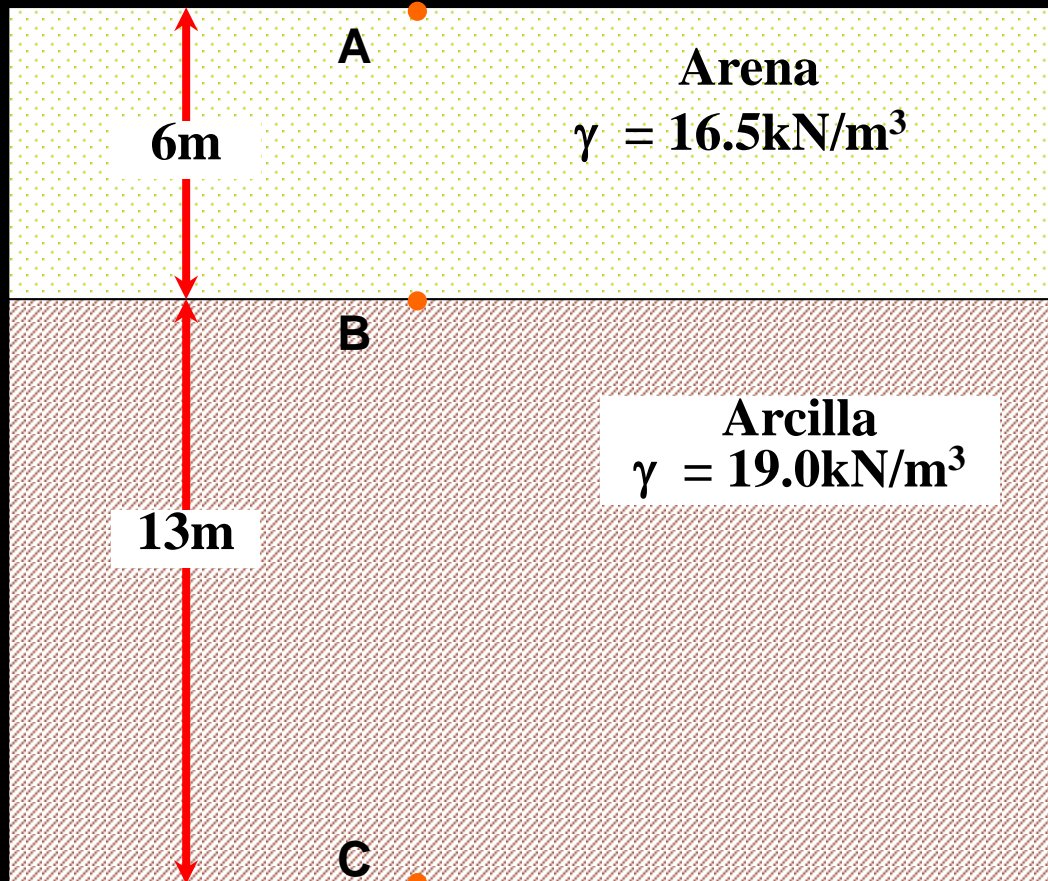


Esfuerzos Horizontales y Presiones Laterales

Parte I: Conceptos Básicos de Mecánica de Suelos

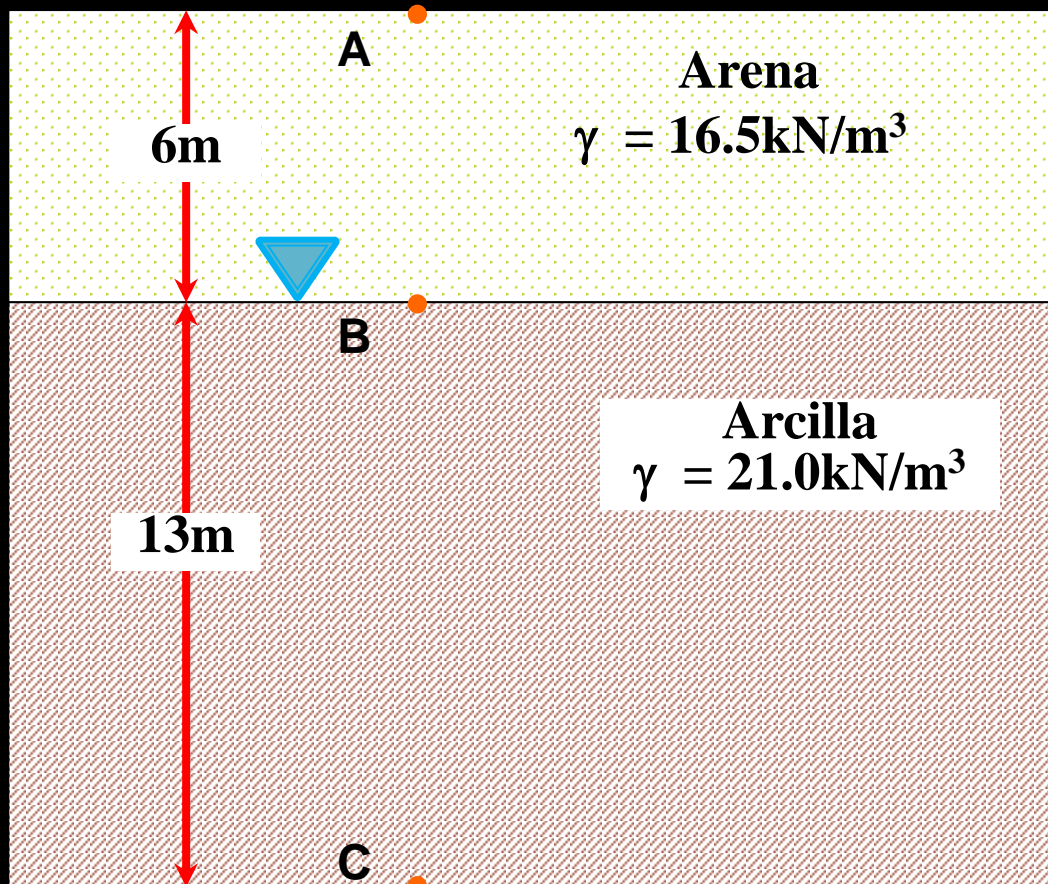
Esfuerzos Geostáticos Verticales – Ejemplo

Suelo Seco



Esfuerzos Geostáticos Verticales – Ejemplo

Suelo Seco



Esfuerzos geostáticos verticales

Asumimos que este esfuerzo vertical actúa sobre toda el área analizada y lo denominamos:

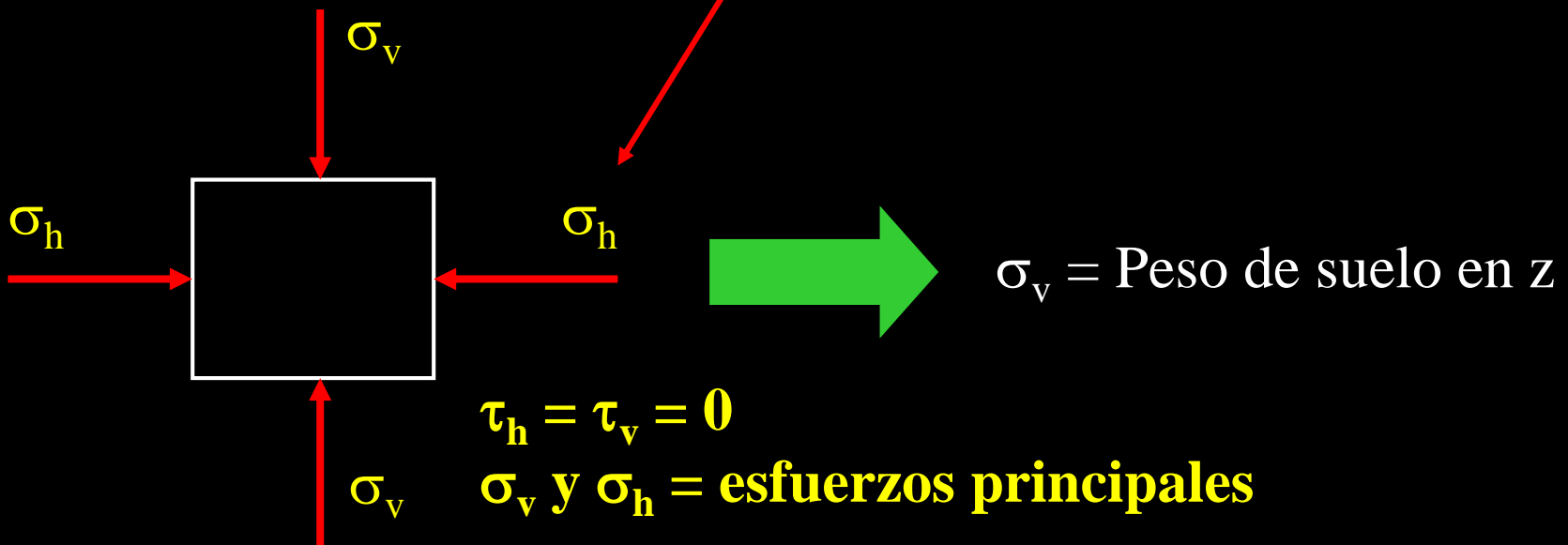
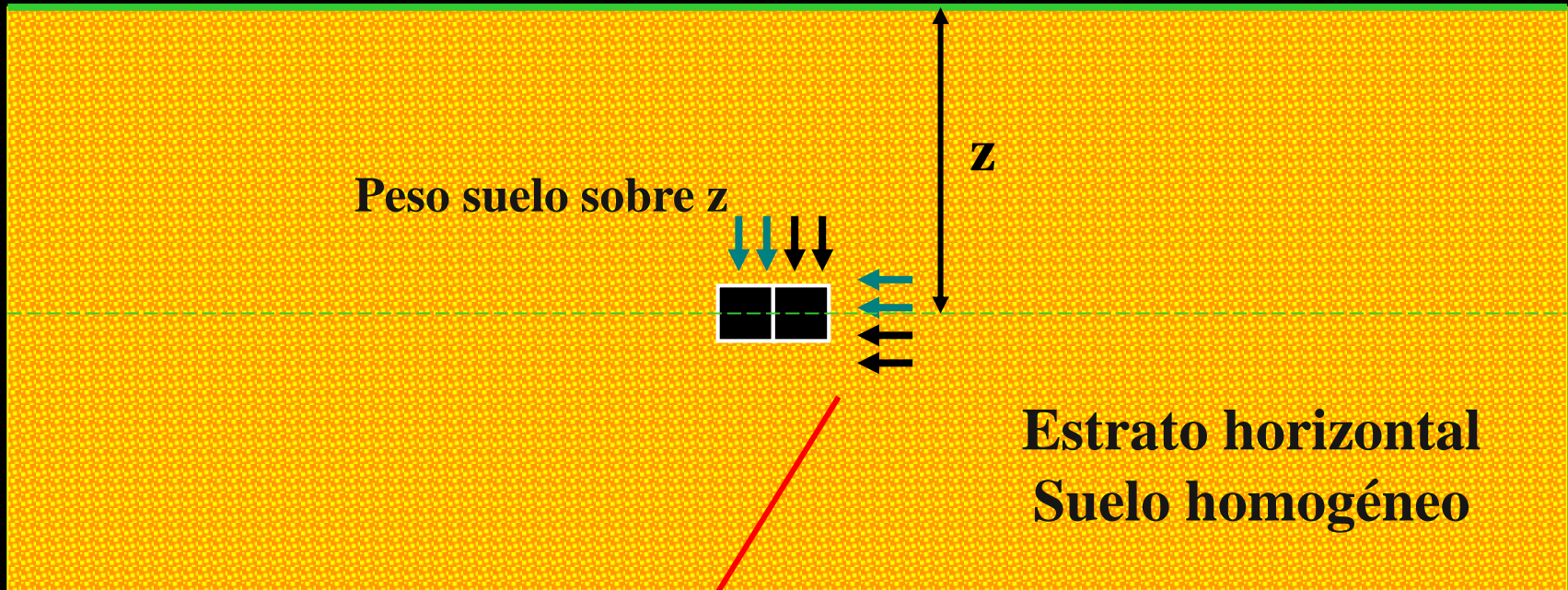
Esfuerzo vertical total (σ_{VT})

Suelos estratificados

$$\sigma_{VT} = \sum \gamma \cdot \Delta z$$

Si el suelo se encuentra saturado:

Esfuerzos Geostáticos HORIZONTALES

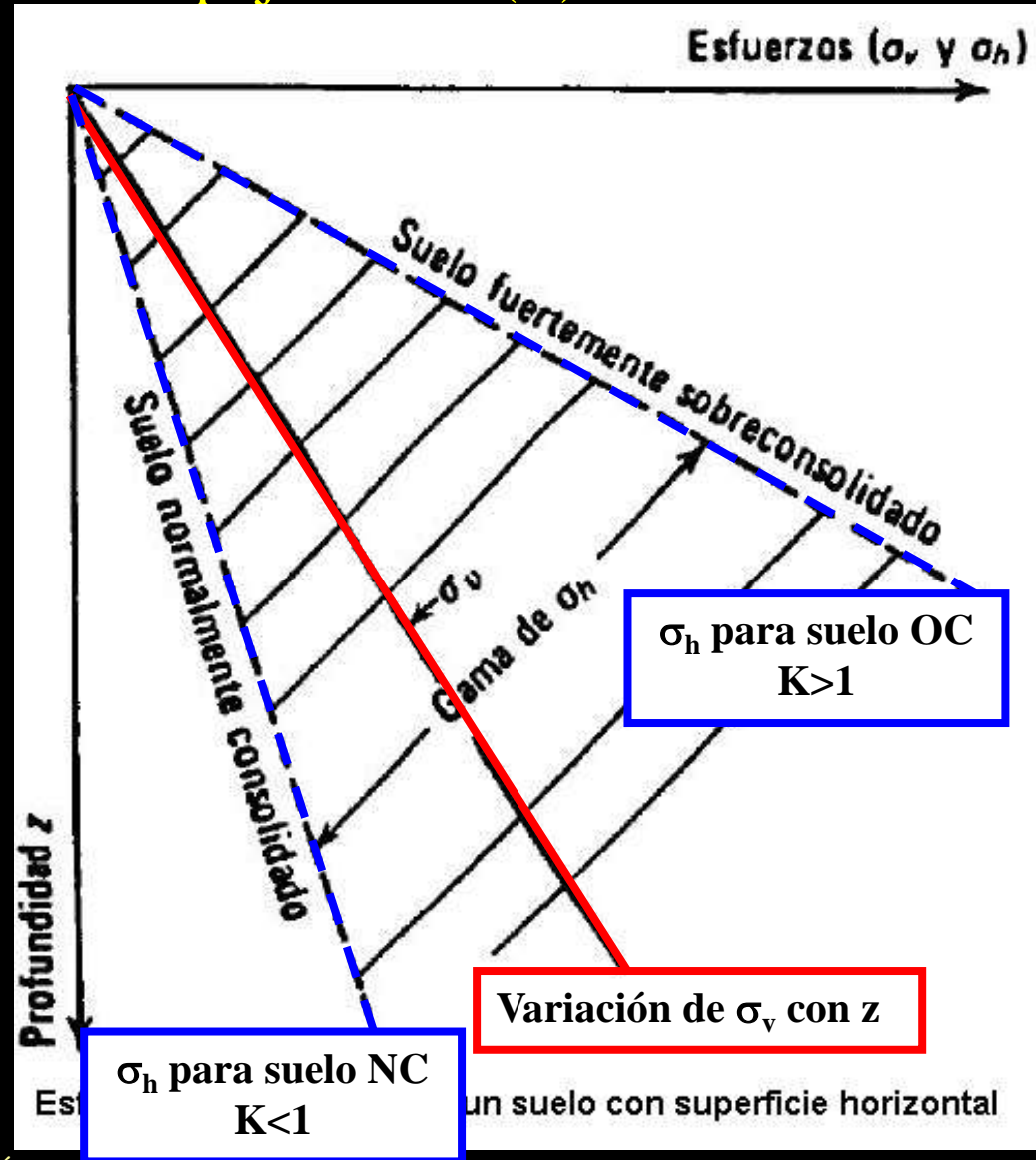


Esfuerzos geostáticos horizontales

En general σ_v vs. σ_h : **Coefficiente de empuje lateral (K)**

$$K = \frac{\sigma_h}{\sigma_v}$$

K varía según el suelo se comprima o expanda en dirección horizontal por razones naturales o por intervención humana



Coeficiente de Empuje Lateral en Reposo (K_0)

Caso particular de K sin deformación lateral del terreno

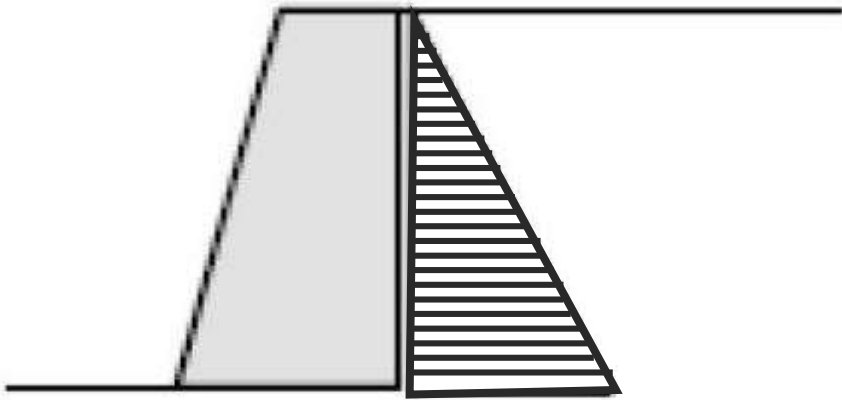
$$K_0 = \frac{\sigma_h}{\sigma_v}$$

- Suelo sedimentario “normalmente consolidado (NC)”: ($\sigma_h < \sigma_v$)
Depósito de arena formado por deposición de abajo hacia arriba:
 - $K_0 = 0.4$ a 0.5
- Suelo sedimentario “sobreconsolidado (OC)”: σ_h no se disipa al descargar, queda “congelado” $\therefore (\sigma_h > \sigma_v)$
 - K_0 puede llegar a 3

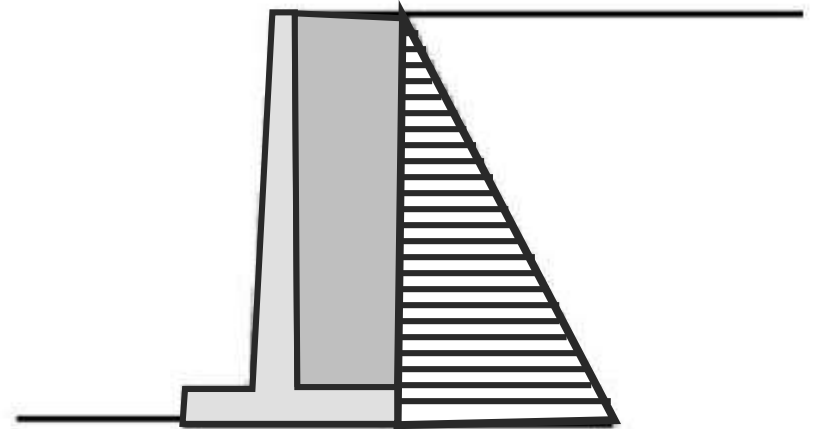
Empujes de tierras

- ◆ Problema de interacción suelo-estructura
- ◆ Presiones dependerán de:
 - la dirección en la que se mueve la estructura con respecto al suelo de relleno (hacia adentro o hacia afuera),
 - la magnitud del movimiento (1 in. versus 6 in.),
 - a su vez el movimiento de la estructura dependerá de la magnitud de las presiones

Presiones sobre estructuras de retención

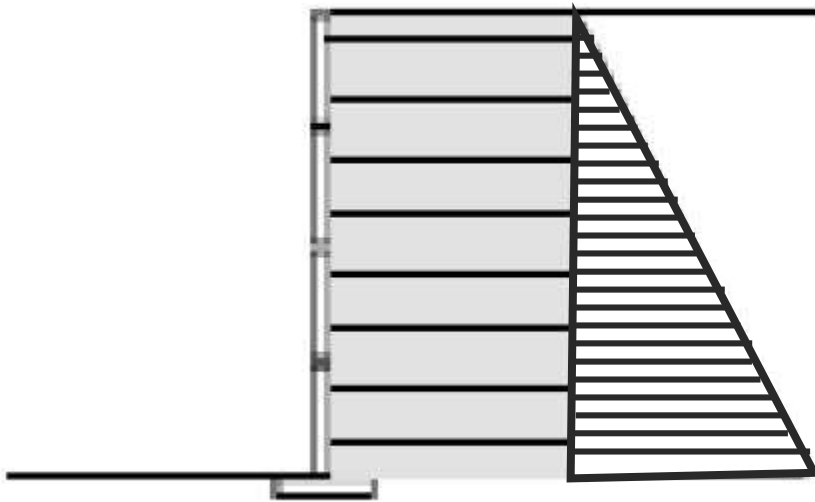


Muros de gravedad
(Gaviones)

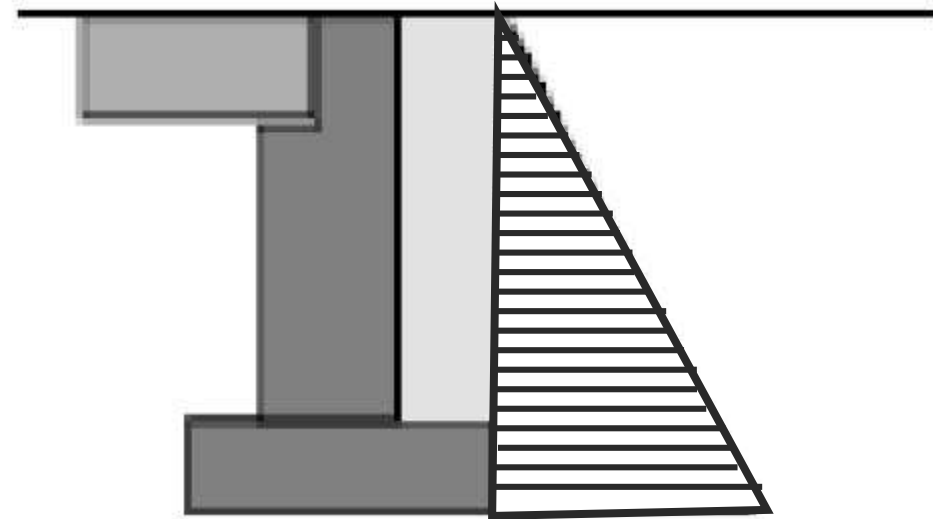


Muros voladizo
(Cantilever retaining wall)

Presiones sobre estructuras de retención

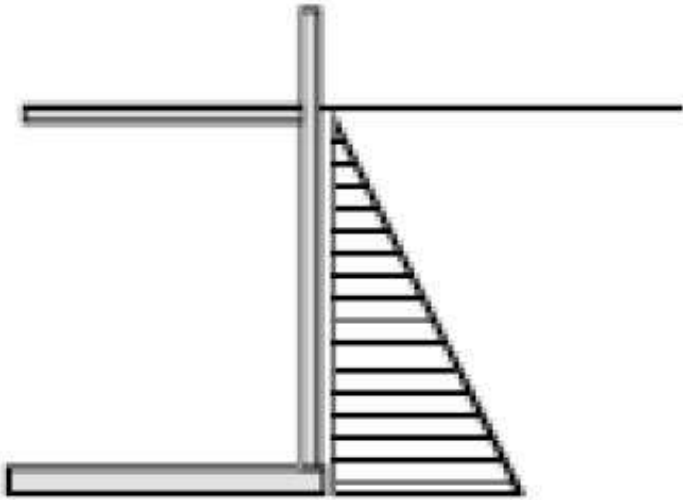


Muros de Tierra Reforzada

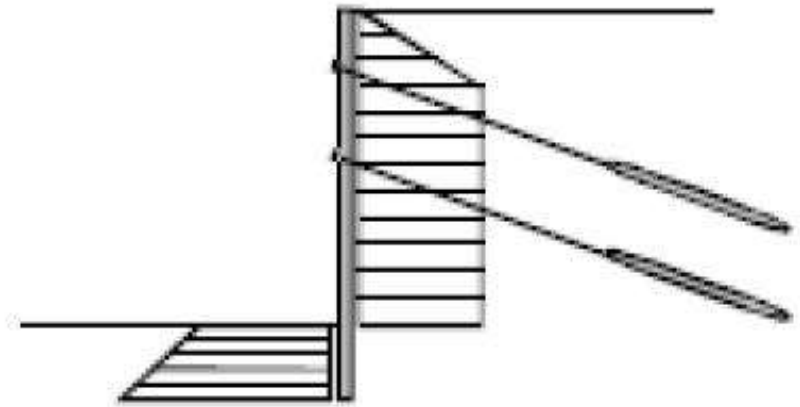


Estribos de un puente

Presiones sobre estructuras de retención

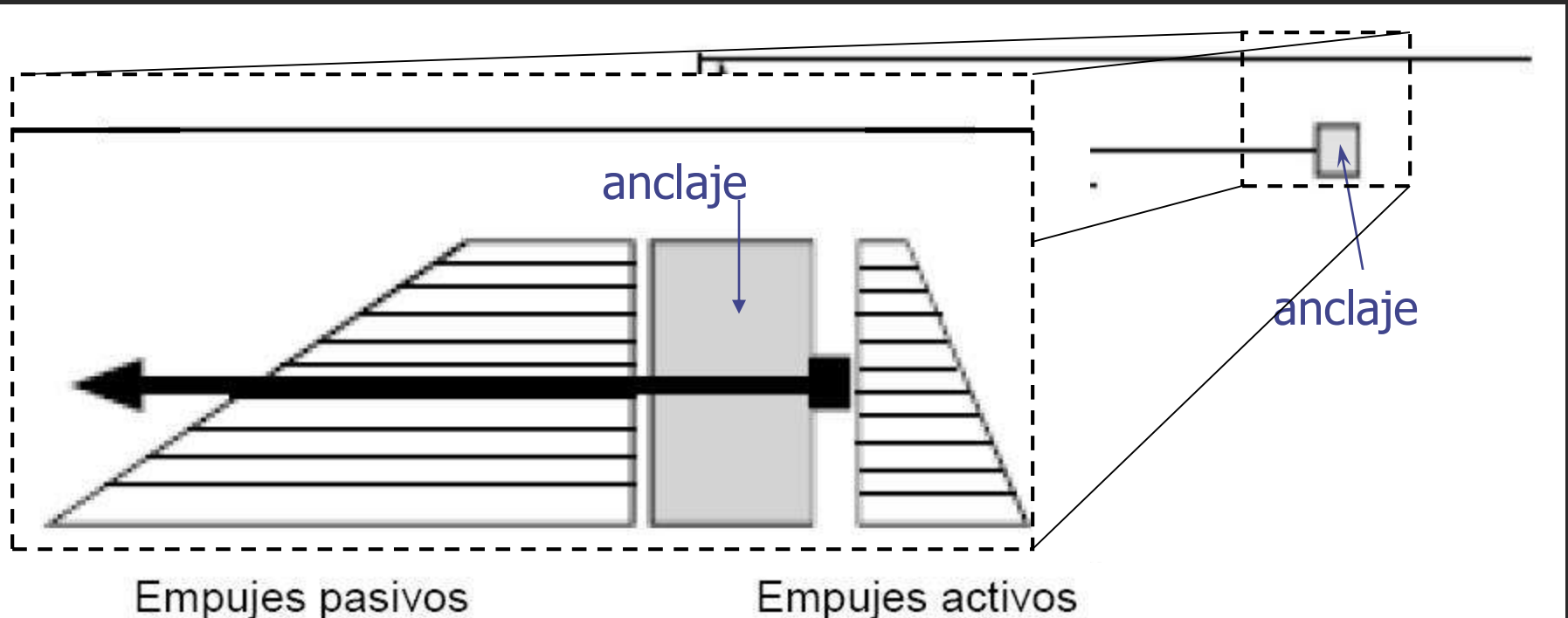


Sótano (basement)



Excavación-tieback

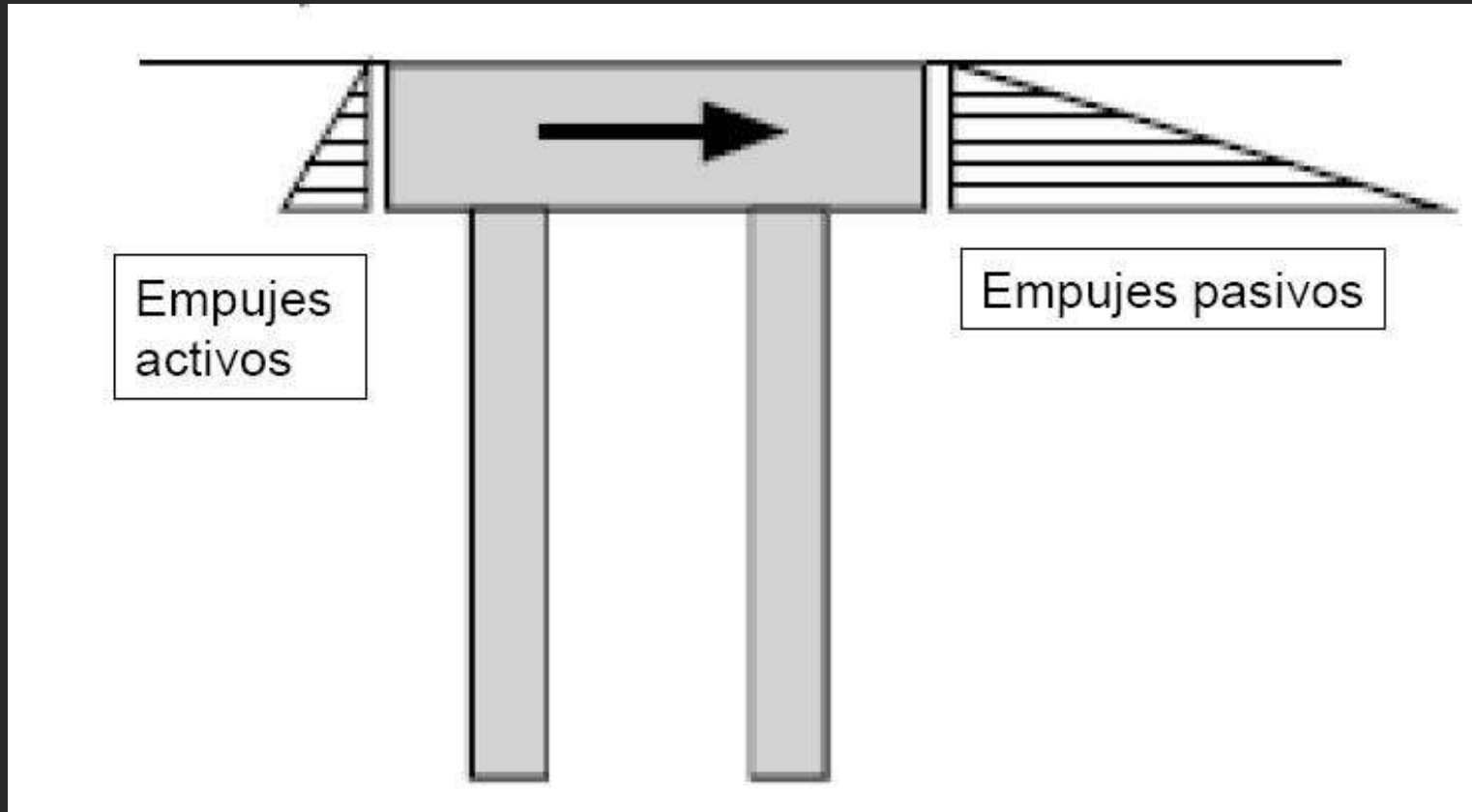
Presiones sobre estructuras de retención



Tablaestacas con anclaje "deadman"

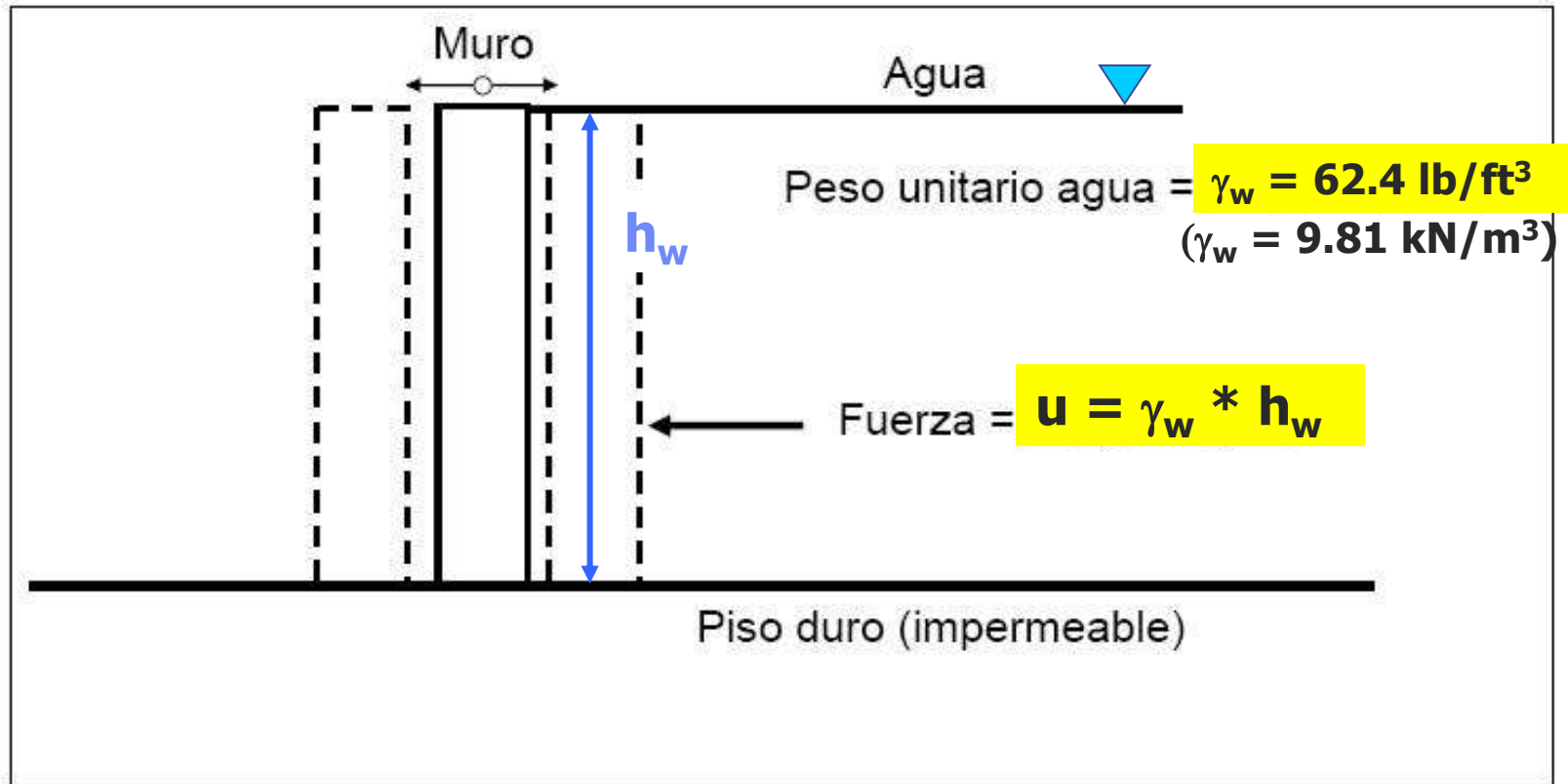
Las presiones son generadas al resistir el movimiento de las estructuras

Presiones generadas al resistir movimiento de estructuras

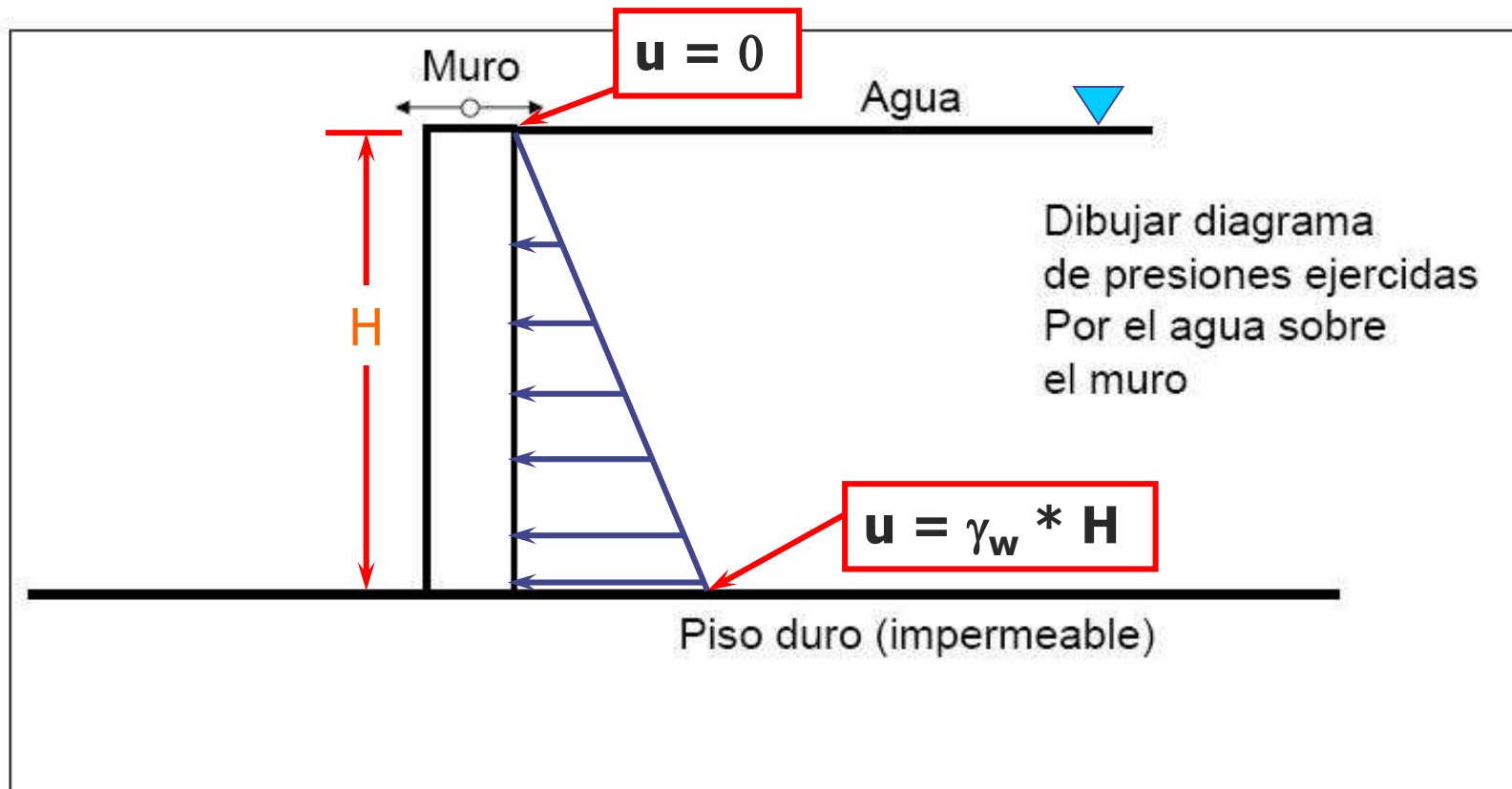


Grupo de pilotes con viga cabezal (pile cap)

Presiones ejercidas por el agua



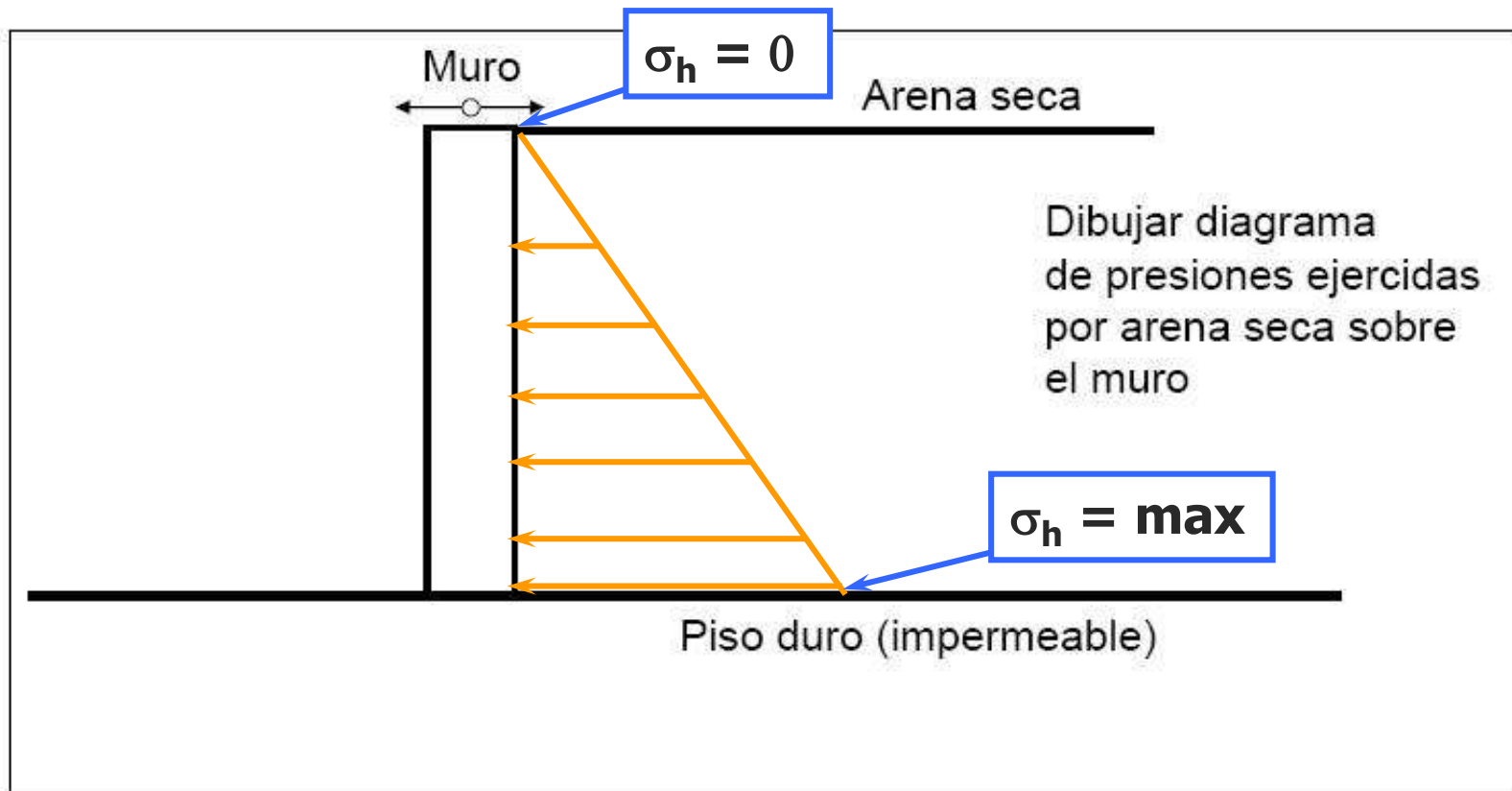
Presiones ejercidas por el agua



Presiones ejercidas por arena seca



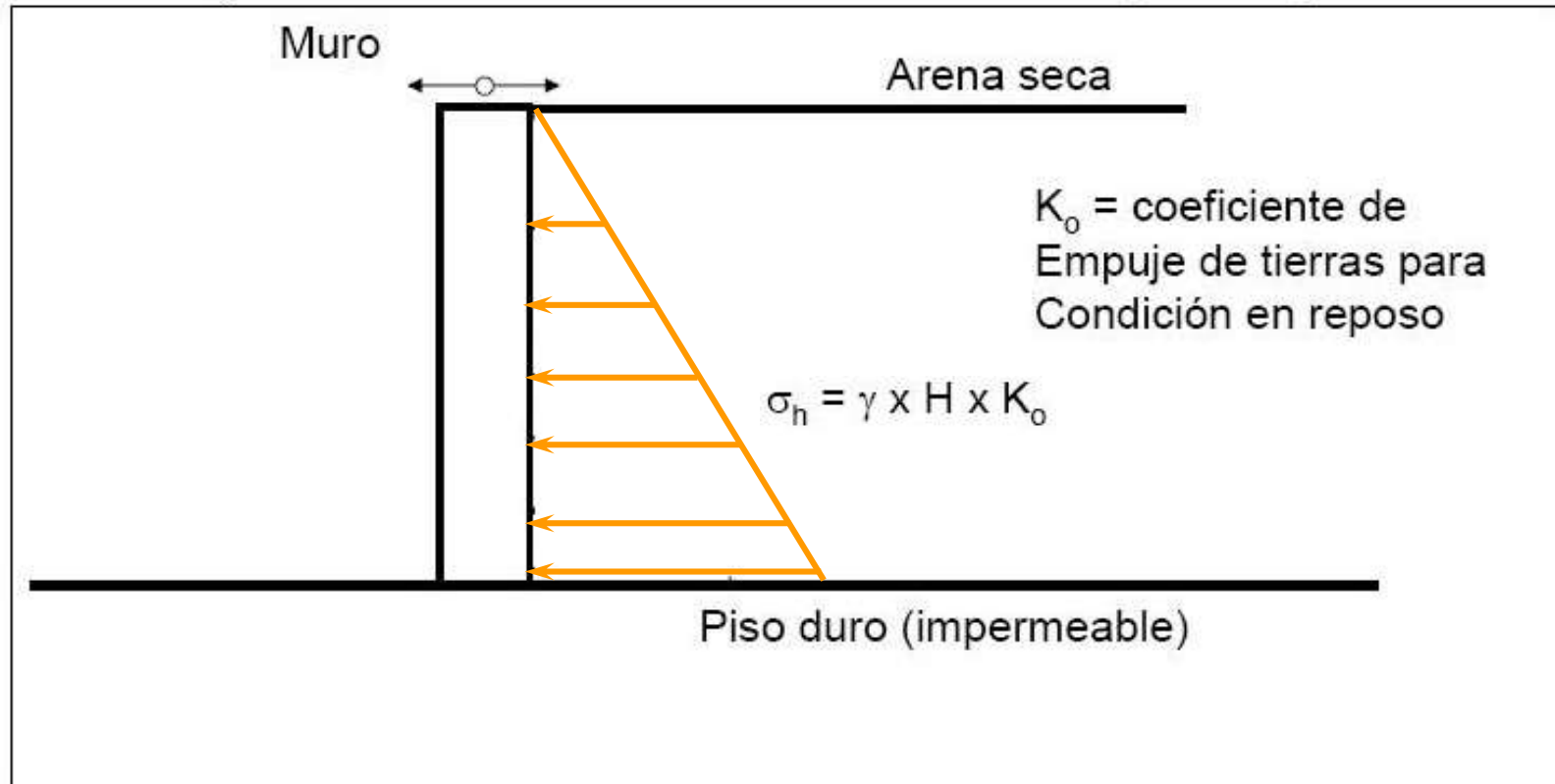
Presiones ejercidas por arena seca



Importante diferencia! Aquí las presiones dependen de la dirección del movimiento del muro (adentro o afuera) y magnitud del movimiento

Presiones ejercidas por arena seca

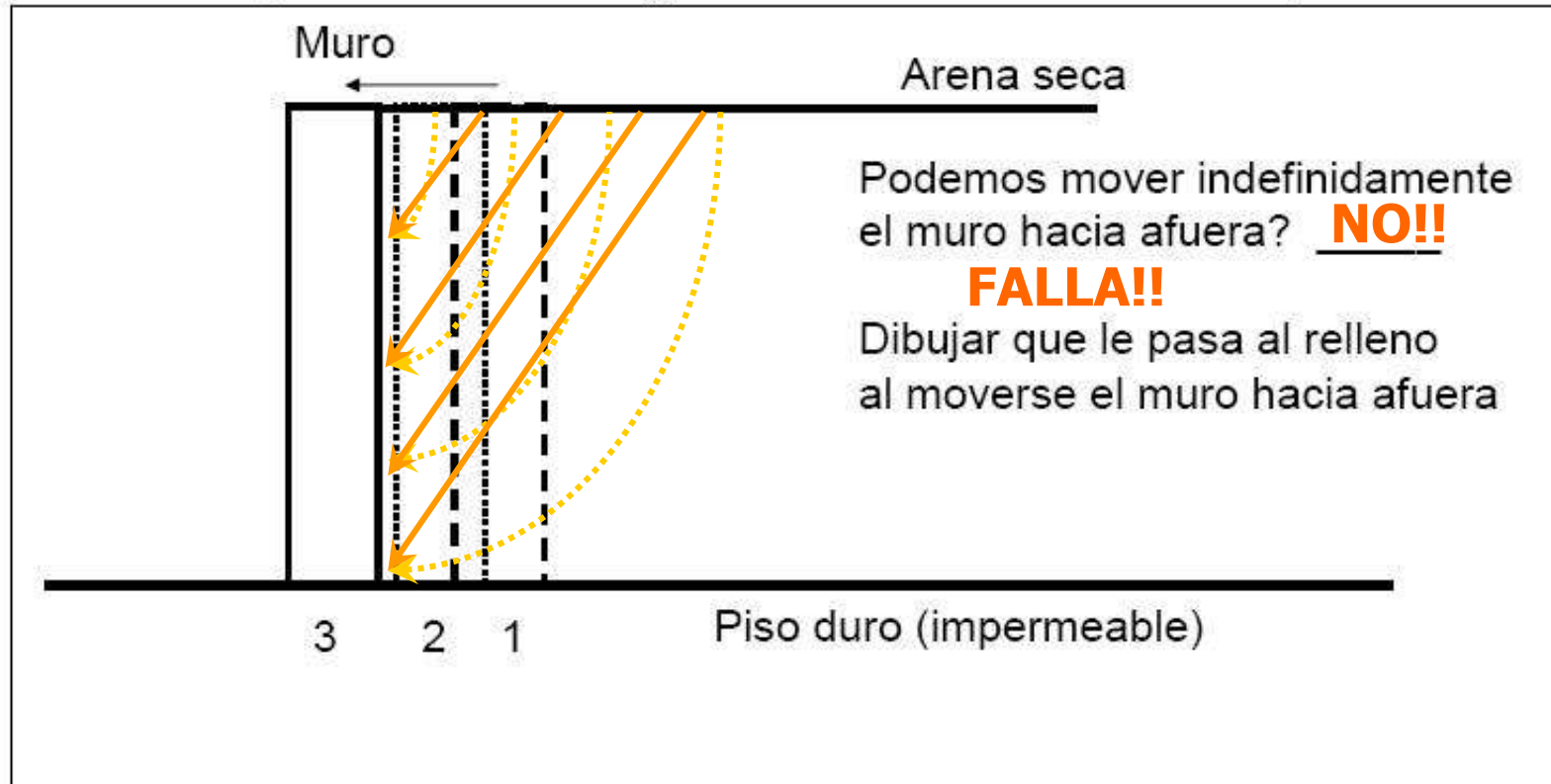
a) Muro que no se mueve
(cero deformación = en reposo)



Movimiento lateral del muro es cero !!!
No hay agua en el relleno

Presiones ejercidas por arena seca

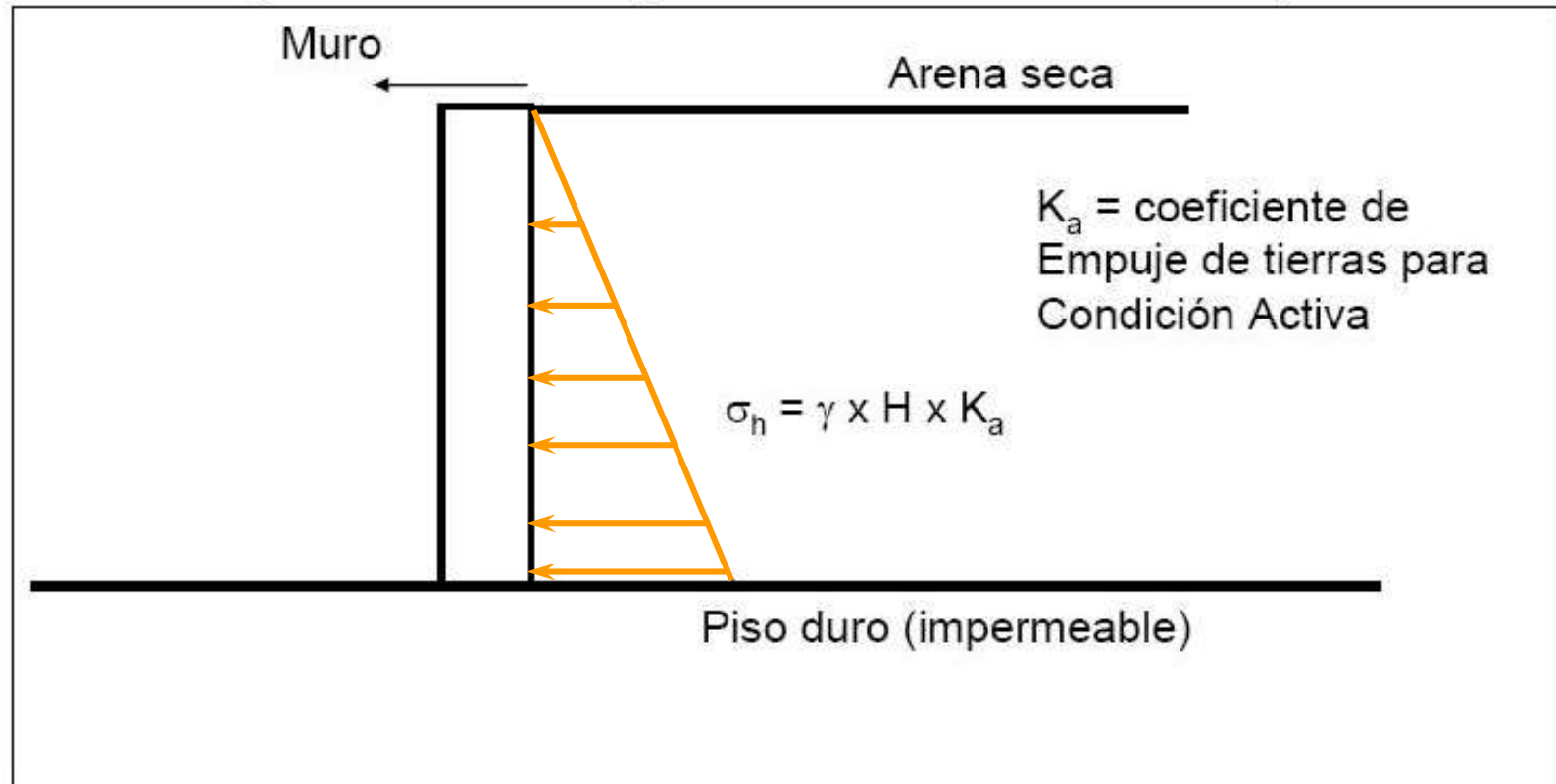
b) Muro que se mueve hacia afuera
(al fallar llega a estado activo)



Nota: Movimiento lateral del muro es hacia afuera (se muestra en forma exagerada)
No hay agua en el relleno

Presiones ejercidas por arena seca

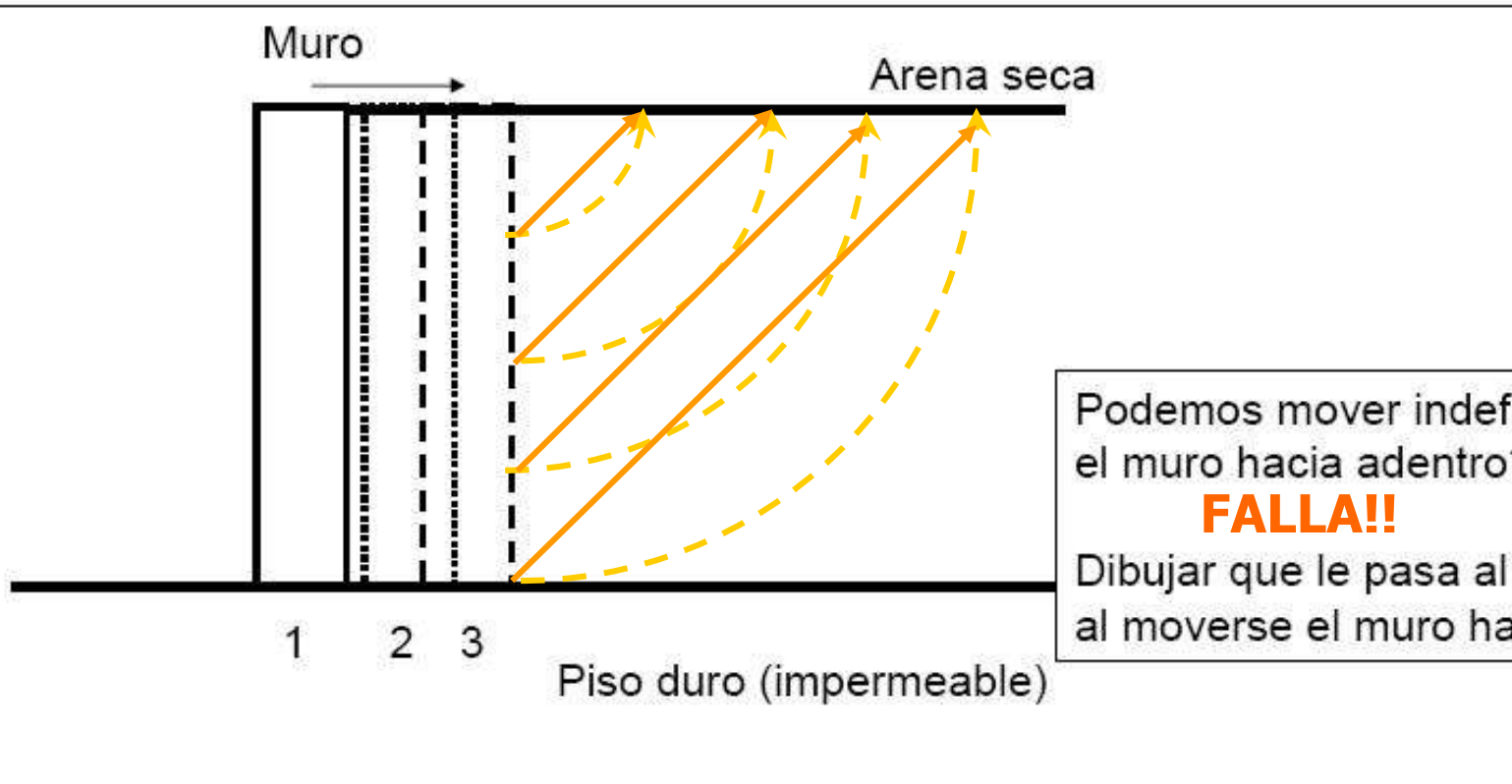
b) Muro que se mueve hacia afuera
(al fallar llega a estado activo)



Movimiento lateral del muro es hacia afuera
No hay agua en el relleno

Presiones ejercidas por arena seca

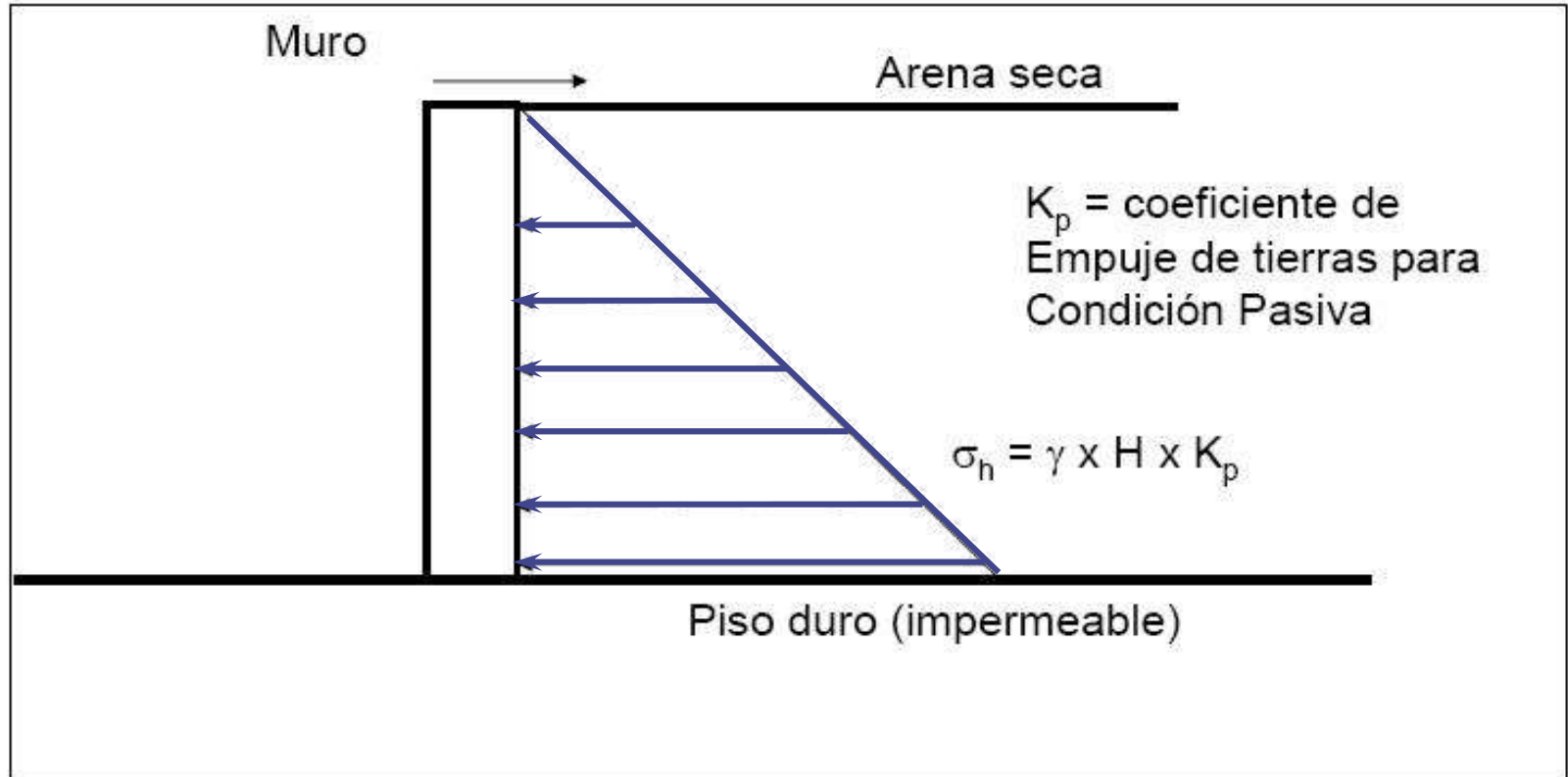
c) Muro que se mueve hacia adentro
(al fallar llega a estado pasivo)



Nota: Movimiento lateral del muro es hacia adentro (se muestra en forma exagerada)
No hay agua en el relleno

Presiones ejercidas por arena seca

c) Muro que se mueve hacia adentro
(al fallar llega a estado pasivo)

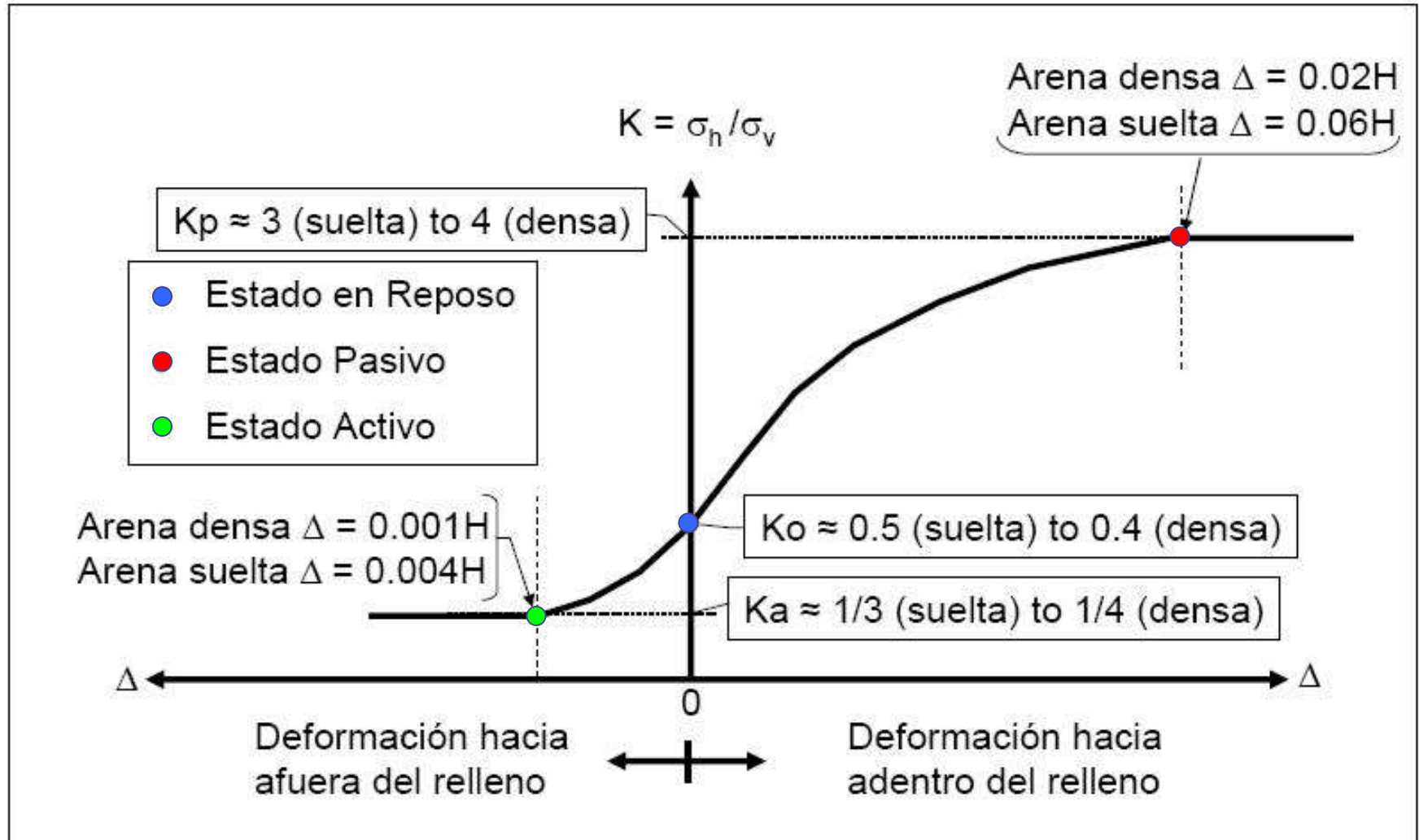


Movimiento lateral del muro es hacia adentro.

Presiones son las mas altas de los 3 estados (reposo y activo)

No hay agua en el relleno

Variación de empujes laterales con dirección y magnitud de movimiento



Como estimar el coeficiente (K_0)

- Para arena

$$K_0 = 1 - \sin \phi \text{ (Jaky)}$$

- Para arcillas normalmente consolidadas (NC)

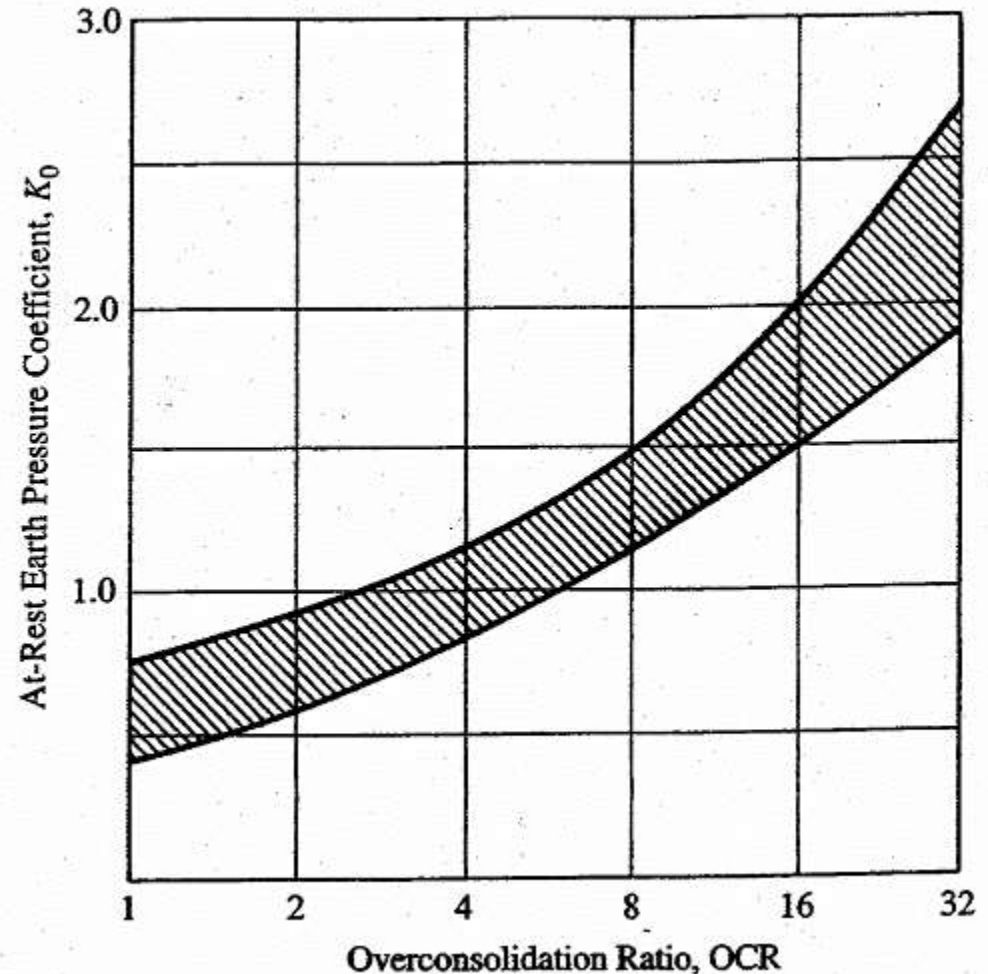
$$K_0 = 0.19 + 0.233 \log(\text{PI})$$

Donde: PI=índice de plasticidad

Como estimar el coeficiente (K_0)

- Para arcillas sobreconsolidadas (OC)
- $OCR = \sigma'_p / \sigma'_v$

FIGURE 12-5 Relationship between K_0 and OCR [3].



Como estimar el coeficiente (K_0) (cont...)

- Para todo tipo de suelo

$$K_0 = (1 - \sin \phi') \text{OCR}^{\sin \phi'}$$

Donde: K_0 = coeficiente de presión lateral en reposo

ϕ' = ángulo de fricción efectiva del suelo

OCR = razón de sobreconsolidación del suelo

Nota:

- Esta ecuación esta basada en pruebas de laboratorio realizadas en 170 suelos, variando entre arcillas y gravas.
- Esta ecuación aplica únicamente cuando la superficie del relleno es horizontal.

Fuerza en reposo

$$P_0 = \frac{1}{2} \gamma H^2 K_0$$

Donde:

P_0 = Fuerza en reposo por longitud de pared unitaria

γ = peso unitario del suelo

H = altura de la pared

K_0 = coeficiente de presión lateral en reposo

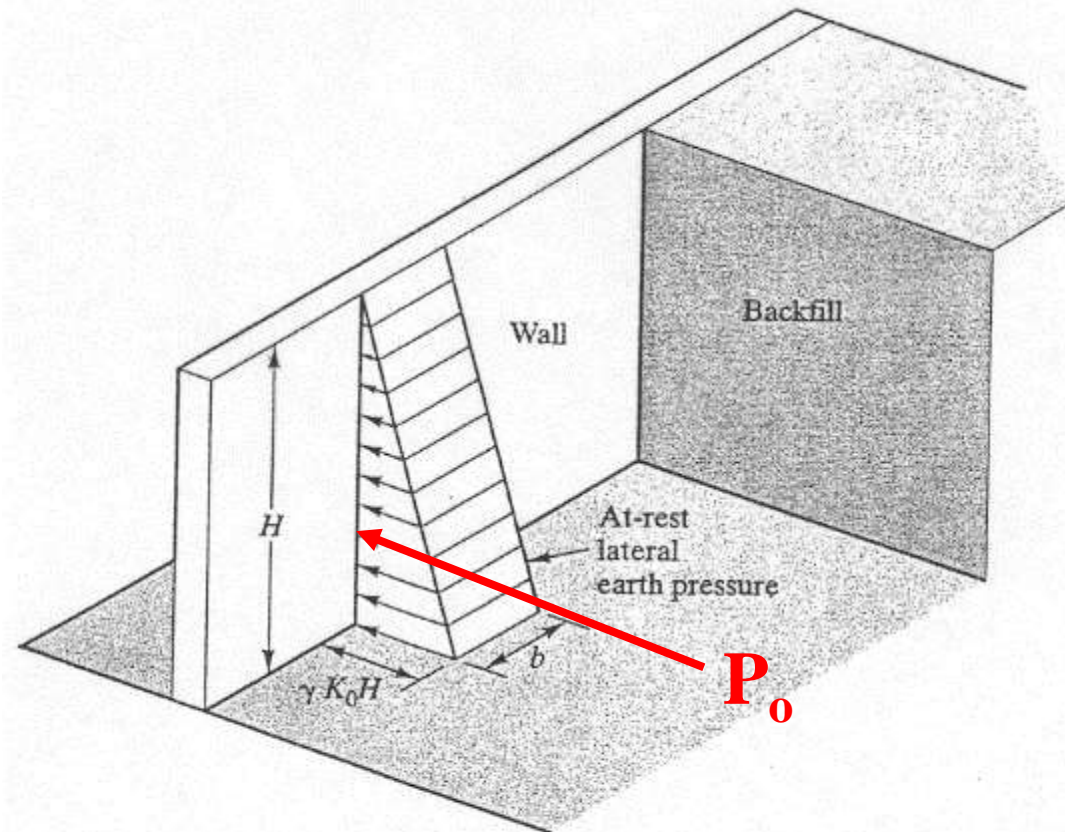
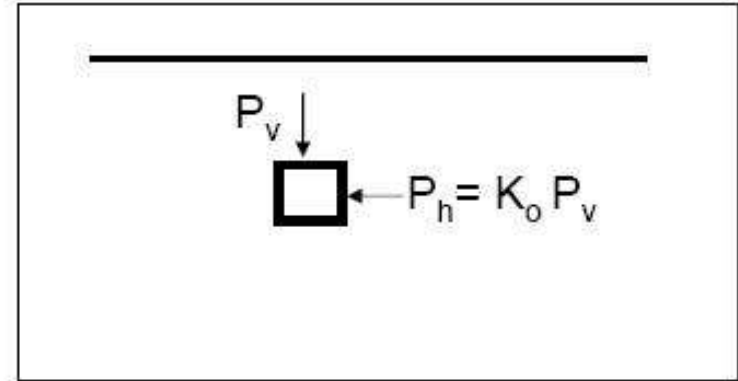


Figure 23.2 At-rest pressure acting on a retaining wall.

Empuje en Reposo (K_o)

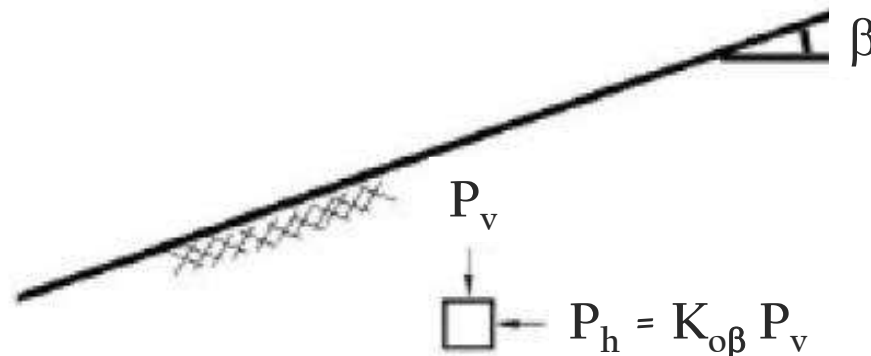
- Relleno horizontal:

$$K_o \approx 1 - \text{sen } \phi'$$



- Relleno inclinado:

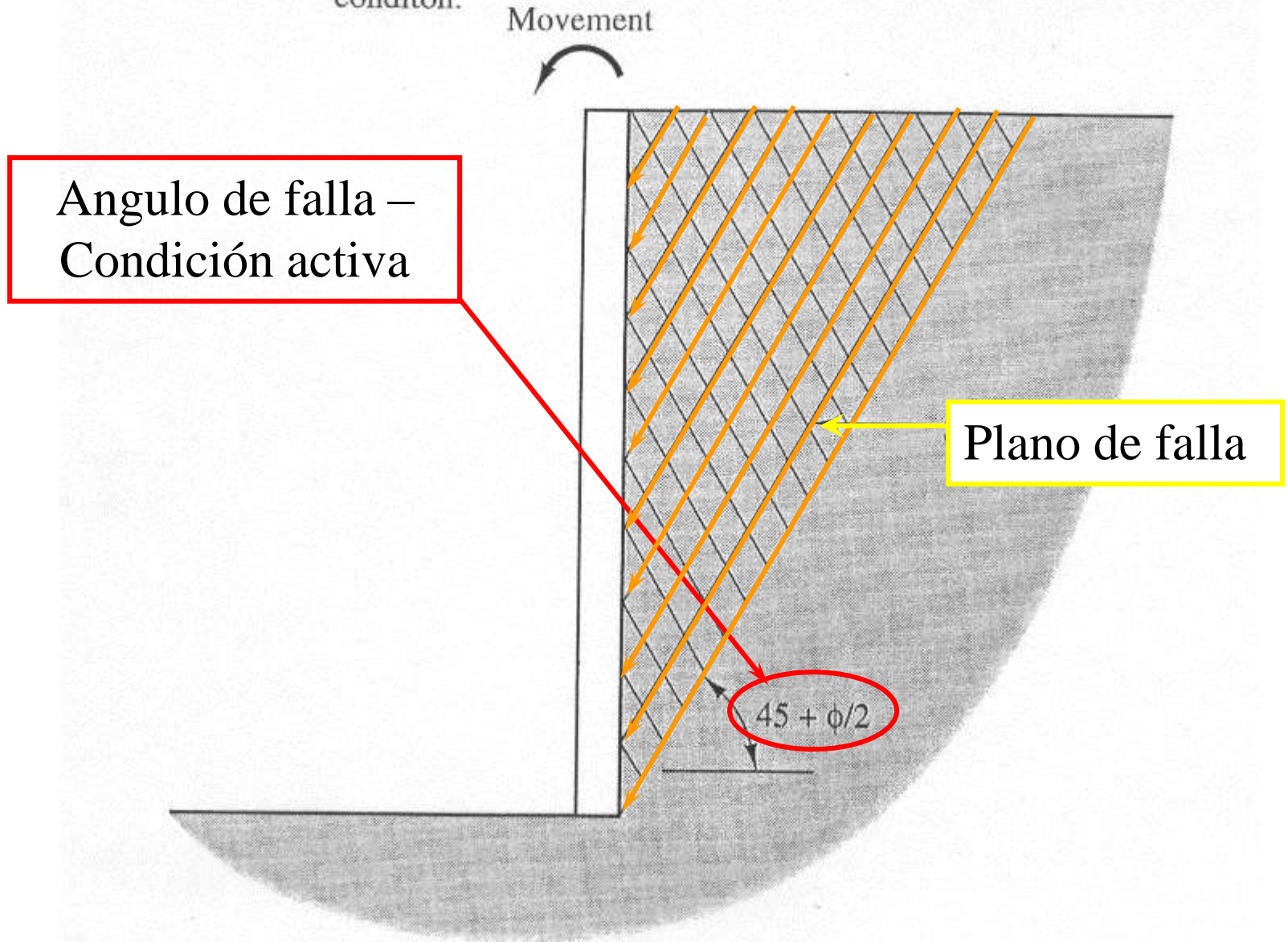
$$K_{o\beta} \approx (1 - \text{sen } \phi') \times (1 - \text{sen } \beta)$$



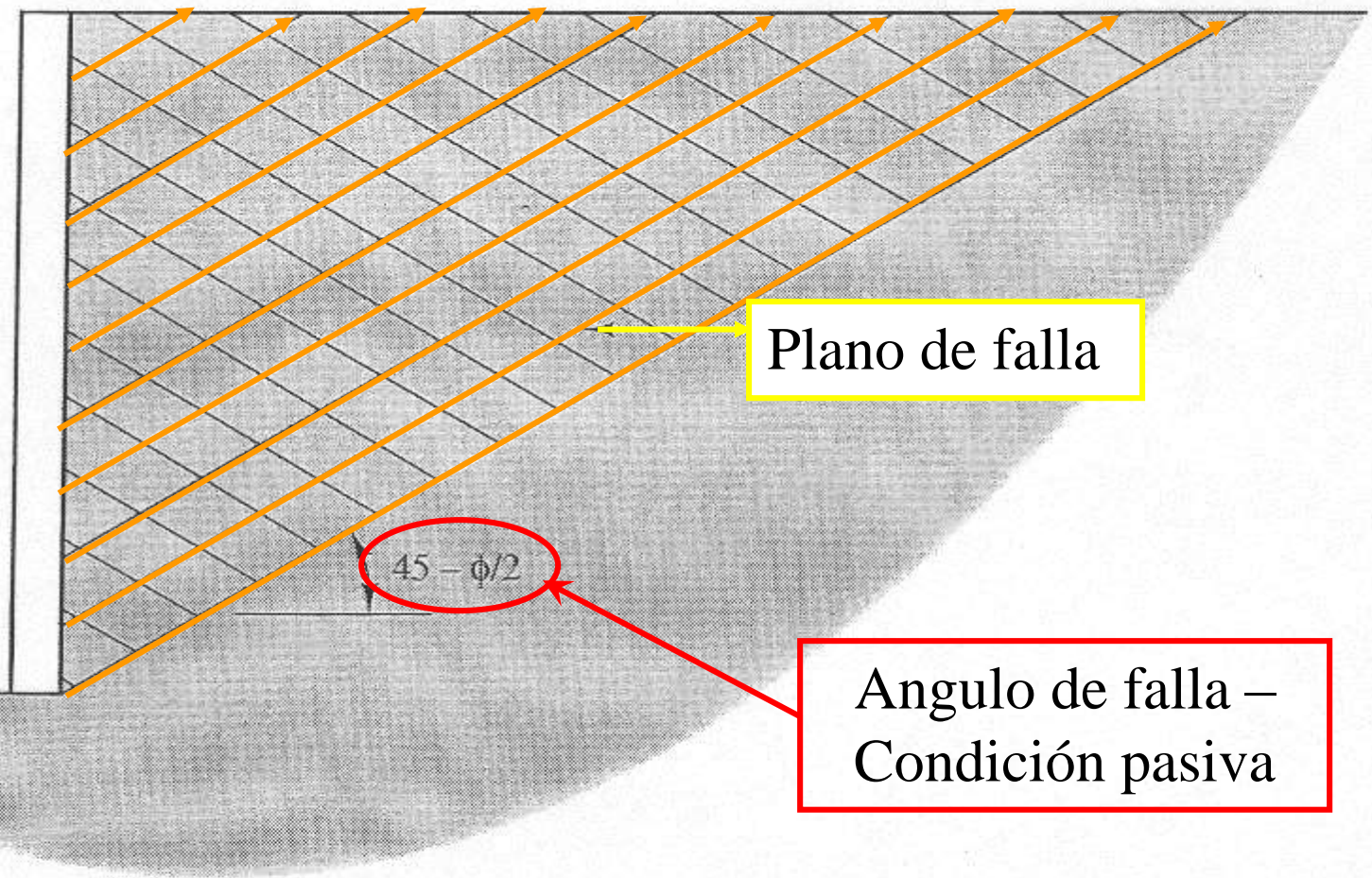
Teoría de Rankine para suelos con $c = 0$ y $\phi \geq 0$

- Suposiciones
 - El suelo es homogéneo e isotrópico
 - La superficie más crítica es un plano
 - La superficie del terreno es un plano (no tiene que ser horizontal)
 - El movimiento de la pared es suficiente para desarrollar la condición activa o pasiva.
 - La fuerza lateral resultante está inclinada a un ángulo paralelo a la superficie del relleno
 - La teoría de Rankine se limita a paredes verticales
 - No existe fricción entre el suelo y la pared

Figure 23.4 Development of shear failure planes in the soil behind a wall as it transitions from the at-rest condition to the active condition.



Movement



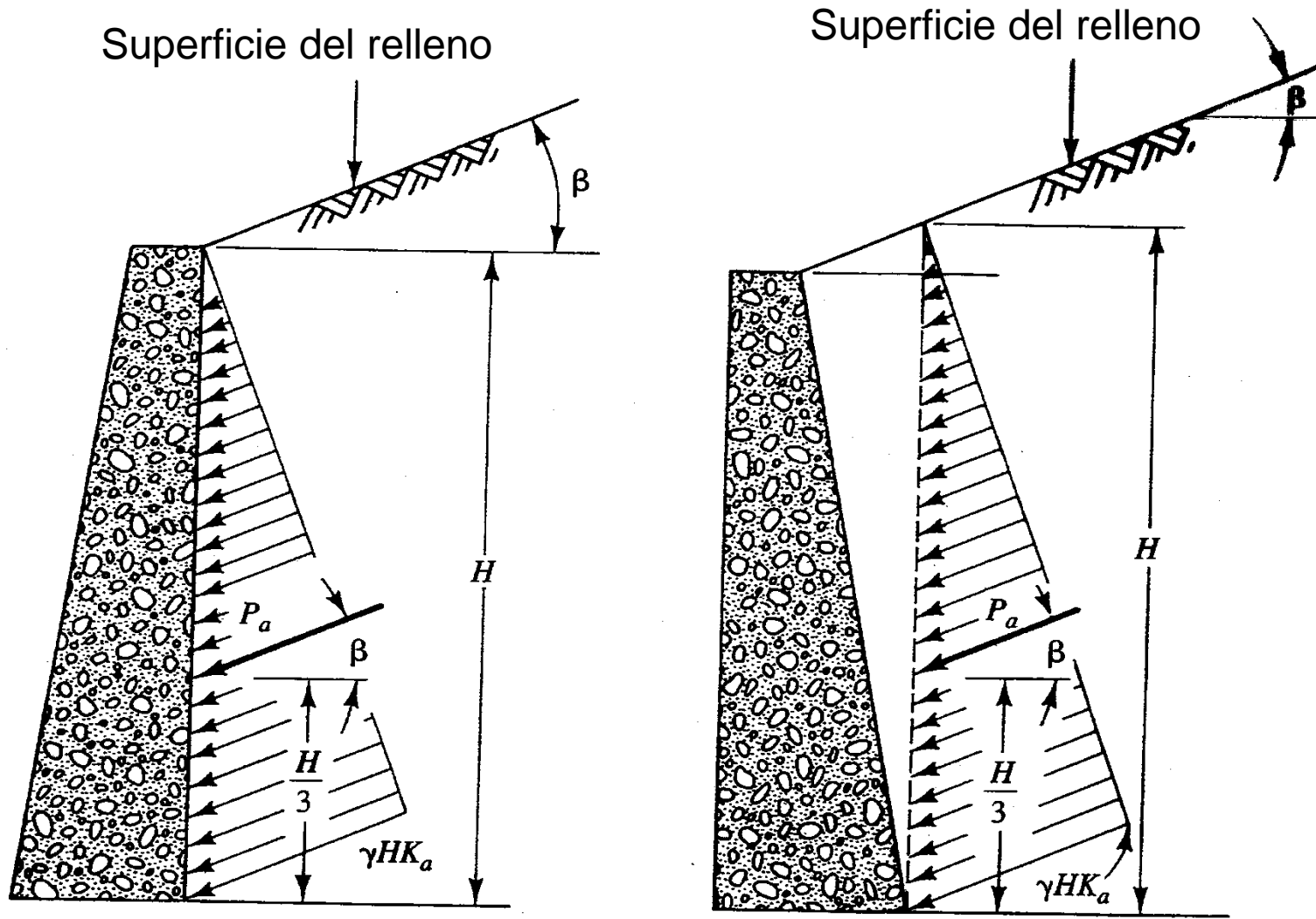
Plano de falla

$45 - \phi/2$

Angulo de falla –
Condición pasiva

Figure 23.6 Development of shear failure planes in the soil behind a wall as it transitions from the at-rest condition to the passive condition.

Teoría de Rankine – Relleno Inclinado



(a) cara posterior vertical

(b) cara posterior

Teoría de Rankine – Relleno Inclinado

Coeficiente de presión lateral activo (K_a):

$$K_a = \cos \beta \frac{\cos \beta - \sqrt{\cos^2 \beta - \cos^2 \phi}}{\cos \beta + \sqrt{\cos^2 \beta - \cos^2 \phi}}$$

Donde:

K_a = coeficiente de presión lateral activo,

ϕ = ángulo de fricción interna del suelo en el relleno

β = ángulo entre la superficie del terreno y la línea horizontal

- Si $\beta=0$ entonces,

$$K_a = \frac{1 - \sin \phi}{1 + \sin \phi} = \tan^2 \left(45^\circ - \frac{\phi}{2} \right)$$

Teoría de Rankine – Relleno Inclinado

(Fuerza Activa)

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

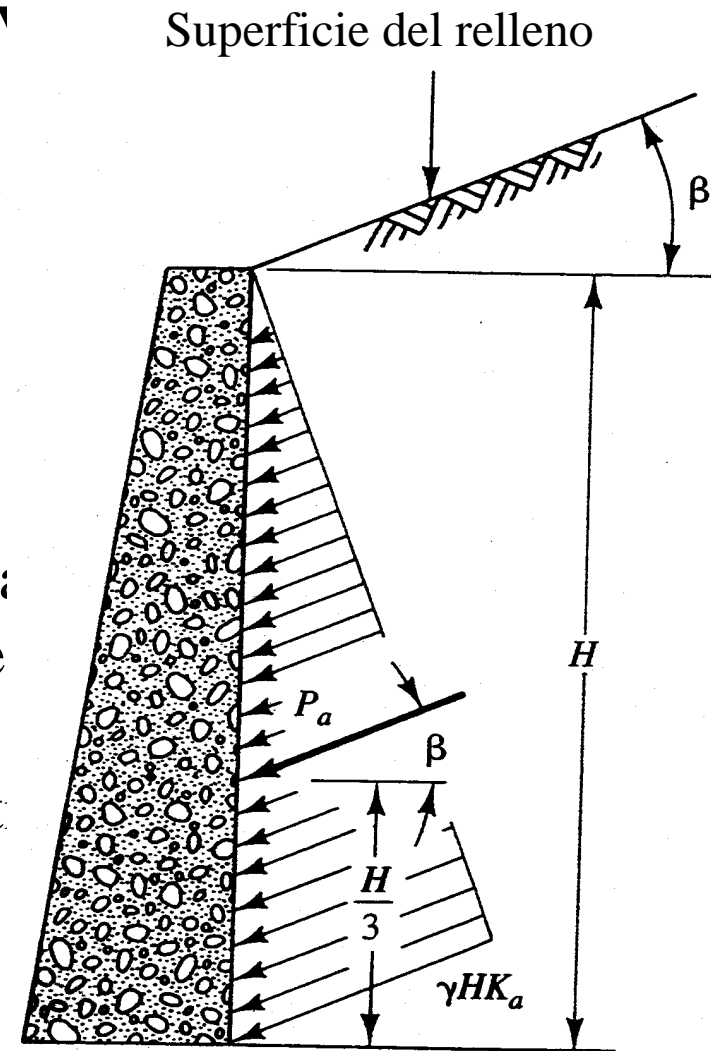
Donde:

P_a = fuerza activa por longitud unitaria

γ = peso unitario del suelo en el relleno

H = altura de la pared,

K_a = coeficiente de presión lateral activa



(a) cara posterior vertical

Teoría de Rankine – Relleno Inclinado

Coeficiente de presión lateral pasivo (K_p):

$$K_p = \cos \beta \frac{\cos \beta + \sqrt{\cos^2 \beta - \cos^2 \phi}}{\cos \beta - \sqrt{\cos^2 \beta - \cos^2 \phi}}$$

Donde:

K_p = coeficiente de presión lateral pasivo,

ϕ = ángulo de fricción interna del suelo en el relleno

β = ángulo entre la superficie del terreno y la línea horizontal

- Si $\beta=0$ entonces,

$$K_p = \frac{1 + \sin \phi}{1 - \sin \phi} = \tan^2 \left(45^\circ + \frac{\phi}{2} \right) = \frac{1}{K_a}$$

Teoría de Rankine – Relleno Inclinado (Fuerza Pasiva)

$$P_p = \frac{1}{2} \gamma H^2 K_p$$

Donde:

P_p = fuerza pasiva por longitud unitaria de pared,

γ = peso unitario del suelo en el relleno

H = altura de la pared,

K_p = coeficiente de presión lateral activo

Teoría de Coulomb para suelos con $c = 0$ y $\phi \geq 0$

- Suposiciones
 - El suelo es homogéneo e isotrópico
 - La superficie mas critica es un plano
 - La superficie del terreno es un plano (no tiene que ser horizontal)
 - El movimiento de la pared es suficiente para desarrollar la condición activa o pasiva.
 - La fuerza lateral resultante esta inclinada a un ángulo igual a δ medido desde una línea perpendicular al muro
 - Existe fricción entre el suelo y la pared

Teoría de Coulomb-Coeficientes

$$K_a = \frac{\cos^2(\phi - \alpha)}{\cos^2 \alpha \cos(\delta + \alpha) + \left[1 + \sqrt{\frac{\sin(\phi + \delta) \sin(\phi - \beta)}{\cos(\delta + \alpha) \cos(\alpha - \beta)}} \right]^2}$$

Donde:

K_a = coeficiente de presión lateral activo,

ϕ = ángulo de fricción interna del suelo en el relleno,

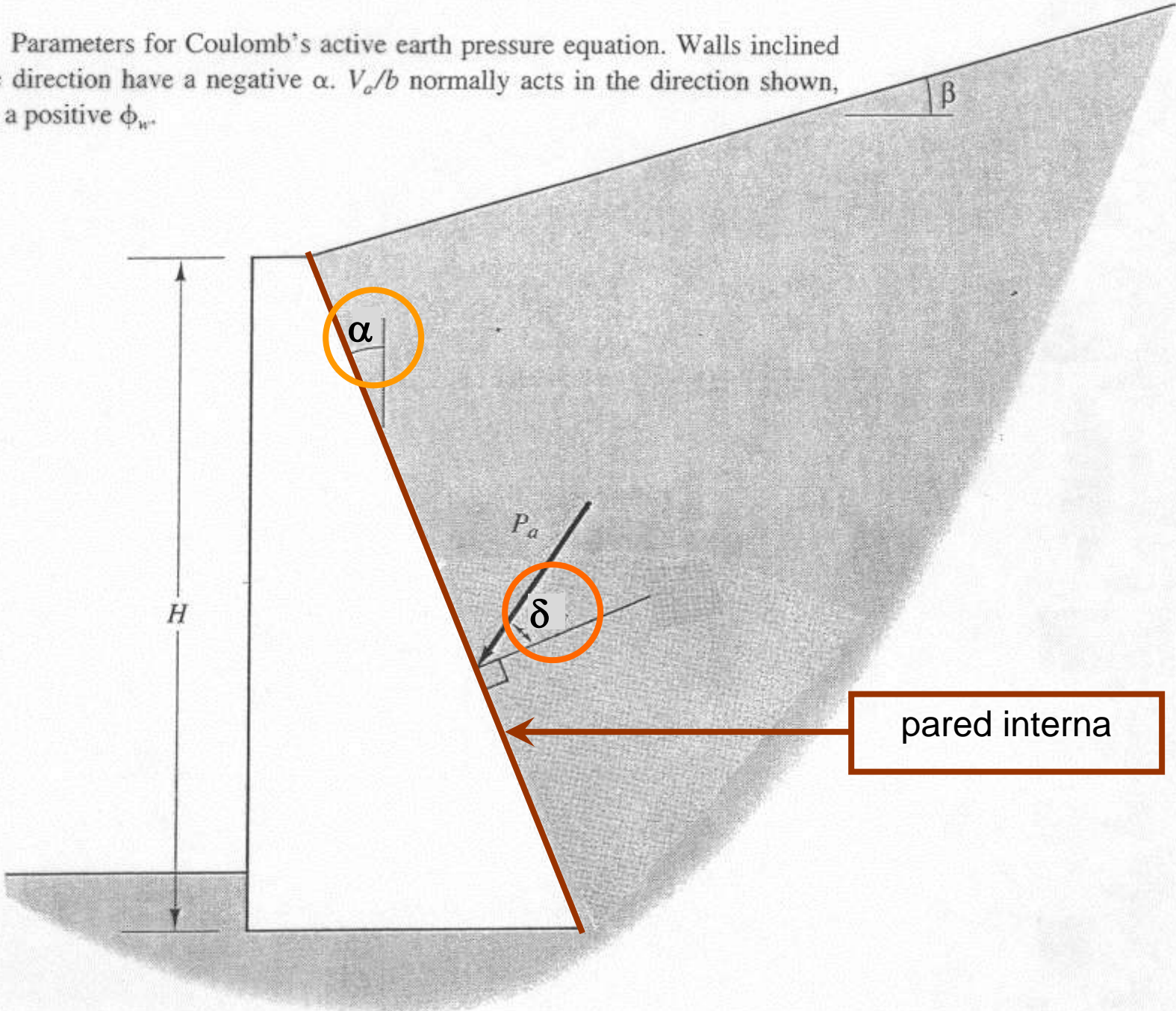
β = ángulo entre la superficie del terreno y la línea horizontal,

α = ángulo de inclinación del interior de la pared medido desde la vertical, y

δ = ángulo de fricción en la interface entre la pared y el relleno. Para paredes de concreto usar, δ entre 0.5ϕ y 0.67ϕ .

Nota: Esta ecuación es valida sólo para $\beta \leq \phi$

Figure 23.12 Parameters for Coulomb's active earth pressure equation. Walls inclined in the opposite direction have a negative α . V_o/b normally acts in the direction shown, thus producing a positive ϕ_w .



Teoría de Coulomb

$$K_a = \frac{\cos^2(\phi - \alpha)}{\cos^2 \alpha \cos(\delta + \alpha) \left(1 + \sqrt{\frac{\sin(\phi + \delta) \sin(\phi - \beta)}{\cos(\delta + \alpha) \cos(\alpha - \beta)}}\right)^2}$$

$$K_p = \frac{\cos^2(\phi + \alpha)}{\cos^2 \alpha \cos(\delta - \alpha) \left(1 - \sqrt{\frac{\sin(\phi + \alpha) \sin(\phi + \beta)}{\cos(\delta - \alpha) \cos(\beta - \alpha)}}\right)^2}$$

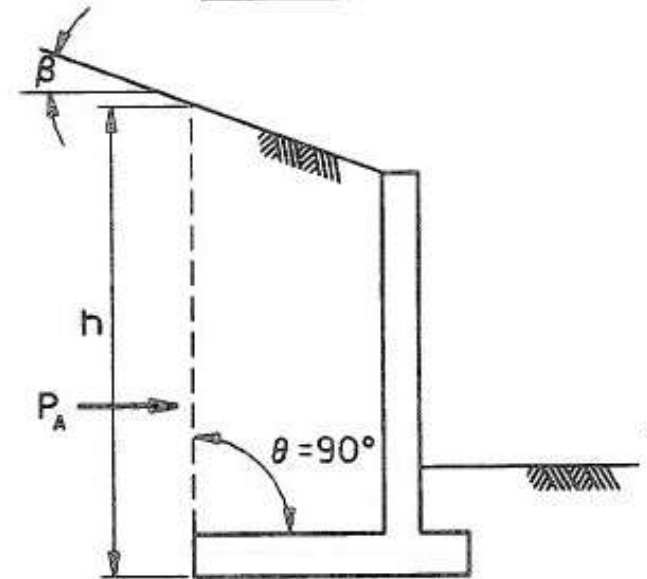
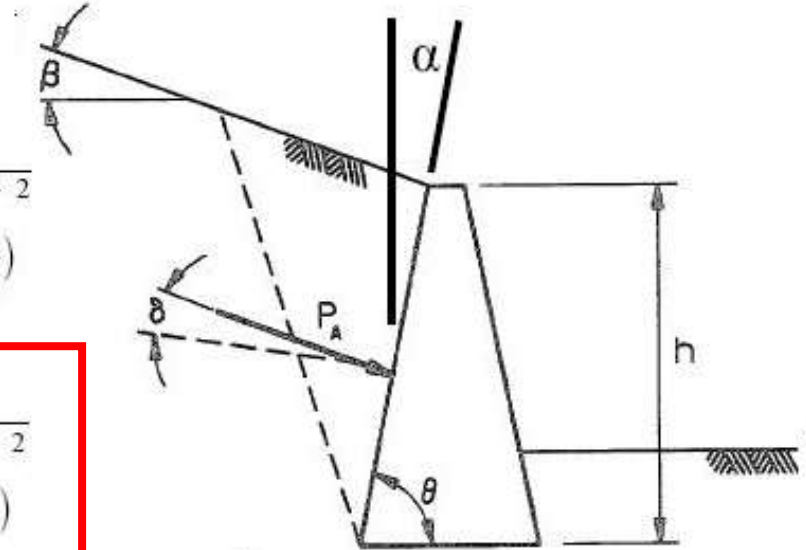
ϕ = ángulo de fricción

θ = ángulo inclinación cara interna del muro ($\theta =$ cero, muro vertical)

β = inclinación del relleno

$\delta = \phi_{\omega}$ = ángulo fricción muro/relleno

(adaptado de vulcanhammer.com)



Método de Fluido Equivalente

- ◆ Simplificación utilizada para el cálculo de presiones laterales actuando en los muros
- ◆ Transforma el suelo actuando sobre la pared del muro en un fluido equivalente
- ◆ Puede ser utilizado para ambas teorías
 - Rankine, y
 - Coulomb
- ◆ Puede ser utilizado para los tres tipos de condiciones; en reposo, pasiva y activa.

Método de Fluído Equivalente

Tabla 4.6. Coeficientes y pesos unitarios para presiones de fluido equivalente (after Clough and Duncan, 1991)

Pesos Unitarios y Coeficientes de Presión para Método de Fluído Equivalente								
Tipo de suelo	Relleno Horizontal				Relleno 2(H):1(V)			
	En Reposo		$\Delta/H = 1/240$		En Reposo		$\Delta/H = 1/240$	
	γ_{eq} (pcf)	K	γ_{eq} (pcf)	K	γ_{eq} (pcf)	K	γ_{eq} (pcf)	K
Arena Suelta o Grava	55	0.45	40	0.35	65	0.55	50	0.45
Arena Densidad Media o Grava	50	0.40	35	0.25	60	0.50	45	0.35
Arena Densa o Grava	45	0.35	30	0.20	55	0.45	40	0.30
Limo Compactado (ML)	60	0.50	40	0.35	70	0.60	50	0.45
Arcilla Compactada (CL)	70	0.60	45	0.40	80	0.70	55	0.50
Arcilla Compactada Alta Plasticidad (CH)	80	0.65	55	0.50	90	0.75	65	0.60

Superficie horizontal

$$P_h = \gamma_{eq} \times z$$

Recomendado para rellenos finos:

- Limos (ML) y/o
- Arcillas (CL o CH)

$$P_h = \gamma_{eq}(z) + K (q_s)$$

donde, γ_{eq} = peso unitario del fluido equivalente

z = profundidad por debajo de la superficie del terreno

K = coeficiente horizontal de presión del suelo

q_s = sobrecarga uniforme sobre el terreno

Empujes – Espiral logarítmica

Importante para el caso pasivo donde la fricción entre el muro y el relleno no es despreciable

δ = ángulo de fricción entre muro y relleno

$\tan \delta = \mu$ = coeficiente fricción

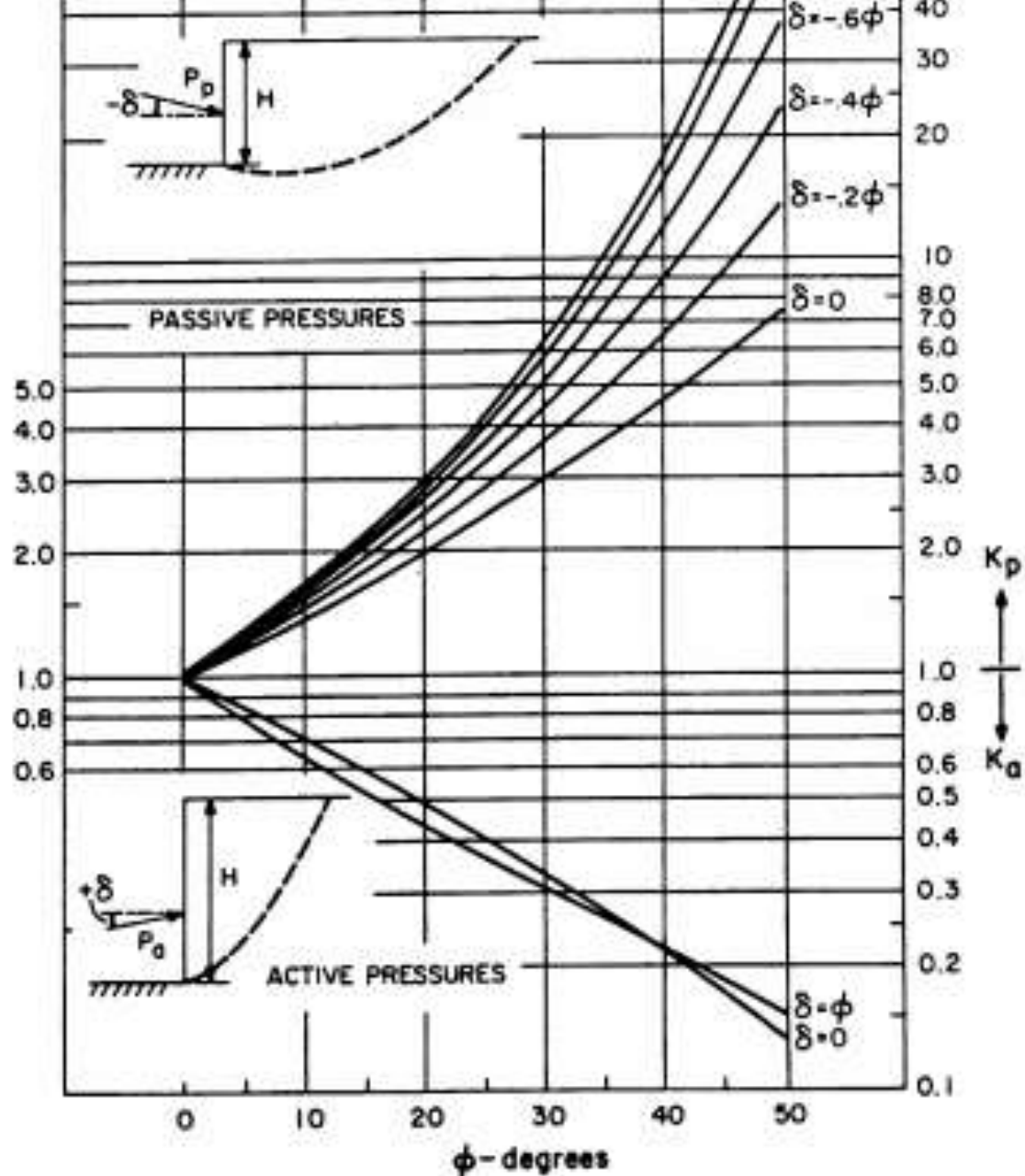


Fig. 6.9 Active and passive pressure coefficients for vertical wall and horizontal backfill, based on log-spiral failure surfaces. (After Caquot and Kerisel, 1948.)

Empujes – Espiral logarítmica

Importante para el caso pasivo
donde la fricción entre el muro
y el relleno no es despreciable

δ = ángulo de fricción entre
muro y relleno

$\tan \delta = \mu$ = coeficiente fricción

Por ejemplo:

si $\delta = 0.6 \phi'$ y $\phi' = 30^\circ$:

$K_p = 3.0$ (Rankine)

$K_p = 5.0$ (Espiral logarítmica)

Diferencia del 67% !!
(No es despreciable)

[Para caso activo no es crítico]

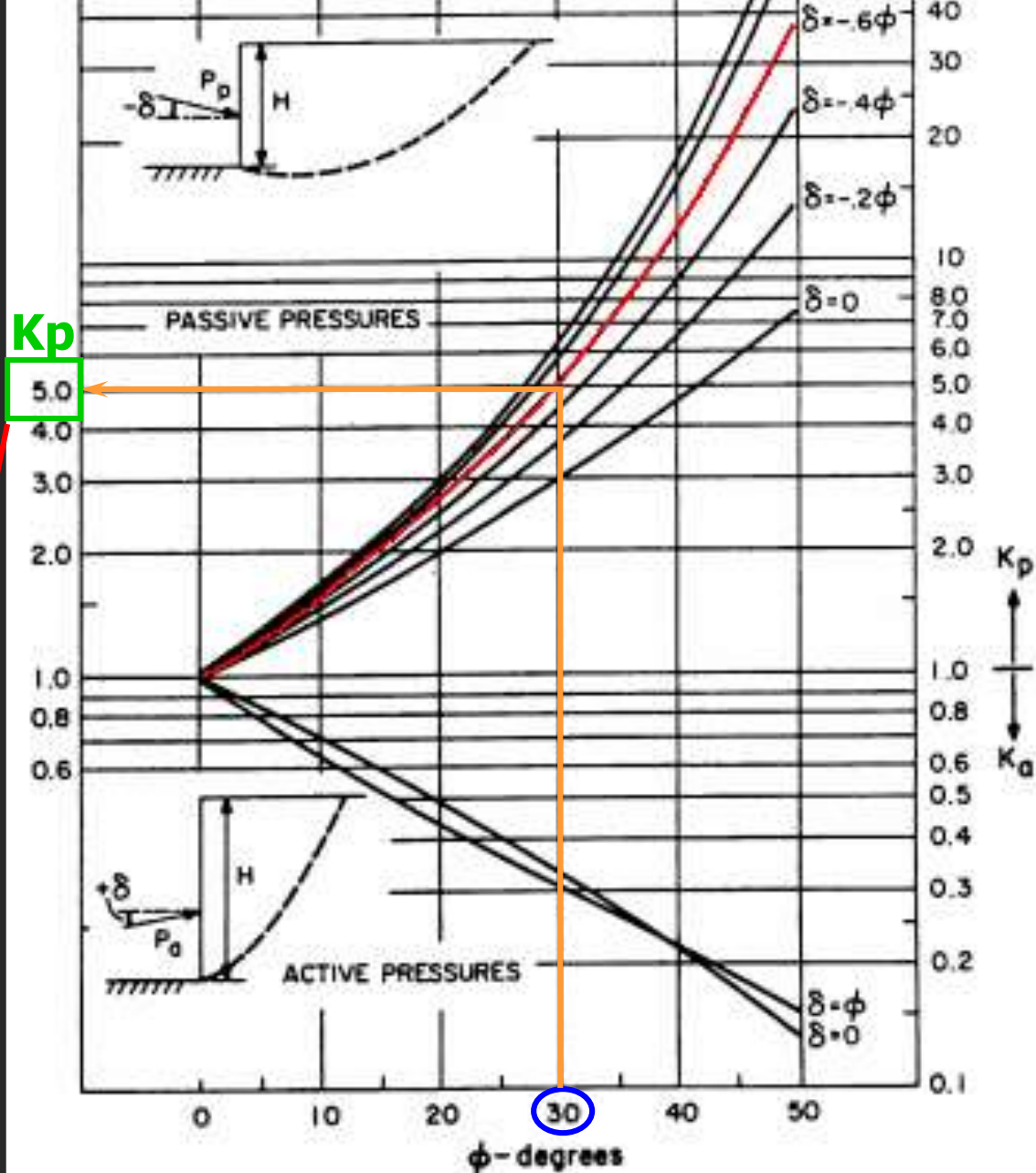


Fig. 6.9 Active and passive pressure coefficients for vertical wall and horizontal backfill, based on log-spiral failure surfaces. (After Caquot and Kerisel, 1948.)

Presión lateral de diseño - Activa

- ◆ Para casos donde el relleno o la fundación del muro contengan suelos arcillosos,
 - Las teorías clásicas de empuje lateral de tierra no toman en consideración la tendencia de estos suelos a deformarse bajo esfuerzos constantes (creep)
 - Utilizar el método de Terzaghi y Peck
- ◆ Para paredes con suelos granulares (arenas y gravas) en el relleno o bajo la fundación del muro.
 - Utilizar la teoría de Coulomb
 - Fijar $\phi_w =$ entre (0.5ϕ) y (0.67ϕ)
 - Otra opción es utilizar el método de Terzaghi y Peck.

Presión lateral de diseño - Pasiva

- ◆ Utilizar la teoría de Rankine
- ◆ Los ingenieros generalmente utilizan un valor menor al obtenido teóricamente por las siguientes razones,
 - El desplazamiento horizontal requerido para movilizar la presión pasiva en ocasiones es mayor a las deformaciones permisibles del muro. Se utiliza la mitad de los valores permisibles.
 - El suelo en la cara exterior del muro es generalmente alterado por "landscaping" o alguna otra actividad por lo que este generalmente no es tan resistente como se anticipa

Sobrecargas

(generan presiones adicionales sobre el muro)

considerar sobrecarga si esta localizada a distancia \leq altura del muro

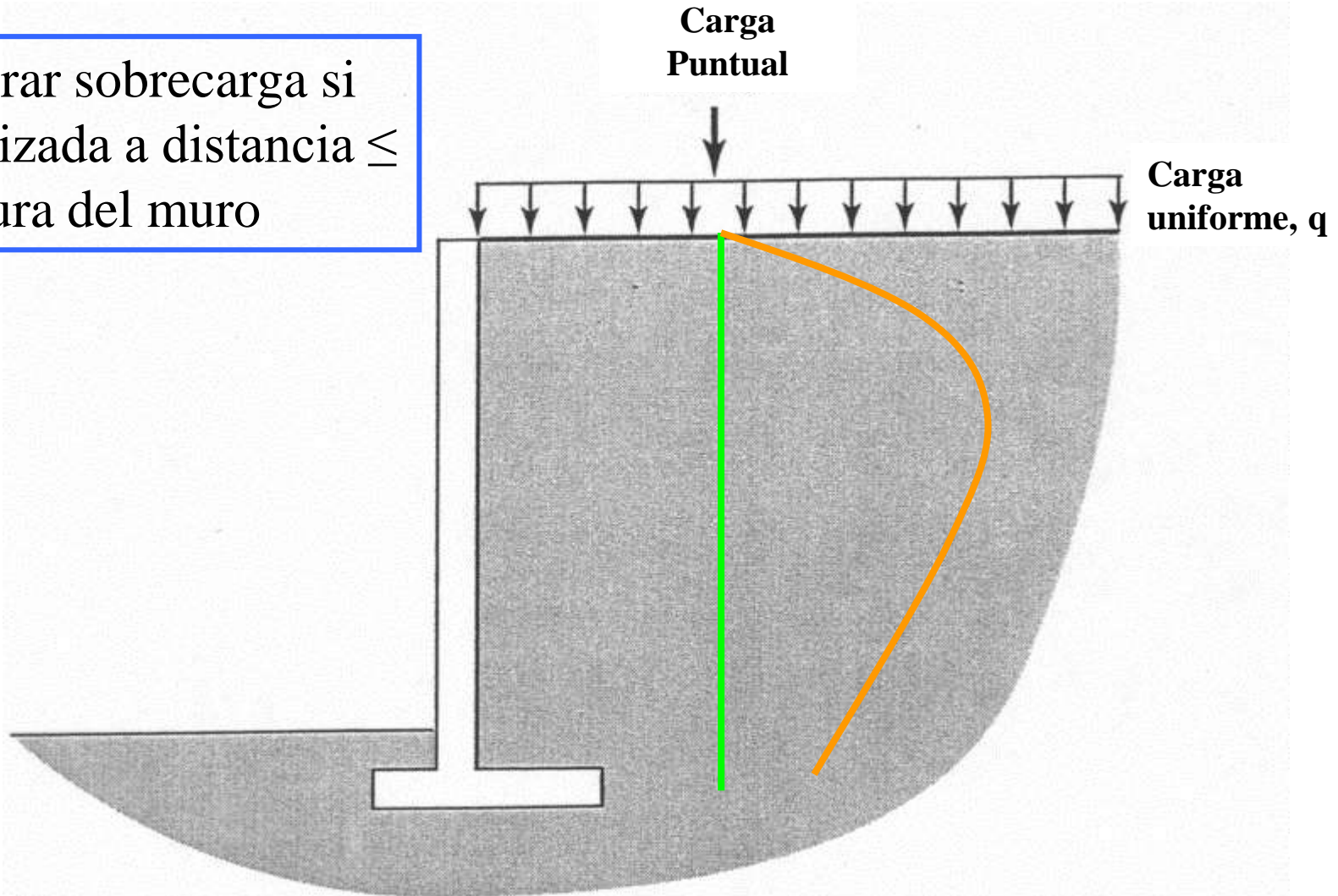
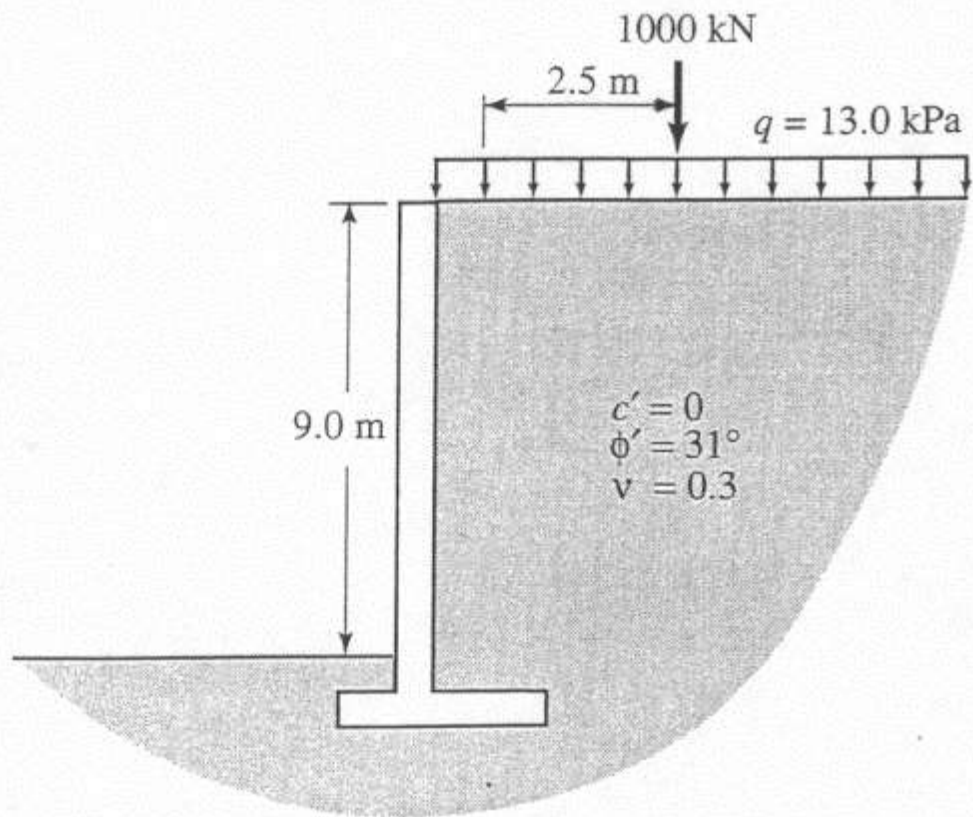


Figure 23.18 Typical surcharge loads near a retaining wall.



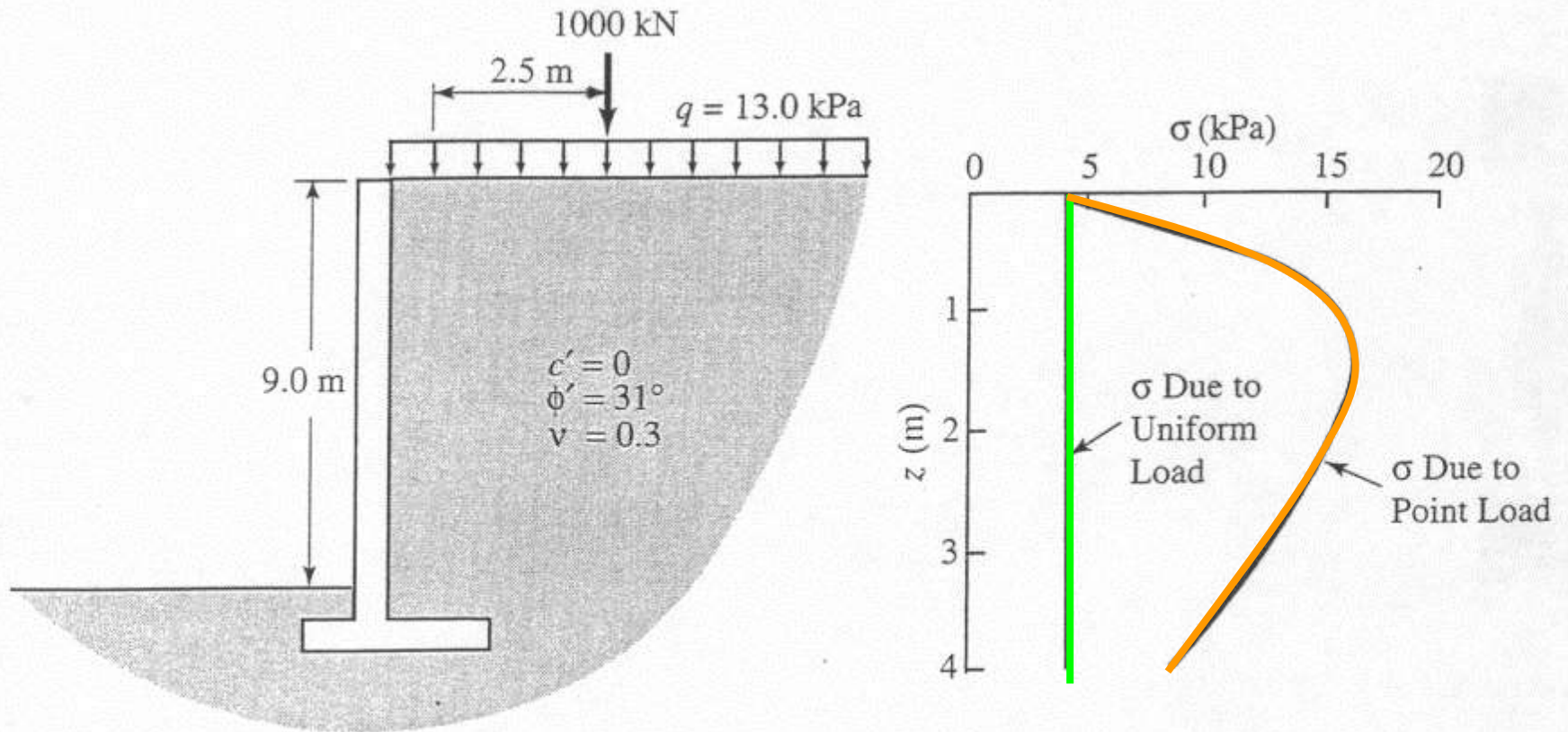
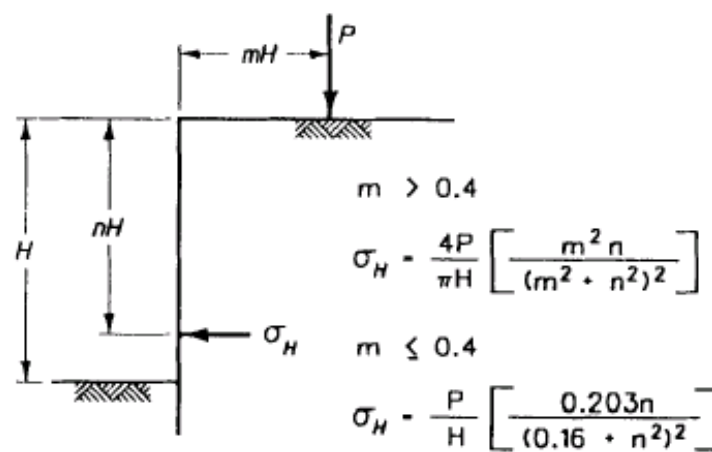
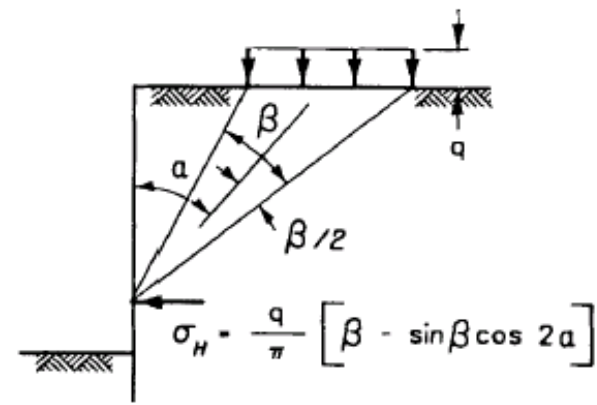


Figure 23.19 Proposed retaining wall with surcharge load for Example 23.6.

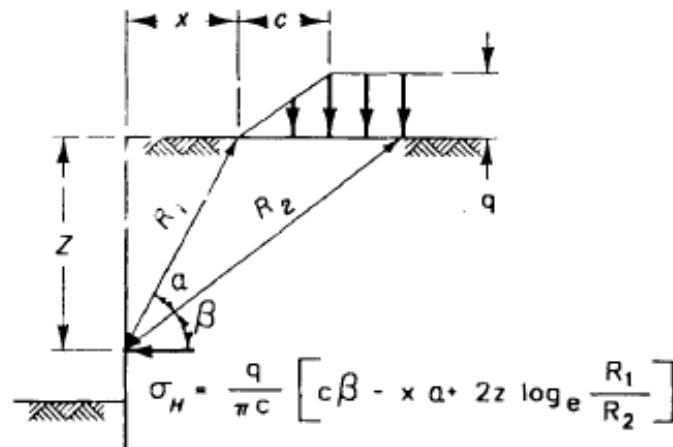
Efecto de sobrecarga, algunas ecuaciones



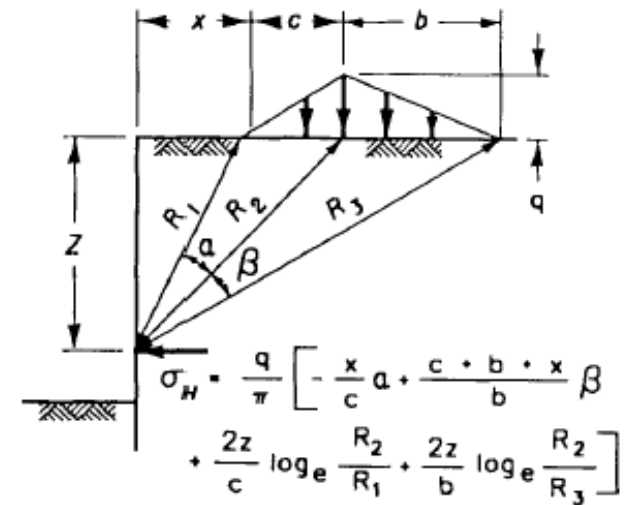
a. Line load (factor of two included) from Terzaghi (1954)



b. Strip load



c. Ramp load



d. Triangular load

from Dawkins (1991)

NOTES:

- (1) FOR FIGURES (c) AND (d) THE ANGLES α AND β ARE EXPRESSED IN UNITS OF RADIANS.
- (2) NEGATIVE PRESSURES MAY BE COMPUTED AT SHALLOW DEPTHS (Z).

Efecto del Agua

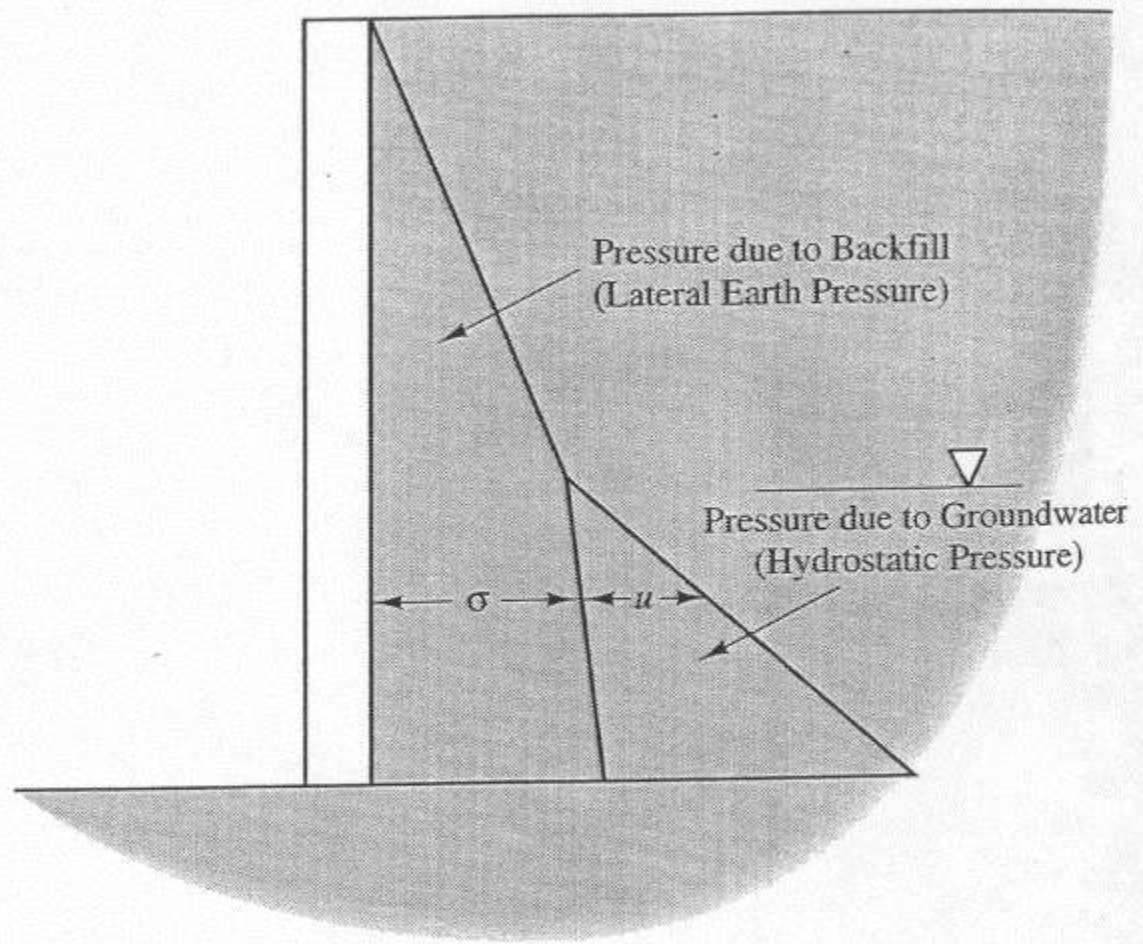


Figure 16.16 Theoretical lateral pressure distribution with shallow groundwater table.

Sobrecarga y nivel freático

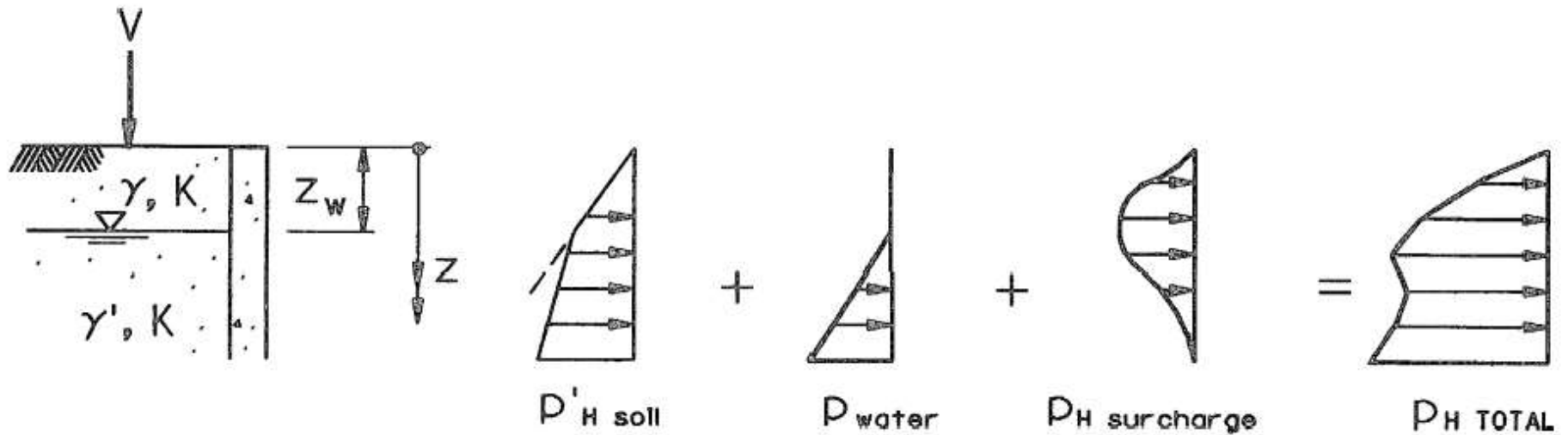


Figure 3-20 Lateral pressures, one soil, water, finite surcharge

DESIGN OF MECHANICALLY STABILIZED EARTH (MSE) WALL

Dr. Beatriz Camacho

Associate Professor

Department of Civil Engineering
and Surveying

University of Puerto Rico at
Mayaguez

SCHEDULE

- ◉ Definition
- ◉ Historical Development
- ◉ Applications
- ◉ Advantages & Disadvantages
- ◉ Relative Costs
- ◉ Systems Differentiation
- ◉ Site Evaluation
- ◉ Project Evaluation
- ◉ Design
- ◉ Contracting Methods

MECHANICALLY STABILIZED EARTH WALL (MSEW)

- ⦿ Generic term that includes reinforced soil
 - When multiple layers of inclusions act as reinforcement in soils placed as fill.
- ⦿ Multiple horizontal layers of man-made elements that act as reinforcements for the soil used as infill materials.
- ⦿ Constructed with artificial reinforcing.
 - Usually steel or geosynthetics.

HISTORICAL DEVELOPMENT

○ Retaining structures

- Reinforced concrete
- Designed as gravity or cantilever walls
 - Essentially rigid structures and cannot accommodate significant differential settlements unless founded on deep foundations.

HISTORICAL DEVELOPMENT

- ◉ Many primitive people used sticks and branches to reinforce mud dwellings.
- ◉ French settlers along the Bay of Fundy in Canada used sticks to reinforce mud dikes.
- ◉ Some other early examples include dikes of earth and tree branches, which have been used in China and along the Mississippi River in the 1880s.
- ◉ Other examples include wooden pegs used for erosion and landslide control in England, and bamboo or wire mesh, used universally for revetment erosion control.

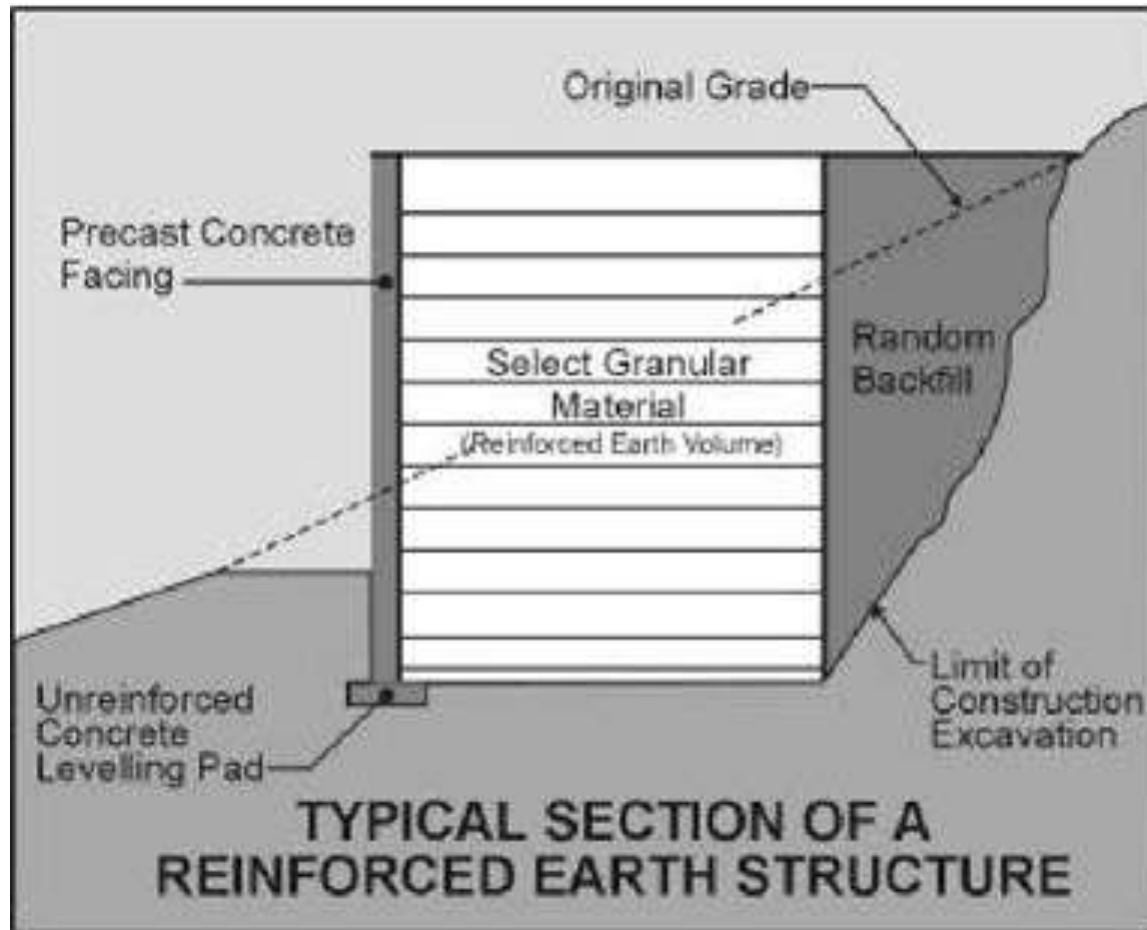
HISTORICAL DEVELOPMENT

- ◎ The modern methods of soil reinforcement
 - Pioneered by the French architect and engineer Henri Vidal in the early 1960s.
 - His research led to the invention and development of Reinforced Earth®, a system in which steel strip reinforcement is used.
 - First wall to use this technology in the United States was built in 1972 on California State Highway 39, northeast of Los Angeles.

HISTORICAL DEVELOPMENT

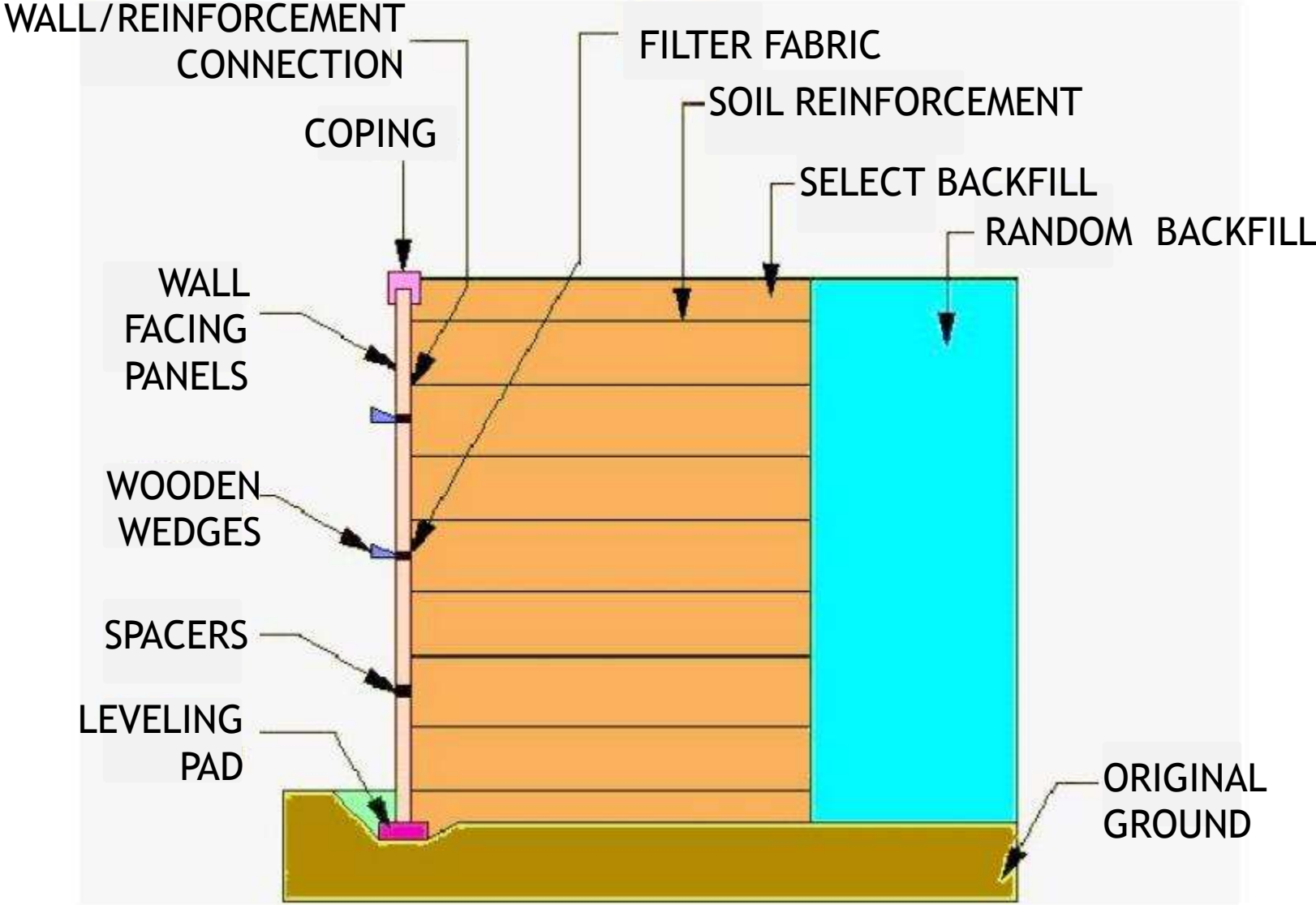
- Geogrids for soil reinforcement were developed around 1980.
 - The first use of geogrid in earth reinforcement was in 1981.

TYPICAL SECTION OF A MSE WALL USED NOWADAYS



Typical Section of a Reinforced Earth
Structure

WALL COMPONENTS



DEFINITION OF KEY TERMS

⦿ Retained backfill

- Fill material located between the mechanically stabilized soil mass and the natural soil.

⦿ Reinforced backfill

- Fill material in which the reinforcements are placed.

DEFINITION OF KEY TERMS

◎ Facing

- To prevent the soil from raveling out between the rows of reinforcement.



Precast concrete panels

DEFINITION OF KEY TERMS - COMMON FACINGS

- precast concrete panels,



DEFINITION OF KEY TERMS - COMMON FACINGS

- dry cast modular blocks,



DEFINITION OF KEY TERMS - COMMON FACINGS

- gabions,



DEFINITION OF KEY TERMS - COMMON FACINGS

- sheets of geosynthetics,



DEFINITION OF KEY TERMS - COMMON FACINGS

- wire mesh, shotcrete, wood lagging and panels.



DEFINITION OF KEY TERMS

- ◉ Modular Block wall (MBW)
 - Most common retaining wall constructed today.



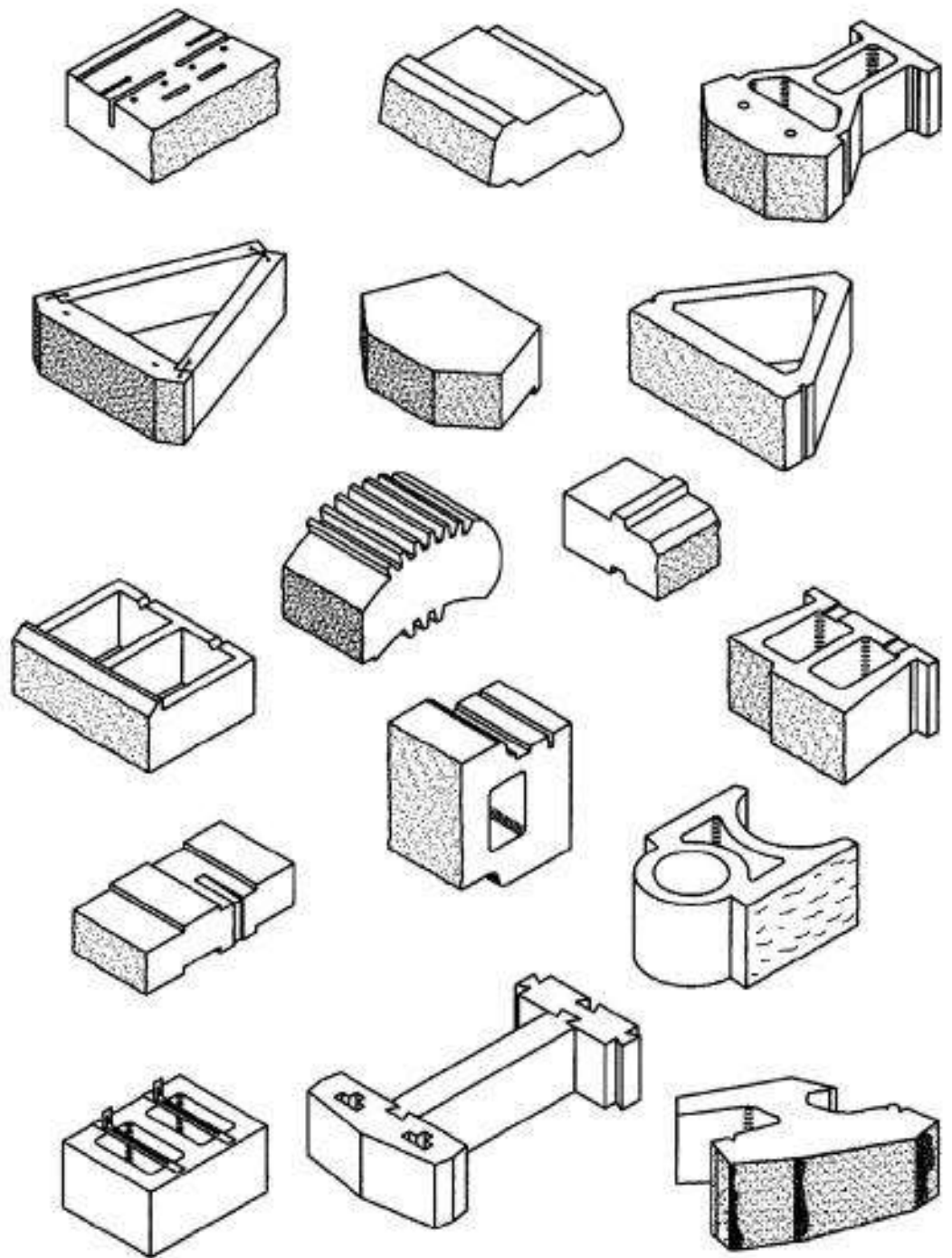
Modular Block Retaining Wall

DEFINITION OF KEY TERMS

◉ Modular Block wall (MBW)

- One of the advantages of MBW is that they are individual blocks so if a block shifts a little, the wall won't break.
- They are porous so water will pass through the wall which makes them less susceptible to hydrostatic pressure.

DIFFERENT CONFIGURATIONS



DEFINITION OF KEY TERMS

- Geosynthetics
 - Polymeric materials



Geostrip

DEFINITION OF KEY TERMS

- Geosynthetics

- geotextiles, geomembranes, geonets, and grids.



Geotextile



Geogrid

DEFINITION OF KEY TERMS

◎ **Coping**

- The coping is used to tie in the top of the wall panels and to provide a pleasing finish to the wall top. It can be cast-in-place or prefabricated segments.

◎ **Extensible Reinforcement**

- Polymeric reinforcement materials (exhibits creep characteristics under stress).

◎ **Filter Fabric**

- A geotextile filter fabric is used to cover the joint between panels. It is placed on the backside of the panels. This keeps the soil from being eroded through the joints and allows any excess water to flow out.

◎ **Inextensible Reinforcement**

- Metallic reinforcement material (both strips and grids) (does not exhibit creep characteristics under stress).

DEFINITION OF KEY TERMS

⦿ **Leveling Pad**

- The leveling pad is a non-reinforced concrete pad used to provide a level, consistent surface at the proper grade to place the panels.

⦿ **Original Ground**

- This is the existing ground surface at the site.

⦿ **Soil Reinforcement**

- Soil reinforcement holds the wall facing panels in position and provides reinforcement for the soil.
- Can be strips, grids, or mesh.
- Can be made of steel (inextensible materials) or polymers (extensible materials).

DEFINITION OF KEY TERMS

◎ Spacers

- Wall panel spacers are typically ribbed elastomeric or polymeric pads.
- inserted between panels to help provide the proper spacing.
 - Proper spacing keeps the panels from having point contact and spalling the concrete.

◎ Wall/Reinforcement Connection

- This is where the connection is made between the wall facing panel and the soil reinforcement

◎ Wooden Wedges

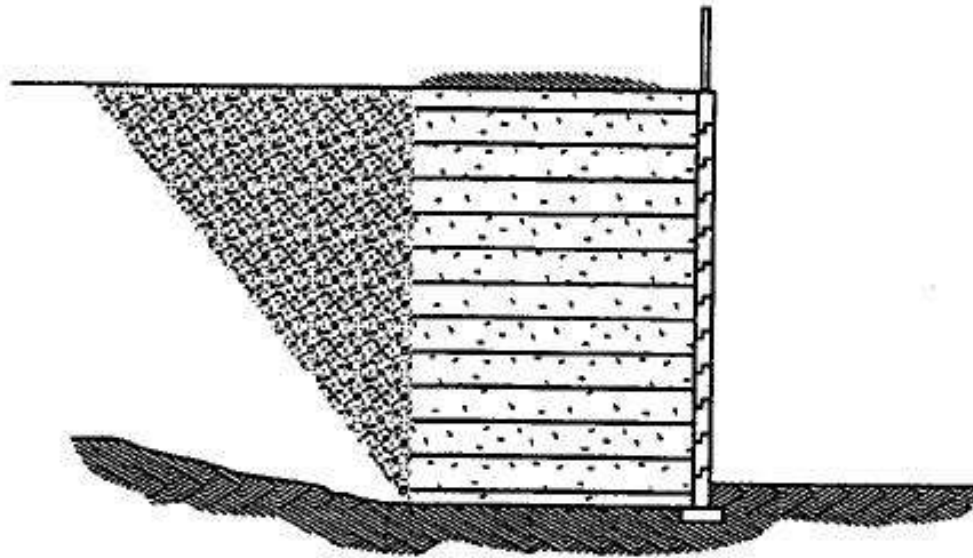
- Used to help hold the panels at the correct batter during the filling operation.
- Should be made from hard wood (such as oak, maple or ash).

APPLICATIONS

◎ Used for:

- retaining walls,
- access ramps,
- bridge abutments,
- waterfront structures (seawalls),
- dams,
- dikes,
- among others.

APPLICATIONS



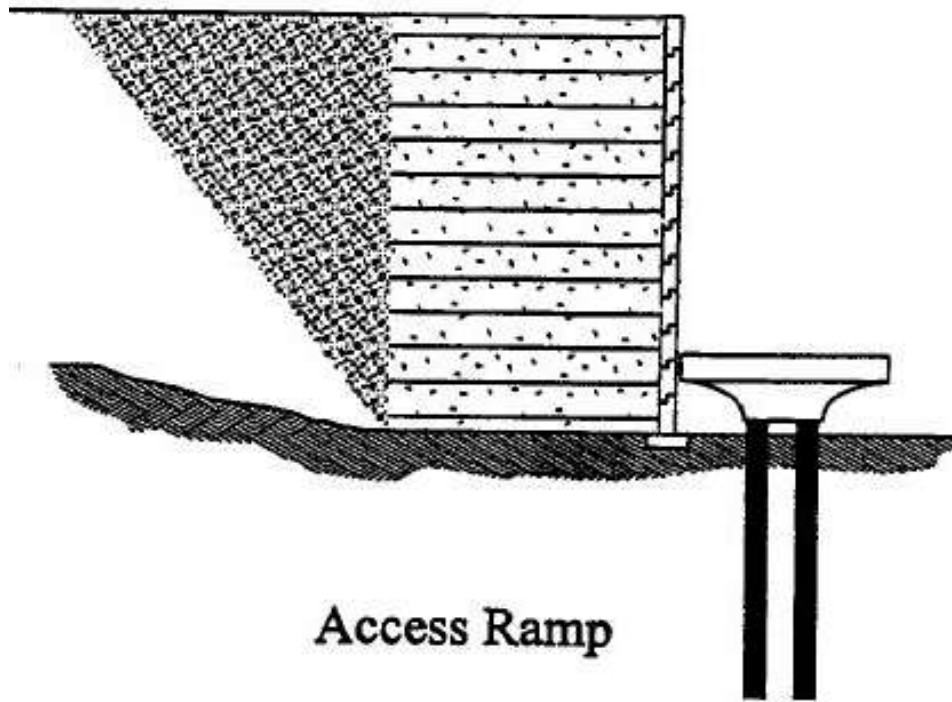
Retaining Wall

APPLICATIONS

Retaining Wall



APPLICATIONS



Access Ramp

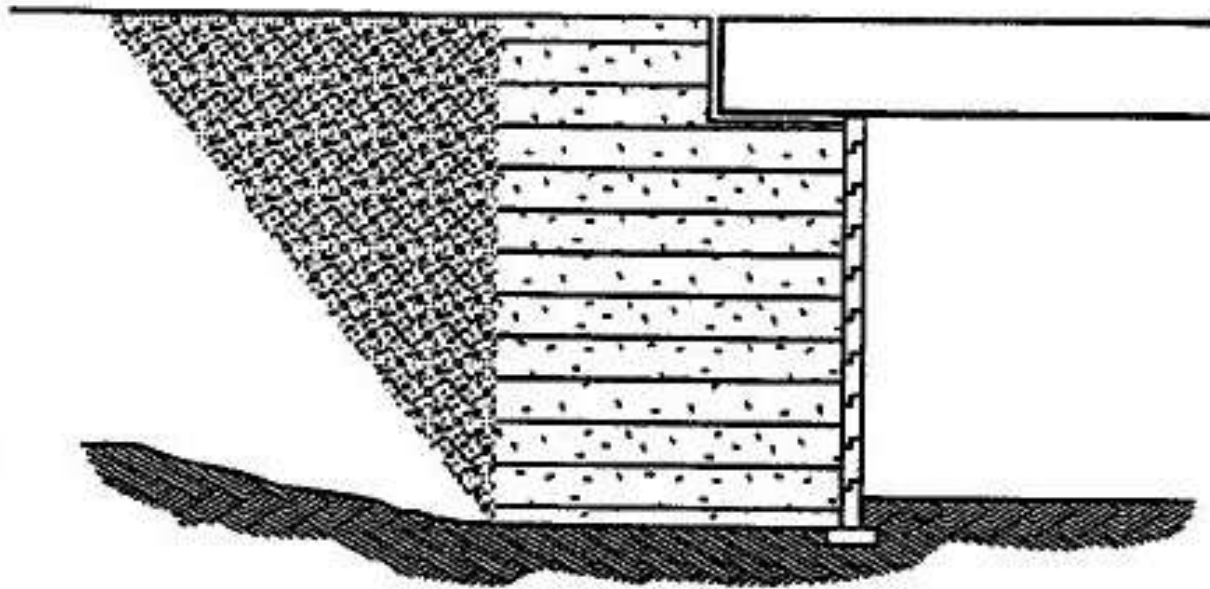
APPLICATIONS

Access Ramp



I-25 South Broadway Access Ramp-Denver, Colorado-photo simulation

APPLICATIONS



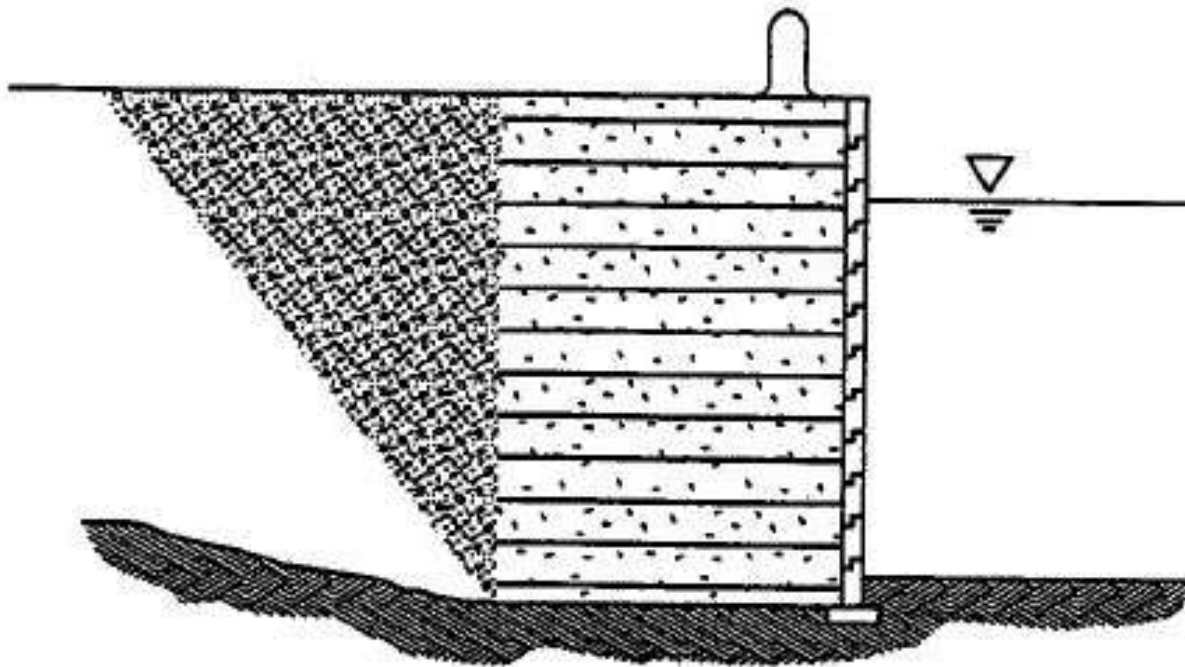
Bridge Abutment

APPLICATIONS

Bridge Abutment



APPLICATIONS



Waterfront Structure

PRECAST CONCRETE MODULAR BLOCK WALL

NEWPORT, RHODE ISLAND

Waterfront structure-Seawall



VAQUEROS DAM EXPANSION

GEOSYNTHETIC-STRIP REINFORCED MSE WALL

California



VAQUEROS DAM EXPANSION

GEOSYNTHETIC-STRIP REINFORCED MSE WALL



Figure 8 Construction of MSE wall 2. Photos courtesy of the authors

VAQUEROS DAM EXPANSION

GEOSYNTHETIC-STRIP REINFORCED MSE WALL



ADVANTAGES

- ⦿ Simple construction procedure
- ⦿ Reduced construction time.
- ⦿ No need of special skills for construction
- ⦿ Requires less site preparation than other alternatives.
- ⦿ For construction need less space in front of the structure

ADVANTAGES

- ⦿ Reduce right-of-way acquisition.
- ⦿ Tolerant to deformations
 - No need of rigid unyielding foundation support
 - Higher resistance to seismic loading
- ⦿ Cost effective construction technique.
- ⦿ Can be built to heights larger than 100ft (30m)

DISADVANTAGES

- ⦿ Requires a large space behind the wall for internal and external stability.
- ⦿ cost of importing suitable fill material may increase construction cost
 - At sites where there is a lack of granular soils
- ⦿ Suitable design criteria are required to
 - address corrosion of steel reinforcing elements,
 - deterioration of certain types of exposed facing elements and
 - potential degradation of polymer reinforcement in the ground.

DISADVANTAGES

- ⦿ Specifications and contracting practices have not been fully standardized.
- ⦿ The design of soil-reinforced systems often requires a shared design responsibility between material suppliers and owners.

RELATIVE COSTS

- ◎ Site specific costs of a soil-reinforced structure are a function of:
 - cut-fill requirements,
 - wall/slope size and type,
 - in-situ soil type,
 - available backfill materials,
 - facing finish,
 - temporary or permanent application.

RELATIVE COSTS

- ◎ MSE walls result in savings on the order of 25 to 50 percent in comparison with a conventional reinforced concrete retaining structure
 - Substantial savings is obtained by elimination of the deep foundations.
- ◎ Savings are evident in walls larger than 10 ft (3m)

RELATIVE COSTS

- For segmental precast concrete faced structures, typical relative costs are:
 - Erection of panels and contractors profit - 20 to 30 percent of total cost.
 - Reinforcing materials - 20 to 30 percent of total cost.
 - Facing system - 25 to 30 percent of total cost.
 - Backfill materials including placement - 35 to 40 percent of total cost

SYSTEMS DIFFERENTIATION

- ◎ A system is defined as a complete supplied package that includes:
 - design, specifications and all prefabricated materials.
 - Often technical assistance during the planning and construction phase is also included.

TYPES OF SYSTEMS

- ◎ MSE systems can be described by:
 - reinforcement geometry,
 - stress transfer mechanism,
 - reinforcement material,
 - extensibility of the reinforcement material, and
 - type of facing and connections.

TYPES OF SYSTEMS

○ Reinforcement Geometry

- Linear unidirectional - e.g.
 - Strips, including smooth or ribbed steel strips, or
 - coated geosynthetic strips over a load-carrying fiber.
- Composite unidirectional -
 - Grids or bar mats
- Planar bidirectional -
 - Continuous sheets of geosynthetics,
 - welded wire mesh, and
 - woven wire mesh.

TYPES OF SYSTEMS

◎ Reinforcement Material:

- Metallic reinforcements - Typically of mild steel.
 - Usually galvanized or may be epoxy coated.
- Nonmetallic reinforcements - Generally polymeric materials
 - polypropylene, polyethylene, or polyester.

TYPES OF SYSTEMS

○ Reinforcement Extensibility

■ Inextensible -

- Deformation of the reinforcement at failure is much less than the deformability of the soil.
- Steel strip and bar mats

■ Extensible -

- Deformation of the reinforcement at failure is comparable to or greater than the deformability of the soil.
- Geogrid, geobar, woven steel wire mesh

FACING SYSTEMS

- A wide range of finishes and colors can be provided in the facing.
- Provides protection against backfill sloughing and erosion
- In certain cases provides drainage paths.
- The type of facing influences settlement tolerances.

FACING SYSTEMS

◎Types:

- Segmental precast concrete panels
 - cruciform, square, rectangular, diamond, or hexagonal geometry.



FACING SYSTEMS

◎ Types:

- Segmental precast concrete panels
 - cruciform, square, rectangular, diamond, or hexagonal geometry.
- Dry cast modular block wall (MBW) units
 - Relatively small, squat concrete units that have been specially designed and manufactured for retaining wall applications.
 - Full height cores are filled with aggregate during erection.

FACING SYSTEMS

⦿ Metallic Facings

- Appropriate in structures where difficult access or difficult handling requires lighter facing elements.

⦿ Welded Wire Grids and Twisted Wire

- Can be bent up at the front of the wall to form the wall face.

⦿ Gabion Facing

- Rock-filled wire baskets can be used as facing with reinforcing elements consisting of welded wire mesh, welded bar-mats, geogrids, geotextiles or the double-twisted woven mesh.

WELDED WIRE



TWISTED WIRE



**Twisted Wire Mesh Gabion Machine
-Mesh is Produced in Rolls-**

FACING SYSTEMS

- Facings using welded wire or gabions
 - Disadvantages
 - uneven surface,
 - exposed backfill materials,
 - more tendency for erosion of the retained soil,
 - possible shorter life from corrosion of the wires, and
 - more susceptibility to vandalism.
 - Can be countered by providing shotcrete or by hanging facing panels on the exposed face and compensating for possible corrosion.

FACING SYSTEMS

○ Facings using welded wire or gabions

■ Advantages

- low cost,
- ease of installation,
- design flexibility,
- good drainage that provides increased stability, and
- possible treatment of the face for vegetative and other architectural effects.

FACING SYSTEMS

◎ Geosynthetic Facing

- Looped around at the facing to form the exposed face of the retaining wall.
- Susceptible to ultraviolet light degradation, vandalism and damage due to fire.
- Alternately, a geosynthetic grid used for soil reinforcement can be looped around to form the face of the completed retaining structure.
- Vegetation can grow through the grid structure to provide both ultraviolet light protection for the geogrid and a pleasing appearance.

FACING SYSTEMS



Vegetation growing through the grid structure

FACING SYSTEMS

◎ Postconstruction Facing

- For wrapped faced walls, the facing can be attached after construction of the wall by shotcreting, cast-in-place concrete or attaching prefabricated facing panels made of concrete, wood, or other materials.
- Adds cost but is advantageous where significant settlement is anticipated.

FACING SYSTEMS



Shotcreting



Cast In-Place Concrete

REINFORCEMENT TYPES

- Two types of steel reinforcements are in current use:
 - Steel strips
 - Ribbed top and bottom
 - Steel grids
 - Welded wire grid
 - Some MBW systems use steel grids with 2 longitudinal wires.

REINFORCEMENT TYPES



Steel strips



Welded Wire Grid

REINFORCEMENT TYPES

- ◎ Most MBW systems use geosynthetic reinforcement, principally geogrids.
 - High Density Polyethylene (HDPE) geogrid.
 - PVC coated polyester (PET) geogrid.
 - Geotextiles

REINFORCED BACKFILL MATERIALS

- ◎ Require high quality backfill for:
 - durability, good drainage, constructability, and good soil reinforcement interaction.
 - In most cases a material with high friction characteristics is specified and required.
 - generally eliminate soils with high clay contents.

REINFORCED BACKFILL MATERIALS

- ⦿ Lower quality backfills could be used for MSEW structures.
- ⦿ However, a high quality granular backfill has the advantages of
 - being free draining, providing better durability for metallic reinforcement, and requiring less reinforcement, increased rate of wall erection and improved maintenance of wall alignment tolerances.

MISCELLANEOUS CONSTRUCTION MATERIALS

- All joints are covered with a polypropylene (PP) geotextile strip to prevent the migration of fines from the backfill.

SITE EVALUATION

◎ Site Exploration

- Feasibility of using any type of earth retention system depends on the existing topography, subsurface conditions, and soil/rock properties.
- Perform a comprehensive subsurface exploration program to evaluate site stability, settlement potential, need for drainage, among others.
- Investigations must be conducted to locate and test locally available materials that can be used for backfill with the selected system.

SITE EVALUATION

Field Reconnaissance

- Preliminary subsurface investigation, consists in collecting data relating to subsurface conditions and making a field visit to obtain data on:
 - Limits and intervals for topographic cross sections.
 - Access conditions for work forces and equipment.
 - Surface drainage patterns, seepage, and vegetation characteristics.
 - Surface geologic features.
 - The extent, nature, and locations of existing or proposed below-grade utilities and substructures.
 - Available right-of-way.
 - Areas of potential instability.

SITE EVALUATION

◎ Subsurface Exploration

- Soil soundings, borings, and test pits.
- Minimum guidelines for subsurface exploration:
 - Soil borings should be performed at intervals of:
 - 30 m (100 ft) along the alignment of the soil-reinforced structure
 - 45 m (150 ft) along the back of the reinforced soil structure

SITE EVALUATION

- ◎ Causes for problems in projects
 - often traced to inadequate subsurface exploration programs that did not disclose local or significant areas of soft soils causing local differential settlement and distress to the facing panels.
- ◎ Select backfill is to be obtained from on-site sources
 - Extent and quality must be fully explored to minimize contractor claims for changed conditions.

SITE EVALUATION

○ Laboratory Testing

- Soil samples should be visually examined and appropriate tests performed for classification according to the Unified Soil Classification System (ASTM D 2488-69).
- Test results will provide:
 - Necessary information for planning degradation protection measures.
 - Will help in the selection of reinforcement elements with adequate durability.

PROJECT EVALUATION

◎ Structure Selection Factors

- The major factors that influence the selection of an MSE alternative for any project:
 - Geologic and topographic conditions.
 - Environmental conditions.
 - Size and nature of the structure.
 - Aesthetics.
 - Durability considerations.
 - Performance criteria.
 - Availability of materials
 - Experience with a particular system or application.
 - Cost.

PROJECT EVALUATION

◎ Geologic and Topographic Conditions

- Where soft compressible soils are encountered, preliminary stability analyses must be made to determine if sufficient shear strength is available to support the weight of the reinforced fill.
- Where these conditions are not satisfied, ground improvement techniques must be considered to increase the bearing capacity at the foundation level.

PROJECT EVALUATION

- ◎ Ground improvement techniques include but are not limited to:
 - Excavation and removal of soft soils and replacement with a compacted structural fill.
 - Use of lightweight fill materials
 - In situ densification by dynamic compaction or improvement by use of surcharging with or without wick drains.
 - Construction of stone columns.

PROJECT EVALUATION

◉ Environmental Conditions

- Primary environmental issue:
 - ◉ Aggressiveness of the in situ ground regime that can cause deterioration to the reinforcement.
 - Post construction changes must be considered where de-icing salts or fertilizers are subsequently used.
- A secondary environmental issue:
 - ◉ Site accessibility
 - lightweight facings such as metal skins, modular blocks (MBW), or the use of geotextile or geogrid wrapped facings and vegetative covers

PROJECT EVALUATION

◎ Size and nature of structure

- Theoretically there is no upper limit to the height of MSEW that can be constructed.
- The lower limit to height is usually dictated by economy.
- Practical limits are often dictated by:
 - economy
 - available R.O.W.
 - tensile strength of commercially available soil reinforcing materials.

PROJECT EVALUATION

◎Aesthetics

- Precast concrete facing panels may be cast with an unlimited variety of texture and color.
- Modular block wall facings are often comparable in cost to precast concrete panels.
- MBW facings may be manufactured in color and with a wide variety of surface finishes.

PROJECT EVALUATION

◉ Questionable Applications

- MSE walls should not be used under the following conditions:
 - ◉ When utilities other than highway drainage must be constructed within the reinforced zone where future access for repair would require the reinforcement layers to be cut.
 - ◉ With galvanized metallic reinforcements exposed to surface or contaminated ground water.
 - ◉ When floodplain erosion may undermine the reinforced fill zone.

DESIGN APPROACH

- ⦿ Working Stress analyses
- ⦿ Limit Equilibrium analyses
 - Check of the overall stability of the structure.
- ⦿ Deformation Evaluations
 - Evaluation of the anticipated performance of the structure with respect to horizontal and vertical displacement

WORKING STRESSES ANALYSIS:

- ① Selecting the location for reinforcement.
- ① Checking that stresses in the stabilized soil mass are compatible with the properties of the soil and inclusions.
- ① Evaluating local stability at the level of each reinforcement.
- ① Predicting progressive failure.

LIMIT EQUILIBRIUM ANALYSIS

- Types of stability that must be considered:
 - External stability
 - Involves the overall stability of the stabilized soil mass considered as a whole and is evaluated using slip surfaces outside the stabilized soil mass.

LIMIT EQUILIBRIUM ANALYSIS

- Types of stability that must be considered:
 - Internal stability analysis
 - Evaluation of potential slip surfaces within the reinforced soil mass.
 - Combined stability analysis
 - For when the critical slip surface is partially outside and partially inside the stabilized soil mass.

DEFORMATION EVALUATIONS

- ◉ Influence and variations in the type of reinforcement on the performance of the structure can be evaluated.
- ◉ Horizontal analysis is done so that the usual factors of safety against external or internal stability failure will ensure that deformations will be within tolerable limits.
- ◉ Vertical deformation analyses are obtained from conventional settlement computations.

DESIGN METHODS, INEXTENSIBLE REINFORCEMENTS

- ◎ State of stress for external stability
 - Assumed to be equivalent to a Coulomb state of stress with a wall friction angle δ equal to zero.
- ◎ State of stress for internal stability
 - A variable state of stress varying from a multiple of K_a to an active earth pressure state.

DESIGN METHODS, EXTENSIBLE REINFORCEMENTS

◎ For external stability

- The method assumes an earth pressure distribution, consistent with the method used for inextensible reinforcements.

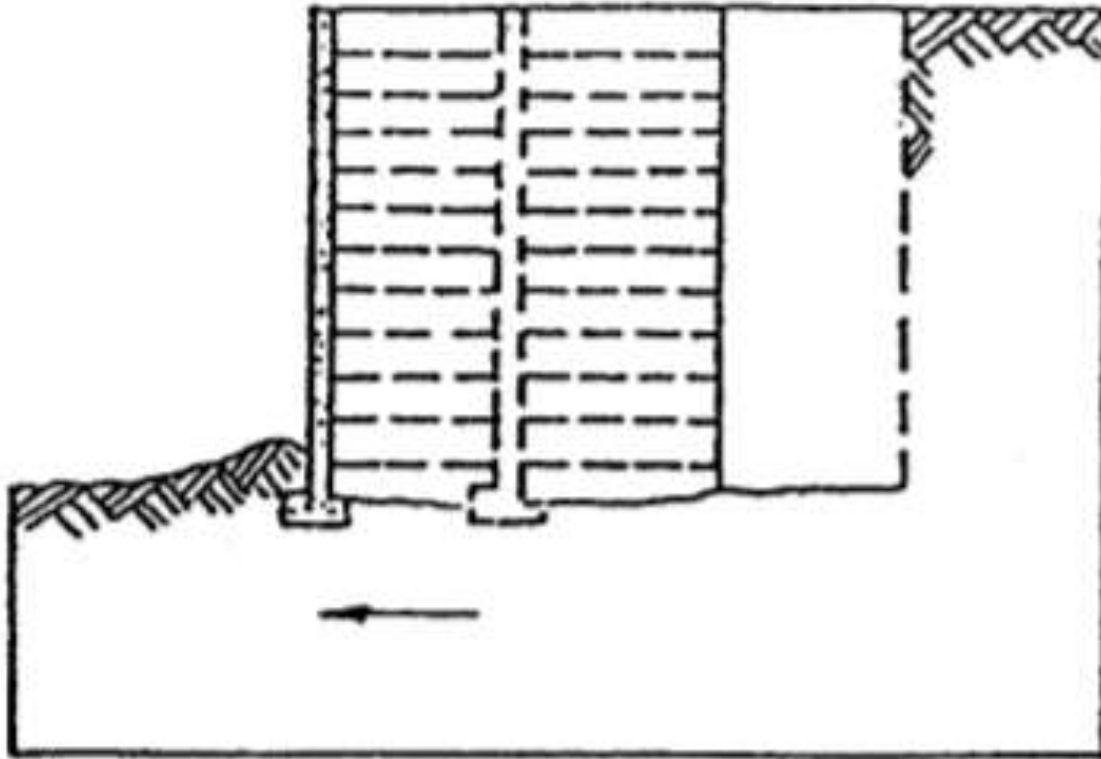
◎ For internal stability

- A Rankine failure surface is considered, because the extensible reinforcements can elongate more than the soil, before failure.

SIZING FOR EXTERNAL STABILITY

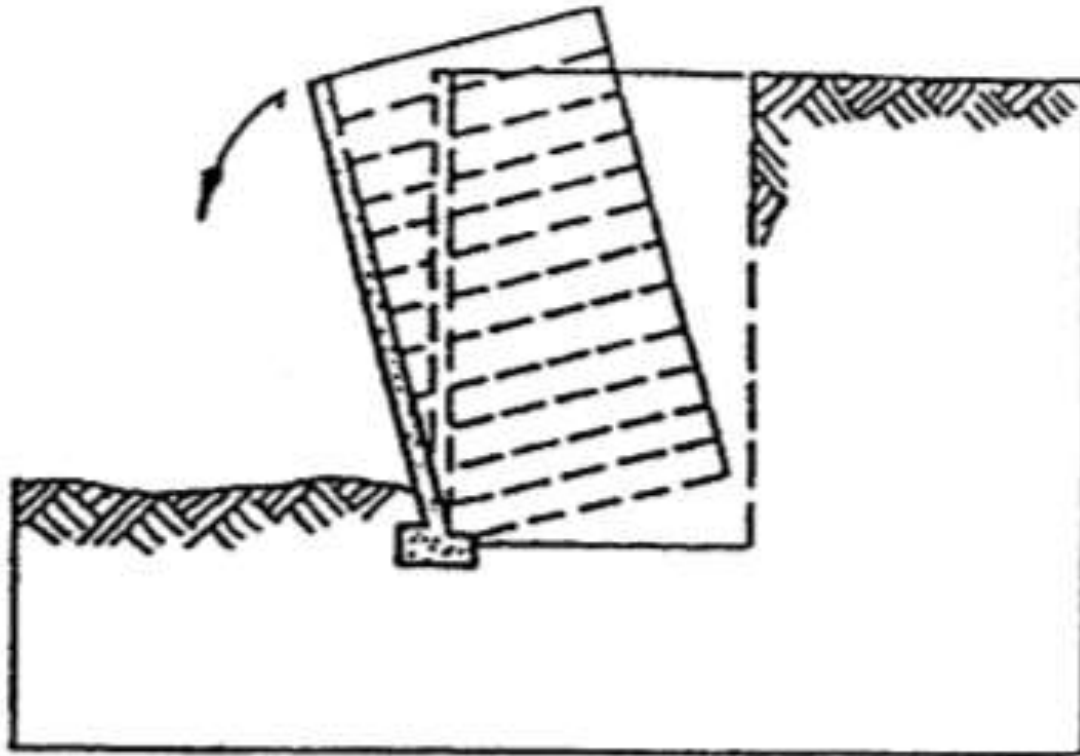
- Potential external failure mechanisms:
 - Sliding on the base.
 - Limiting the location of the resultant of all forces.
 - Bearing capacity.
 - Deep seated stability
 - rotational slip-surface or slip along a plane of weakness.

SIZING FOR EXTERNAL STABILITY



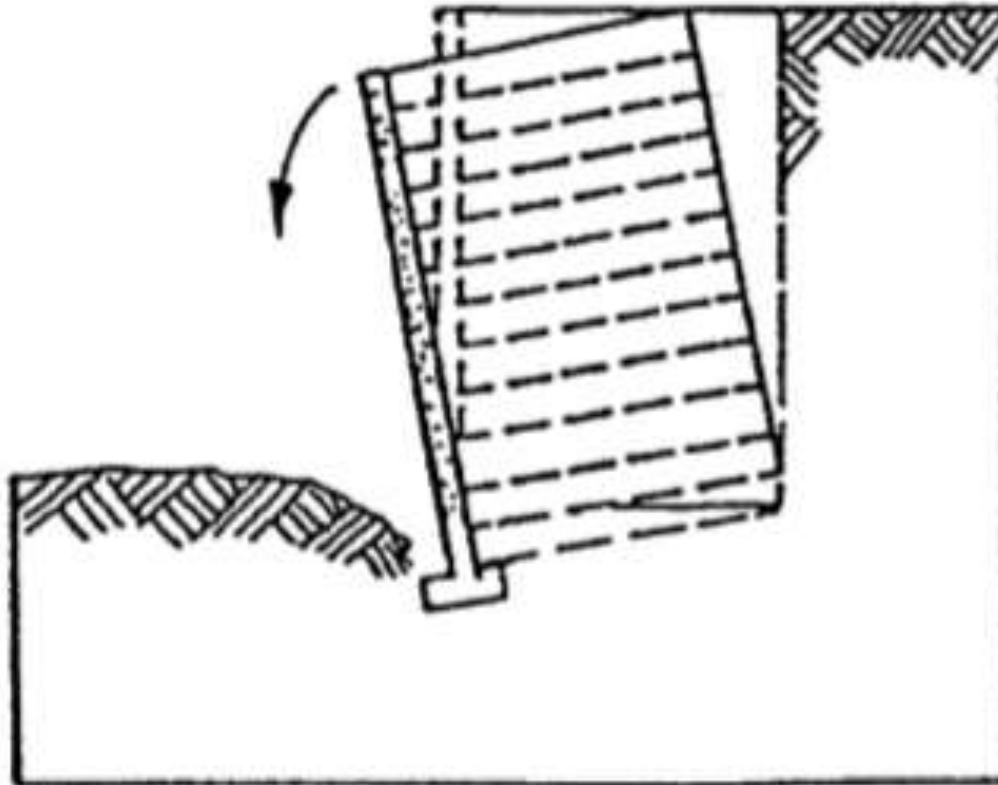
Sliding

SIZING FOR EXTERNAL STABILITY



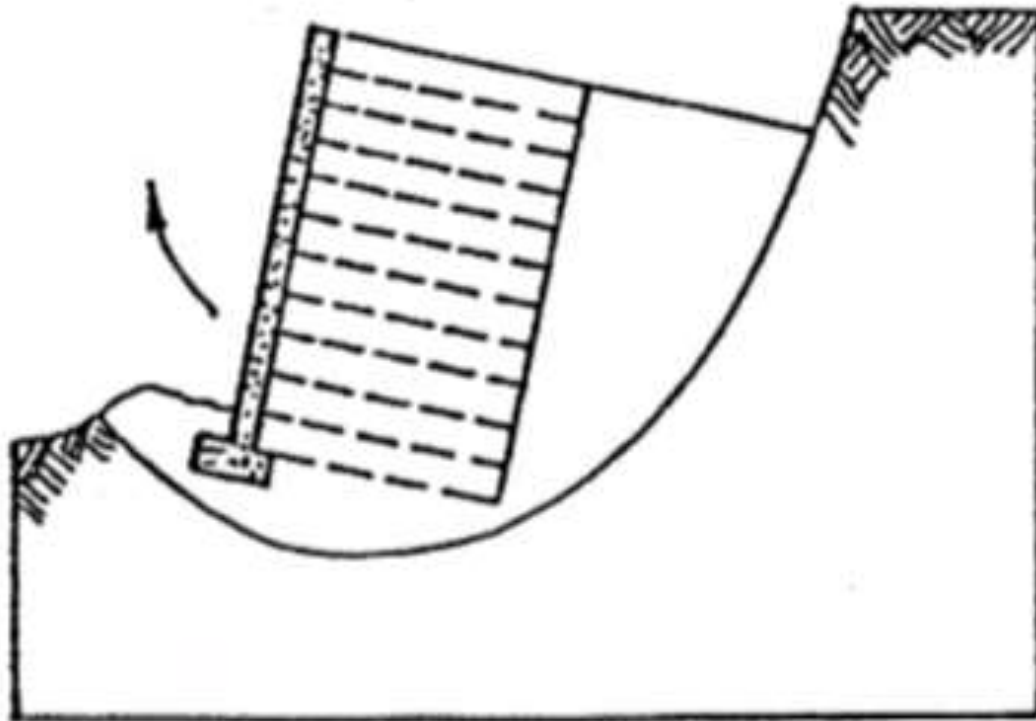
Overturning (eccentricity)

SIZING FOR EXTERNAL STABILITY



Bearing Capacity

SIZING FOR EXTERNAL STABILITY

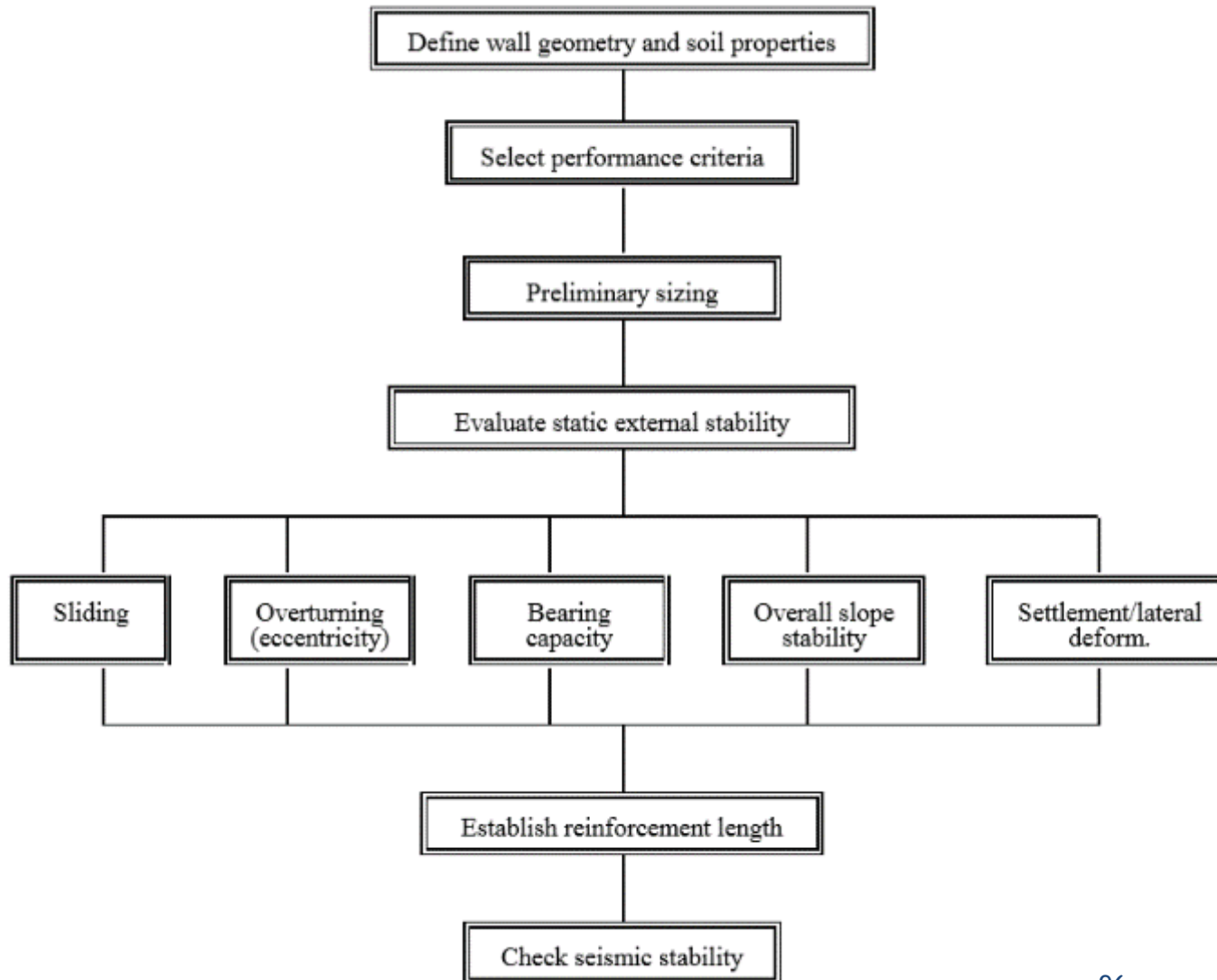


Deep Seated Stability (Rotational)

EXTERNAL STABILITY

- External stability evaluations treat the reinforced section as a composite homogeneous soil mass.
- Evaluate the stability according to conventional failure modes for gravity type wall systems.

EXTERNAL STABILITY DESIGN PROCESS:



DEFINE WALL GEOMETRY AND SOIL PROPERTIES

- Must be defined by the designer:
 - Wall height, batter.
 - Soil surcharges, live load surcharges, dead load surcharges, etc.
 - Seismic loads.
 - Engineering properties of foundation soils (γ , c , φ).
 - Engineering properties of the reinforced soil volume (γ , c , φ).
 - Engineering properties of the retained fill (γ , c , φ).
 - Groundwater conditions.

SELECT PERFORMANCE CRITERIA

- Should reflect site conditions and agency or AASHTO code requirements.
 - External stability factors of safety (Sliding, bearing capacity location of resultant force).
 - Global stability factor of safety.
 - Maximum differential settlement.
 - Maximum horizontal displacement.
 - Seismic stability factor of safety.
 - Design life

PRELIMINARY SIZING

- ⦿ Process begins by adding the required embedment to the wall height to determine the design heights for each section.
- ⦿ Preliminary length of reinforcement is chosen to be greater than $0.7H$ and 2.5 m.
 - H - design height of the structure.

PRELIMINARY SIZING

- ◎ Structures with sloping surcharge fills or other concentrated loads, generally require longer reinforcements for stability, often from $0.8H$ to $1.1H$.

STANDARD MSEW DESIGNS

- Customarily designed on a project-specific basis.
- Most agencies use a line-and-grade contracting approach, with the contractor selected providing the detailed design.
- However, standard designs can be developed and implemented by an agency for MSEW structures.
 - Similar to standard concrete cantilever wall designs used by many agencies.

STANDARDIZED DESIGNS

- ⦿ Require generic designs and generic materials.
- ⦿ Generic designs require definition of:
 - wall geometry and surcharge loads
 - soil reinforcement strength
 - structure height limit
 - Modular block wall (MBW) unit properties of width and batter.

STANDARDIZED DESIGNS

- ④ Definition of generic material properties for the standard designs requires the development of an approved product list for MBW units, soil reinforcement and MBW unit-soil reinforcement combinations.
- ④ The combinations require a separate approved product list.
- ④ An additional requirement for MBW units is an approved manufacturing quality control plan on file with the agency.

EXAMPLE DESIGN CROSS SECTION FROM THE MINNESOTA DEPARTMENT OF TRANSPORTATION

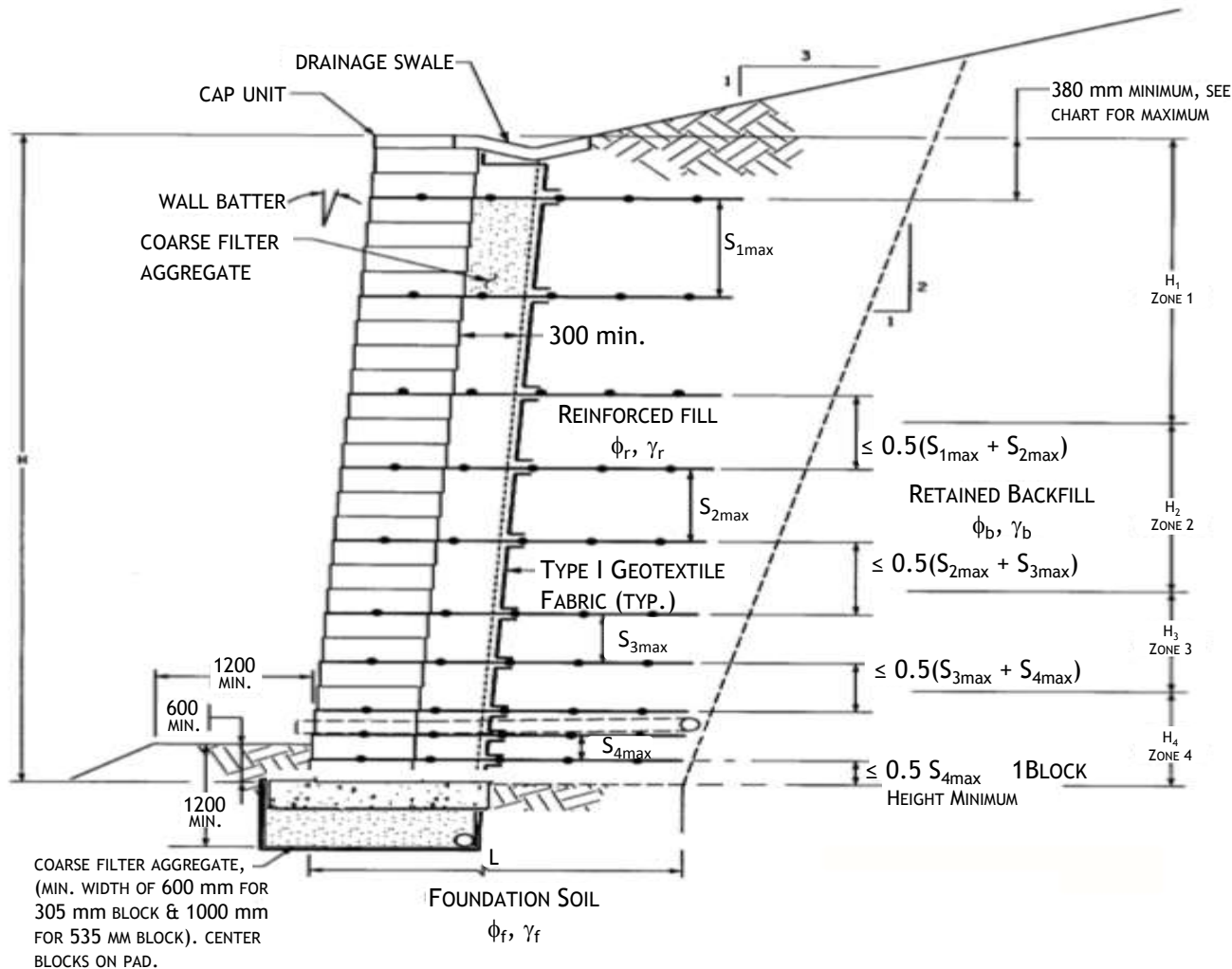


Figure 9: Design Cross Section

REINFORCEMENT LAYOUT TABLE FROM THE MN/DOT

MODULAR BLOCK WALL REINFORCEMENT LAYOUT — CASE 4 - 1:3 FILL SLOPE —														
MBW Reinforcement Class	Strength of Soil Reinf. (kN/m)		Minimum Reinforcement Length, L (m)	Maximum Wall Height (m)	Nominal Block Width (mm)	Wall Batter Range (degrees)		Maximum Unreinforced Wall Height (mm)	Zone 1		Zone 2		Zone 3	
	L. Term (Ta)	Design (Ta)				≥	<		H1 (m)	S1 _{max} (mm)	H2 (m)	S1 _{max} (mm)	H3 (m)	S1 _{max} (mm)
MBW-10	15	10	0.7 H	6.8	305	0	3	610	2.6	610	1.6	410	2.6	205
						3	7	610	2.8	610	2.0	410	2.0	205
				7		10	610	3.4	610	2.1	410	1.5	205	
				10		15	610	3.6	610	2.4	410	1.0	205	
MBW-15	22.5	15	0.7 H	7.0	305	0	3	610	4.4	610	1.8	460	0.8	305
						3	7	610	4.8	610	1.7	460	0.5	305
						7	10	610	5.4	610	1.6	410		
						10	15	610	5.9	610	1.1	410		
MBW-20	30	20	0.7 H	7.0	305	0	3	610	5.4	610	0.8	460		
						3	7	610	5.8	610	1.2	460		
						7	10	610	7.0	610				
						10	15	610	7.0	610				

Reinforcement layout table from
the MN/DOT

CONTRACTING METHODS

- MSE wall contracted using two approaches:
 - Agency or material supplier designs
 - system components, drainage details, erosion measures, and construction execution explicitly specified in the contracting documents
 - Performance or end-result approach
 - Uses approved or generic systems or components, with lines and grades noted on the drawings and geometric and design criteria specified.

AGENCY OR SUPPLIER DESIGN

- This approach includes the development of a detailed set of plans and material specifications in the bidding documents.
- Advantage
 - The complete design, details, and material specifications can be developed and reviewed over a longer design period.
- Disadvantage
 - For alternate bids, additional sets of designs and plans must be processed.
 - Newer and potentially less expensive systems or components may not be considered during the design stage.

AGENCY OR SUPPLIER DESIGN

- Fully detailed plans shall include:
 - Plan and Elevation Sheets
 - Plan view.
 - Elevation views.
 - Length, size, and type of soil reinforcement.
 - Panel and MBW unit layout and the designation of the type or module.
 - Internal drainage alignment, elevation, and method of passing reinforcements around such structures.
 - Cross sections.
 - Limits and extent of reinforced soil volume.
 - All construction constraints.
 - Payment limits and quantities.

AGENCY OR SUPPLIER DESIGN

◎ Facing/Panel Details

- Facing details for erosion control, reinforced slopes, and all details for facing modules.
- All details of the architectural treatment or surface finishes.

◎ Drainage Facilities/Special Details

- All details for construction around drainage facilities, overhead sign footings, and abutments.
- All details for connection to traffic barriers, copings, parapets, noise walls, and attached lighting.
- All details for temporary support including slope face support where warranted.

AGENCY OR SUPPLIER DESIGN

◉ Design Computations

- Plans shall be supported by detailed computations for internal and external stability and life expectancy for the reinforcement.

◉ Geotechnical Report

- Engineering properties of the foundation soils.
- Engineering properties of the reinforced soil.
- Engineering properties of the fill or in situ soil behind the reinforced soil mass.
- Groundwater or free water conditions and required drainage schemes if required

◉ Construction Specifications

END RESULT DESIGN APPROACH

- ◉ Often referred as "line and grade" or "two line drawing"
- ◉ The agency prepares drawings of the geometric requirements for the structure or reinforced slope and material specifications for the components or systems that may be used.
- ◉ The components or systems that are permitted are specified or are from a pre-approved list maintained by the agency, from its prequalification process.
- ◉ Performed by trained and experienced staff.

END RESULT DESIGN APPROACH

◉ Advantage

- The system specification approach lessens engineering costs and manpower for an agency and transfers some of the project's design cost to construction.

◉ Disadvantages

- Agency engineers may not fully understand the technology at first, therefore may not be fully qualified to review and approve construction modifications.
- Complex phasing and special details are not addressed until after the contract has been awarded.

END RESULT DESIGN APPROACH

- ⦿ As part of the contract documents:
 - Geometric Requirements
 - Plan and elevation of the areas to be retained.
 - Typical cross section.
 - Elevation view of each structure.
 - Location of utilities and signs.
 - Construction constraints.
 - Mean high water level, design high water level, and drawdown conditions where applicable.

END RESULT DESIGN APPROACH

⦿ Geotechnical Requirements

- The same as in Agency or Supplier Design except that the design responsibility is delineated as to areas of contractor/supplier and agency responsibility.

END RESULT DESIGN APPROACH

◉ Structural and Design Requirements

- Reference to specific governing sections of the agency design manual, construction specifications and special provisions.
- Magnitude, location, and direction of external loads.
- Limits and requirements of drainage features.
- Slope erosion protection requirements for reinforced slopes.
- Size and architectural treatment of concrete panels for MSE walls.

END RESULT DESIGN APPROACH

◎ Performance Requirements

- Tolerable movement of the structure both horizontal and vertical.
- Tolerable face panel movement.
- Monitoring and measurement requirements.

TRICON MSE WALL



Visual simulation

- Proposed MSE wall
- Highway construction
- Los Angeles



- Video from You Tube for MSE wall construction
- [Reinforced Earth](#)

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 - (787) 832-4040
 - X6342 (office extension)
 - X3434 (civil engineering department)

REFERENCES

- ⦿ Elias, V., Christopher, B., Berg, R. (2001). *Mechanically Stabilized Earth Walls and Reinforced Soil Slopes Design and Construction Guidelines*. FHWA-NHI-00-043. Washington, D.C. :National Highway Institute.
- ⦿ http://www.tencate.com/pt/lam/Images/bro_mse0208_tcm31-10770.pdf.
- ⦿ <http://www.dot.state.oh.us/Divisions/ConstructionMgt/OnlineDocs/2009MOP/SS%20840,%20850,851,%20S-1015/SS-840/SS.htm>
- ⦿ <http://www.tensarcorp.com/Systems-and-Products/Ares-Retaining-Wall-Systems>
- ⦿ <http://www.terrasiteco.com/construction-services/>

REFERENCES

- ⦿ <http://www.geostructures.com/solutions/structures-walls/retaining-walls>
- ⦿ <https://teddywanders.wordpress.com/2013/06/28/yangsan-site-visit-geosynthetics-course/>
- ⦿ <http://www.ensolretaining.com/portfolio.php?do=hmc>
- ⦿ <https://www.rocscience.com/usage/use/4/Retaining-Walls>
- ⦿ <http://www.earthteccorp.com/>
- ⦿ http://www.tencate.com/pt/lam/Images/bro_mse0208_tcm31-10770.pdf
- ⦿ <http://www.icainversiones.com/?cat=1004..>

QUESTIONS?



INTERNAL AND EXTERNAL STABILITY OF MSE WALLS

Dr. Beatriz Camacho

Associate Professor

Department of Civil Engineering
and Surveying

University of Puerto Rico at
Mayagüez

SCHEDULE

- ◎ External stability Design Process
- ◎ Internal stability Design Process

EXTERNAL STABILITY

- ◎ Reinforced section for external stability evaluations treated as:
 - a composite homogeneous soil mass.

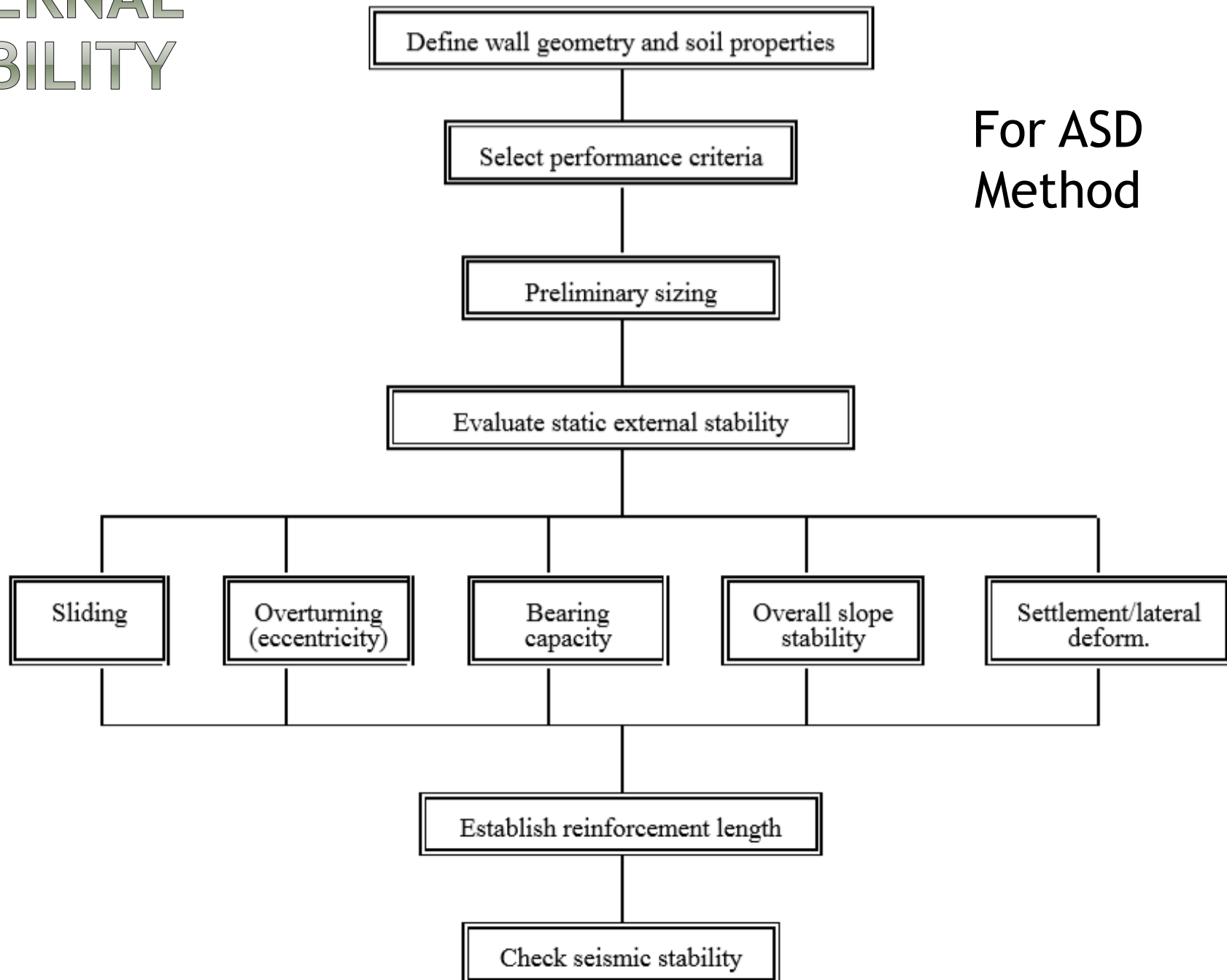
- ◎ Stability evaluated according to conventional failure modes for gravity type wall systems.

EXTERNAL STABILITY

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For ASD
Method



(LRFD)

Basic Design Steps for MSE Walls

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(LRFD)

Basic Design Steps for MSE Walls

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LOAD RESISTANCE FACTOR DESIGN

LRFD METHOD

- ◎ Important points regarding LRFD methodology to prevent any confusion in application of the various theories and equations presented:
 - The symbol ϕ (phi) is used for both the
 - soil friction angle and
 - LRFD resistance factor.
 - The symbol γ (gamma) is used for both
 - soil unit weight and
 - LRFD load factor.

LOAD RESISTANCE FACTOR DESIGN

LRFD METHOD

- ◎ Important points regarding LRFD methodology
 - Load and resistance factors for MSE walls are currently calibrated by fitting to ASD results.
 - Thus, LRFD design should be similar to ASD designs.
 - For most MSE wall system designs,
 - Strength limit states control member sizes.
 - Service limit states may control aspects such as
 - joint width openings and
 - construction sequence based on the anticipated deformations.
 - Extreme event limit states may affect both the member sizes as well as deformations.

APPLICABLE LOADS

LRFD METHOD

- ◎ The applicable loads for most MSE wall applications are:

Permanent Loads

EH = Horizontal earth loads

ES = Earth surcharge load

EV = Vertical pressure from dead load of earth fill

eg. the pressure from a spread footing above the reinforced mass.

Transient Loads

CT = Vehicular collision force

EQ = Earthquake load

LL = Vehicular live load

LS = Live load surcharge

eg. is a sloping fill above the top of an MSE wall.

LOAD COMBINATION-MOST MSE WALLS

LRFD METHOD

Table 4-1. Typical MSE Wall Load Combinations and Load Factors
(after Table 3.4.1-1, AASHTO {2007}).

Load Combination Limit State	EH ES EV	LL LS	Use One of These at a Time	
			EQ	CT
STRENGTH I	γ_p	1.75	—	—
EXTREME EVENT I	γ_p	γ_{EQ}	1.00	—
EXTREME EVENT II	γ_p	0.50	—	1.00
SERVICE I	1.00	1.00	—	—

Notes:

γ_p = load factor for permanent loading. May subscript as γ_{p-EV} , γ_{p-EH} , etc.

γ_{EQ} = load factor for live load applied simultaneously with seismic loads

LOAD FACTORS

LRFD METHOD

Table 4-2. Typical MSE Wall Load Factors for Permanent Loads, γ_p
(after Table 3.4.1-2, AASHTO {2007}).

Type of Load	Load Factor	
	Maximum	Minimum
<i>DC</i> : Component and Attachments	1.25	0.90
<i>EH</i> : Horizontal Earth Pressure <ul style="list-style-type: none"> • Active 	1.50	0.90
<i>EV</i> : Vertical Earth Pressure <ul style="list-style-type: none"> • Overall Stability • Retaining Walls and Abutments 	1.00 1.35	N/A 1.00
<i>ES</i> : Earth Surcharge	1.50	0.75

Note: May subscript as γ_{EV-MIN} , γ_{EV-MAX} , γ_{EH-MIN} , γ_{EH-MAX} , etc.

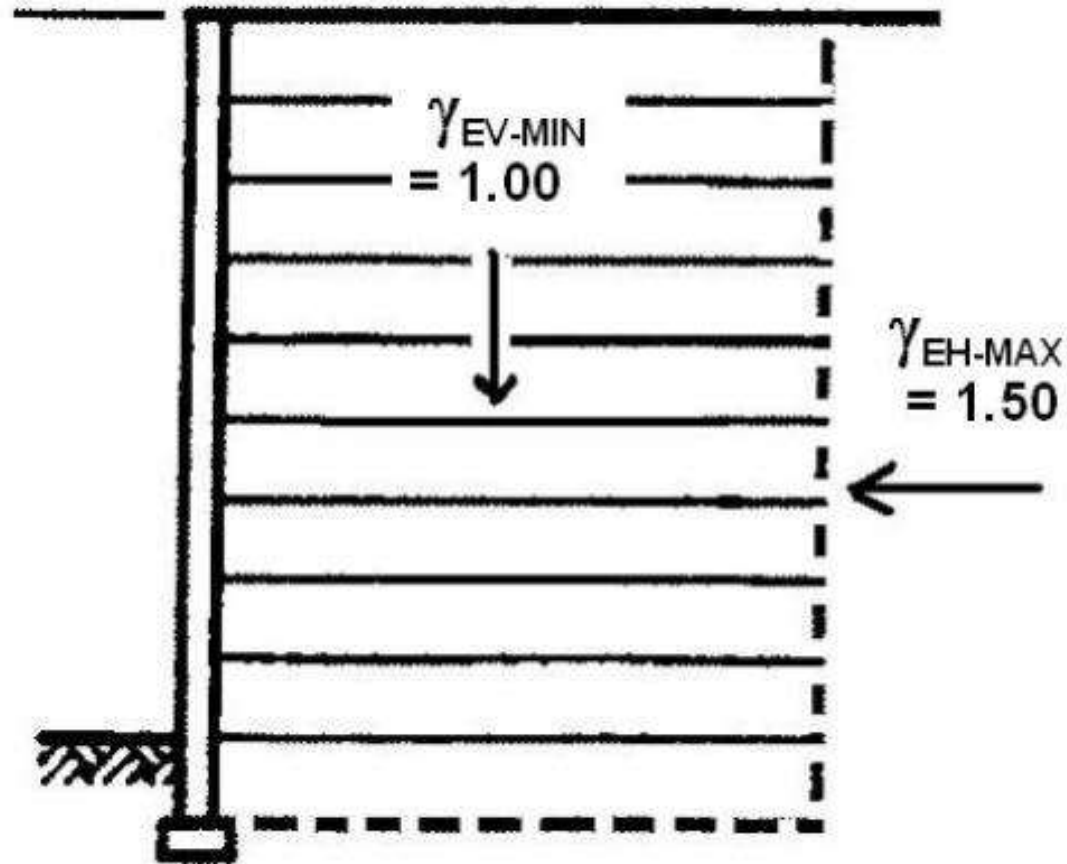
LOAD FACTORS

LRFD METHOD

- ◎ In general, AASHTO's guidance can be applied by
 - using minimum load factors if permanent loads increase stability and
 - use maximum load factors if permanent loads reduce stability.
 - For simple walls, e.g., level backfill with or without surcharges due to traffic, or sloping backfill, the load factor (minimum or maximum) to use for a particular stability check may be readily identifiable.

LOAD FACTORS-SIMPLE WALLS

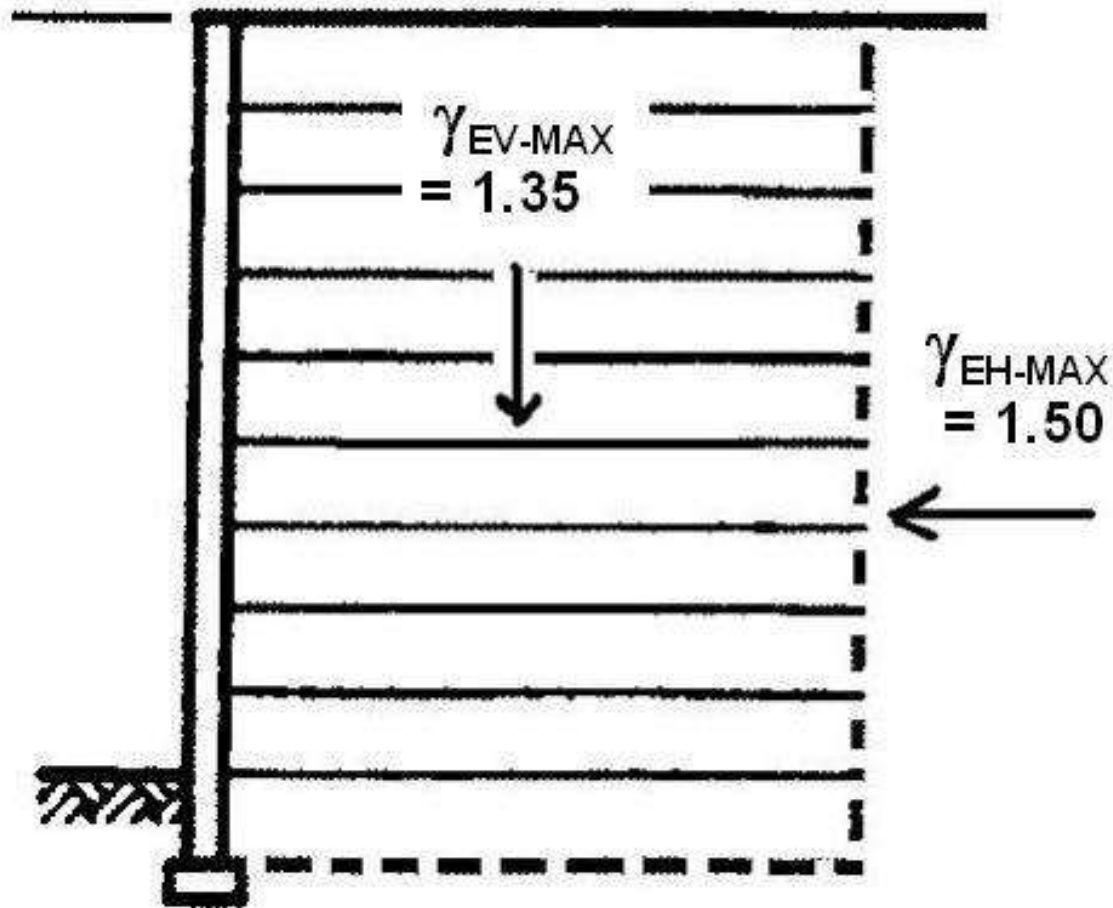
LRFD METHOD



Typical load factors for sliding stability and eccentricity check.

LOAD FACTORS-SIMPLE WALLS

LRFD METHOD



Typical load factors for bearing calculations.

STRENGTH LIMIT STATES

Specific checks for the strength limit states required for MSE wall design

◎ External Stability

- Limiting Eccentricity
- Sliding
- Bearing Resistance

◎ Internal Stability

- Tensile Resistance of Reinforcement
- Pullout Resistance of Reinforcement
- Structural Resistance of Face Elements
- Structural Resistance of Face Element Connections

OTHER LIMIT STATES ANALYSIS

Specific checks for the service limit states and global stability required for MSE wall design

◎ Service Limit States for MSE walls

- External Stability
 - Vertical Wall Movements
 - Lateral Wall Movements

◎ Global Stability of MSE walls

- Overall Stability
- Compound Stability

DESIGN PROCEDURE-LRFD

PROJECT REQUIREMENTS

Must be defined by the designer (owner):

◎ Geometry

- Wall height,
- Wall batter,
- Backslope
- Toe slope

◎ Loading conditions

- Soil surcharges,
- live load surcharges,
- dead load surcharges,
- loads from adjacent structures
- Seismic loads.

PROJECT REQUIREMENTS

Must be defined by the designer (owner):

◎ Performance Criteria

- Design code
- Maximum tolerable differential settlement
- Maximum tolerable horizontal displacement
- Design life
- Construction Constrains

PROJECT PARAMETERS

Must be defined by the designer (owner):

- ◎ Existing and proposed topography
- ◎ Subsurface conditions across the site
 - Engineering properties of foundation soils (γ_f , c'_f , ϕ'_f , c_u).
 - Groundwater conditions.
- ◎ Reinforced wall fill
 - Engineering properties of the reinforced soil volume (γ_r , ϕ_r).
- ◎ Retained backfill
 - Engineering properties of the retained fill (γ_b , c_b , ϕ_b), cohesion usually assumed cero

PRELIMINARY SIZING

◎ Process begins by determining

- required embedment and
- Final exposed wall height

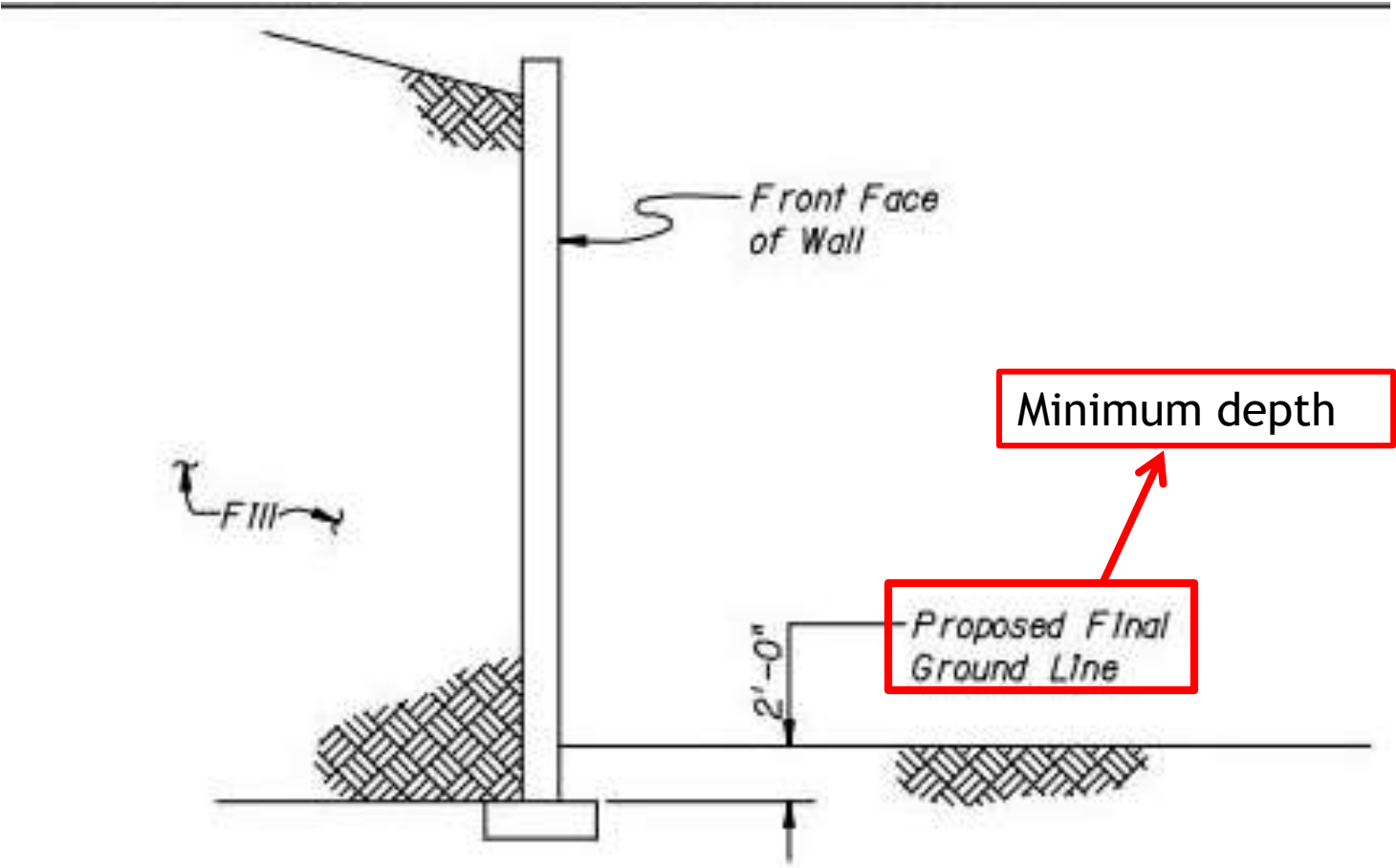
(combination of these two = design height, H)

Table 2-2. Minimum MSEW Embedment Depths.

Slope in Front of Wall	Minimum Embedment Depth to Top of Leveling Pad*
All Geometries	2 ft minimum
horizontal (walls)	H/20
horizontal (abutments)	H/10
3H:1V	H/10
2H:1V	H/7
1.5H:1V	H/5
* Minimum depth is the greater of applicable values listed, frost depth, or scour depth.	

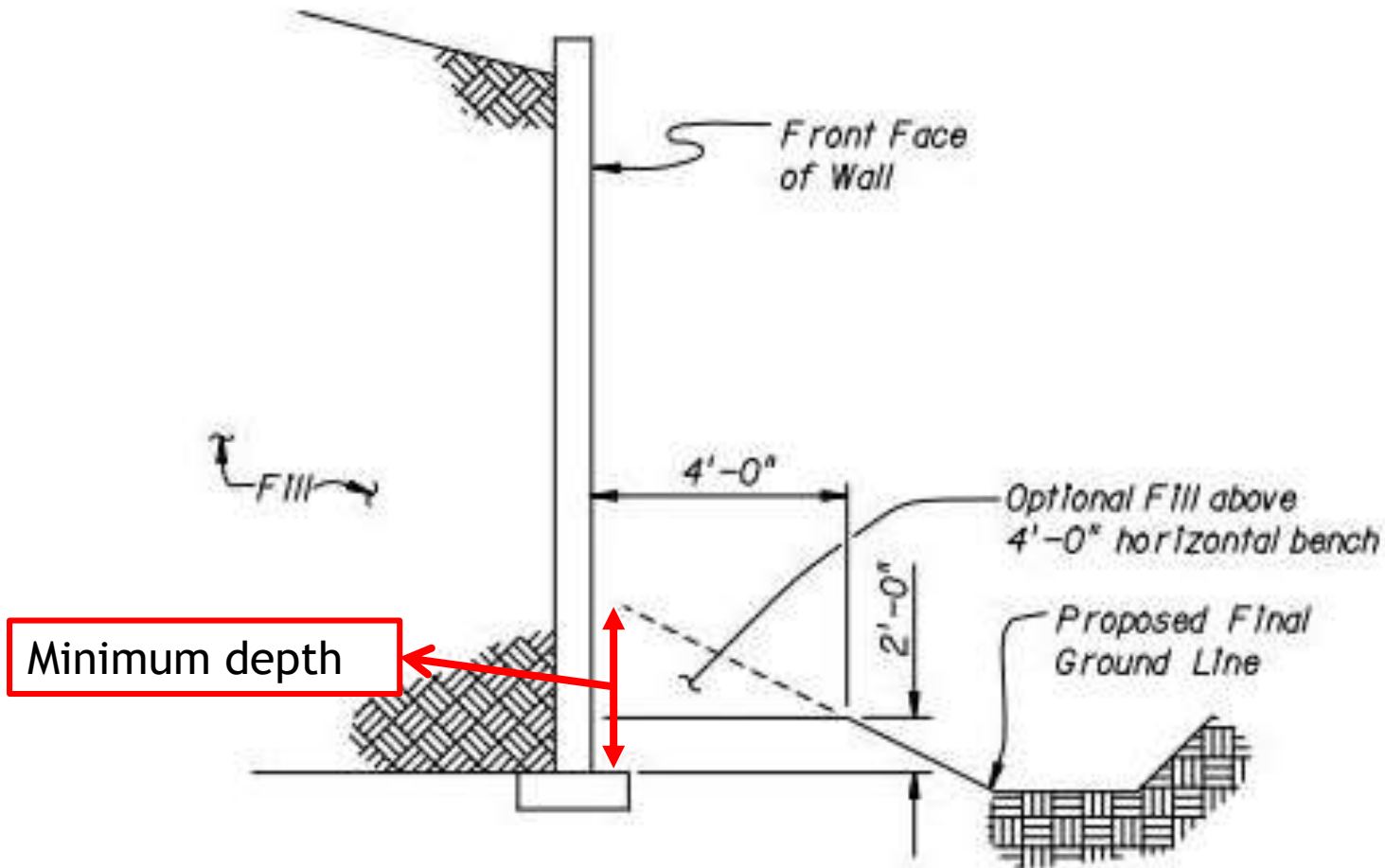
MINIMUM FRONT FACE EMBEDMENT

Horizontal slope



MINIMUM FRONT FACE EMBEDMENT

Slope in Front of wall=Sloping toe



PRELIMINARY SIZING

- ◎ Preliminary length of reinforcement is chosen to be the greater of:
 - $0.7H$ and
 - 2.5 m (8ft)

- ◎ Structures with sloping surcharge fills or other concentrated loads,
 - generally require longer reinforcements for stability,
 - often on the order of $0.8H$ to $1.1H$.

PRELIMINARY SIZING

Table 2-1. Typical Minimum Length of Reinforcement.

Case	Typical Minimum L/H Ratio
Static loading with or with traffic surcharge	0.7
Sloping backfill surcharge	0.8
Seismic loading	0.8 to 1.1

- ◎ Reinforcement should be uniform
 - However, it is recommended to add an extra 3ft (0.9m) on the upper two layers of soil reinforced
(Where post-construction movement occurs)

NOMINAL LOADS

(EARTH PRESSURES FOR EXTERNAL STABILITY)

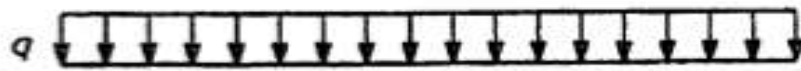
◎ Computations for walls with a vertical face

- Made assuming that wall mass acts as a rigid body with earth pressures developed on a vertical pressure plane arising from the back end of the reinforcements.
- This is because, when properly designed, the wall facing and the reinforced soil act as a coherent block with lateral earth pressures acting on the back side of that block

NOMINAL LOADS FOR MSE

- ◎ The primary sources of external loading on an MSE wall are
 - the earth pressure from the retained backfill behind the reinforced zone and
 - any surcharge loadings above the reinforced zone.
- ◎ Thus, the loads for MSE walls may include:
 - loads due to horizontal earth pressure (EH),
 - vertical earth pressure (EV),
 - live load surcharge (LS), and
 - earth surcharge (ES),
 - water (WA) and seismic (EQ) should also be evaluated if applicable

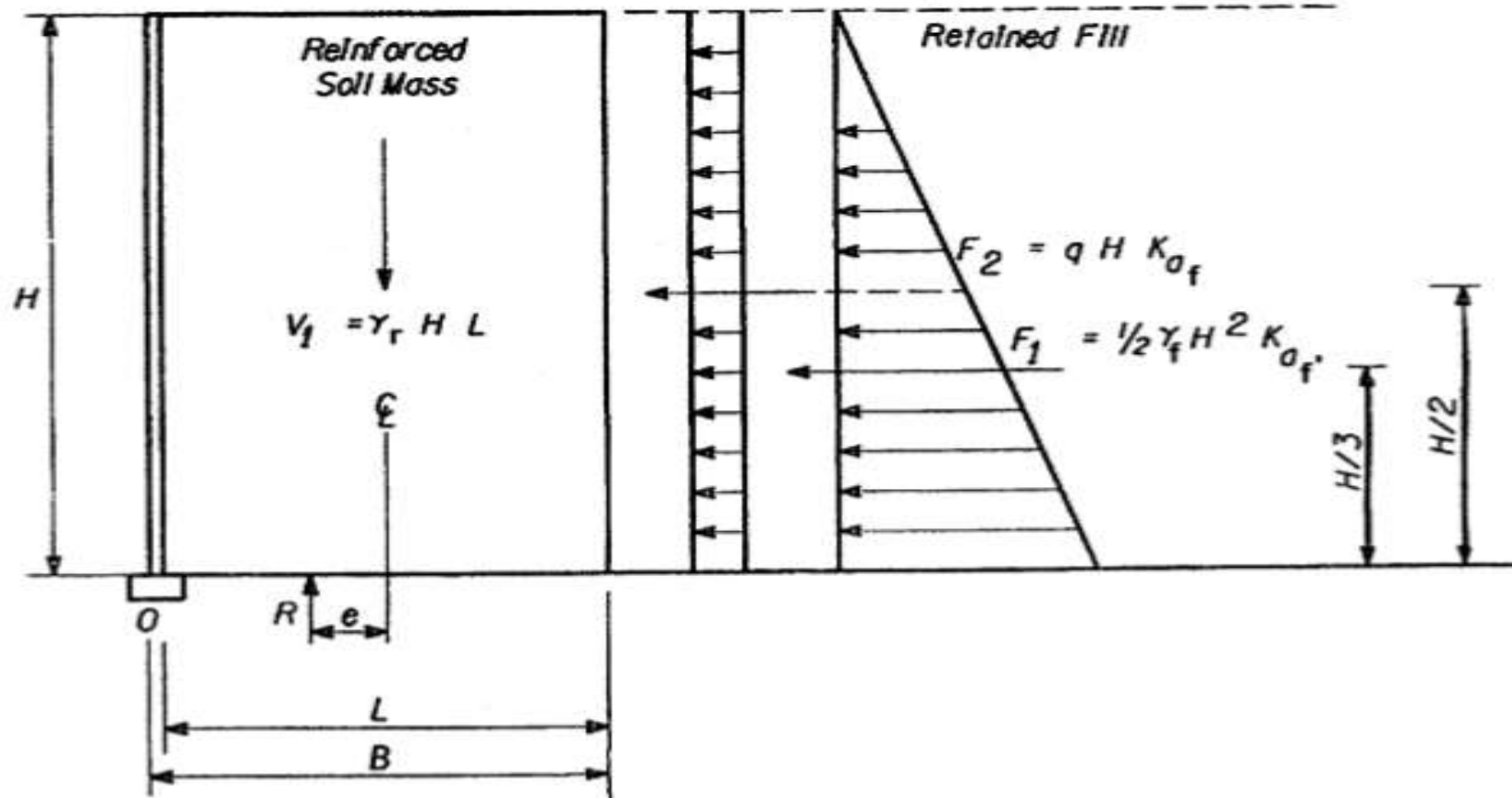
Forces acting on wall with horizontal backslope and traffic surcharge (Earth pressure / eccentricity)



Assumed for bearing capacity and overall (global) stability coms.



Assumed for overturning (eccentricity) sliding & pullout resistance coms.

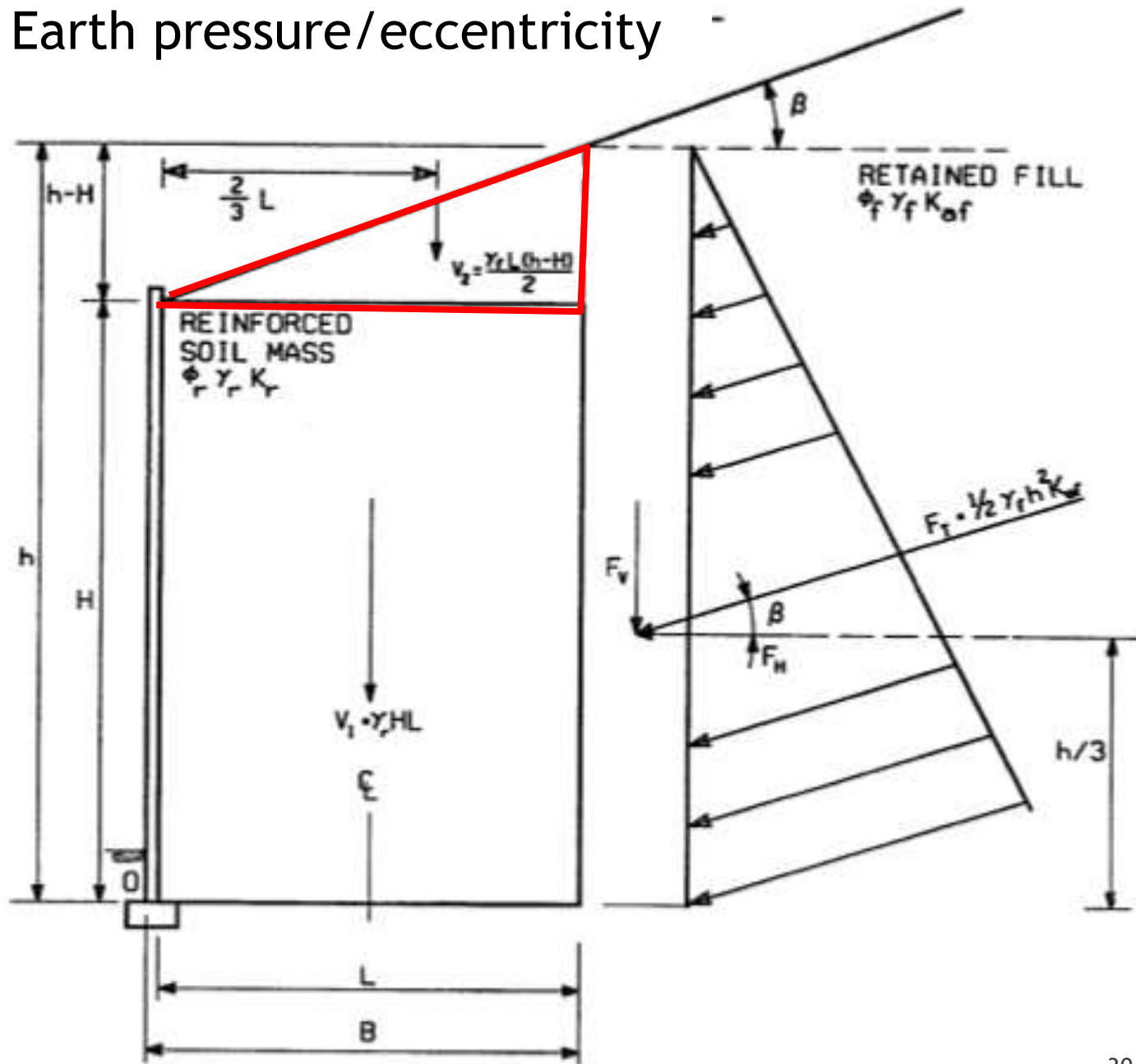


where: e = Eccentricity
 q = Traffic surcharge

R = Resultant of vertical forces ($V_f + qL$)

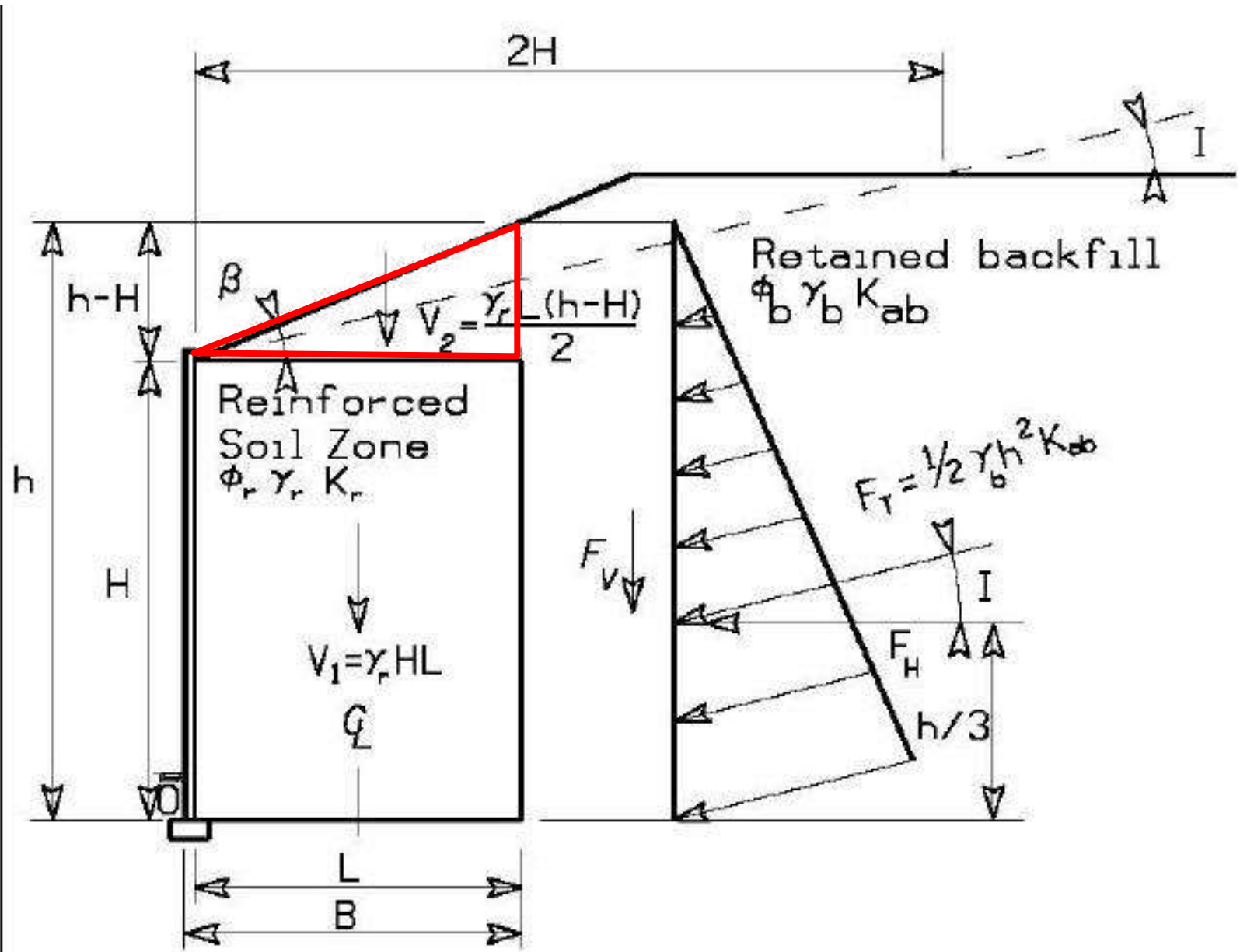
Forces acting on wall with sloping backslope

Earth pressure/eccentricity



Forces acting on wall with broken backslope

Earth pressure/eccentricity



NOMINAL LOADS

(EARTH PRESSURES FOR EXTERNAL STABILITY)

- The active coefficient of earth pressure (K_a) for vertical walls with horizontal backslope is calculated using the following equation:

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

where, ϕ'_b = angle of internal friction of the backfill

NOMINAL LOADS

(EARTH PRESSURES FOR EXTERNAL STABILITY)

○ For vertical wall with a surcharge slope:

$$K_{ab} = \frac{\sin^2(\theta + \phi'_b)}{\Gamma \sin^2 \theta \sin(\theta - \delta)}$$

Where:

δ = angle of friction between retained backfill and reinforced soil, set equal to β

$\theta = 90^\circ$ for vertical, or near ($<10^\circ$) vertical walls

Γ = next slide

NOMINAL LOADS

(EARTH PRESSURES FOR EXTERNAL STABILITY)

- ⊙ For vertical wall with a surcharge slope
(cont..):

$$\Gamma = \left[1 + \sqrt{\frac{\sin(\phi'_b + \delta) \sin(\phi'_b - \beta)}{\sin(\theta - \delta) \sin(\theta + \beta)}} \right]^2$$

NOMINAL LOADS

(EARTH PRESSURES FOR EXTERNAL STABILITY)

- For vertical wall with broken backslope:
 - Same equations as before, but:
 - Design β angle and interface angle $\delta = \beta$

$$\beta = \arctan \left(\frac{(h-H)}{2H} \right)$$

NOMINAL LOADS

(EARTH PRESSURES FOR EXTERNAL STABILITY)

- For battered wall -inclined front face equal to or greater than 10 degrees from vertical , K_a calculated with:
 - Same equations as before
 - Where:
 - θ - face inclination from horizontal
 - β - surcharge slope angle
 - The wall friction angle δ is assumed to be equal to β .

NOMINAL LOADS

(TRAFFIC LOADS)

- ◎ Should be treated as uniform surcharge live load of not less than 2.0 ft (0.6m).
 - For external and internal stability, walls parallel to traffic, the equivalent height of soil, $h_{eq} = 2.0$ ft.
 - For retaining wall abutments use values on the table

Abutment Height (ft)	h_{eq} (ft)
5.0	4.0
10.0	3.0
≥ 20.0	2.0

EVALUATION OF EXTERNAL STABILITY

◎ Consider

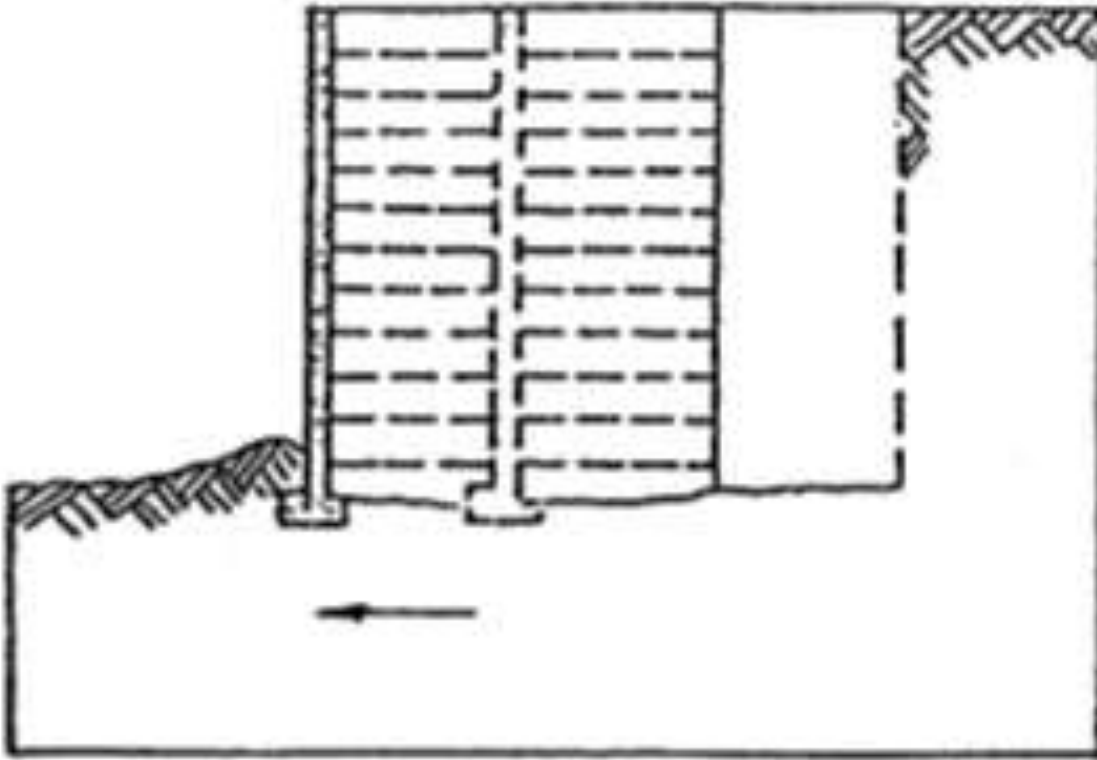
- Sliding on base
- Limiting eccentricity (overturning)
- Bearing resistance
- Overall/global stability

◎ Resistance factor used:

Stability Mode	Condition	Resistance Factor
Bearing Resistance		$\phi = 0.65$
Sliding		$\phi = 1.0$
Overall (global) Stability	Where <u>geotechnical parameters are well defined</u> , and the slope does not support or contain a structural element	$\phi = 0.75$
	Where <u>geotechnical parameters are based on limited information</u> , or the slope contains or supports a structural element	$\phi = 0.65$

EVALUATION OF EXTERNAL STABILITY

(SLIDING STABILITY)



Sliding

EVALUATION OF EXTERNAL STABILITY

(SLIDING STABILITY)

- ◎ Check the preliminary sizing with respect to sliding at the base layer:

$$CDR = \frac{R_r}{P_d} \geq 1.0$$

where, CDR=capacity to demand ratio

R_r = factored sliding resistance

P_d = factored driving force

SLIDING STABILITY

◎ Calculate thrust:

- Wall with horizontal backslope

$$F_1 = \frac{1}{2} K_{ab} \gamma_b H^2$$

- Wall with uniform surcharge:

$$F_2 = K_{ab} q H$$

where,

F_1 = retained backfill resultant

F_2 = resultant due to uniform surcharge

K_{ab} = active earth pressure coefficient for the retained backfill

γ_b = moist unit weight of the retained backfill

H = height of the retaining wall

q = uniform live load surcharge = $(\gamma_b)(h_{eq})$

SLIDING STABILITY

◎ Calculate thrust:

- Wall with sloping backfill:

$$F_T = \frac{1}{2} K_{ab} \gamma_b h^2$$

where

F_T = nominal retained backfill resultant per unit width,

K_{ab} = active earth pressure coefficient for the sloping backfill

h = total height of wall and slope at the back of the reinforced zone

$h = H + L \tan \beta$

SLIDING STABILITY

◎ Calculate the nominal and factored horizontal driving forces:

- Wall with horizontal backslope and uniform live load surcharge:

$$\sum F = F_1 + F_2$$

Horizontal backslope

Uniform surcharge

$$P_d = \gamma_{EH} F_1 + \gamma_{LS} F_2$$

SLIDING STABILITY

- ◎ Calculate the nominal and factored horizontal driving forces:
 - Wall with sloping backfill:

$$F_H = F_T \cos\beta$$

$$P_d = \gamma_{EH} F_H = \gamma_{EH} F_T \cos\beta$$

Use the maximum EH load factor ($\gamma_{EH} = 1.50$) in these equations because it creates the maximum driving force effect for the sliding limit state.

SLIDING STABILITY

- ◎ Determine the most critical frictional properties at the base. Choose the minimum ϕ for:
 - Sliding along the foundation soil (ϕ'_f).
 - Sliding along the reinforced backfill (ϕ'_r).
 - For sheet type reinforcement
 - sliding along the weaker of the upper and lower soil-reinforcement interfaces.
 - soil-reinforcement friction angle (ρ) = $\frac{2}{3} \tan \phi'_r$ or measured with direct shear test.

SLIDING STABILITY

- Calculate nominal components of resisting force and factored resisting force per unit length of wall :
 - For horizontal backslope and uniform live load surcharge: (surcharge not considered because increases stability)

$$R_r = \gamma_{EV} V_1 \times \mu$$

where,

μ = min soil friction angle [$\tan \phi'_f$, $\tan \phi'_r$, or (for continuous reinforcement) $\tan \rho$]

SLIDING STABILITY

- Calculate nominal components of resisting force and factored resisting force per unit length of wall :
 - For sloping backfill:

$$R_r = [\gamma_{EV}(V_1 + V_2) + \gamma_{EH}(F \sin \beta)] \mu$$

External loads that increase sliding resistance considered ONLY if they are PERMANENT

Use the minimum EV load factor ($\gamma_{EV} = 1.00$) in these equations because it results in minimum resistance for the sliding limit state.

SLIDING STABILITY

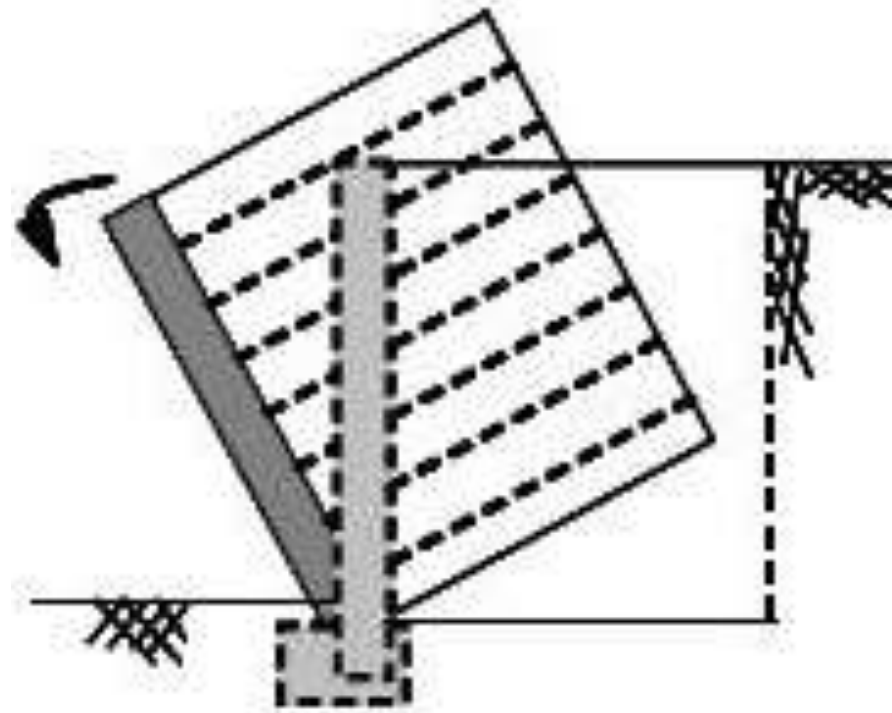
- ◎ Check the capacity demand ratio:

$$CDR = \frac{R_r}{P_d} \geq 1.0$$

- ◎ If $CDR < 1.0$ increase length of reinforcement (L) and repeat

LIMITING ECCENTRICITY OR OVERTURNING

- ⦿ Is a strength limit state check
- ⦿ Weight and width of wall neglected
- ⦿ Only considers live load above retained backfill

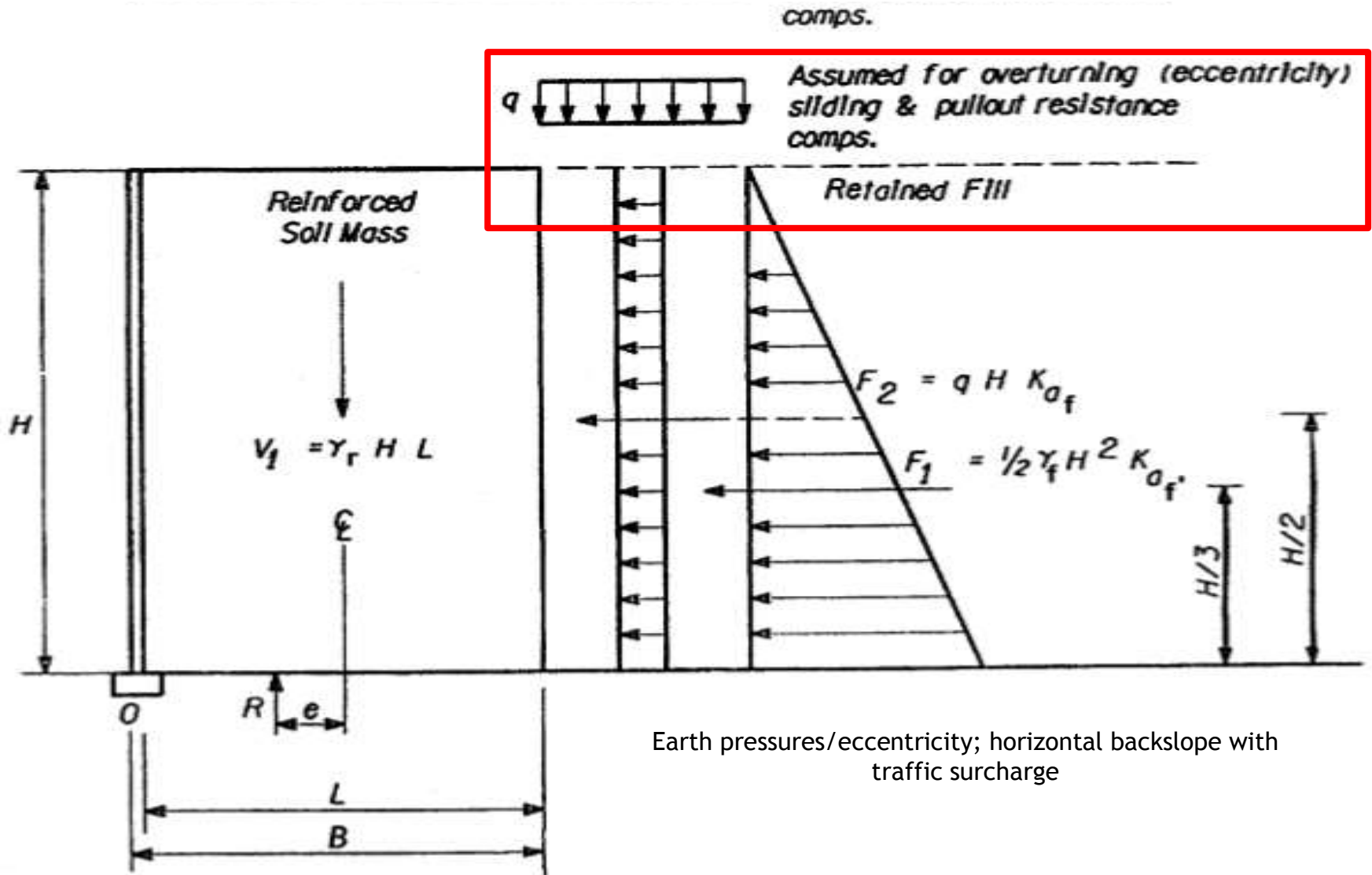


Limiting Eccentricity

LIMITING

Horizontal Backslope With Traffic Surcharge

Applies live load (surcharge) above retained backfill only

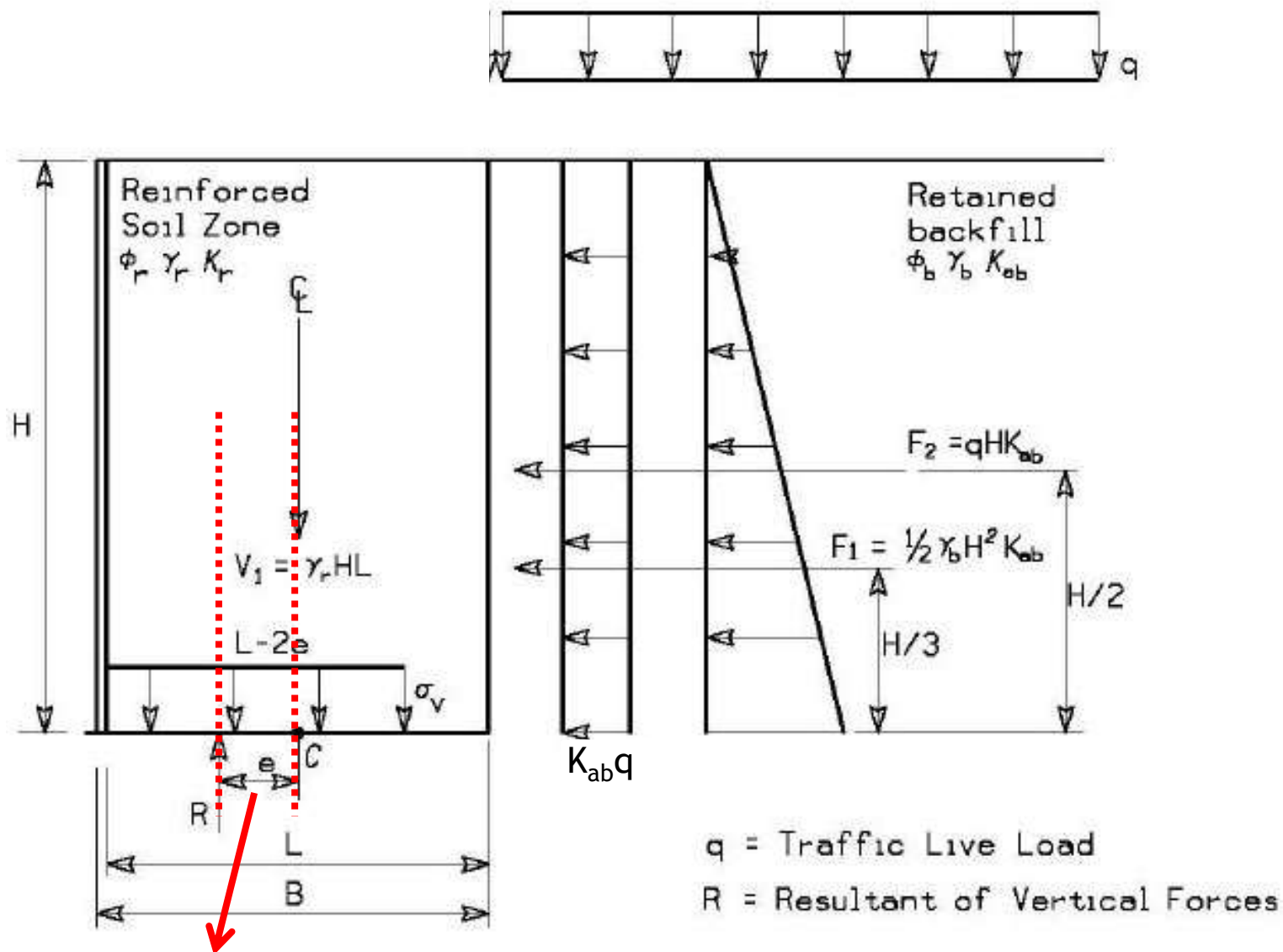


where: e = Eccentricity
 q = Traffic surcharge

R = Resultant of vertical forces ($V_1 + qL$)

LIMITING

ECCENTRICITY

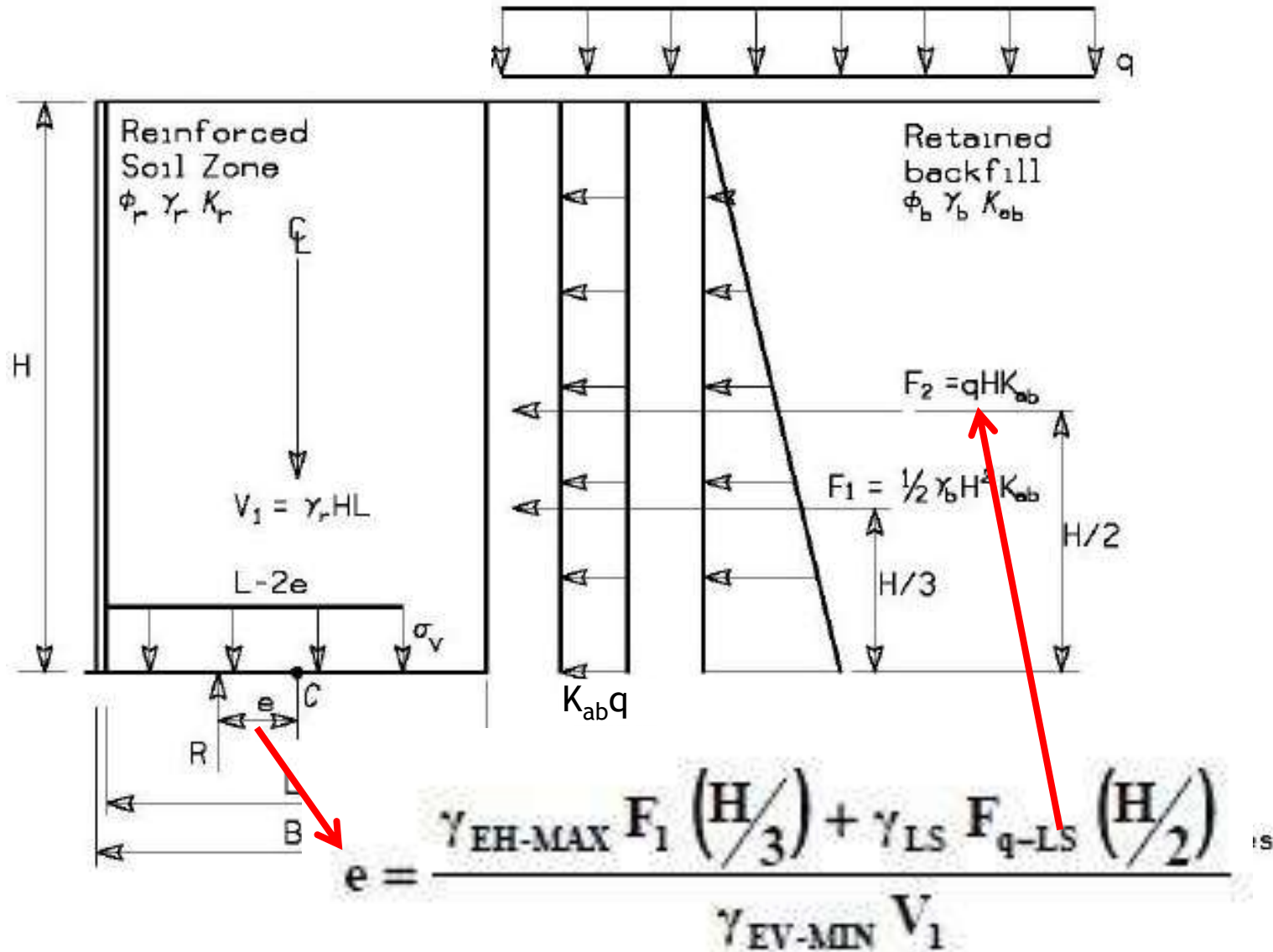


Distance between resultant of vertical forces (R) and the center of the reinforced zone

LIMITING

For wall with horizontal backslope and traffic surcharge

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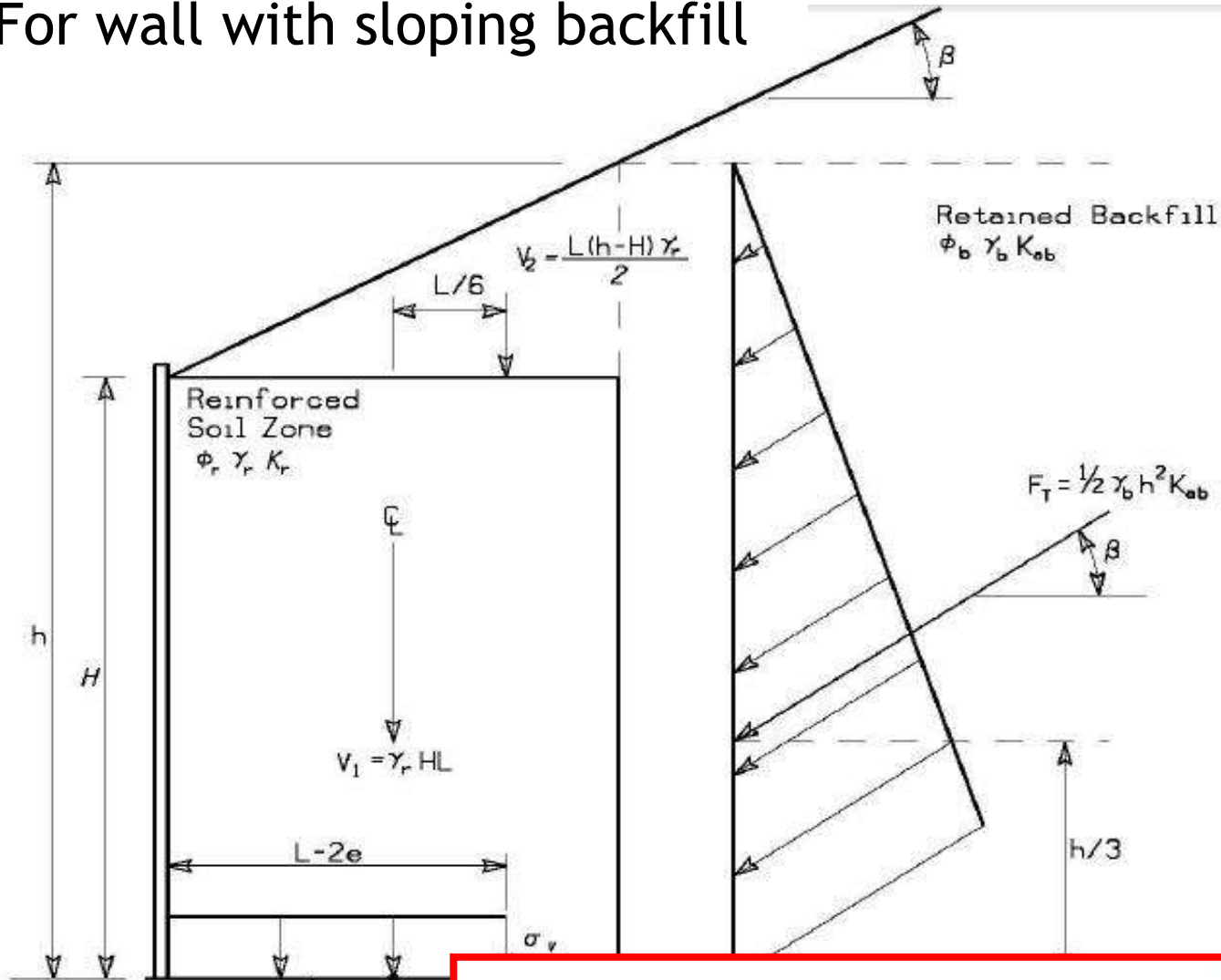


γ 's are load factors, EH=horizontal earth, LS=live surcharge

LIMITING

For wall with sloping backfill

E
C
C
E
N
T
R
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$$e = \frac{\gamma_{EH-MAX} F_T \cos\beta \left(\frac{h}{3}\right) - \gamma_{EH-MAX} F_T \sin\beta \left(\frac{L}{2}\right) - \gamma_{EV-MIN} V_2 \left(\frac{L}{6}\right)}{\gamma_{EV-MIN} V_1 + \gamma_{EV-MIN} V_2 + \gamma_{EH-MAX} F_T \sin\beta}$$

LIMITING ECCENTRICITY/OVERTURNING

◎ Check the eccentricity criteria:

- *For wall base over soil*

$$e_{max} = \frac{L}{4}$$

- *For wall base over rock*

$$e_{max} = \frac{3}{8}L$$

LIMITING ECCENTRICITY/OVERTURNING

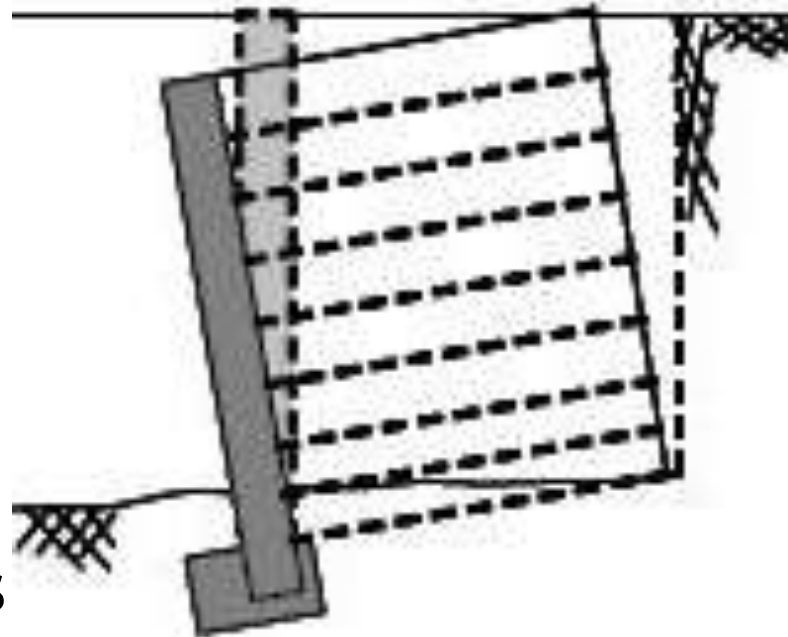
⦿ For each strength limit group

- $e < e_{\max}$

⦿ If $e > e_{\max}$ then longer length reinforcement is needed

BEARING CAPACITY FAILURE

- ◎ Two modes exist:
 - general shear failure
 - local shear failure
 - Characterized by *punching or squeezing* of the foundation soil when soft or loose soils exist the below wall



Bearing Capacity

BEARING CAPACITY FAILURE

- ◎ This analysis require two types of calculations:
 - Strength limit state and
 - Check soil strength
 - Service limit state
 - Used in settlement calculations

BEARING CAPACITY FAILURE: GENERAL SHEAR

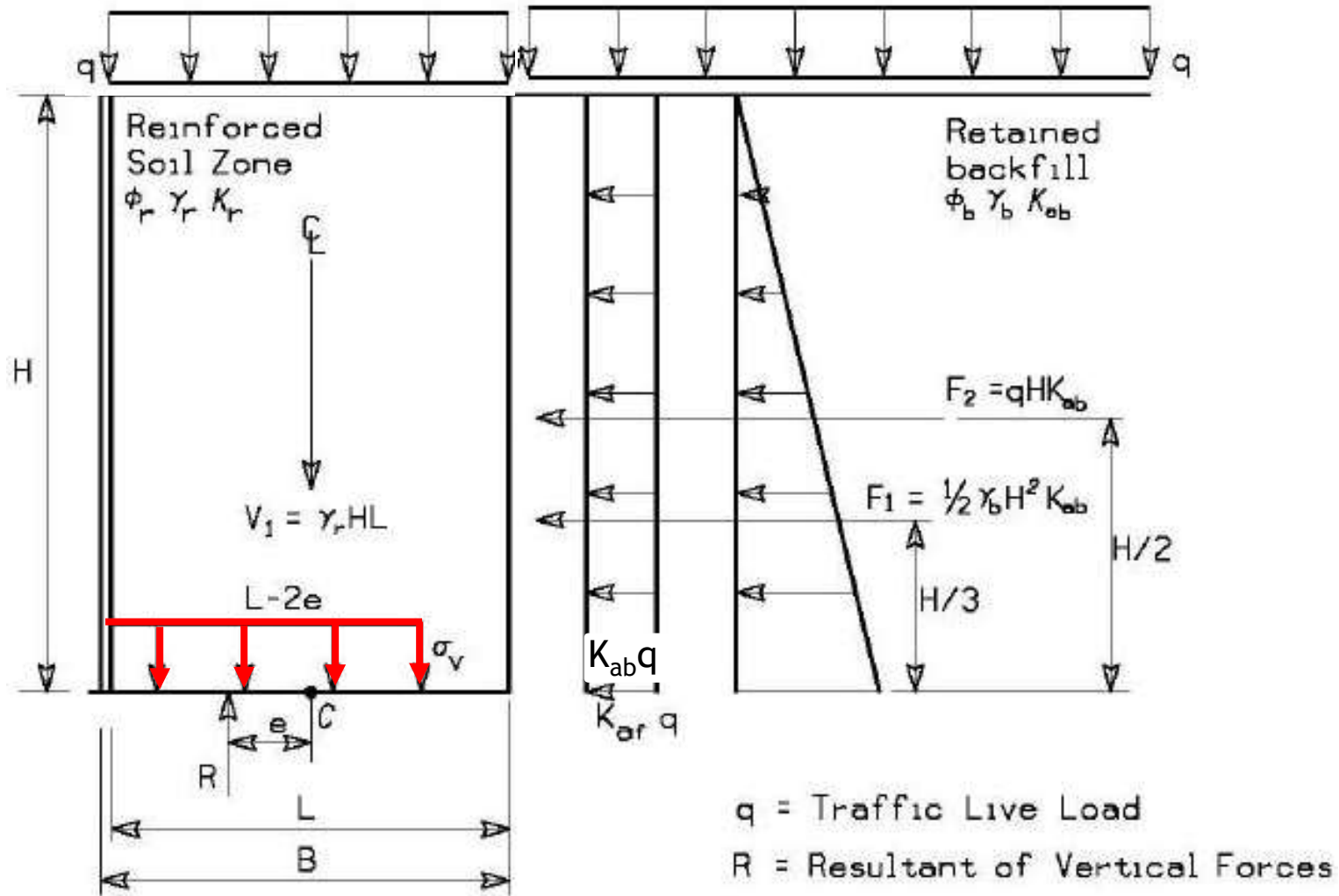
- ◎ To prevent bearing capacity failure
 - The factored vertical pressure at the base of the wall (q_R), should not exceed the factored bearing resistance of the foundation soil ($q_{uniform}$)

$$q_R \geq q_{uniform}$$

BEARING CAPACITY ANALYSIS

Applies live load (surcharge) above both:

reinforced zone and retained backfill



Also assumes: σ_v uniform throughout length = $L - 2e$

BEARING CAPACITY FAILURE: GENERAL SHEAR

- ◎ The uniform vertical pressure (σ_v) at the base of the wall is defined as:

$$\sigma_v = \frac{\sum V}{L - 2e_B}$$

- $\sum V$ = summation of vertical forces
- L = reinforcement length
- e_B = eccentricity for bearing calculation (different from limit eccentricity check)

BEARING CAPACITY FAILURE: GENERAL SHEAR


- ⊙ Calculate eccentricity, e_B , of the resulting force at base of wall
 - For wall with horizontal backslope and uniform live load surcharge centered about reinforced zone:

$$e_B = \frac{\gamma_{EH-MAX} F_1 \left(\frac{H}{3}\right) + \gamma_{LS} F_{q-LS} \left(\frac{H}{2}\right)}{\gamma_{EV-MAX} V_1 + \gamma_{LS} q L}$$

BEARING CAPACITY FAILURE: GENERAL SHEAR


- Calculate vertical factored stress at the base.
 - For horizontal backslope and uniform live load surcharge

Factored bearing pressure


$$\sigma_{V-F} = \frac{\gamma_{EV-MAX} V_1 + \gamma_{LS} q L}{L - 2e_B} = q_{V-F}$$

- For wall with sloping backfill:

Factored bearing pressure


$$q_{V-F} = \frac{\gamma_{EV-MAX} V_1 + \gamma_{EV-MAX} V_2 + \gamma_{EH-MAX} F_T \sin\beta}{L - 2e_B}$$

BEARING CAPACITY FAILURE: GENERAL SHEAR

- Determine nominal bearing resistance q_n :

$$q_n = c_f N_c + 0.5L' \gamma_f N_\gamma$$

This represents the bearing capacity of the foundation soil-
defined from bearing capacity theories

where

c_f = cohesion of the foundation soil,

γ_f = unit weight of the foundation soil,

N_c & N_γ = dimensionless bearing capacity
coefficients (see next slide)

$L' = L - 2e_B$, effective foundation width;

if $e_B < 0$ $L' = L$

Bearing resistance factors

ϕ	N_c	N_q	N_γ	ϕ	N_c	N_q	N_γ
0	5.14	1.0	0.0	23	18.1	8.7	8.2
1	5.4	1.1	0.1	24	19.3	9.6	9.4
2	5.6	1.2	0.2	25	20.7	10.7	10.9
3	5.9	1.3	0.2	26	22.3	11.9	12.5
4	6.2	1.4	0.3	27	23.9	13.2	14.5
5	6.5	1.6	0.5	28	25.8	14.7	16.7
6	6.8	1.7	0.6	29	27.9	16.4	19.3
7	7.2	1.9	0.7	30	30.1	18.4	22.4
8	7.5	2.1	0.9	31	32.7	20.6	25.9
9	7.9	2.3	1.0	32	35.5	23.2	30.2
10	8.4	2.5	1.2	33	38.6	26.1	35.2
11	8.8	2.7	1.4	34	42.2	29.4	41.1
12	9.3	3.0	1.7	35	46.1	33.3	48.0
13	9.8	3.3	2.0	36	50.6	37.8	56.3

Bearing resistance factors (cont..)

ϕ	N_c	N_q	N_γ	ϕ	N_c	N_q	N_γ
14	10.4	3.6	2.3	37	55.6	42.9	66.2
15	11.0	3.9	2.7	38	61.4	48.9	78.0
16	11.6	4.3	3.1	39	37.9	56.0	92.3
17	12.3	4.8	3.5	40	75.3	64.2	109.4
18	13.1	5.3	4.1	41	83.9	73.9	130.2
19	13.9	5.8	4.7	42	93.7	85.4	155.6
20	14.8	6.4	5.4	43	105.1	99.0	186.5
21	15.8	7.1	6.2	44	118.4	115.3	224.6
22	16.9	7.8	7.1	45	133.9	134.9	271.8

Note:

N_c (Prandtl, 1921), N_q (Reisner, 1924), and N_γ (Vesic, 1975).

N_q is embedment term, which is typically not used in MSE wall design.

BEARING CAPACITY FAILURE: GENERAL SHEAR

- ⊙ Determine factored bearing resistance q_R :

$$q_R = \phi q_n$$

where

ϕ = resistance factor for MSE = 0.65

- ⊙ Check bearing capacity criteria:

$$q_R \geq q_{V-F}$$

q_{V-F} can be decreased and q_R increased by increasing the length of the reinforcement

BEARING CAPACITY FAILURE: LOCAL SHEAR

- To prevent local shear of structures on weak cohesive soil:

Nominal unit weight of reinforced fill

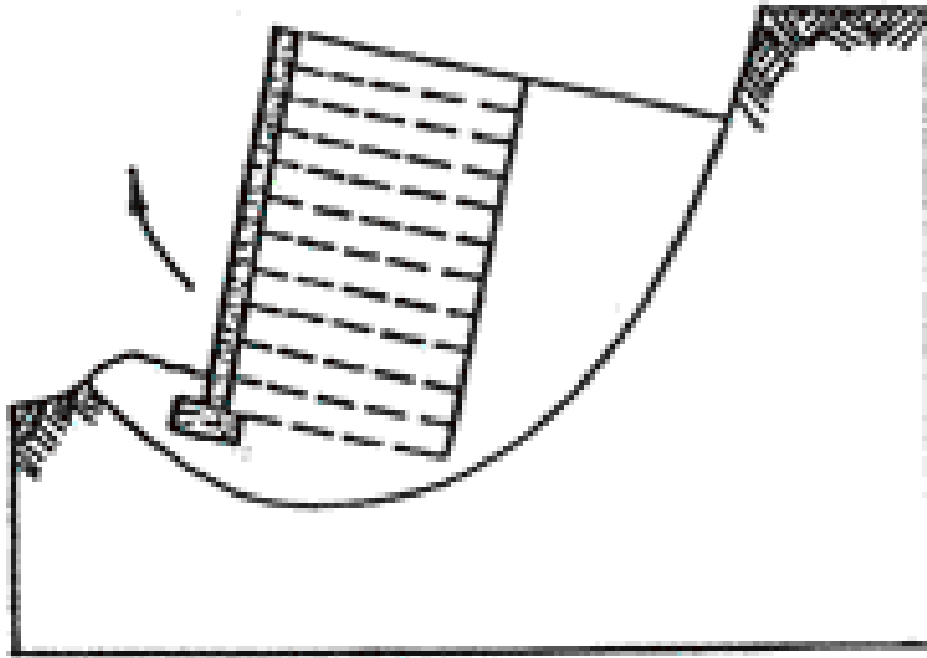
$$\gamma_r H \leq 3c_u$$

Nominal total stress cohesion of the foundation soil

Wall height

- If adequate support conditions cannot be achieved,
 - soft soils should be removed or
 - ground improvement of the foundation soils should be considered.

OVERALL STABILITY



(d) Deep seated stability (Rotational)

OVERALL STABILITY

- ◎ Determined using
 - rotational analyses or wedge analyses
 - Computer programs
- ◎ Based on Limit Equilibrium Analysis the reinforced soil wall is considered as a rigid body and only failure surfaces outside the reinforced mass are analyzed.
- ◎ If the minimum safety factor (FS) is less than 1.3, increase the reinforcement length or improve the foundation soil.

SEISMIC LOADING

- ⊙ During an earthquake, the retained fill exerts a dynamic horizontal thrust, PAE, on the MSE wall in addition to the static thrust.
- ⊙ Force PAE can be evaluated by the pseudo-static Mononobe-Okabe analysis and added to the static forces acting on the wall (weight, surcharge, and static thrust).

SEISMIC LOADING-ASD

- ◎ The dynamic stability with respect to external stability is then evaluated.
 - Allowable minimum dynamic safety factors are assumed as 75 percent of the static safety factors.

$$FS_{dynamic} = 0.75FS_{static}$$

SEISMIC LOADING-ASD

◎ The seismic external stability evaluation:

- Select a peak horizontal ground acceleration based on the design earthquake.
- Calculate the maximum acceleration A_m developed in the wall:

$$A_m = (1.45 - A) A$$

○ where:

- A = max. ground acceleration coefficient, AASHTO, Division 1A.
- A_m = max. wall acceleration coefficient at the centroid of the wall mass.

SEISMIC LOADING-ASD

- Calculate the horizontal inertia force P_{IR} and seismic thrust P_{AE} .

$$P_{IR} = 0.5 A_m \gamma_f H^2 \quad (\text{Horizontal backslope})$$

$$P_{AE} = 0.375 A_m \gamma_f H^2 \quad (\text{Horizontal backslope})$$

- Add to the static forces acting on the structure
 - 50 percent of the seismic thrust P_{AE}
 - and the full inertial force P_{IR} .

SEISMIC LOADING-ASD

- ◎ For structures with sloping backfills
 - The inertial force (P_{IR}) and the dynamic horizontal thrust (P_{AE}) shall be based on a height H_2 near the back of the wall mass determined as follows:

$$H_2 = H + \frac{\tan\beta \cdot 0.5H}{(1 - 0.5\tan\beta)}$$

SEISMIC LOADING-ASD

- ◎ For structures with sloping backfills
 - ◎ PIR for sloping backfills should be calculated as follows:

$$P_{IR} = P_{ir} + P_{is}$$

$$P_{ir} = 0.5 A_m \gamma_f H_2 H$$

$$P_{is} = 0.125 A_m \gamma_f (H_2)^2 \tan \beta$$

$$P_{AE} = 0.5 \gamma_f (H_2)^2 \Delta K_{AE} \text{ (sloping backfill)}$$

- ◎ P_{ir} = inertial force caused by acceleration of the reinforced backfill
- ◎ P_{is} = inertial force caused by acceleration of the sloping soil surcharge above the reinforced backfill.

SEISMIC LOADING-ASD

- Total seismic earth pressure coefficient K_{AE} based on the Mononobe-Okabe general expression is computed from:

$$K_{AE} = \frac{\cos^2(\varphi - \xi - 90 + \theta)}{\cos \xi \cos^2(90 - \theta) \cos(I + 90 - \theta + \xi) \left[1 + \sqrt{\frac{\sin(\varphi + I) \sin(\varphi - \xi - I)}{\cos(I + 90 - \theta + \xi) \cos(I - 90 + \theta)}} \right]^2}$$

- Where:

- I = the backfill slope angle = β
- ξ = $\arctan(k_h / 1 - k_v)$ k_h = horizontal seismic coefficient and k_v = vertical seismic coefficient
- φ = the soil angle of friction
- θ = the slope angle of the face

Assume:

$$k_v = 0$$

$$k_v = k_{av}$$

SEISMIC LOADING-ASD

◎ To complete the design:

- Evaluate sliding stability, eccentricity and bearing capacity as detailed previously.
- Check:
 - Computed safety factors are equal to or greater than 75 percent of the minimum static safety factors
 - Eccentricity falls within $L/3$ for both soil and rock.

SEISMIC LOADING-LRFD

- Should define the CDR as previously explained for the different failure modes but considering the additional dynamic loading

SETTLEMENT ESTIMATE

- ◎ Conventional settlement analyses should be carried out to ensure:
 - Immediate consolidation and secondary settlement of the wall are less than the performance requirements of the project.

SETTLEMENT ESTIMATE

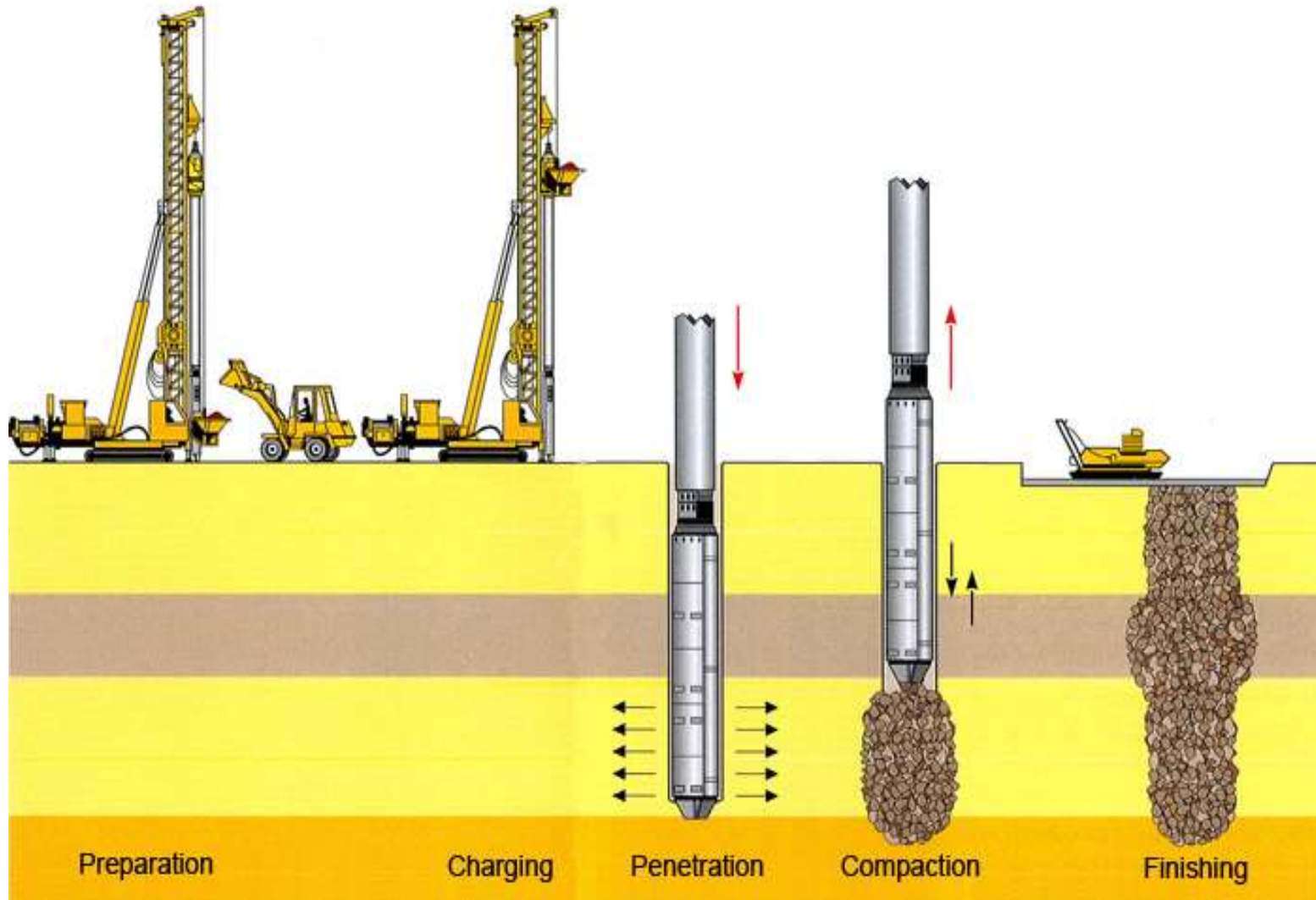
- ◎ Significant total settlements at the end of construction indicate that the planned top of wall elevations need to be adjusted.
 - Can be accomplished by increasing the top of wall elevations during design, by delaying the casting of the top row of panels to the end of erection.

SETTLEMENT ESTIMATE

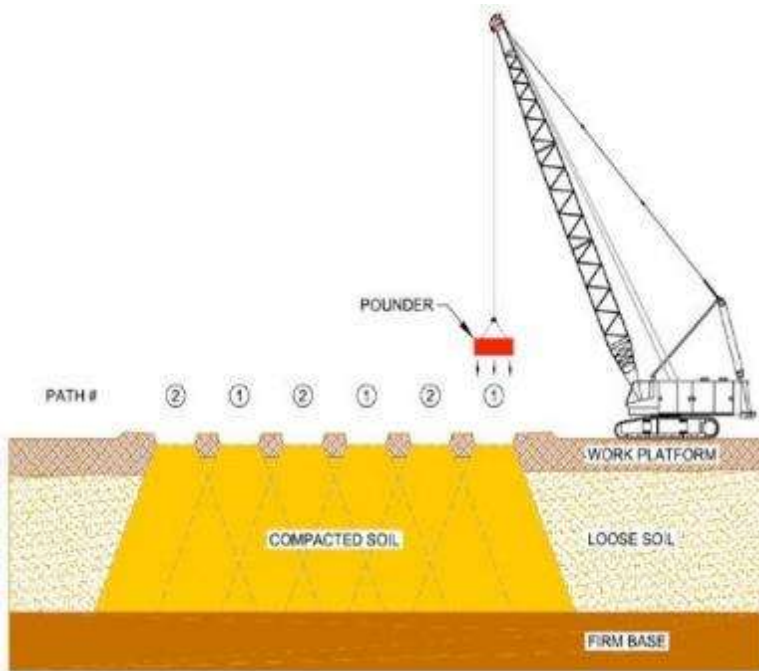
- Where the anticipated settlements and their duration, cannot be accommodated by these measures, consider ground improvement techniques:
 - wick drains, stone columns, and dynamic compaction

GROUND IMPROVEMENT TECHNIQUES

Vibro replacement to form stone columns



GROUND IMPROVEMENT TECHNIQUES



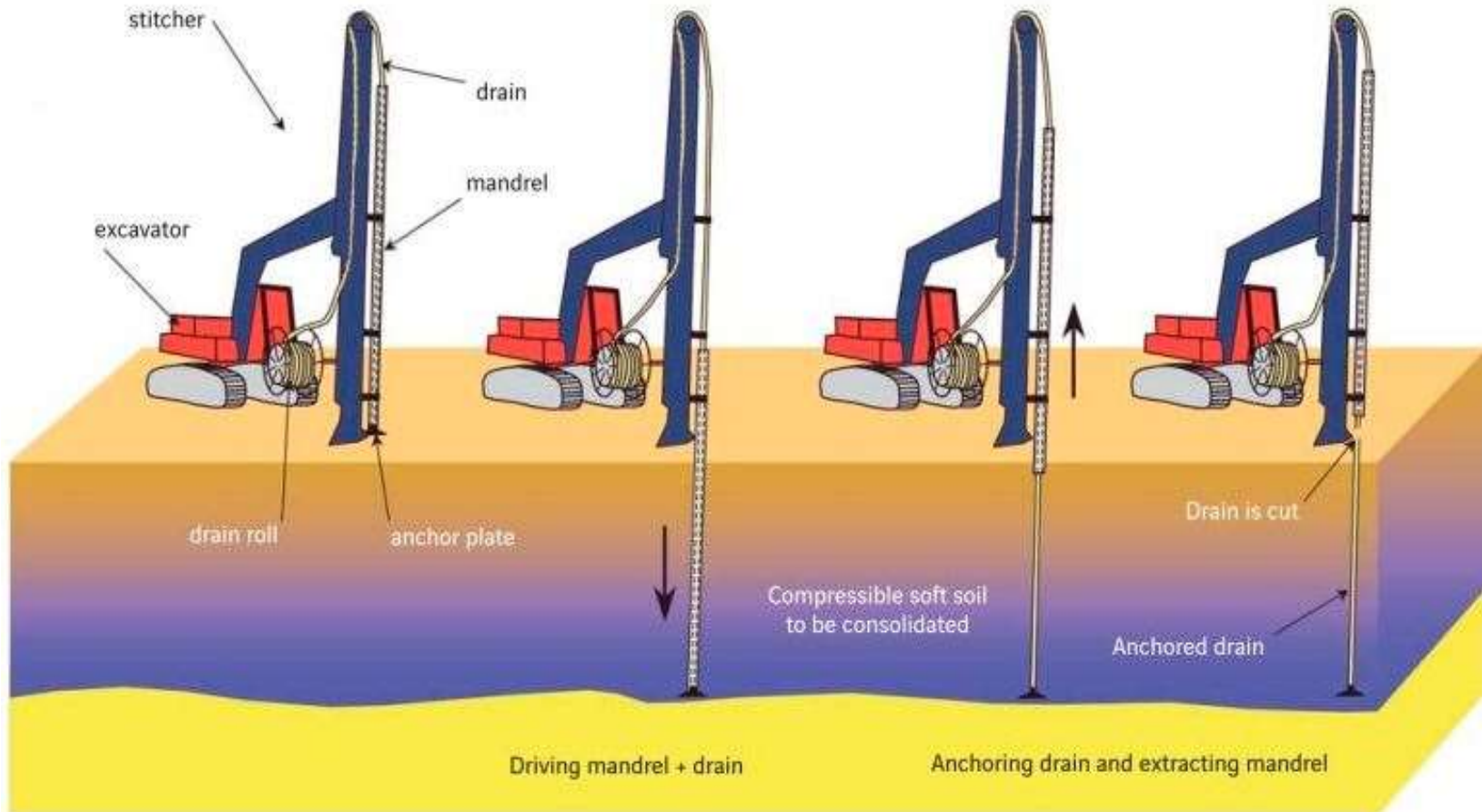
Dynamic Compaction,
Installation Process



Dynamic Compaction

GROUND IMPROVEMENT TECHNIQUES

Wick Drain



INTERNAL STABILITY

◎ Internal failure of MSE wall can occur in two ways:

- Failure by elongation or breakage of the reinforcement
 - Tensile forces on the inclusions too large
- Failure by pullout
 - Tensile forces in the reinforcement becomes larger than pullout resistance

INTERNAL STABILITY

- ◎ Treated as a response of discrete elements in a soil mass.
 - Deformations are controlled by the reinforcements rather than total mass.
- ◎ Determines the reinforcement required,
 - In the development of the internal lateral stress and
 - The assumption as to the location of the most critical failure surface.

INTERNAL STABILITY

◎ Consists on determining:

- maximum developed tension forces and their location along a locus of critical slip surfaces.
- resistance provided by the reinforcements both in pullout capacity and tensile strength.

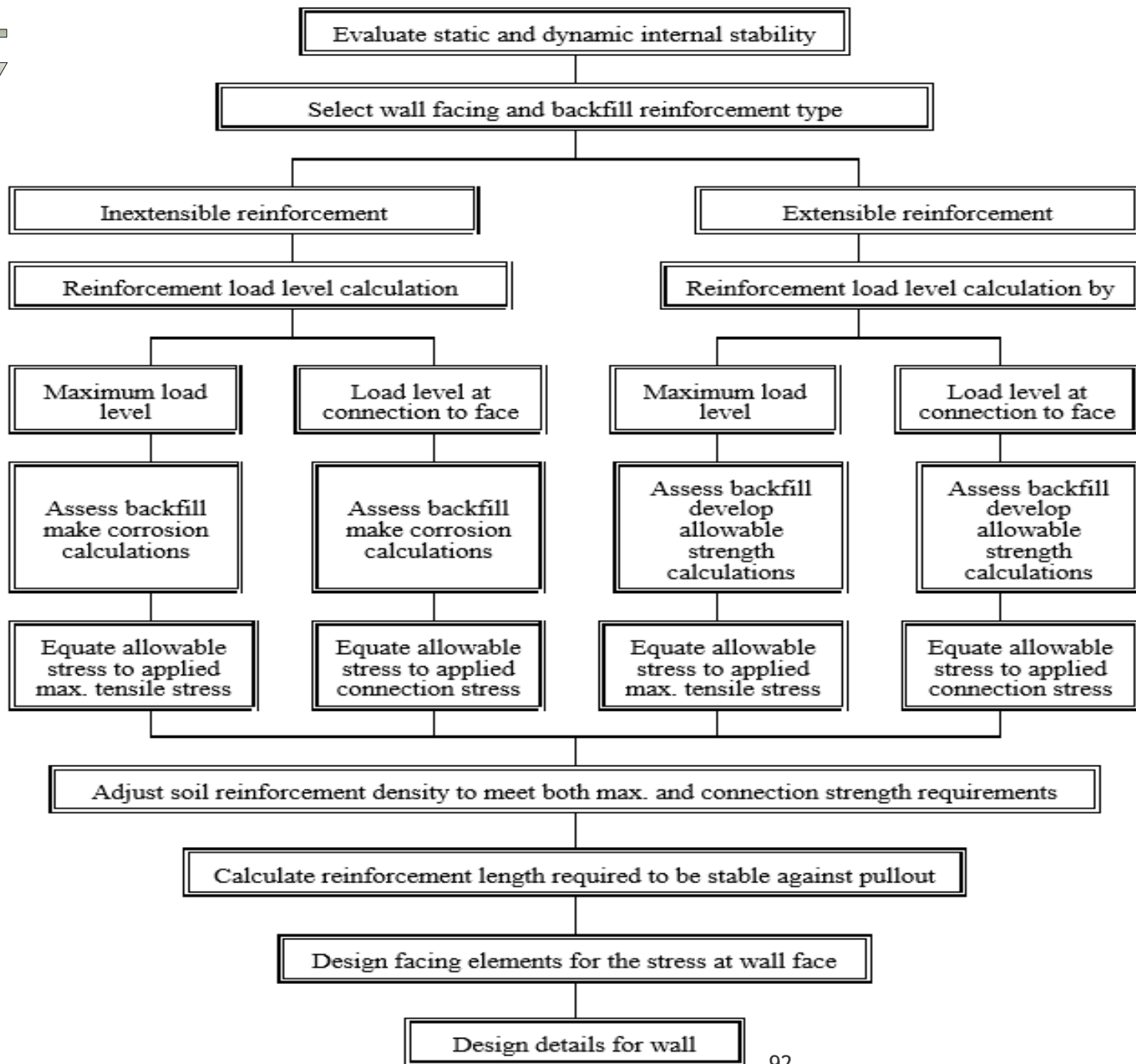
INTERNAL STABILITY

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INTERNAL STABILITY

DESIGN PROCESSES



STEP BY STEP INTERNAL DESIGN PROCESS

- ◉ Select a reinforcement type (inextensible or extensible).
- ◉ Select the location of the critical failure surface.
- ◉ Select a reinforcement spacing.
- ◉ Calculate the maximum tensile force at each reinforcement level, static and dynamic.
- ◉ Calculate the maximum tensile force at the connection to the facing.
- ◉ Calculate the pullout capacity at each reinforcement level.

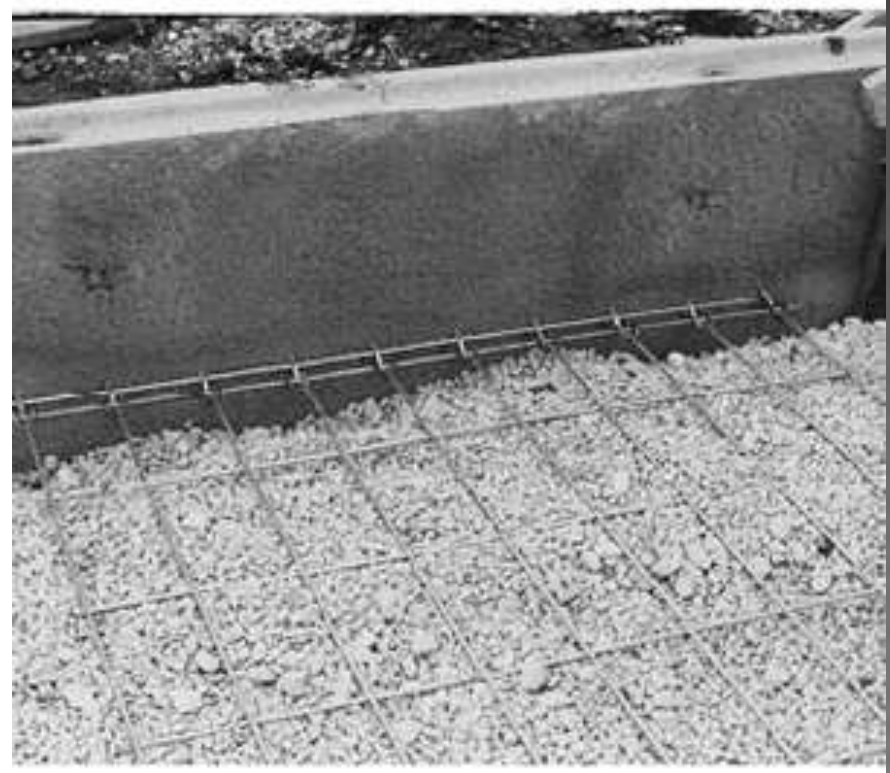
1-TYPE OF REINFORCEMENT

◎ Inextensible - Mostly metallic

Steel strip



Wire mesh



TYPE OF REINFORCEMENT

◎ Extensible - Mostly polymeric material

Geogrid



TYPE OF REINFORCEMENT

- ◎ Extensible - Mostly polymeric material
Geogrid

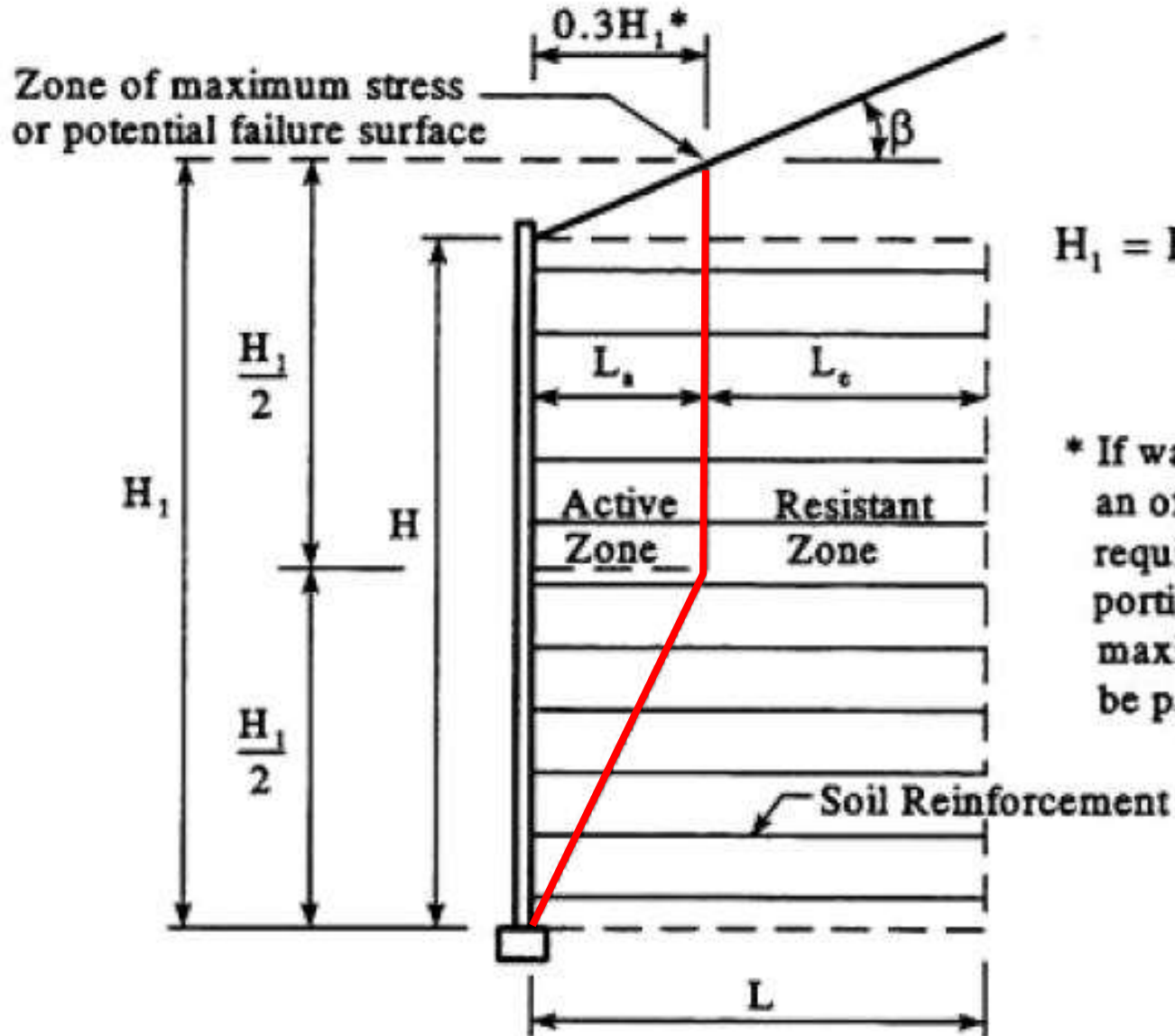


2-CRITICAL SLIP SURFACES

- ◎ It is assumed to coincide with the locus of maximum tensile force, T_{\max} .
- ◎ When failure develops, the reinforcement may elongate and be deformed at its intersection with the failure surface.
 - The tensile force in the reinforcement would increase and rotate.
 - The component in the direction of the failure surface would increase and the normal component may increase or decrease.

CRITICAL SLIP SURFACE- INEXTENSIBLE

(Bilinear Surface)

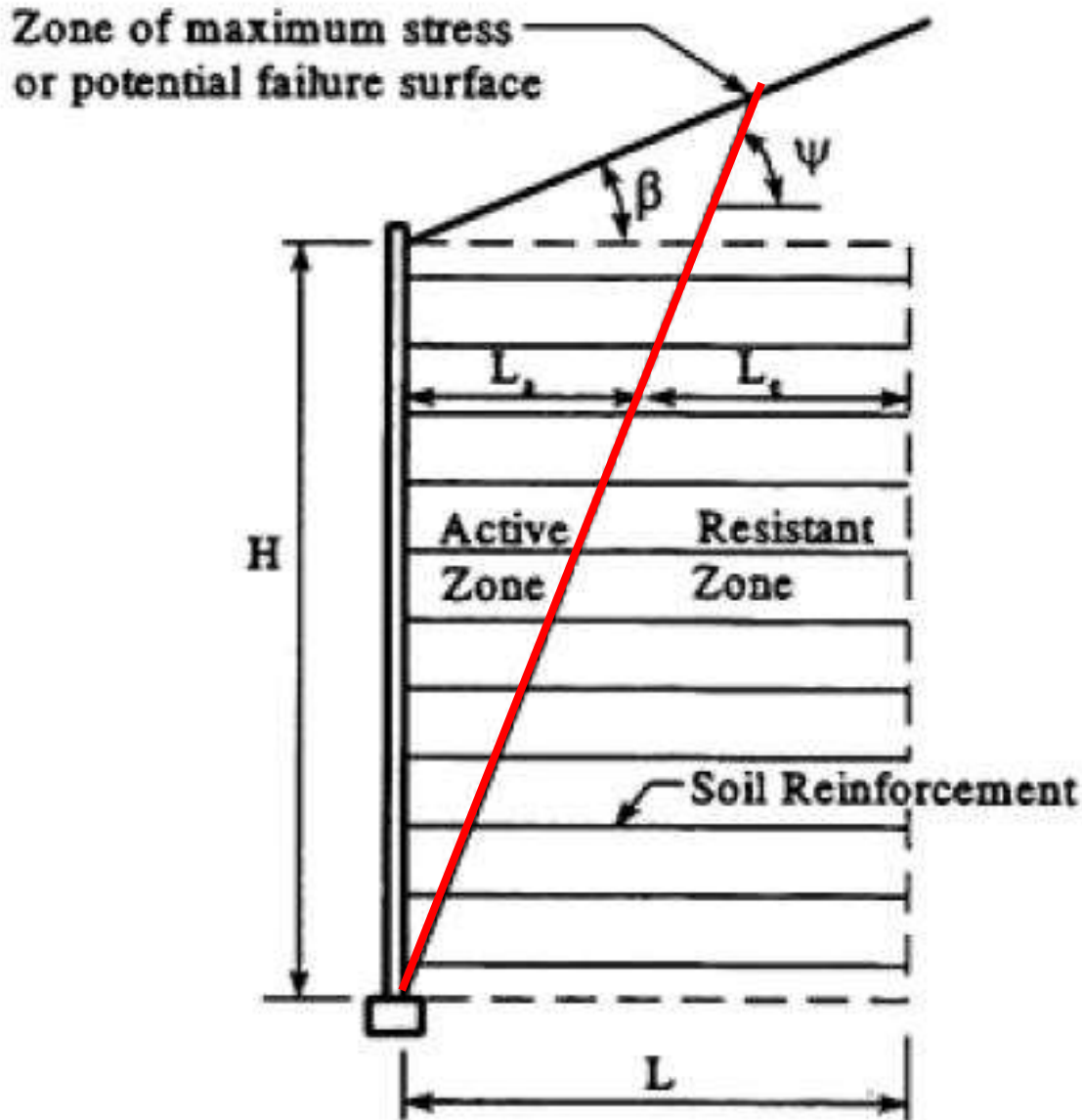


$$H_1 = H + \frac{\tan \beta \times 0.3H}{1 - 0.3 \tan \beta}$$

* If wall face is battered, an offset of $0.3H_1$ is still required, and the upper portion of the zone of maximum stress should be parallel to the wall face

CRITICAL SLIP SURFACE- EXTENSIBLE

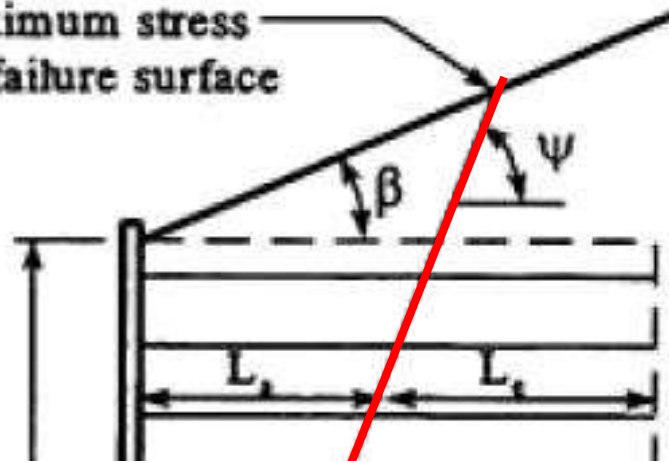
(Linear Surface)



CRITICAL SLIP SURFACE-EXTENSIBLE

(Linear Surface)

Zone of maximum stress
or potential failure surface



For vertical face

$$\psi = 45 + \frac{\phi}{2}$$

For walls with a face batter angle (θ) 10° or more from the vertical,

$$\tan(\psi - \theta) = \frac{-\tan(\phi - \beta) + \sqrt{\tan(\phi - \beta)[\tan(\phi - \beta) + \cot(\phi + \theta - 90)][1 + \tan(\delta + 90 - \theta)\cot(\phi + \theta - 90)]}}{1 + \tan(\delta + 90 - \theta)[\tan(\phi - \beta) + \cot(\phi + \theta - 90)]}$$

with $\delta = \beta$

θ = wall batter angle (b)

For wall with a broken backslope, use $\delta = \beta_{ca}$



3-REINFORCEMENT SPACING

- ◎ Using an economical design may be possible by varying the reinforcement density with depth.
- ◎ To provide a coherent reinforced soil zone, vertical spacing of primary reinforcement should not exceed 32 inches (800 mm)

REINFORCEMENT SPACING

- Ways to accomplish this for MSEW with segmental precast concrete facings:
 - Reinforcements consisting of strips, grids, or mats:
 - Vertical spacing is maintained constant
 - reinforcement density is increased with depth by increasing the number and/or size of the reinforcements.
 - Continuous sheet reinforcements, made of geotextiles or geogrids
 - Change the vertical spacing S_v .

REINFORCEMENT SPACING

- ◎ Low-to-medium-height walls (<16ft = 5m)
 - Usually constructed with one strength geosynthetic

- ◎ Taller walls
 - Multiple strength geosynthetic

- ◎ Walls with modular blocks
 - $S_{v-max} = 2$ times block depth (front face to back face) or 32in. (810mm)
 - Top row limited to 1.5 block depth

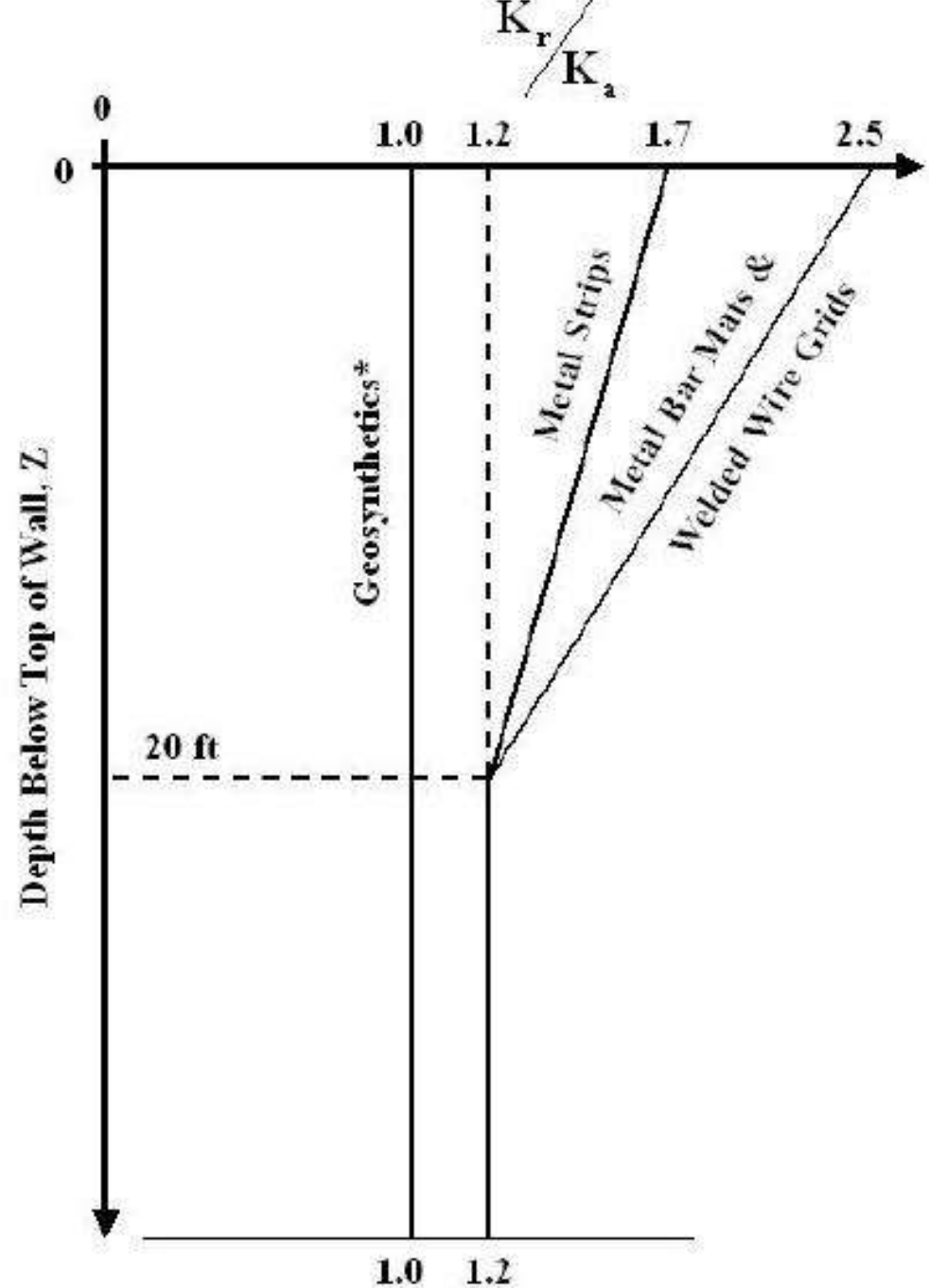
REINFORCEMENT SPACING

- ◎ Large face units e.g. 3 ft x 3 ft gabions (9.0m x 0.9m)
 - Vertical spacing (S_v) = face height (i.e., 3 ft = 0.9m)

4-CALCULATIONS OF MAXIMUM TENSILE FORCES IN THE REINFORCEMENT LAYER

- ◎ The resulting K_r/K_a for inextensible reinforcements ratio decreases from the top of the wall to a constant value below 6 m (20 ft).
- ◎ Ratio of K_r/K_a obtained from figure in next slide

VARIATION OF K_r/K_a



*Does not apply to polymer strip reinforcement

CALCULATIONS OF MAXIMUM TENSILE FORCES IN THE REINFORCEMENT LAYER

- ◉ Once the ratio of K/K_a is obtained need to define K_a .
- ◉ For a vertical wall the earth pressure coefficient defined by Coulomb reduces to the Rankine equation:

$$K_a = \tan^2 (45 - \phi'/2)$$

CALCULATIONS OF MAXIMUM TENSILE FORCES IN THE REINFORCEMENT LAYER

- For wall face batters equal to or greater than 8 degrees from the vertical:

$$K_a = \frac{\sin^2 (\theta + \phi')}{\sin^3 \theta \left[1 + \frac{\sin \phi'}{\sin \theta} \right]^2}$$

CALCULATIONS OF MAXIMUM TENSILE FORCES IN THE REINFORCEMENT LAYER

- ⊙ Calculate at each reinforcement level the horizontal stresses σ_H

$$\sigma_H = K_r \sigma_v + \Delta\sigma_h$$

- Where:

$$\sigma_v = \gamma_r Z + \sigma_2 + q + \Delta\sigma_v$$

Weight of the reinforced zone

Stress due to sloping backfill

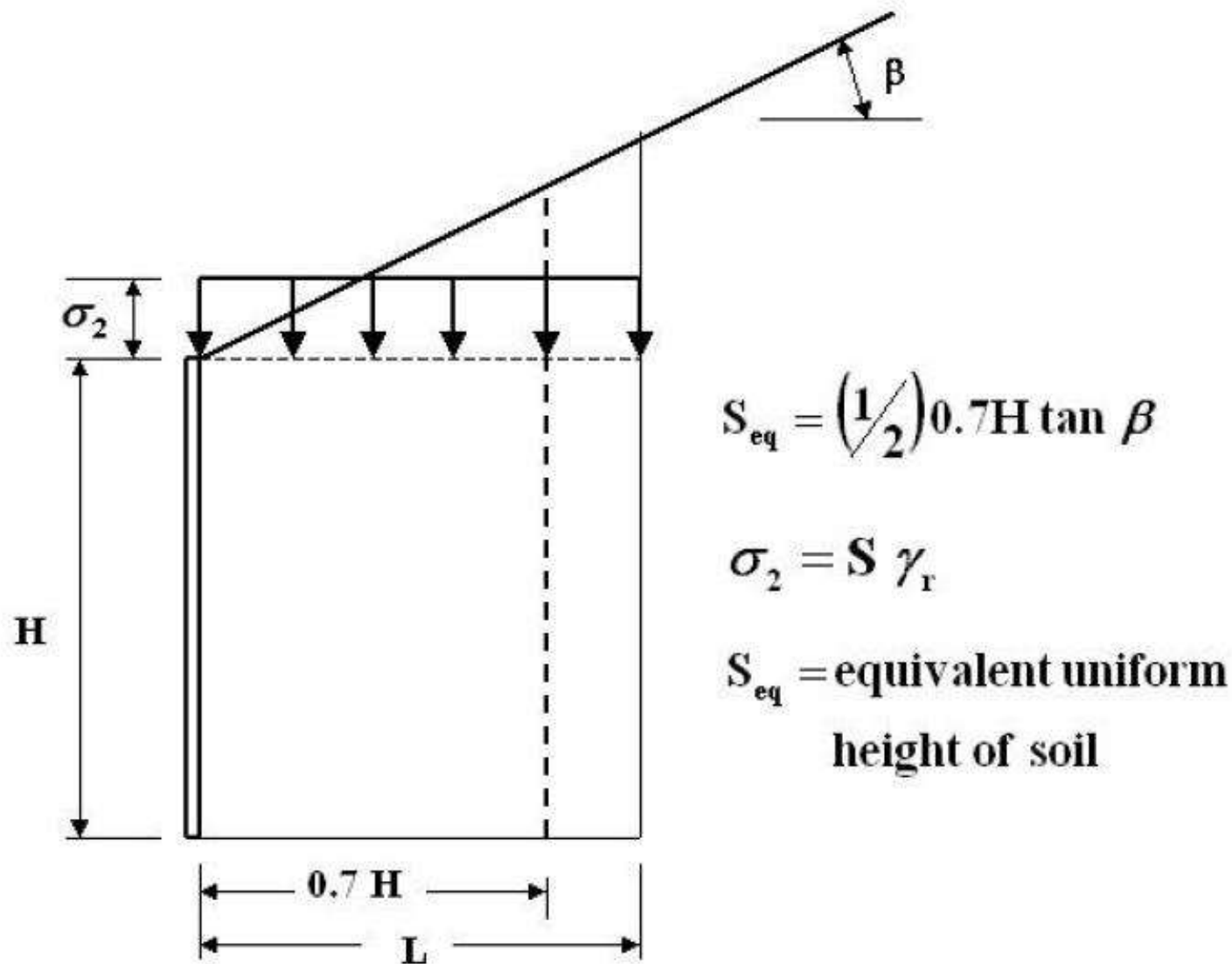


Figure 4-11. Calculation of vertical stress for sloping backfill conditions for internal stability.

SUPPLEMENTAL FACTORED HORIZONTAL PRESSURE

- ◎ The supplemental factored horizontal pressure, $\Delta\sigma_h$, could be from a variety of sources. Two examples of supplemental horizontal pressures are as follows:
 1. Horizontal pressures due to the horizontal (shear) stresses at the bottom of a spread footing on top of reinforced soil zone.
 2. Horizontal pressures from deep foundation elements extending through the reinforced soil zone.

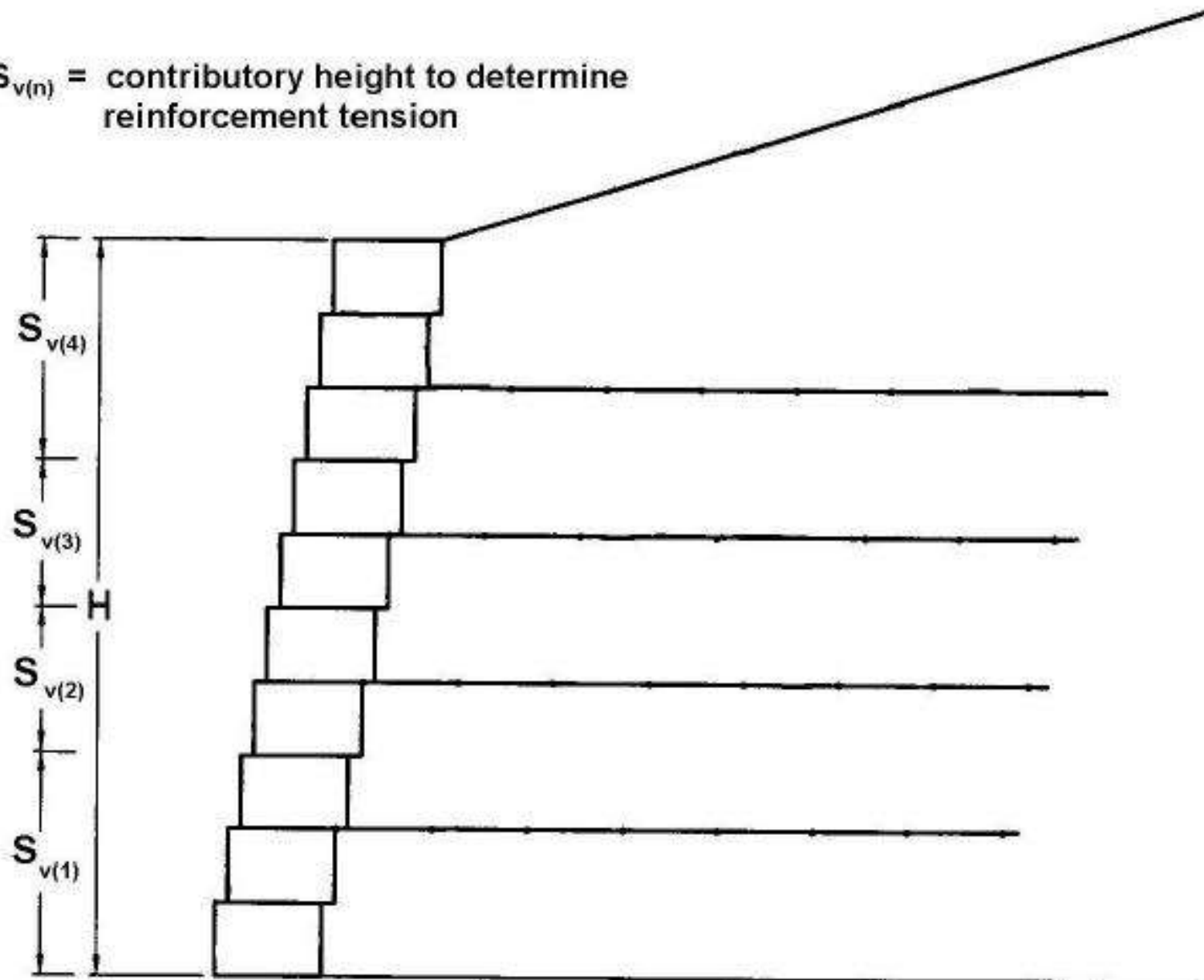
CALCULATIONS OF MAXIMUM TENSILE FORCES IN THE REINFORCEMENT LAYER

- ◎ Calculate maximum tension T_{\max} in each reinforcement layer per unit width based on the vertical spacing S_v

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

- ◎ σ_H , calculated at the level of the reinforcement, is at the center of the contributory height.
 - The contributory height is defined as the midpoint between vertically adjacent reinforcement elevations, except for the top and bottom layers reinforcement.

$S_{v(n)}$ = contributory height to determine reinforcement tension



CALCULATIONS OF MAXIMUM TENSILE FORCES IN THE REINFORCEMENT LAYER

- ◎ Calculate factored tensile resistance T_r

$$T_r = \phi T_{al}$$

- ◎ Where

- ϕ = reduction factor for tensile resistance
- T_{al} = allowable tension force per unit width of the reinforcement.

- ◎ Stability with respect to breakage of the reinforcements requires that:

$$T_{MAX} \leq T_r$$

$$T_{al} = \frac{F_y A_c}{b}$$

◎ where:

- b = the gross width of the strip, sheet or grid
- F_y = yield stress of steel
- A_c = design cross section area of the steel, defined as the original cross section area minus corrosion losses anticipated to occur during the design life of the wall.

Resistance Factors ϕ for tensile resistance

Reinforcement Type and Loading Condition		Resistance Factor
Metallic reinforcement and connectors	Strip reinforcements ^(A)	
	Static loading	0.75
	Combined static/earthquake loading	1.00
	Combined static/traffic barrier impact ^(B)	1.00
	Grid reinforcements ^(A, C)	
	Static loading	0.65
	Combined static/earthquake loading	0.85
	Combined static/traffic barrier impact ^(B)	0.85
	Geosynthetic reinforcement and connectors	Static loading
Combined static/earthquake loading		1.20
Combined static/traffic barrier impact ^(B)		1.20
Pullout resistance of tensile reinforcement (metallic and geosynthetic)	Static loading	0.90
	Combined static/earthquake loading	1.20
	Combined static/traffic barrier impact ^(B)	1.00

Notes:

- A. Apply to gross cross-section less sacrificial area. For sections with holes, reduce gross area in accordance with AASHTO (2007) Article 6.8.3 and apply to net section less sacrificial area.
- B. Combined static/traffic barrier impact resistance factors are not presented in AASHTO.
- C. Applies to grid reinforcements connected to rigid facing element, e.g., a concrete panel or block. For grid reinforcements connected to a flexible facing mat or which are continuous with the facing mat, use the resistance factor for strip reinforcements.

INTERNAL STABILITY WITH RESPECT TO PULLOUT FAILURE-ASD

◎ The following criteria must be satisfied:

$$T_{\max} \leq \frac{1}{FS_{PO}} F^* \gamma Z_p L_e C R_c \alpha$$

■ Where

- FS_{PO} = Safety factor against pullout ≥ 1.5 .
- T_{\max} = Maximum reinforcement tension.
- $C = 2$ for strip, grid, and sheet type reinforcement.
- α = Scale correction factor.
- F^* = Pullout resistance factor.
- R_c = Coverage ratio.
- γZ_p = The overburden pressure
- L_e = The length of embedment in the resisting zone.

INTERNAL STABILITY WITH RESPECT TO PULLOUT FAILURE-ASD

- ◎ The required embedment length in the resistance zone

$$L_e \geq \frac{1.5 T_{\max}}{C F^* \gamma Z_p R_c \alpha} \geq 1 \text{ m}$$

- ◎ If the criterion is not satisfied
 - Reinforcement length has to be increased and/or reinforcement with a greater pullout resistance per unit width must be used, or the vertical spacing may be reduced which would reduce T_{\max} .

INTERNAL STABILITY WITH RESPECT TO PULLOUT FAILURE-ASD

- ⊙ The total length of reinforcement, L , required is determined using:

$$L = L_a + L_e$$

- ⊙ For MSEW with extensible reinforcement, vertical face and horizontal backfill

$$L_a = (H - Z) \tan (45 - \phi' / 2)$$

- Where:
 - Z = depth to the reinforcement level

INTERNAL STABILITY WITH RESPECT TO PULLOUT FAILURE-ASD

- For walls with inextensible reinforcement from the base up to $H/2$:

$$L_a = 0.6 (H-Z)$$

- For the upper half of a wall with inextensible reinforcements

$$L_a = 0.3H$$

QUESTIONS?



REFERENCES

- © Elias, V., Christopher, B., Berg, R. (2001). *Mechanically Stabilized Earth Walls and Reinforced Soil Slopes Design and Construction Guidelines*. FHWA-NHI-00-043. Washington, D.C. :National Highway Institute.

Design of Reinforced Slope (RSS)

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Professor

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Reinforced Soil Slopes (RSS)

- Incorporates multiple horizontal layers of geosynthetics or wire mesh that act as reinforcements for the soil with face inclinations of less than 70 degrees.
- By placing tensile reinforcing elements in the soil, the strength of the soil can be improved significantly such that the vertical face of the soil/reinforcement system is essentially self supporting.
- Can tolerate larger settlements than reinforced concrete walls.

Reinforced Soil Slopes (RSS)



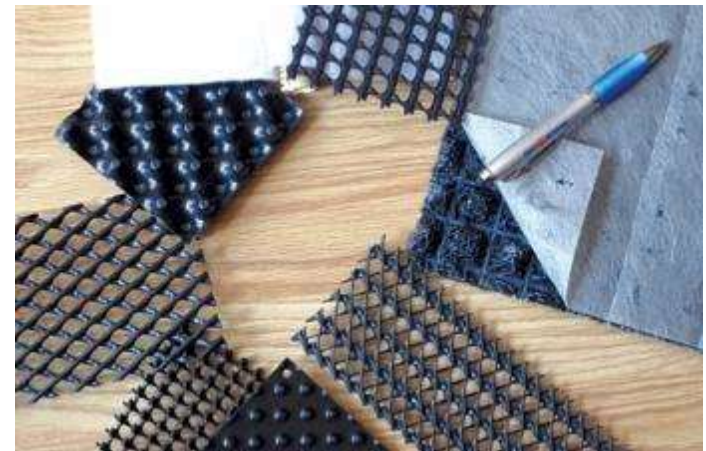
Reinforced Soil Slope using
Geogrids

Definition of key terms

- Geosynthetics
 - Polymeric materials
 - geotextiles, geomembranes, geonets, and geogrids.
 - The use of geotextiles in RSS started after noticing the beneficial effect in highway embankments over weak subgrades.
 - The first geotextile reinforced wall was constructed in France in 1971.



Geogrids



Geonets

Definition of key terms

- Facing
 - Consists of some type of erosion control material.
 - usually consists of welded wire mesh, geosynthetic wrap-around, and/or some type of erosion control material
 - precast concrete panels, dry cast modular blocks, metal sheets and plates, gabions, shotcrete, wood lagging and panels, their use need to be evaluated.



Wrapped Sheets of Geosynthetics

Definition of key terms

- Retained backfill
 - Fill material located between the mechanically stabilized soil mass and the natural soil.
- Reinforced backfill
 - Fill material in which the reinforcements are placed.

Purposes for using reinforcement in slopes

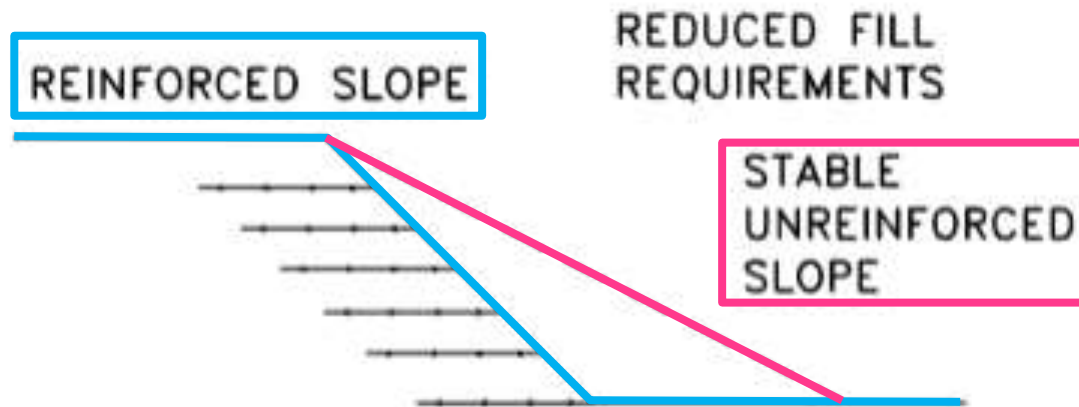
- Improved stability for steepened slopes and slope repair.
- Compaction aids, for support of construction equipment and improved face stability.

Purpose for using reinforcement in slopes

- **Principal purpose**
 - Construct an RSS embankment at an angle steeper than could otherwise be safely constructed with the same soil.
 - Roadways can also be widened over existing flatter slopes without invading existing right-of-ways.
 - If repairing a slope failure, the new slope will be safer, and reusing the slide debris rather than importing higher quality backfill may result in substantial cost savings.

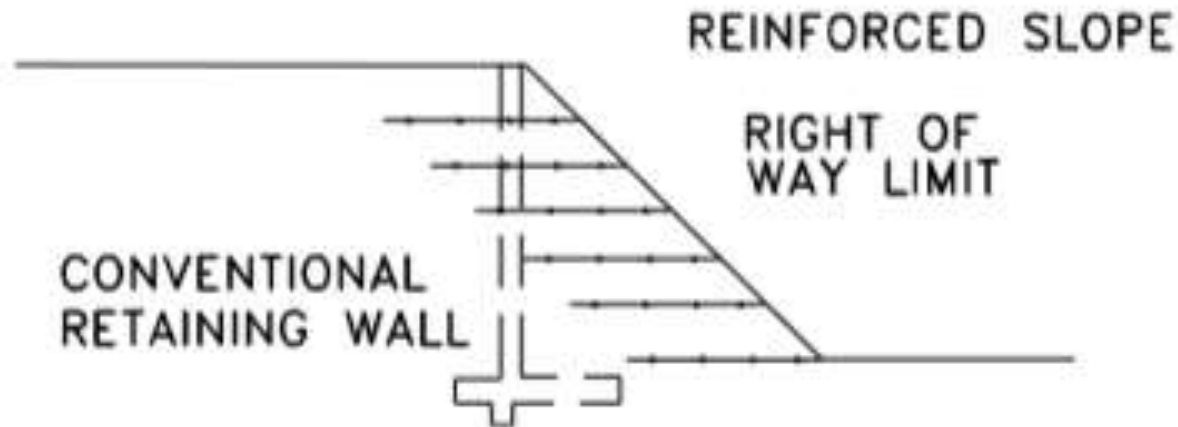
Application for reinforced soil slope

For a New Construction



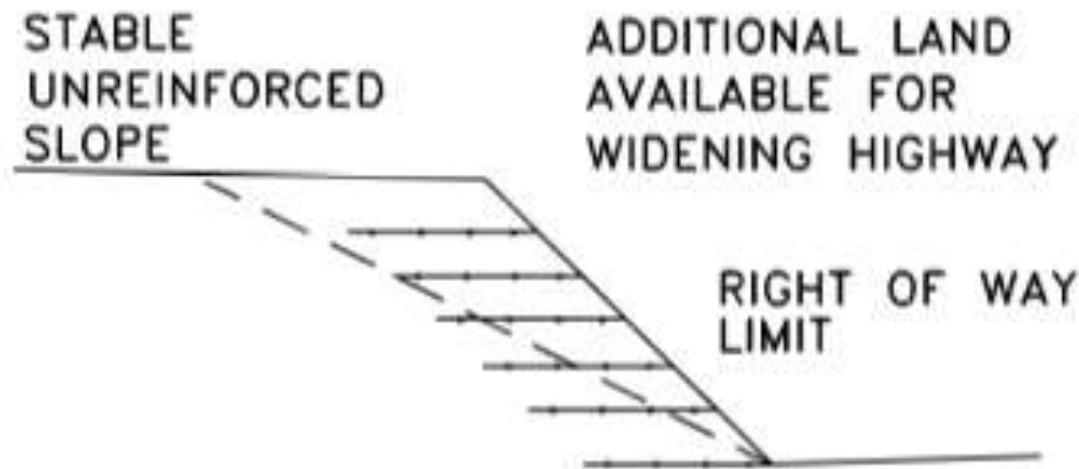
Application for reinforced soil slope

As a Wall Alternative



Application for reinforced soil slope

For Road Widening



Application for reinforced soil slope

For Slide Repair



Purpose for using reinforcement in slopes

- Second purpose
 - To provide lateral resistance during compaction at the edges of a compacted fill slope.
 - Increased lateral resistance allows for an increase in compacted soil density which provides increased lateral confinement for the soil at the face.

Other Applications

- Upstream/downstream face improvements to increase height of dams.
- Permanent levees.
- Temporary flood control structures.
- Decreased bridge spans.
- Temporary road widening for detours.
- Prevention of surface sloughing during periods of saturation.
- Embankment construction with wet, fine-grained soils.

Applications



Highway Embankment



RSS to prevent surface sloughing

Advantages

- Material and right-of-way savings.
- In some cases, RSS can be constructed at about one-half the cost of MSEW structures.
- The use of vegetated-faced reinforced soil slopes can be landscaped to blend with natural environments.
- Lower risk of long-term stability problems developing in the slopes due to more conservative designs.

Disadvantages

- Requires large space behind the wall for internal and external stability.
- Suitable design criteria is required to address corrosion of steel reinforcing elements, deterioration of certain types of exposed facing elements and potential degradation of polymer reinforcement in the ground.
- Specifications and contracting practices have not been fully standardized.
- Requires a shared design responsibility between material suppliers and owners and greater input from agencies geotechnical specialists .

Relative Costs

- The economy must be assessed on a case-by-case basis, where use is not dictated by space constraints.
 - An appropriate benefit to cost ratio analysis should be carried out.
 - Guardrails or traffic barriers are often necessary for steeper embankment slopes and additional costs such as erosion control systems for slope face protection must be considered.

Relative Costs

- The factors to consider are as follows:
 - Cut or fill earthwork quantities.
 - Size of slope area.
 - Average height of slope area.
 - Angle of slope.
 - Cost of nonselect versus select backfills.
 - Temporary and permanent erosion protection requirements.
 - Cost and availability of right-of-way needed.
 - Horizontal and vertical alignment changes.
 - Need for temporary excavation support systems.
 - Maintenance of traffic during construction.
 - Aesthetics.
 - Requirements for guardrails and traffic barriers.

Relative Costs

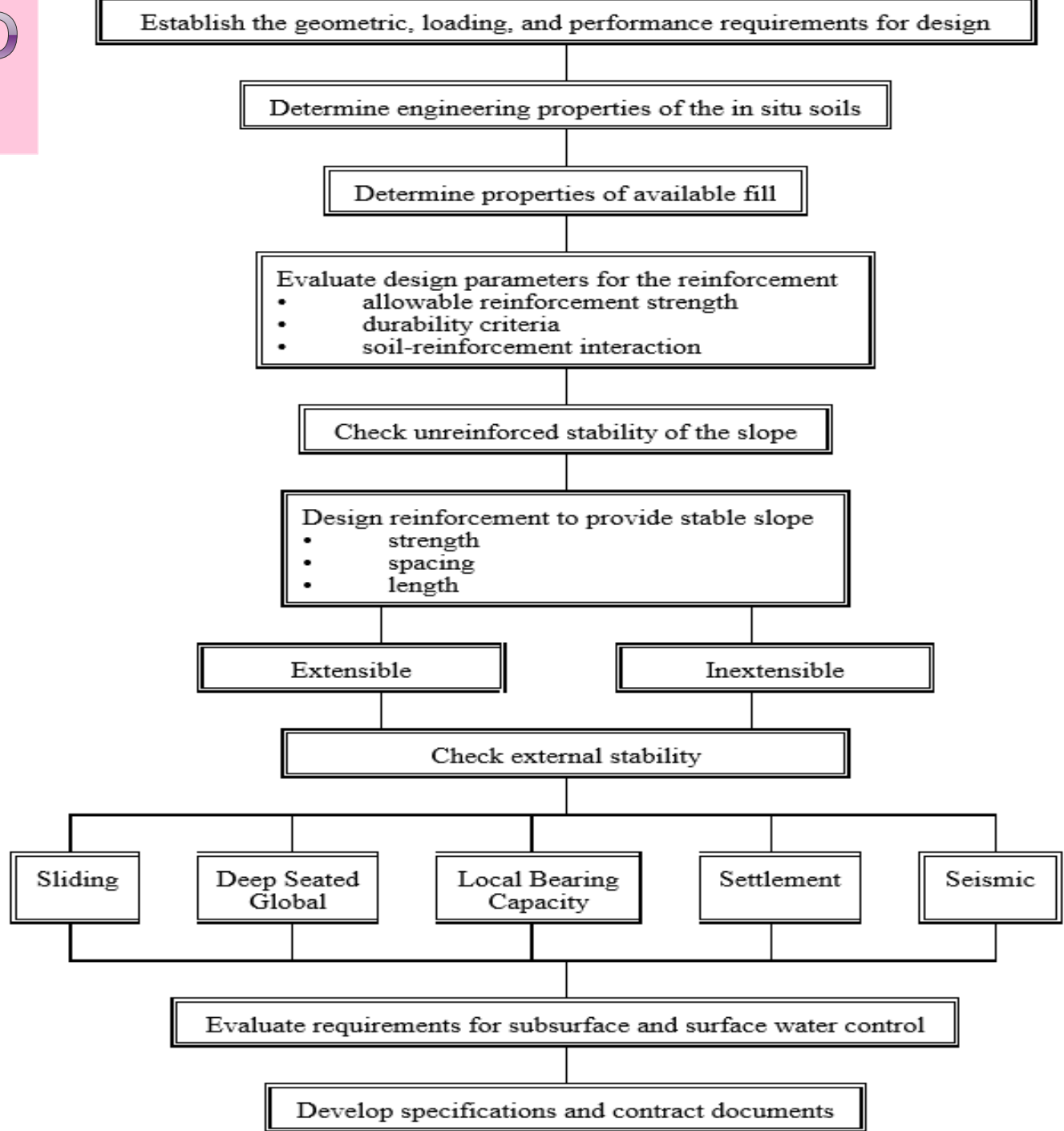
- The bid cost of a specific RSS structure depends on the cost of:
 - Reinforcement - 45 to 65 % of total cost
 - Backfill - 30 to 45 % of total cost
 - Face treatment - 5 to 10 % of total cost

Systems Differentiation

- A system is defined as a complete supplied package that includes:
 - design, specifications and all prefabricated materials.
 - Often technical assistance during the planning and construction phase is also included.

REINFORCED SOIL SLOPE

DESIGN PROCESSES



Types of Systems

- RSS systems can be described by:
 - Reinforcement geometry
 - Stress transfer mechanism
 - Reinforcement material
 - Extensibility of the reinforcement material
 - Type of facing and connections

Reinforcement Geometry

- Three types that can be considered:
 - **Linear unidirectional**
 - Strips: smooth or ribbed steel strips
 - Coated geosynthetic strips over a load-carrying fiber
 - **Composite unidirectional**
 - Grids or bar mats characterized by grid spacing greater than 150 mm (6 inches).
 - **Planar bidirectional**
 - **Continuous sheets of geosynthetics, welded wire mesh, and woven wire mesh.**

Reinforcement Material

- **Metallic reinforcements**
 - **Typically of mild steel**
 - Usually galvanized or epoxy coated.
- **Nonmetallic reinforcements**
 - **Generally polymeric materials**
 - polypropylene, polyethylene, or polyester

Reinforcement Extensibility

- **Classes of extensibility:**
 - **Inextensible**
 - The deformation of the reinforcement at failure is much less than the deformability of the soil.
 - **Extensible**
 - The deformation of the reinforcement at failure is comparable to or even greater than the deformability of the soil.

Construction Materials: Reinforcement Types

- Even though discrete strip type reinforcing elements can be used, the majority of the systems are constructed with continuous sheets of geosynthetics or wire mesh.
- Small, discrete micro reinforcing elements such as fibers, yarns, and microgrids have also been used.

Construction Materials:

Reinforced Fill Requirements

- The recommended reinforced fill is limited to low-plasticity, granular material
- However, with good drainage, careful evaluation of soil and soil-reinforcement interaction characteristics, field construction control, and performance monitoring, most indigenous soil can be considered.

Reinforced Backfill Materials

- Slopes constructed with a flexible face can tolerate minor distortions that could result from settlement, freezing and thawing, or wet-drying of the backfill.
- Any soil meeting the requirements for embankment construction could be used in a reinforced slope system.
- A higher quality material offers less durability concerns for the reinforcement, and is easier to handle, place and compact, which speeds up construction.

Structure Selection Factors

- Major factors that influence the selection of an RSS alternative for any project include:
 - Geologic and topographic conditions.
 - Environmental conditions.
 - Size and nature of the structure.
 - Aesthetics.
 - Durability considerations.
 - Performance criteria.
 - Availability of materials.
 - Experience with a particular system or application.
 - Cost

Geologic and Topographic Conditions

- For RSS embankments the required foundation strength is somewhat less than for MSE walls and depends on the actual slope considered.
- If these conditions are not satisfied, ground improvement techniques must be considered. The techniques include but are not limited to:
 - Excavation and removal of soft soils and replacement with a compacted structural fill.
 - Use of lightweight fill materials.
 - In situ densification by dynamic compaction or improvement by use of surcharging with or without wick drains.
 - Construction of stone columns.

Environmental Conditions

- RSS construction with an organic vegetative cover must be carefully chosen to
 - be consistent with native perennial cover that would establish itself quickly.
 - thrive with available site rainfall.

Size and nature of structure

- RSS may be cost effective in
 - rural environments
 - where *ROW* restrictions exist or on widening projects where long sliver fills are necessary.
 - urban environments
 - they should be considered where *ROW* is available, as they are always more economical than MSEW structures.

Aesthetics

- Outward face treatment
 - generally by vegetation
 - Initially more economical than the concrete facing used for MSE structures.
 - Maintenance costs may be considerably higher, and the long-term performance of many outward face treatments has not been established.

Establishment of project criteria

- The engineer should consider each topic area at a preliminary design stage and determine appropriate elements and performance criteria.
- The process consists of:
 - Consider all possible alternatives.
 - Choose a system (MSEW or RSS).
 - Consider facing options.
 - Develop performance criteria.
 - Consider effect of site on corrosion/degradation of reinforcements.

Facing Considerations

- The choice of slope facing may be controlled by climatic and regional factors.
- For structures of less than 10 m (33 ft) height with slopes of 1:1 or flatter
 - a vegetative "green slope" can be usually constructed using an erosion control mat or mesh and local grasses.
 - if vegetation cannot be established, armored slopes using natural or manufactured materials may be the only choice.

Design Approach

- Determine the purpose for using reinforcement
- Design of Reinforcement for Compaction Aid
- Design of Reinforcement for Steepening Slopes and Slope Repair
- Computer-Assisted Design
- Evaluation of External Stability

Use Considerations

- Determine the purpose for using RSS:
 - Improved stability for steepened slopes and slope repair.
 - Compaction aids, for support of construction equipment and improved face stability.

Use considerations

- Failure Modes
 - Internal
 - Failure plane passes through the reinforcing elements.
 - External
 - Failure surface passes behind and underneath the reinforced mass.
 - Compound
 - Failure surface passes behind and through the reinforced soil mass.

Failure Modes

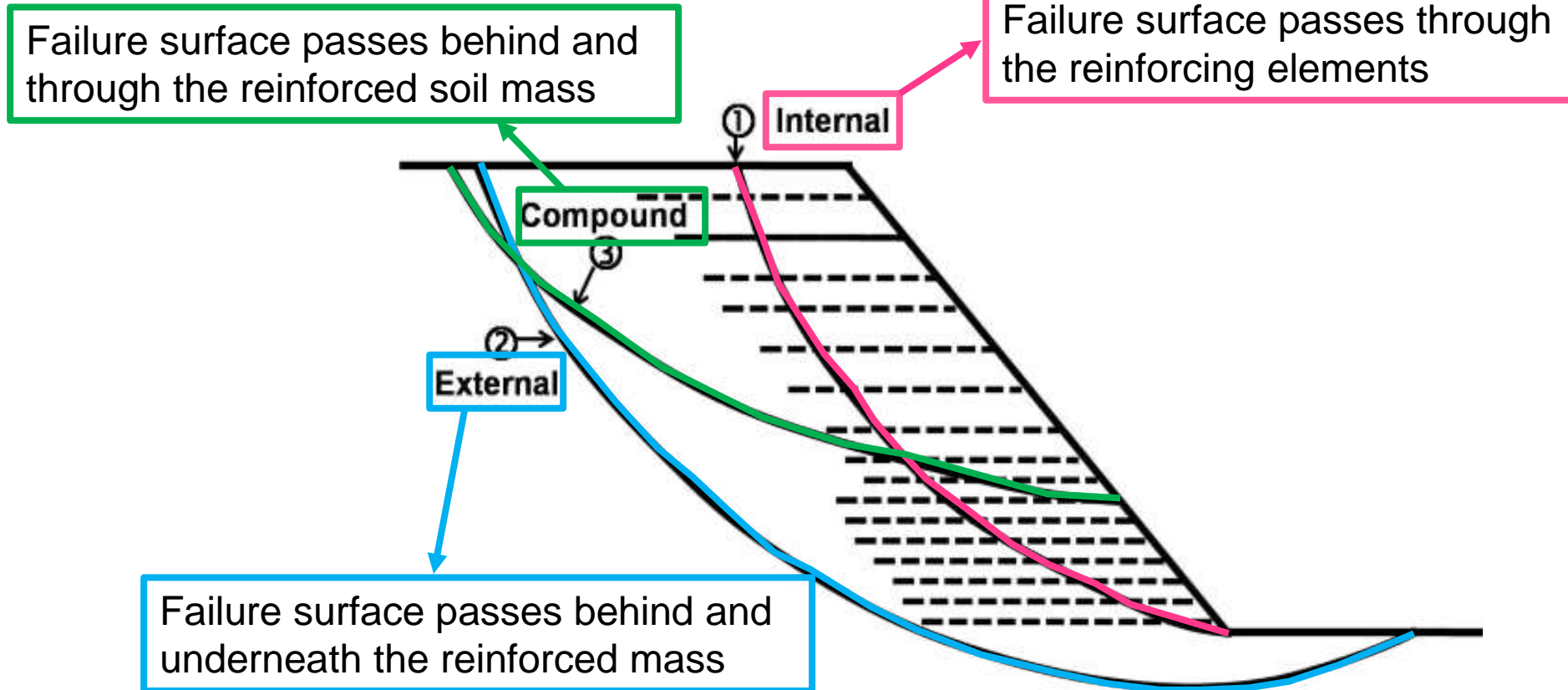


Figure : Failure Modes for Reinforced Slopes

Design of Reinforcement for Compaction Aid

- For geosynthetics as compaction aids
 - If the slope is safe without reinforcement, no reinforcement design is required.
 - Only narrow strips, about 4 to 6 ft (1.2 to 1.8 m) in width, at 8 to 18 in. (200 to 500 mm) vertical spacing are required.
 - Where the slope angle approaches the angle of repose of the soil, it is recommended that a face stability analysis be performed.
 - Where reinforcement is required by analysis
 - the narrow strip reinforcement may be considered as secondary reinforcement used to improve compaction and stabilize the slope face between primary reinforcing layers.

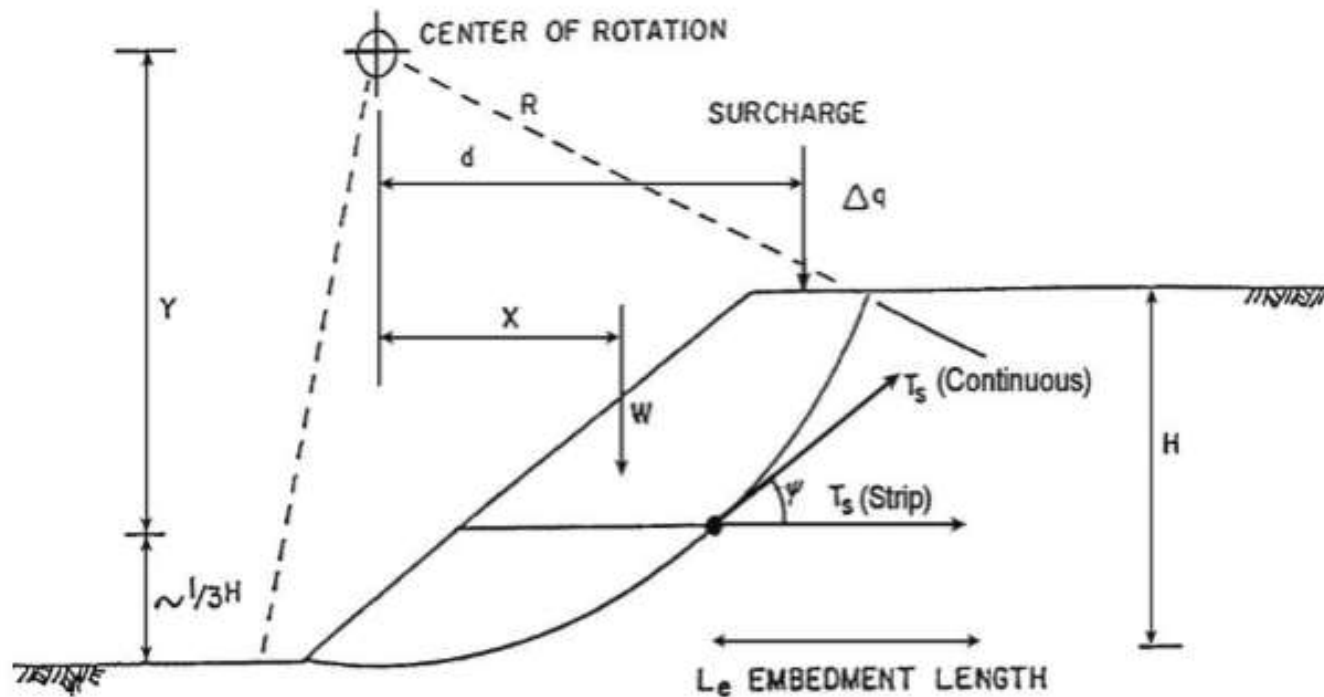
Design of Reinforcement for Steepening Slopes and Slope Repair

- For steepened reinforced slopes (face inclination up to 70 degrees) and slope repair, design is based on modified versions of the classical limit equilibrium slope stability methods:
 - Circular or wedge-type potential failure surface is assumed.
 - The relationship between driving and resisting forces or moments determines the slope factor of safety.

Design of Reinforcement for Steepening Slopes and Slope Repair (cont.)

- Reinforcement layers intersecting the potential failure surface are assumed to increase the resisting force or moment based on their tensile capacity and orientation.
- The tensile capacity of a reinforcement layer is taken as the minimum of its allowable pullout resistance behind (or in front of) the potential failure surface and its long-term allowable design strength, T_{al} .

Modified limit equilibrium analysis for reinforced slope design



Design of Reinforcement for Steepening Slopes and Slope Repair

- A wide variety of potential failure surfaces must be considered.
 - **Internal analysis**
 - The critical slope stability factor of safety is taken from the internal unreinforced failure surface requiring the maximum reinforcement.
 - This is the failure surface with the largest unbalanced driving moment to resisting moment.

Design of Reinforcement for Steepening Slopes and Slope Repair: Internal analysis

- The failure surface is equivalent to the critical reinforced failure surface with the lowest factor of safety.
- Detailed design of reinforced zone is performed by determining the factor of safety with successively modified reinforcement layouts until the target factor of safety is achieved.
- External and compound stability of the reinforced zone are then evaluated.

Design of Reinforcement for Steepening Slopes and Slope Repair

- For slope repair applications
 - Important to identify the cause of the original failure to make sure that the new reinforced soil slope will not have the same problems.
 - In natural soils, it is necessary to identify any weak seams that might affect stability.
- The computer program ReSSA (ADAMA, 2001) was developed by the FHWA to perform this analysis.

Design of Reinforcement for Steepening Slopes and Slope Repair

- The rotational slip surface approach is used for slopes up to 70 degrees, although technically it is a valid method for evaluating even steeper slopes.
- Slopes steeper than 70 degrees are considered walls.

Computer-Assisted Design

- Ideal method for reinforced slope design
 - Conventional slope stability computer programs that have been modified to account for the stabilizing effect of reinforcement.
 - A number of reinforced slope programs are commercially available.
 - The development of program ReSSA was initially sponsored by the FHWA.

Computer-Assisted Design

- ReSSA also provides alternate methods of analysis.
- Some of the less sophisticated programs do not design the reinforcement but allow for an evaluation of a given reinforcement layout.
 - Many are limited to simple soil profiles and, in some cases, simple reinforcement layouts.
- With computerized analyses, the factor of safety value (FS) is dependent upon how the program accounts for the reinforcement tension in the moment equilibrium equation.

Computer-Assisted Design

- Method of analysis in ReSSa
 - Assumes the reinforcement force as contributing to the resisting moment:

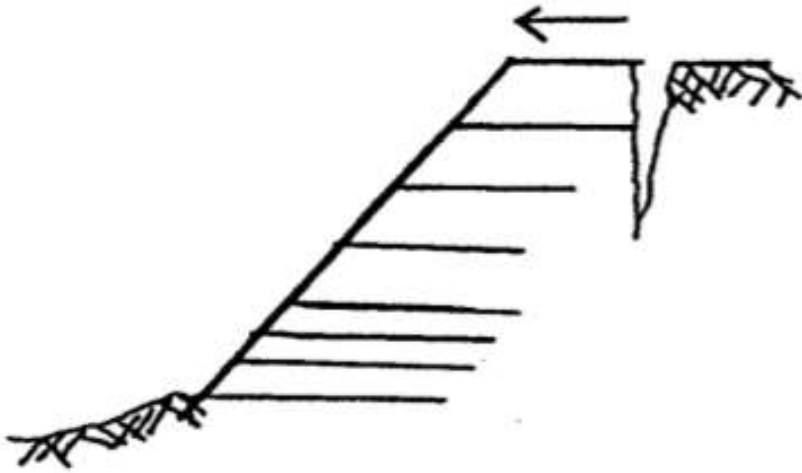
$$FS_R = \frac{M_R + T_s R}{M_D}$$

- where,
 - FSR = the required stability factor of safety
 - MR = resisting moment provided by the strength of the soil
 - MD = driving moment about the center of the failure circle
 - Ts= sum of tensile force per unit width of reinforcement in all reinforcement layers intersecting the failure surface
 - R = moment arm of Ts about the center of failure circle

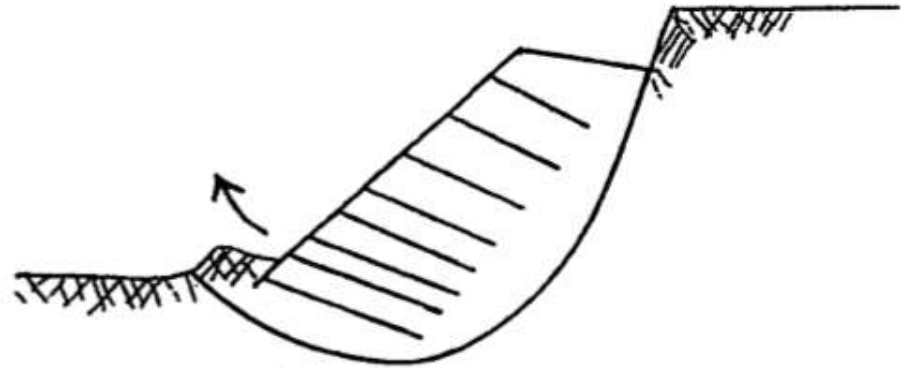
Evaluation of External Stability

- Depends on the ability of the reinforced zone to act as a stable block and withstand all external loads without failure.
- Identify any weak soil layers in the retained fill and natural soils.
- Conventional soil mechanics stability methods should be used to evaluate the global stability of the reinforced soil zone.
- Evaluation of potential seepage forces is especially critical for global stability analysis.

Failure Possibilities



Sliding Instability

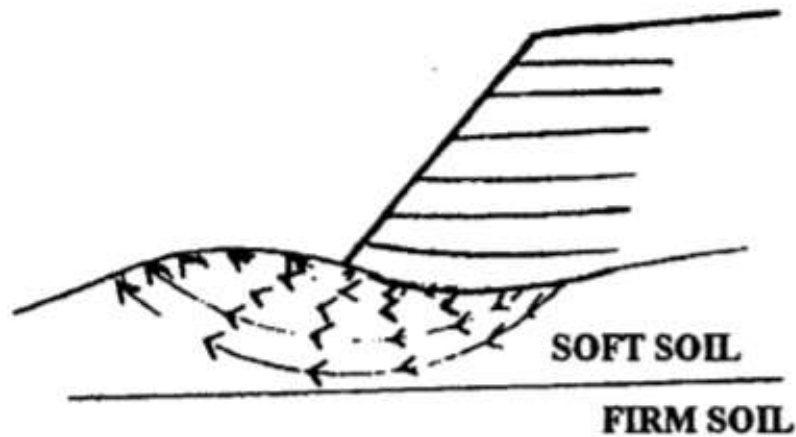


Deep Seated
Overall Instability

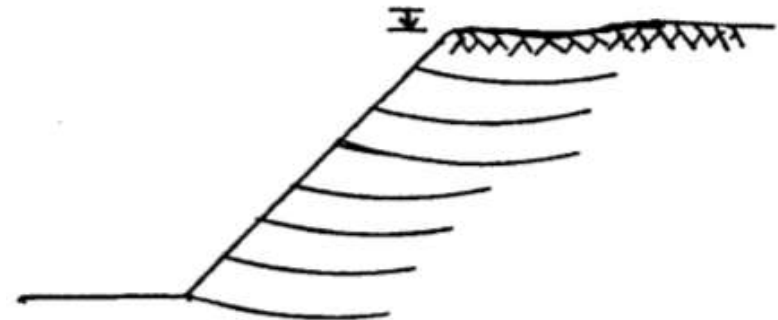
Sliding Instability

- The reinforced zone must be sufficiently wide at any level to resist wedge and block type sliding.
- To evaluate sliding stability
 - A wedge type failure surface defined by the limits of the reinforcement can be analyzed using the conventional sliding block method of analysis.

Failure Possibilities



Local Bearing
Capacity Failure



Excessive Settlement

Evaluating External Stability

- Settlement should be evaluated for:
 - total and differential movement.
- While settlement of the reinforced slope is not of concern, adjacent structures or structures supported by the slope may not tolerate such movements.
- Reinforced slopes are flexible systems and, unless used for bridge abutments, they are not laterally restrained.

Evaluating External Stability

- If any of the external stability safety factors are less than the required, the following foundation improvement options should be considered:
 - Excavate and replace soft soil.
 - Flatten the slope.
 - Construct a berm at the toe of the slope to provide an equivalent flattened slope.
 - Stage construct the slope to allow time for consolidation of the foundation soils.
 - Embed the slope below grade (> 3 ft), or construct a shear key at the toe of the slope.
 - Use ground improvement techniques (e.g., wick drains, stone columns, etc.)

CONSTRUCTION SEQUENCE

- Construction of reinforced slopes is very similar to normal slope construction. The elements of construction consist of:
 - Placing the soil
 - Placing the reinforcement
 - Constructing the face

Usual construction sequence

- Site Preparation
- Reinforcing Layer Placement
- Reinforced fill Placement
- Compaction
- Face Construction

Site Preparation

- Clear and grub site.
- Remove all slide debris.
- Prepare a level subgrade for placement of the first level of reinforcement.
- Proof-roll subgrade at the base of the slope with a roller or rubber-tired vehicle.
- Observe and approve foundation prior to fill placement.

Reinforcing Layer Placement

- Reinforcement should be placed with the principal strength direction perpendicular to the face of the slope.
- Secure reinforcement with retaining pins to prevent movement during fill placement.
- A minimum overlap of 150 mm (6 inches) is recommended along the edges perpendicular to the slope for wrapped face structures.
 - For geogrid reinforcement, the edges may be clipped or tied together.
 - When geosynthetics are not required for face support no overlap is required.

Reinforcement Backfill Placement

- Place fill to the required lift thickness on the reinforcement using a front end loader or dozer operating on previously placed fill or natural ground.
- Compact
 - For granular materials use a vibratory roller or plate type compactor
 - For cohesive materials use a rubber-tired or smooth drum roller.
- - Use lightweight compaction equipment near the slope face to help maintain face alignment.

Compaction Control

- Provide close control on the water content and density of the backfill.
- If the backfill is a coarse aggregate
 - A relative density or a method type compaction specification should be used.

Face Construction

- Slope facing requirements will depend on soil type, slope angle and the reinforcement spacing
- A face wrap may not be required for slopes up to 1H:1V.
 - The reinforcement can be extended to the face.
- Slopes steeper than approximately 1:1 typically require facing support during construction.

RSS slope facing options

Slope Face Angle and Soil Type	Type of Facing			
	When Geosynthetic is not Wrapped at Face		When Geosynthetic is Wrapped at Face	
	Vegetated Face ¹	Hard Facing ²	Vegetated Face ¹	Hard Facing ²
> 50° (> ~0.9H:1V) All Soil Types	Not Recommended	Gabions	Sod, Permanent Erosion Blanket w/ seed	Wire Baskets, ³ Stone, Shotcrete
35° to 50° (~ 1.4H:1V to 0.9H:1V) Clean Sands (SP) ⁴ Rounded Gravel (GP)	Not Recommended	Gabions, Soil-Cement	Sod, Permanent Erosion Blanket w/ seed	Wire Baskets, ³ Stone, Shotcrete
35° to 50° (~ 1.4H:1V to 0.9H:1V) Silts (ML) Sandy Silts (ML)	Soil Bio reinforcement, Drainage Composites ⁵	Gabions, Soil-Cement, Stone Veneer	Sod, Permanent Erosion Blanket w/ seed	Wire Baskets, ³ Stone, Shotcrete
35° to 50° (~ 1.4H:1V to 0.9H:1V) Silty Sands (SM) Clayey Sands (SC) Well graded sands and gravels (SW & GW)	Temporary Erosion Blanket w/ Seed or Sod, Permanent Erosion Mat w/ Seed or Sod	Hard Facing, Not Needed	Geosynthetic Wrap Not Needed	Geosynthetic Wrap Not Needed
25° to 35° (~ 2H:1V to 1.4H:1V) All Soil Types	Temporary Erosion Blanket w/ Seed or Sod, Permanent Erosion Mat w/ Seed or Sod	Hard Facing Not Needed	Geosynthetic Wrap Not Needed	Geosynthetic Wrap Not Needed

- Notes:
1. Vertical spacing of reinforcement (primary/secondary) shall be no greater than 16 in. (400 mm) with primary reinforcements spaced no greater than 32 in. (800 mm) when secondary reinforcement is used.
 2. Vertical spacing of primary reinforcement shall be no greater than 32 in. (800 mm).
 3. 18 in. (450 mm) high wire baskets are recommended.
 4. Unified Soil Classification
 5. Geosynthetic or natural horizontal drainage layers to intercept and drain the saturated soil at the face of the slope.

Treatment of outward face

- Grass Type Vegetation
- Soil Bioengineering (Woody Vegetation)
- Armored

Grass Type Vegetation

- Erosion control and revegetation measures must be an integral part of all reinforced slope system designs and specifications.
- Reinforced slopes should be vegetated after construction to prevent or minimize erosion due to rainfall and runoff on the face.
- For the soil surface exposed, erosion control measures are necessary to prevent raveling and sloughing of the face.

Grass Type Vegetation

- A wrapped face helps reduce erosion problems
 - treatments are still required on the face to shade geosynthetic soil reinforcement and prevent ultraviolet light exposure that will degrade the geosynthetic over time.
- A synthetic erosion control mat is normally used to improve the performance of grass cover.

Grass Type Vegetation

- The erosion control mat serves to:
 - protect the bare soil face against erosion until the vegetation is established
 - assist in reducing runoff velocity for increased water absorption by the soil
 - reinforce the superficial root system of the vegetative cover.

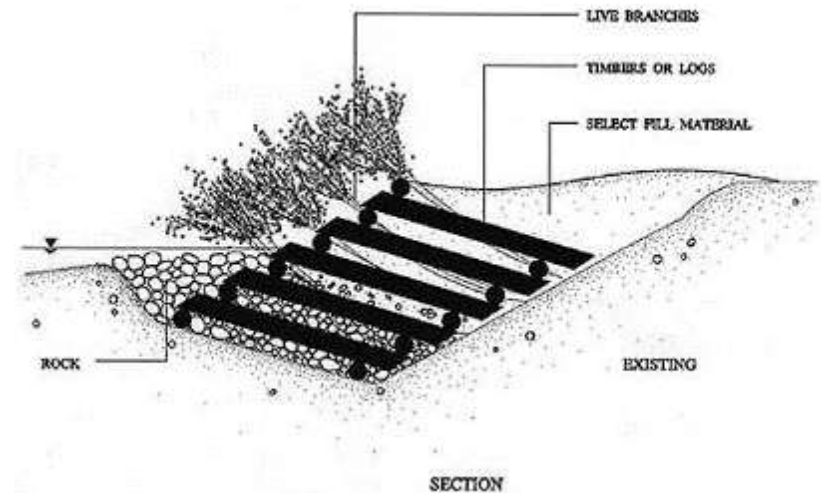
Grass Type Vegetation

- Maintenance issues, must be carefully considered.
- The low erosion tolerance combined with other factors creates a need to evaluate revegetation measures as an integral part of the design.
- Guidance should be obtained from maintenance and regional landscaping groups to select the most appropriate low maintenance vegetation.

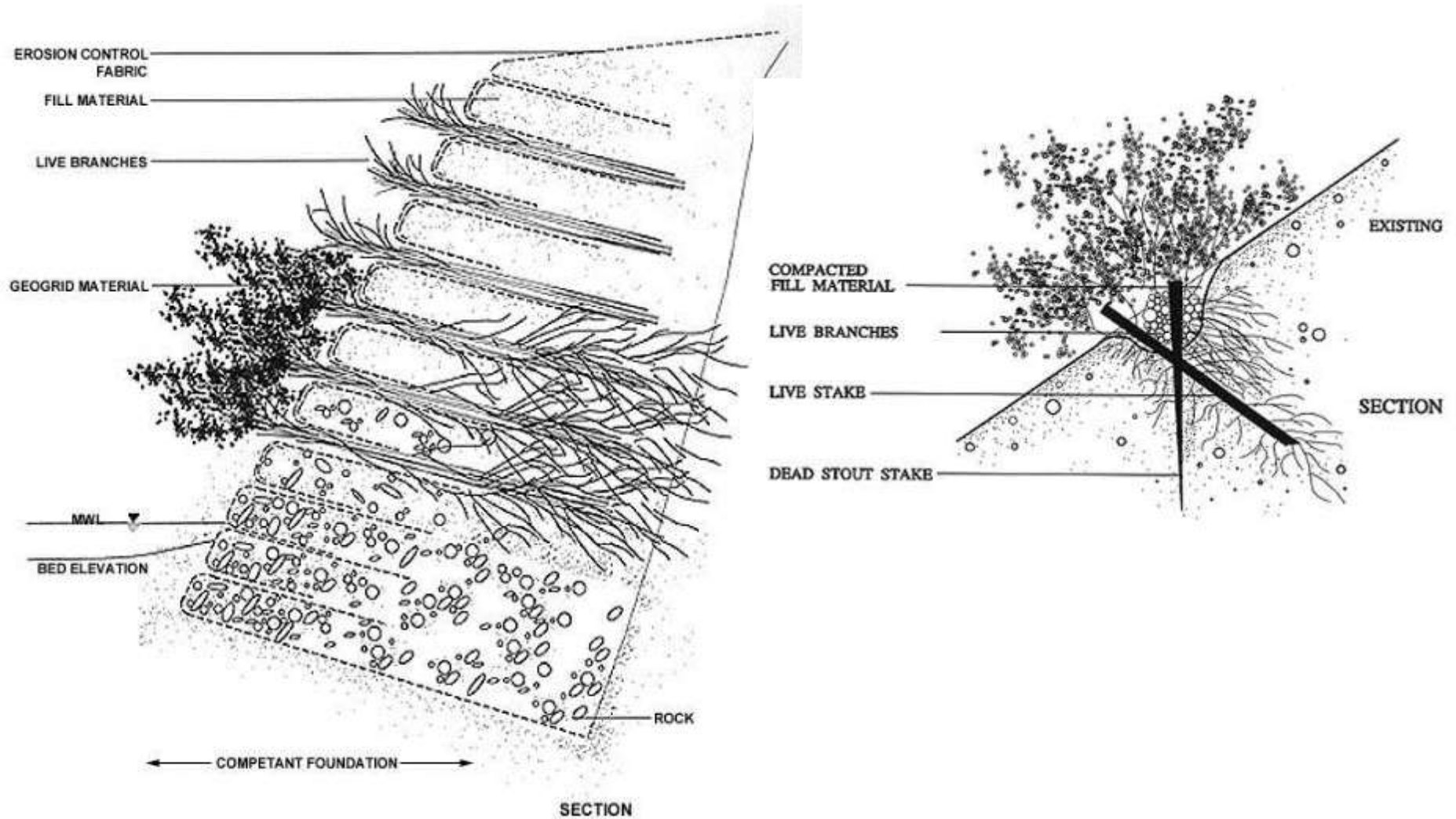
Soil Bioengineering (Woody Vegetation)

- Alternative to low growth, grass type vegetation
- Soil bioengineering uses living vegetation purposely arranged and imbedded in the ground to prevent shallow mass movement and superficial erosion.
 - limited to stable slope masses.
 - Combining it with geosynthetic reinforcement produces a durable and low maintenance structure.
- Woody vegetation improves the hydrology and mechanical stability of slopes through root reinforcement and surface protection.

Soil Bioengineering (Woody Vegetation)



Soil Bioengineering (Woody Vegetation)



Soil Bioengineering (Woody Vegetation)

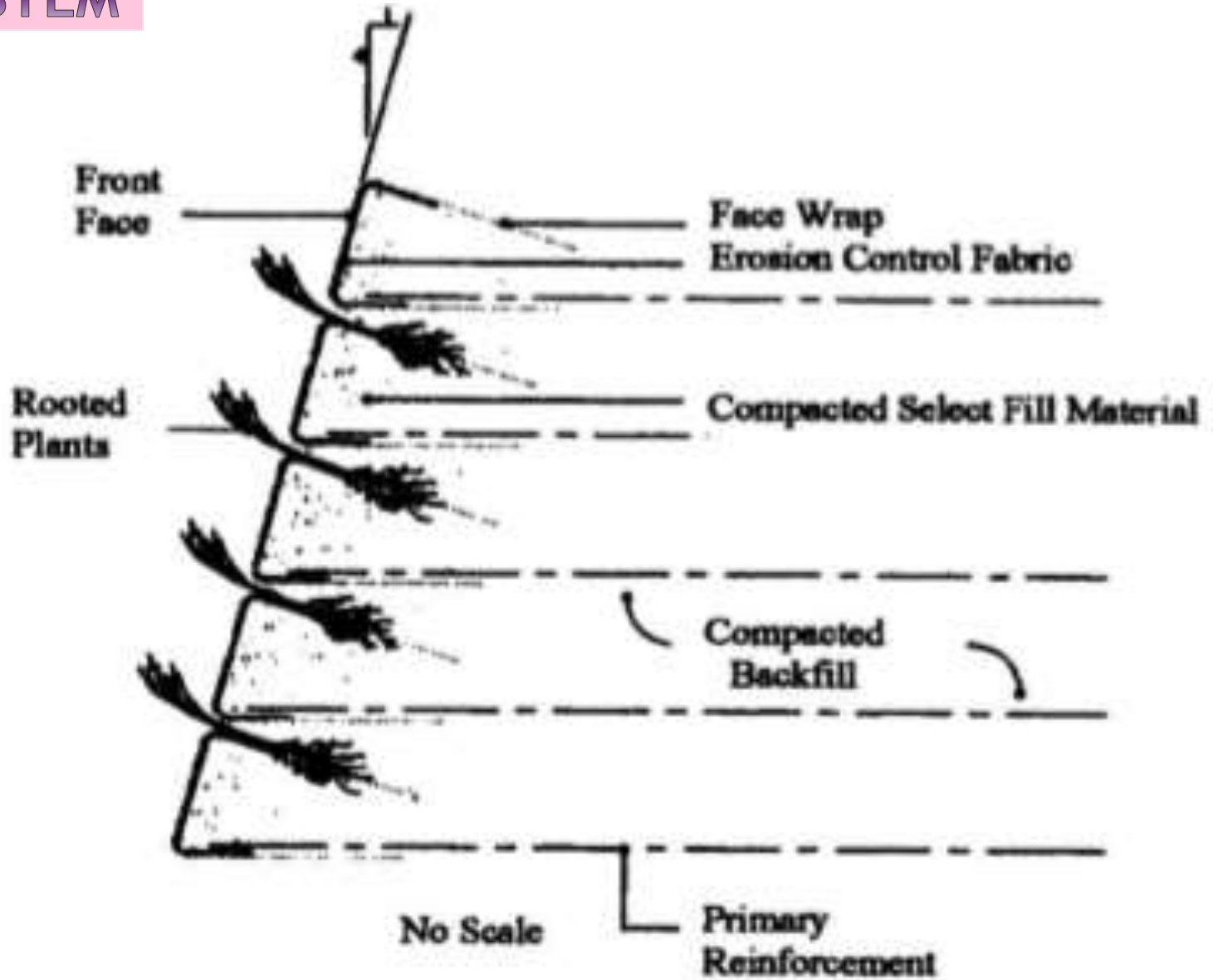
- The use of deeply-installed and rooted woody plant materials, purposely arranged and imbedded during slope construction offers:
 - Immediate erosion control.
 - Improved face stability.
 - Reduced maintenance costs.
 - Modification of soil moisture regimes.
 - Enhanced wildlife habitat and ecological diversity.
 - Improved aesthetic quality and naturalization.

Soil Bioengineering (Woody Vegetation)

- Plant science and horticulture are needed to select and establish the appropriate vegetation for:
 - root reinforcement
 - erosion control
 - aesthetics
 - the environment.

VEGETATED REINFORCED SLOPE SYSTEM

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Soil Bioengineering (Woody Vegetation)

- The vegetation used in the VRSS system is typically in the form of:
 - live woody branch cuttings from species that root adventitiously
 - bare root and/or container plants.

Armored

- A permanent facing such as gunite or emulsified asphalt may be applied to provide long-term ultra-violet protection.
- Galvanized welded wire mesh reinforcement or gabions may also be used to facilitate face construction and provide permanent facing systems.
 - Other armored facing elements may include riprap, stone veneer, articulating modular units, or fabric-formed concrete.
 - Structural elements.

Establish the geometric, loading, and performance requirements for design

- Geometric and loading requirements
 - Slope height, H .
 - Slope angle, θ .
 - External (surcharge) loads
 - Surcharge load, q
 - Temporary live load, Δq
 - Design seismic acceleration, A_m
 - Traffic Barrier

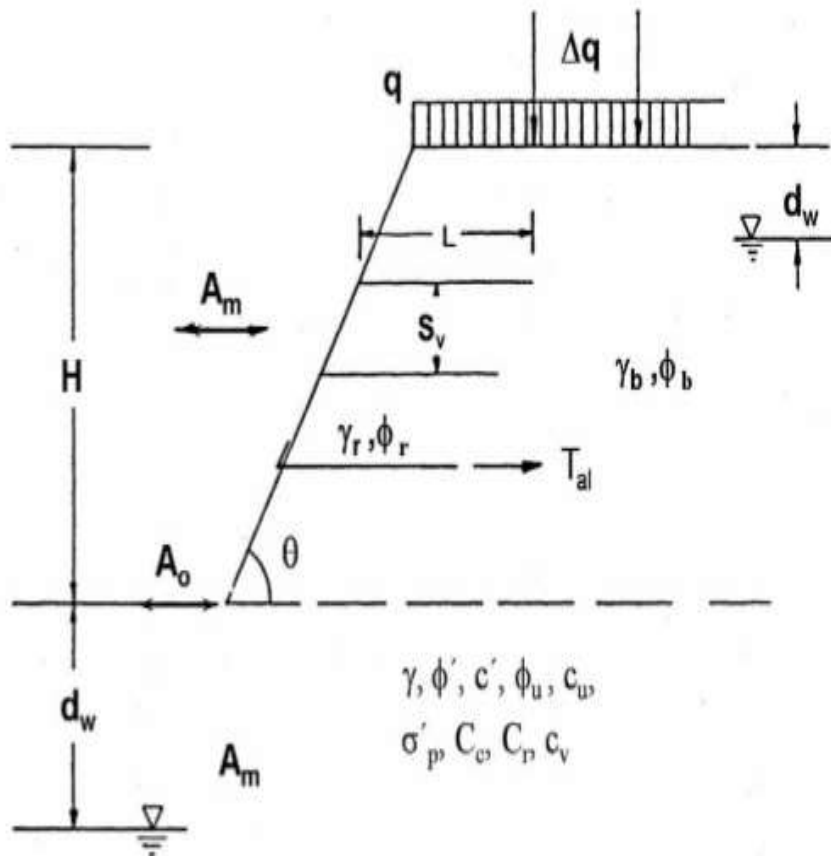
Establish the geometric, loading, and performance requirements for design

- Performance requirements.
 - External stability and settlement.
 - Sliding: $F.S. \geq 1.3$.
 - Deep seated (overall stability): $F.S. \geq 1.3$.
 - Local bearing failure (lateral squeeze) : $F.S. \geq 1.3$.
 - Dynamic loading: $F.S. \geq 1.1$.
 - Settlement-post construction magnitude and time rate based on project requirements.
 - Compound failure: $F.S. \geq 1.3$.
 - Internal slope stability: $F.S. \geq 1.3$.

Determine the engineering properties of the in situ soils

- The foundation and retained soil profiles.
- Strength parameters for each soil layer
 - c_u and ϕ_u , or c' and ϕ'
- Unit weights
 - γ_{wet} and γ_{dry}
- Consolidation parameters
 - C_c , C_r , c_v and σ'_p
- Location of the ground water table d_w , and piezometric surfaces.
- For failure repair
 - Identify location of previous failure surface and cause of failure.

Requirements for design of reinforced soil slopes



Notations:

- H = slope height
- θ = slope angle
- T_{al} = allowable strength of reinforcement
- L = length of reinforcement
- S_v = vertical spacing of reinforcement
- q = surcharge load
- Δq = temporary live load
- A_o = ground acceleration coefficient
- A_m = design seismic acceleration
- d_w = depth to ground water table in slope
- d_{wf} = depth to ground water table in foundation
- c_u and ϕ_u or c' and ϕ' = strength parameters for each soil layer
- γ_{wet} and γ_{dry} = unit weights for each soil layer
- C_c, C_r, C_v and σ'_p = consolidation parameters for each soil layer

Determine the properties of reinforced fill and, if different, the retained fill

- Gradation and plasticity index.
- Compaction characteristics based on 95% AASHTO T-99, γ_d and $\pm 2\%$ of optimum moisture, W_{opt} .
- Compacted lift thickness.
- Shear strength parameters
 - c_u , ϕ_u or c' , and ϕ'
- Chemical composition of soil (pH)

Evaluate design parameters for the reinforcement

- Allowable geosynthetic strength
 - Significant cost advantage in obtaining lower RF from test data supplied by the manufacture and/or from agency evaluation.
- Allowable steel strength
- Pullout Resistance
 - F.S. = 1.5 for granular soils.
 - F.S. = 2 for cohesive soils.
 - Minimum anchorage length, L_e , = 1 m (3 ft)

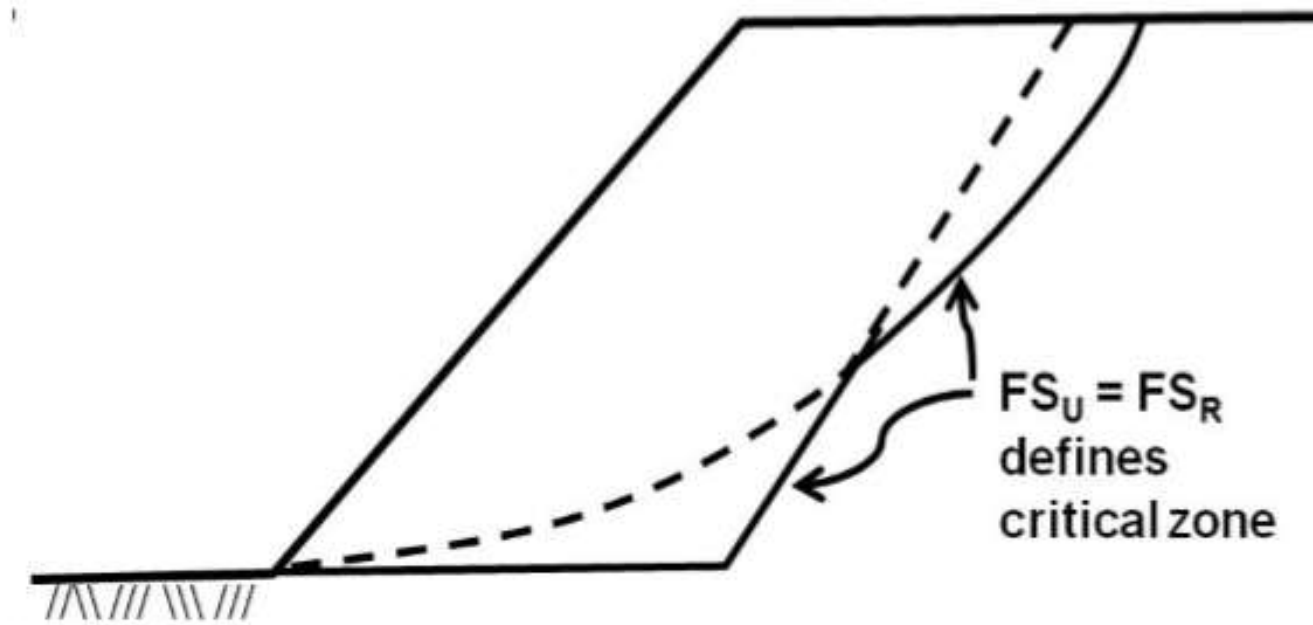
Check unreinforced stability

- Evaluate unreinforced stability to determine:
 - If reinforcement is require
 - critical nature of the design
 - potential deep-seated failure problems
 - extent of the reinforced zone.
 - Use circular-arc and sliding-wedge methods to consider failure through
 - Toe, face (at several elevations), and deep-seated below the toe.

Check unreinforced stability

- Determine the size of the critical zone to be reinforced.
 - Examine full range of potential failure surfaces:
 - Unreinforced safety factor (FSU) \leq Required safety factor (FSR)
 - Plot surfaces on the cross-section of the slope.
 - The surfaces that just meet the required safety factor roughly envelope the limits of the critical zone to be reinforced.

Critical zone defined by rotational and sliding surfaces



Check unreinforced stability

- Critical failure surfaces extending below the toe of the slope are indications of deep foundation and edge bearing capacity.
 - More extensive foundation analysis is warranted.
 - Foundation improvement measures should be considered.

Design reinforcement to provide a stable slope

- Calculate the total reinforcement tension per unit width of slope (T_S) required to obtain the required factor of safety FSR for each potential failure surface inside the critical zone:

$$T_S = (FS_R - FS_U) \frac{M_D}{D}$$

Where

T_S = the sum of the required tensile force per unit width of reinforcement (considering rupture and pullout) in all reinforcement layers intersecting the failure surface

M_D = driving moment about the center of the failure circle

D = the moment arm of T_S about the center of failure circle
= radius of circle R for **continuous, sheet type extensible reinforcement** (i.e., assumed to act tangentially to the circle)

= radius of circle R for **continuous, sheet type inextensible reinforcement** (e.g., wire mesh reinforcement) to account for normal stress increase on adjacent soil

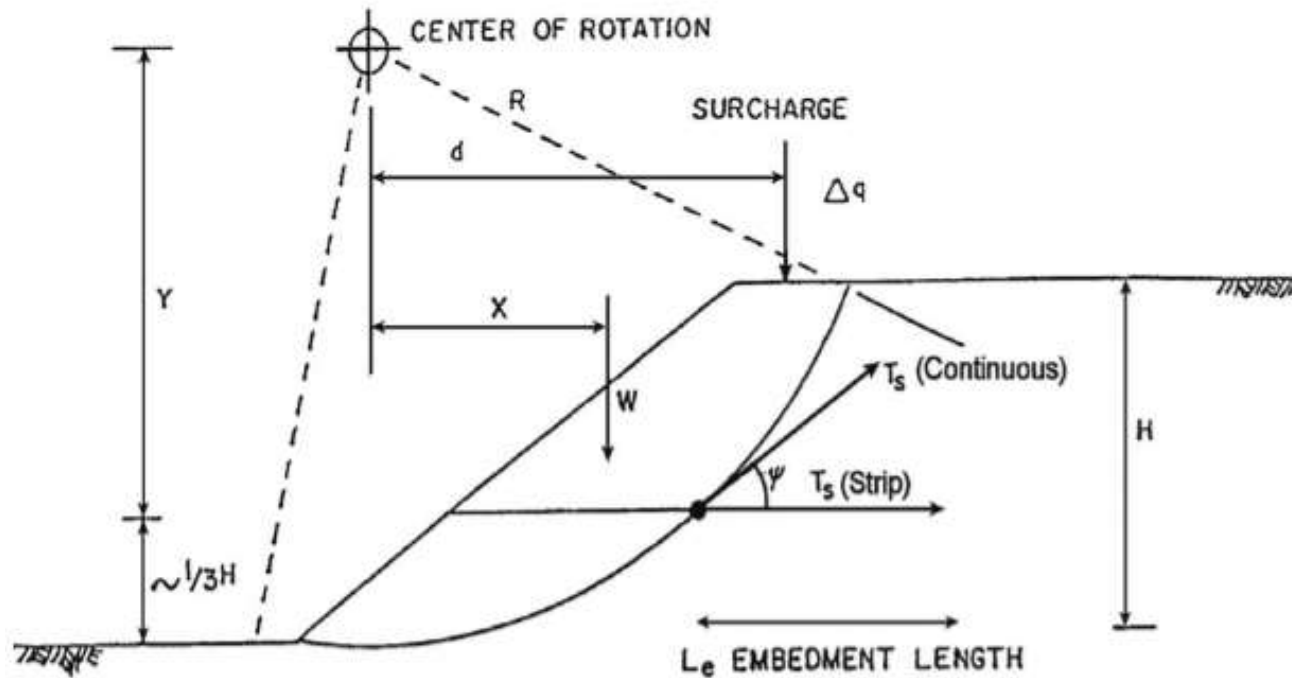
= vertical distance, Y , to the centroid of T_S for **discrete element, strip type reinforcement**. Assume $H/3$ above slope base for preliminary calculations (i.e. assumed to act in a horizontal plane intersecting the failure surface at $H/3$ above the slope base)

FS_U = unreinforced slope safety factor

FS_R = target minimum slope factor of safety which is applied to both the soil and reinforcement

T_{S-MAX} = the largest T_S calculated and establishes the total design tension

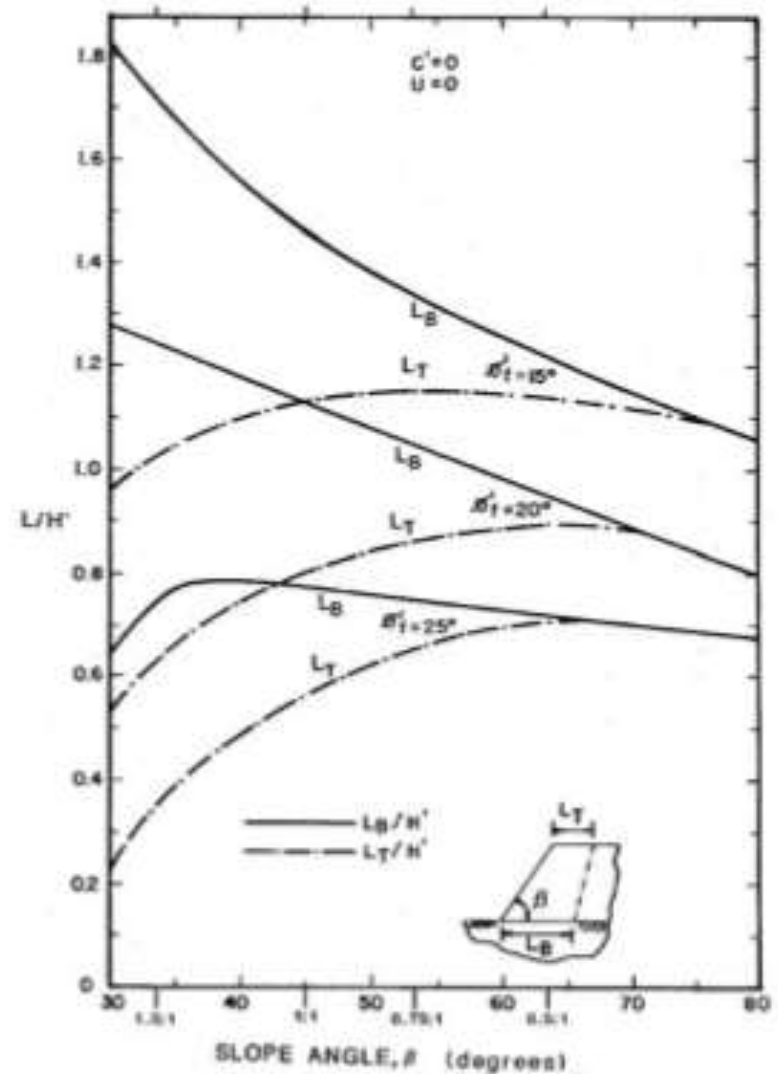
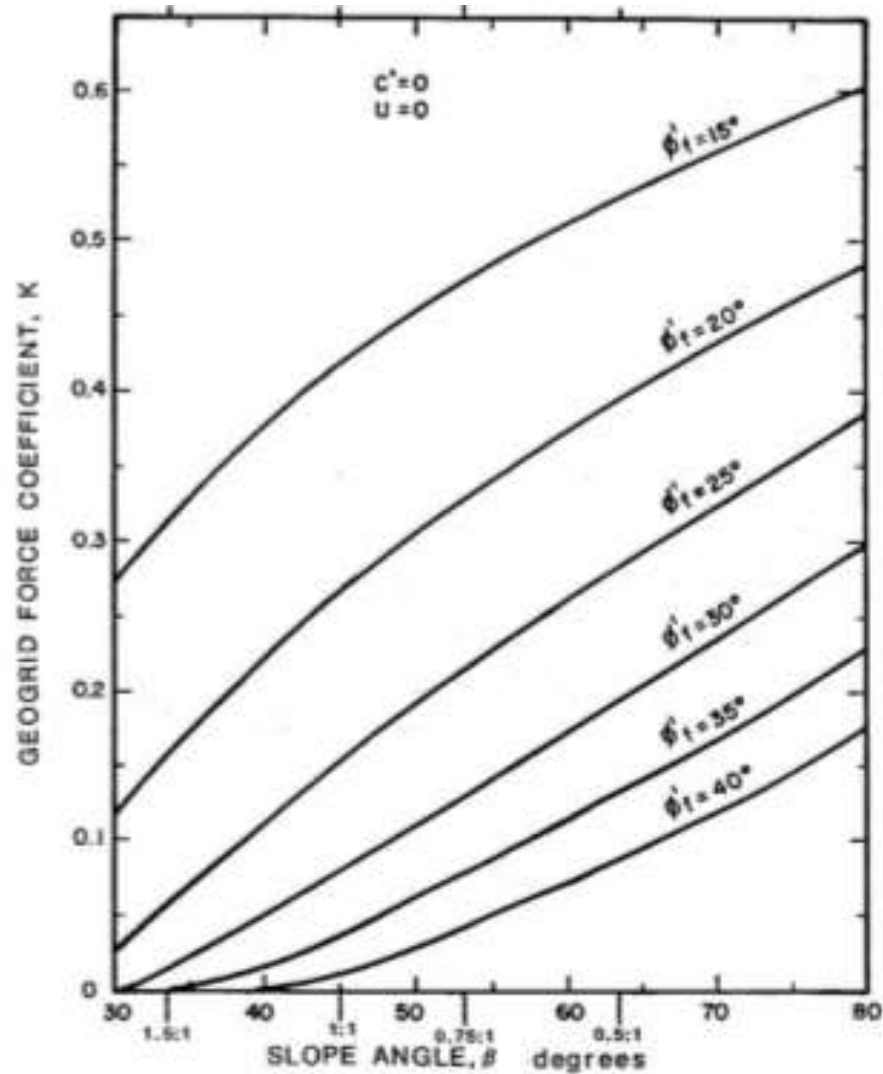
Rotational shear approach to determine required strength of reinforcement



Design reinforcement to provide a stable slope

- Determine the total design tension per unit width of slope, T_{s-MAX} , using the chart solution for determining the reinforcement strength requirements and compare with T_{s-MAX} from the previous step.
 - Several computer programs are also available for analyzing a slope with given reinforcement and can be used as a check.

Chart solution for determining the reinforcement strength requirements (after Schmertmann et.al., 1987)



Limiting Assumptions

- Extensible reinforcement
- Slopes constructed with uniform, cohesionless soil, ($c = 0$)
- No pore pressures within the slope
- Competent, level foundation soils
- No seismic forces
- Uniform surcharge not greater than $0.2 \gamma_r H$
- Relatively high soil/reinforcement interface friction angle, $\varphi_{sg} = 0.9 \varphi_r$
 - may not be appropriate for some geosynthetics

Design reinforcement to provide a stable slope

- Determine reinforcement vertical spacing S_v or the maximum design tension T_{MAX} requirements for each reinforcement layer.
 - For each zone, calculate T_{MAX} :

$$T_{max} = \frac{T_{zone} S_v}{H_{zone}} = \frac{T_{zone}}{N} \leq T_{al} R_c$$

- Where

R_c = coverage ratio of the reinforcement which equals the width of the reinforcement b divided by the horizontal spacing S_h

S_v = vertical spacing of reinforcement in meters; multiples of compacted layer thickness for ease of construction

T_{zone} = maximum reinforcement tension required for each zone
 = T_{S-MAX} for low slopes ($H < 6m$)

T_{al} = T_{ult}/RF (see Chapter 3 and equation 3-12)

H_{zone} = height of zone

= T_{top} , T_{middle} , and T_{Bottom} for high slopes ($H > 20$ ft {6 m})

N = number of reinforcement layers

Design reinforcement to provide a stable slope

- Use short 4 to 6.5 ft (1.2 to 2 m) lengths of intermediate reinforcement layers to maintain a maximum vertical spacing of 16 in.
- To ensure that the rule-of-thumb reinforcement force distribution is adequate for critical or complex structures
 - recalculate TS using equation

$$T_s = (1.3 - FS_U) \frac{M_D}{R}$$

- to determine potential failure above each layer of primary reinforcement

Design reinforcement to provide a stable slope

- Determine the reinforcement lengths required:

$$L_e = \frac{T_{\max} FS}{F^* \alpha \sigma'_v R_c C}$$

- Minimum value of L_e is 3 ft (1 m).
- For long-term design
 - Φ'_r and $c'_r = 0$
- For short-term evaluation
 - ϕ_r with $c_r = 0$ from consolidated undrained triaxial or direct shear tests or run pullout tests

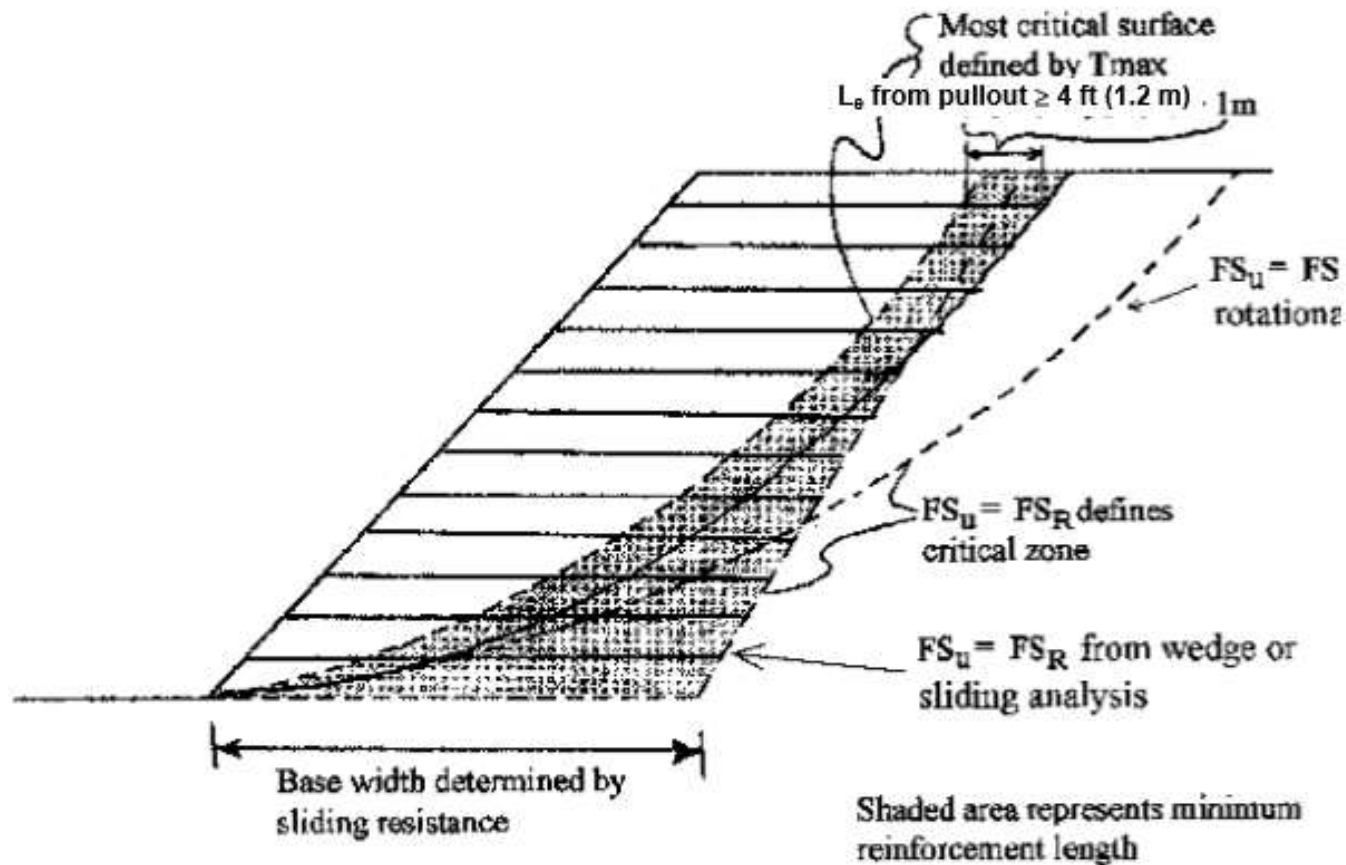
Design reinforcement to provide a stable slope

- Plot the reinforcement lengths as obtained from the pullout evaluation on a slope cross section containing the rough limits of the critical zone determined in the **check unreinforced stability step**.
 - The length required for sliding stability at the base will generally control the length of the lower reinforcement levels.
 - Lower layer lengths must extend at least to the limits of the critical zone. Longer reinforcements may be required to resolve deep seated failure problems.
 - Upper levels of reinforcement may not be required to extend to the limits of the critical zone.

Design reinforcement to provide a stable slope

- Check that the sum of the reinforcement forces passing through each failure surface is greater than T_s required for that surface.
 - If the available reinforcement force is not sufficient
 - increase the length of reinforcement not passing through the surface or increase the strength of lower level reinforcement.

Developing reinforcement lengths



Check external stability

- Sliding resistance
 - Evaluate the width of the reinforced soil zone at any level to resist sliding along the reinforcement.
 - The analysis can best be performed using a computerized method which takes into account all soil strata and interface friction values.
 - The frictional resistance provided by the weakest layer should be used in the analysis.

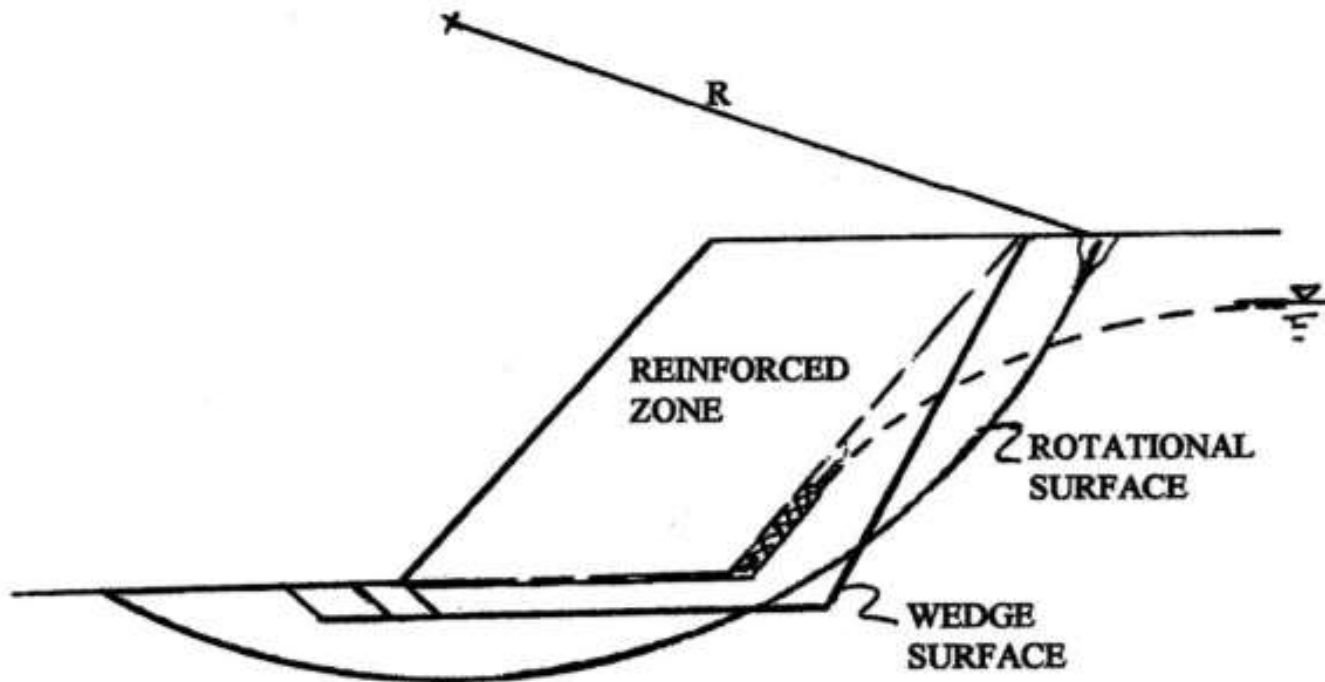
Check external stability

- Deep seated global stability
 - Evaluate potential deep-seated failure surfaces behind the reinforced soil zone:

$$\text{F.S.} = \frac{M_R}{M_D} \geq 1.3 \text{ minimum}$$

- F.S. ≥ 1.3 is recommended as a minimum and that value should be increased based on the criticality of the slope

Deep seated (global) stability analysis



Check external stability

- Local bearing failure at the toe
 - If a weak soil layer exists beneath the embankment to a limited depth D_s , the factor of safety against failure by squeezing may be calculated from:

- Where

θ = angle of slope

γ = unit weight of soil in slope

D_s = depth of soft soil beneath slope base of the embankment

H = height of slope

c_u = undrained shear strength of soft soil beneath slope

$$FS_{\text{squeezing}} = \frac{2c_u}{\gamma D_s \tan\theta} + \frac{4.14c_u}{H\gamma} \geq 1.3$$

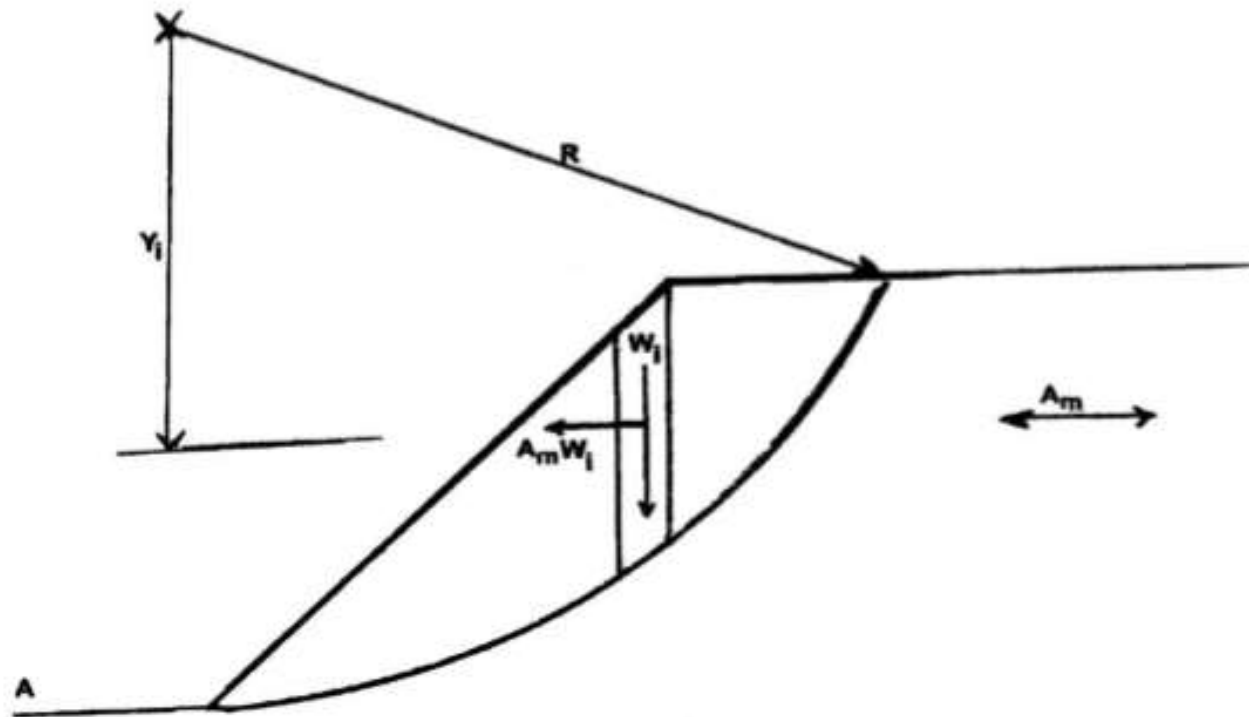
Check external stability

- Foundation settlement.
 - Determine the magnitude and rate of total and differential foundation settlements using classical geotechnical engineering procedures

Seismic stability

- Dynamic stability
 - Perform a pseudo-static type analysis using a seismic ground coefficient A , obtained from local building code and a design seismic acceleration A_m equal to $A_m = A/2$.

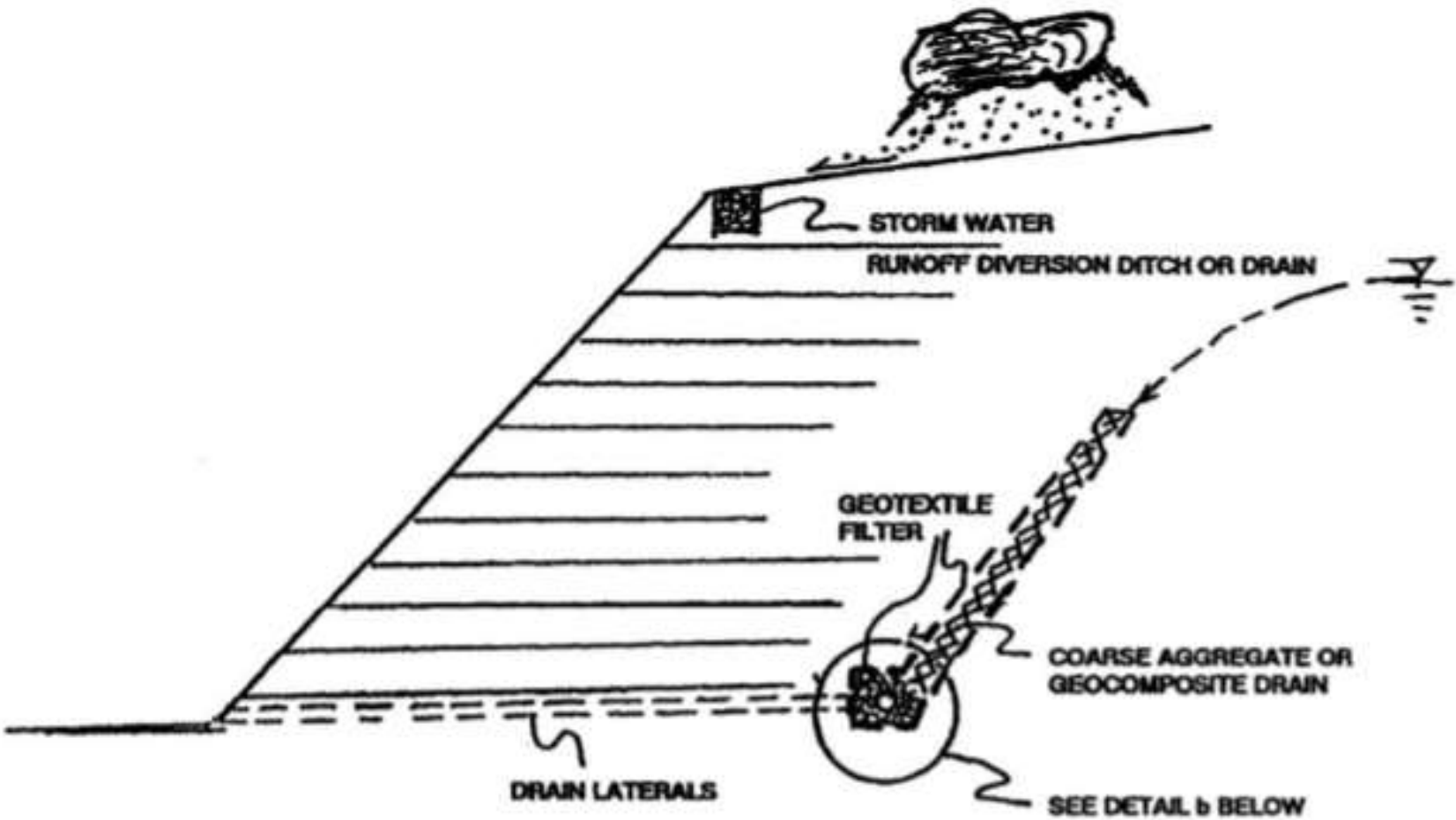
Seismic stability analysis



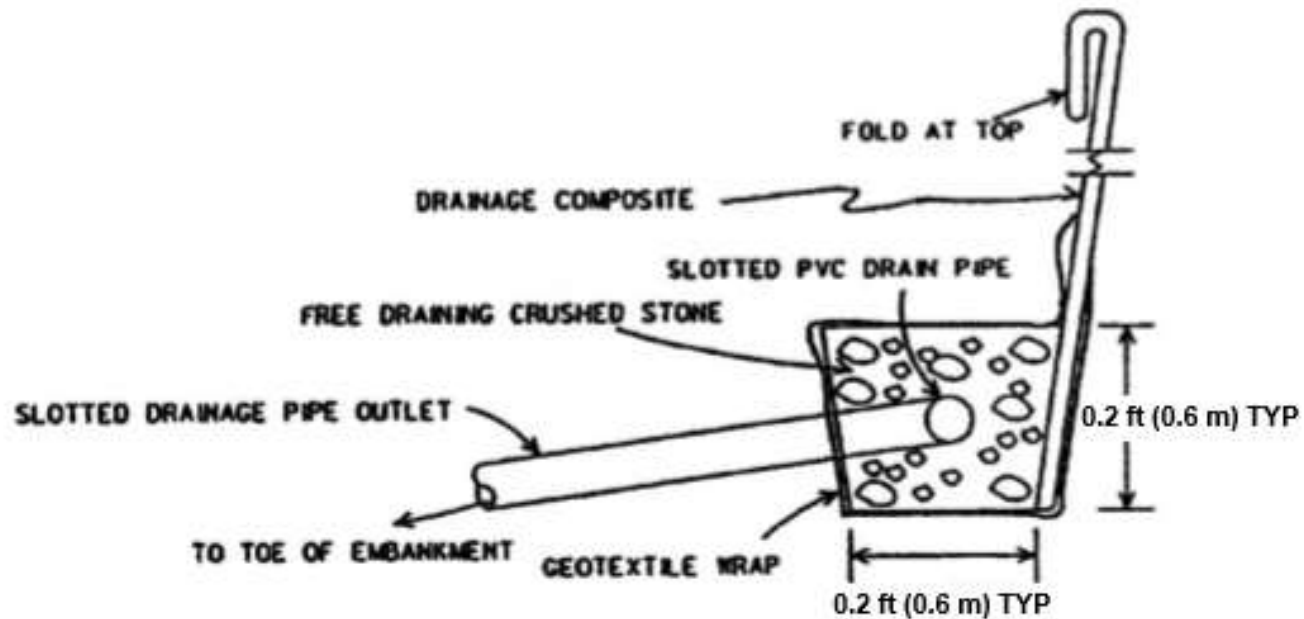
Evaluate requirements for subsurface and surface water runoff control

- Subsurface water control.
 - Design should address
 - flow rate, filtration, placement, and outlet details
 - Drains are typically placed at the rear of the reinforced zone.
 - Geocomposite drainage systems or conventional granular blanket and trench drains could be used (see Chapter 5).

Ground water and surface drainage



Typical drain details



Evaluate requirements for subsurface and surface water runoff control

- Geosynthetic drainage composites can be used in subsurface water drainage design.
- Should be designed with consideration of:
 - Geotextile filtration/clogging
 - Long-term compressive strength of polymeric core
 - Reduction of flow capacity due to intrusion of geotextile into the core
 - Long-term inflow/outflow capacity

Questions?



References

- http://www.tencate.com/pt/lam/Images/bro_mse0208_tcm31-10770.pdf
- Elias, V., Christopher, B., Berg, R. (2001). *Mechanically Stabilized Earth Walls and Reinforced Soil Slopes Design and Construction Guidelines*. FHWA-NHI-00-043. Washington, D.C. :National Highway Institute.