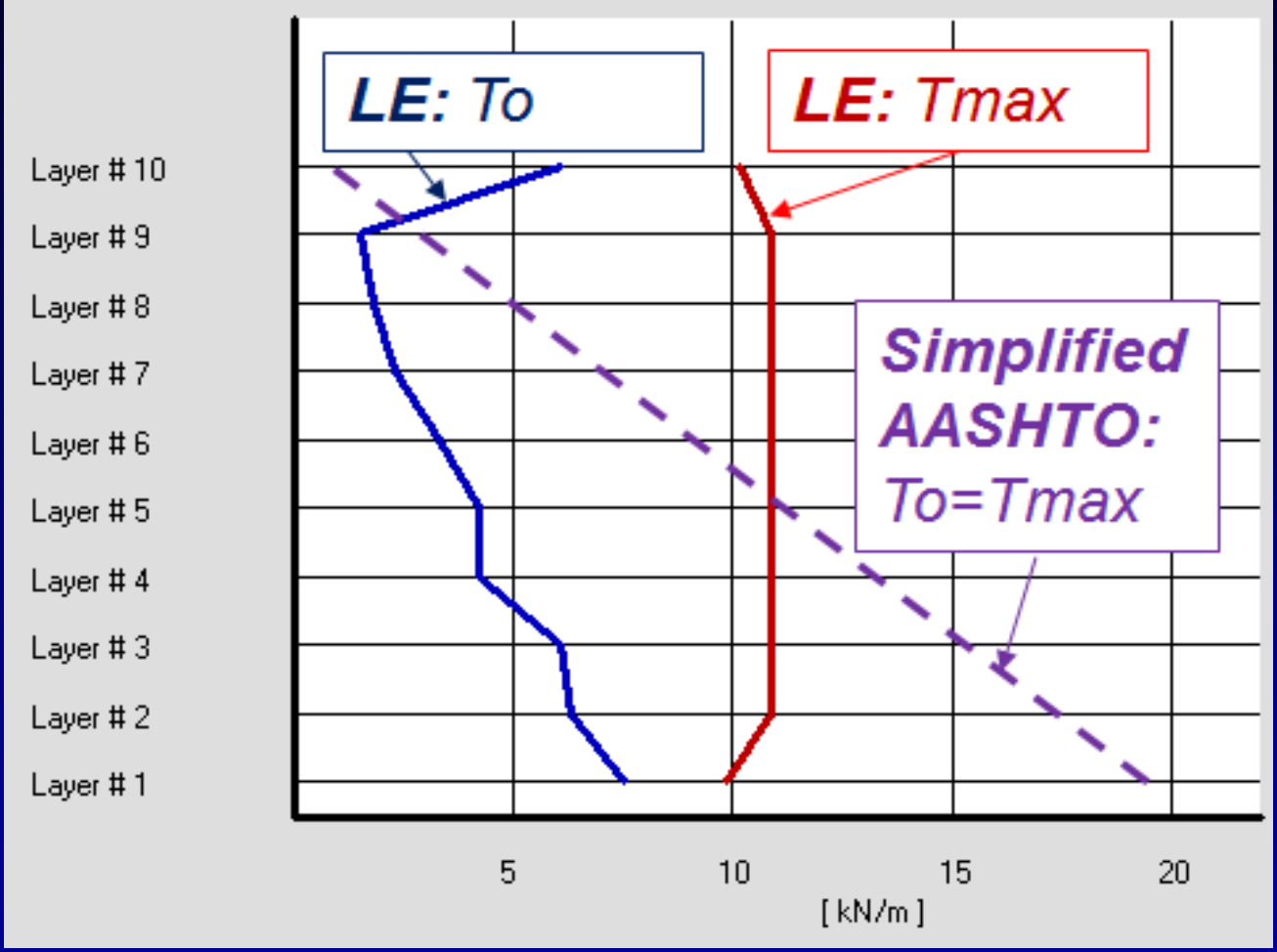


Tension Map (note locus of T_{max})

The mobilization of tension in each reinforcement can be visualized through the Tension Map.



T_{max} and T_o Distribution

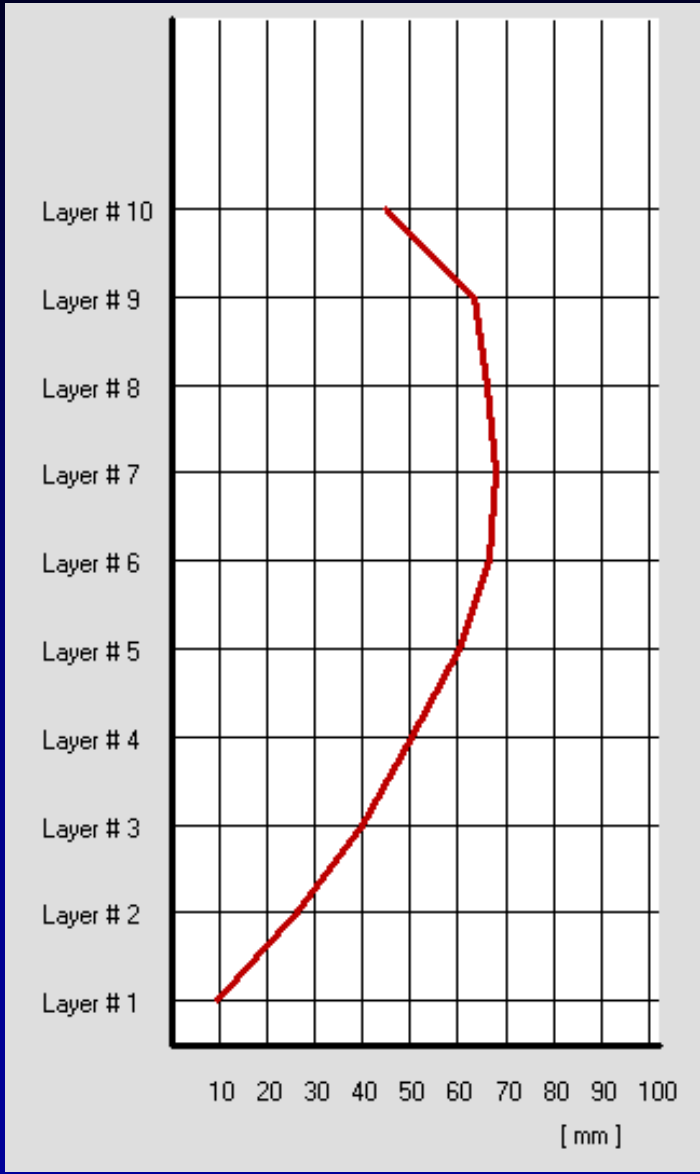


max(T_{max}): LE ➔ 10.9 kN/m AASHTO ➔19.3 kN/m

Horizontal Displacement Distribution

Knowing the distribution of tensile loading, estimates of lateral displacement can be assessed at a limit state.

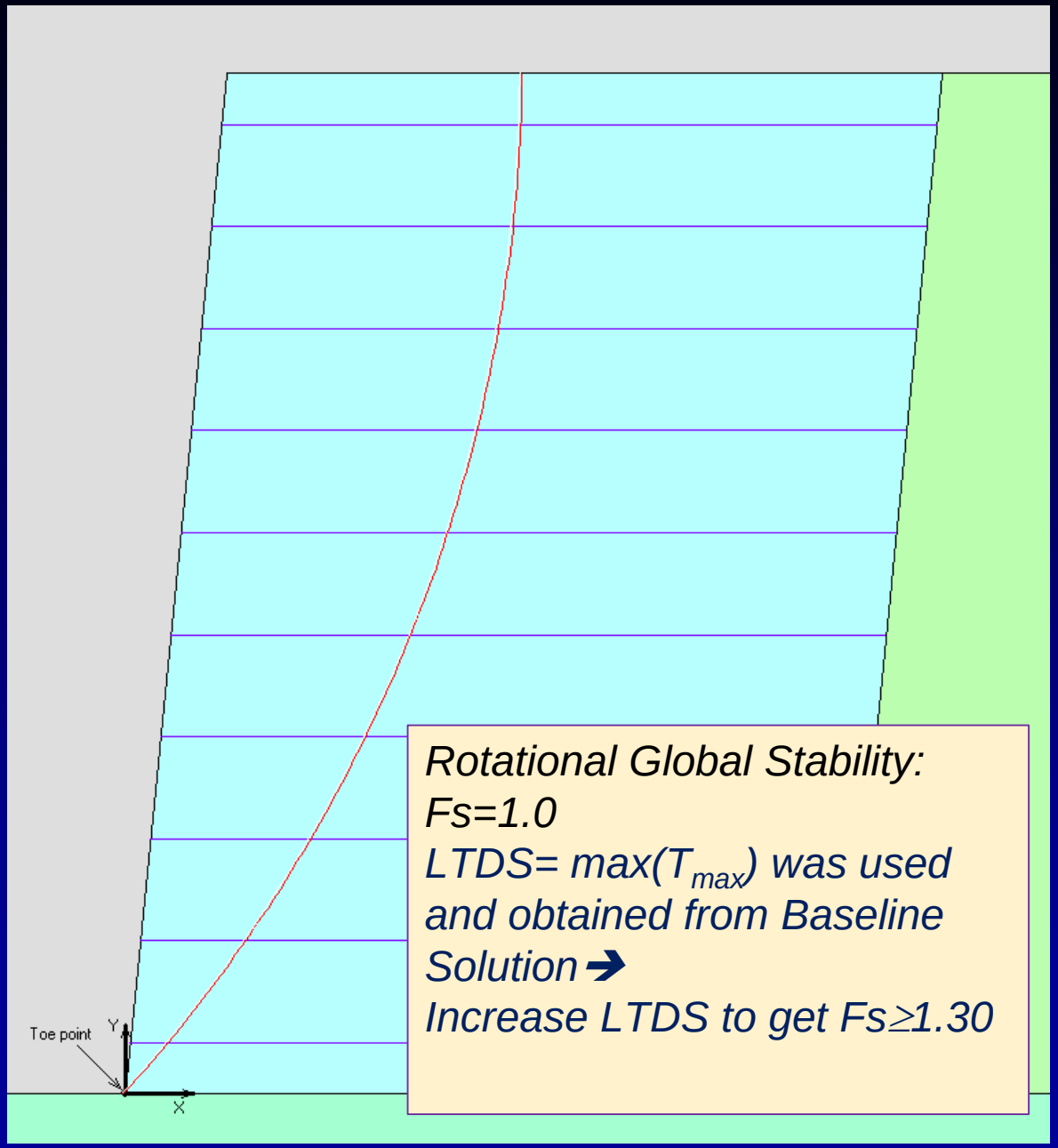
Shown is the computed face profile for reinforcement stiffness of J=500 kN/m (Note that it is for Fs=1.0; i.e., soil strength is fully mobilized)



Global Stability

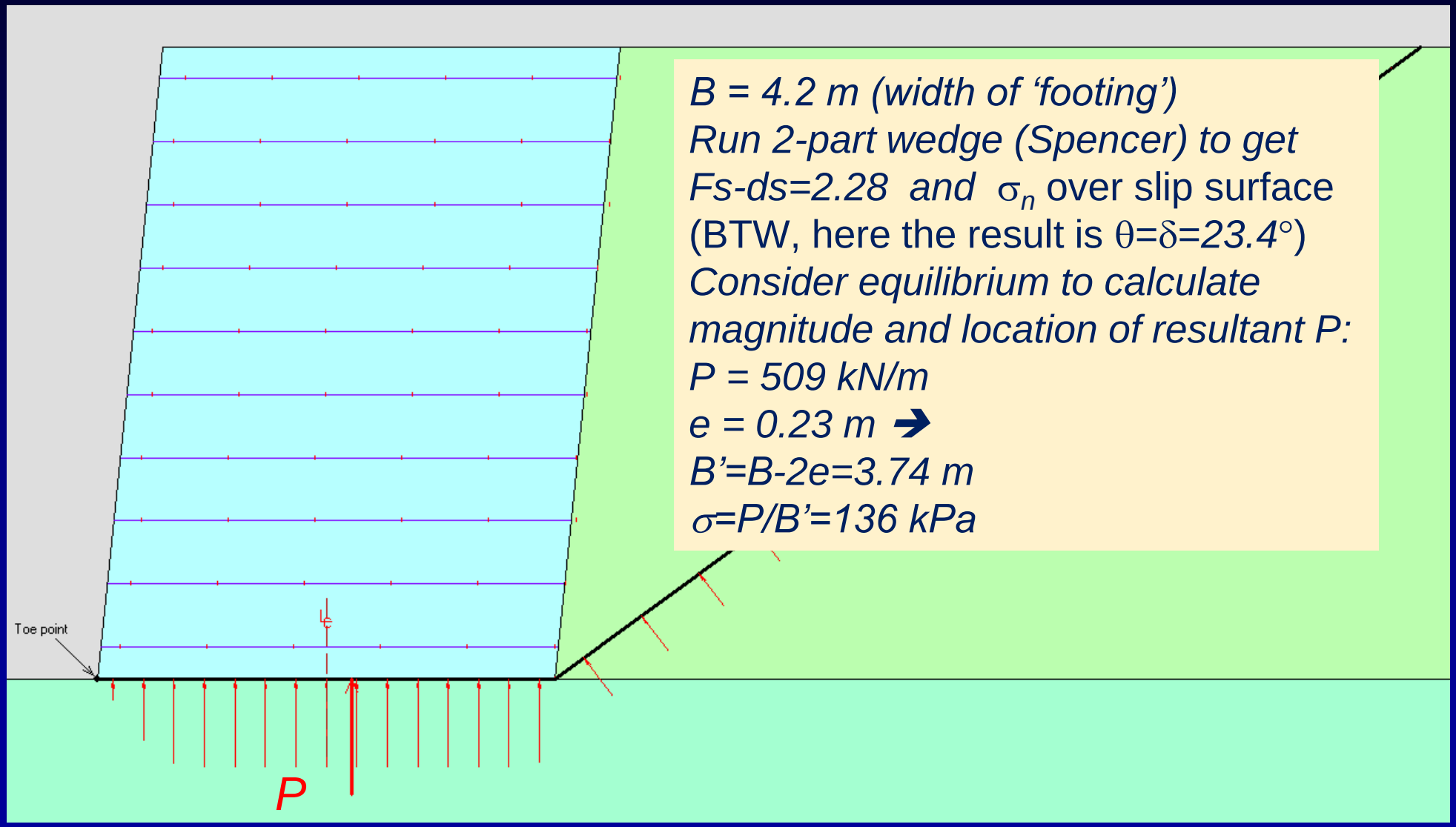
Global stability (Stage 2) is assessed here using Bishop's method.

The reinforcement strength was determined from Stage 1 (Baseline Solution)



Rotational Global Stability: Fs=1.0
LTDS= max(T_{max}) was used and obtained from Baseline Solution ➔
Increase LTDS to get Fs≥1.30

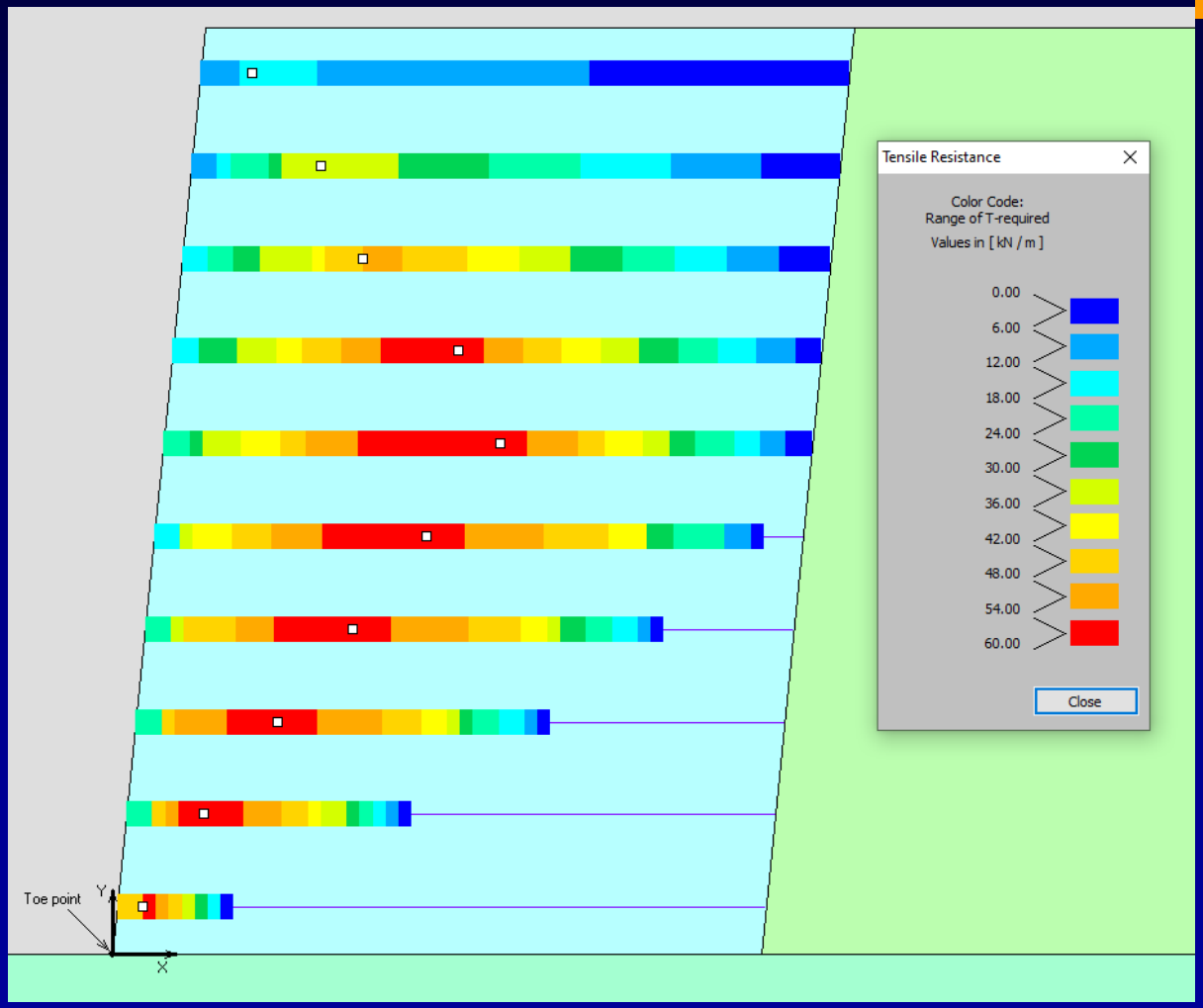
Data for Bearing Capacity and Eccentricity Derived from Rigorous Direct Sliding

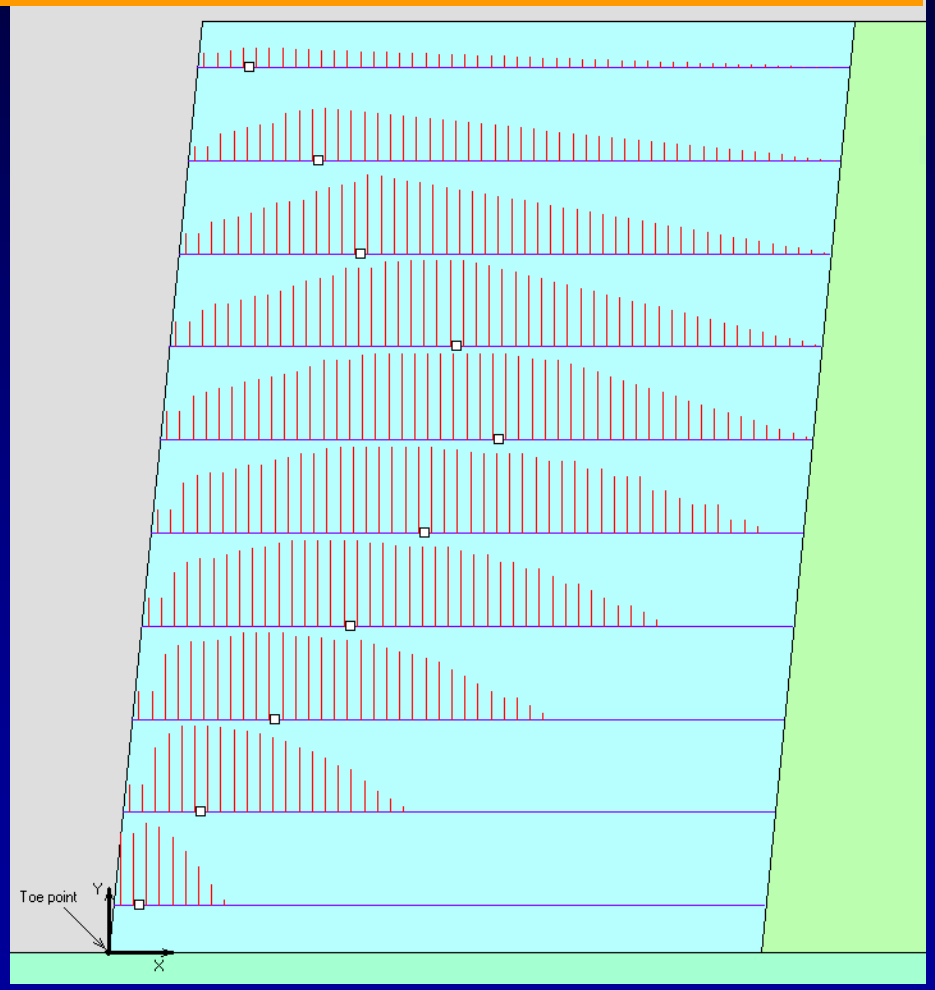


B = 4.2 m (width of 'footing')
Run 2-part wedge (Spencer) to get
Fs-ds=2.28 and σ_n over slip surface
(BTW, here the result is $\theta=\delta=23.4°$)
Consider equilibrium to calculate magnitude and location of resultant P:
P = 509 kN/m
e = 0.23 m ➔
B'=B-2e=3.74 m
σ*=P/B'=136 kPa*

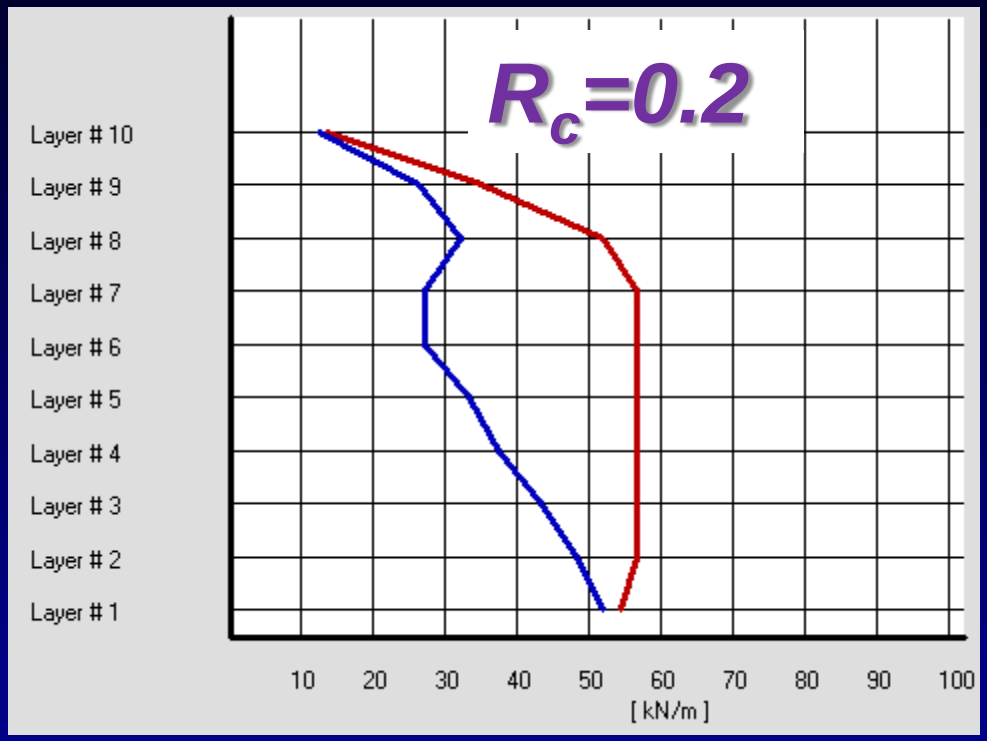
Computed Distribution of T(x): Straps Having Coverage Ratio of R_c=0.2

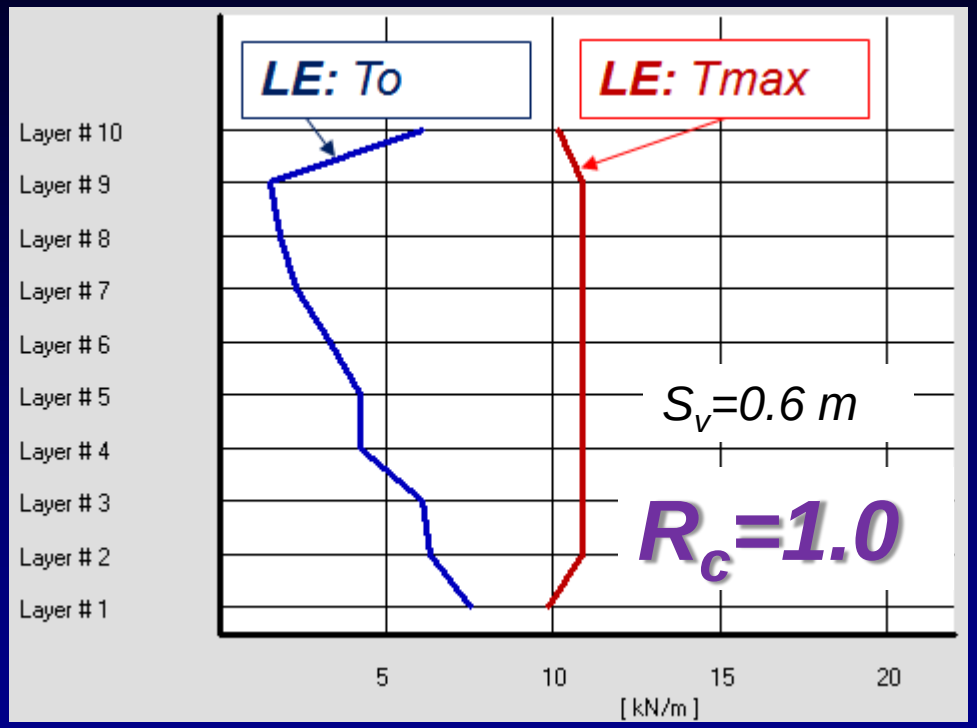
Note impact of rear pullout





Effects of R_c on T_{max} and T_o





Note the different drawings scale for T_{max} and T_o

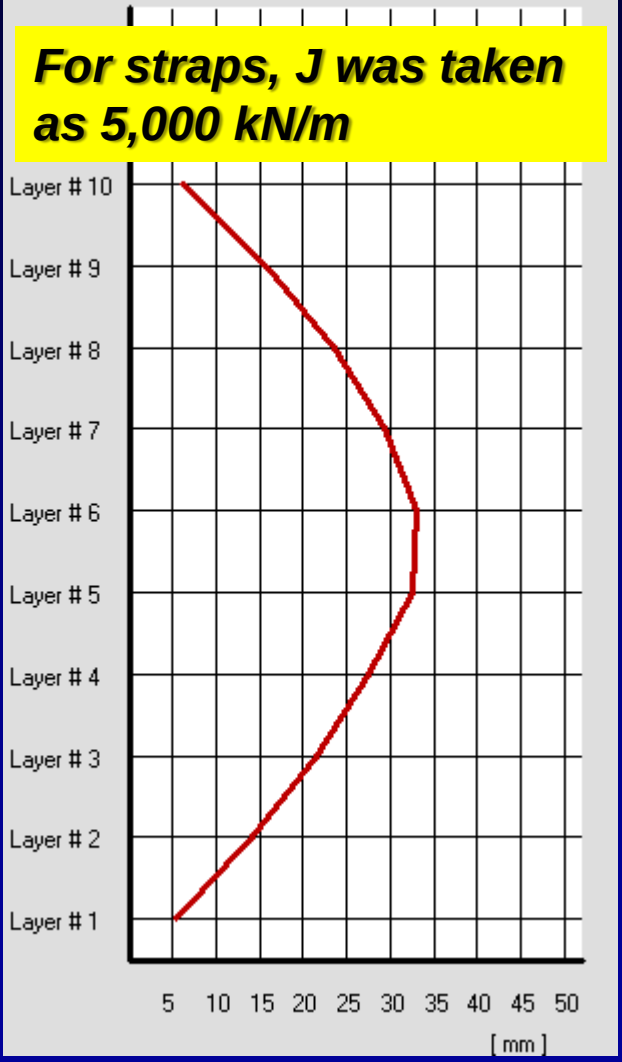
Due to smaller front and rear pullout resistance:

1. T_{max} in upper layers is small

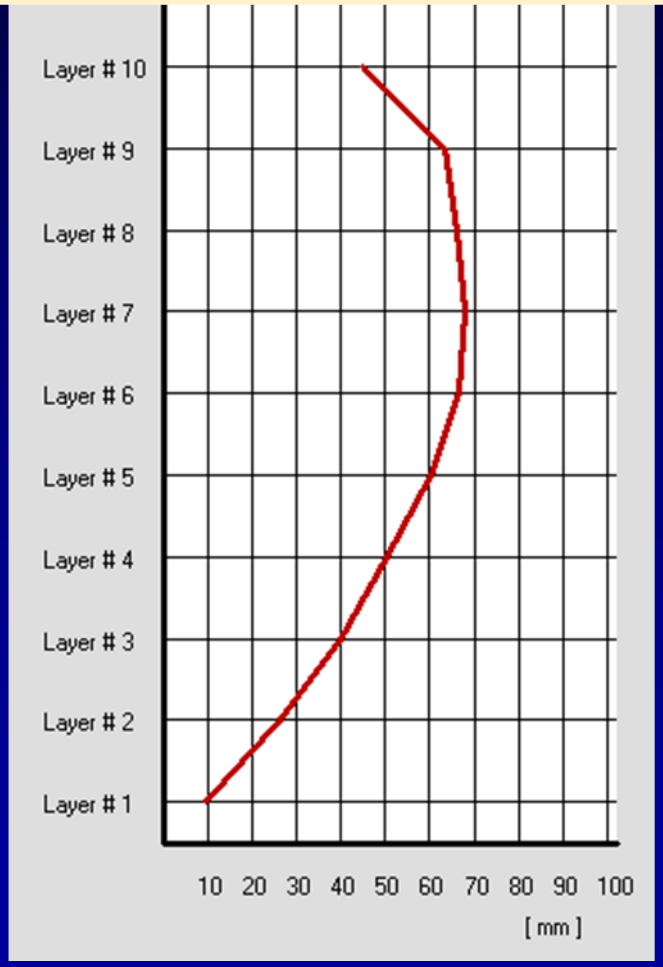
2. T_o is relatively large in most layers

Effects of Reduced R_c on Displacements

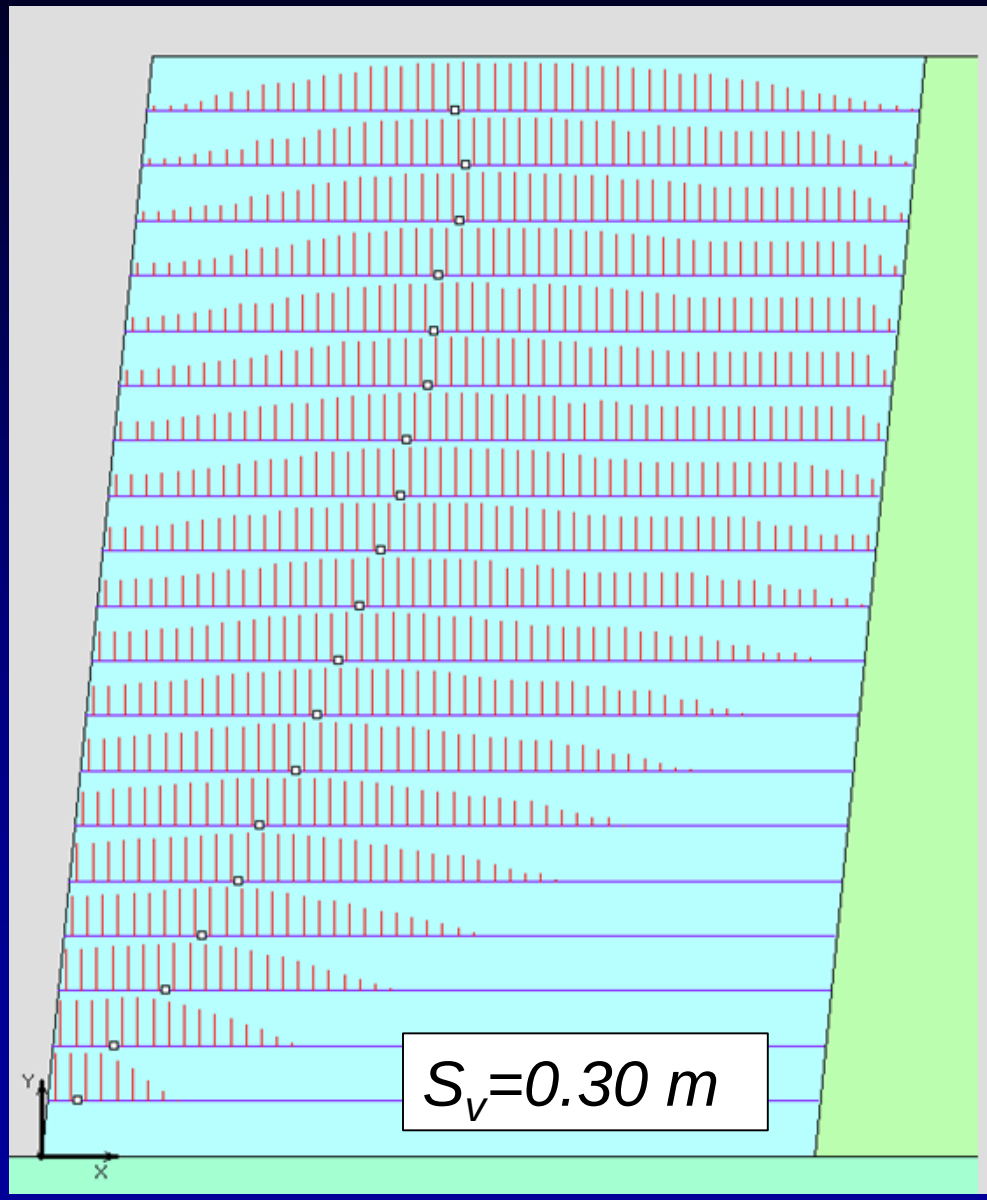
For straps, J was taken as 5,000 kN/m

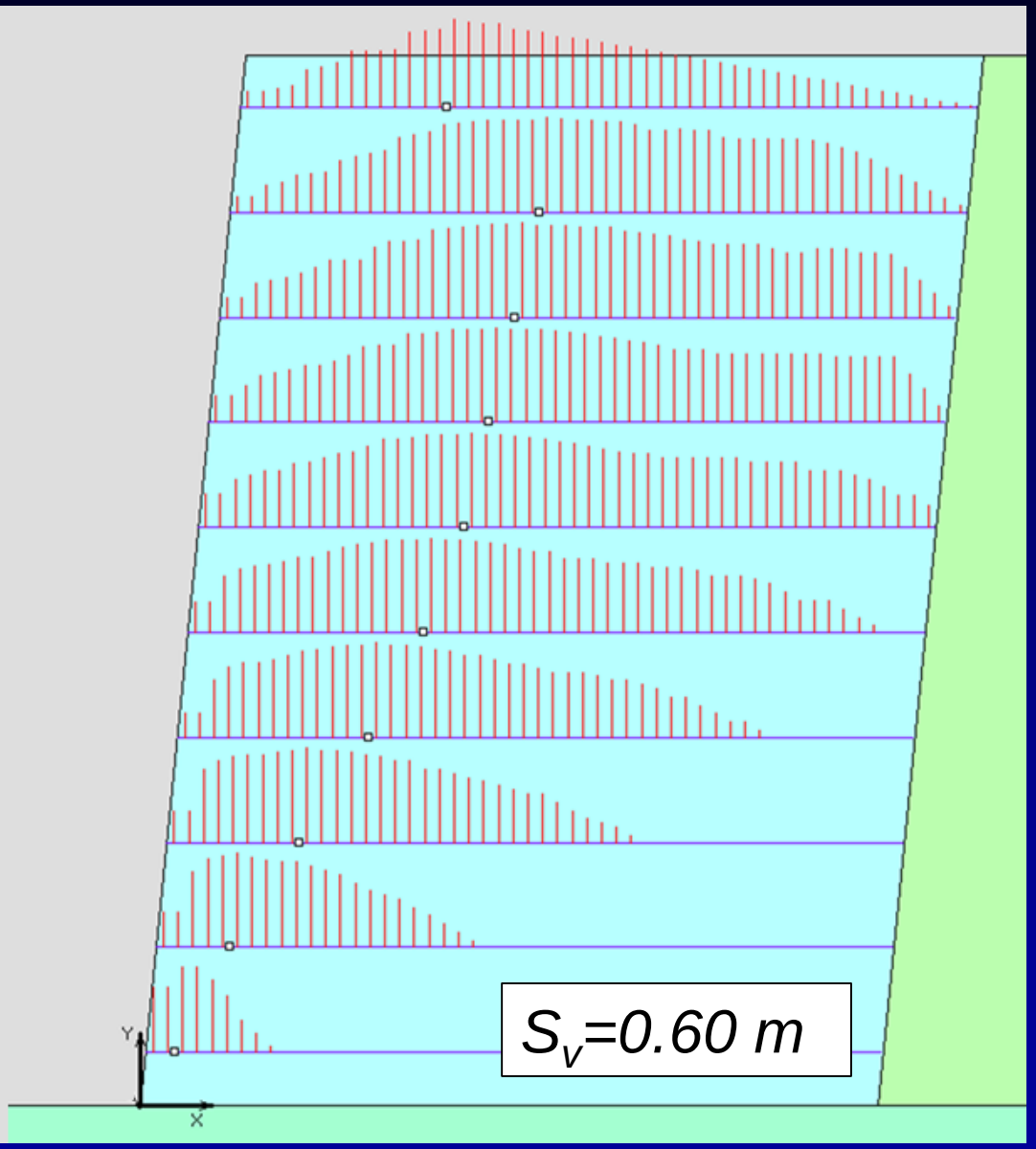


Δ profile for J=500 kN/m
(For Fs=1.0; i.e., soil strength is fully mobilized)

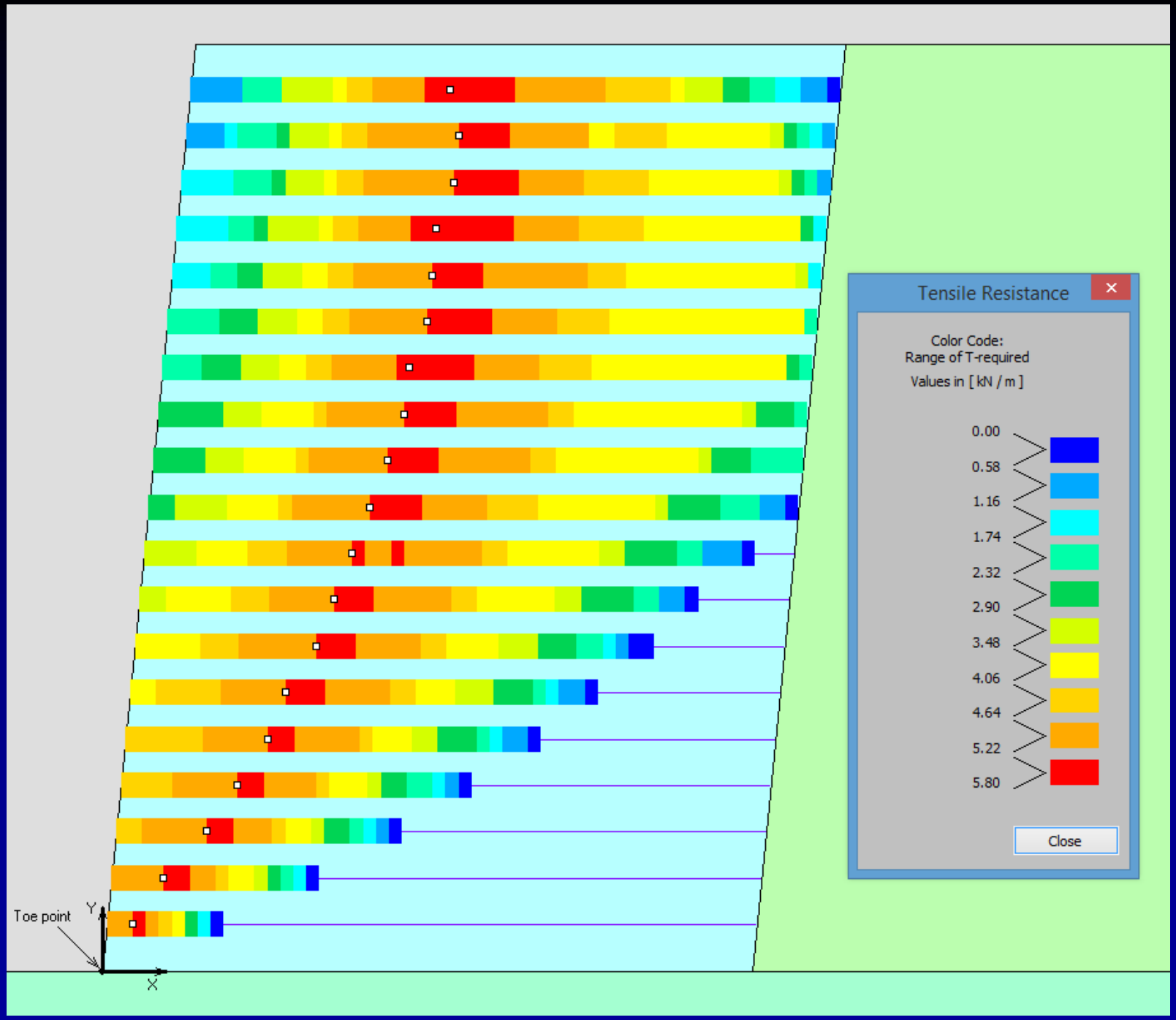


Close Reinforcement Spacing –T_{max} Decreases

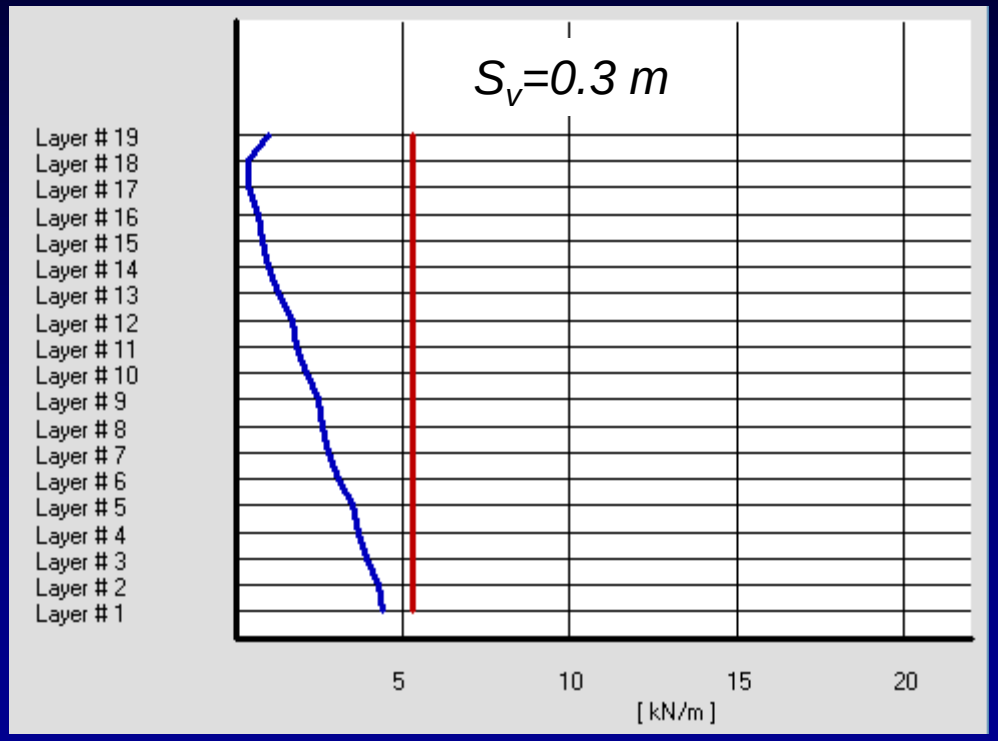


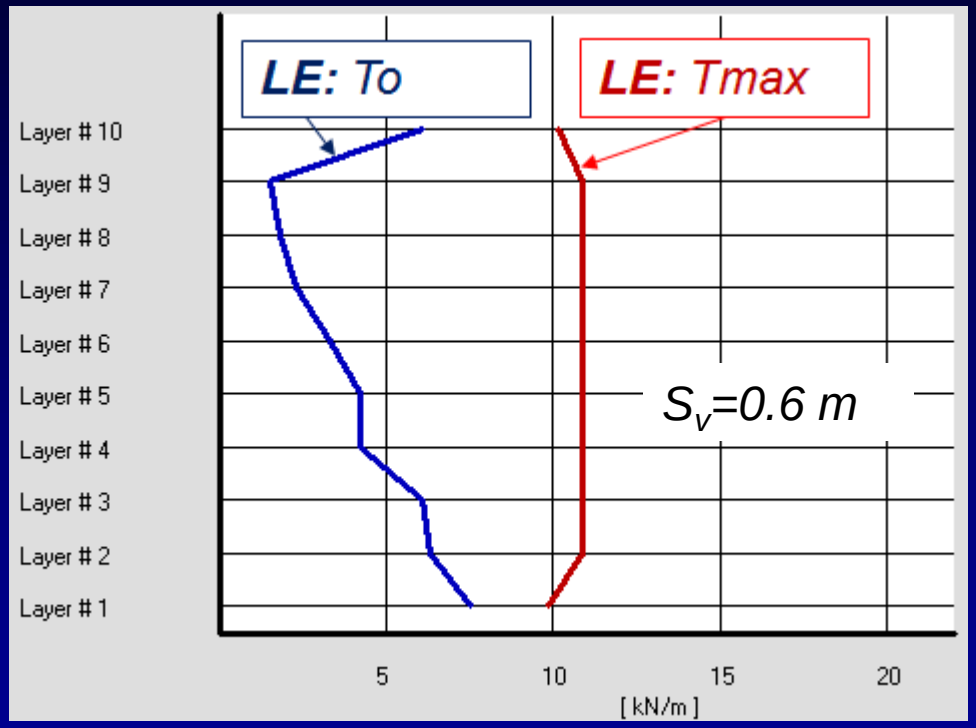


Tension Map S_v=0.3m



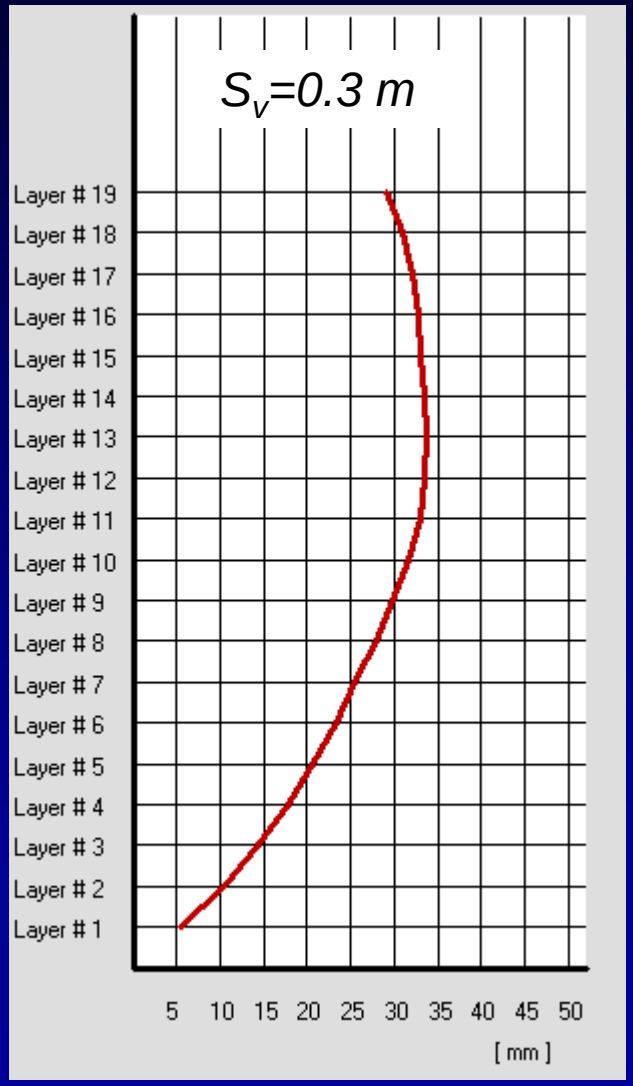
Effects of Reduced S_v: T_{max} and T_o



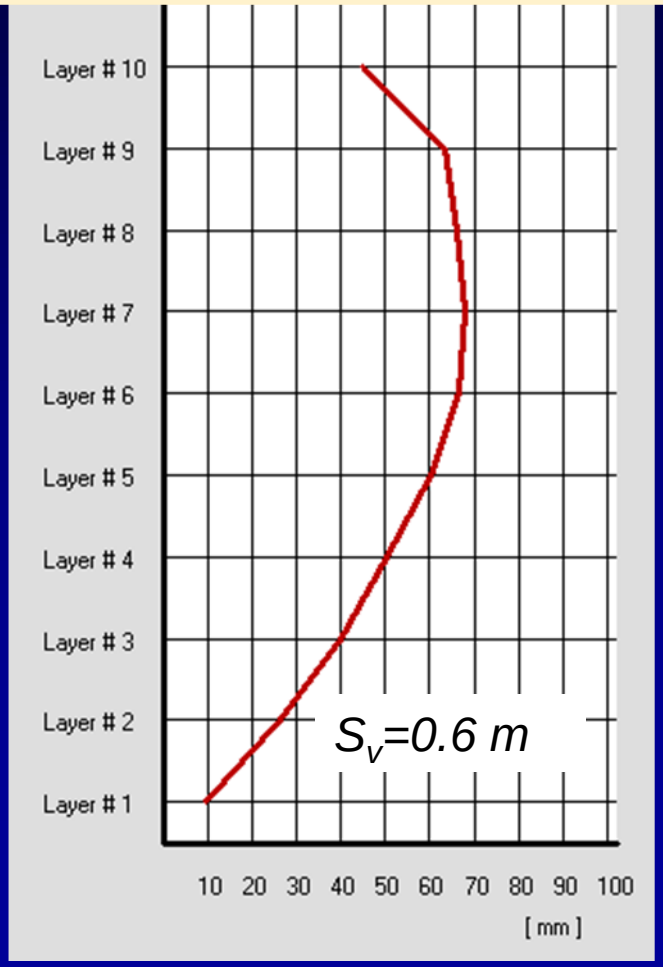


Generally, T_o drops nonlinearly when S_v decreases. Reason: Front-end pullout resistance remains constant while T_{req} drops proportional to spacing

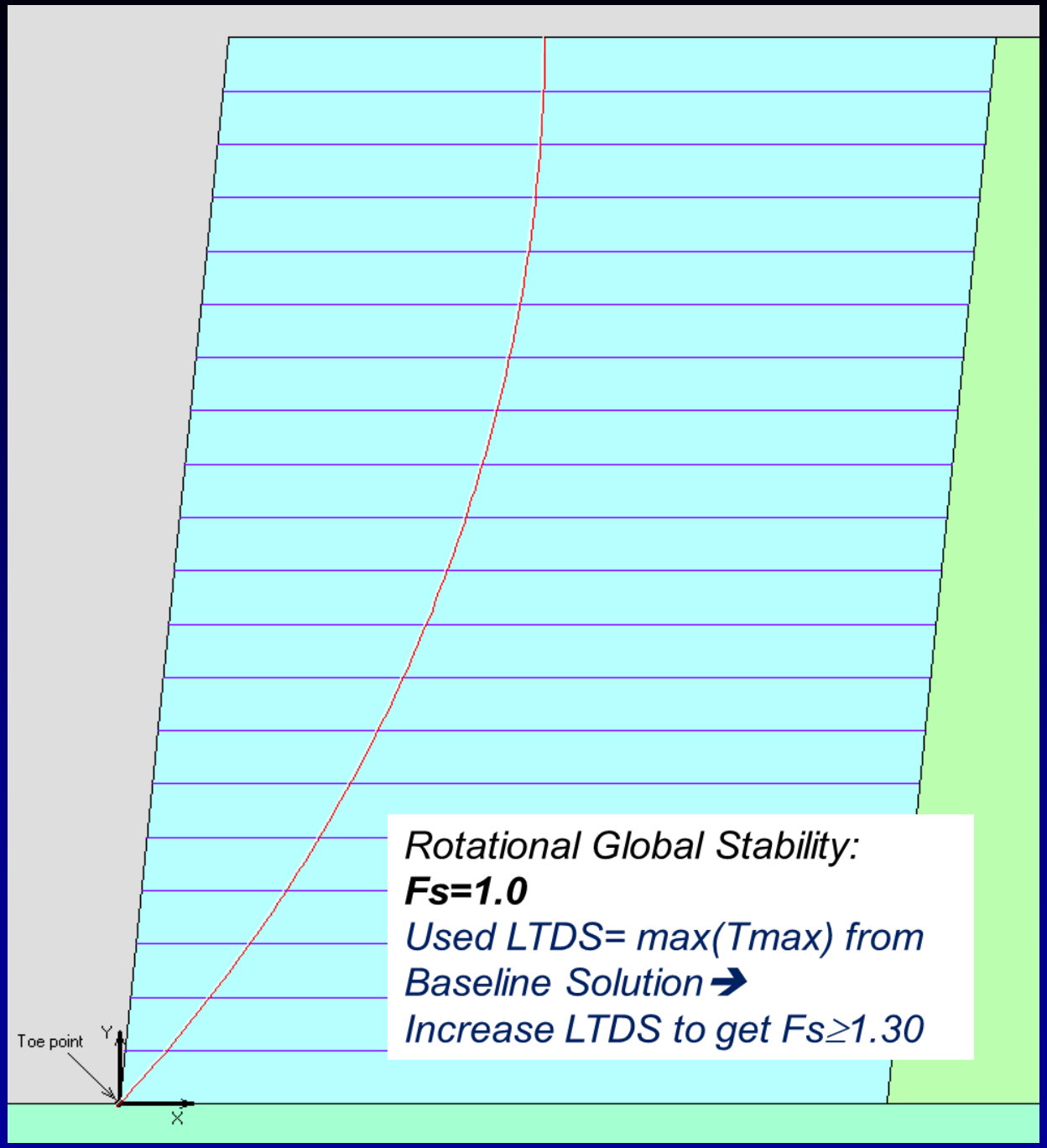
Effects of Reduced S_v on Displacements



Δ profile for J=500 kN/m
(For Fs=1.0; i.e., soil strength is fully mobilized)



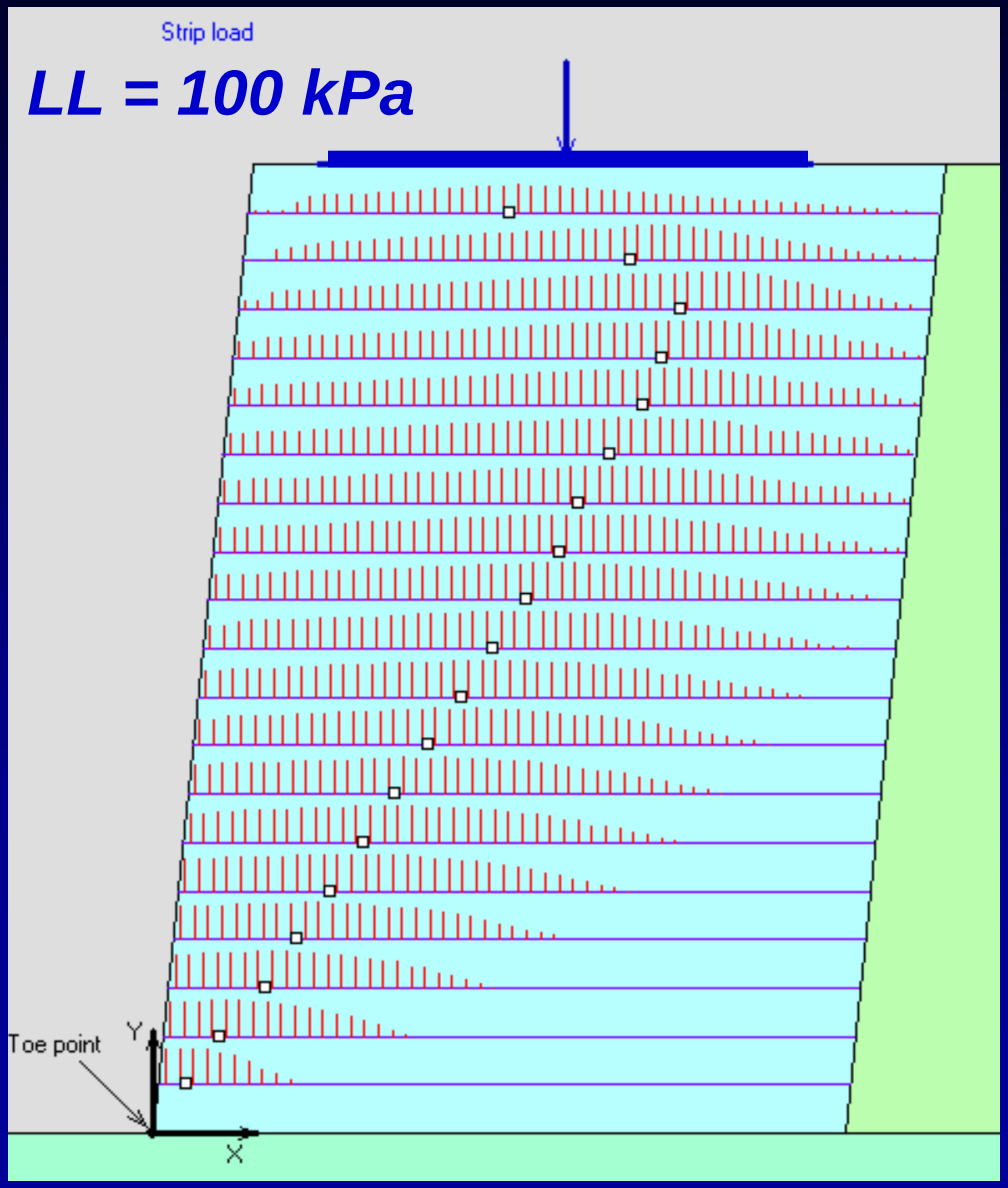
Global Stability

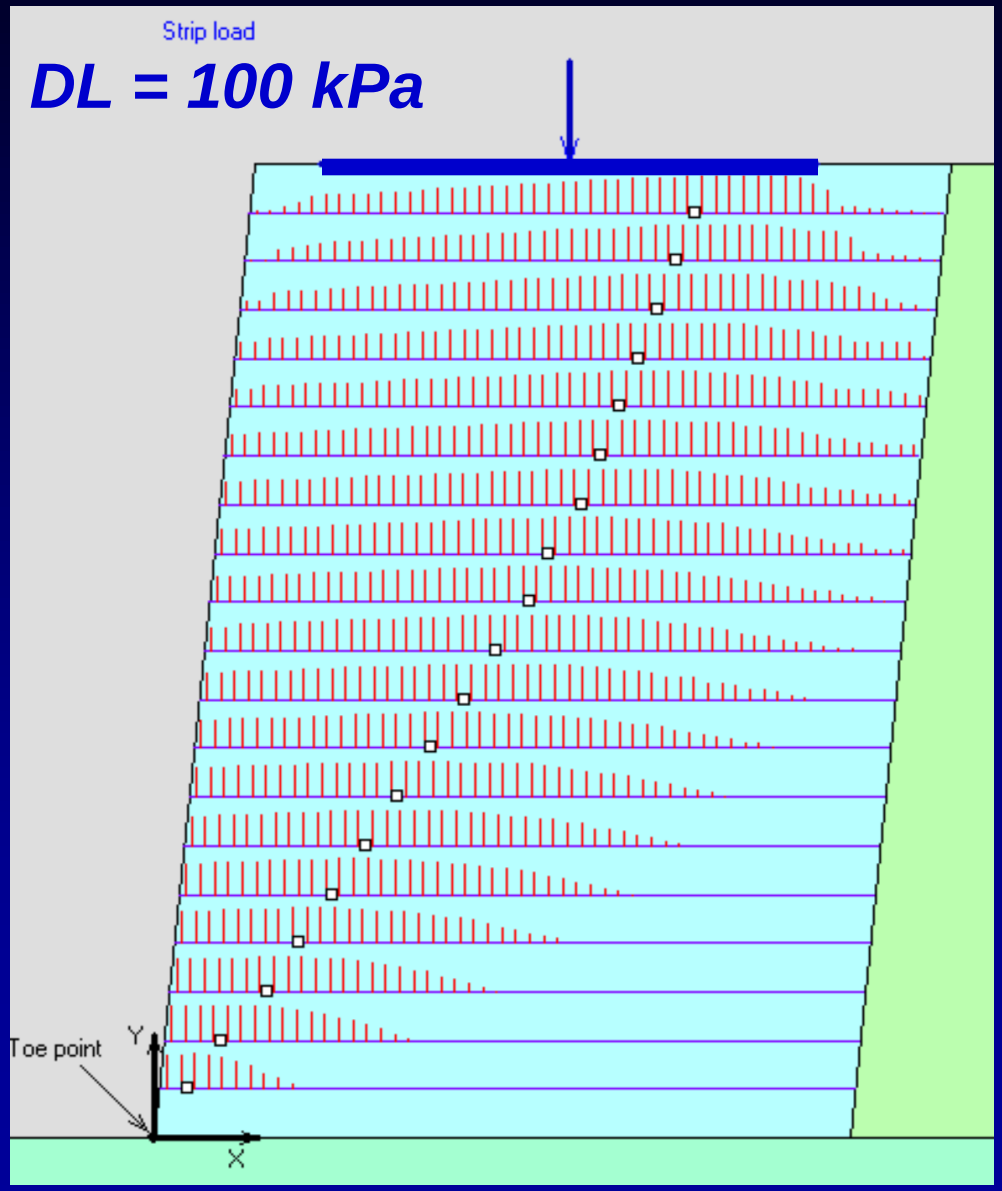


Rotational Global Stability:
Fs=1.0
Used LTDS= max(Tmax) from Baseline Solution ➔
Increase LTDS to get Fs≥1.30

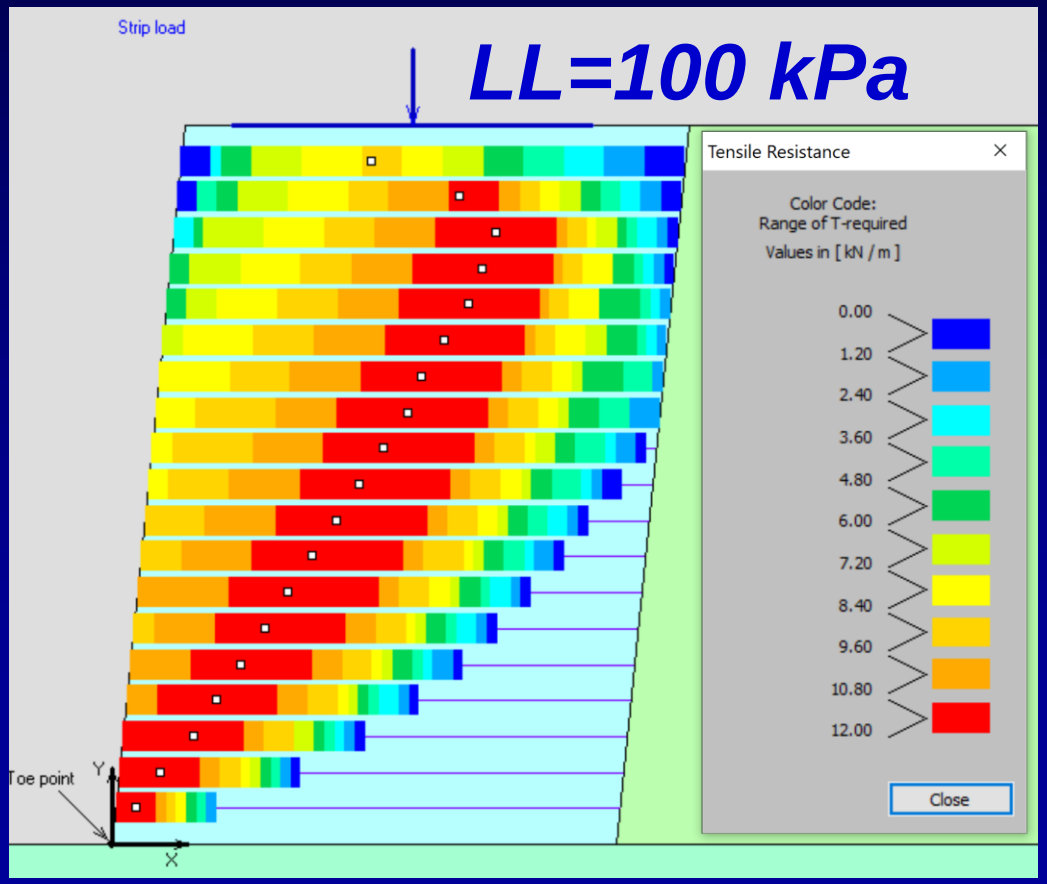
Close Spacing: Dead and Live Loads

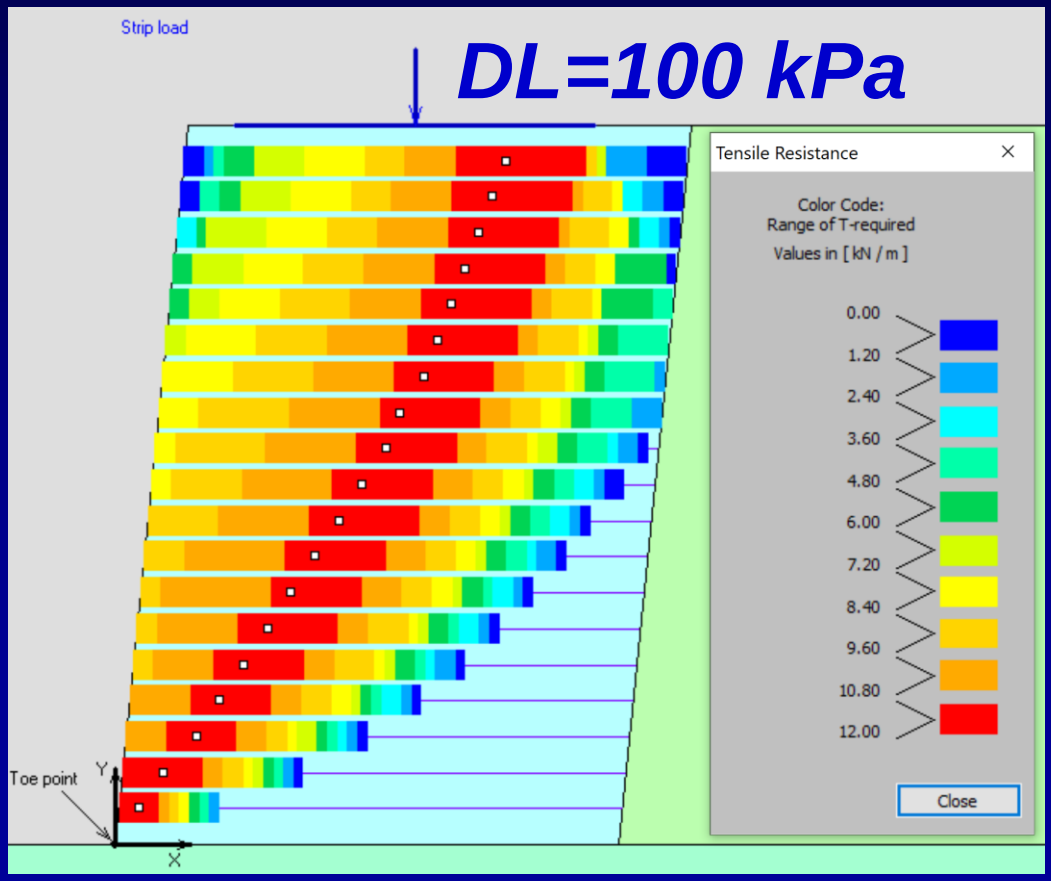
(LL does not affect front and rear pullout; DL affects)



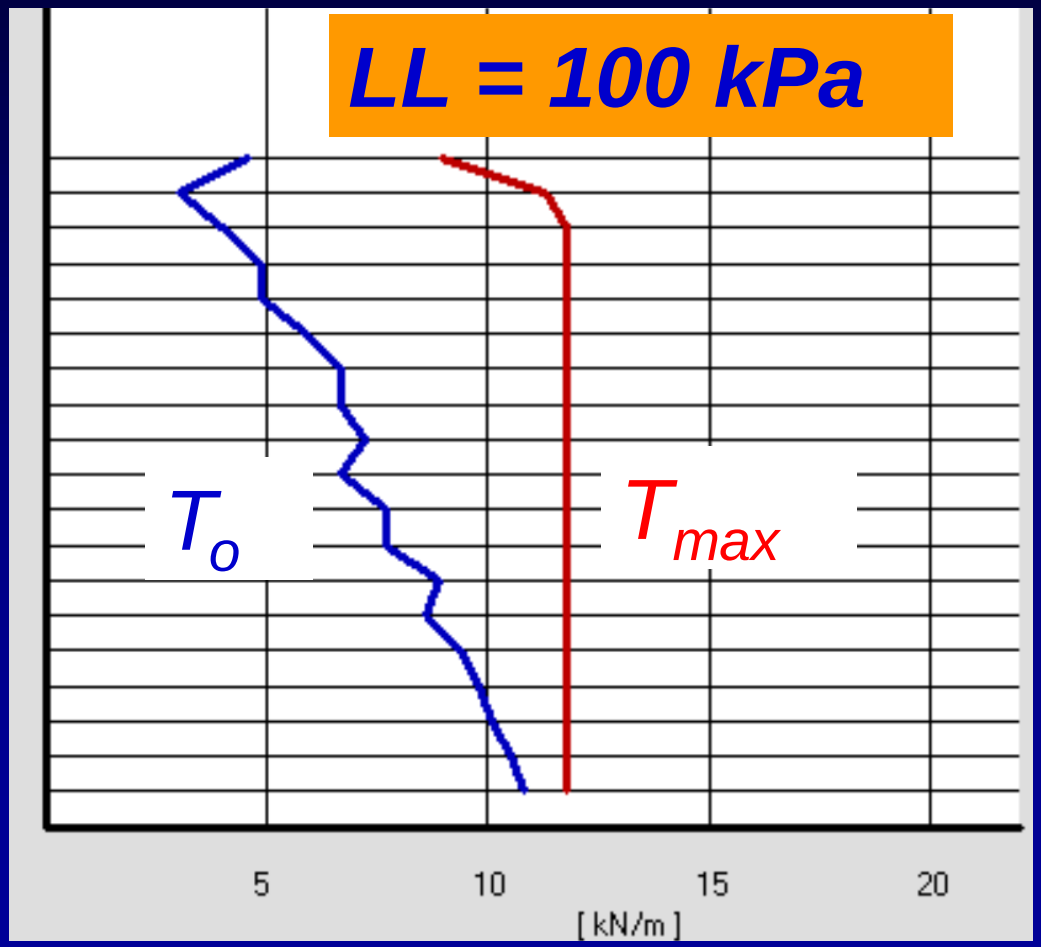


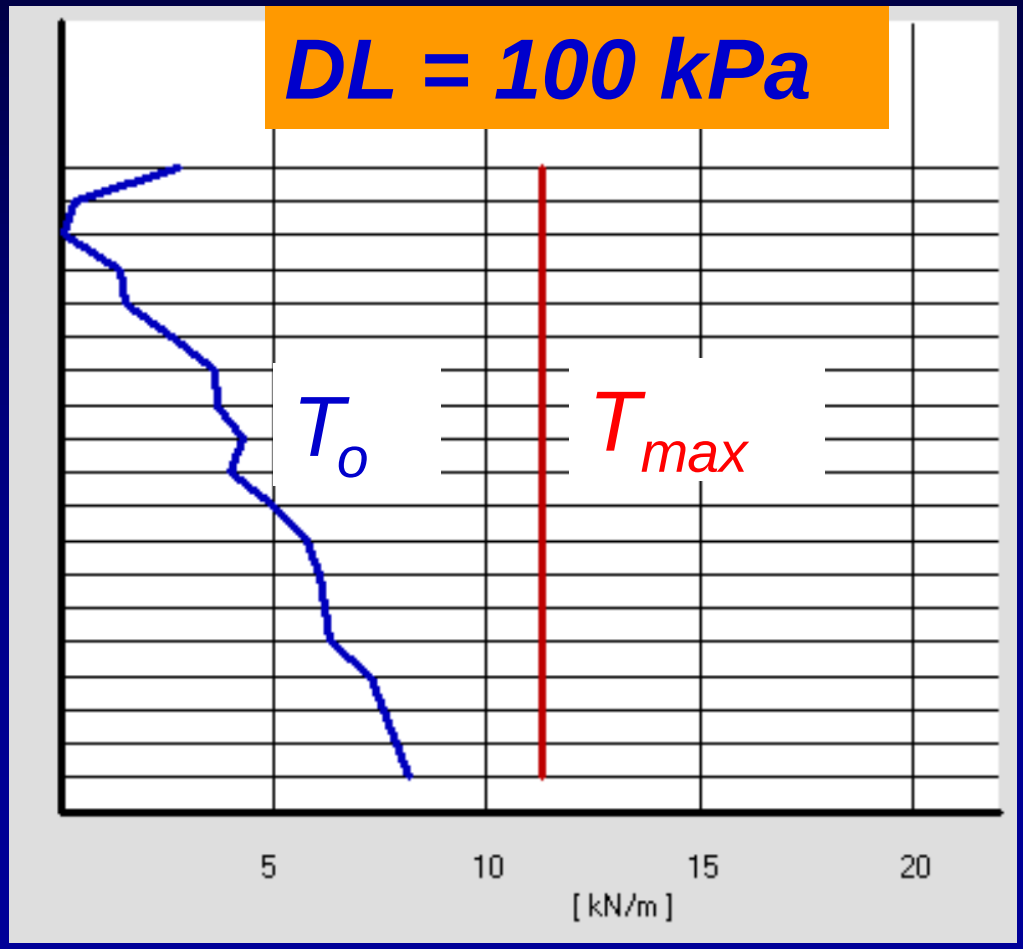
Close Spacing: Dead and Live Loads
(LL does not affect front and rear pullout; DL affects)





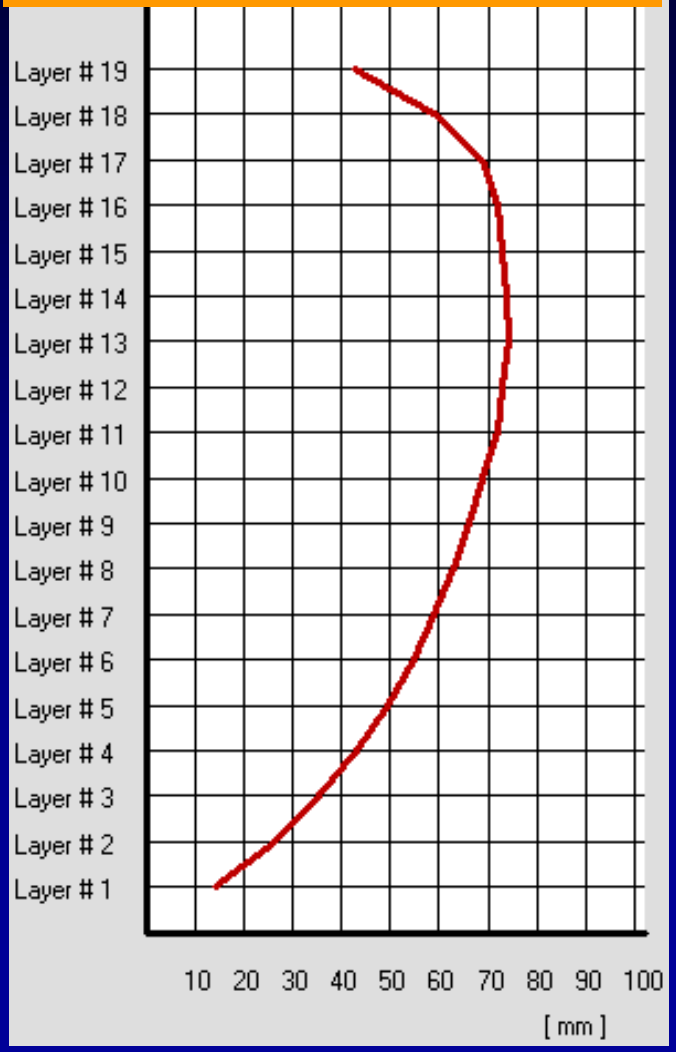
Close Spacing: Dead and Live Loads (note effects on T_o)



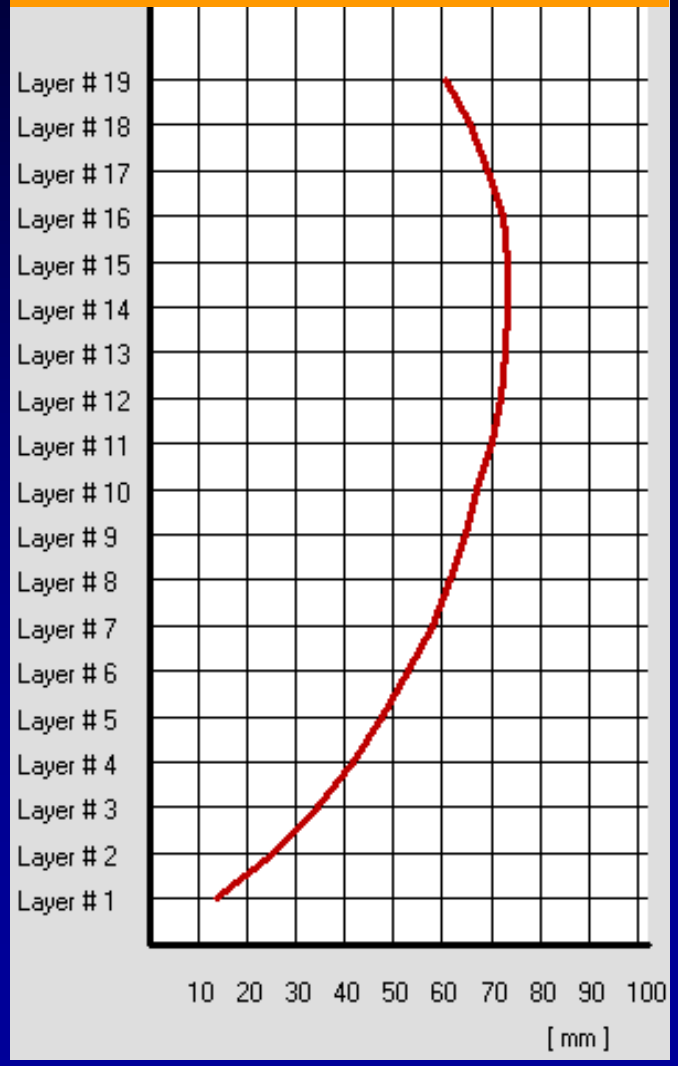


S_v=0.30 m, DL and LL: Displacements

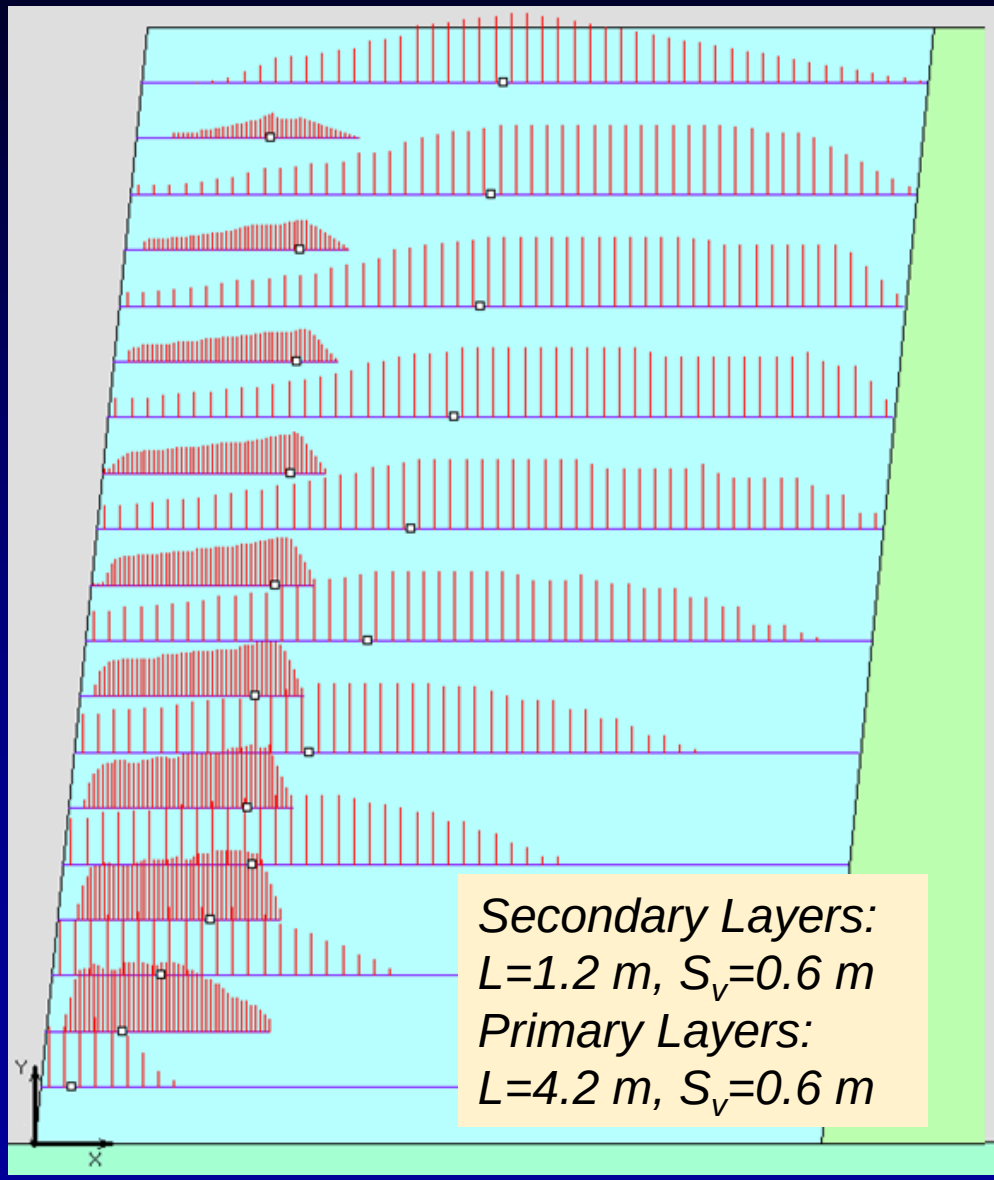
LL = 100 kPa

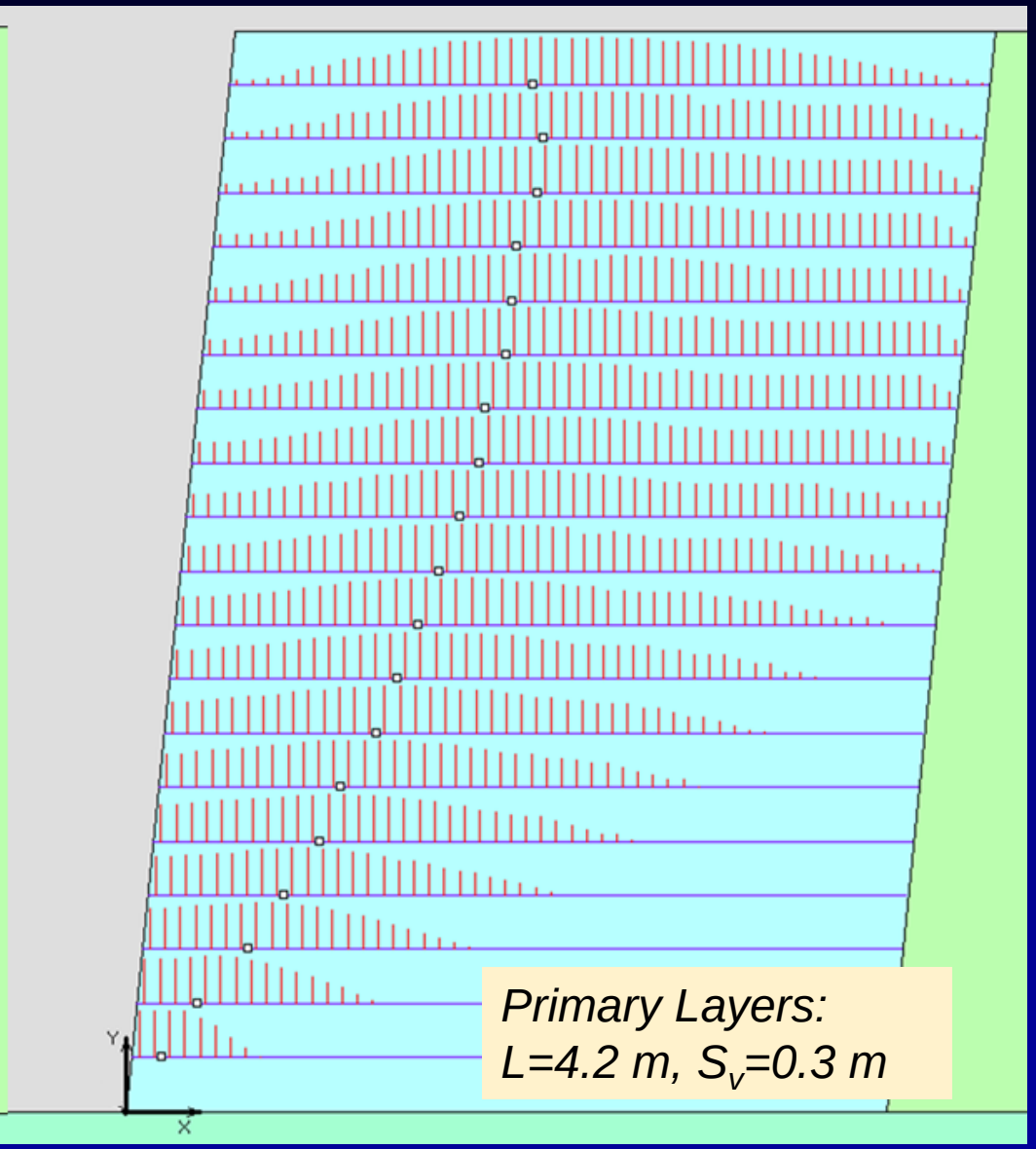


DL = 100 kPa

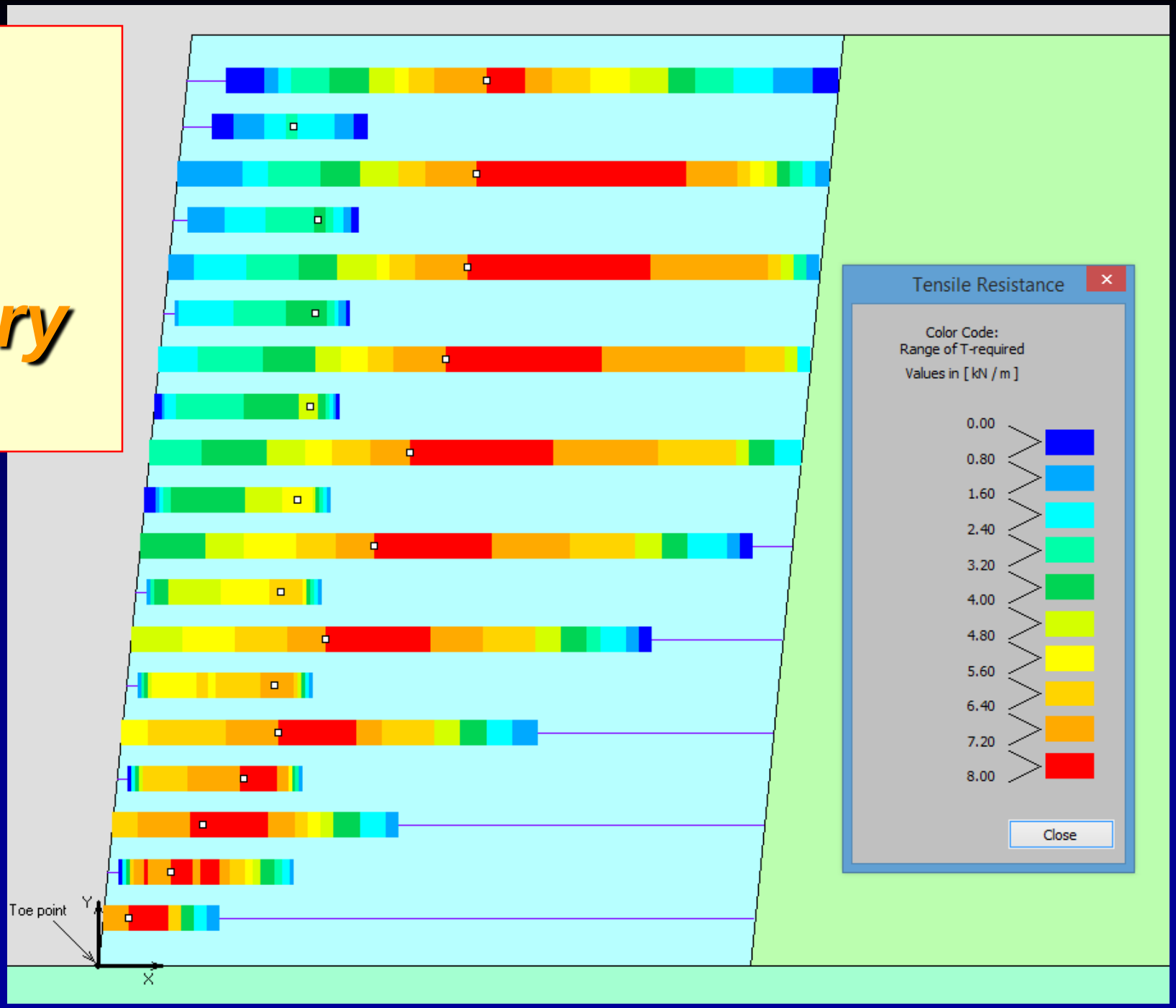


Effects of Secondary Layers

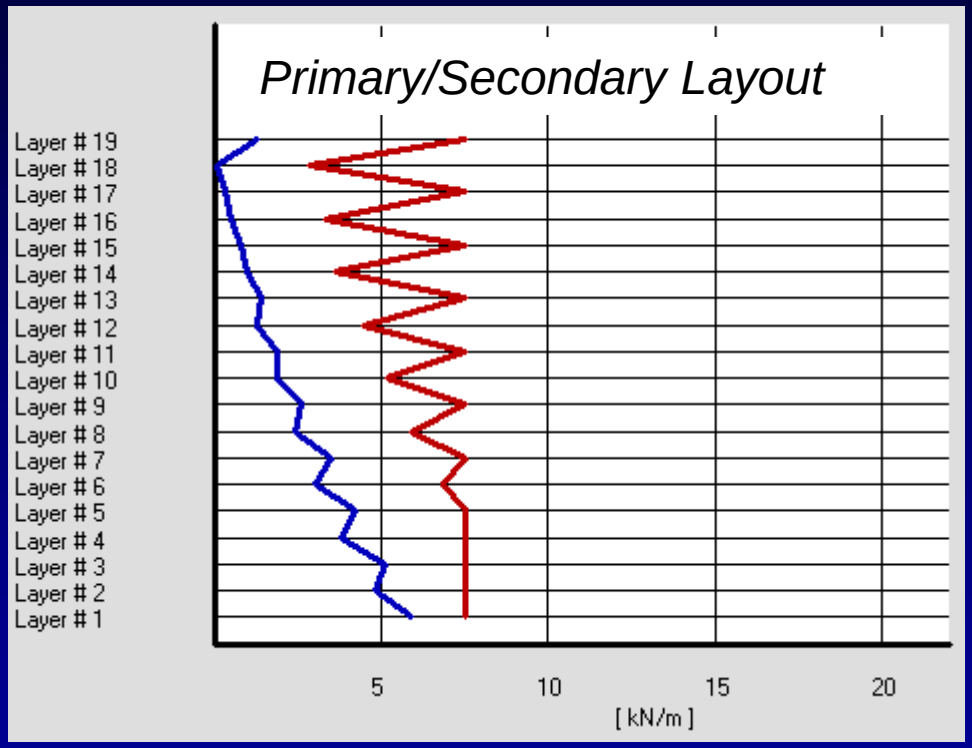


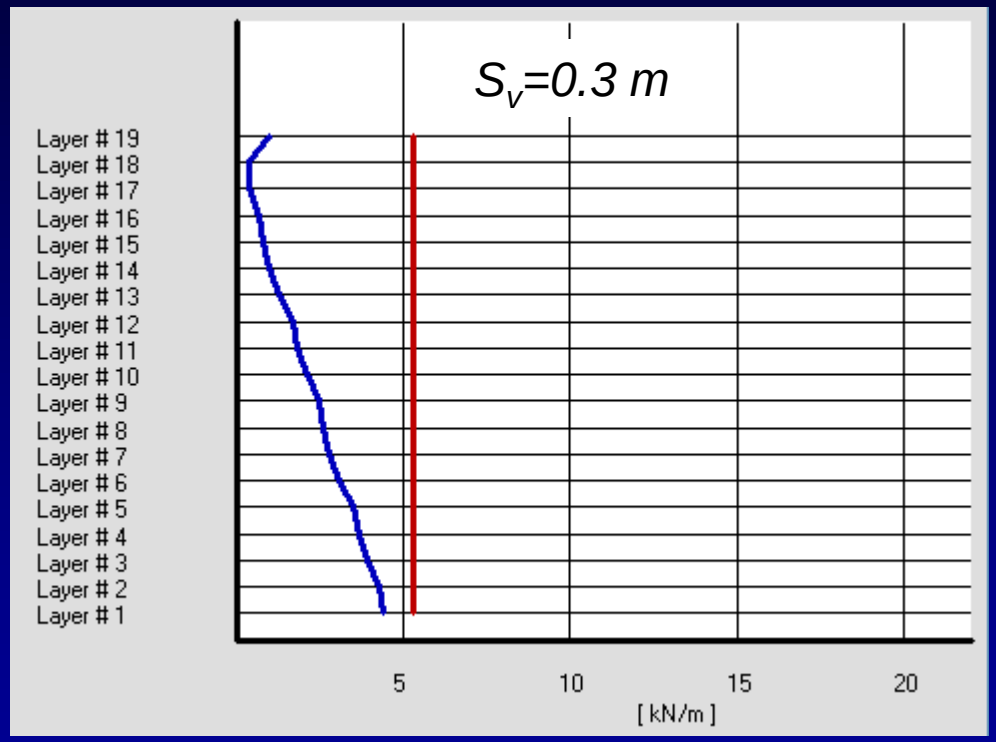


Tension Map and Secondary Layers



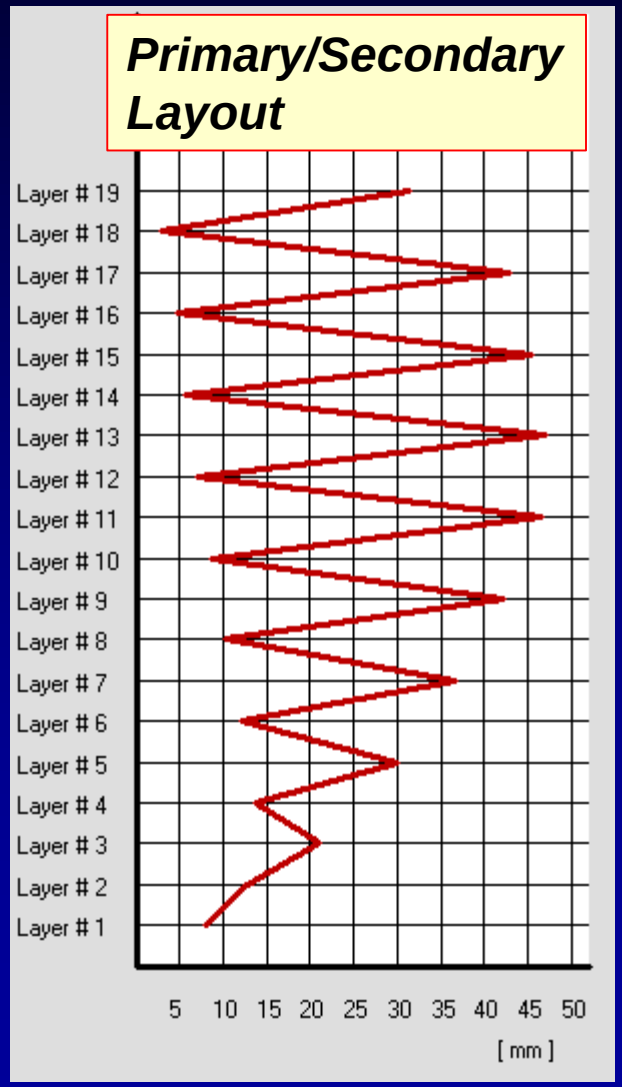
T_{max} and T_o: Secondary versus Close Spacing

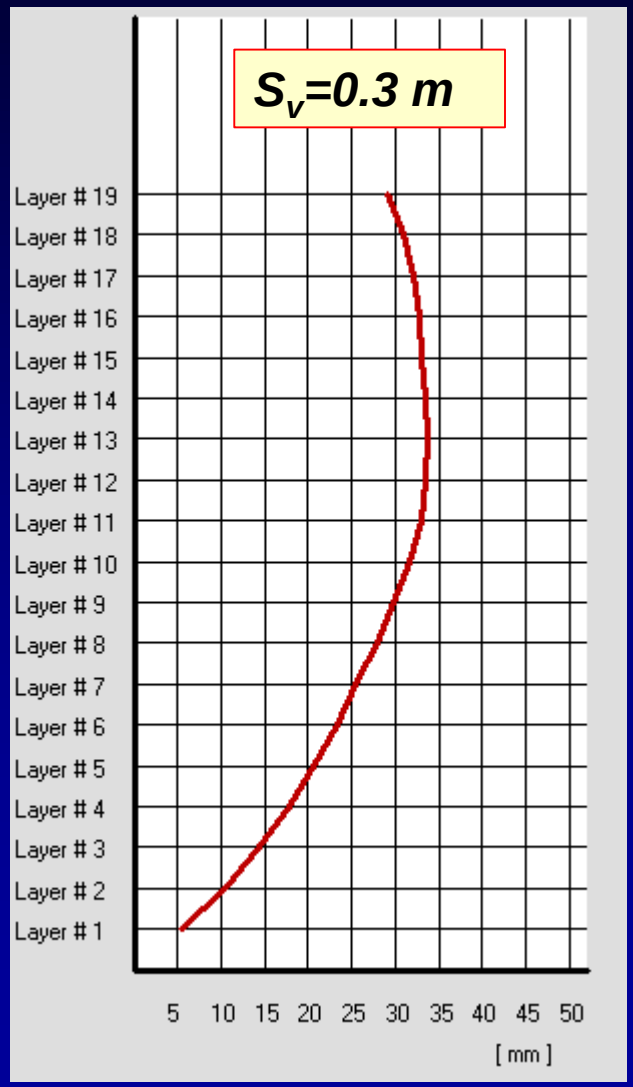




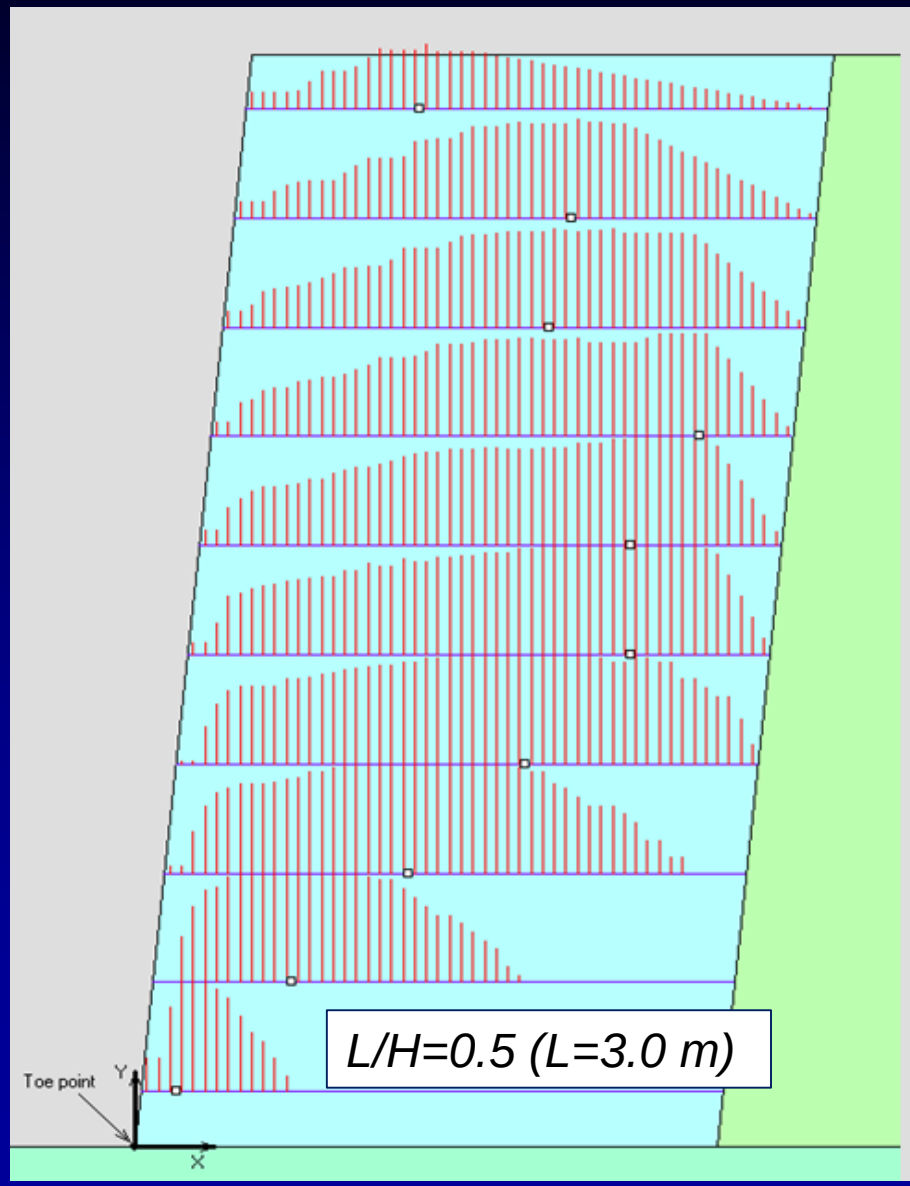
Depending on relative length of secondary reinforcement, it may decrease T_{max}. Generally it has significant effects on T_o (connection loading).

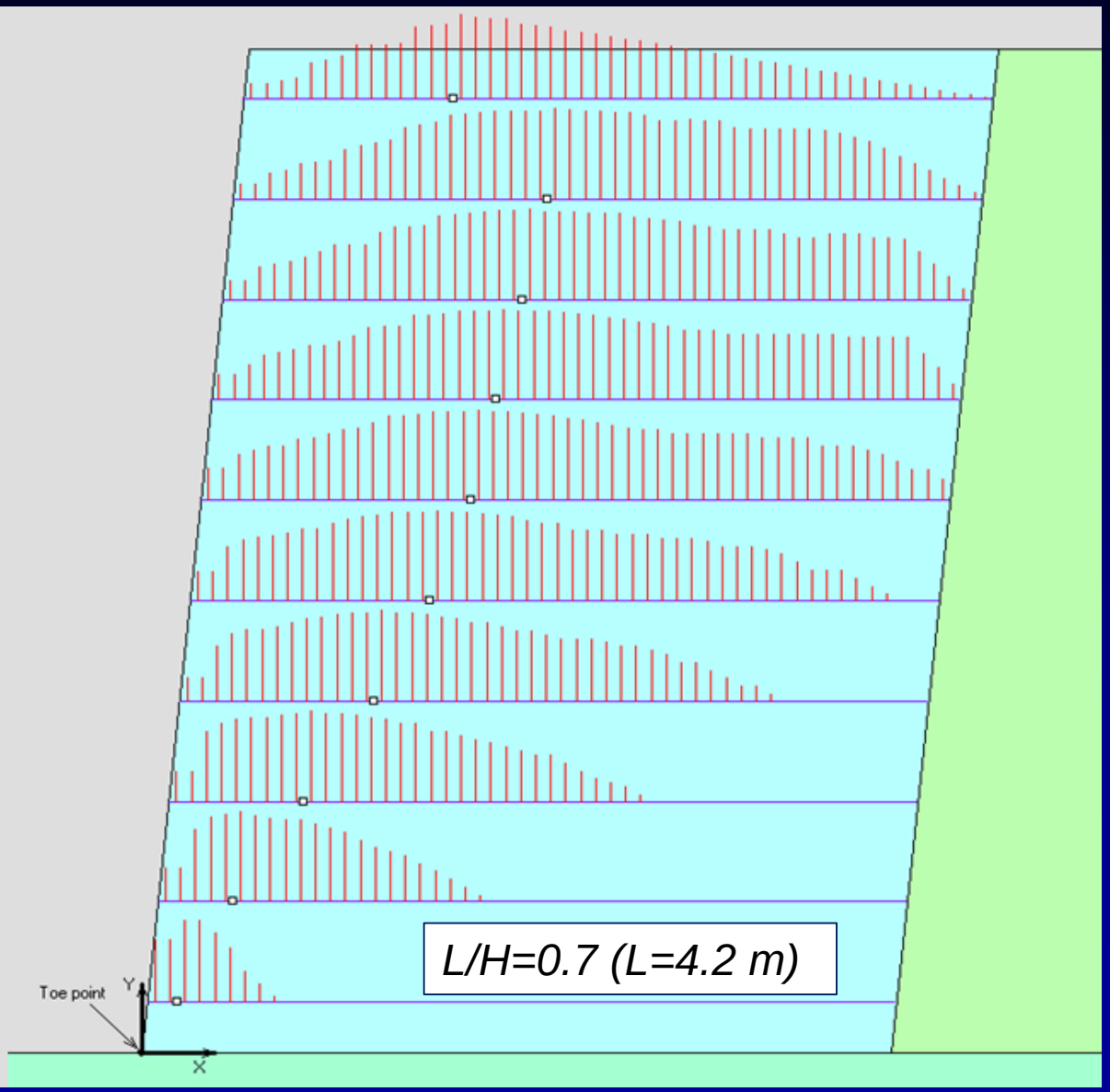
Face Displacements: Secondary versus Close Spacing





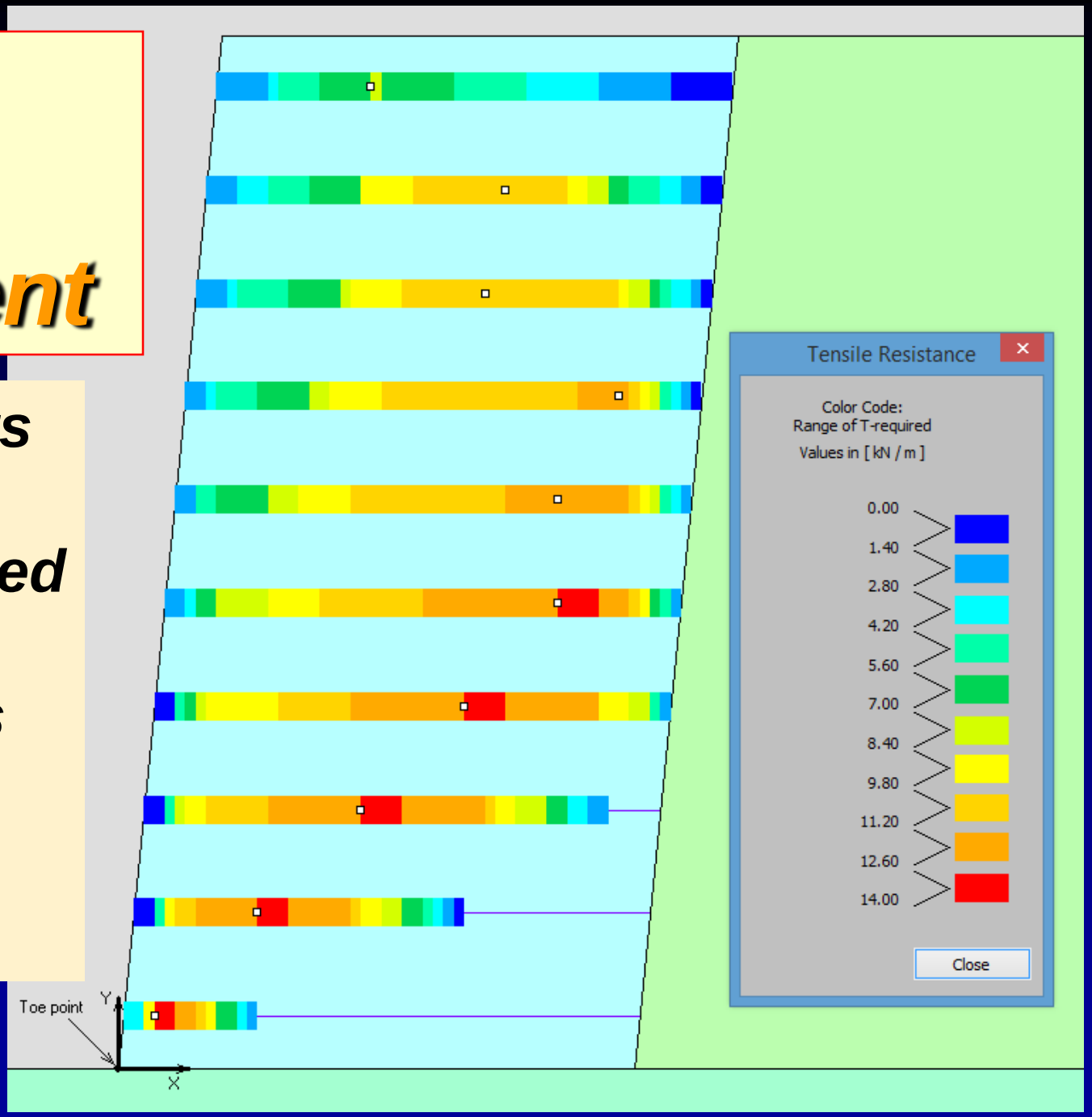
Effects of Shorter Reinforcement



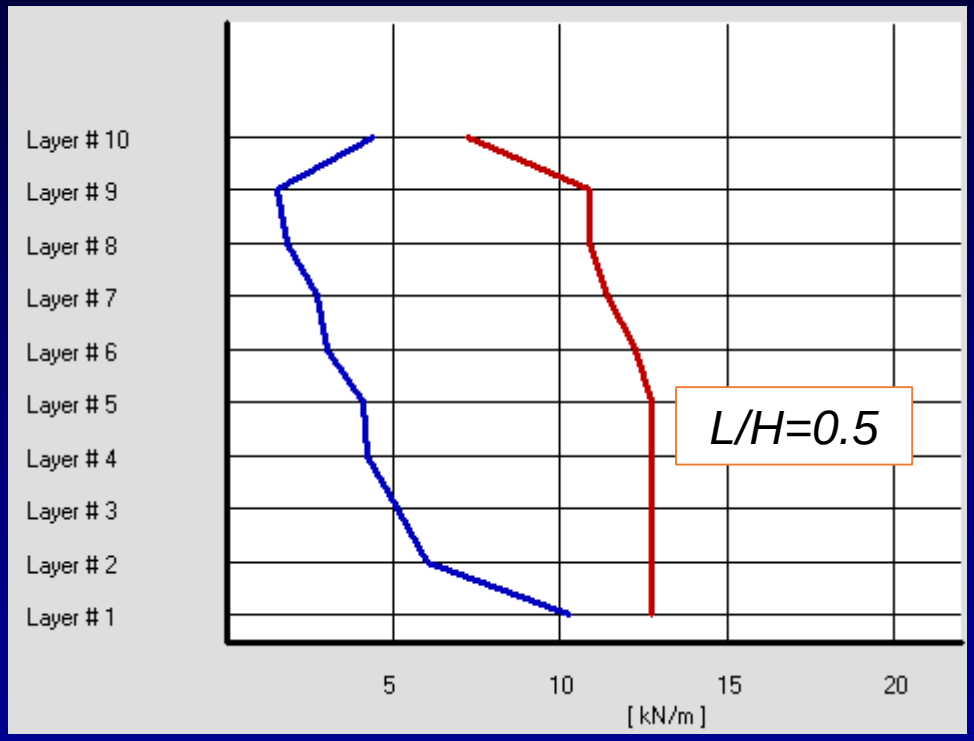


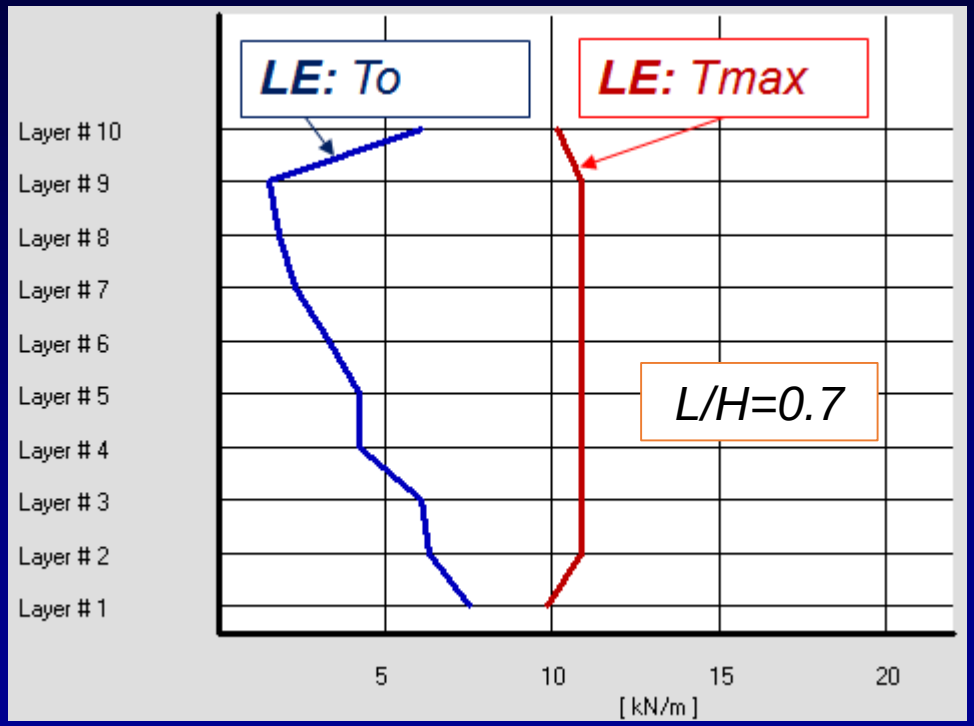
Effects of Shorter Reinforcement

Short reinforcements can be considered, but result in increased T_{max} as compound failure prevails. This can be explicitly accounted for using the LE framework.



Effects of Shorter Reinforcement: T_{max} and T_o

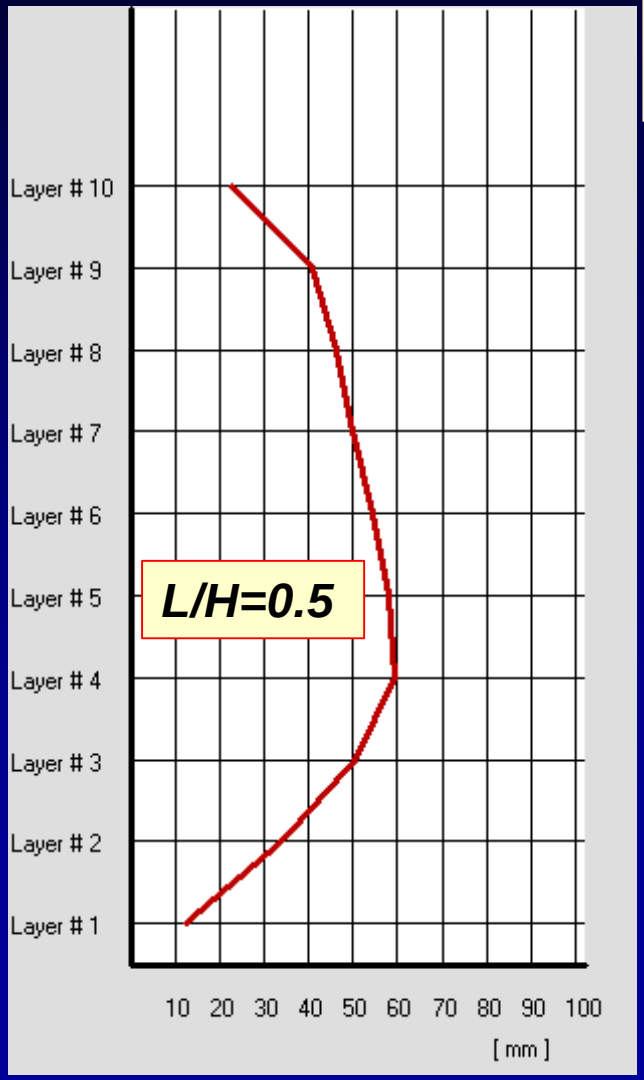




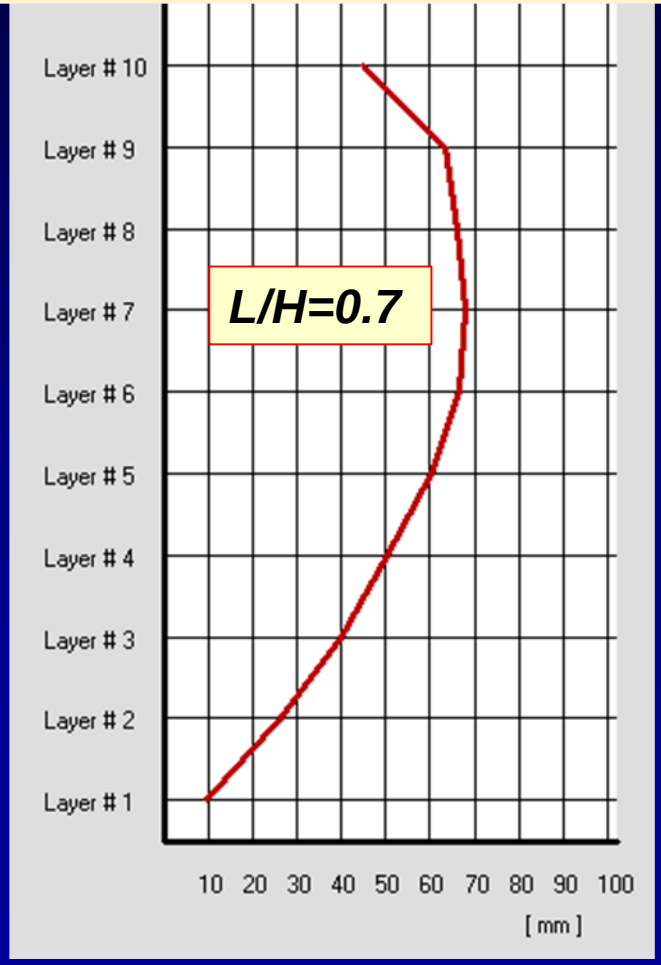
Generally, lower layers carry higher load due to compound failures ➔ Upper layers need to contribute less to produce Fs=1.0 ➔ Upper layer carries marginally less load thus resulting in smaller T_{max} and T_o

Effects of Shorter Reinforcement: Displacement

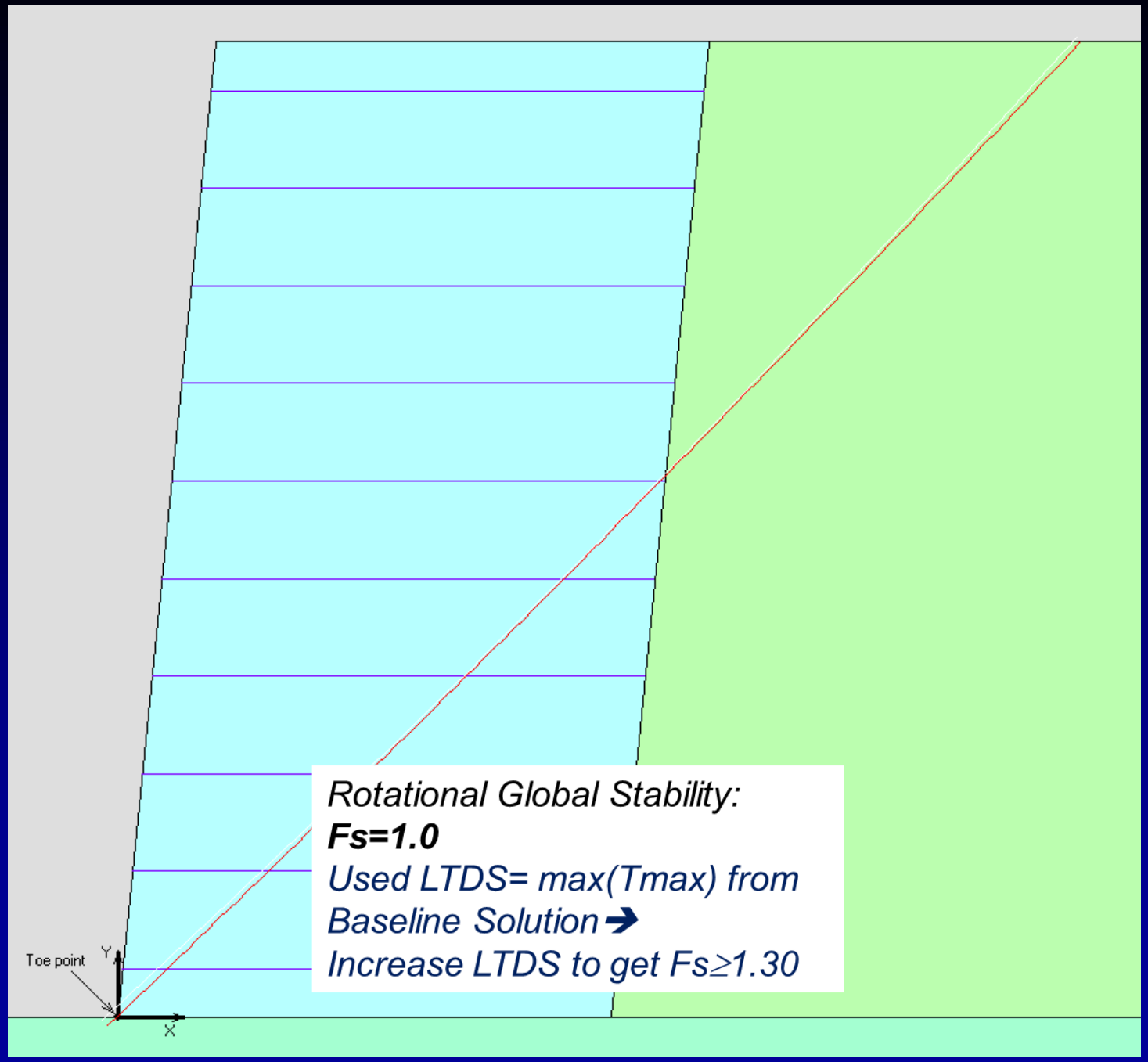
Note:
Lower layers carry higher load but are shorter, yielding here about the same max displacement as in baseline problem. This is not always the case.



Δ profile for J=500 kN/m
(For Fs=1.0; i.e., soil strength is fully mobilized)

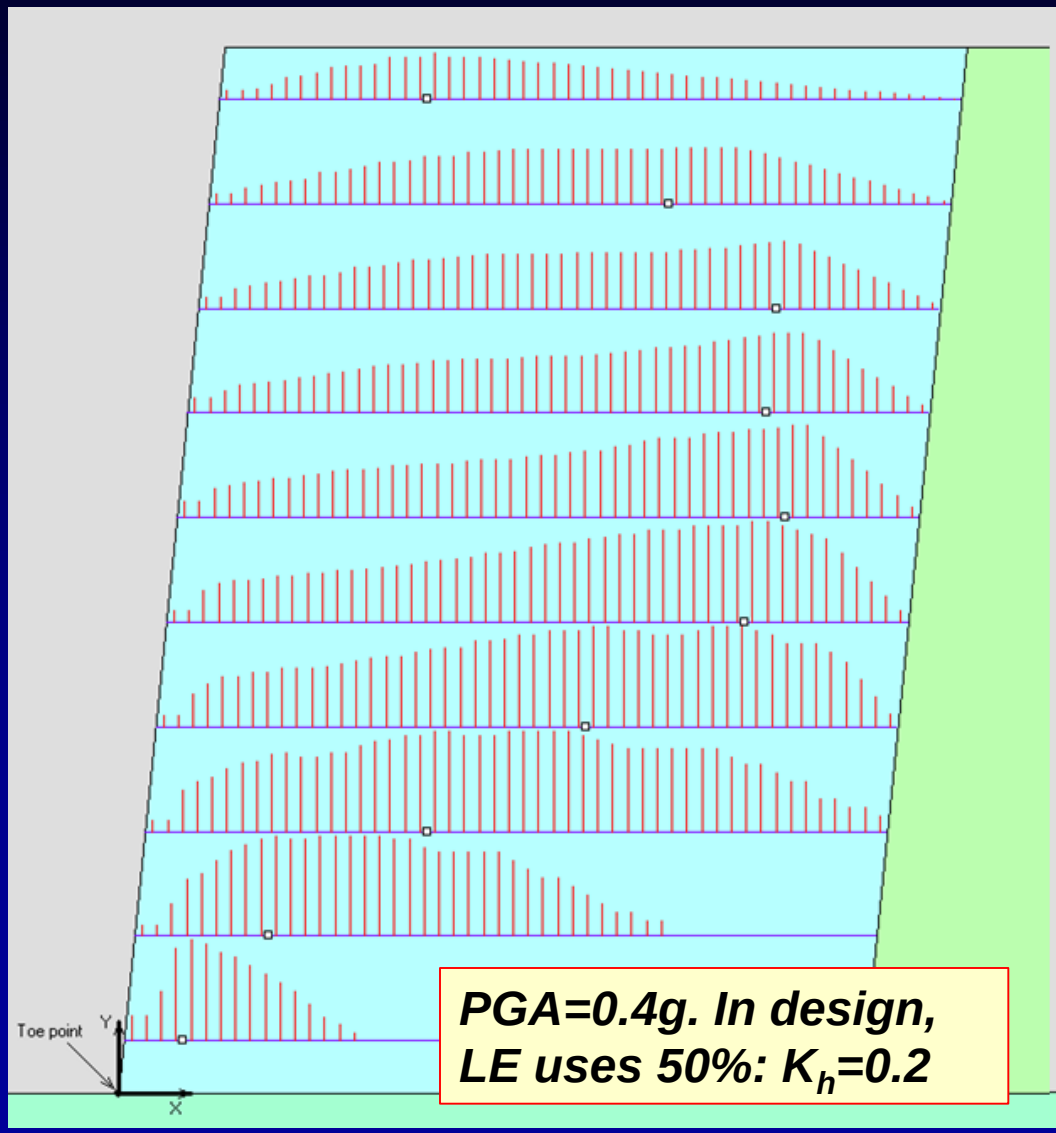


Short Layers and Global Stability

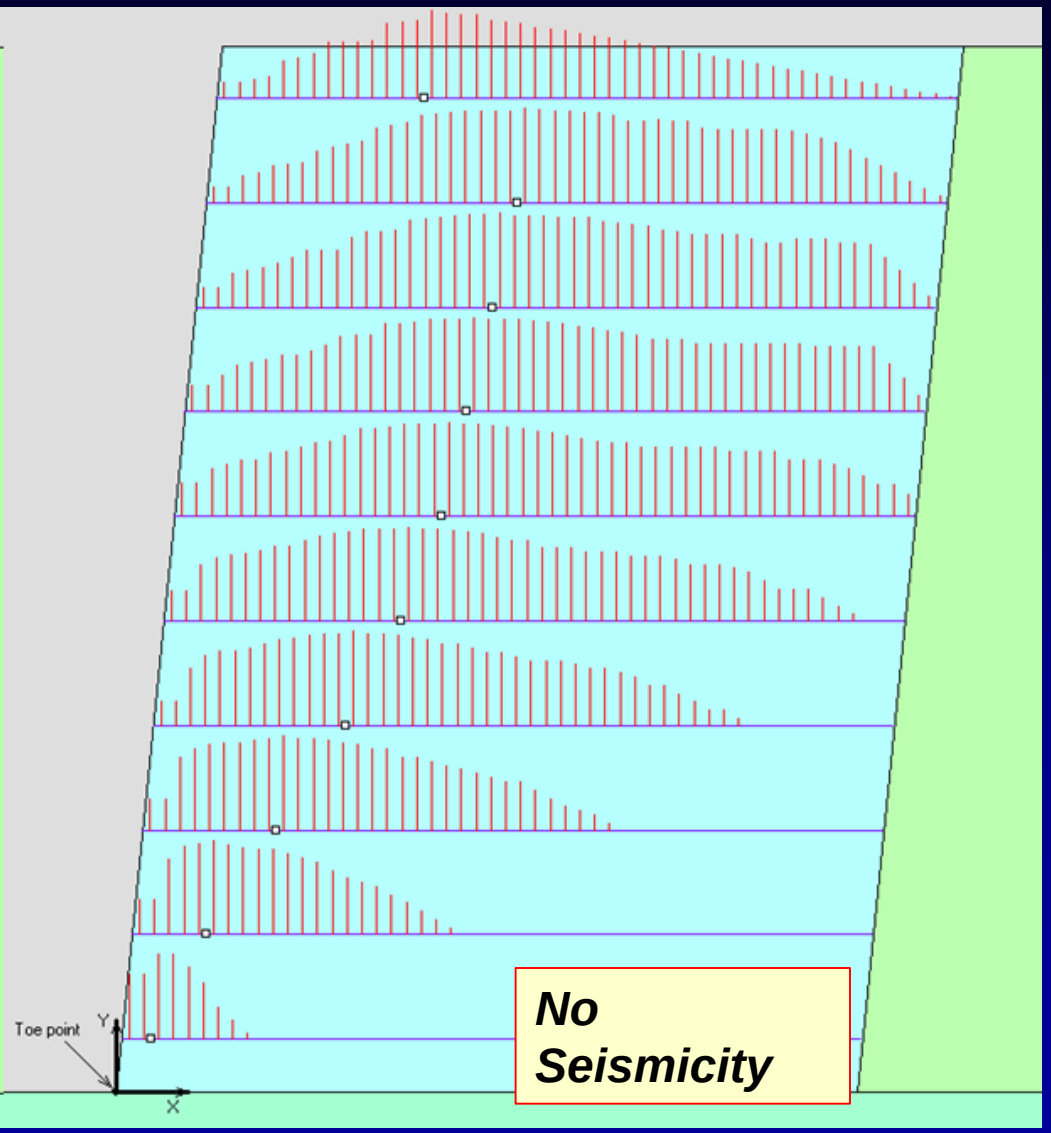


Rotational Global Stability:
Fs=1.0
Used LTDS= max(Tmax) from Baseline Solution ➔
Increase LTDS to get Fs≥1.30

Effects of Seismicity



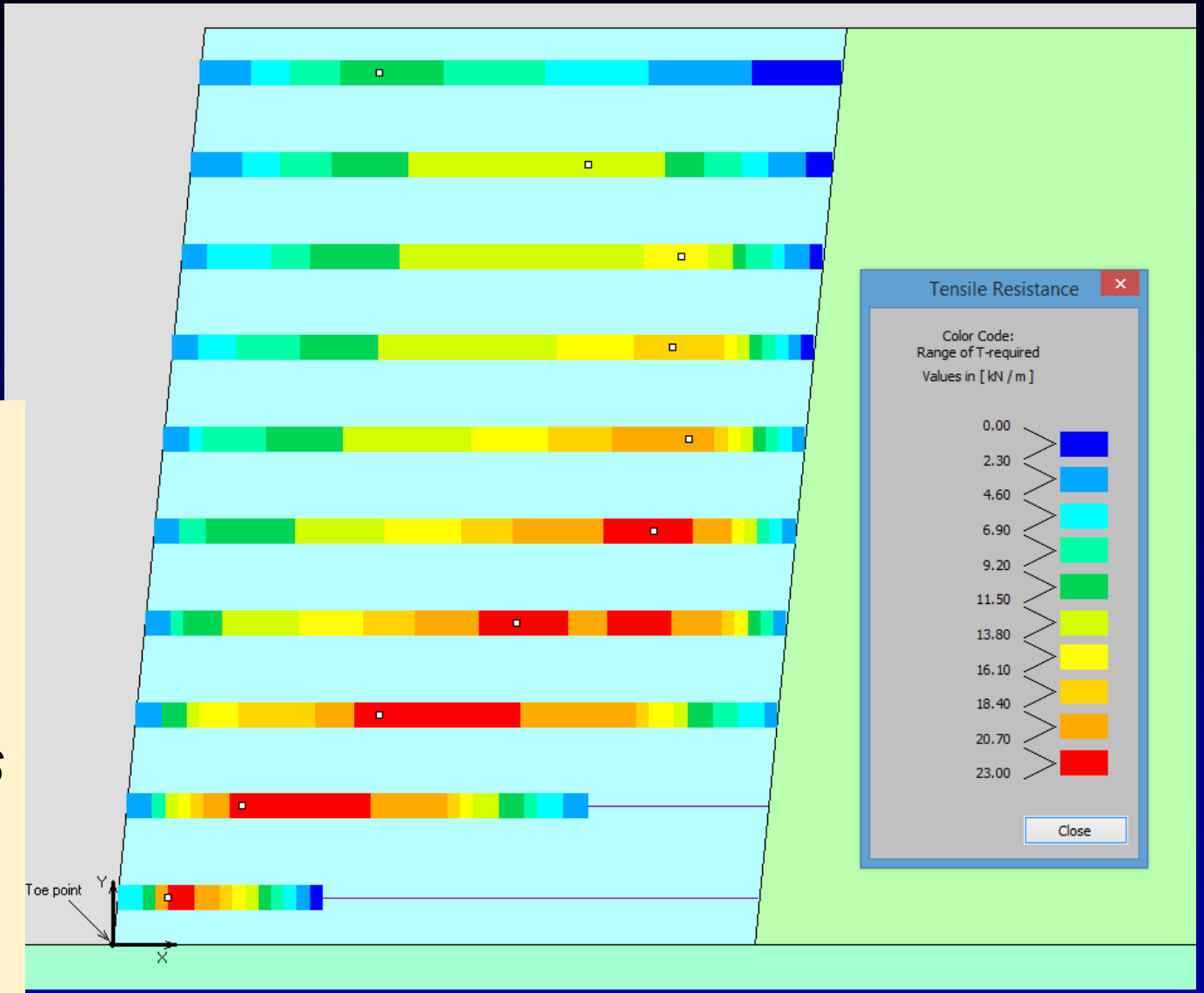
PGA=0.4g. In design, LE uses 50%: K_h=0.2



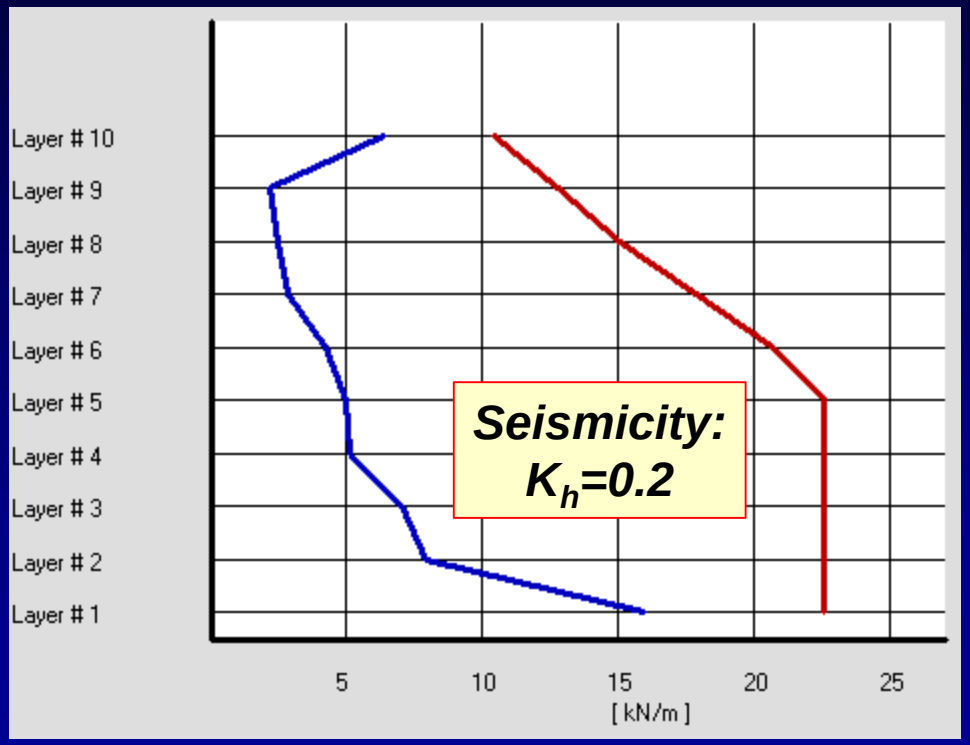
No Seismicity

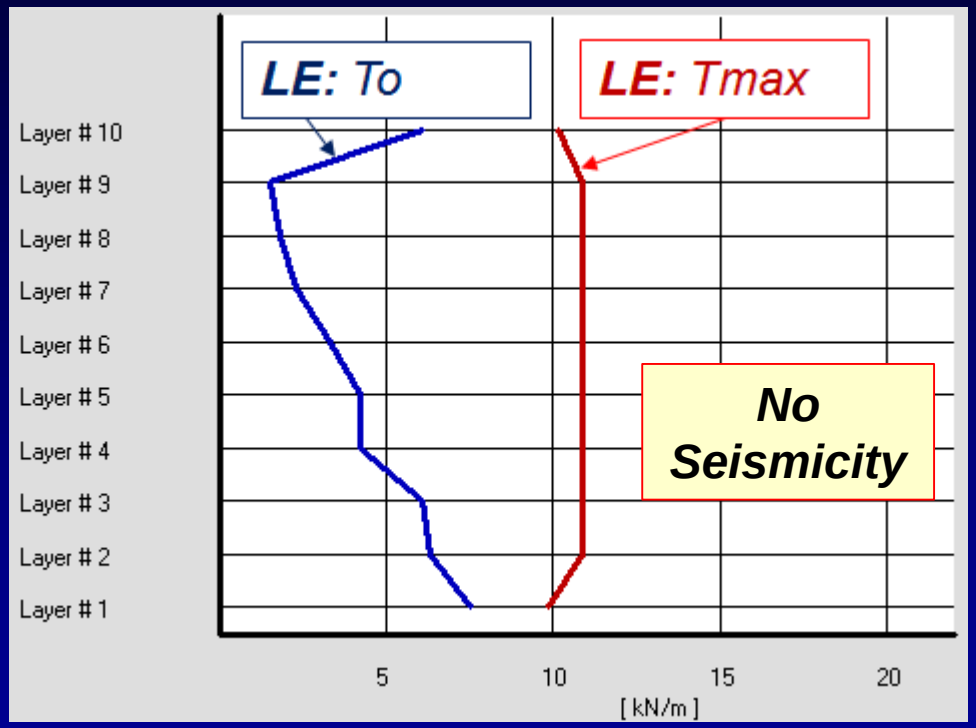
Tension Map Under Seismic Loading

Seismicity can be considered, but results in increased T_{max} as compound failure prevails. This can be explicitly accounted for using the LE framework.

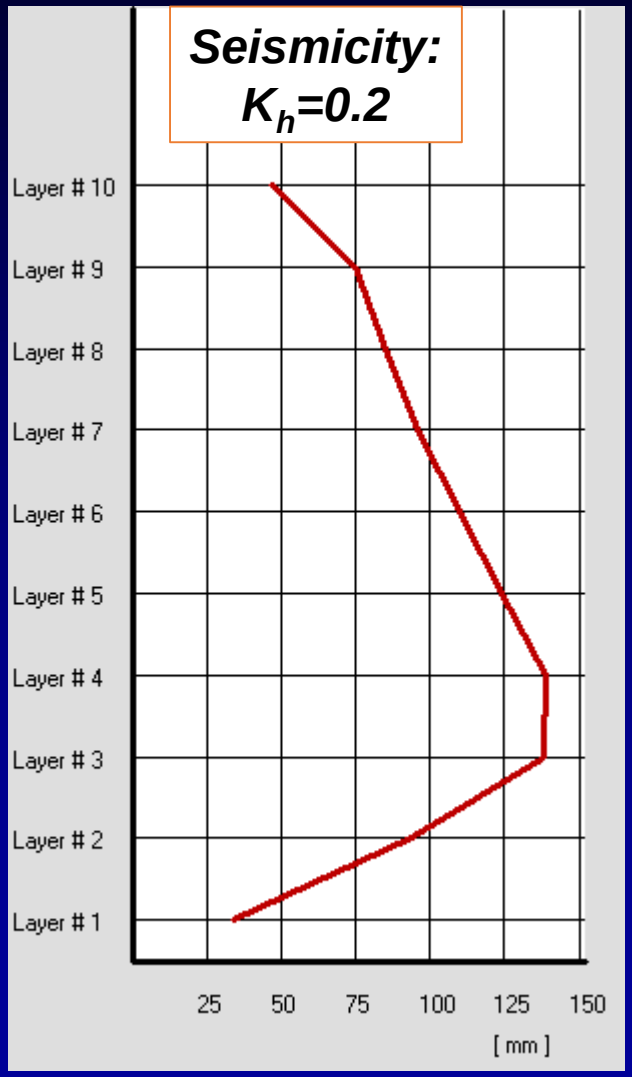


Seismic Effects: T_o and T_{max}

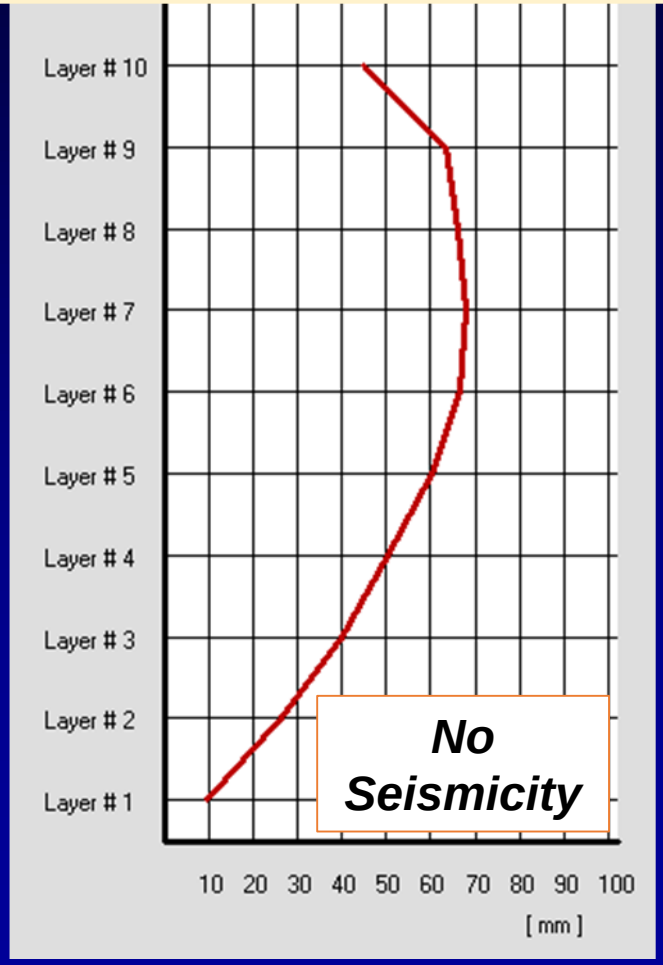




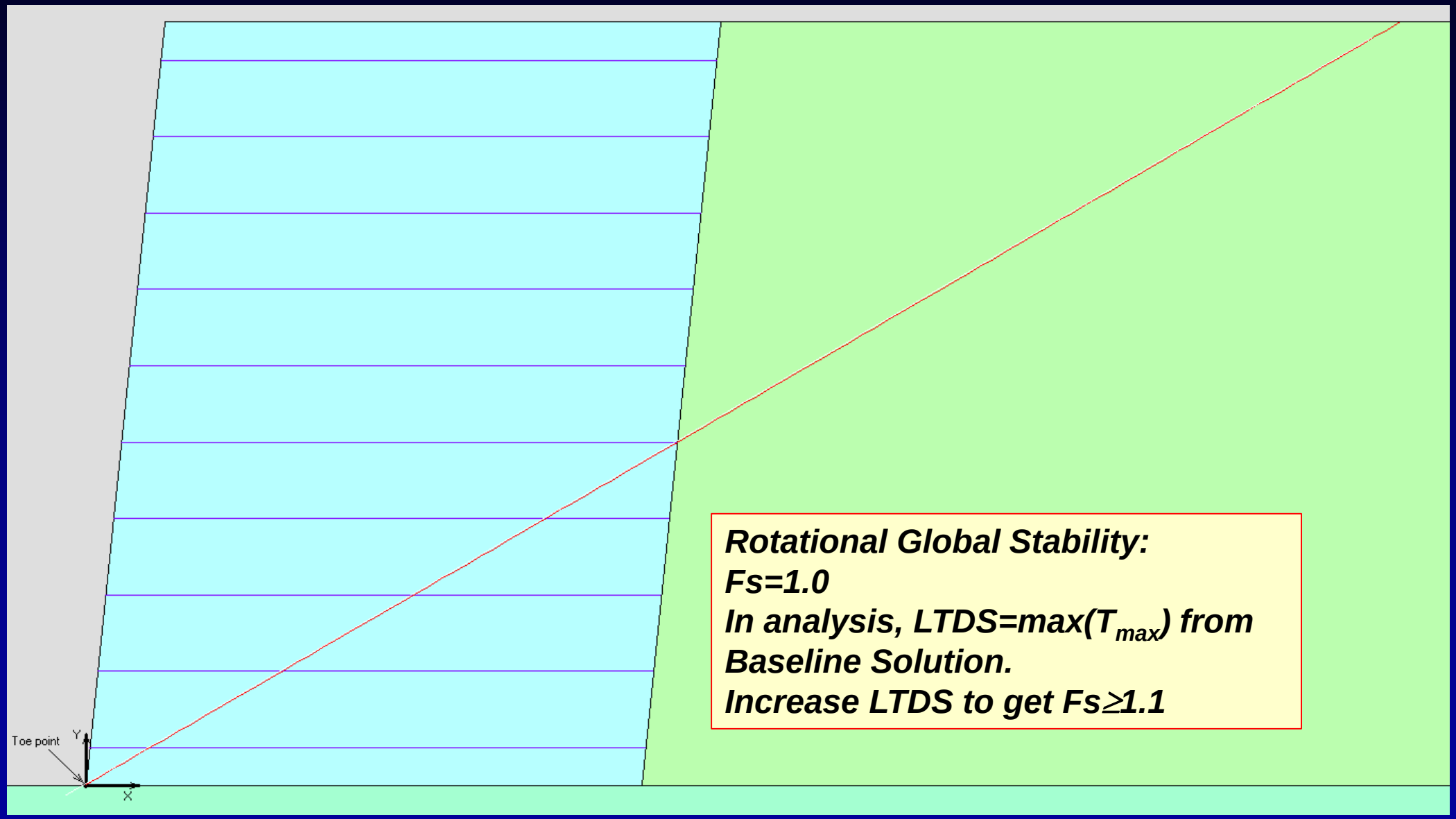
Seismic Displacements



Δ profile for J=500 kN/m
(For Fs=1.0; i.e., soil strength is fully mobilized)

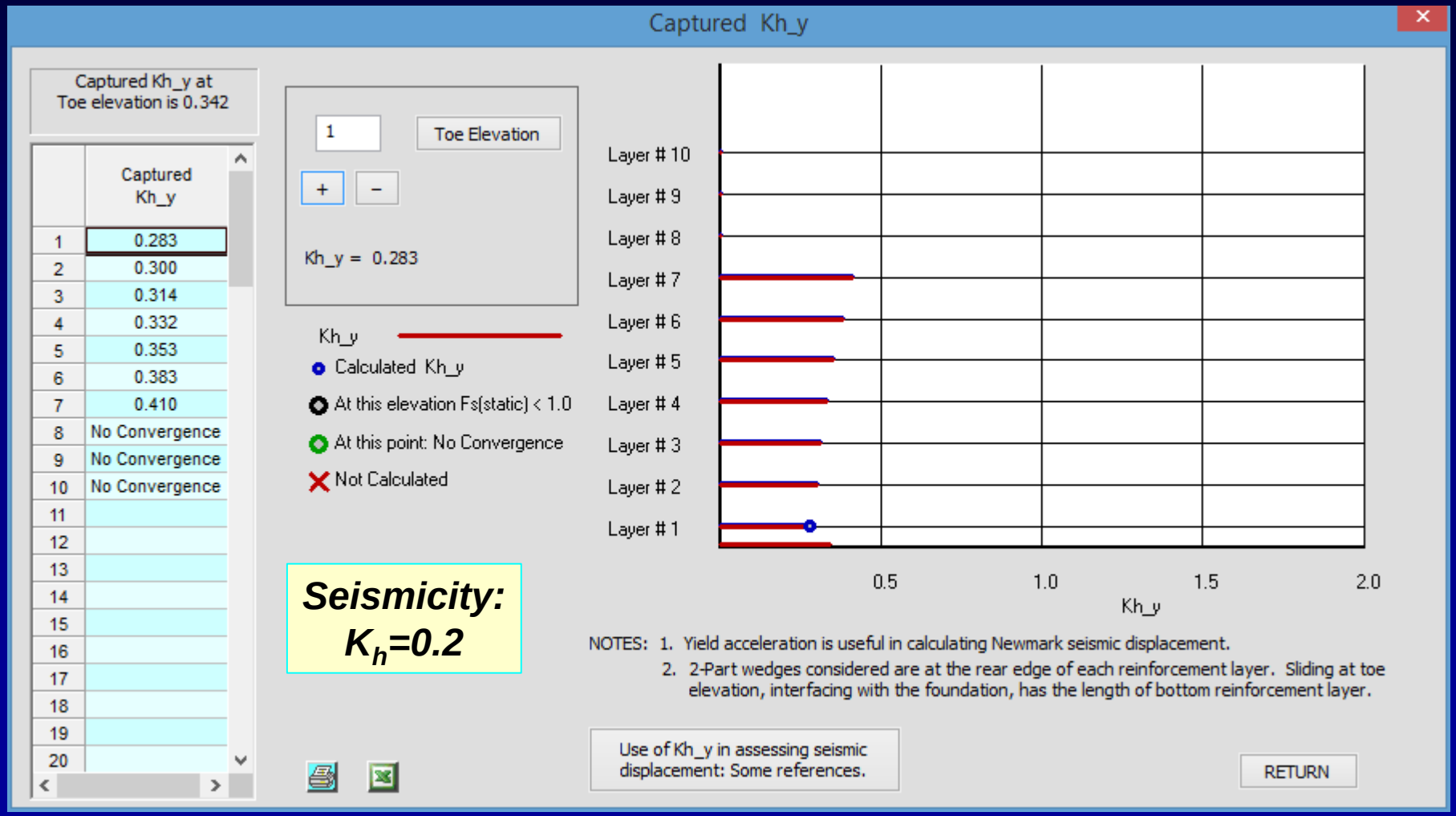


Seismic Global Rotational Stability

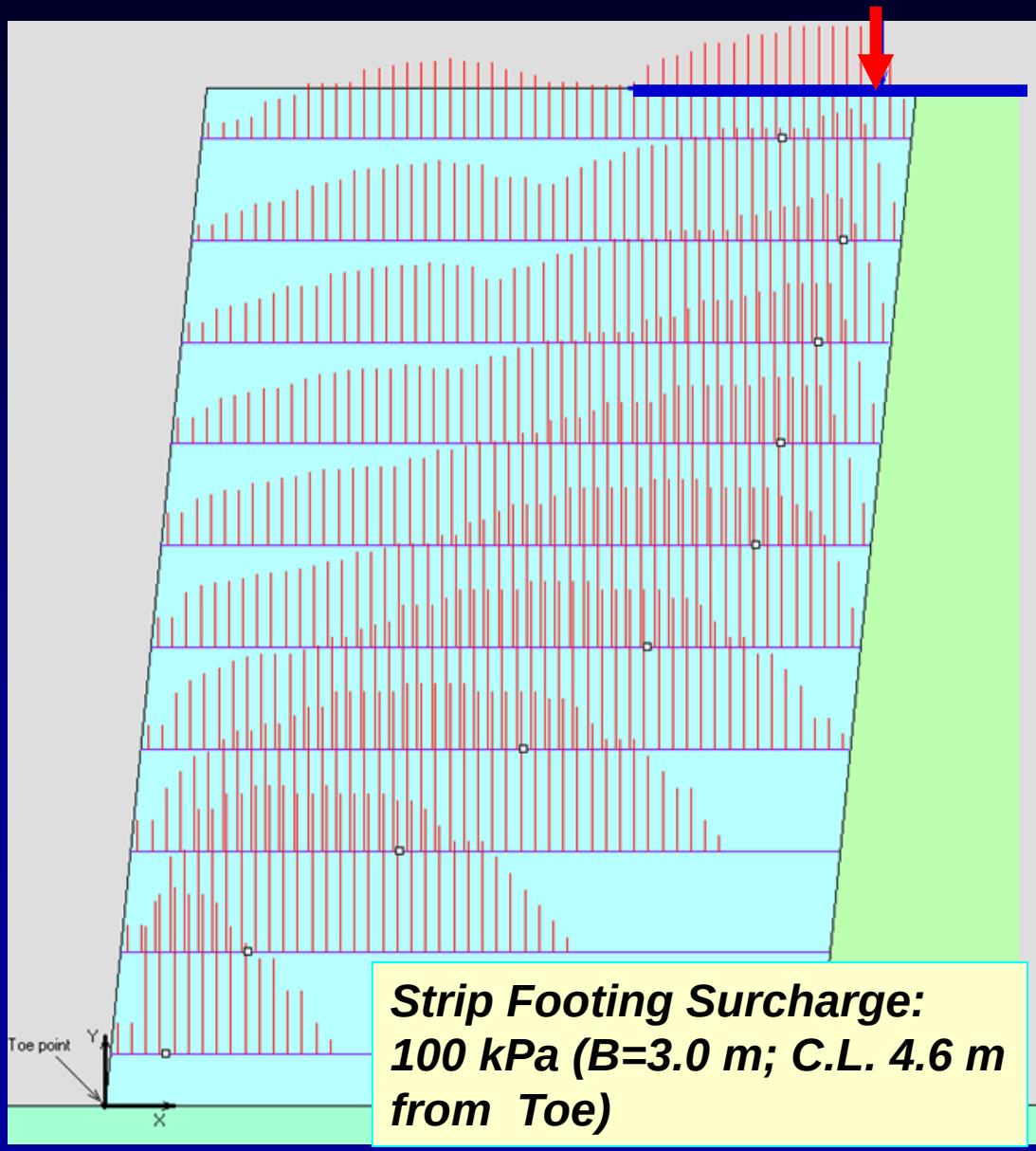


Rotational Global Stability:
Fs=1.0
In analysis, LTDS=max(T_{max}) from Baseline Solution.
Increase LTDS to get Fs≥1.1

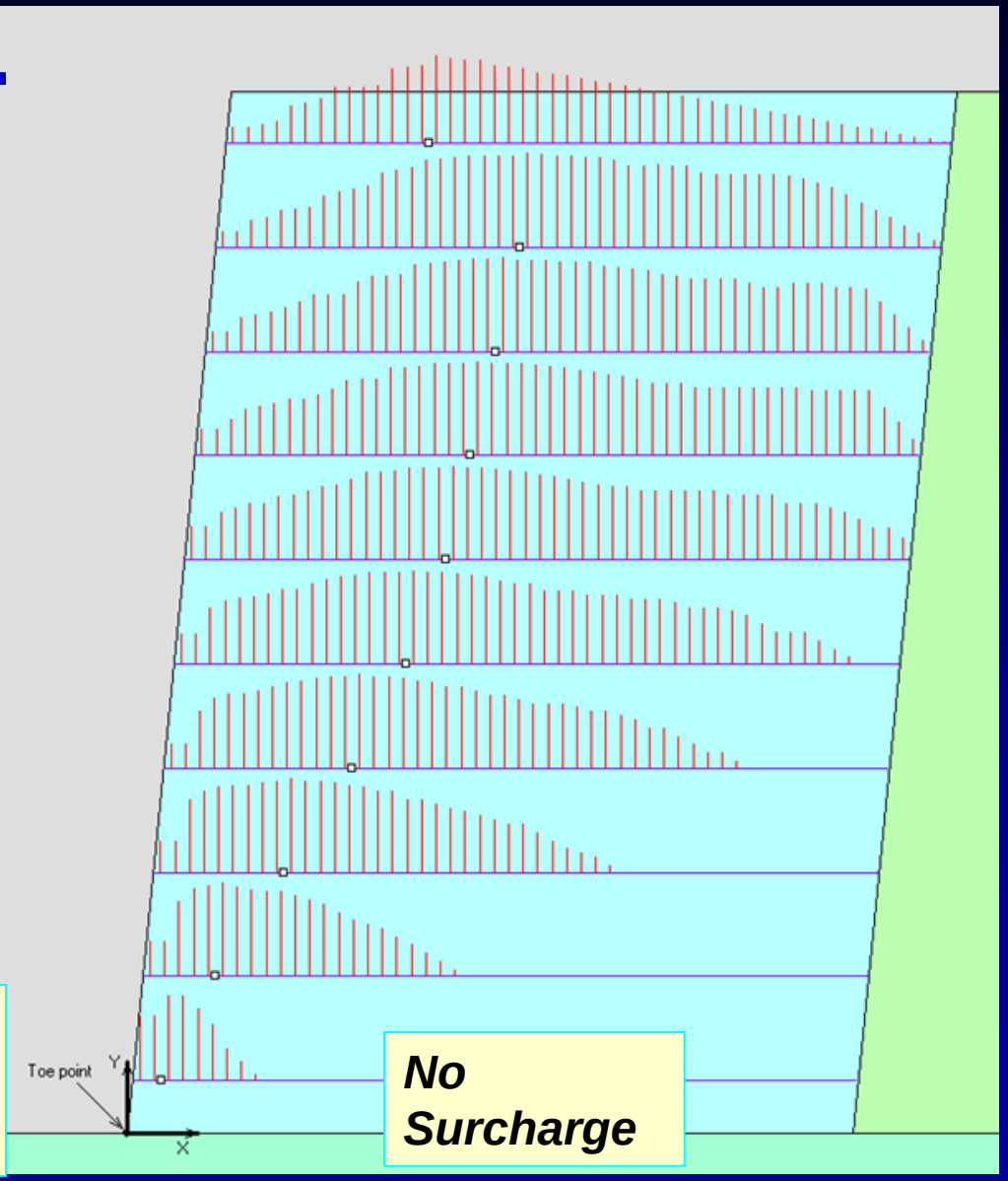
Computed Yield Acceleration at Each Layer, $K_{h\text{-}y}$, using Spencer 2-part wedge ($K_{h\text{-}y}$ renders Fs=1.0 for sliding at each elevation)



Effects of Surcharge (Dead Load)

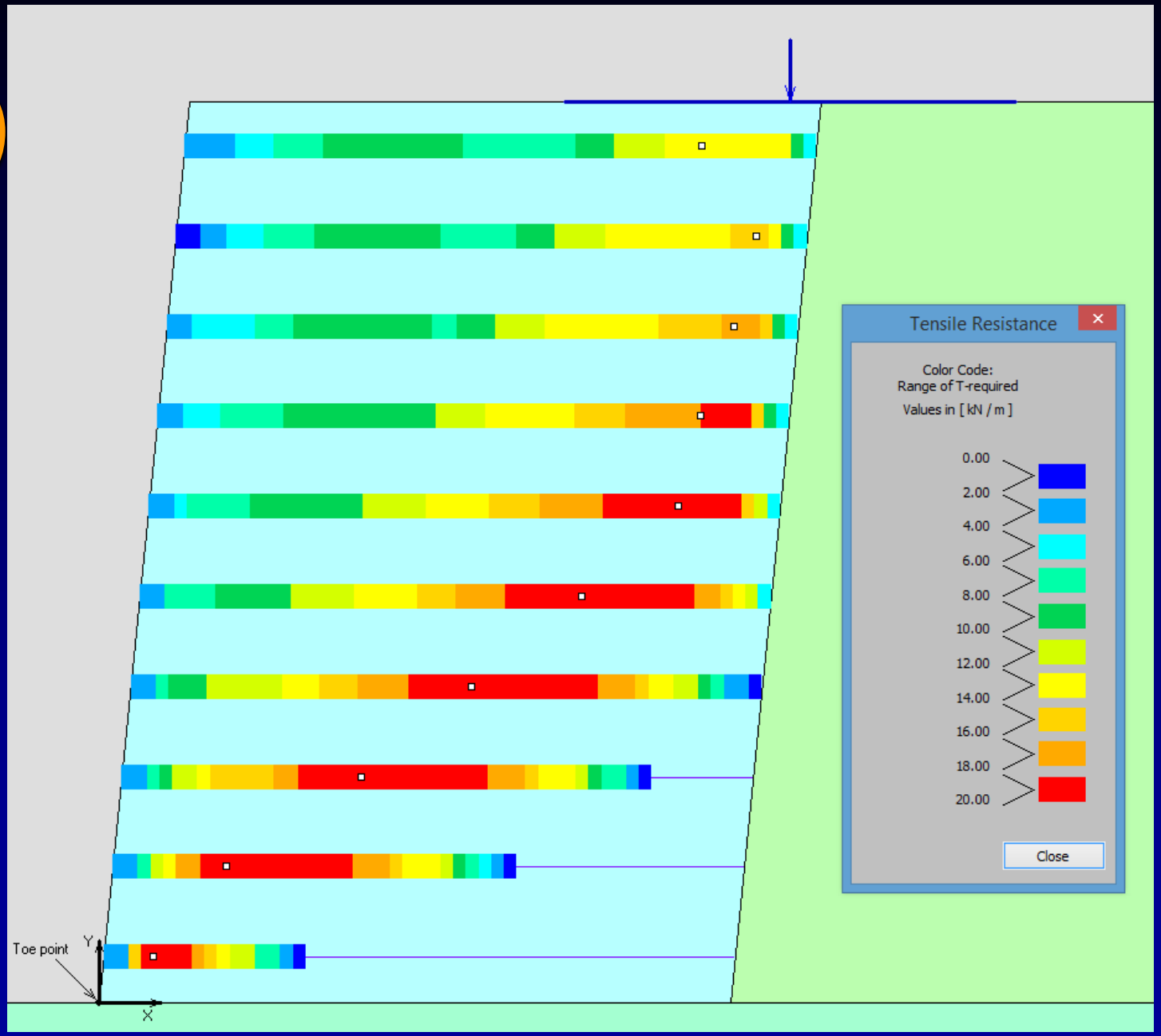


Strip Footing Surcharge: 100 kPa (B=3.0 m; C.L. 4.6 m from Toe)

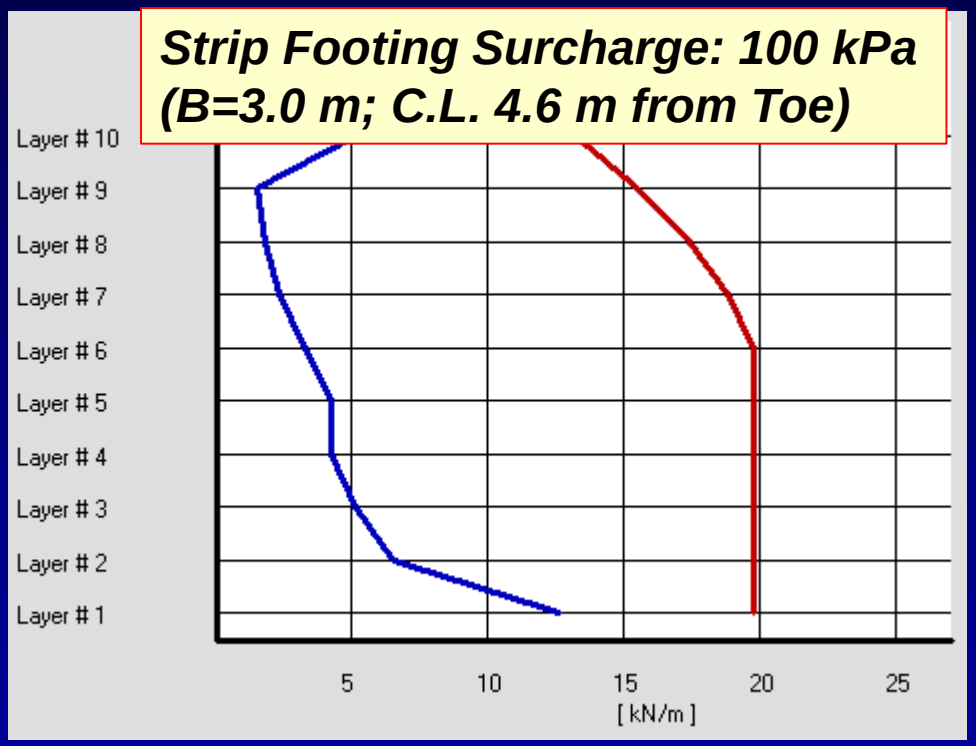


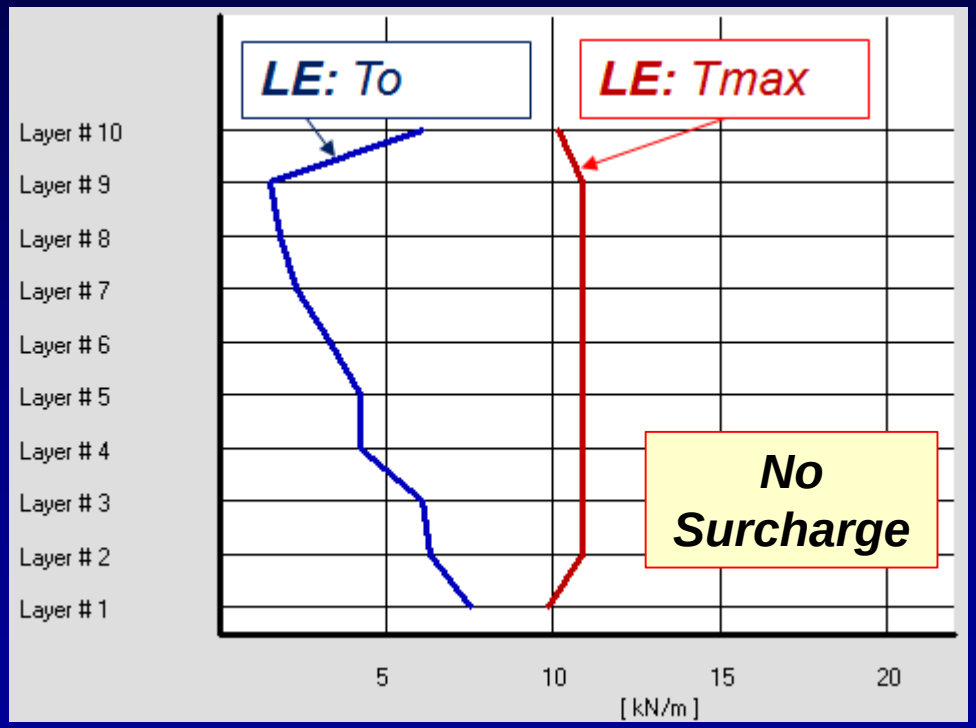
No Surcharge

Surcharge (dead load) and Tension Map



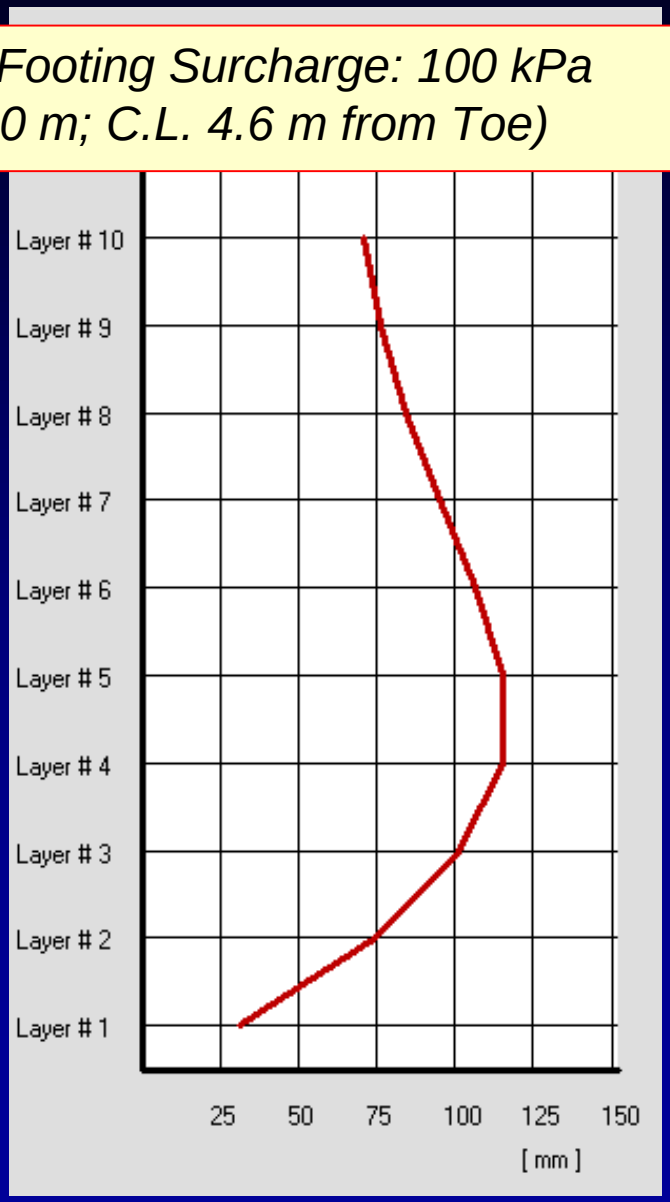
Effects of Surcharge (dead load): T_o and T_{max}



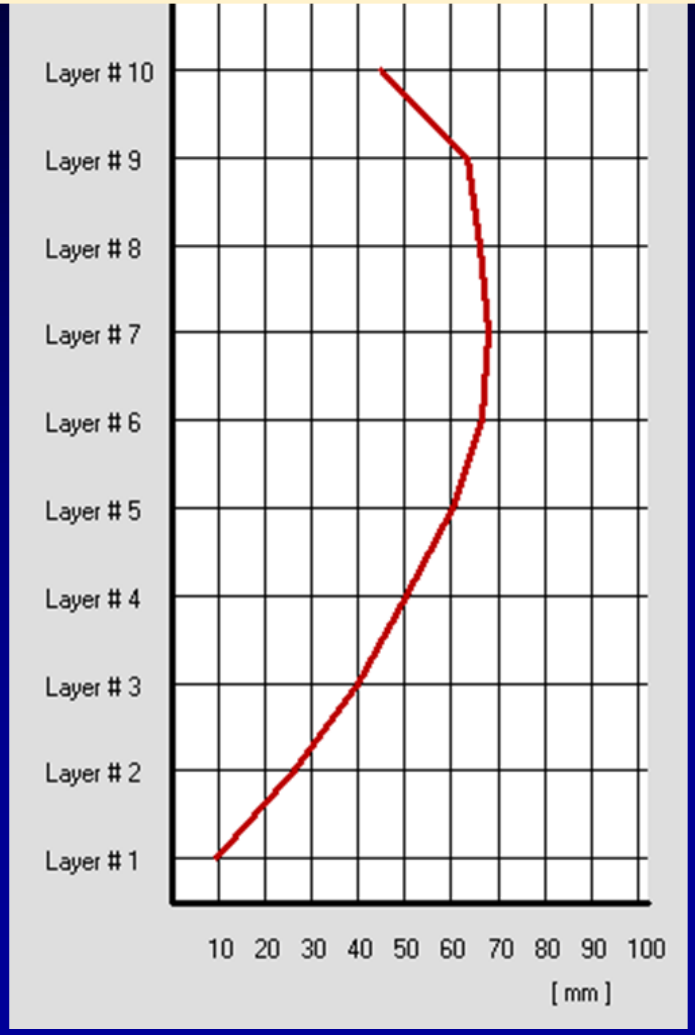


Surcharge (DL) and Displacements

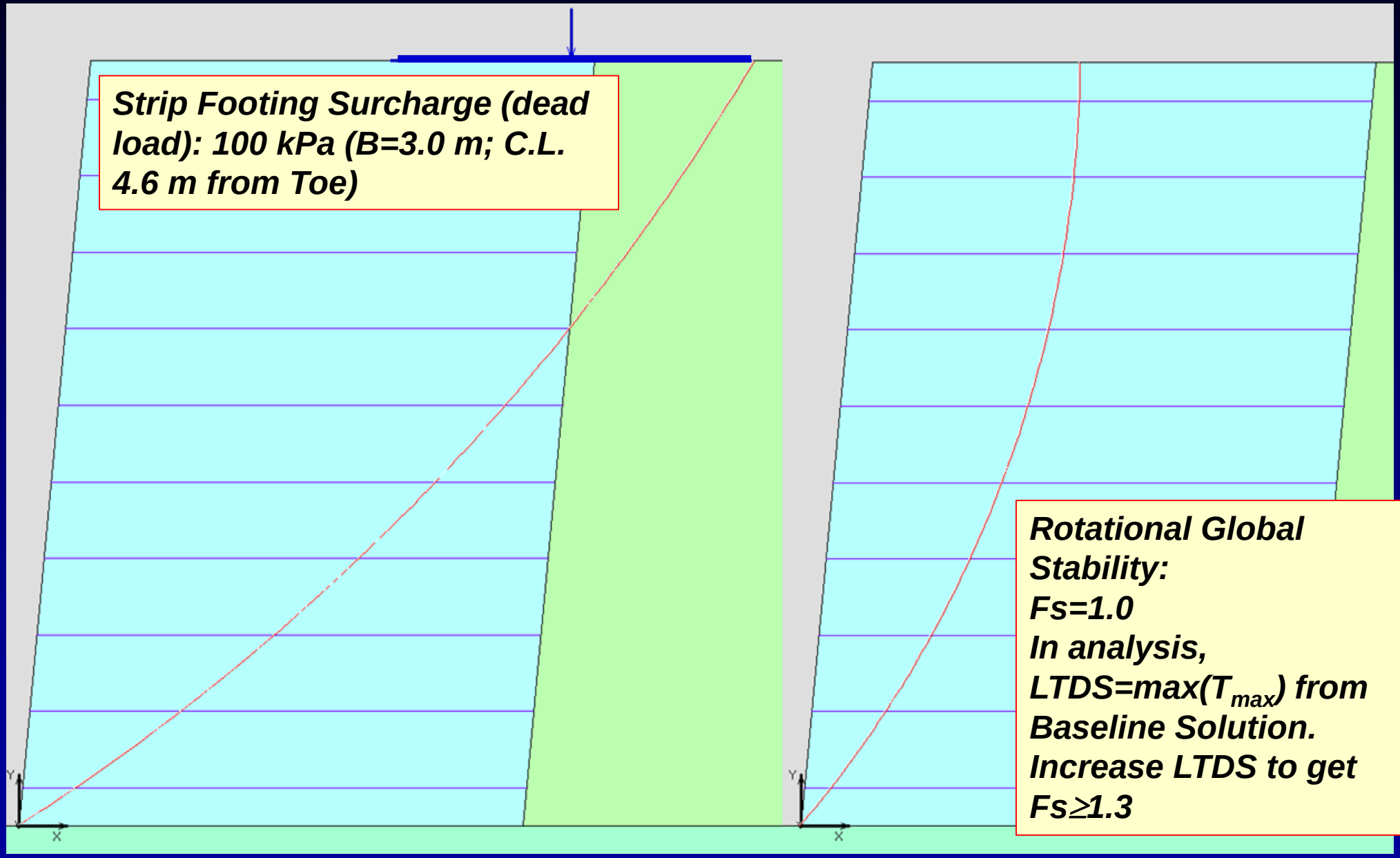
Strip Footing Surcharge: 100 kPa
(B=3.0 m; C.L. 4.6 m from Toe)



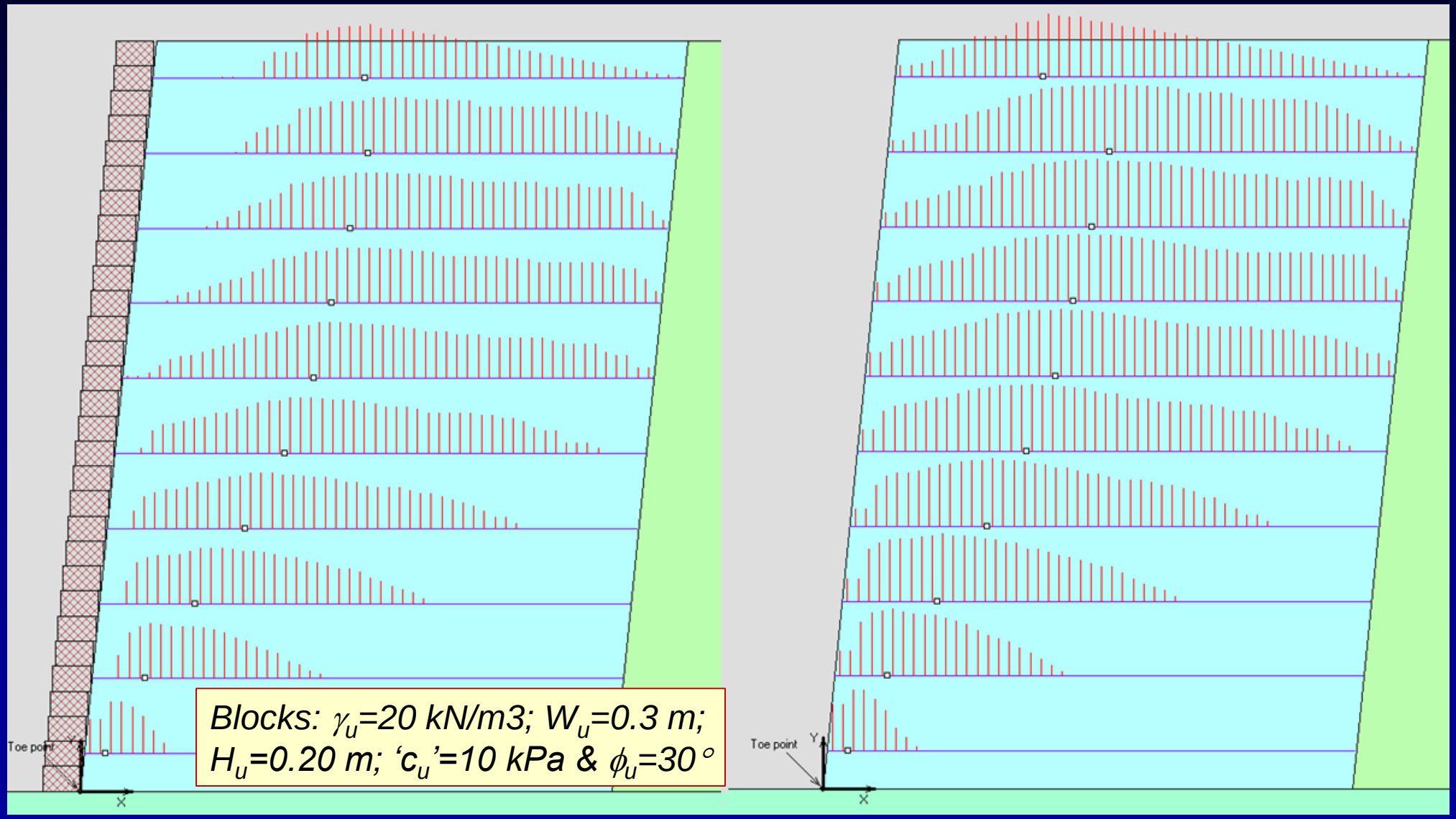
Δ profile for J=500 kN/m
(For Fs=1.0; i.e., soil strength is fully mobilized)



Rotational Global Stability



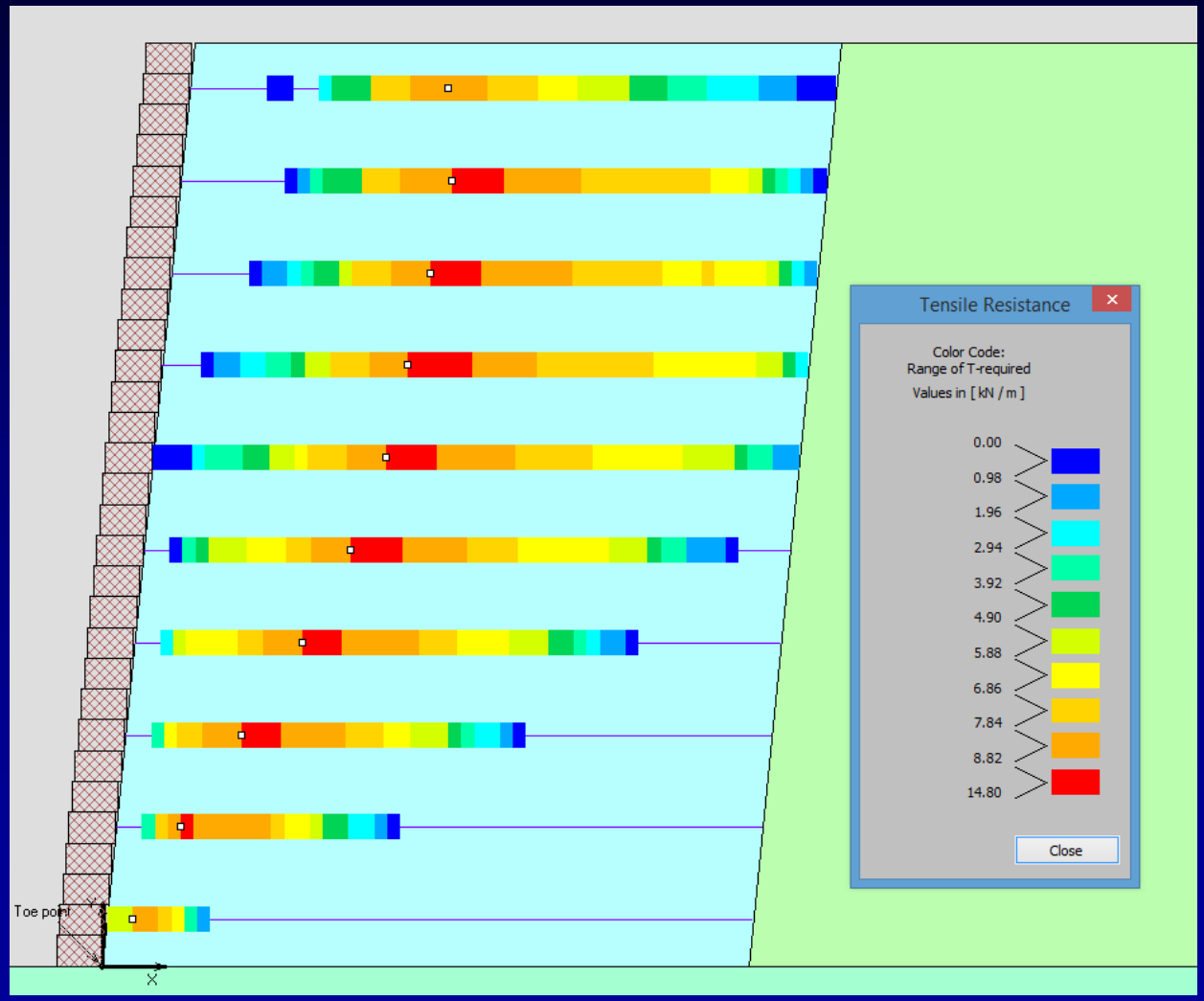
Effects of Small Blocks Facing



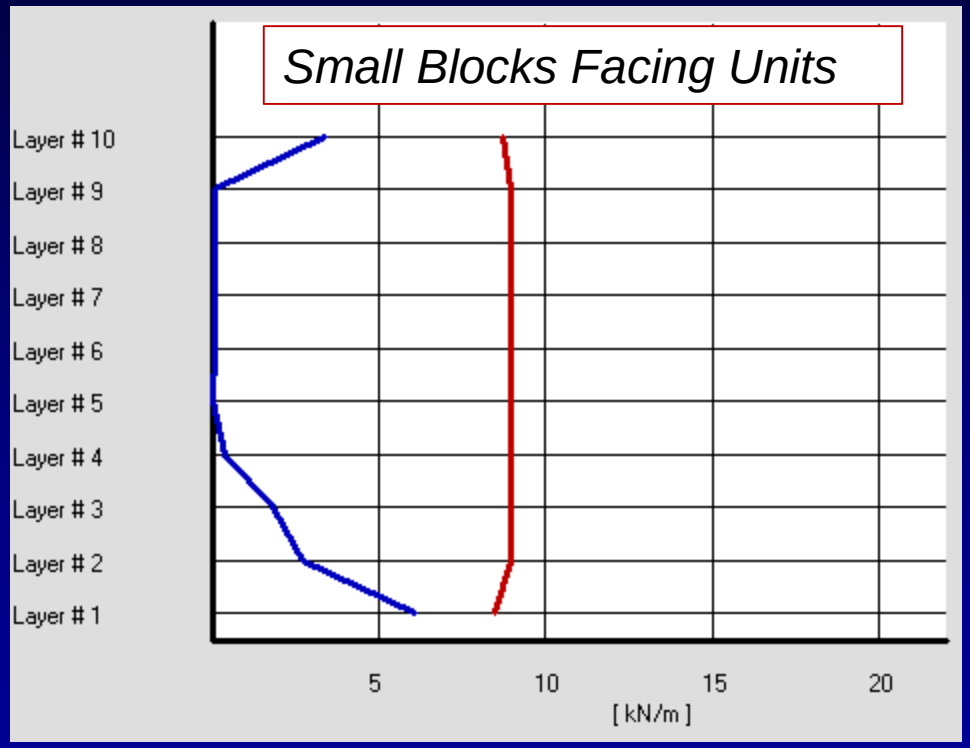
Blocks: γ_u=20 kN/m3; W_u=0.3 m; H_u=0.20 m; 'c_u'=10 kPa & ϕ_u=30°

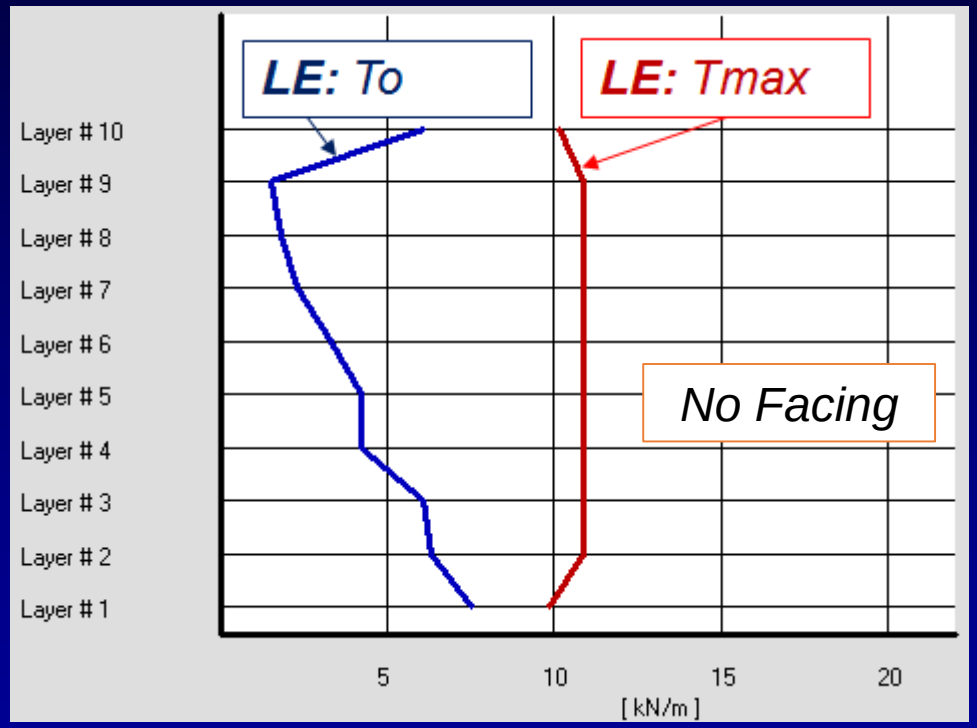
Facing Units and Tension Map

Can account for facing units. These components may decrease T_{max} and connection loading, T_o.



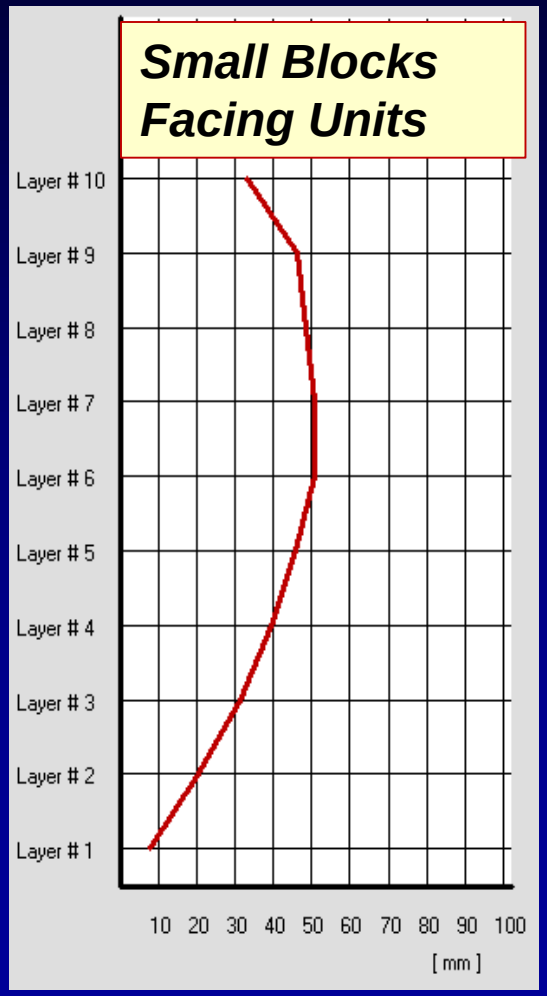
Effects of Small Blocks Facing: T_{max} and T_o

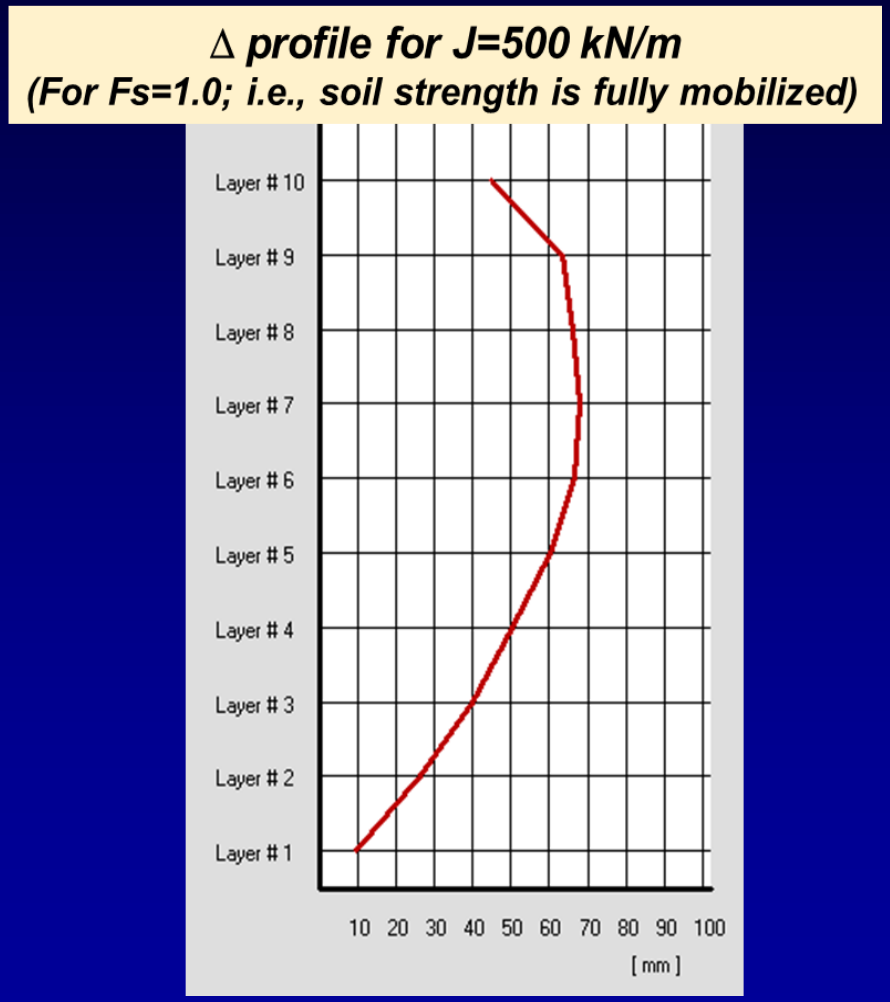




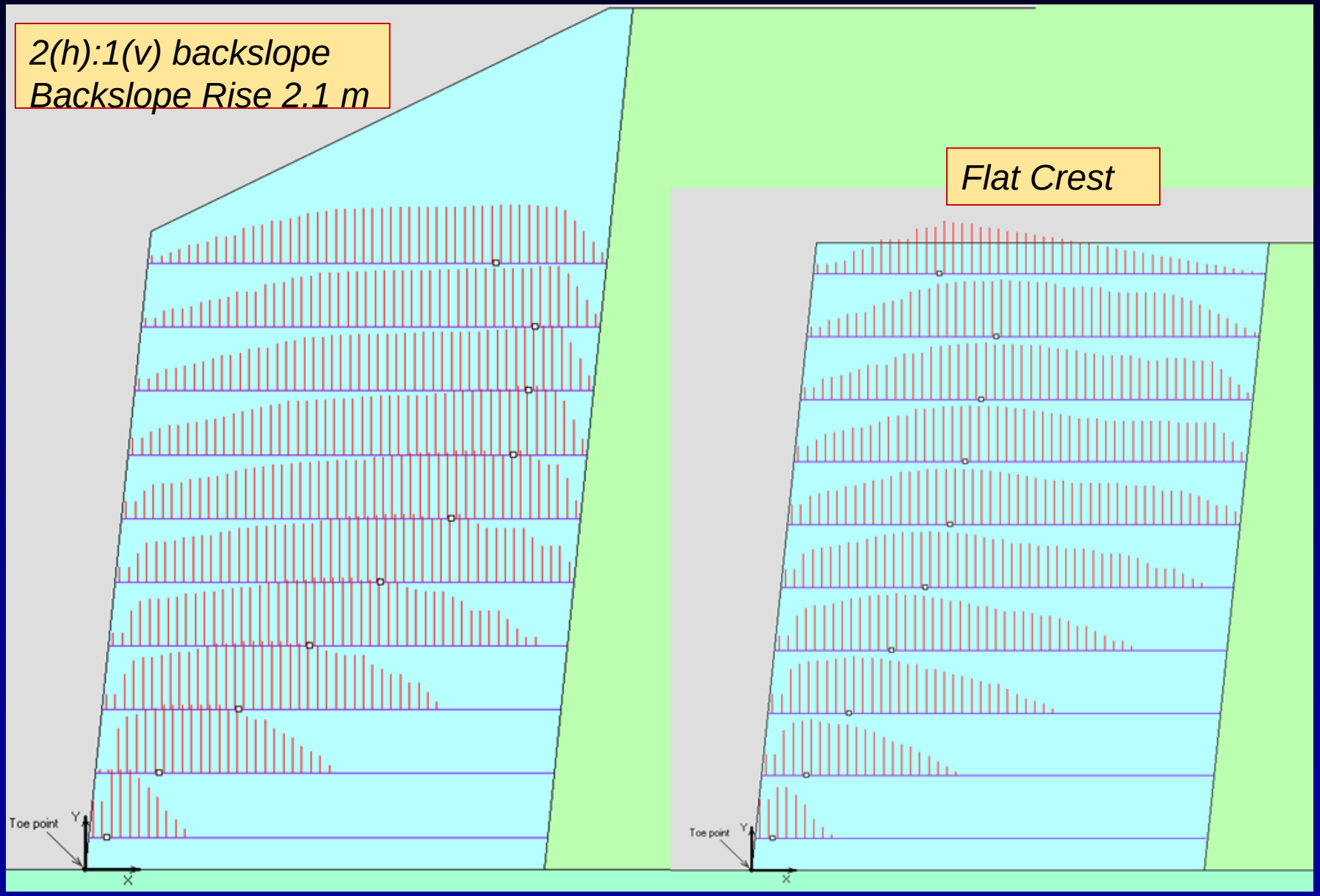
Although T(x) near the face is zero near top layer, T_o is required to enable T(x) at to mobilize without being pulled out. Layers below the top can mobilize T(x) because sufficient front-end pullout resistance is available even if T_o=0.

Impact of Small Blocks Facing on Displacements

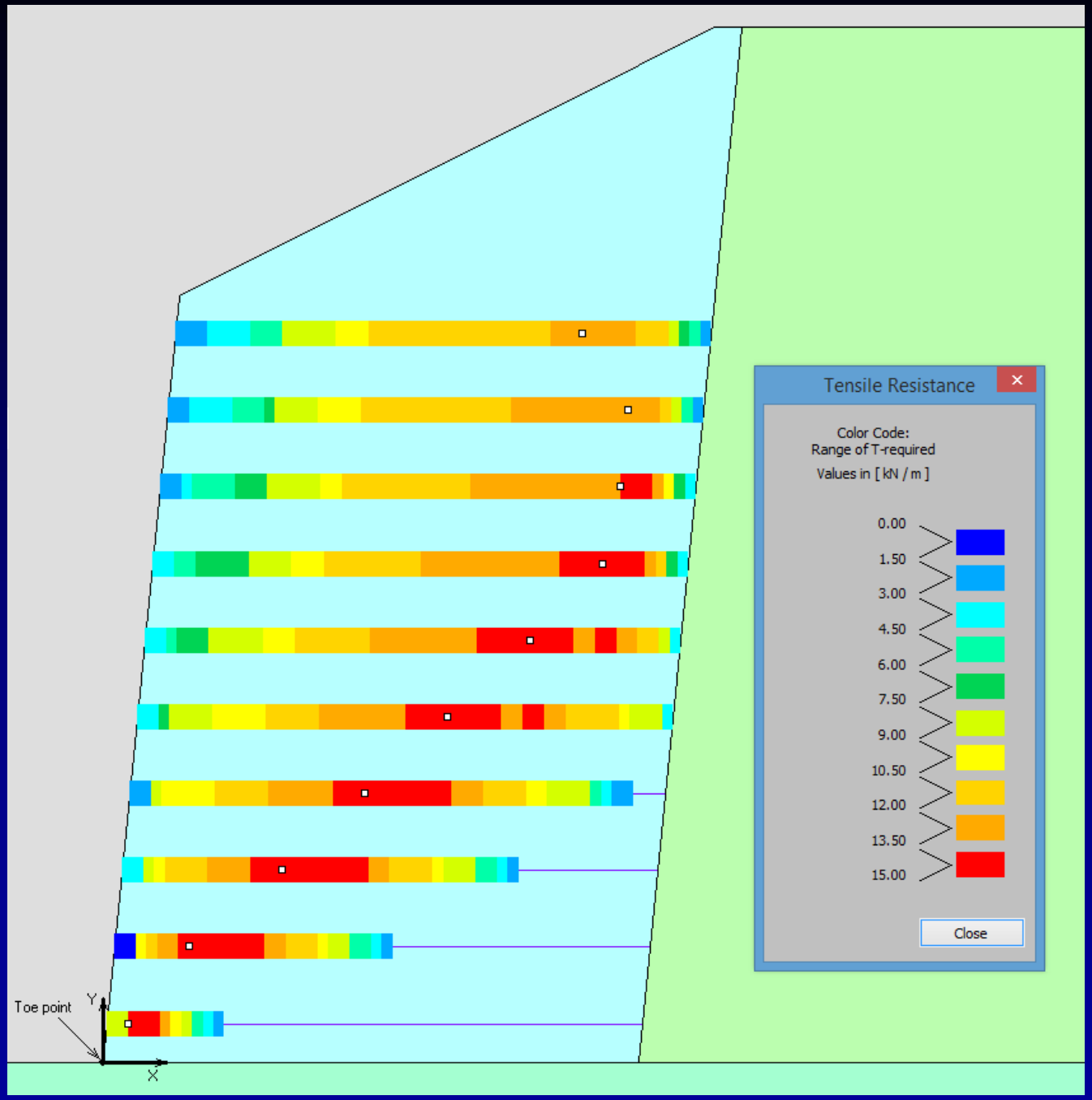




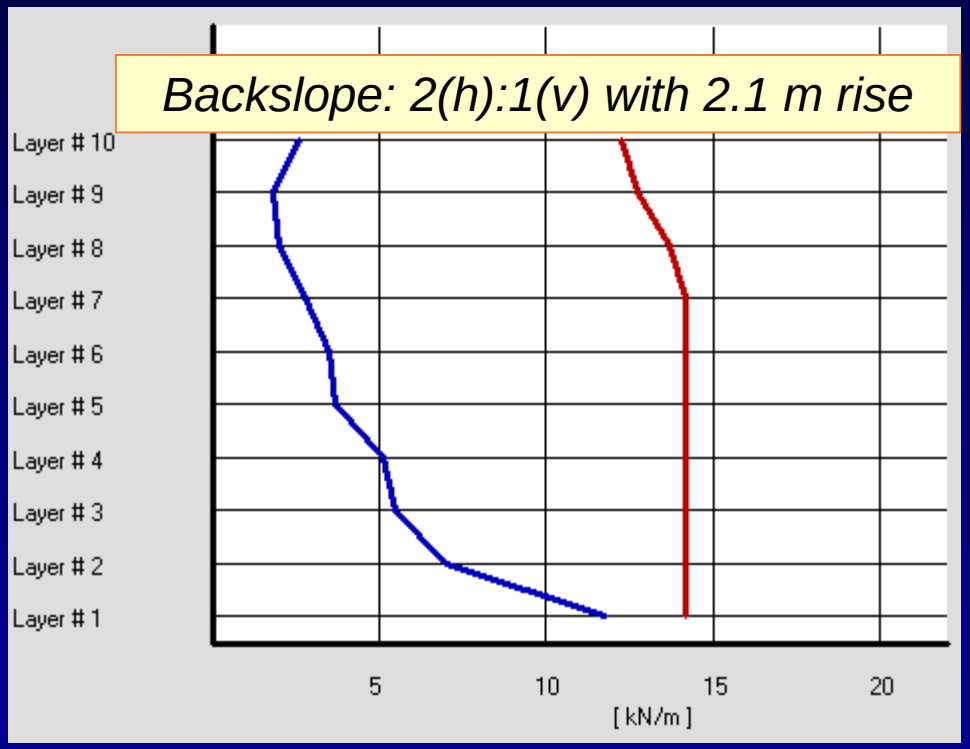
Effects of Backslope

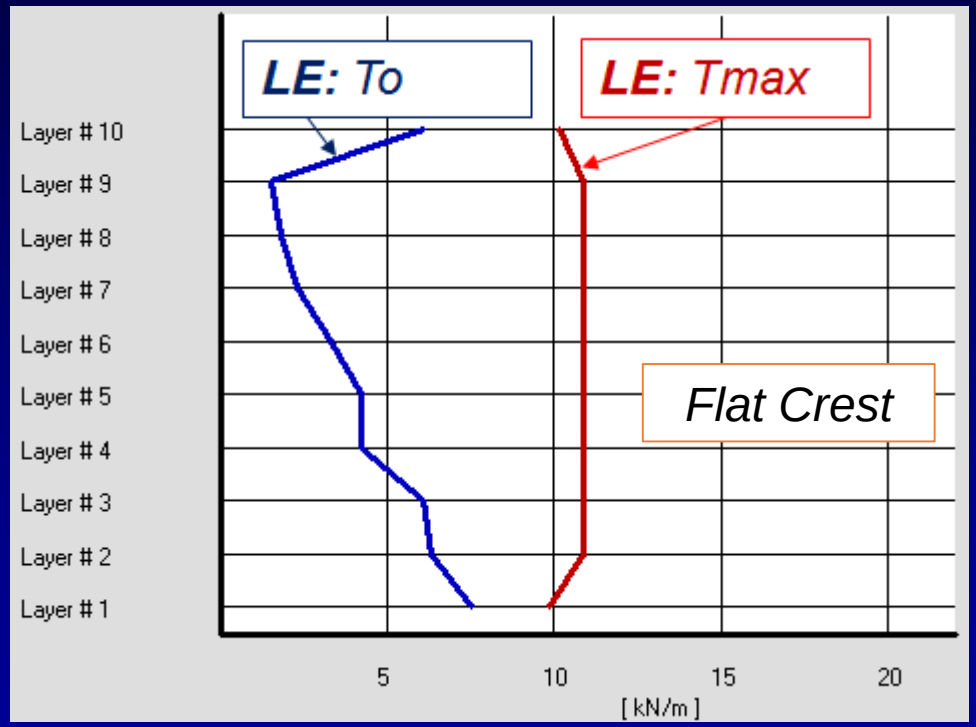


Backslope and Tension Map



Effects of Backslope: T_{max} and T_o

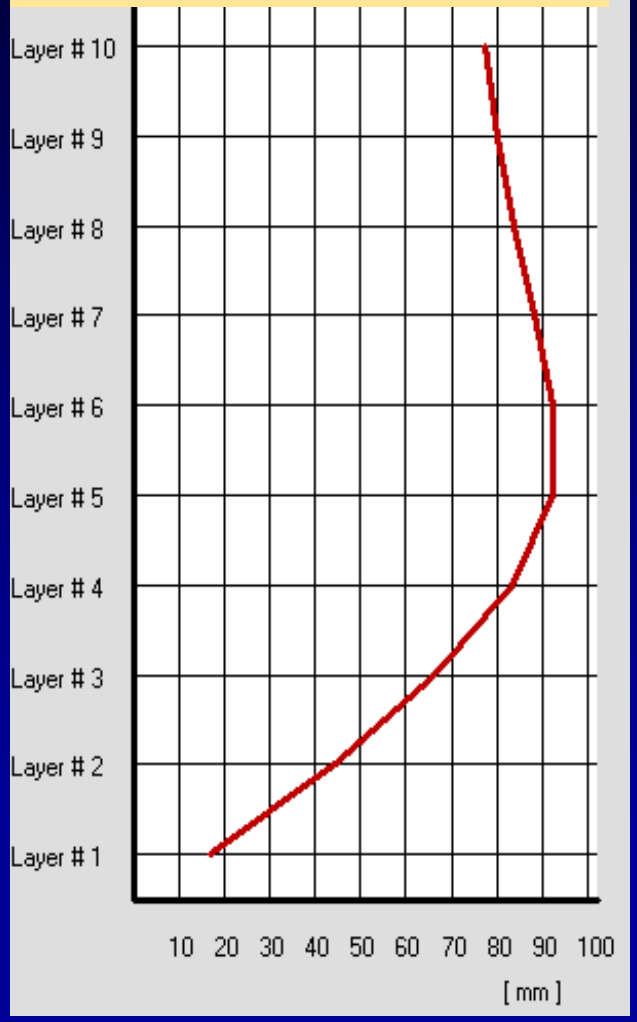




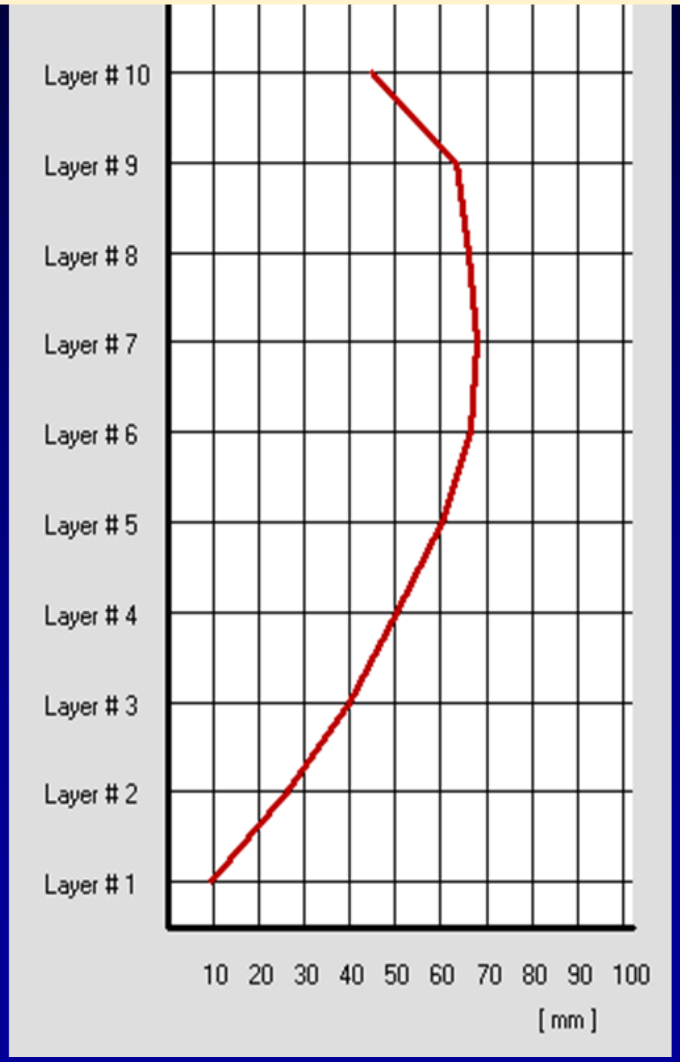
Note: T_o in upper layer is smaller for backslope than for flat slope ➔ Rate of increase in T(x) in front due to backslope is slower than front-end increase in pullout resistance

Effects of Backslope on Displacements

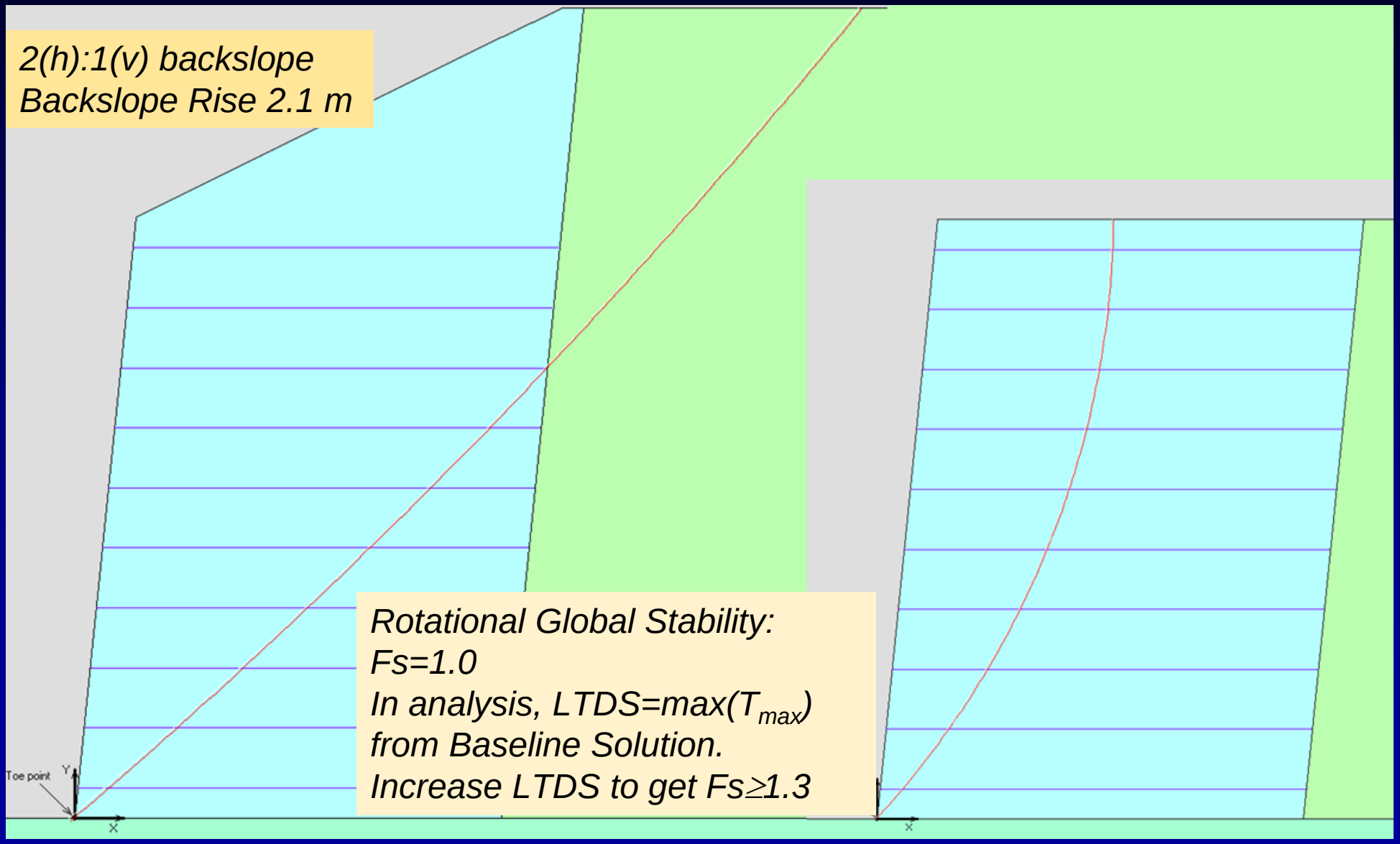
2(h):1(v) backslope
Backslope Rise 2.1 m



Δ profile for J=500 kN/m
(For Fs=1.0; i.e., soil strength is fully mobilized)

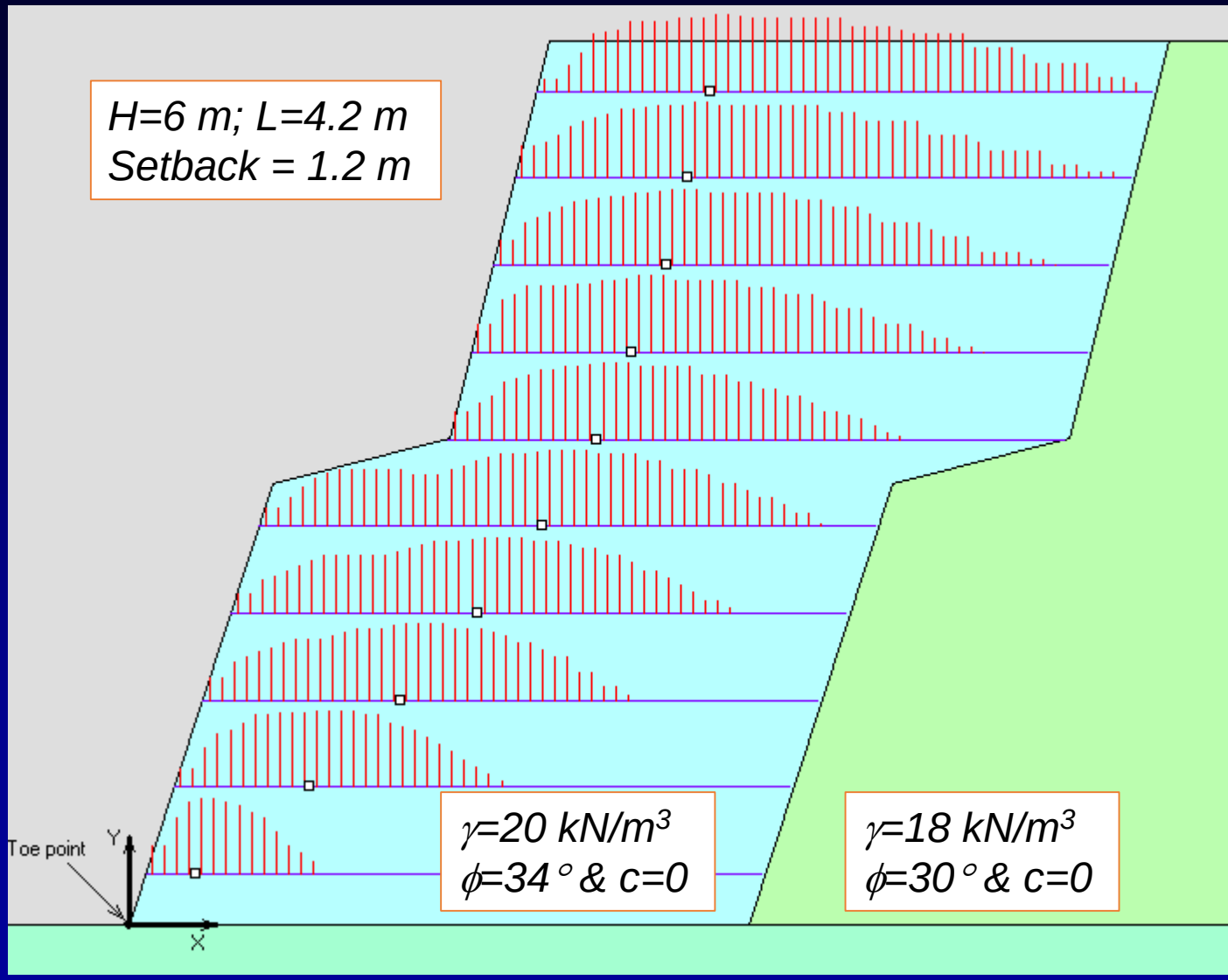


Global Rotational Stability

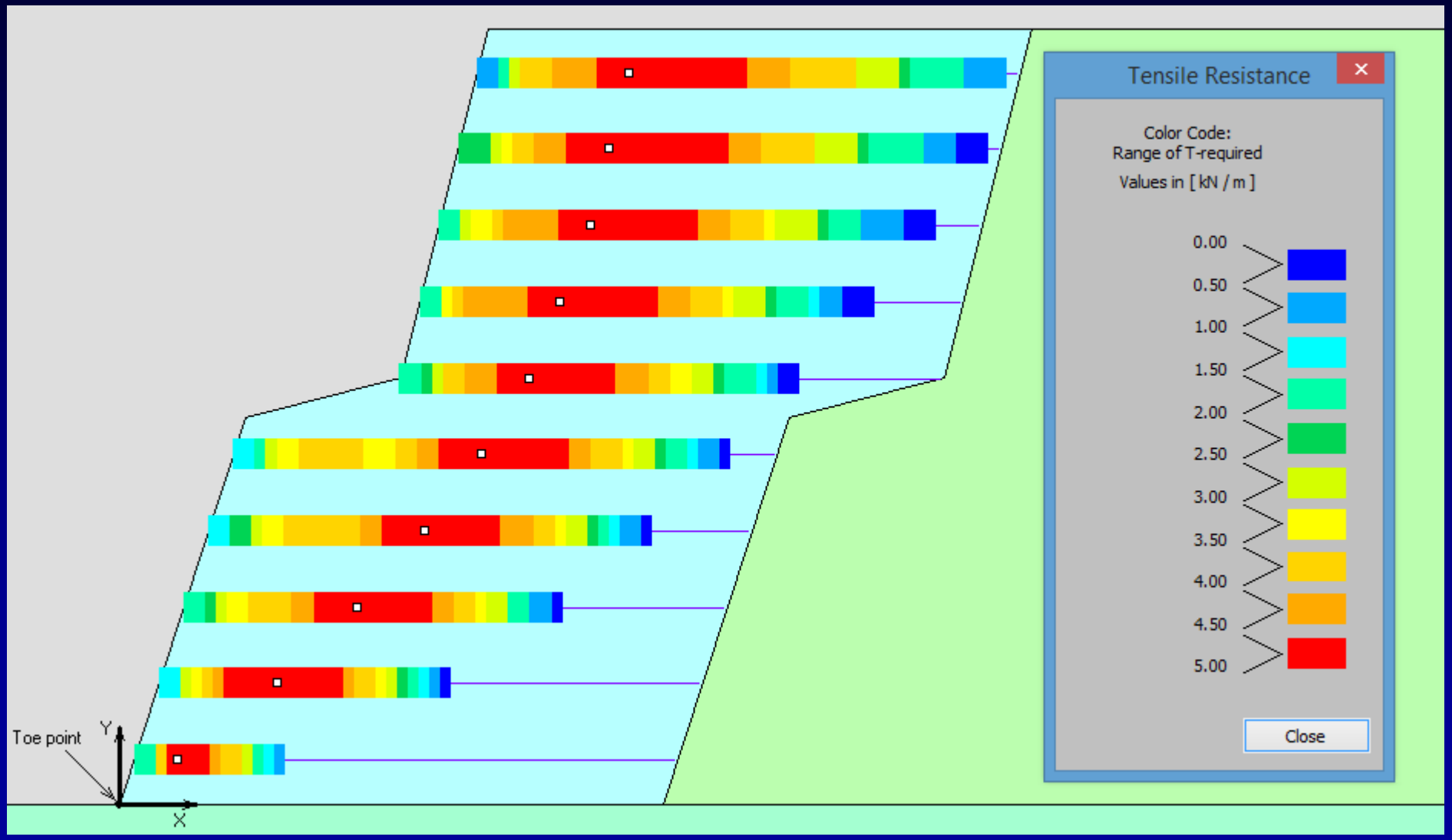


3(v):1(h) Two-Tier Wall

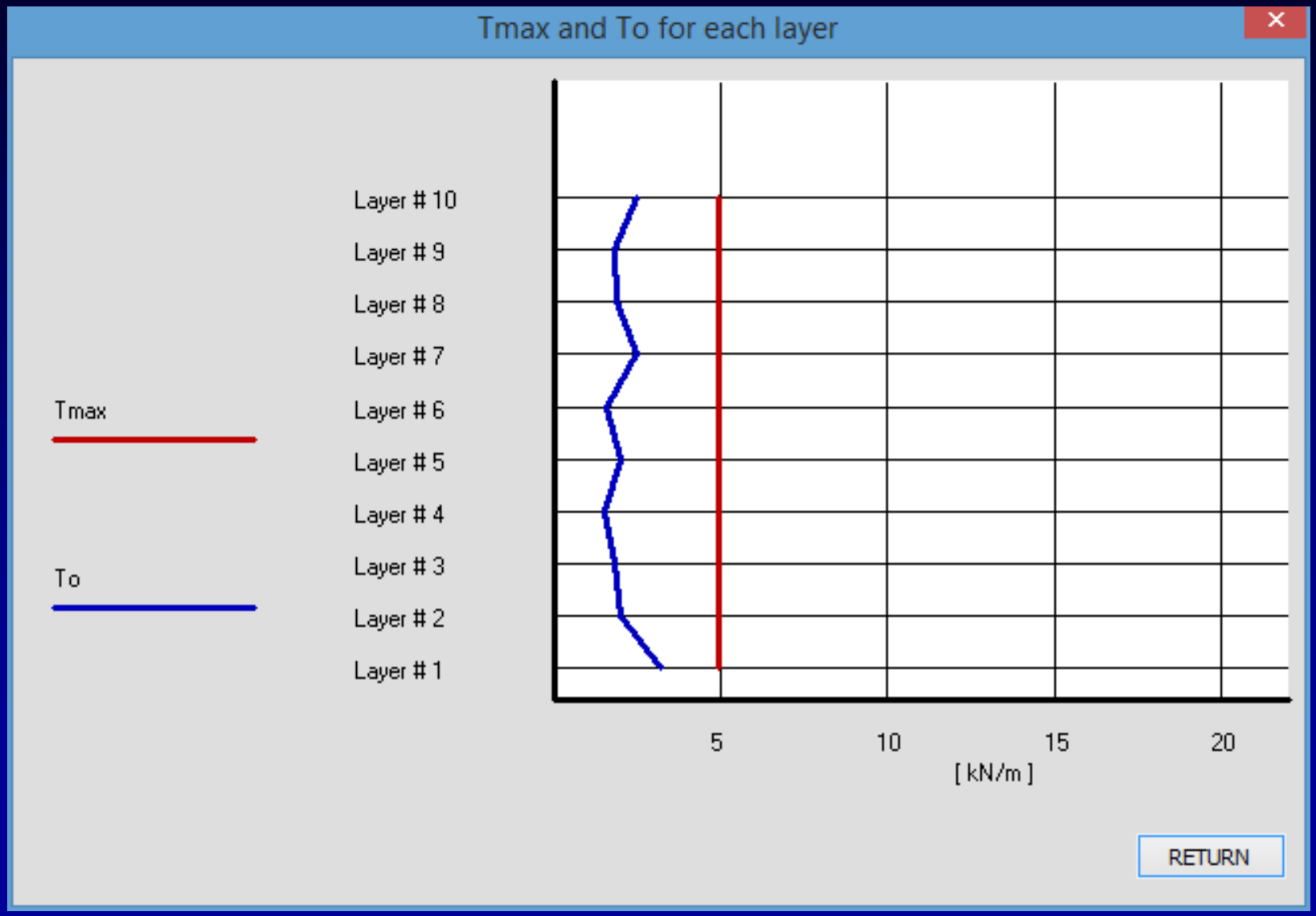
Actual reinforced structures can be complex in geometry and site conditions. This can be accounted for using the baseline solution.



Tension Map: 2-Tier Wall



T_{max} and T_o in 2-Tier Wall

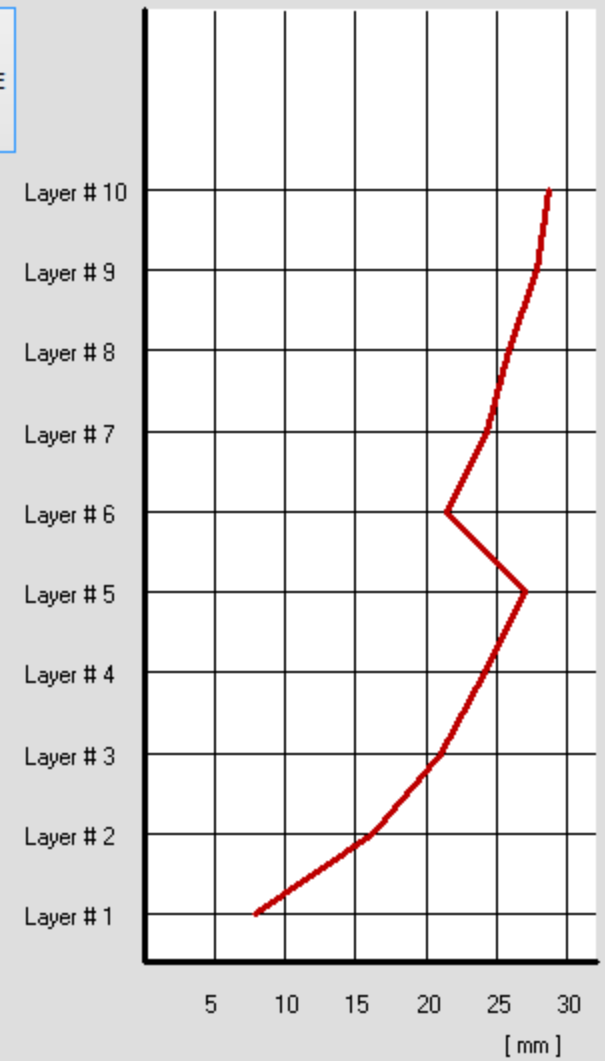


Displ. in 2-Tier Wall

Estimated Horizontal Displacement, d, at Face of Slope for Specified Fs

Layer No.	Height from Toe [m]	Current input of LTDS [kN/m]	Tensile Modulus of Geosynthetics, J [kN/m]	Horizontal Displacement at Face of Slope, d [mm]
1	0.35	4.96	500	7.84
2	0.95	4.96	500	16.16
3	1.55	4.96	500	21.03
4	2.15	4.96	500	24.20
5	2.75	4.96	500	26.96
6	3.35	4.96	500	21.40
7	3.95	4.96	500	24.25
8	4.55	4.96	500	25.80
9	5.15	4.96	500	27.76
10	5.75	4.96	500	28.61

CALCULATE



NOTES:

1. The approximated horizontal displacement at the face of the slope is appropriate for limit state; i.e., when your specified Fs=1.0 in top-down approach leading to full mobilization of the soil strength considering rotational slip surfaces.
2. The approximated horizontal displacement, d, is calculated following this expression:

$$d=\sum_{i=1}^{n}\left(\frac{T_i}{J}\right)\Delta X_i$$

Where: Ti is the force calculated at segment i and ΔX_i is the length of segment i. That is, $\Delta X_i = L/n$ where L is length of the considered reinforcement layer and n is the number of segments along a layer specified in your data (between 50 and 200). J is the tensile modulus of the reinforcement having unit of [Force/Length].

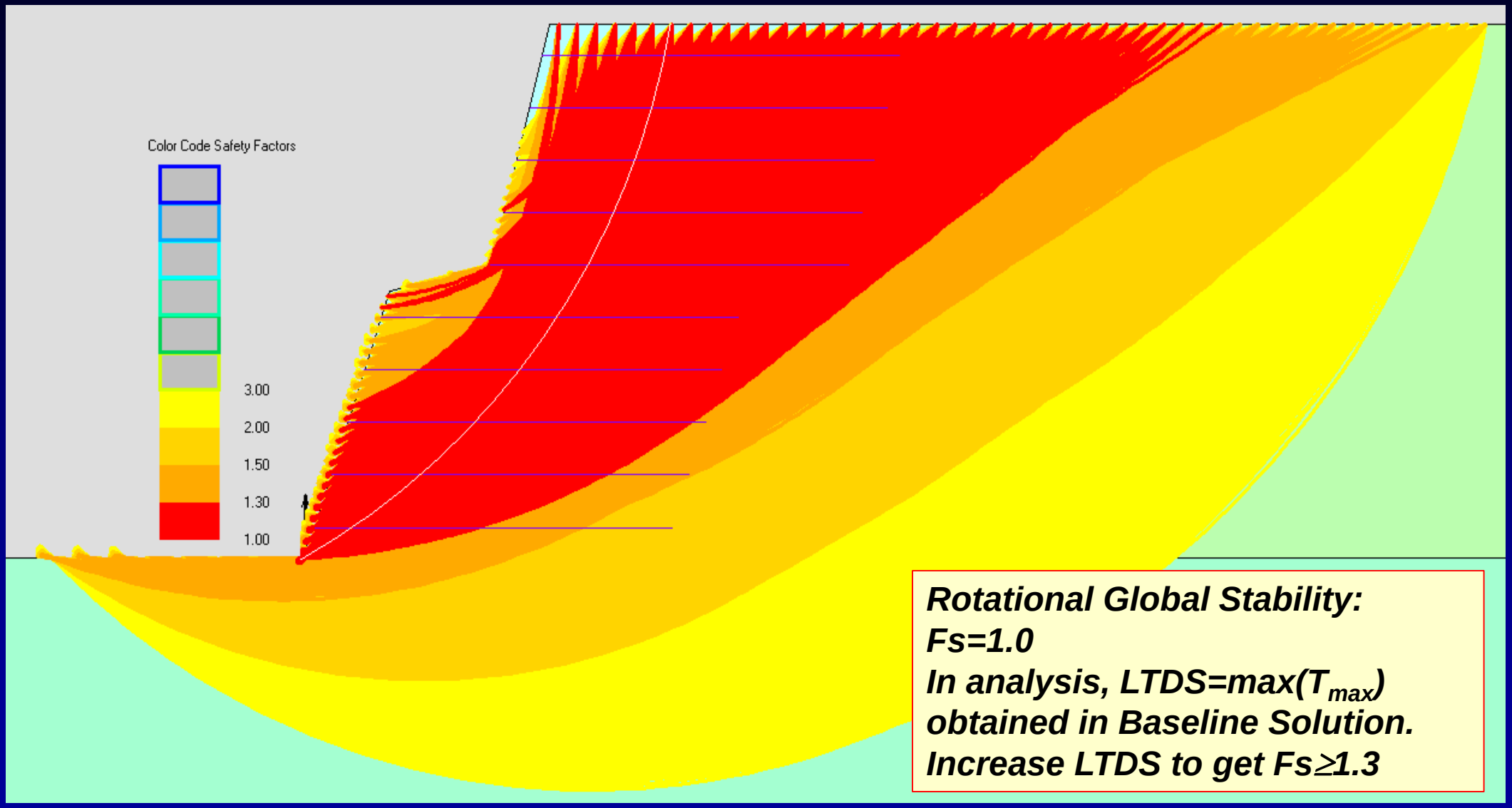
3. The displacement d is solely due to estimated cumulative elongation of the reinforcement. It does not reflect possible translational movement of the reinforced mass. To avoid translational movement, conduct 2-part wedge global stability analysis (in Global Stability mode) verifying that for the selected layout of reinforcement the global Fs is adequate, typically >1.3 .

DEFAULT

OK

Cancel

Safety Map in 2-Tier Wall



Rotational Global Stability:
Fs=1.0
In analysis, LTDS=max(T_{max}) obtained in Baseline Solution.
Increase LTDS to get Fs≥1.3

Roadmap of Presentation

- Why Limit State analysis is needed?
- Available Limit State Methods of Analysis
- Limit Equilibrium: Global Approach
- The Safety Map Tool
- Limit Equilibrium Analysis: Baseline Solution (aka Internal Stability)
- Limit Equilibrium: Design Approach
- Limit Equilibrium: Design Examples
- Concluding Remarks

Concluding Remarks

What about LRFD?

- AASHTO does not factor ϕ in its synergistic approach combining results from internal and external stability

- However, AASHTO requires LE global stability, applying only 'resistance factor' = (1/Fs) ➔ This is an ad hoc remedy ➔ Hence, LRFD in global stability, Fs>1.3, is considered in Stage 2

- In the Baseline Solution, Stage 1, Fs=1.0 is used to determine LTDS, consistent with the internal stability principles ➔ LRFD can be used as in AASHTO

Concluding Remarks

Last Minute News:

- AASHTO has voted to approve the LE approach as presented in FHWA-HIF-17-004 (2016), which is the basis for ReSSA
- It is scheduled to be implemented in AASHTO 2020, presented as an **alternative design approach for Internal Stability**
- The global aspects of LE (Stage 2) has been in use since AASHTO 1998
- AASHTO 2020 suggests some explicit multipliers which should make the internal stability (Stage 1) in ReSSA+ compatible with LRFD

Thank You!