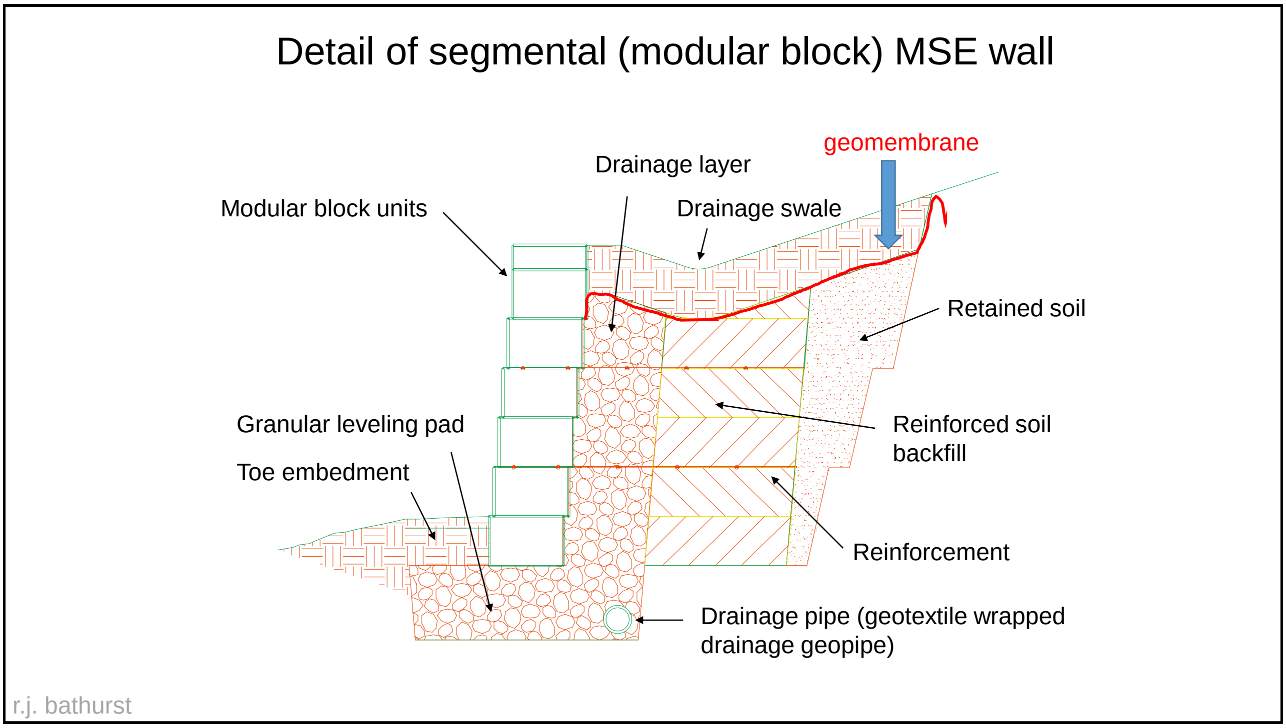

Detail of segmental (modular block) MSE wall

geomembrane

Drainage layer

Modular block units

Drainage swale

Retained soil

Reinforced soil backfill

Granular leveling pad

Toe embedment

Reinforcement

Drainage pipe (geotextile wrapped drainage geopipe)

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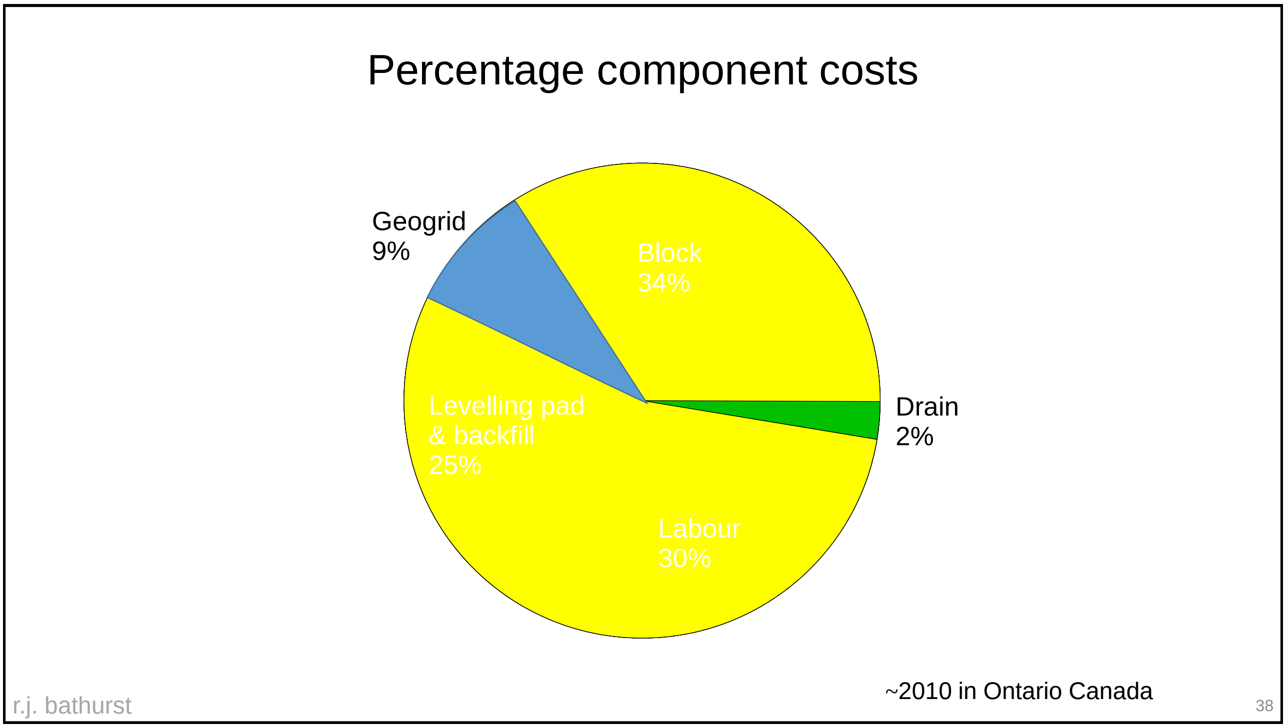

Percentage component costs

Geogrid 9%

Block 34%

Levelling pad & backfill 25%

Drain 2%

Labour 30%

~2010 in Ontario Canada

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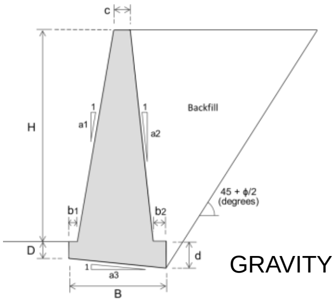
Sustainability

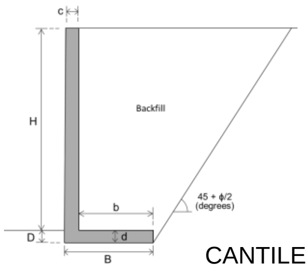
Broadly defined, sustainability is related to satisfying <u>three sets of requirements (pillars)</u>
based on

1. <u>environmental impact</u>
2. <u>economic (cost)</u>
3. <u>societal/functional criteria</u>

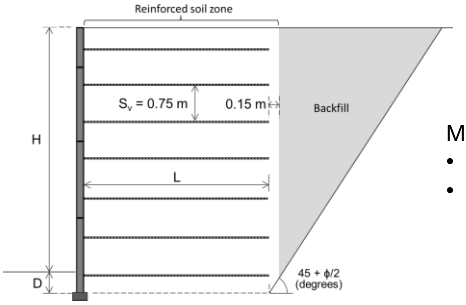
Sustainability



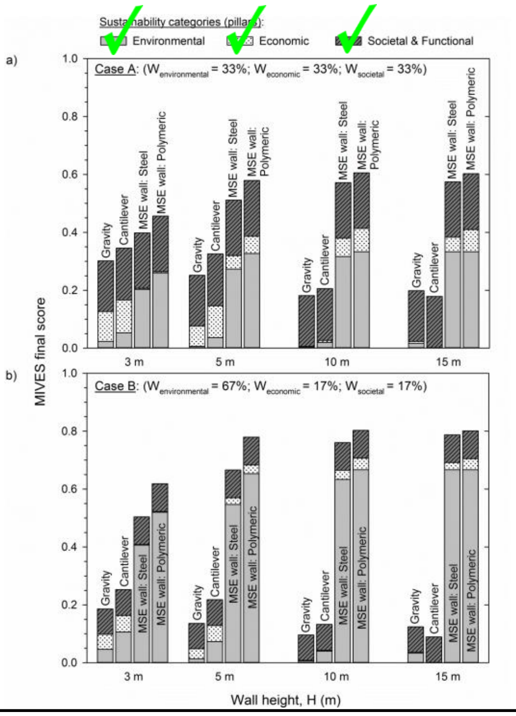
GRAVITY



CANTILEVER



MSE
- Polymeric
- Steel

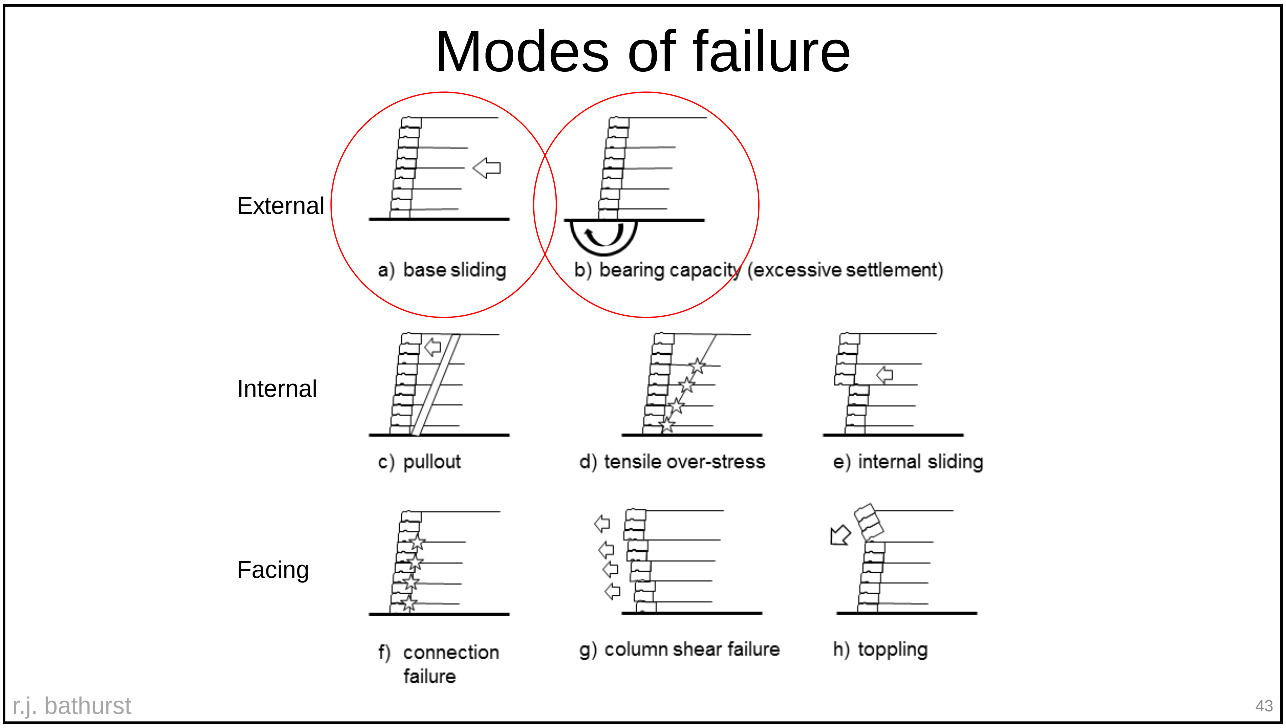


SUSTAINABILITY

Damians, I.P., Bathurst, R.J., Adroguer, E.G., Josa, A. and Lloret, A. 2018. **Sustainability assessment of earth retaining wall structures**. *Environmental Geotechnics* 5(4): 187-203 (http://dx.doi.org/10.1680/jenge.16.00004).

Course Outline

1. Overview of geosynthetic reinforced soil walls. The history of GRS walls is briefly reviewed including important new construction methods and materials. The basic components of these systems are explained. The relatively higher sustainability of these systems over conventional earth retaining wall systems is highlighted.
2. Design and analysis of GRS walls. External, global and internal design limit states are presented. The characterization of the mechanical properties of geosynthetic reinforcement materials is discussed and how these properties are determined from physical testing and used in internal stability design and analysis is demonstrated. The new stiffness method recently adopted in the US and Canada is explained. The essential features of emerging probabilistic methods of analysis are introduced.
3. Seismic design: GRS walls have most often performed well during earthquake. Examples of their performance under seismic loading are given. The reasons for their good performance are explained and the design methods used to quantify the additional seismic-induced external and internal loading are discussed.



Modes of failure

External

a) base sliding

b) bearing capacity (excessive settlement)

Internal

c) pullout

d) tensile over-stress

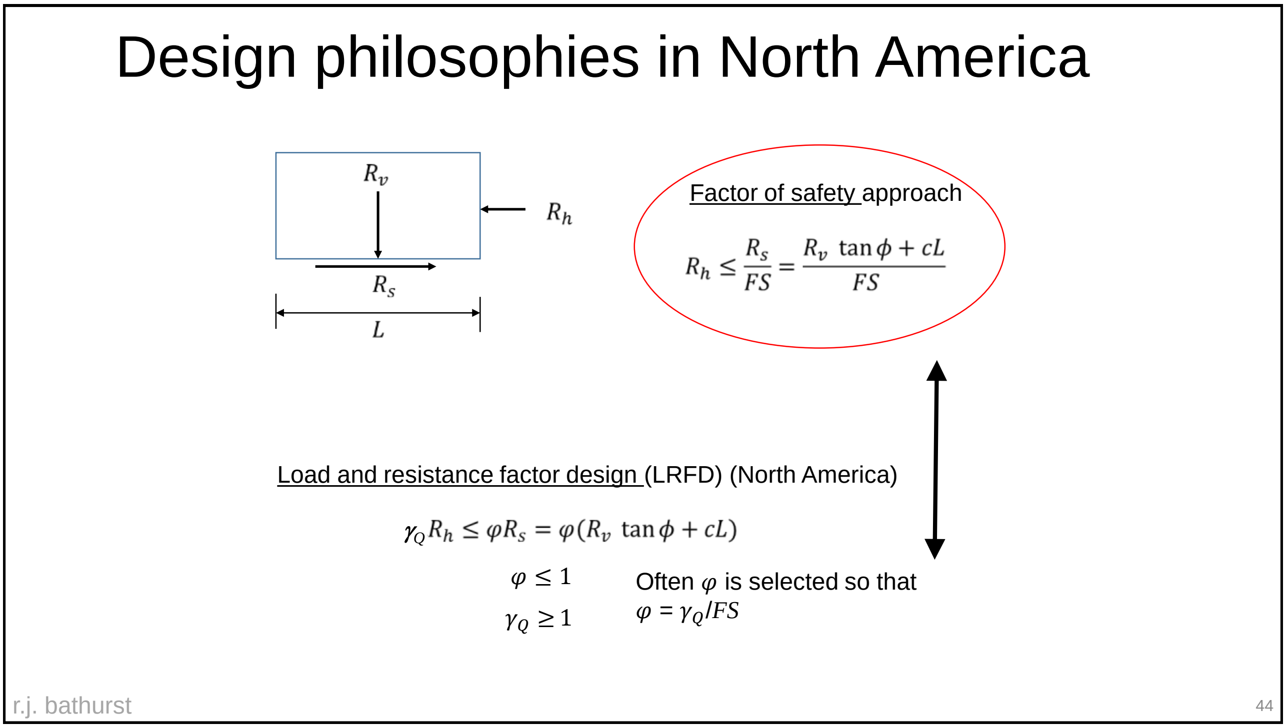
e) internal sliding

Facing

f) connection failure

g) column shear failure

h) toppling



Design philosophies in North America

Factor of safety approach

$$R_h \leq \frac{R_s}{FS} = \frac{R_v \tan\phi + cL}{FS}$$

Load and resistance factor design (LRFD) (North America)

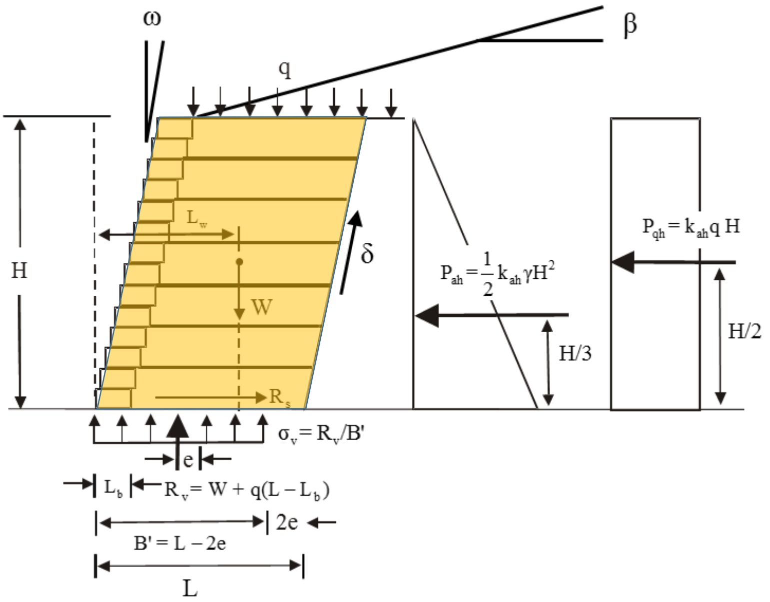
$$\gamma_Q R_h \leq \varphi R_s = \varphi(R_v \tan\phi + cL)$$

$$\varphi \leq 1$$

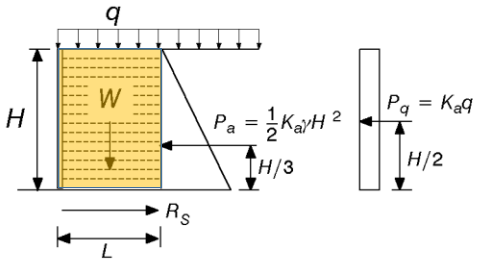
$$\gamma_Q \geq 1$$

Often φ is selected so that $\varphi = \gamma_Q / FS$

Geometry and forces for external stability limit states calculations



Base sliding



$$F.O.S = \frac{resisting\ force}{driving\ forces} = \frac{R_S}{P_a + P_q}$$

$$F.O.S = \frac{(W + qL) \times \mu}{P_a + P_q}$$

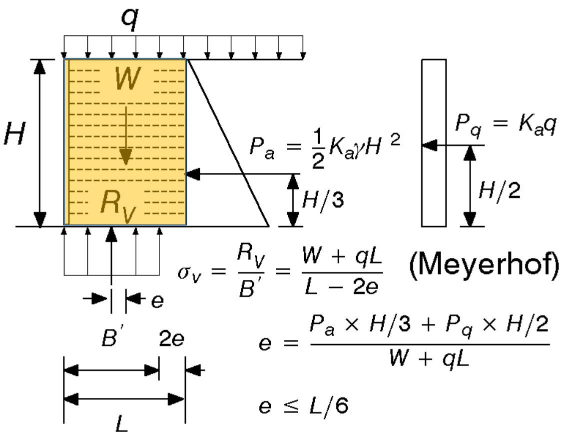
check sliding at soil–geosynthetic interface:

soil–geotextile:

$$\mu = \tan \phi_{sg} = \tan(2/3)\phi$$

$F.O.S \geq 1.5$ (FHWA 1989)

Bearing capacity



$$P_a = \frac{1}{2} K_a \gamma H^2$$

$$P_q = K_a q$$

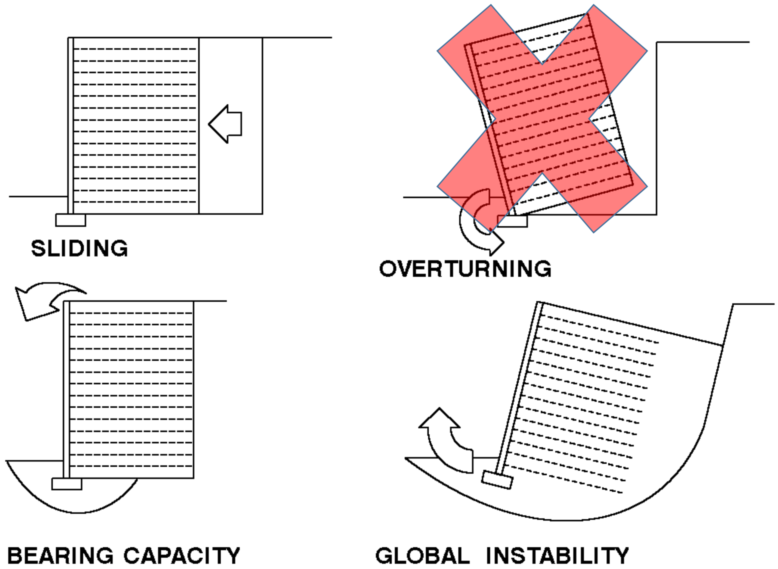
$$\sigma_v = \frac{R_V}{B'} = \frac{W + qL}{L - 2e} \quad \text{(Meyerhof)}$$

$$e = \frac{P_a \times H/3 + P_q \times H/2}{W + qL}$$

$$e \leq L/6$$

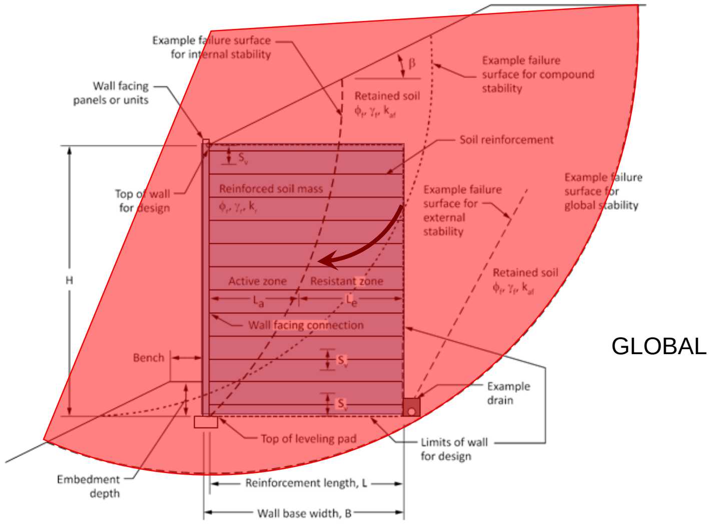
$$F.O.S = \frac{cN_c(\phi) + \frac{1}{2}\gamma B' N_\gamma(\phi)}{R_V/B'}$$

$$F.O.S \geq 2.0$$



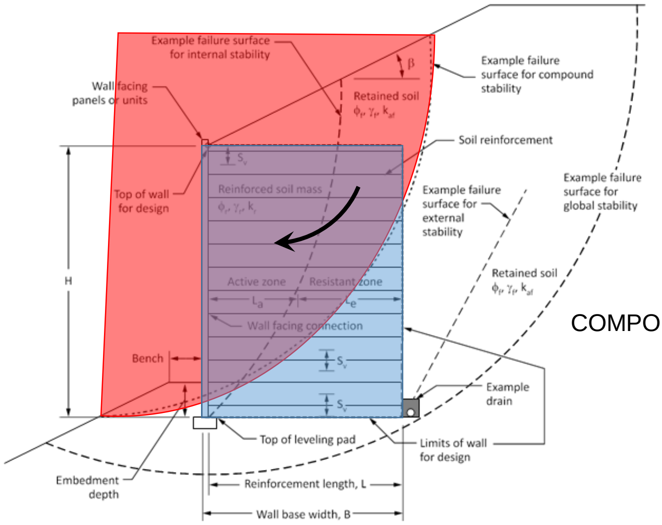
External modes of failure

Global and compound stability

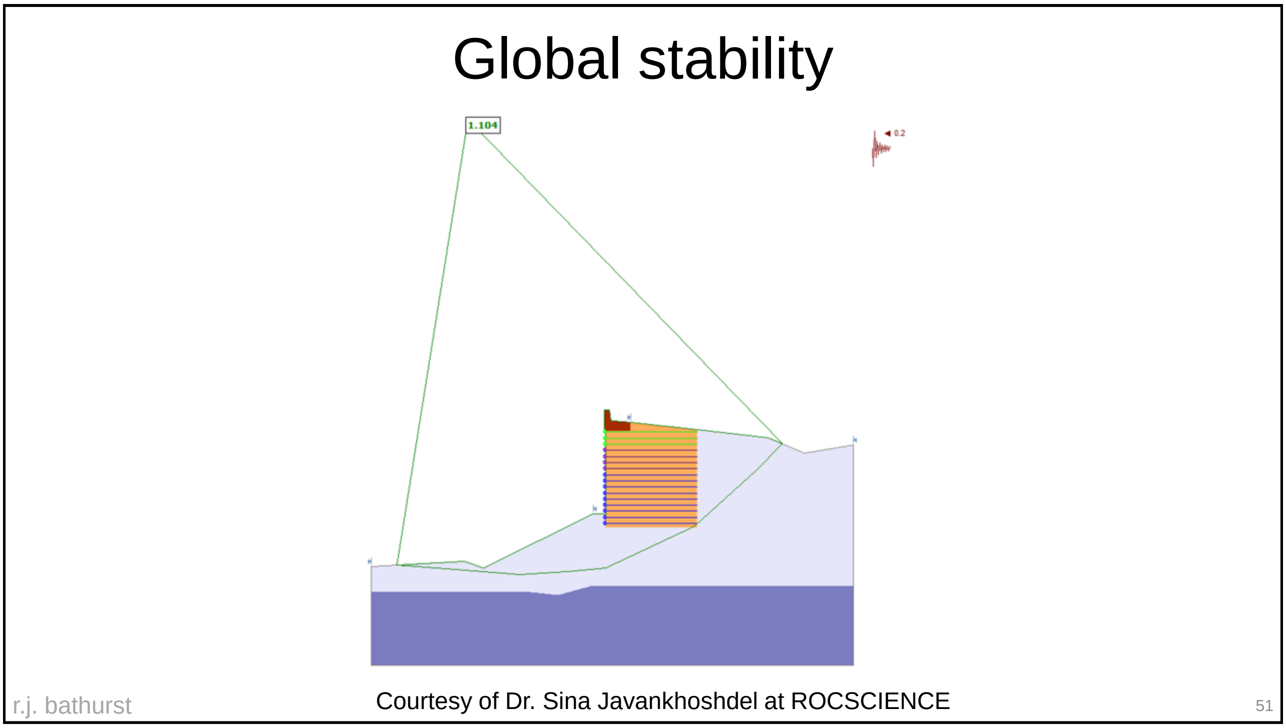


GLOBAL

Global and compound stability

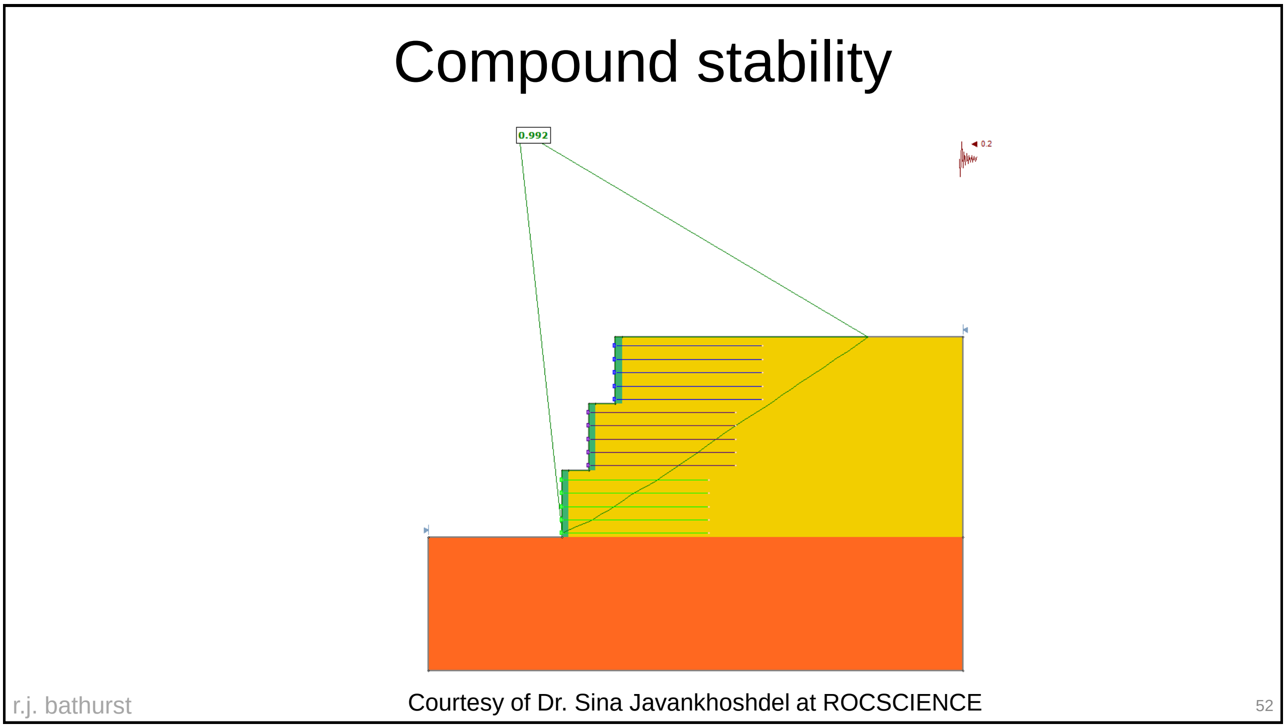


COMPOUND



Global stability

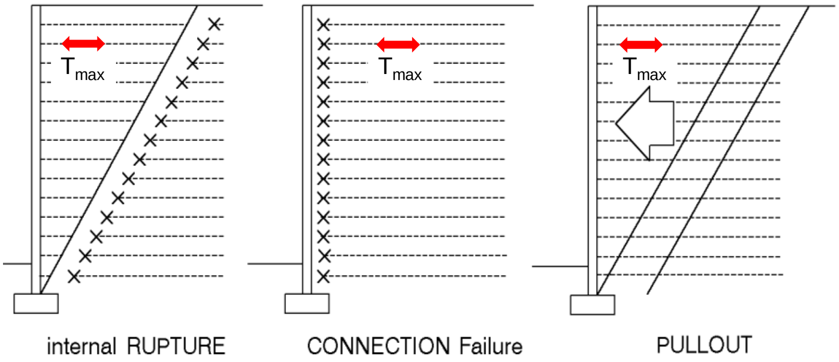
Courtesy of Dr. Sina Javankhoshdel at ROCSCIENCE



Compound stability

Courtesy of Dr. Sina Javankhoshdel at ROCSCIENCE

Calculation of the maximum tensile load T_{max} in the reinforcement under operational (serviceability) conditions

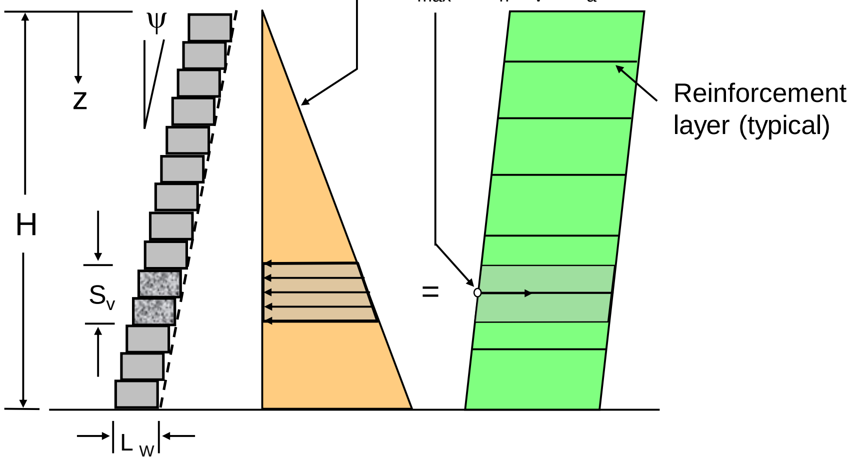


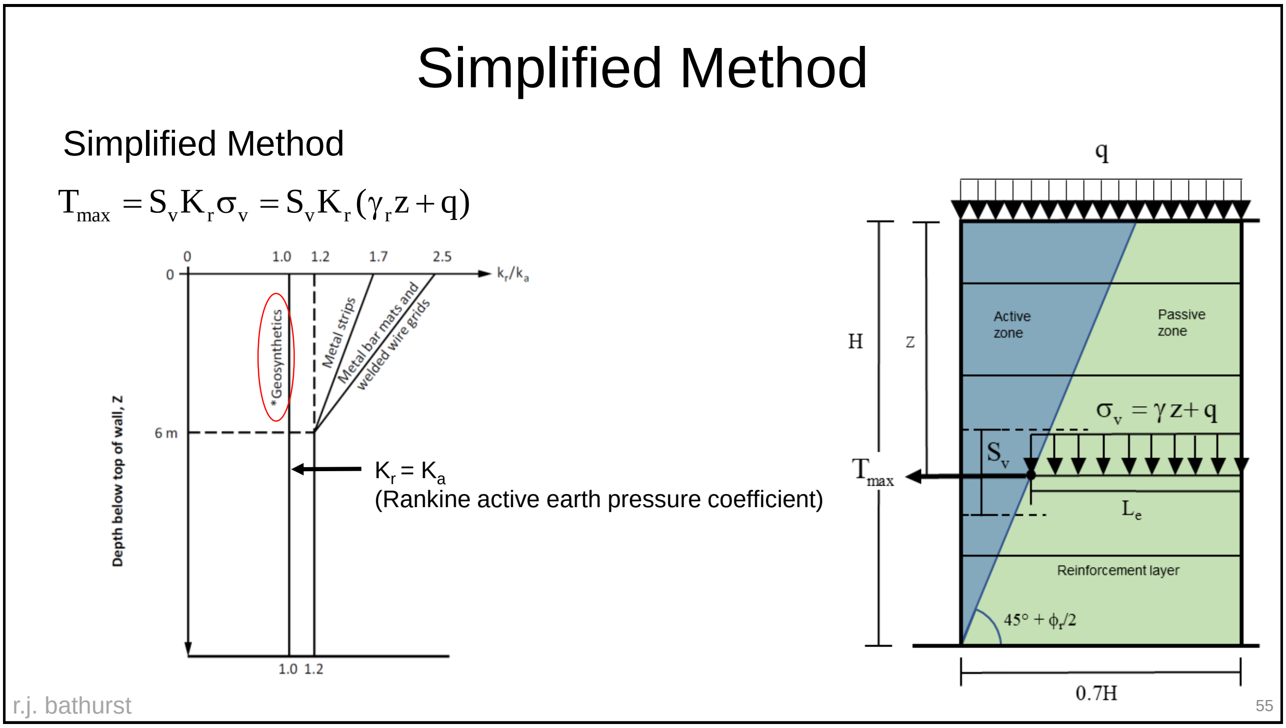
Calculation of reinforcement tensile load

Horizontal component of earth pressure distribution: $\sigma_h = K_r \gamma z$

Equivalent coefficient of earth pressure

$T_{max} = \sigma_h S_v < T_a / FS$





Simplified Method

Simplified Method

$$T_{max} = S_v K_r \sigma_v = S_v K_r (\gamma_r z + q)$$

$K_r = K_a$
(Rankine active earth pressure coefficient)

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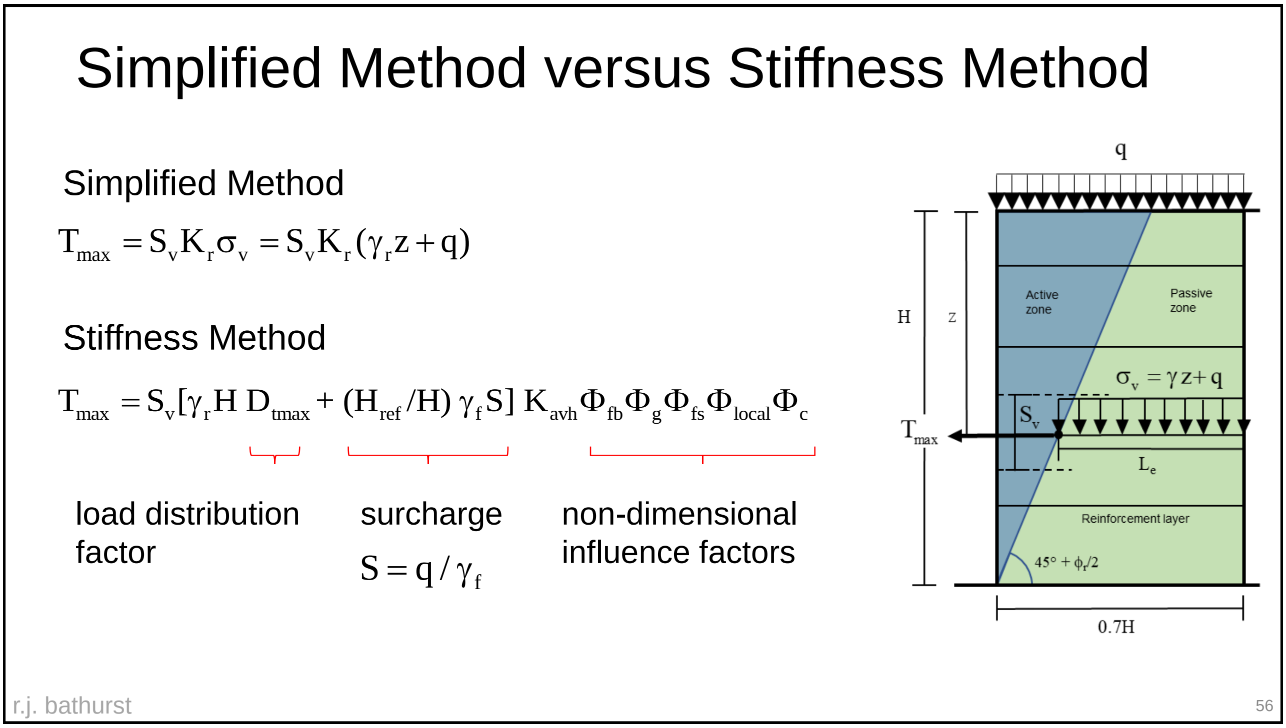

Simplified Method versus Stiffness Method

Simplified Method

$$T_{max} = S_v K_r \sigma_v = S_v K_r (\gamma_r z + q)$$

Stiffness Method

$$T_{max} = S_v [\gamma_r H \underbrace{D_{tmax}}_{\text{load distribution factor}} + \underbrace{(H_{ref}/H)\,\gamma_f S]}_{\text{surcharge}}\, K_{avh} \underbrace{\Phi_{fb}\Phi_g\Phi_{fs}\Phi_{local}\Phi_c}_{\text{non-dimensional influence factors}}$$

load distribution factor

surcharge

$S = q/\gamma_f$

non-dimensional influence factors

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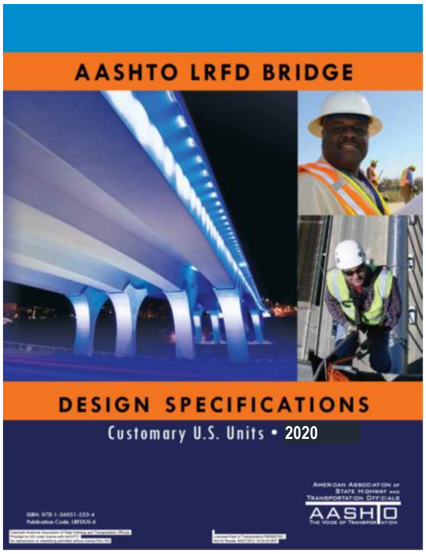
Simplified Method versus Stiffness Method

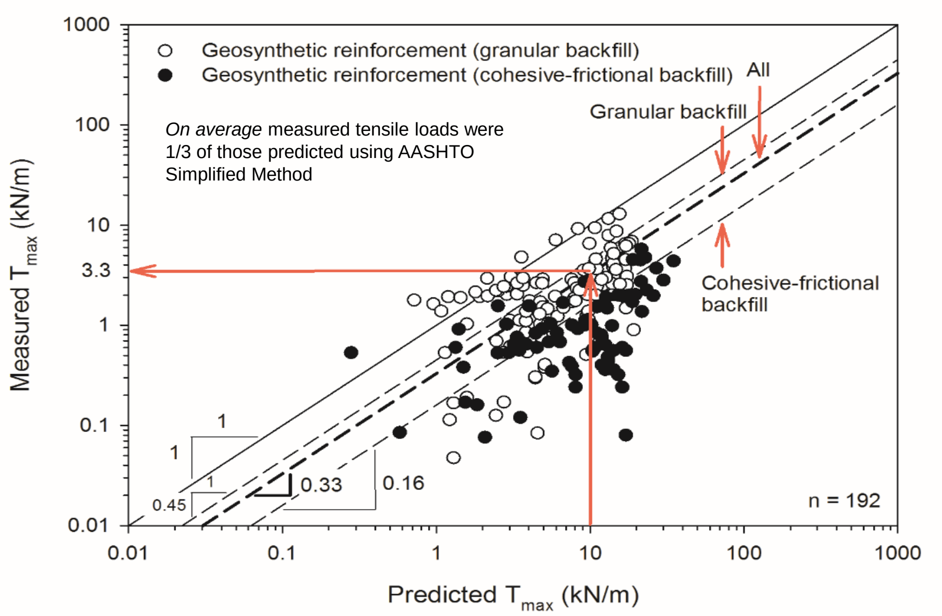
Stiffness Method is now specified for the internal stability design of geosynthetic mechanically stabilized earth (MSE) walls in AASHTO 2020 and as an accepted method in the Canadian Highway Bridge Design Code (CSA 2024) in Canada for extensible and inextensible MSE wall systems

A signature feature of this approach is the use of the creep-reduced tensile stiffness of the reinforcement as a key parameter to compute the magnitude of reinforcement loads under operational conditions

This is a paradigm shift from the Simplified Method in previous editions of the AASHTO code which is based on the soil peak friction angle for geosynthetic MSE walls

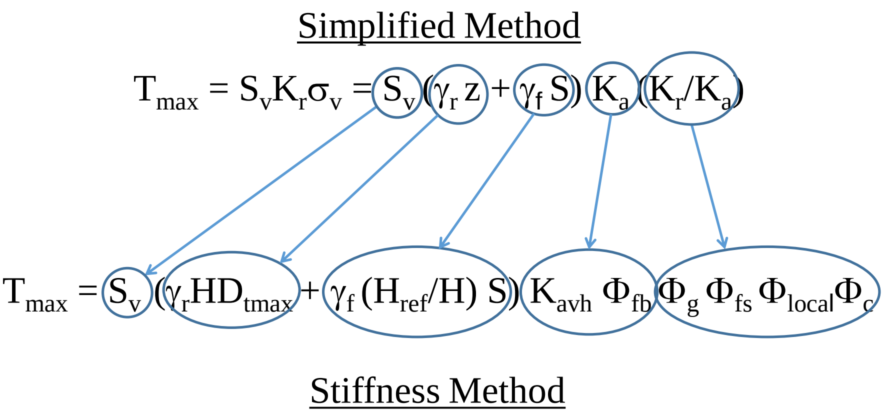


Accuracy of Simplified Method



On average measured tensile loads were 1/3 of those predicted using AASHTO Simplified Method

Simplified Method versus Stiffness Method



Simplified Method

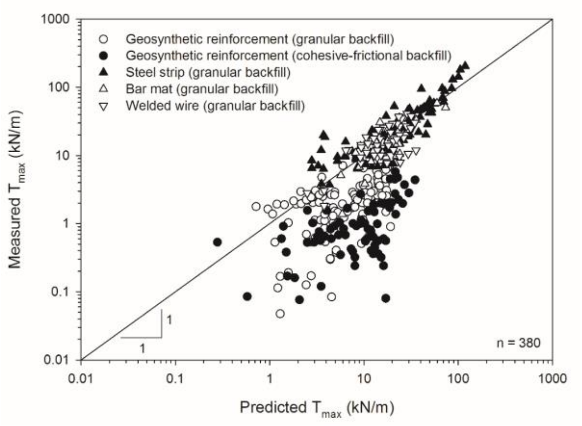
$$T_{max} = S_v K_r \sigma_v = S_v(\gamma_r z + \gamma_f S) K_a (K_r/K_a)$$

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

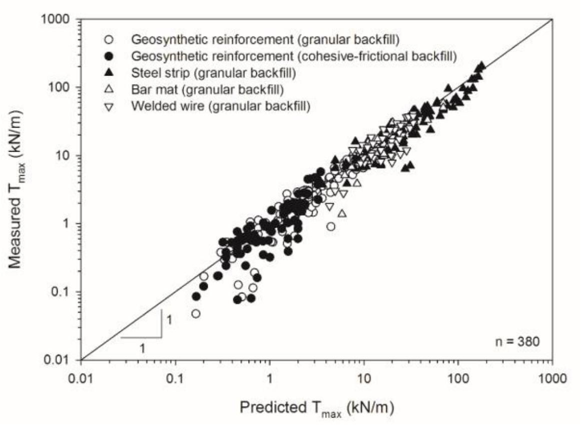
Stiffness Method

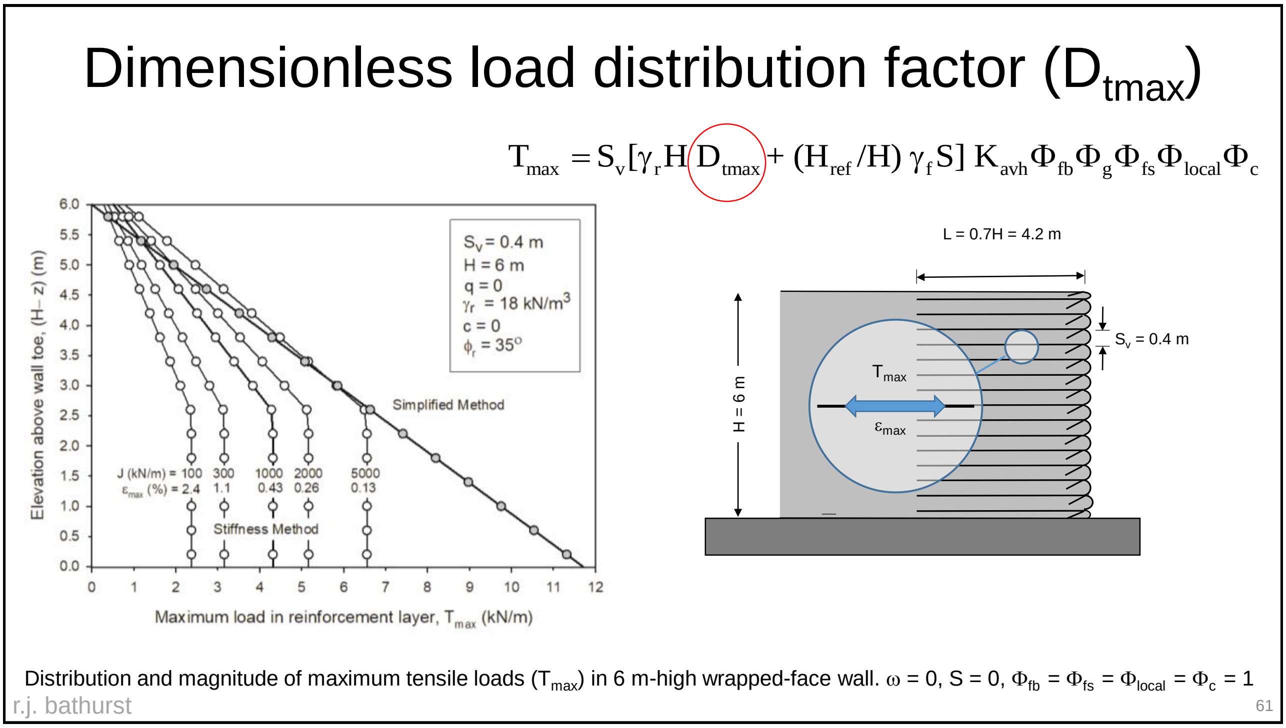
Relative accuracy

Simplified Method



Stiffness Method ✓





Dimensionless load distribution factor (D_{tmax})

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

Distribution and magnitude of maximum tensile loads (T_{max}) in 6 m-high wrapped-face wall. $\omega = 0$, $S = 0$, $\Phi_{fb} = \Phi_{fs} = \Phi_{local} = \Phi_c = 1$

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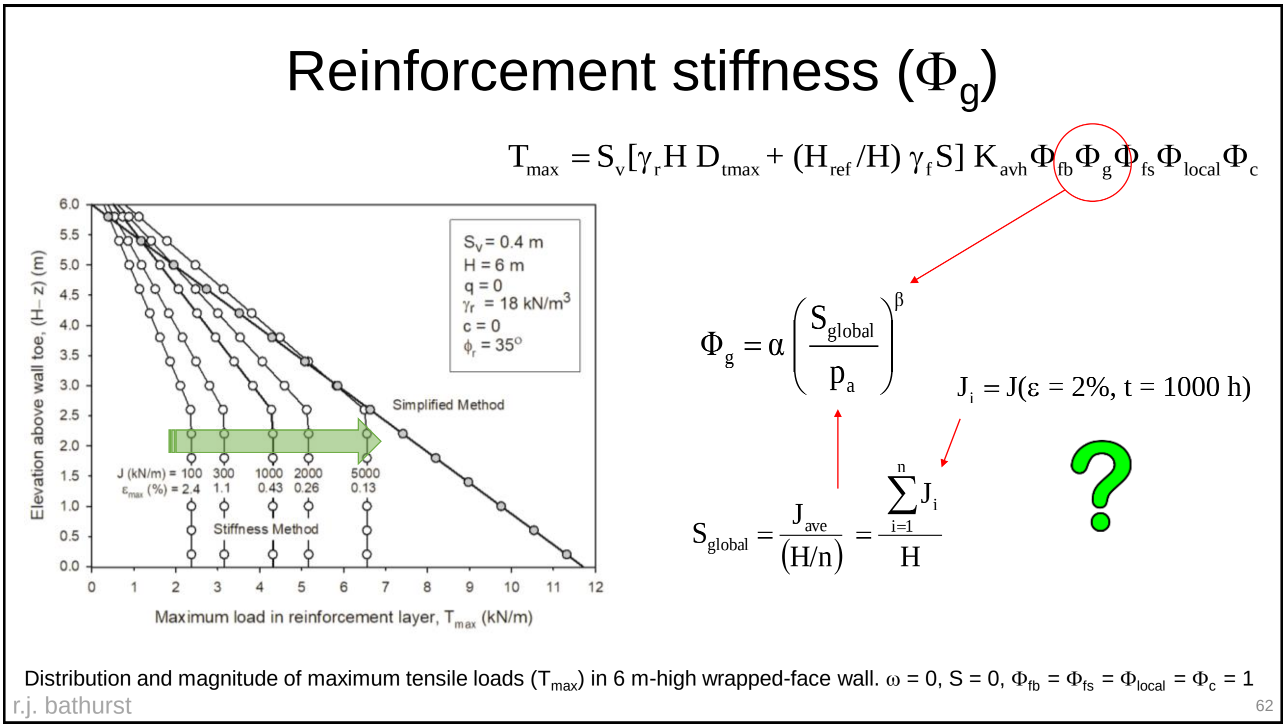

Reinforcement stiffness (Φ_g)

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

$$\Phi_g = \alpha\left(\frac{S_{global}}{p_a}\right)^{\beta}$$

$$J_i = J(\varepsilon = 2\%,\ t = 1000\ h)$$

$$S_{global} = \frac{J_{ave}}{(H/n)} = \frac{\sum_{i=1}^{n} J_i}{H}$$

?

Distribution and magnitude of maximum tensile loads (T_{max}) in 6 m-high wrapped-face wall. $\omega = 0$, $S = 0$, $\Phi_{fb} = \Phi_{fs} = \Phi_{local} = \Phi_c = 1$

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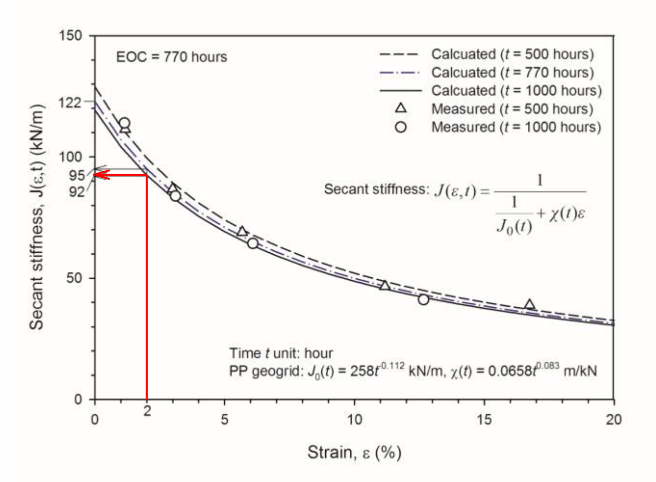
Reinforcement stiffness at 1000 hours and 2% strain



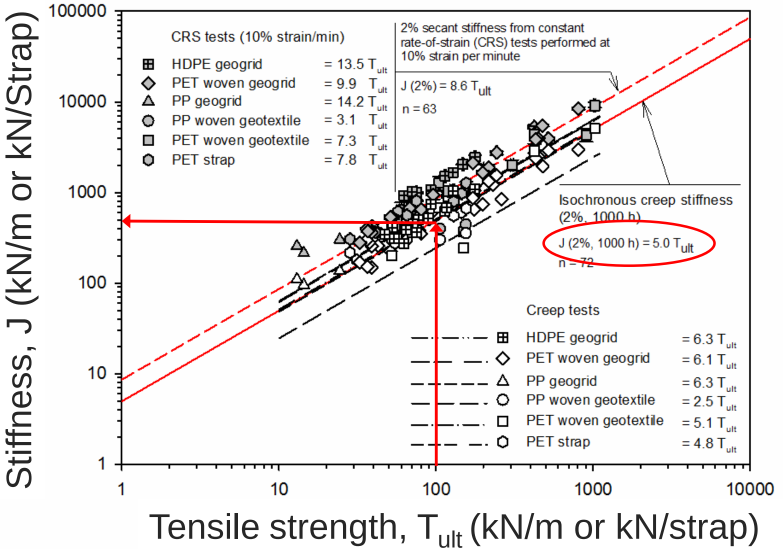
This value is included in manufacturer/supplier AASHTO NTPEP reports

Yu, Y., Bathurst, R.J., Allen, T.M. and Nelson, R. 2016. Physical and numerical modelling of a geogrid reinforced incremental concrete panel retaining wall. Canadian Geotechnical Journal 53(12): 1883-1901

Stiffness versus strength

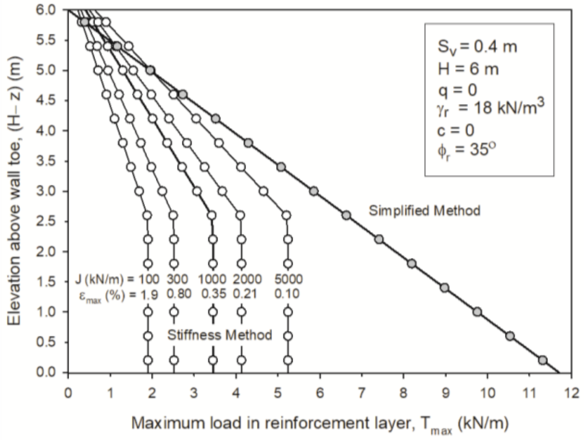
Useful approximations can be found in
Bathurst and Naftchali (2021)

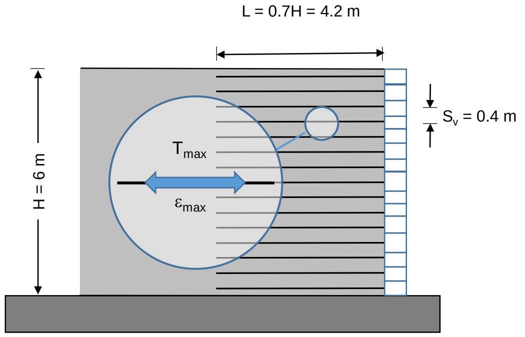
$$J = a \times T_{ult}$$



Facing stiffness factor (Φ_{fs})

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

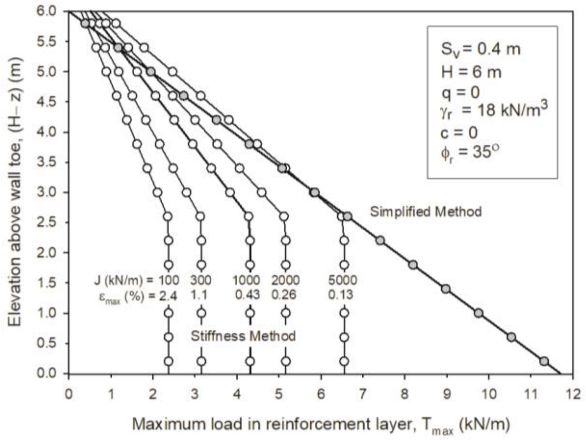


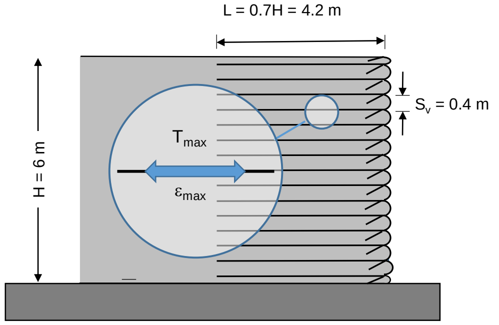


Distribution and magnitude of maximum tensile loads in 6 m-high block-face wall. ω = 0, S = 0, Φ_{fs} = 0.80, Φ_{fb} = Φ_{local} = Φ_c = 1.

Facing stiffness factor (Φ_{fs})

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





Distribution and magnitude of maximum tensile loads (T_{max}) in 6 m-high wrapped-face wall. ω = 0, S = 0, Φ_{fb} = Φ_{fs} = Φ_{local} = Φ_c = 1

Influence factors Φ_{fb} and Φ_{local}

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

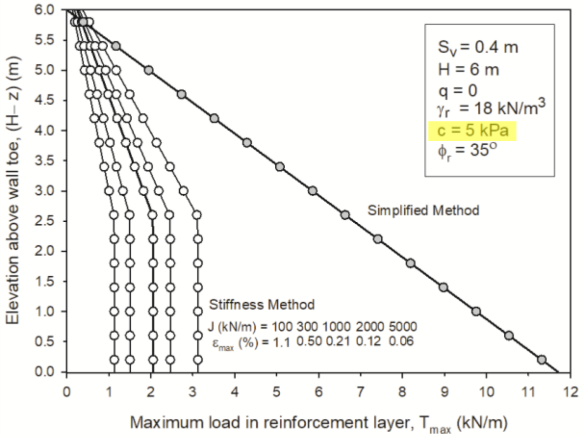
- As the facing batter angle (ω) from the vertical increases, the loads in the reinforcement layers will decrease.
- $\Phi_{fb} = 1$ for vertical-faced walls and decreases with increasing batter angle measured from the vertical.
- For vertical or near-vertical walls (e.g., facing angle $\omega \leq 10°$), Φ_{fb} can be taken as 1 with little practical error.

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

- The magnitude of maximum reinforcement loads can be influenced by local changes in spacing and reinforcement type (i.e., different stiffness J_i).
- Default value $\Phi_{local} = 1$ corresponding to the case when all layers are equally spaced and have the same stiffness.

Soil cohesion

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

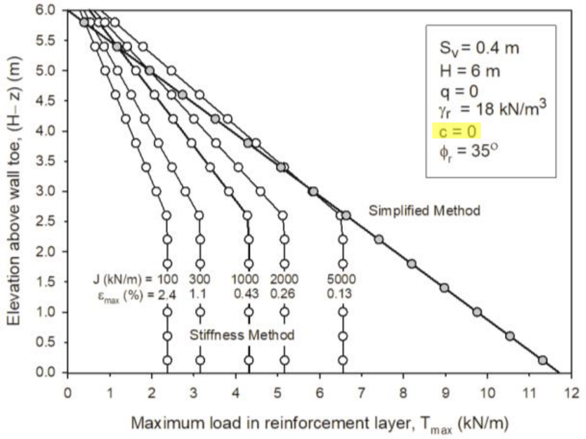


1. A permanent and consistent cohesive strength component ($c > 0$) in the reinforced soil backfill will reduce the earth pressure that would otherwise be carried by a purely frictional soil.
2. Φ_c ranges from 0 to 1 with the value of 1 corresponding to the no-cohesion case ($c = 0$).
3. $\Phi_c < 1$ values can only be used if the c-ϕ soil has significant true cohesion due to clay content and defined by plasticity index PI > 6, and this cohesion will persist over the lifetime of the structure.
4. Excludes the case of a transient apparent cohesion due to matric suction for partially saturated granular soils as well as c-ϕ soils that could soften/weaken over time due to moisture or deformation.

Distribution and magnitude of maximum tensile loads (T_{max}) in 6 m-high wrapped-face wall. $\omega = 0$, $S = 0$, $\Phi_{fb} = \Phi_{fs} = \Phi_{local} = 1$, $\Phi_c = 0.5$

Soil cohesion

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



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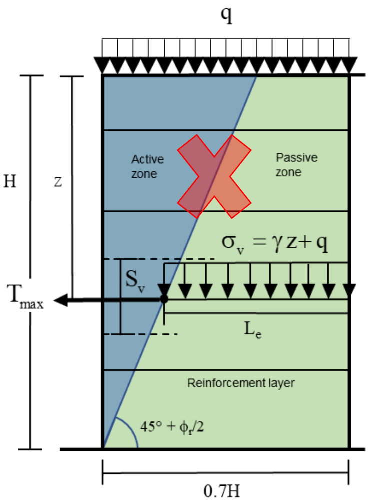
Distribution and magnitude of maximum tensile loads (T_{max}) in 6 m-high wrapped-face wall. $\omega = 0$, S = 0, $\Phi_{fb} = \Phi_{fs} = \Phi_{local} = \Phi_c = 1$

Soil failure limit state

- The soil failure limit state is used to ensure that the reinforced soil zone remains at a working stress condition consistent with operational conditions.
- This limit state does not appear in the Simplified Method which is a fully force-based design approach.
- For the assumption of working stress conditions to be valid, the soil <u>must not fail</u> (i.e., develop a contiguous failure mechanism through the reinforced soil zone).



Soil failure limit state

maximum reinforcement load

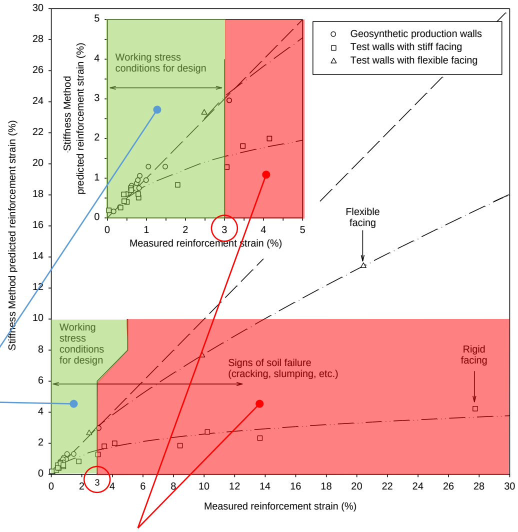
$$\varepsilon = \frac{T_{max}}{J}$$

reinforcement stiffness

Use strain in the reinforcement as indicator of soil failure

Working stress conditions

Signs of soil failure (cracking, slumping, continuous creep, etc)



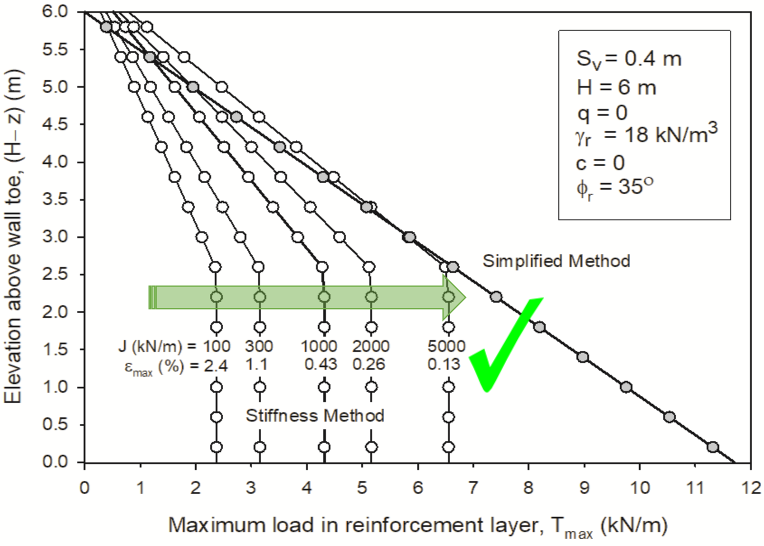
Allen, T.M., Bathurst, R.J., Walters, D.L., Holtz, R.D. and Lee, W.F. 2003. A new working stress method for prediction of reinforcement loads in geosynthetic walls. Canadian Geotechnical Journal, 40(5), 976-994.

Soil failure limit state

maximum reinforcement load

$$\varepsilon = \frac{T_{max}}{J}$$

reinforcement stiffness



For many walls …

facing batter < 10 degrees from vertical

no surcharge

single reinforcement type

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

no cohesion

For many walls ➡ $T_{max} = S_v[\gamma_r H\, D_{tmax}]\, K_{avh}\, \Phi_g\, \Phi_{fs}$

REFERENCES

Bathurst, R.J. and Allen, T.M. 2023. LRFD calibration for soil failure limit state using the Stiffness Method. Canadian Geotechnical Journal 60(7): 1006-1014 (https://doi.org/10.1139/cgj-2022-0499).

Allen, T.M. and Bathurst, R.J. 2019. Geosynthetic reinforcement stiffness characterization for MSE wall design. Geosynthetics International 26(6): 592–610 (https://dx.doi.org/10.1680/jgein.19.00041).

Allen, T.M. and Bathurst, R.J. 2018. Application of the Simplified Stiffness Method to design of reinforced soil walls. ASCE Journal of Geotechnical and Geoenvironmental Engineering 144(5): 04018024.(http://dx.doi.org/10.1061/(ASCE)GT.1943-5606.0001874).

Allen, T.M. and Bathurst, R.J. 2015. An improved simplified method for prediction of loads in reinforced soil walls. ASCE Journal of Geotechnical and Geoenvironmental Engineering 141(11): 04015049 (http://ascelibrary.org/doi/10.1061/%28ASCE%29GT.1943-5606.0001355).