Recent AASHTO Specification Updates and their Impact on MSE Wall Design

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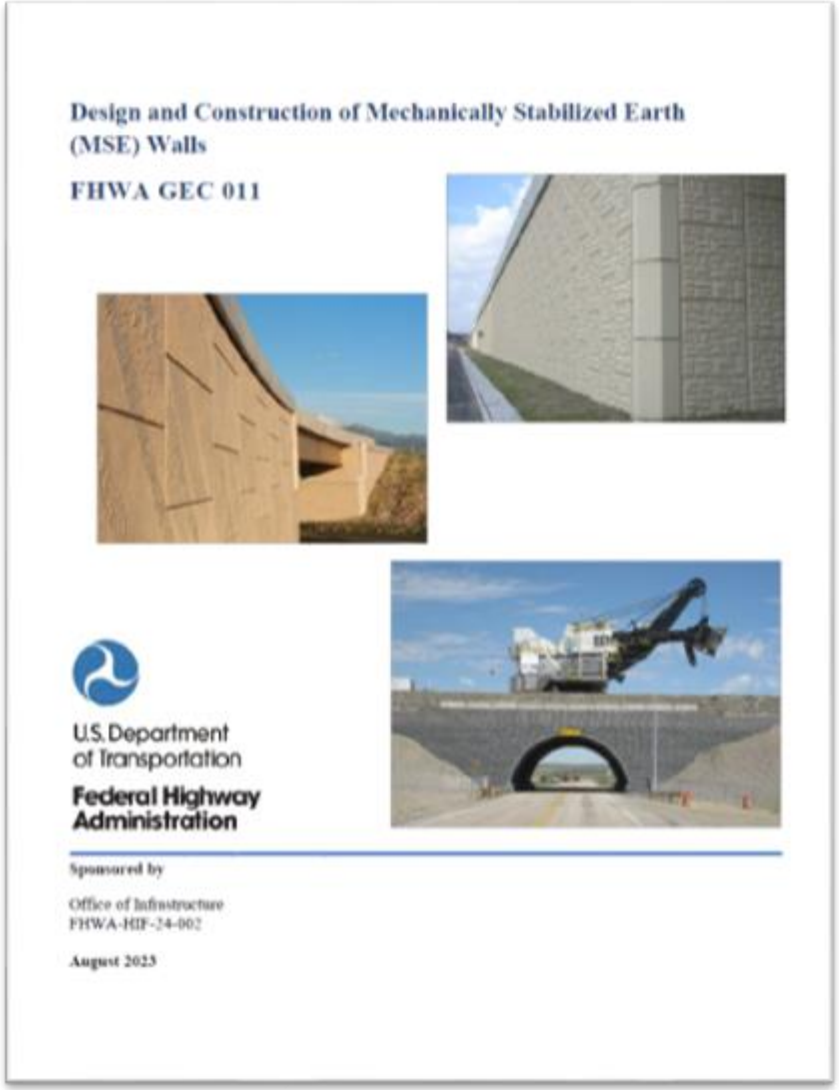
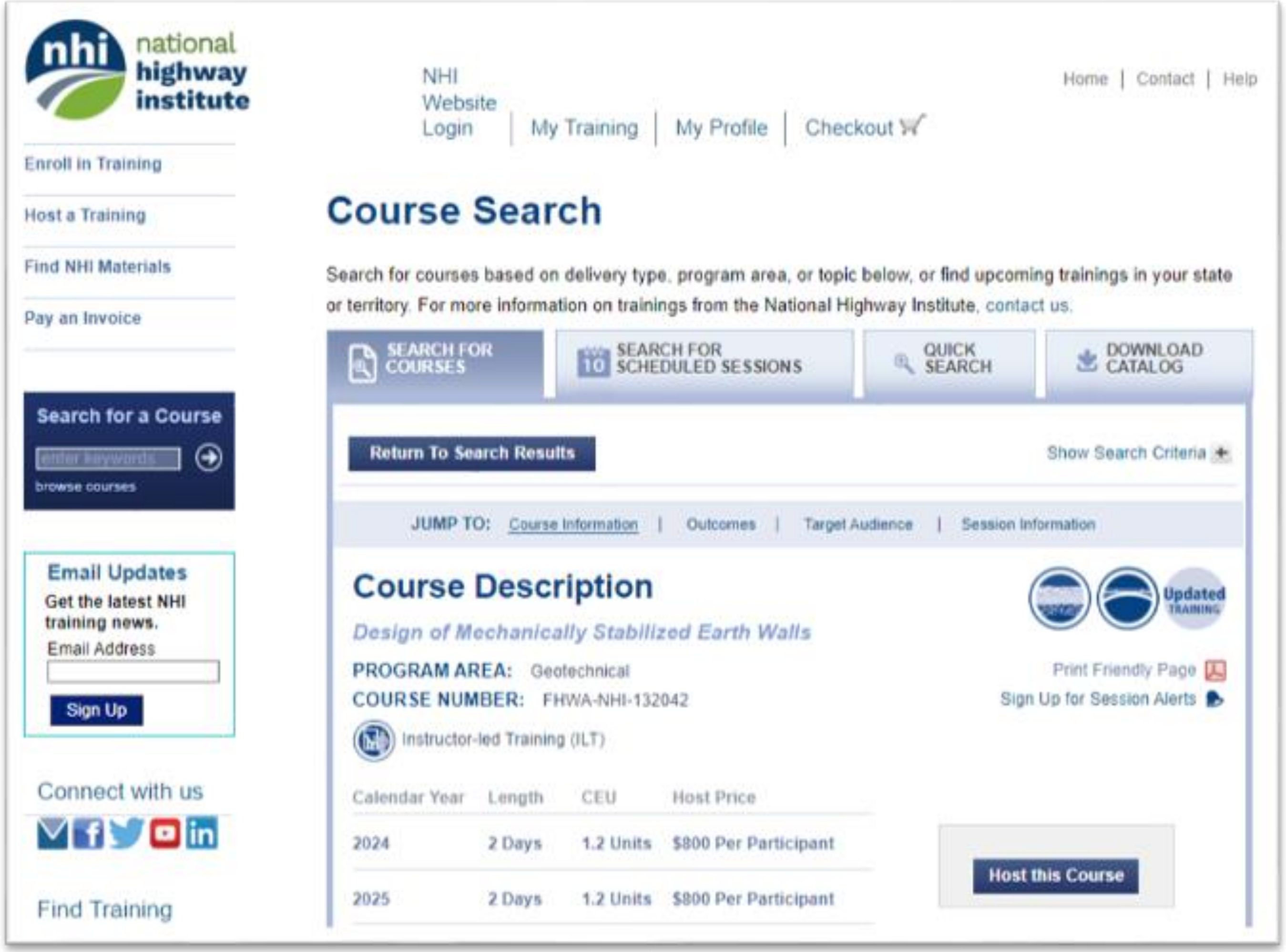
the collingroup

MSE wall Design - Update





Source: FHWA

MSE Wall Design - Update

Source: NHI 132042

Primary changes:

- Removed Reinforced Soil Slopes
    - New Web-training in development for RSS
- Added new internal design methods based on AASHTO LRFD Bridge Design Specifications, 9th Edition, 2020
    - Coherent Gravity Method (CGM)
    - Simplified Method (SM)
    - Stiffness Method (SSM)
    - Limit Equilibrium Method (LEM)
- Updated Resistance factors for SSM
- New design examples for design methods

MSE Wall Design - Update

Applicability of Internal Stability Methods:

Coherent Gravity Method:

- For inextensible reinforcements

Simplified Method:

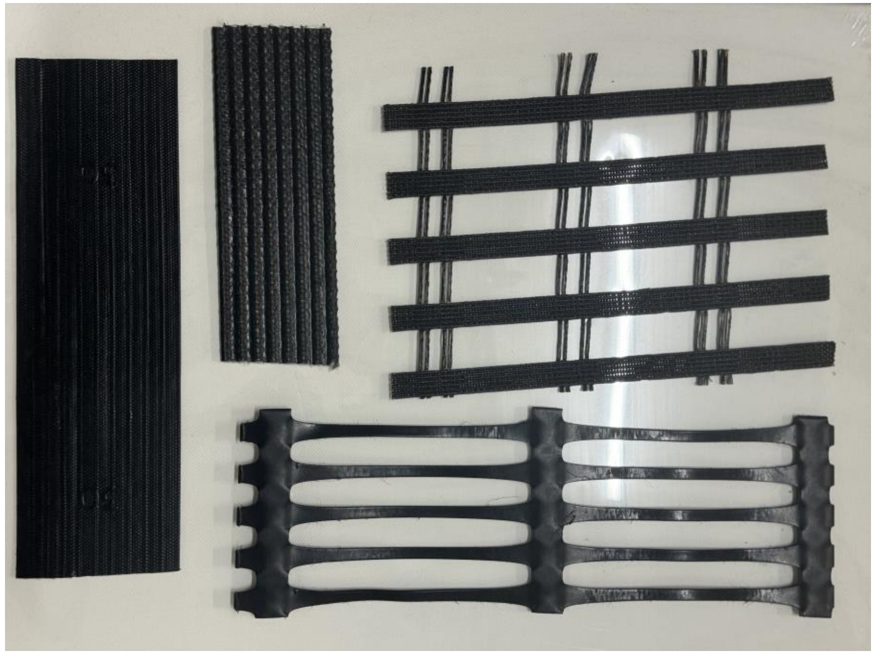
- For Inextensible and Inextensible reinforcements

Stiffness Method:

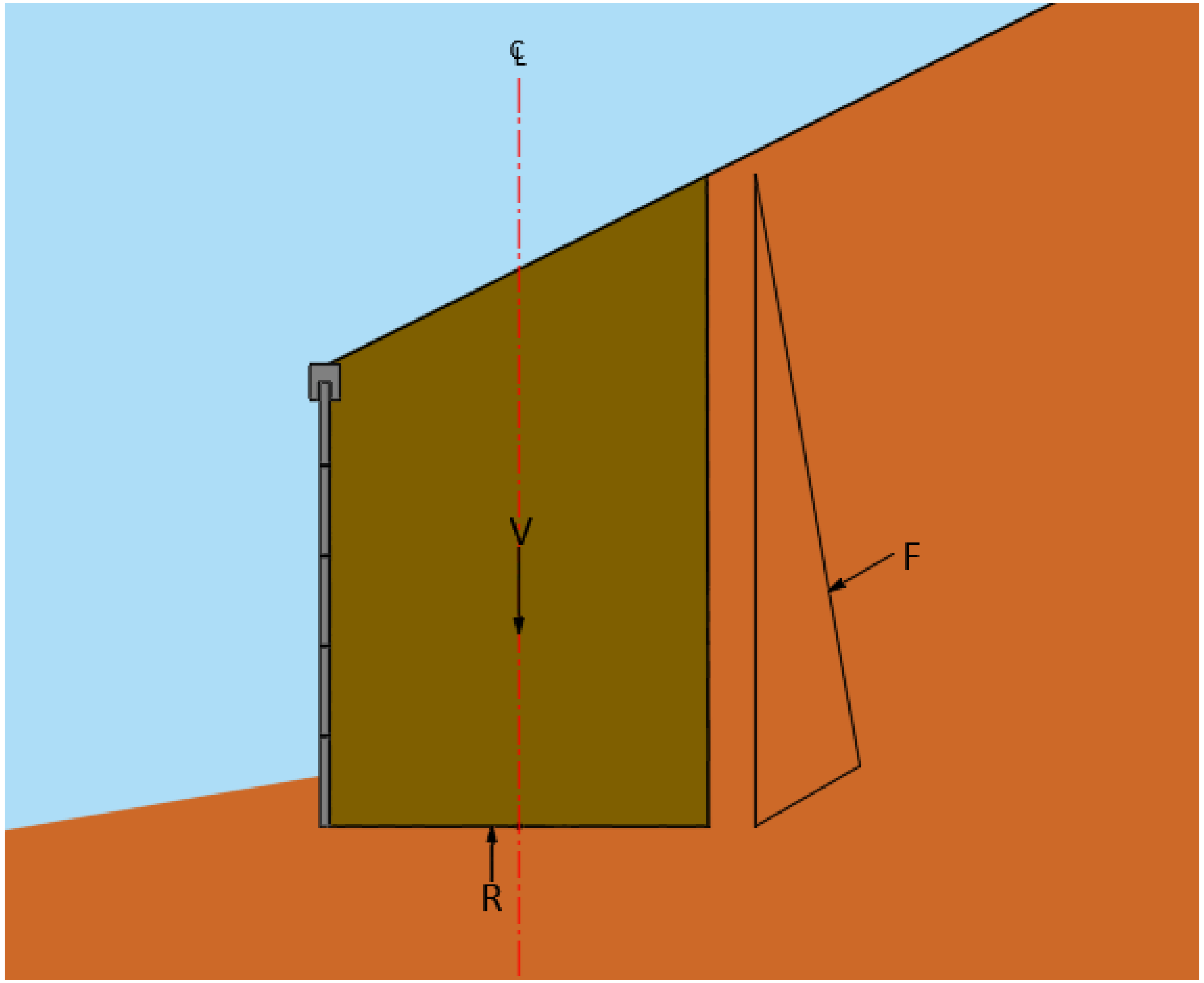
- For extensible reinforcements
- Not applicable for complex geometry and/or loading conditions such as bridge abutments

Limit Equilibrium Method:

- For extensible reinforcements



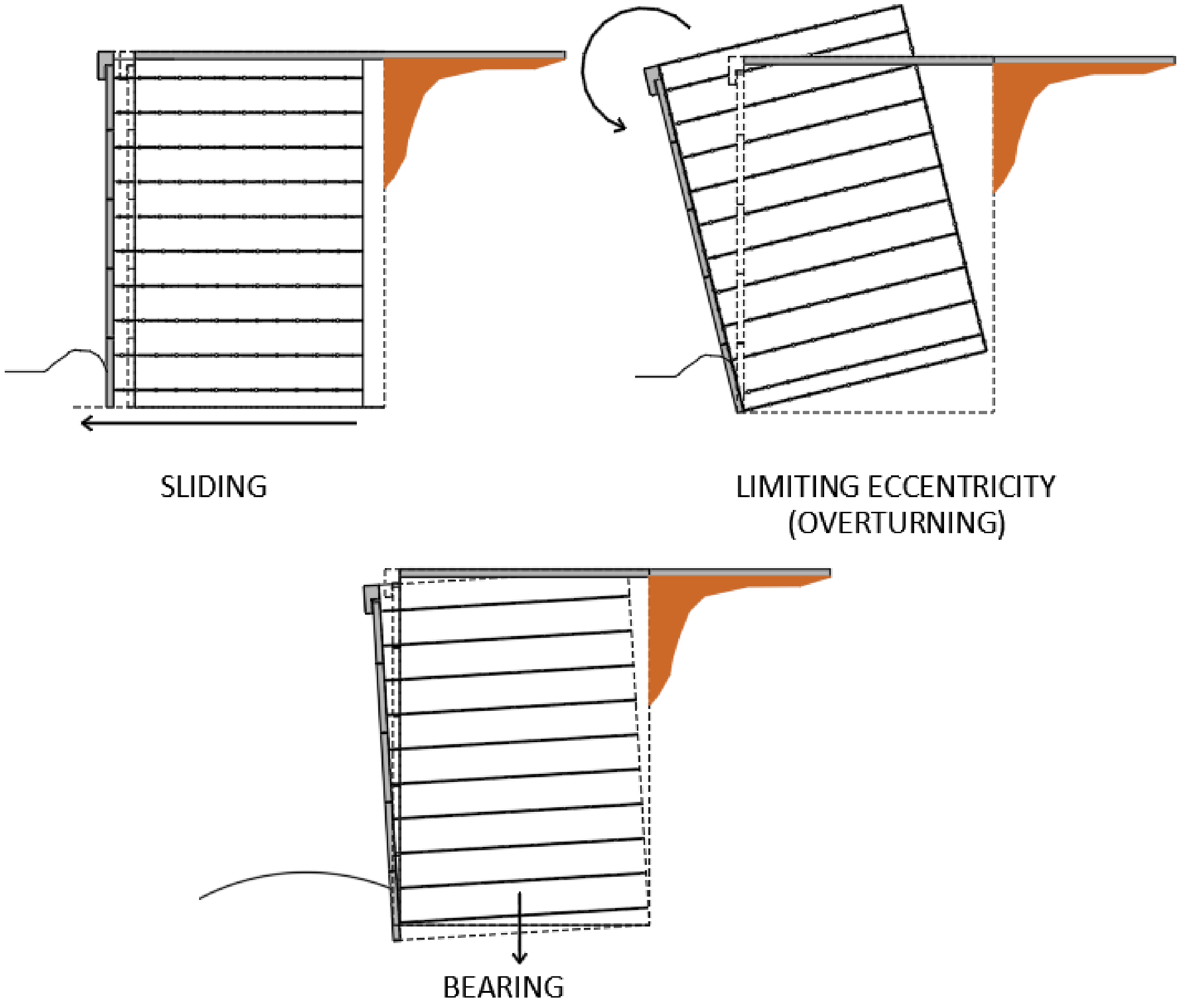
Design of MSE walls – External Stability



Source: The Collin Group

- Designed as a gravity structure
- Assume to behave as a coherent mass
- Resists lateral earth pressure from the retained soil
- Strength Limit State
- Service Limit State
- Use max/min load factors to determine the most critical load effect.

Design of MSE walls – External Stability



Source: The Collin Group

Checks for external stability

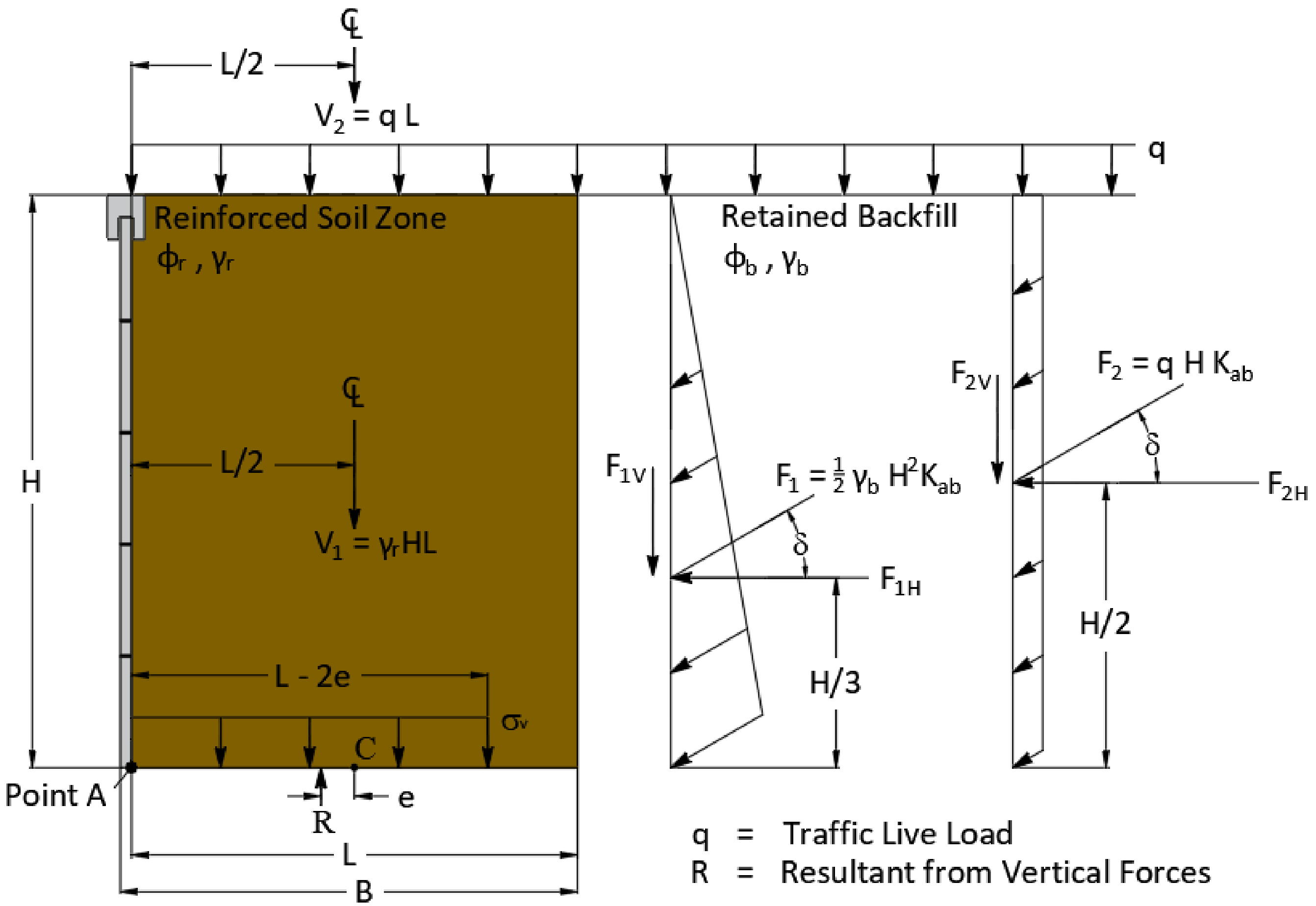
Strength limit state

- Sliding
- Eccentricity
- Bearing Capacity

Service Limit state

- Settlement

Design of MSE Walls – External Stability



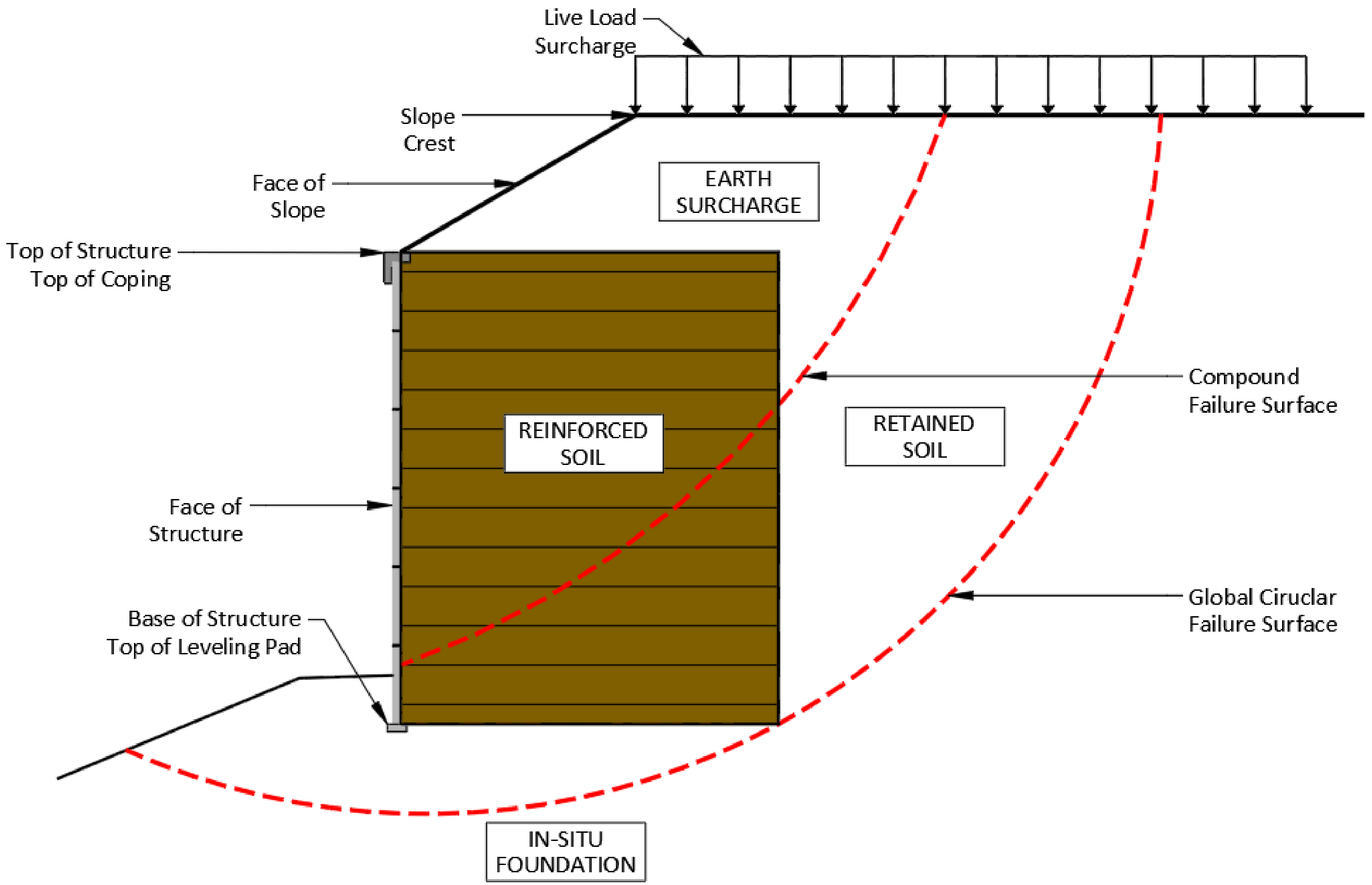
Note: Horizontal forces act at the interface of the reinforced soil and retained soil. The horizontal force diagrams have been moved away from the back of the reinforced zone for clarity.

Source: The Collin Group

External stability

- Meyerhof approach
- Applies to all gravity retaining walls
- Use **Coulomb** earth pressure for all wall configurations

Design of MSE Walls – External Stability



Source: The Collin Group

Compound stability

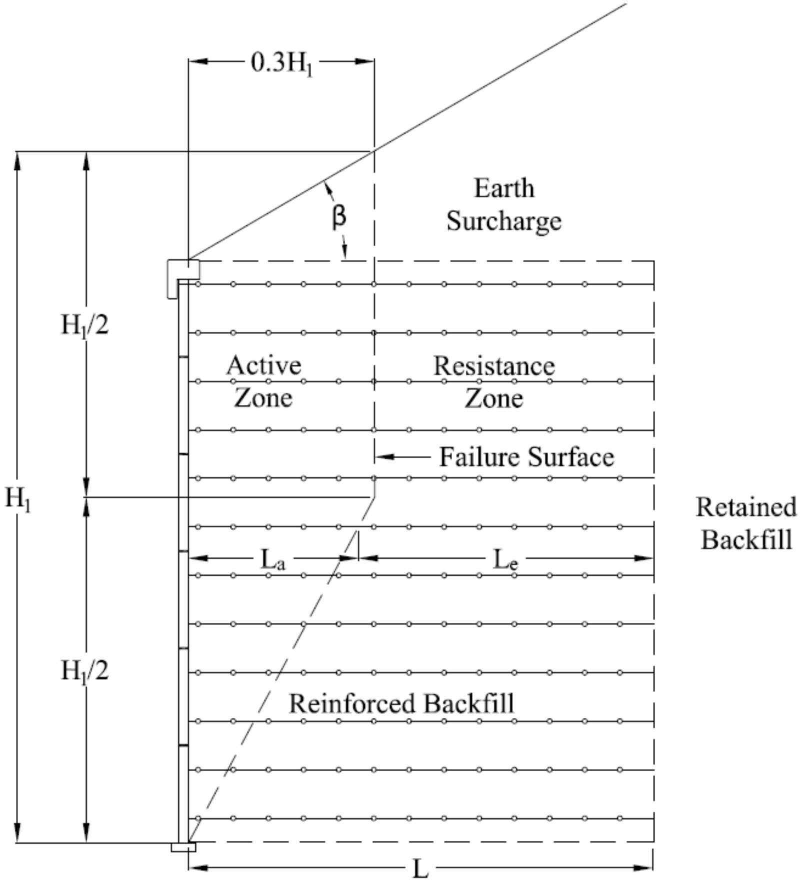
- Considers failure planes that pass through the reinforced fill

Global stability

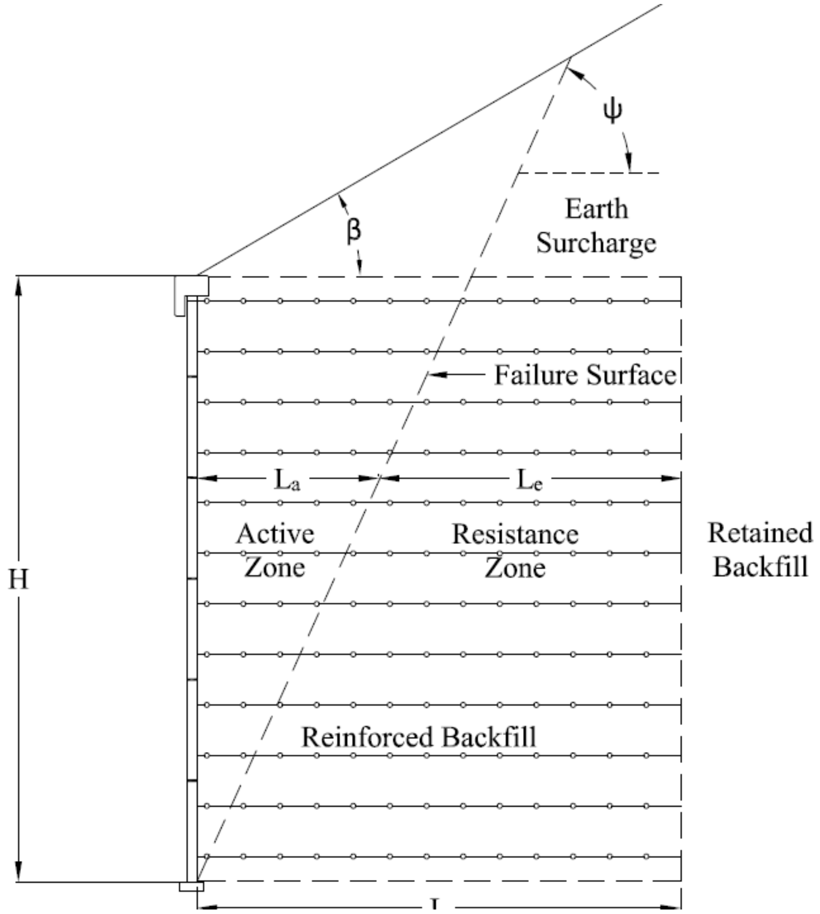
- Failure planes passing under and outside the reinforced fill

Both are analyzed using limit equilibrium methods

Design of MSE Walls – Internal Failure Surface

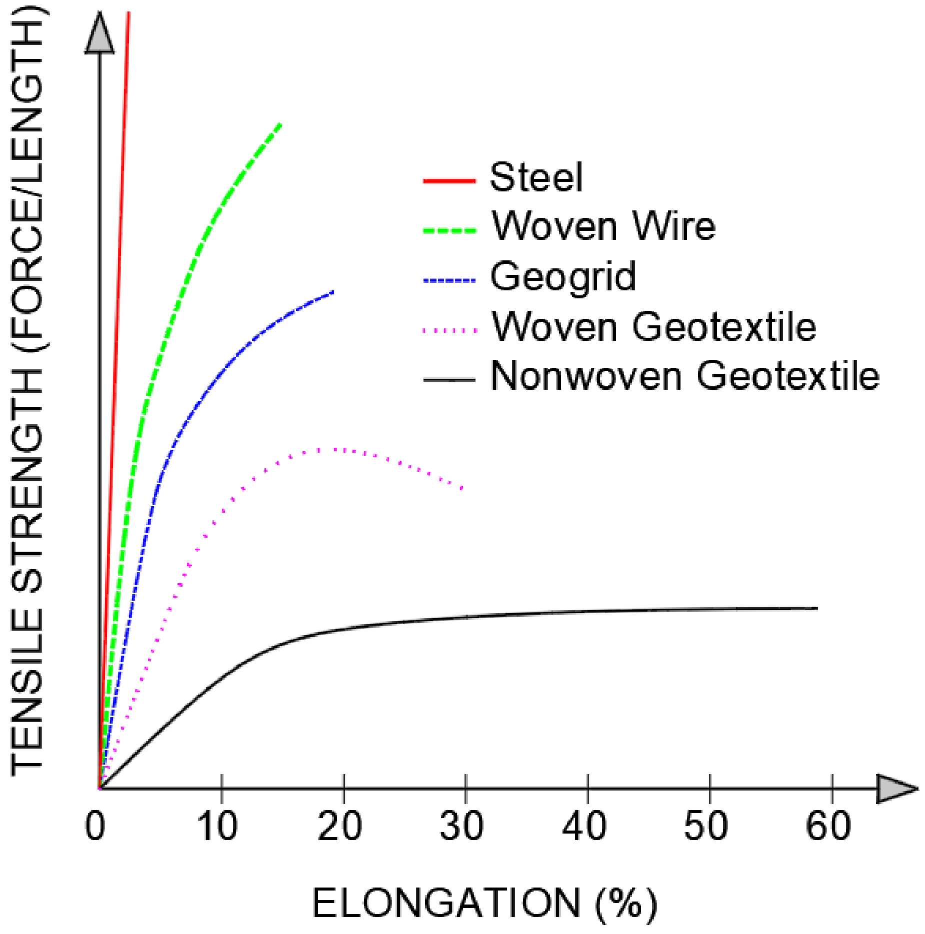


Inextensible Reinforcement

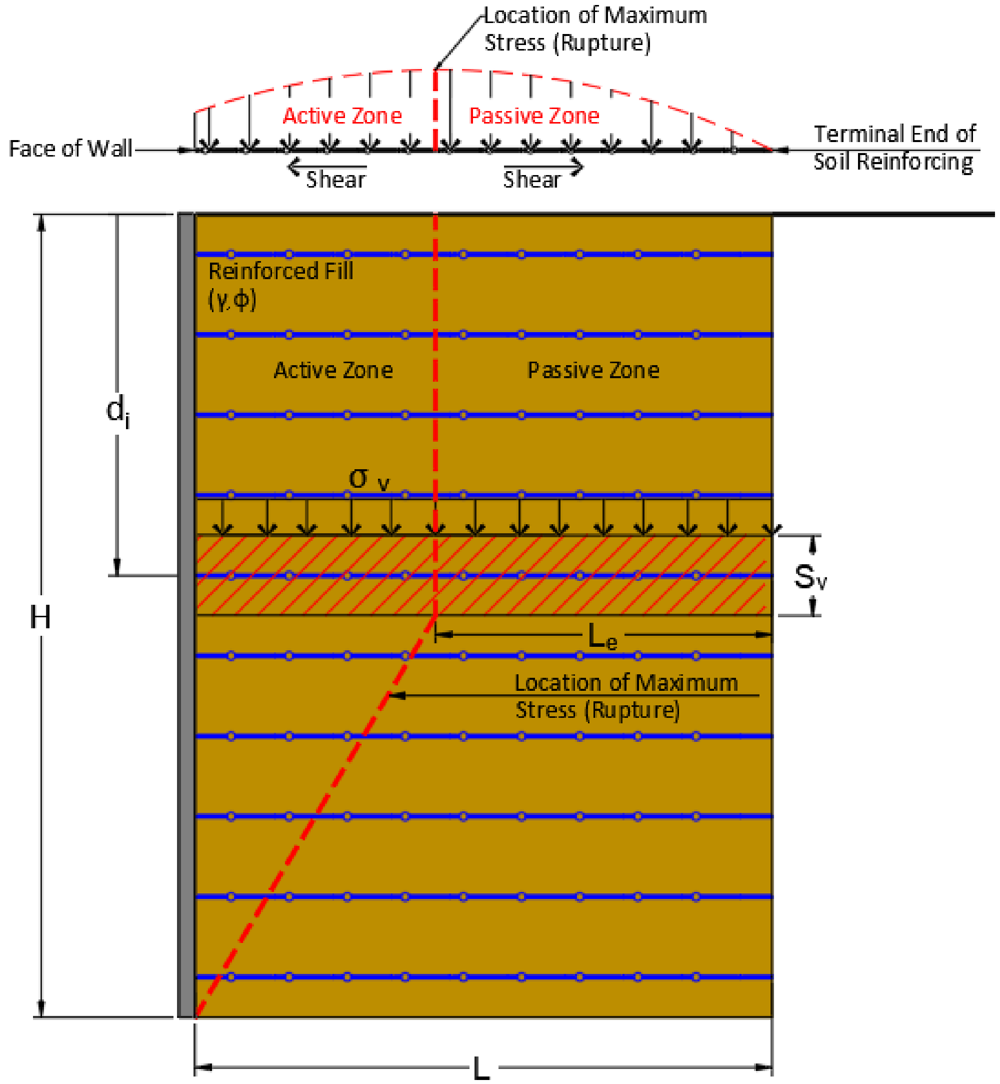


Extensible Reinforcement

Design of MSE Walls - Internal Failure Surface Versus Reinforcement Stiffness



Design of MSE walls – Internal Stability

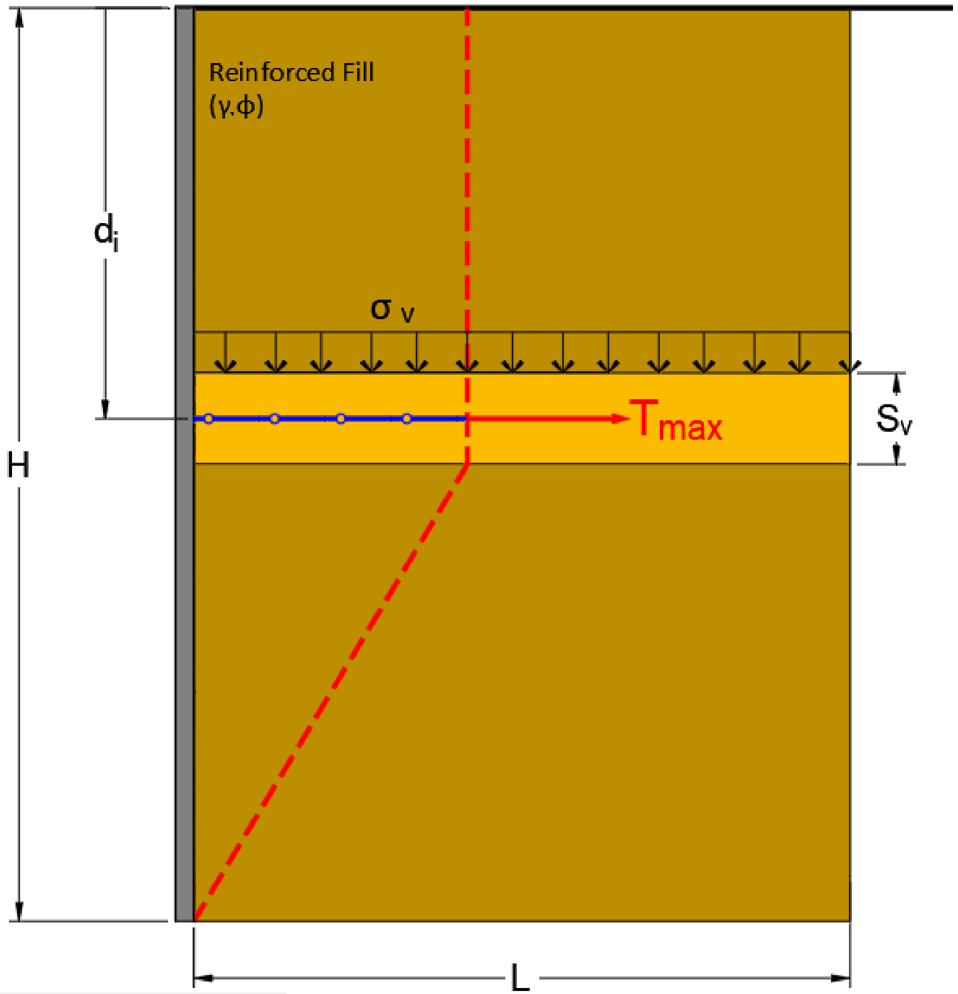


Source: The Collin Group

- Internal stability evaluates the ability of the reinforced fill to withstand the internal forces generated by the self weight of the fill and all externally applied forces.
- Modes of failure
  - Rupture of reinforcement
  - Pullout of reinforcement
  - Connection

Source: FHWA

Design of MSE walls – Internal Stability



Source: The Collin Group

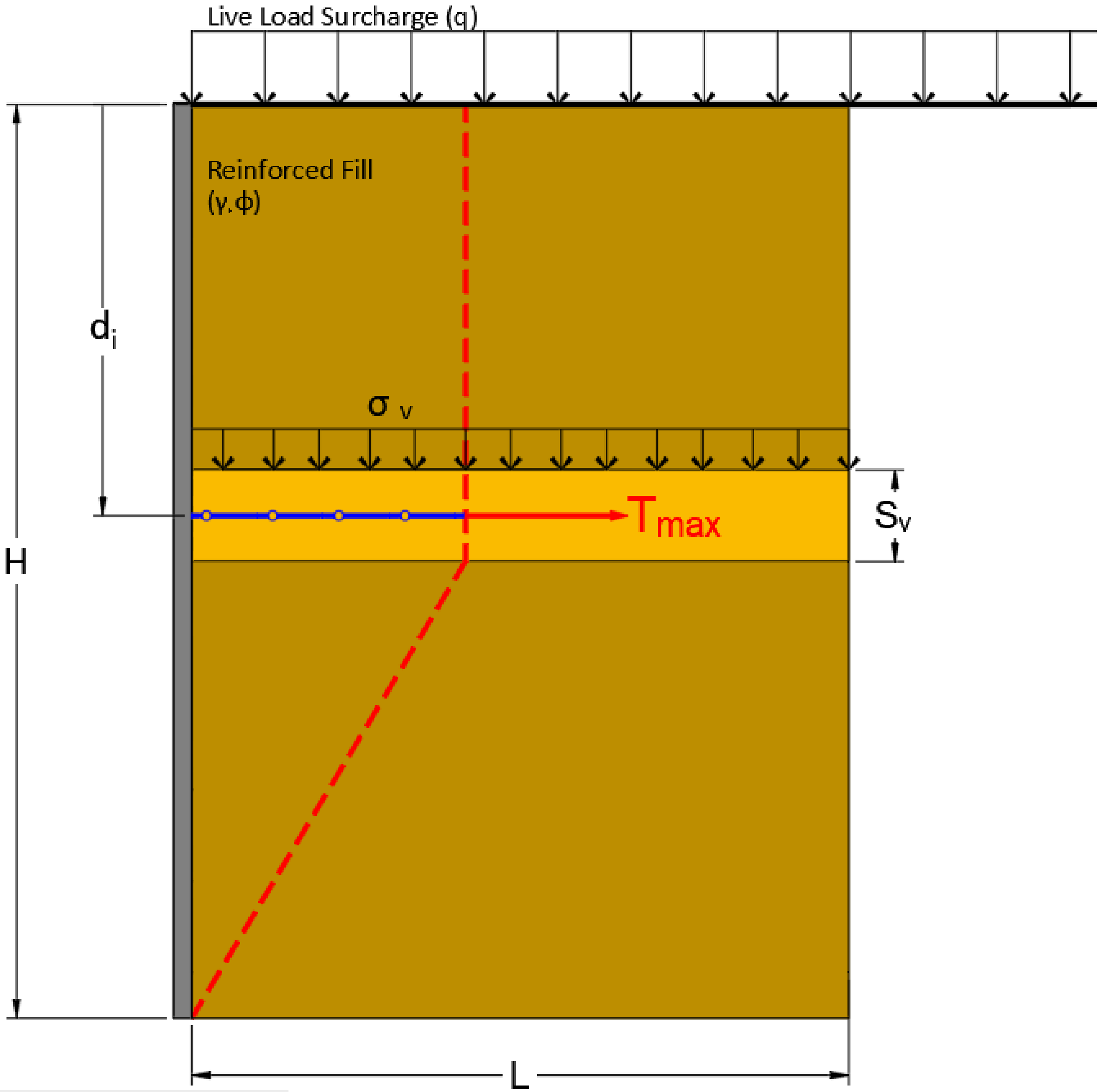
What is T_{max}?

T_{max} is the force acting on the MSE reinforcement at any given depth.

T_{max} is a function of the:

- Vertical stress
- Engineering properties of the soil
- Spacing of the reinforcement
- Reinforcement stiffness
- Facing stiffness

Design of MSE walls – Internal Stability



Source: The Collin Group

T_{max} Calculation

Difference between AASHTO and FHWA is when T_{max} is factored and the load factor used.

AASHTO -

$$T_{max} = \gamma_{EV}\,\sigma_H\,S_V$$

$$\sigma_V = \gamma_r\,di + q + \ldots\ldots$$

$$\sigma_H = K_a(K_r/K_a)\,\sigma_V$$

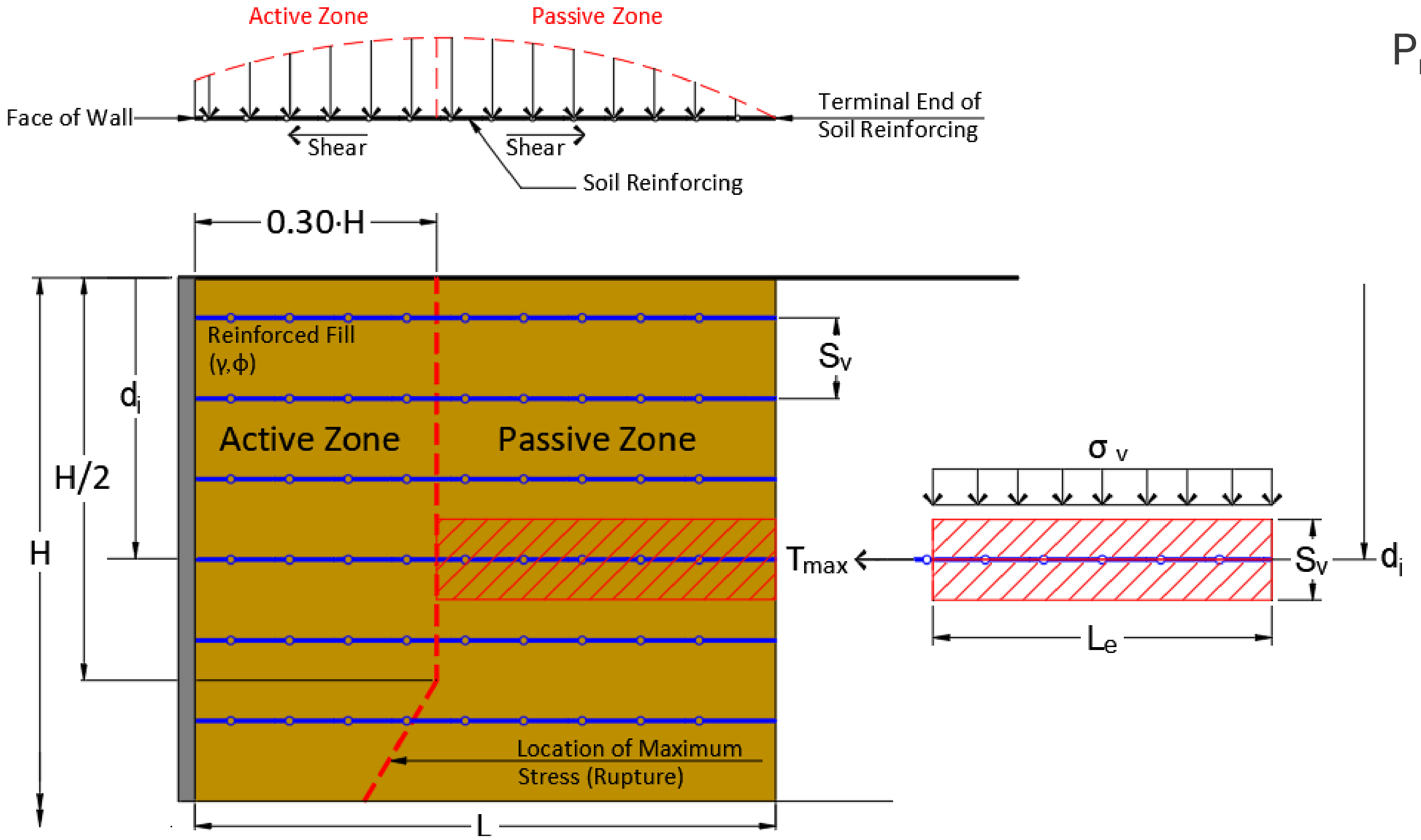
FHWA -

$$T_{max} = \sigma_H\,S_V$$

$$\sigma_V = \gamma_{EV}\gamma_r\,Z + \gamma_{LS}\,q + \ldots\ldots$$

$$\sigma_H = K_a(K_r/K_a)\,\sigma_V$$

Design of MSE walls – Internal Stability



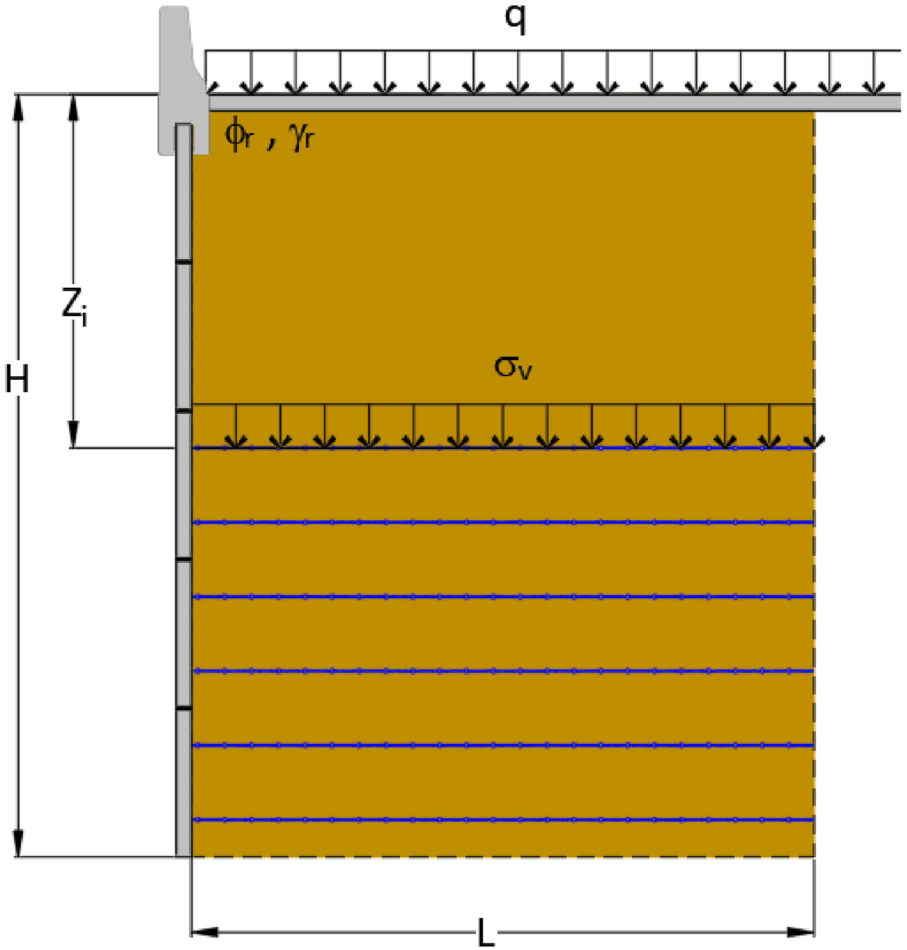
Source: The Collin Group

Pullout Capacity –

$P_r = \phi_r F^* \alpha \, \sigma_v' L_e C R_c \Rightarrow P_r = \phi_r 2 F^* \sigma_v' L_e R_c$

- Φ_r – resistance factor
- F^* - Pullout resistance factor
  - Based on reinforcement interaction with the fill
- α – Scale correction factor for non-linear stress reduction over the embedded length
  - 1.0 for all reinforcements
- σ_v' – Effective vertical stress
  - $\sigma_v' = (\gamma_r \; d_i) + \ldots\ldots$
- L_e – Reinforcement length in resistance zone
- C – Effective unit perimeter
  - 2 for sheet, strips, and grid reinforcement
- R_c = Percent coverage (width/horizontal spacing)

Design of MSE walls – Simplified Method

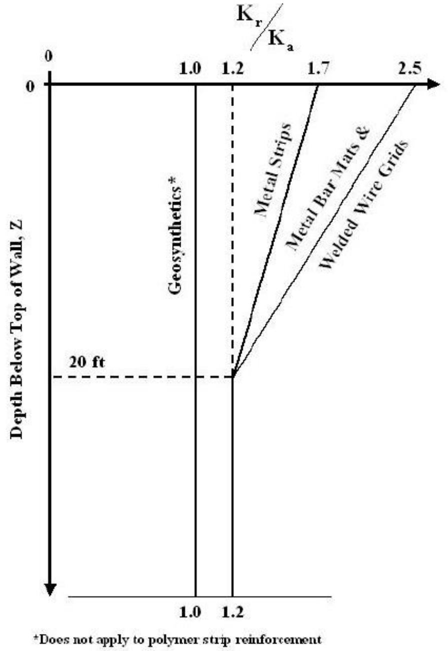


S_V is vertical spacing for the reinforcement being calculated

Source: The Collin Group

K_r / K_a – Varies based on reinforcement stiffness and depth

- For extensible reinforcement $K_r/K_a = 1.0$
- For inextensible reinforcement K_r/K_a ranges from 2.5 to 1.2 to a depth of 20 ft.



Source: FHWA NHI-10-024

The vertical pressure is factored by 1.35.

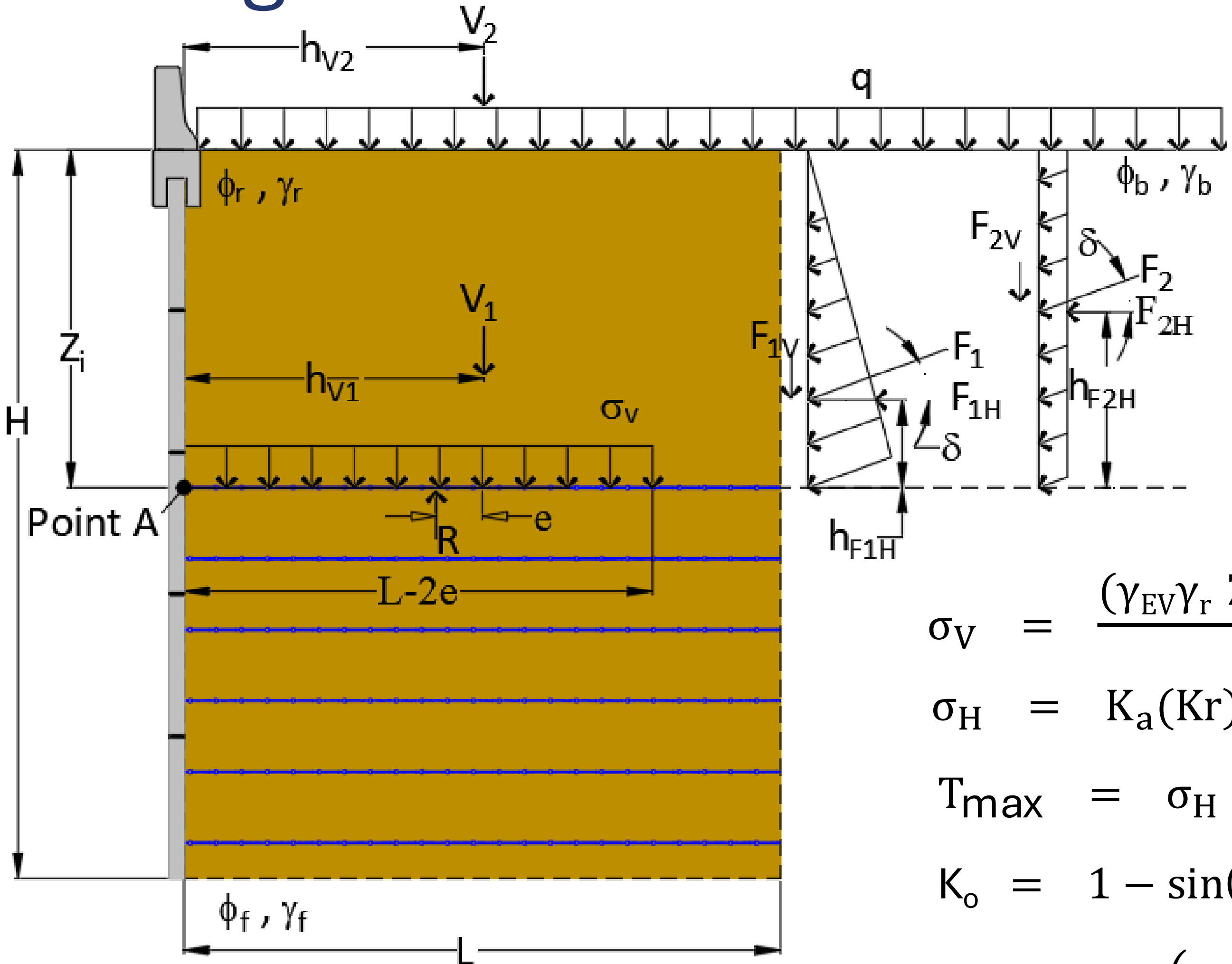
$$\sigma_V = \gamma_{EV}\gamma_r Z + \gamma_{EV} q + \ldots\ldots$$

$$\sigma_H = K_a(K_r/K_a)\,\sigma_V$$

$$T_{max} = \sigma_H S_V$$

$$K_a = \tan^2\left(45 - \frac{\varphi_r}{2}\right)$$

Design of MSE walls – Coherent Gravity Method



S_V is vertical spacing for the reinforcement being calculated

Source: The Collin Group

$$\sigma_V = \frac{(\gamma_{EV}\gamma_r\, Z + \gamma_{LS}\, q + \ldots\ldots)}{L - 2e}$$

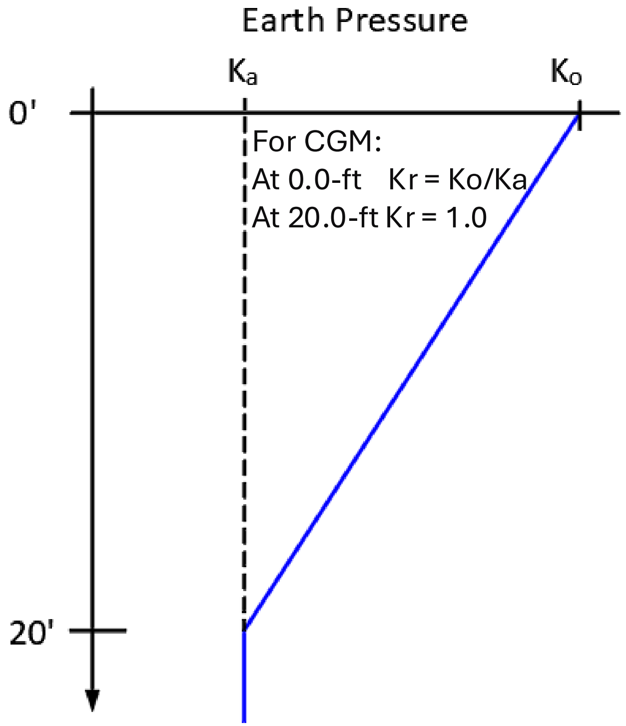
$$\sigma_H = K_a(Kr)\sigma_V$$

$$T_{max} = \sigma_H\, S_V$$

$$K_o = 1 - \sin(\varphi_r)$$

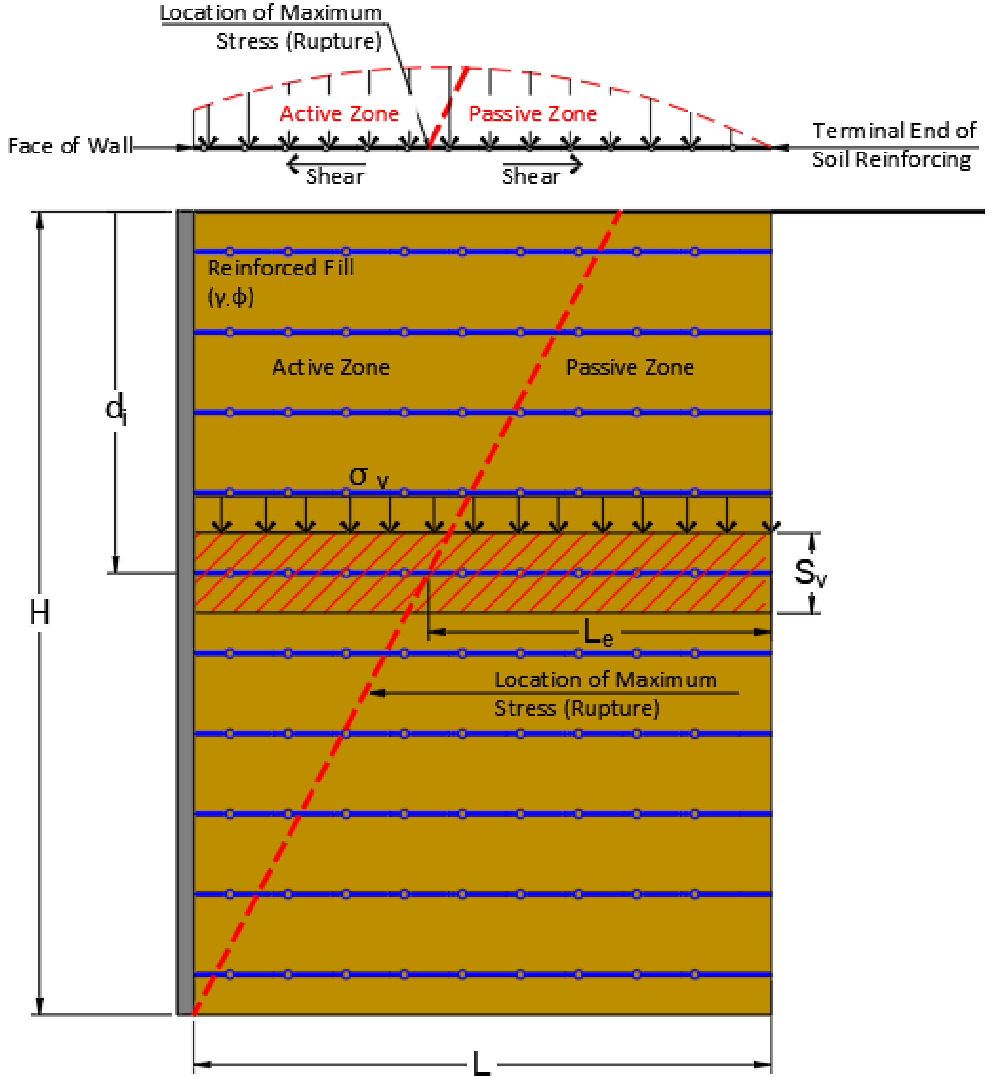
$$K_a = \tan\left(45 - \frac{\varphi_r}{2}\right)$$

Eccentricity (e) is determined at service limits states



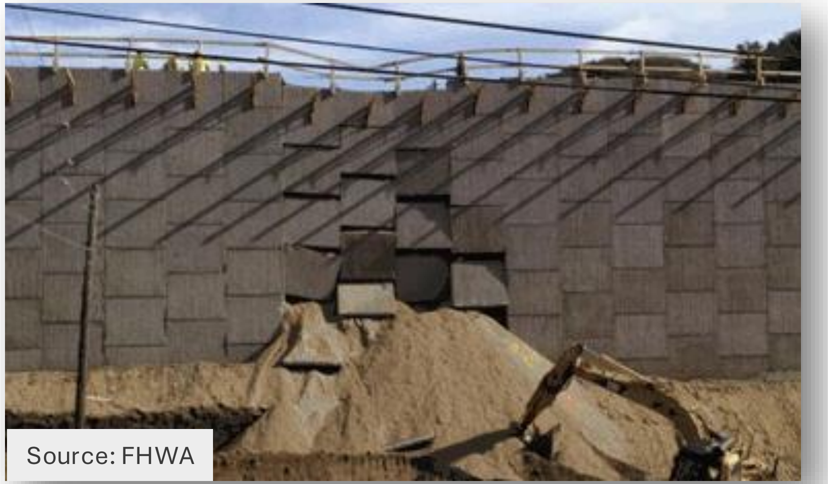
Source: The Collin Group

Design of MSE walls – Internal Stability (SSM)



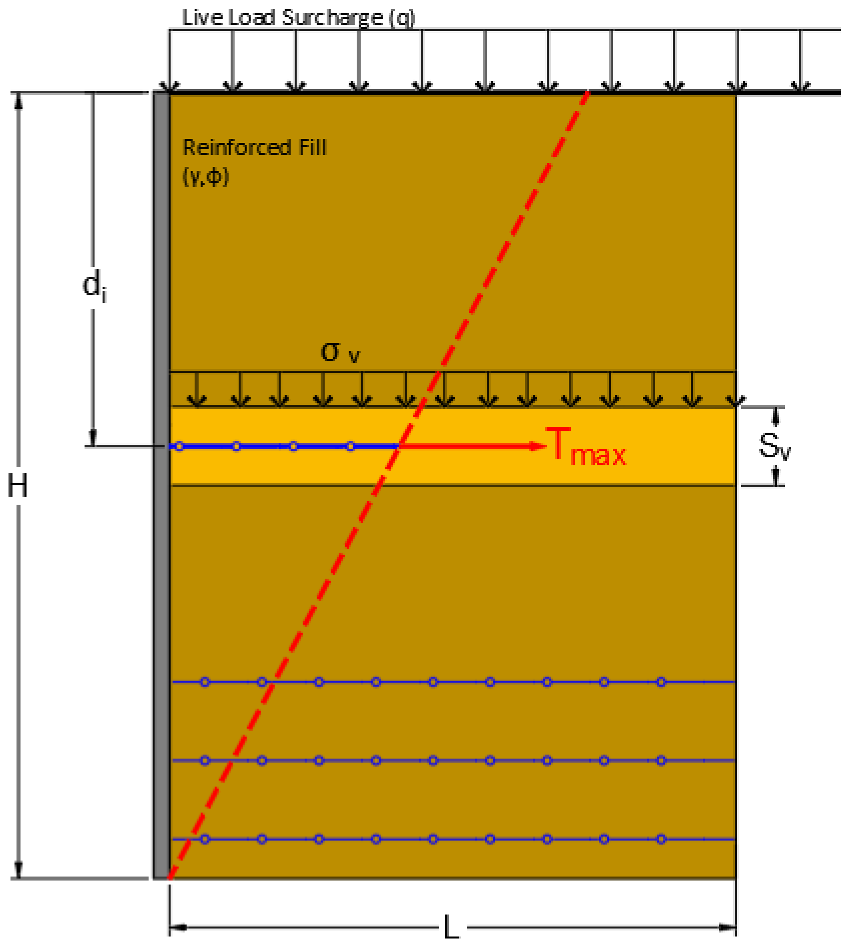
Source: The Collin Group

- Internal stability evaluates the ability of the reinforced fill to withstand the internal forces generated by the self weight of the fill and all externally applied forces.
- Modes of failure
  - Rupture of reinforcement
  - Pullout of reinforcement
  - Connection
  - Soil Failure



Source: FHWA

Design of MSE walls – Simplified Stiffness Method

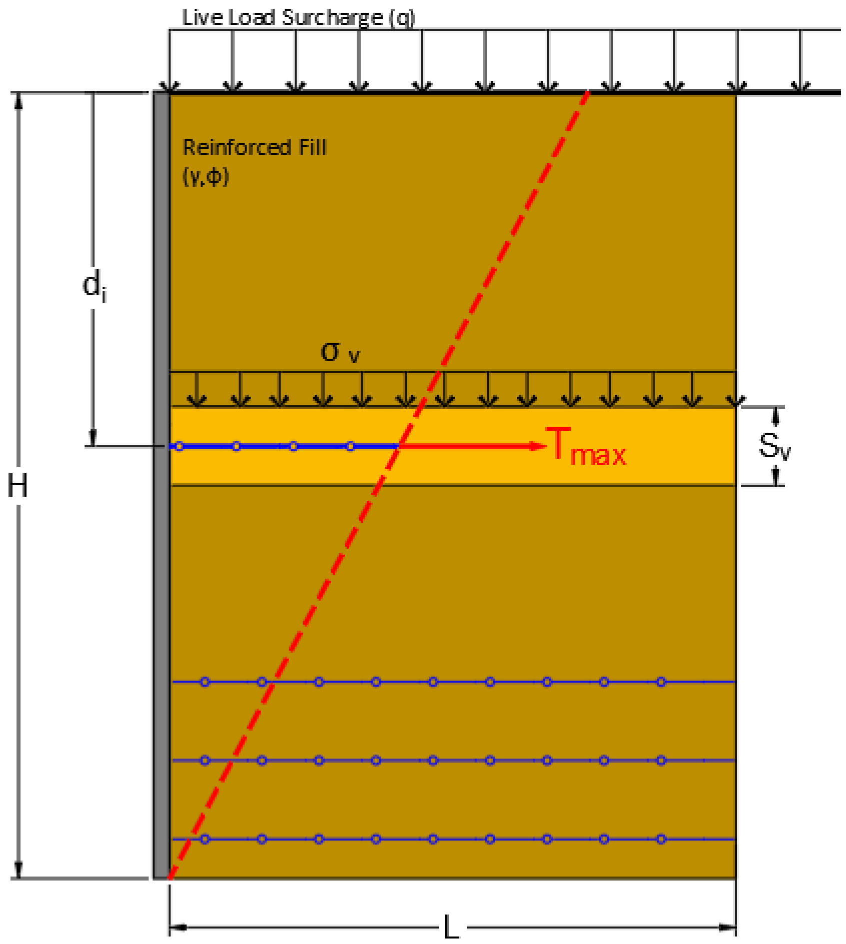


Source: The Collin Group

Key Assumptions

1. Method is formulated based on the reinforcement stiffness
2. Strain Limitation based on Isochronous Stiffness at 2%
3. Empirical calibration
4. Base calibration assumes a wall with a flexible vertical face and a horizontal back slope with no surcharge, though these can be adjusted using influence factors.
5. Cohesionless Soil – Can be adjusted for cohesive soils.
6. Uniform Reinforcement: The method typically assumes a single reinforcement material placed at a constant uniform spacing, though variations can be accounted for.
7. Load and Resistance Factor Design (LRFD).

Design of MSE walls – Simplified Stiffness Method



Source: The Collin Group

General Equations

$$\sigma_V = \gamma_{EV} \cdot \gamma_r \cdot H \cdot D_{tmax} + \gamma_{EV} \cdot \gamma_r \cdot \frac{H_{ref}}{H} \cdot S + \gamma_{LS} \cdot q$$

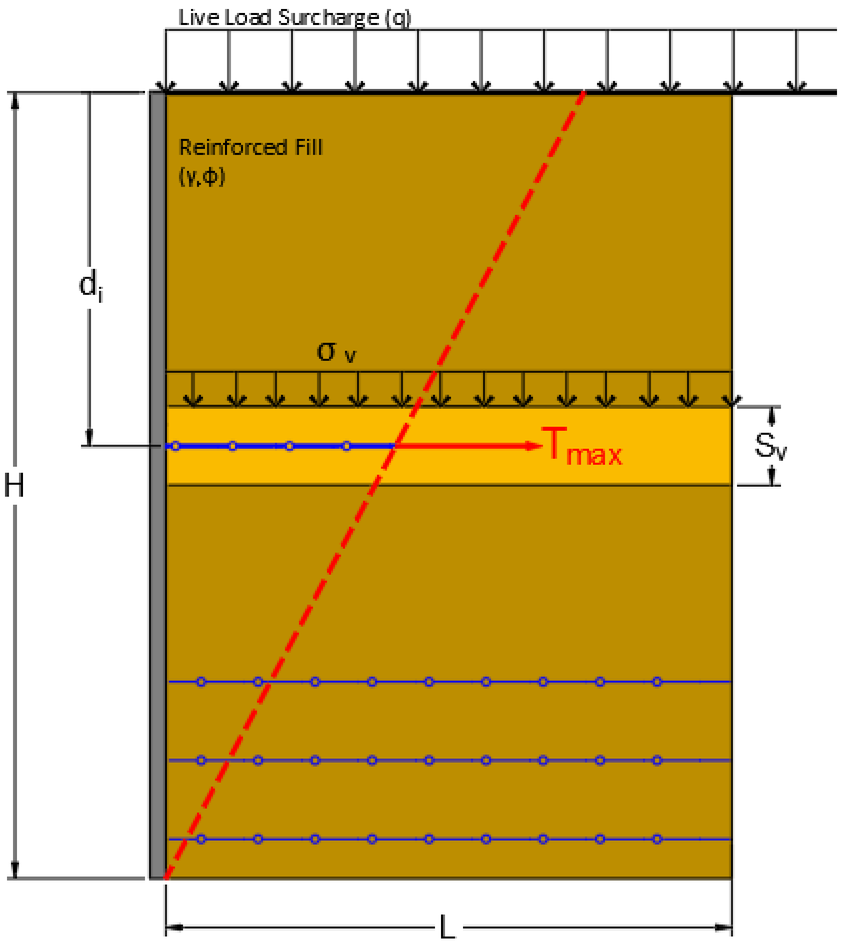
$$\sigma_H = \sigma_V \cdot K_a \cdot \Phi_{fs} \cdot \Phi_g \cdot \Phi_{local} \cdot \Phi_c \cdot \Phi_{fb}$$

$$T_{max} = S_v \cdot \sigma_H$$

Φ	=	influence factors
D_{tmax}	=	stress distribution factor
H_{ref}	=	reference wall height of 20 ft
S	=	Surcharge height

$K_a = \tan^2\left(45^o - \frac{\phi_r}{2}\right)$

Design of MSE walls – Simplified Stiffness Method



Source: The Collin Group

Influence Factors

Φ_g = global stiffness factor

Φ_{fs} = facing stiffness factor

Φ_{local} = local stiffness factor

Φ_c = soil cohesion factor = 1 for AASHTO reinforced soils

Φ_{fb} = facing batter factor = 1 for batters less than 10°

K_a = active earth pressure coefficient for the reinforced zone soil

$$K_a = \frac{\sin^2(\theta + \phi_r)}{\sin^3\theta \cdot \left(1 + \frac{\sin(\phi_r)}{\sin(\theta)}\right)}$$

With batter

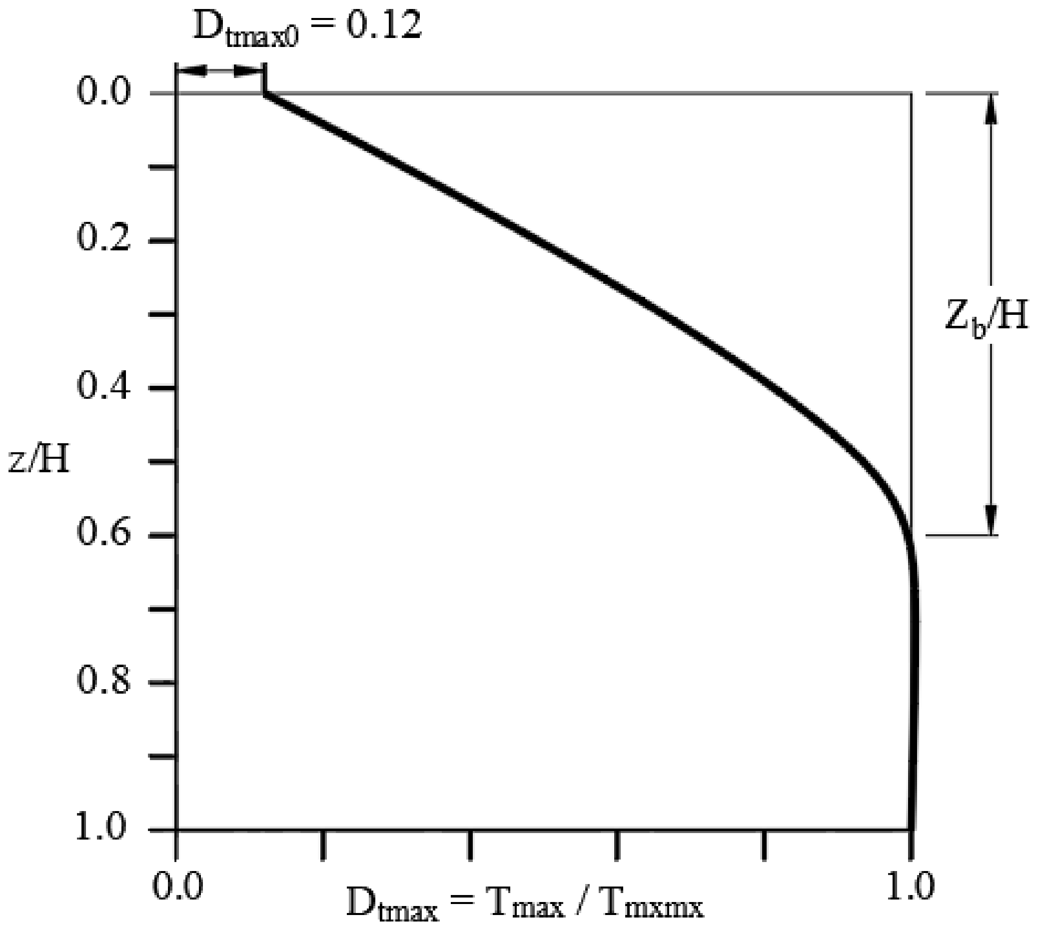
$$K_a = \tan^2\left(45^o - \frac{\phi_r}{2}\right)$$

K_r = horizontal stress ratio

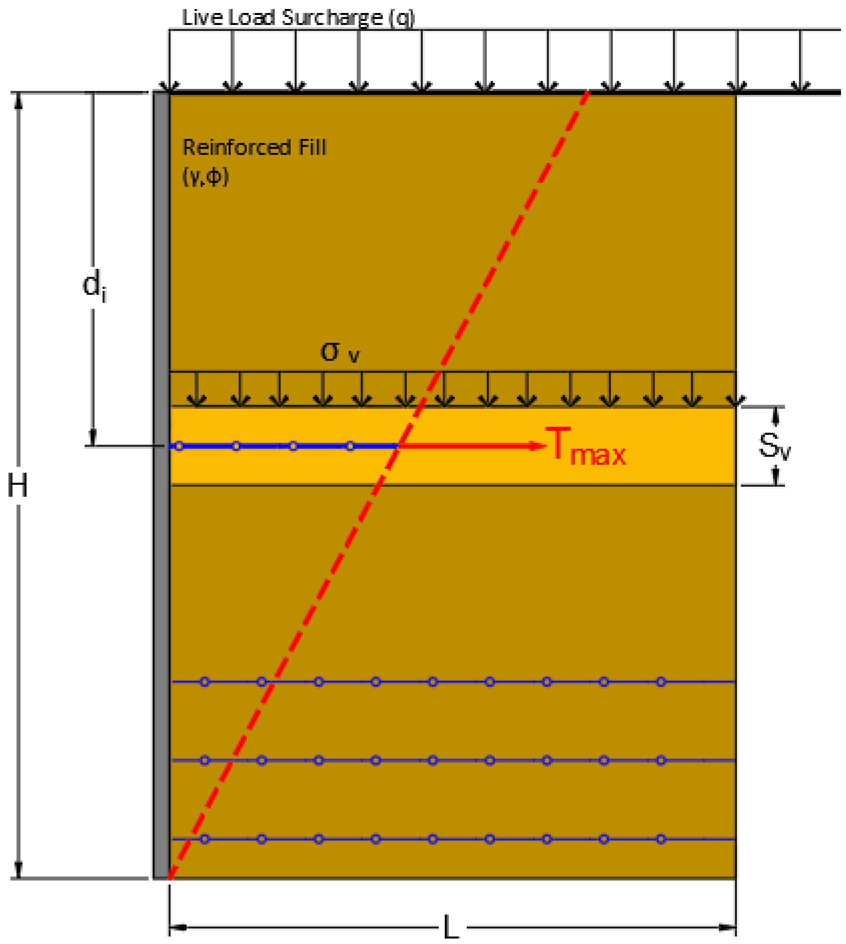
$$\frac{K_r}{K_a} = \Phi_g \cdot \Phi_{fs} \cdot \Phi_{local}$$

Determining T_{max} – SSM (3)

- Vertical Stress from the reinforced fill at the base of wall is determined
- Vertical Stress at bottom of wall distributed to reinforcement layers using empirical distribution factor D_{tmax}



Design of MSE walls – Simplified Stiffness Method



Source: The Collin Group

Comparison of SM/CG T_{max} to SSM T_{max}

$$T_{max} = S_v \sigma_v K = S_v [\gamma_f Z + \gamma_f S] K_a (K_r/K_a)$$

$$T_{max} = S_v [\gamma_f H D_{tmax} + \gamma_f (H_{ref}/H) S] K_{avh} \Phi_{fb} \Phi_g \Phi_{fs} \Phi_{local} \Phi_c$$

Source: AASHTO LRFD Bridge Design Specifications, 9th Edition, 2020

Design of MSE walls – Simplified Stiffness Method

Soil Failure limit state – considered a serviceability limit state, aimed at controlling deformations in the reinforced soil mass

The factored reinforcement peak strain for each layer should be less than ε_{mxmx}:

- ε_{mxmx} = 2.0% (for stiff faced walls)
  - $\Phi_{fs} < 1.0$
- ε_{mxmx} = 2.5% (for flexible faced walls)
  - $\Phi_{fs} = 1.0$

ε_{rein} – Factored reinforcement strain given calculated T_{max}

$$\varepsilon_{rein} = \frac{\gamma_{EVsf} \cdot T_{max\,sf}}{\phi_{sf} \cdot J_i} \leq \varepsilon_{mxmx}$$

J_i	=	Secant tensile stiffness of reinforcement at 2% strain and 1000 hours
γ_{EVsf}	=	1.2 (soil failure load factor)
ϕ_{sf}	=	1.0 (soil failure resistance factor)

Design of MSE walls – Stiffness Method

Soil Failure Check:

$$\varepsilon_{rein} = \frac{\gamma_{EVsf} \cdot T_{max\,sf}}{\phi_{sf} \cdot J_i} \leq \varepsilon_{mxmx}$$

$$T_{max\,sf} = S_V \cdot \left[\gamma_{EVsf} \cdot H \cdot \gamma_r \cdot D_{tmax} + \gamma_{EVsf} \cdot \gamma_{es} \cdot \left(\frac{H_{ref}}{H} \right) \cdot S_{AVG} + \gamma_{LSsf} \cdot \sigma_q \right] \cdot k_{avh} \cdot \Phi$$

γ_{EVsf} = load factor for prediction of T_{max} for the soil failure limit state (dimensionless)

$T_{max\,sf}$ = the reinforcement tensile load occurring at a horizontal strain equal to the soil strain at which the reinforced zone soil is at its peak shear strength.

ϕ_{sf} = the resistance factor that accounts for uncertainty in the measurement of the reinforcement stiffness at the specified strain = 1.0

ϵ_{mxmx} = the maximum acceptable strain (<2% for stiff-faced walls, and <2.5% for flexible-faced walls) in the wall section corresponding to T_{max} in any reinforcement layer (%)

Design of MSE walls – Stiffness Method

Check internal stability – Simplified Stiffness Methods

Rupture

- $T_{max}\,(\gamma_{EV}) < T_{al}\,(\phi)$

Connection

- $T_{max}\,(\gamma_{EV}) < T_{ac}\,(\phi)$

Pullout

- $T_{max}\,(\gamma_{EV}) < P_r\,(\phi)$

Soil Failure

- $\frac{\gamma_{p-EV sf} T_{max}}{\phi_{sf} J_i} \leq \varepsilon_{mxmx}$

γ_{EV} = 1.35 (strength limit)

γ_{EV} = 1.20 (Soil failure limit)

- AASHTO Table 3.4.1-2
- Other load factors may be applicable for additional loads

Table 11.5.7-1—Strength Limit State Resistance Factors for Permanent Retaining Walls

Wall-Type and Condition		Resistance Factor
Nongravity Cantilevered and Anchored Walls		
Axial compressive resistance of vertical elements		Article 10.5 applies
Passive resistance of vertical elements		0.75
Pullout resistance of anchors (1)	• Cohesionless (granular) soils • Cohesive soils • Rock	0.65 (1) 0.70 (1) 0.50 (1)
Pullout resistance of anchors (2)	• Where proof tests are conducted	1.0 (2)
Tensile resistance of anchor tendon	• Mild steel (e.g., ASTM A615 bars) • High-strength steel (e.g., ASTM A722 bars)	0.90 (3) 0.80 (3)
Overall stability, soil failure		Article 11.6.3.7 applies
Flexural capacity of vertical elements		0.90
Mechanically Stabilized Earth Walls, Gravity Walls, and Semigravity Walls		
Bearing resistance	• Gravity and semigravity walls • MSE walls	0.55 0.65
Sliding		1.0
Tensile resistance of metallic reinforcement and connectors	Strip reinforcements (4) Grid reinforcements (4) (5)	0.75 0.65
Tensile resistance of geosynthetic reinforcement and connectors	• Geotextile and geogrid reinforcements • Geostrip reinforcements	0.80 0.55
Pullout resistance of metallic reinforcement	• Steel strip reinforcements • Steel grid reinforcements	0.90 0.90
Pullout resistance of geosynthetic reinforcement	• Geotextiles and geogrids • Geostrip reinforcements	0.70 0.70
Service Limit, for soil failure using stiffness method		1.0
Overall and compound stability, soil failure		Article 11.6.3.7 applies

Source: AASHTO LRFD Bridge Design Specification, 9th Edition, 2020

Design of MSE walls – Limit Equilibrium Method [LEM]

Technical Report Documentation Page

1. Report No. FHWA-HIF-17-004	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Limit Equilibrium Design Framework for MSE Structures with Extensible Reinforcement		5. Report Date October 2016 6. Performing Organization Code
7. Principal Investigator(s): See Acknowledgements for Authors and Contributors Dov Leshchinsky, Ph.D[1], Ora Leshchinsky, P.E.[1], Brian Zelenko, P.E., John Horne, Ph.D., P.E.		8. Performing Organization Report No.
9. Performing Organization Name and Address Parsons Brinckerhoff 1015 Half Street, SE, Suite 650 Washington, DC 20003 [1]ADAMA Engineering, Inc., 12042 SE Sunnyside Rd., Suite 711, Clackamas, OR 97015		10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFH6114D00047-5010
12. Sponsoring Agency Name and Address Federal Highway Administration HIBT-20 Office of Bridge Technology 1200 New Jersey Avenue, SE Washington, DC 20005		13. Type of Report and Period 14. Sponsoring Agency Code
15. Supplementary Notes FHWA COR – Silas Nichols, P.E. FHWA Alt. COR – Khalid Mohamed, P.E.		
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.		
17. Key Words Mechanically Stabilized Earth Wall Design, MSE Wall Design, Limit Equilibrium, Geotechnical, Extensible reinforcement	18. Distribution Statement No restrictions.	
19. Security Classif. (of this report) UNCLASSIFIED	20. Security Classif. (of this UNCLASSIFIED	21. No. of Pages 120 22. Price

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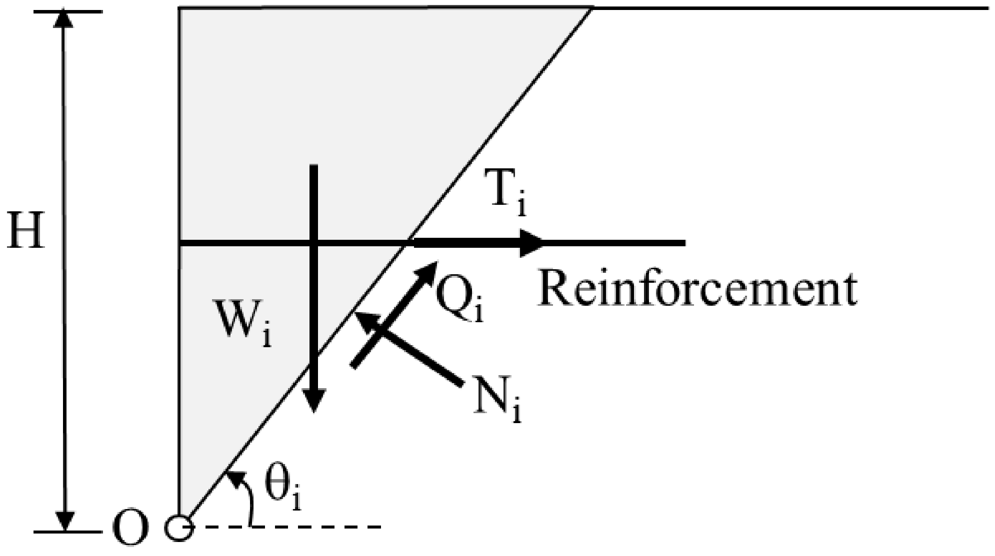
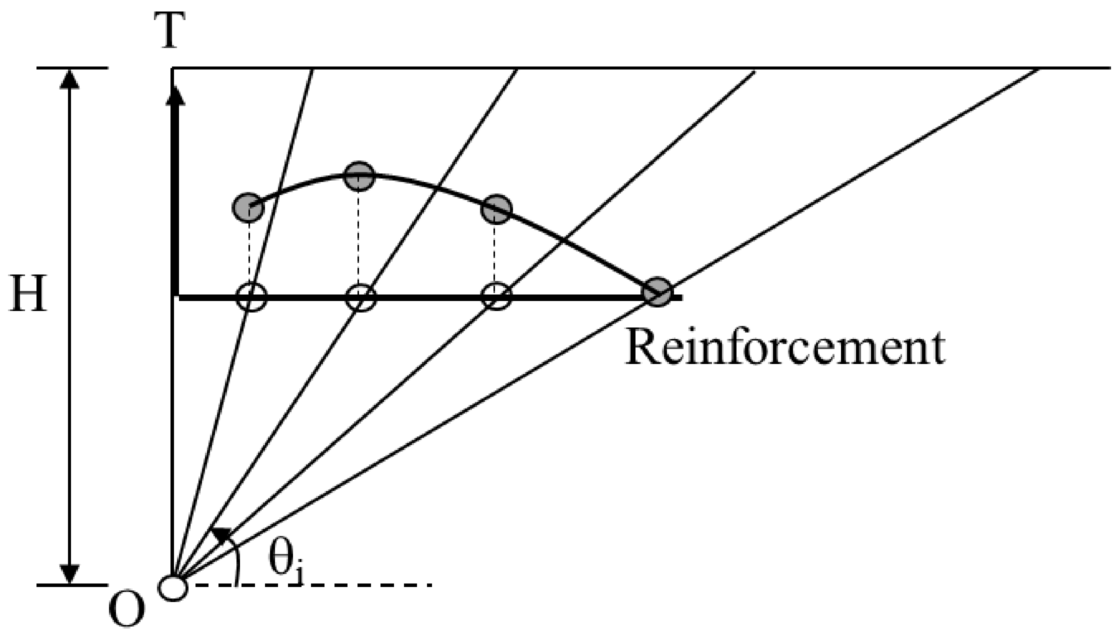
Design of MSE walls – LEM

- The limit equilibrium method (LEM) has been successfully used in practice to ensure the stability of both unreinforced and geosynthetic-reinforced slopes.
- This method is included in the 2020 AASHTO LRFD Bridge Design Specifications for designing the internal stability of MSE walls with extensible reinforcement.
- There are several LEMs available in the literature. (i.e., Bishop, GLE, Spencer, Morgenstern-Price, etc.)
- In the LEM, a slip surface may be assumed, which can be planar, bi-planar, multi-planar, circular or log-spiral
- This method is suitable for flexible earth structures that allow deformations and full mobilization of soil strength at failure.

Design of MSE walls – LEM Method



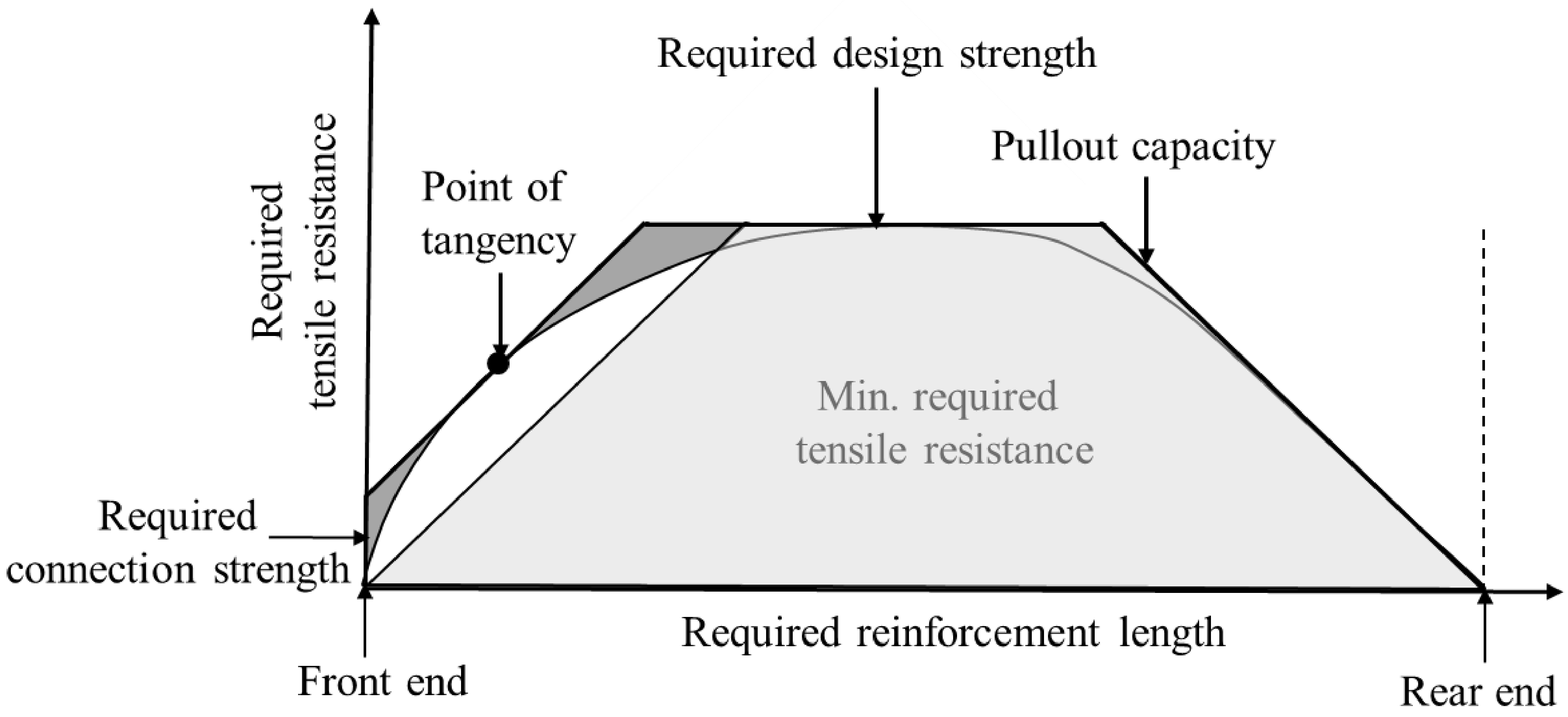
Failure Surface and force diagram



Require tensile resistance distribution

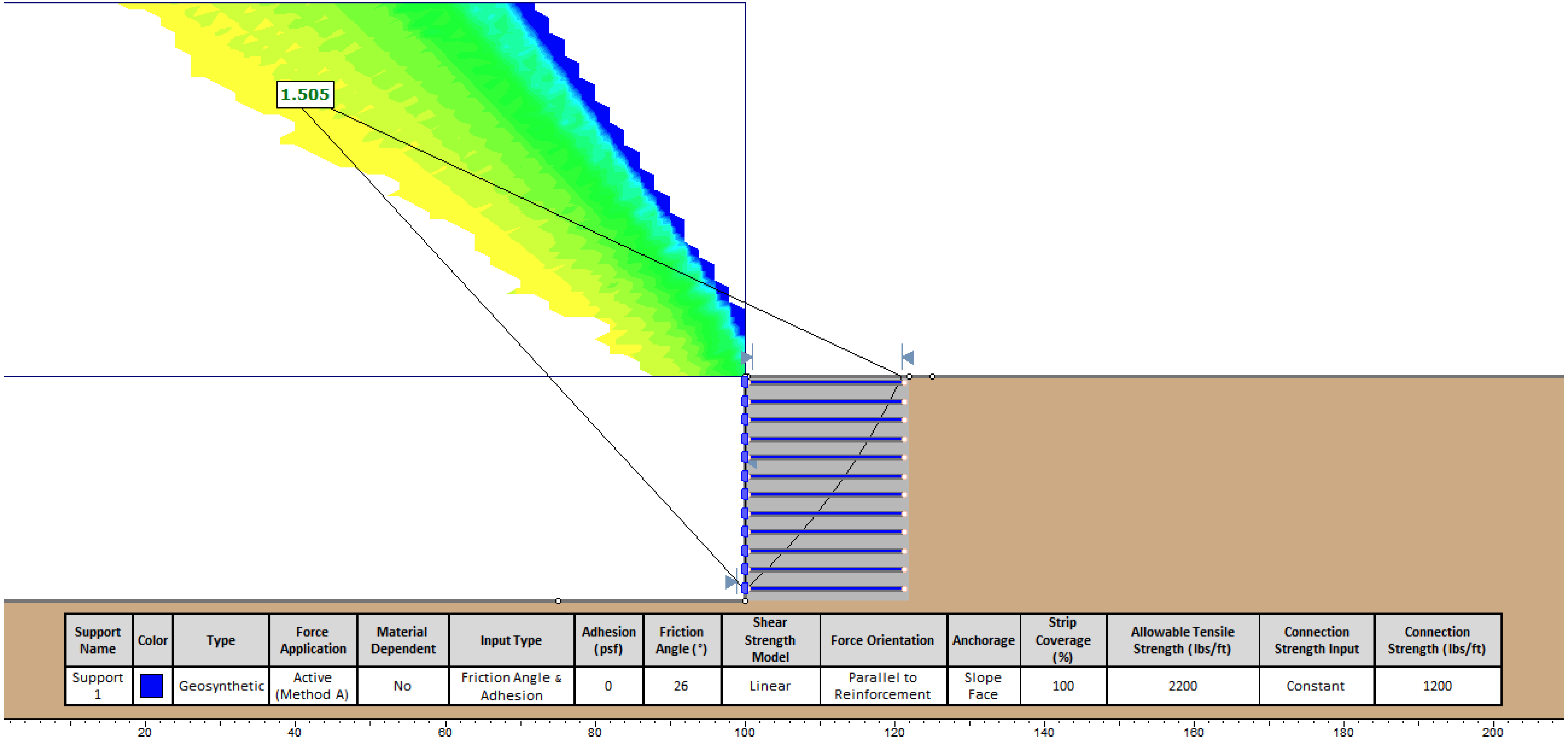
Source: NHI 132042

Design of MSE walls – LEM Method



Source: NHI 132042

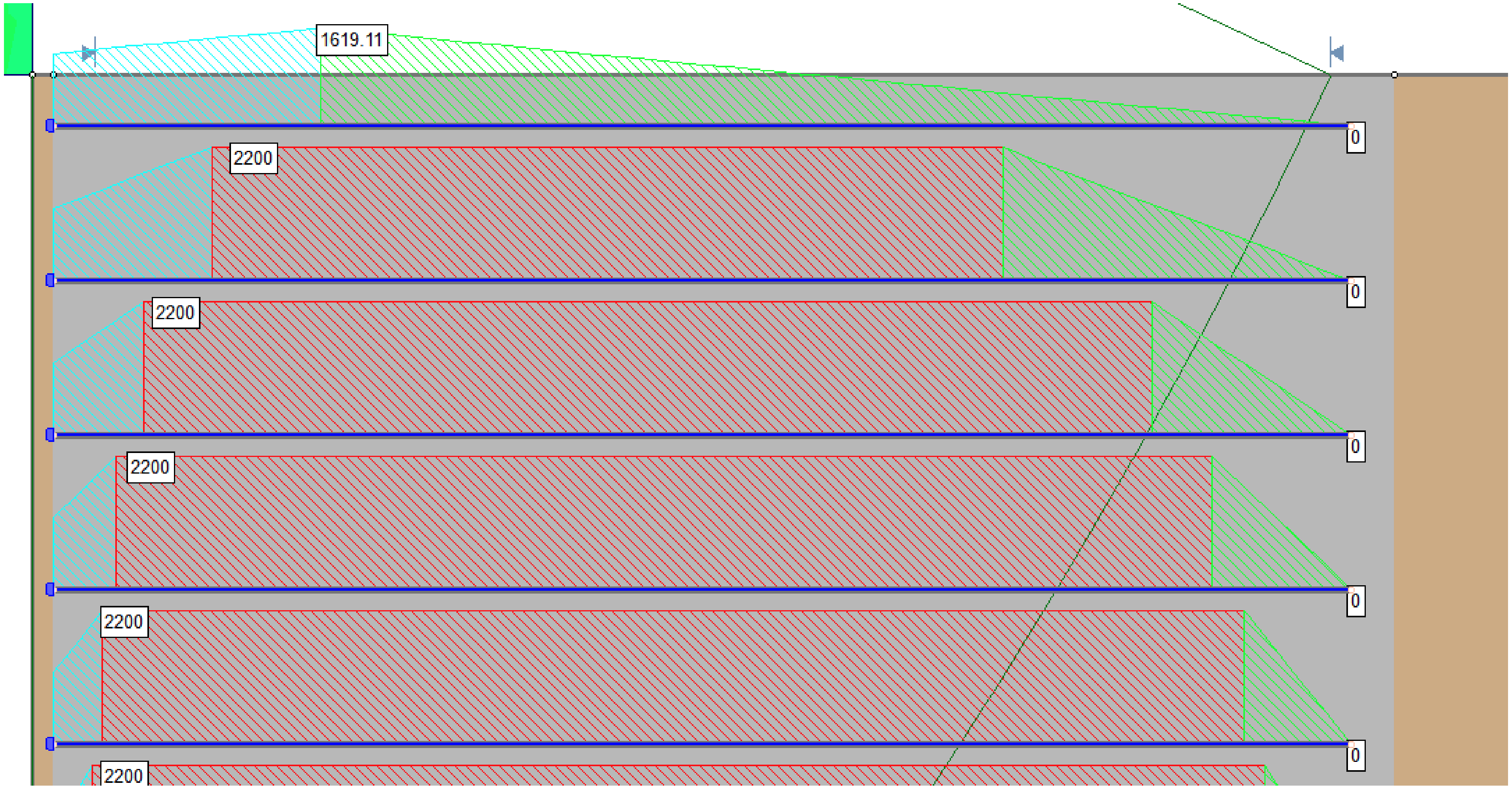
Design of MSE walls – LEM Method



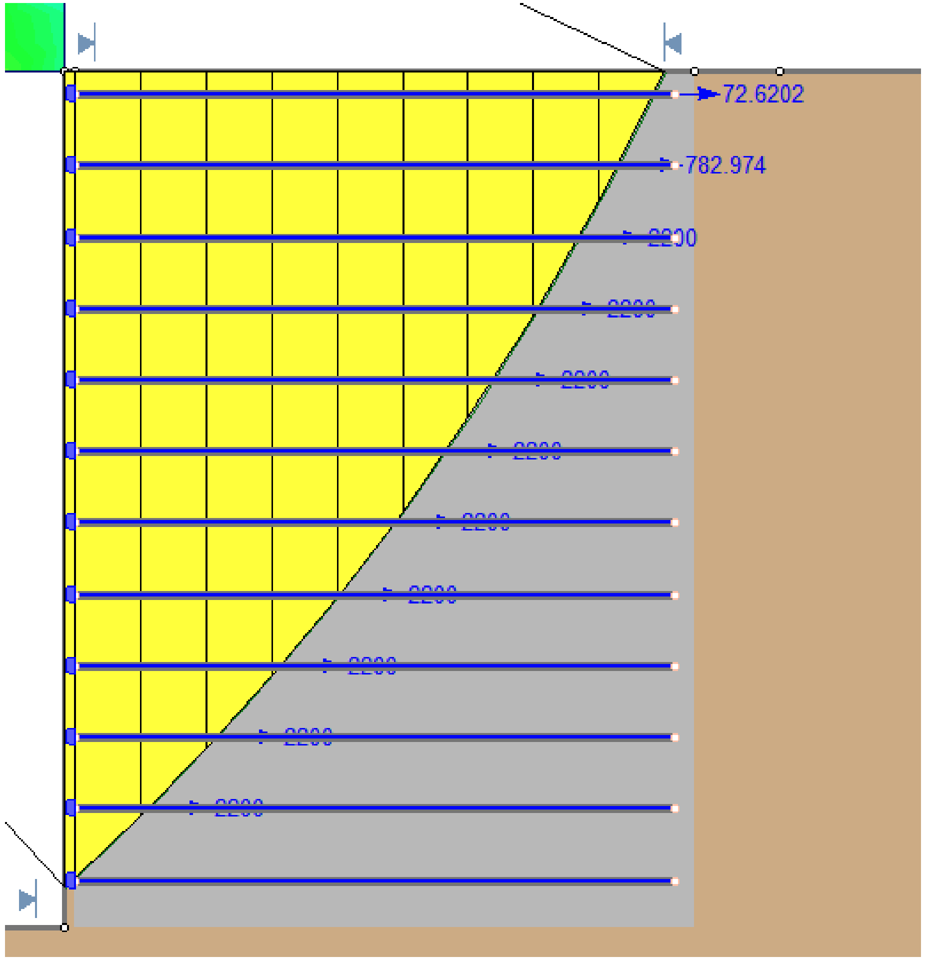
Support Name	Color	Type	Force Application	Material Dependent	Input Type	Adhesion (psf)	Friction Angle (°)	Shear Strength Model	Force Orientation	Anchorage	Strip Coverage (%)	Allowable Tensile Strength (lbs/ft)	Connection Strength Input	Connection Strength (lbs/ft)
Support 1		Geosynthetic	Active (Method A)	No	Friction Angle & Adhesion	0	26	Linear	Parallel to Reinforcement	Slope Face	100	2200	Constant	1200

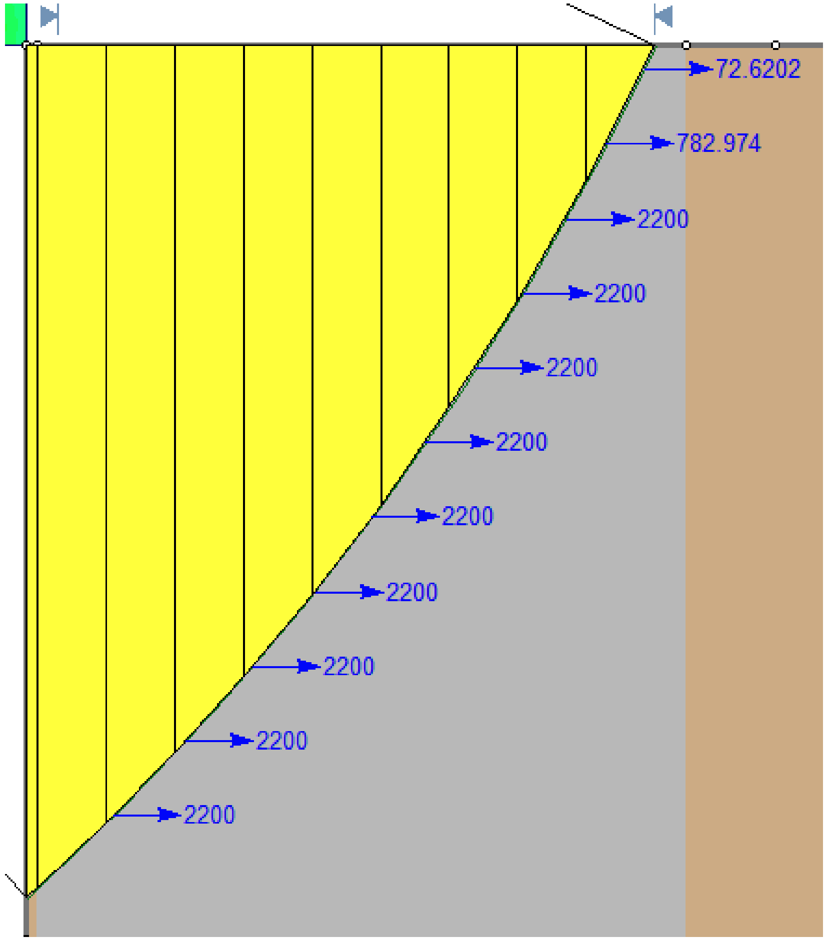
Source: NHI 132042

Determining T_{max} – LEM



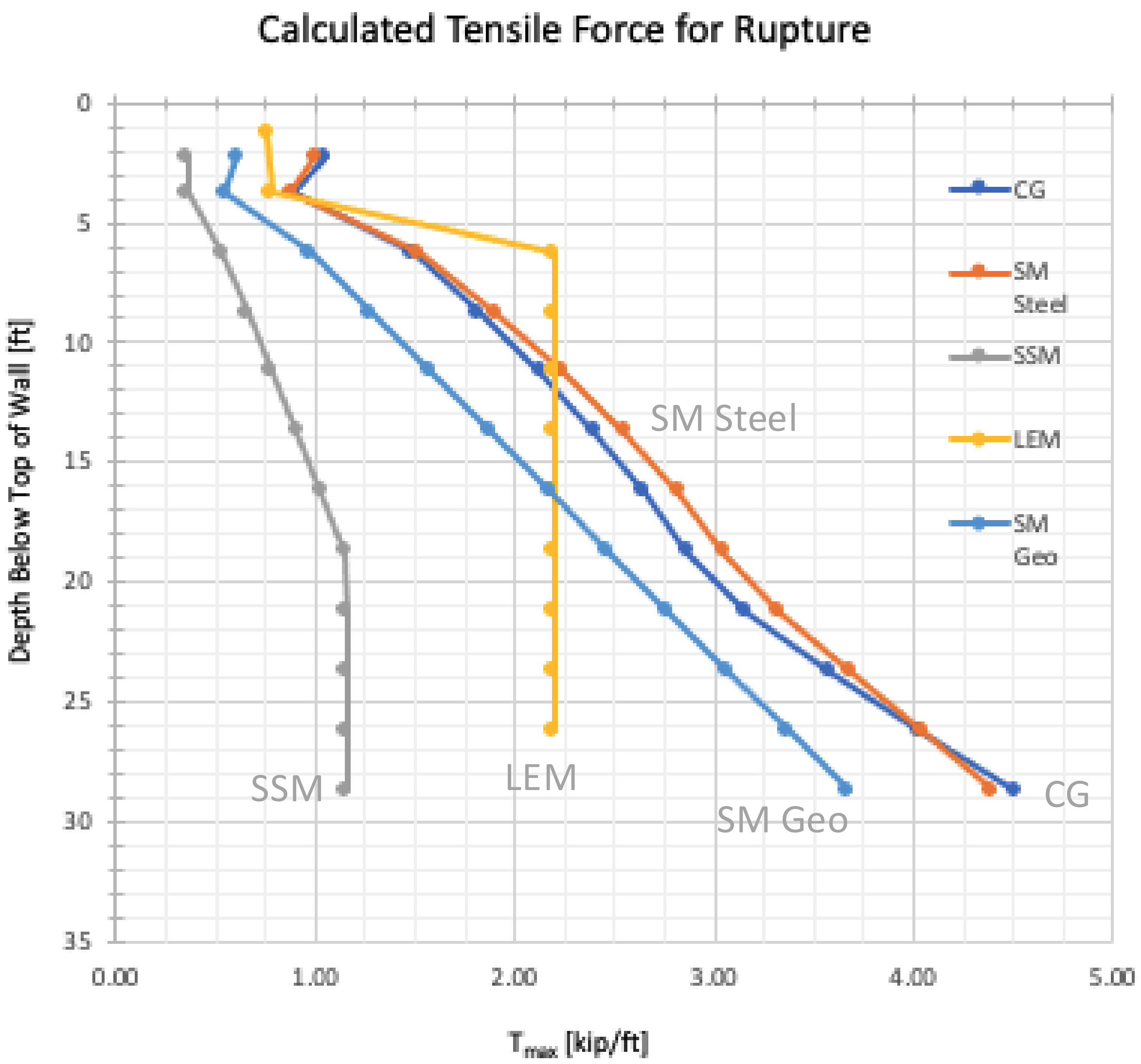
Determining T_{max} – LEM





Summary of CGM, SM, SSM and LEM

T_{req} (kip/ft)					
Depth	CG	SM Steel	SM Geo	SSM	LEM
2.25	1.050	1.000	0.610	0.360	0.760
3.75	0.890	0.880	0.550	0.360	0.782
6.25	1.490	1.520	0.980	0.530	2.200
8.75	1.820	1.900	1.280	0.660	2.200
11.25	2.130	2.240	1.580	0.780	2.200
13.75	2.400	2.550	1.880	0.910	2.200
16.25	2.650	2.820	2.180	1.030	2.200
18.75	2.870	3.050	2.470	1.150	2.200
21.25	3.160	3.330	2.770	1.160	2.200
23.75	3.580	3.690	3.070	1.160	2.200
26.25	4.030	4.040	3.370	1.160	2.200
28.75	4.510	4.400	3.670	1.160	0.000
Total	30.580	31.420	24.410	10.420	21.342



Design of MSE walls – LEM Method

Reinforcement Type and Loading Condition		Resistance Factor	
		CGM/SM	SSM
Geosynthetic reinforcement and connectors	Static loading	0.90	0.80/0.55[4]
	Combined static/earthquake loading	1.00	1.00
	Combined static/traffic barrier impact[2]	1.00	1.00
Pullout resistance of metallic reinforcement	Static loading	0.90	NA
	Combined static/earthquake loading	1.00	
	Combined static/traffic barrier impact[2]	1.00	
Pullout resistance of geosynthetic reinforcement	Static loading	0.90	0.70
	Combined static/earthquake loading	1.00	1.00
	Combined static/traffic barrier impact[2]	1.00	1.00

	FS*
Reinforcement Strength	
Geogrids	1.5
Geosynthetic Strips	2.4
Reinforcement Pullout	1.9
Connection Reinforcement to Facing	
Geogrids	1.5
Geosynthetic Strips	2.4

Source: NHI 132042

*The factor of safety is determined by dividing the vertical load factor (γ_{EV} = 1.35) by the corresponding resistance factor for each mode of failure.

$$FS = \gamma_{EV} / \phi_{sf}$$

MSE wall Design – Update Summary

External Stability – unchanged from previous AASHTO and FHWA guidelines, except Coulomb instead of Rankine Earth Pressure.

Internal Stability – four different methods two for inextensible reinforcement and three for extensible reinforcement

Resistance Factors are different for different reinforcement types and different design methods

AASHTO – has taken a simple easy to use design method and replaced it with a much more confusing method that reduces the required reinforcement by over 50%.

FHWA – preferred method of analysis for extensible reinforcement is the LEM

Questions?