SOIL MECHANICS II

CIVL 311

COURSE NOTES

2012

Module 9
Design of Earth Retaining Structures

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Module 9

Design of Earth Retaining Structures

Overall Learning Objectives

- Application of Lateral Earth Pressures to Retaining Walls (Book 2 pp. 371-373)
- Types of Retaining Walls and Modes of Failure (Book 2 pp. 373 – 377)
- Stability of Gravity Retaining Walls (Book 2 pp. 377 – 385)
- Mechanically Stabilized Earth Walls (Book 2 pp. 431 – 440)
- Stability of Embedded Retaining Walls (Book 2 pp. 392 – 408)
- Excavation Support (Book 2 pp. 408 – 411, 441-445)
- Design Issues (Book 2 pp. 412-413)

Module 9 - Learning objectives

- Upon completion of this module, students will:
  - Understand how temporary and permanent retaining structures are used to prepare sites for construction of engineering works
  - Recognize the difference between external and internal stability of retaining structures
  - Be able to identify the relationship between retaining wall movement and at rest, active and passive pressures
  - Be able to undertake design of simple earth retaining structures

Sources of Information

These slides were developed based on information from the following sources:

- Foundations and Earth Retaining Structures, Muni Budhu, John Wiley & Sons, 2007
- Foundation Design - Principles and Practices 2nd Edition by D. P. Coduto, Prentice Hall, 2001
- Foundation Design and Construction, 7th Edition by M.J. Tomlinson, Prentice Hall, 2001.
- Course material by Dr. C. Haberfield from lecture on sheet pile walls, Monash University, Department of Civil Engineering, Victoria, Australia
- Soil Mechanics-Concepts and Applications by William Powrie, E &FN Spon, 1997
- Canadian Foundation Engineering Manual, 3rd Edition, Canadian Geotechnical Society, 1992.

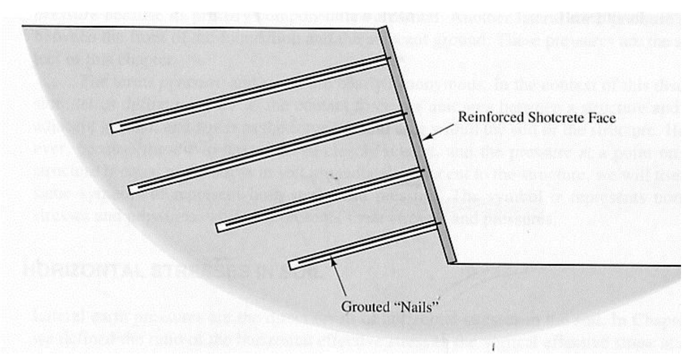
Topics

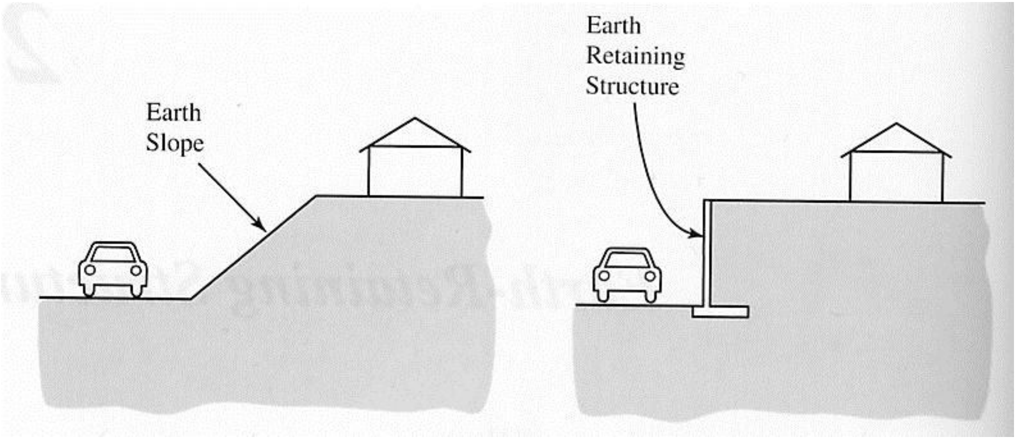
- Introduction to retaining structures
- Review of earth pressures
- Design of gravity retaining structures
- Design of embedded walls
  - Cantilever walls
  - Propped walls (single prop)
  - Propped walls (strutted or tie-backes)

Retaining Structures

Two main uses:

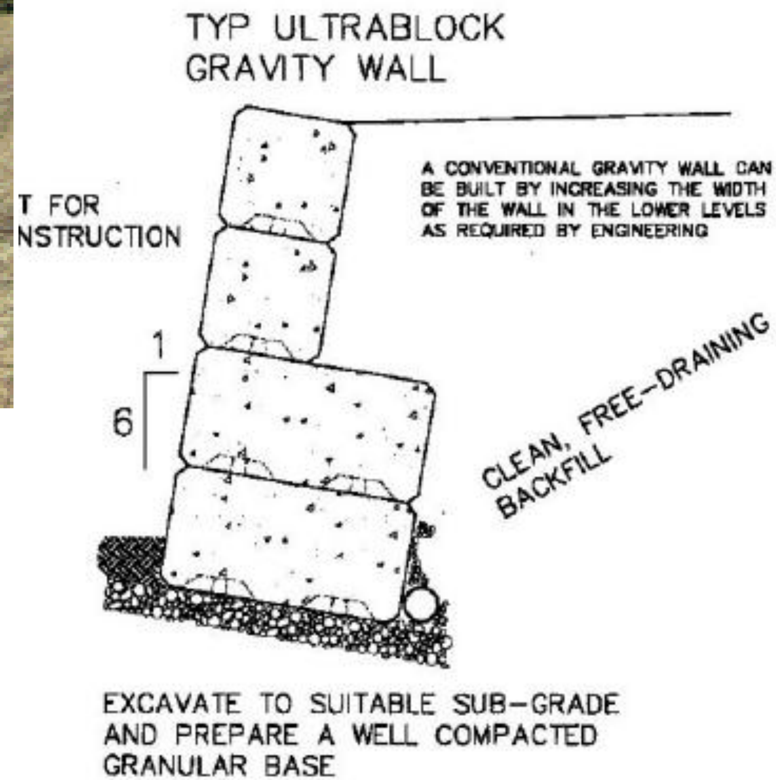
- Provide useable horizontal space
  - permanent
- Support temporary excavations in confined areas





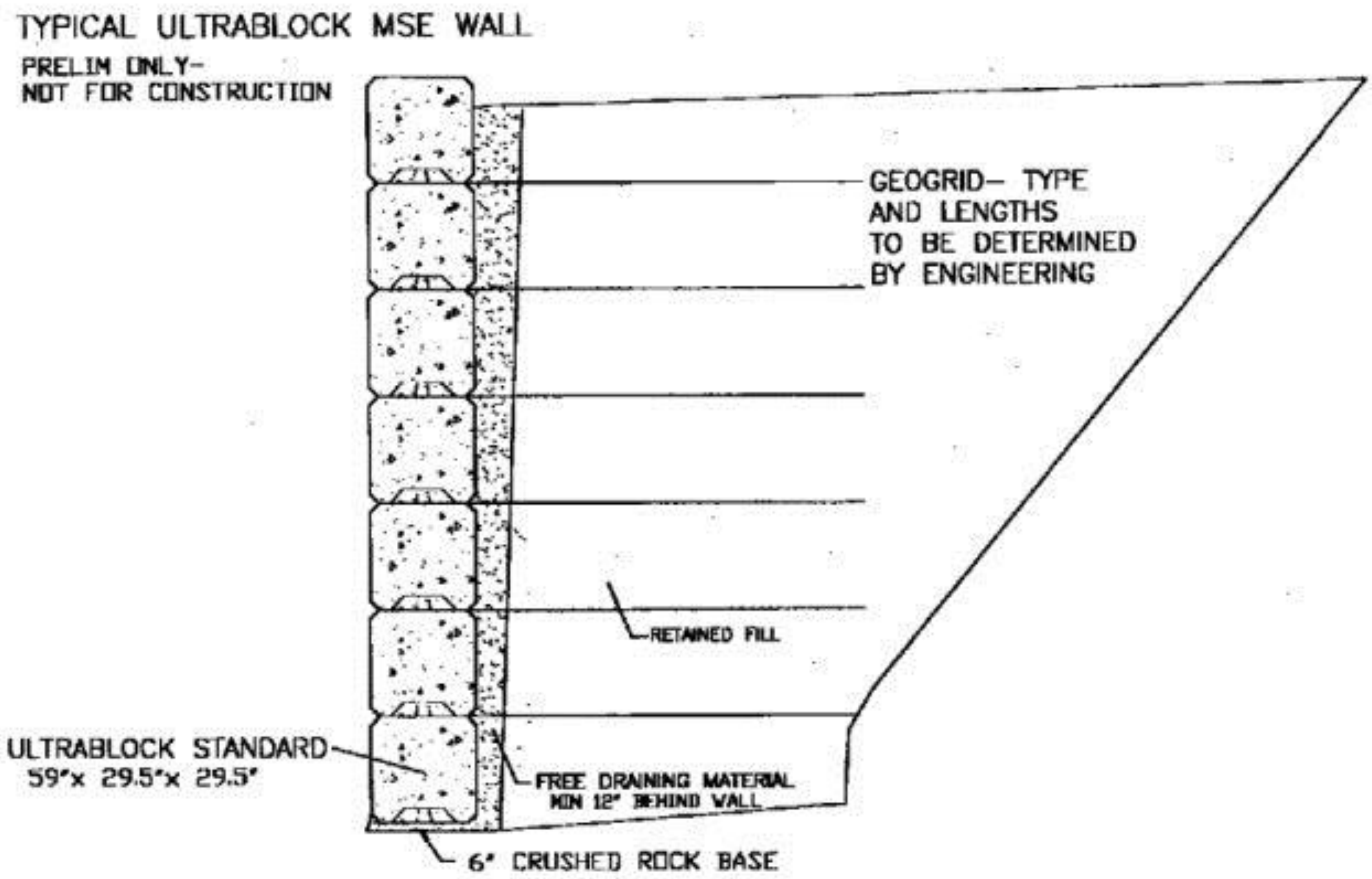
Classification of Walls

- Rigid
  - Gravity
    - Mass concrete, masonry
    - Mechanically stabilized earth (MSE) walls
  - Semi-Gravity
    - Cantilever concrete
  - Flexible or Embedded walls
    - Sheet pile, diaphragm, contiguous pile

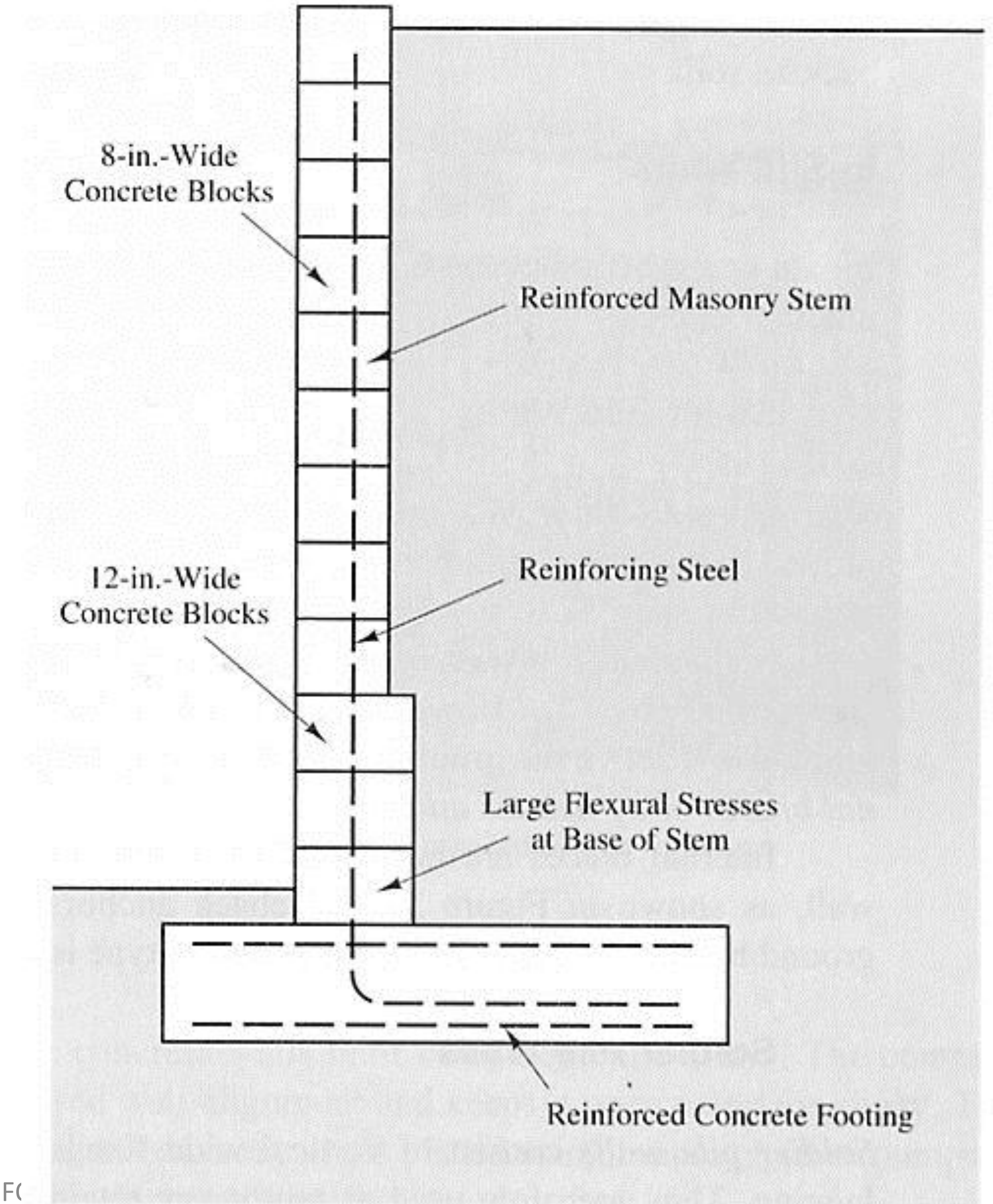


Lock Block
Gravity Retaining Wall

Mechanically Stabilized Earth (MSE) (Gravity wall)

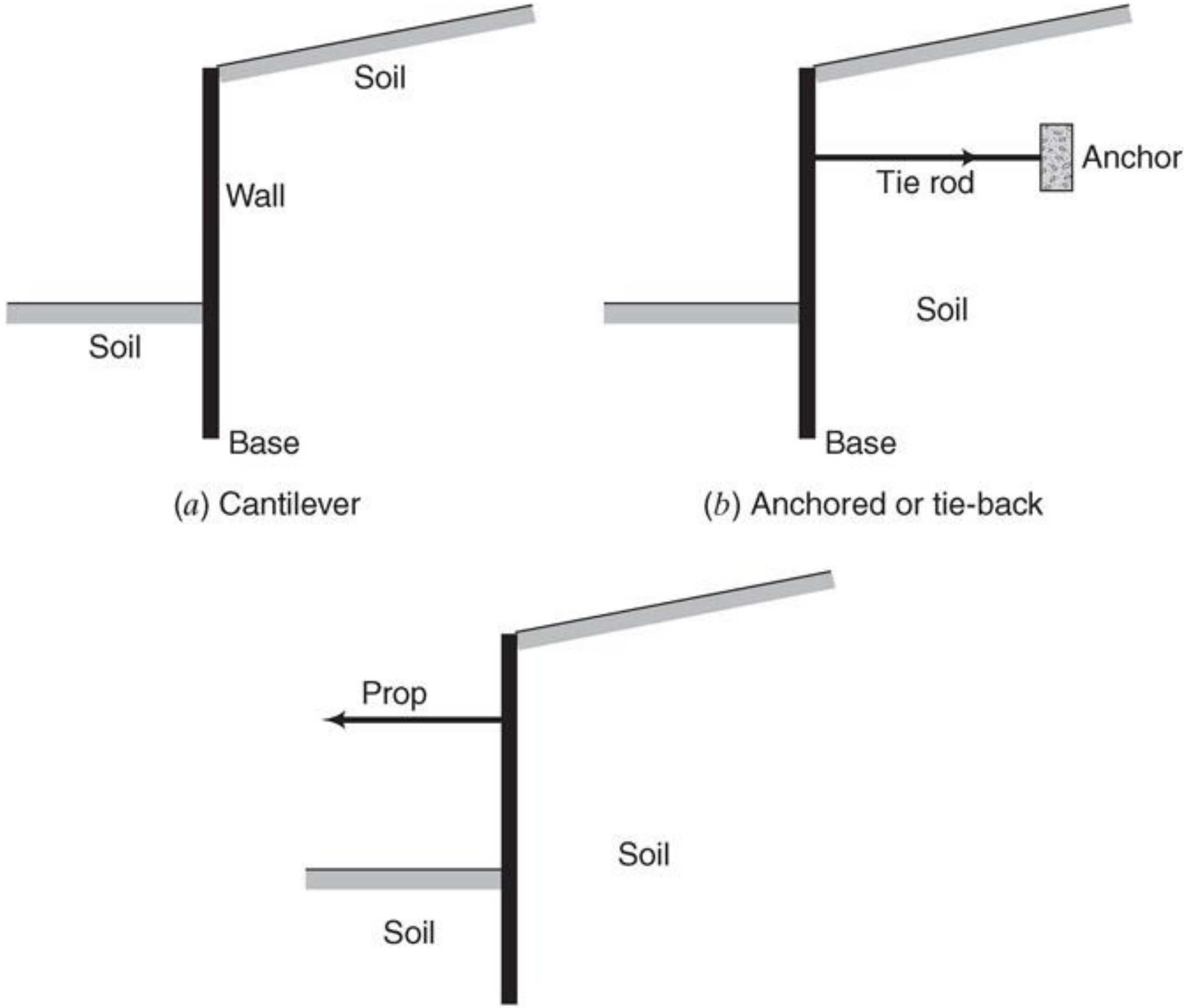


Cantilever Concrete Retaining Wall (Gravity)



Embedded walls

- In saturated granular soils, waterfront edges, etc. the soil will not stand temporarily unsupported and support must be provided continuously during the construction process.
- For these conditions use embedded walls such as sheet piles, diaphragm (slurry) walls, and contiguous pile walls.
- Can be temporary <u>or</u> permanent



(a) Cantilever

(b) Anchored or tie-back

(c) Propped

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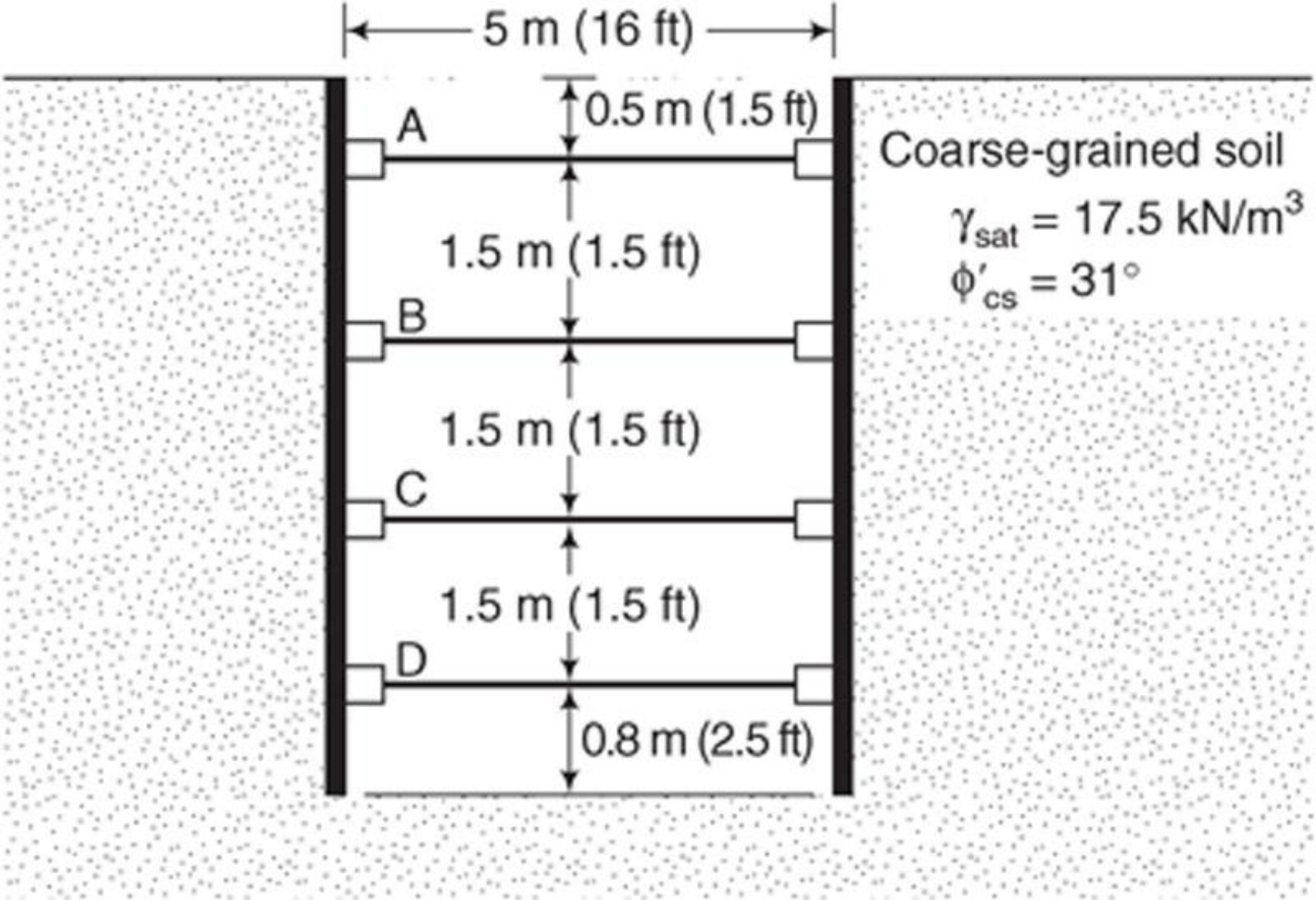
5 m (16 ft)
0.5 m (1.5 ft)
A
Coarse-grained soil
γ_{sat} = 17.5 kN/m^3
ϕ'_{cs} = 31°
1.5 m (1.5 ft)
B
1.5 m (1.5 ft)
C
1.5 m (1.5 ft)
D
0.8 m (2.5 ft)

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Limit states for retaining structures

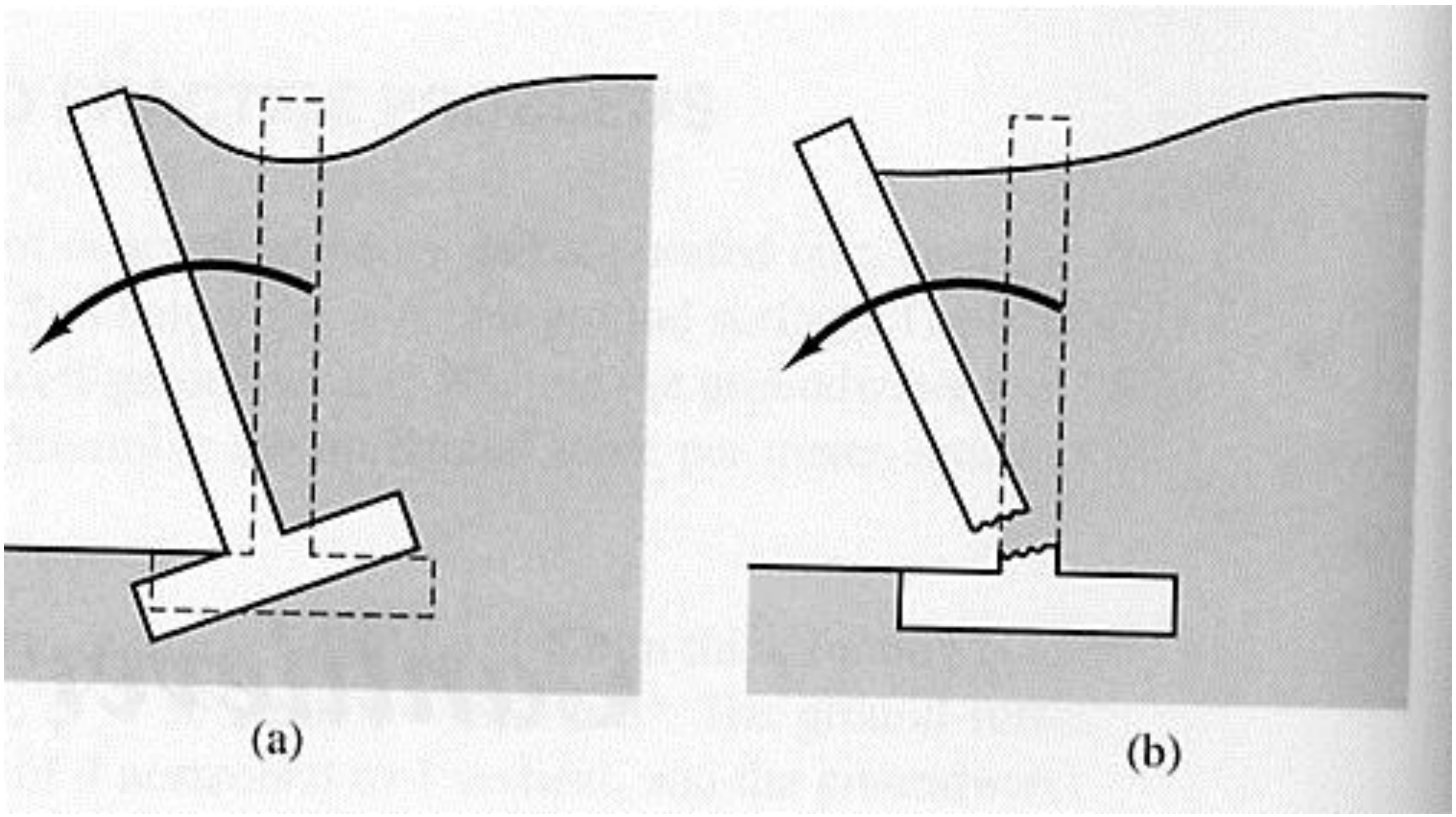
- loss of overall stability
  - failure of a structural element such as a wall, anchor, waler or strut or failure of the connection between such elements;
- combined failure in ground and in structural element
  - movements of the retaining structure which may cause collapse or affect the appearance or efficient use of the structure, nearby structures or services which rely on it;
- unacceptable leakage through or beneath the wall;
- unacceptable transport of soil grains through or beneath the wall;
- unacceptable change to the flow of groundwater.

Design of retaining walls

- Global or external stability
  - Check sliding, overturning resistance and bearing capacity of the wall structure (including retained soil) and surrounding area.
  - Could include assessing overall slope stability including several walls if the slope is benched.
- Internal stability
  - Ensure that the individual components of the retaining structure are adequately designed - may include structural design of any steel, concrete or geosynthetics components, capacity and filtration capability of any seepage control measures, etc.

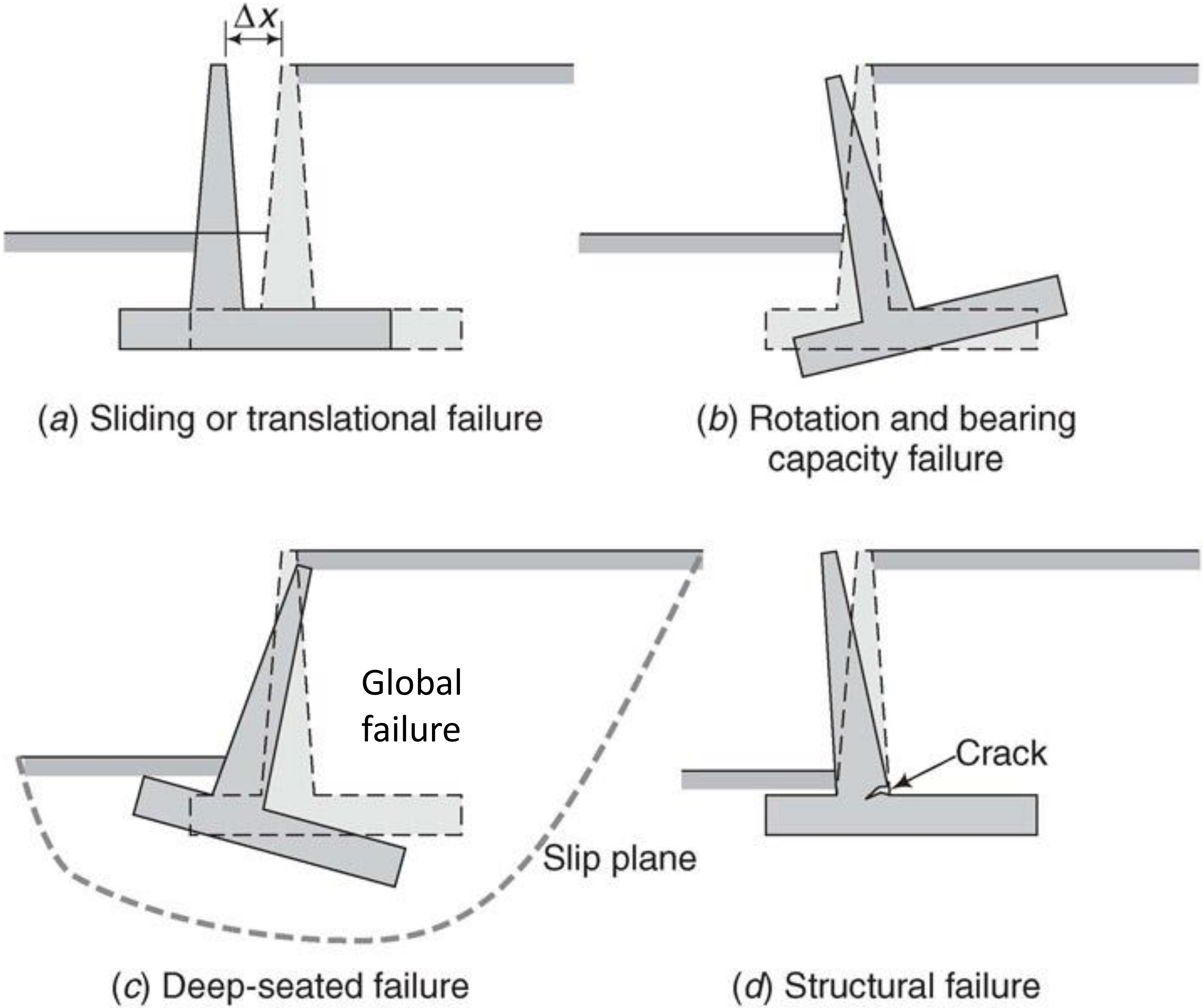
Inadequate external stability

Inadequate internal stability



Gravity and semi-gravity retaining structures

- Limit states
  - bearing resistance failure of the soil below the base;
  - failure by sliding at the base of the wall;
  - failure by toppling of the wall.


Δx
(a) Sliding or translational failure
(b) Rotation and bearing capacity failure
Global failure
Crack
Slip plane
(c) Deep-seated failure
(d) Structural failure

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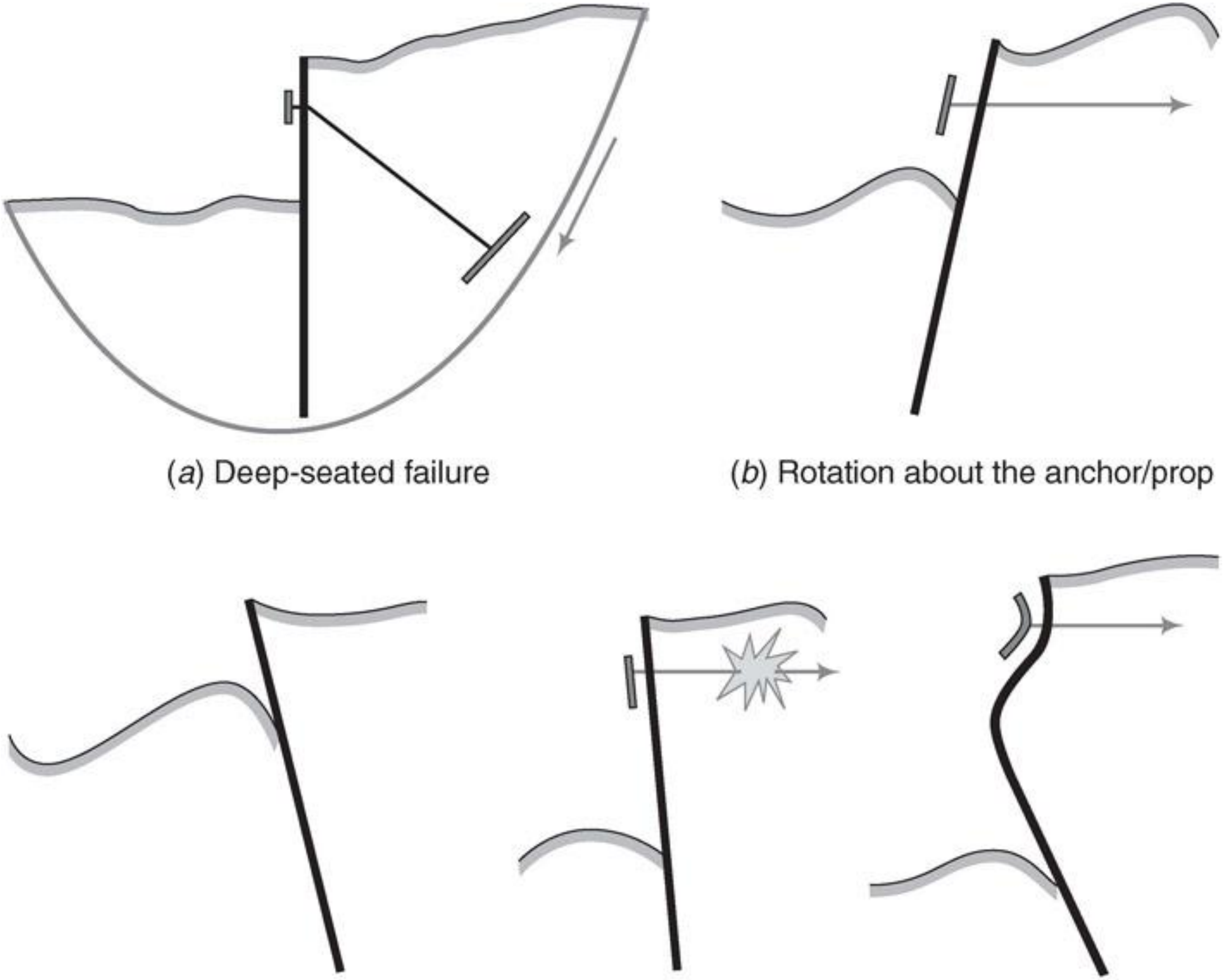
Embedded retaining structures

- Limit states
  - failure by rotation or translation of the wall or parts thereof
  - failure by lack of vertical equilibrium of the wall



(*a*) Deep-seated failure
(*b*) Rotation about the anchor/prop
(*c*) Rotation near base
(*d*) Failure of anchor/prop
(*e*) Failure by bending

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Retaining Walls
Design Considerations

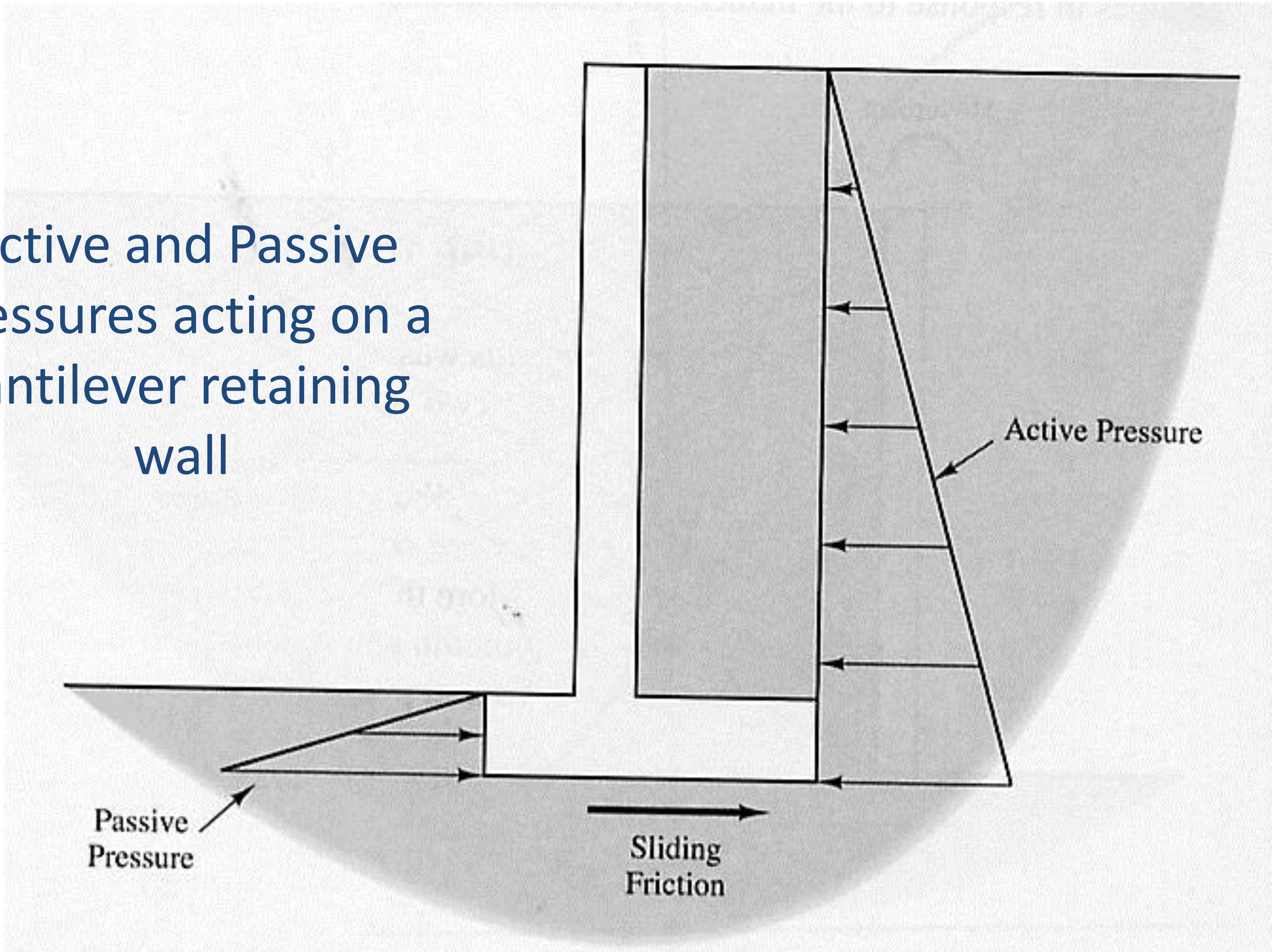
- Soil type and properties
- Possible failure mechanisms – undrained, drained, deep seated, failure of face, bearing failure, sliding, overturning, anchorage pull-out, etc.
- Ground water regime
- Allowable displacements
- Land-use-access restrictions – available working space to build the wall, property line restrictions, etc.
- Loading - surcharge, earthquake, water, etc.

Design of Gravity retaining walls

Design of gravity retaining walls

- Must consider external stability and internal stability
- External failure modes are:
  - Sliding
  - Overturning
  - Bearing capacity
  - Deep seated shear (or slope) failure
  - Excessive settlement
- Resultant normal force on base should be within the middle third of the footing

Active and Passive pressures acting on a cantilever retaining wall



Pressure coefficients vary with

- Shear strength parameters of soil
  - ϕ' for effective stress analysis
  - s_u for total stress analysis of saturated soils
- Geometry (e.g. inclined surface)
- Wall friction

Analytical solutions, tables or charts are available for most common variations

Additional considerations

- Water pressures
  - If they are not hydrostatic then you need to draw a flow net to estimate distribution of water pressures.
- Surcharges near the wall (Budhu 10.3)
- Compaction pressures during construction
  - Compaction tends to increase the lateral pressure. May cause distress to stem of cantilever walls.
- Potential for future excavation in front of wall (effect on passive resistance?)

What about water ?

- Water has a huge influence => drainage is very important
- If uncertain of drainage, must design for worst case
- Use effective stresses below water table
- Don’t forget to allow for any net horizontal water force (will act all the way down)

Effect of Groundwater

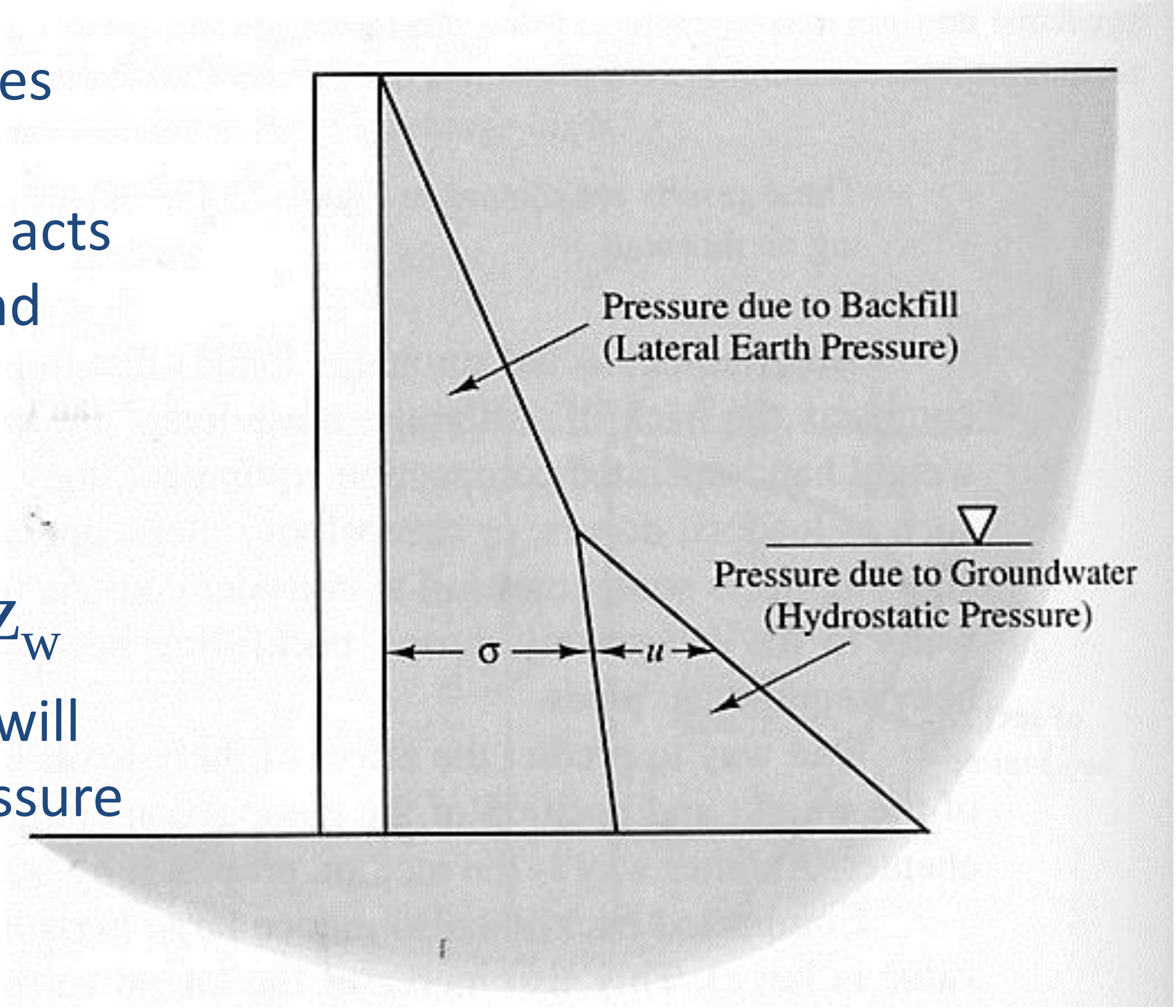
Rankine pressures

$\sigma'_x = K_a \sigma'_z$

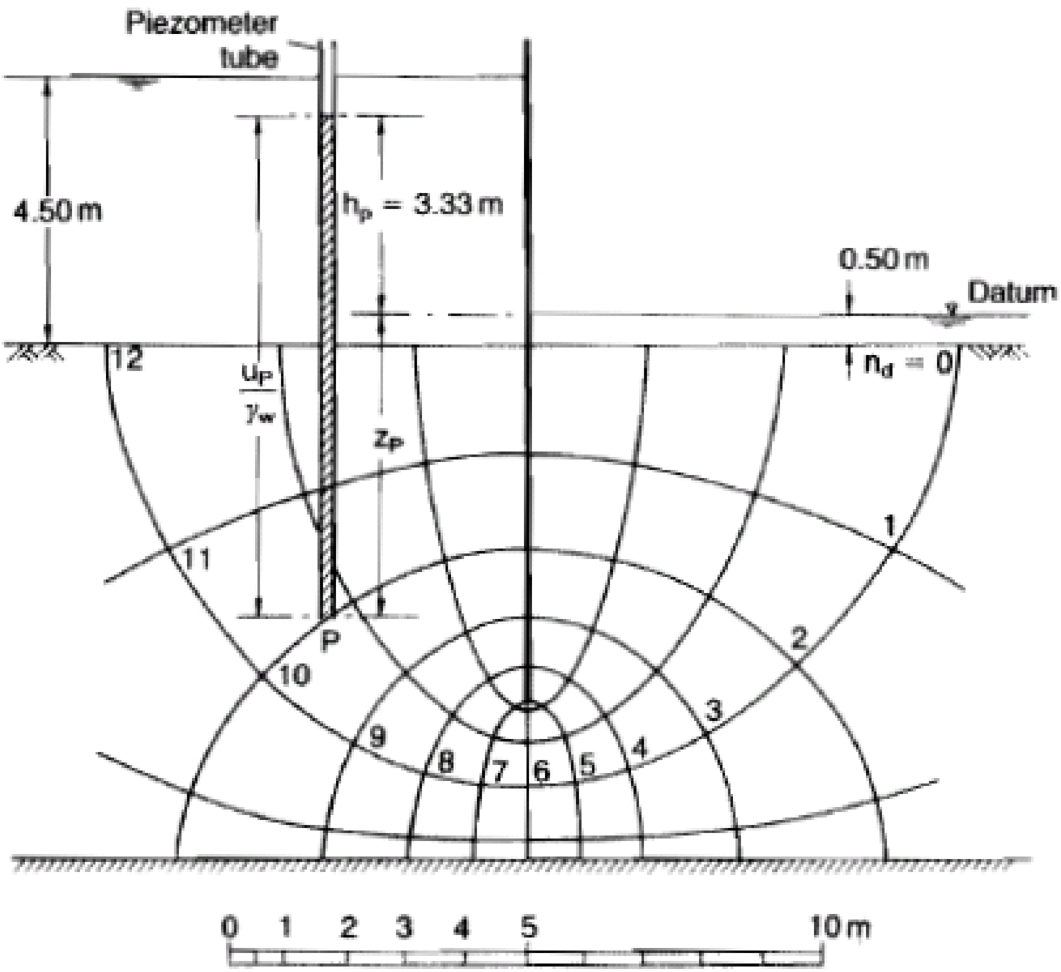
Lateral pressure acts parallel to ground surface

$$\sigma'_z = \sigma_z - u$$
$$= \gamma_t z - \gamma_w z_w$$

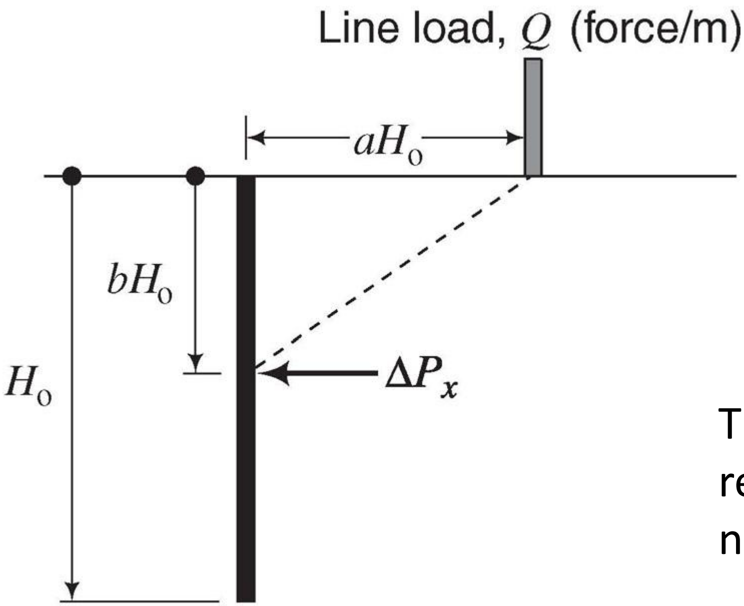
NB. Seepage effects will change the pore pressure



Flow nets to define pore pressure

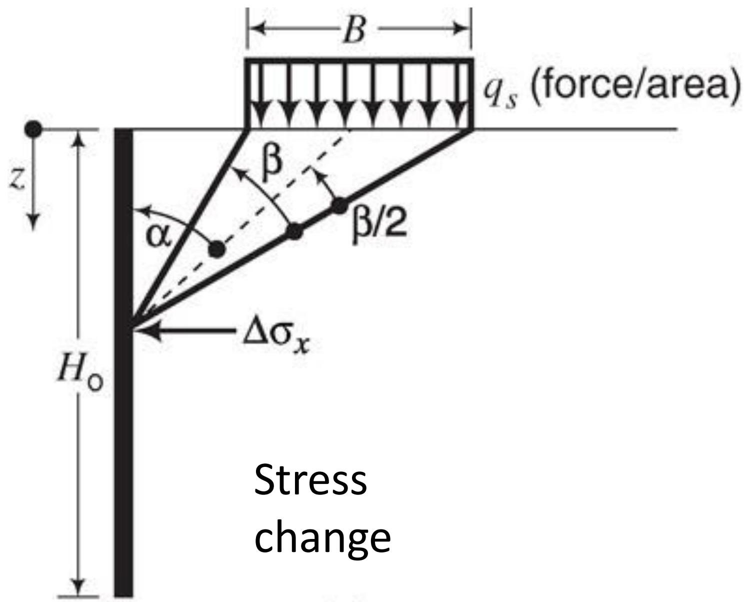


Use linear approximation for wide excavations



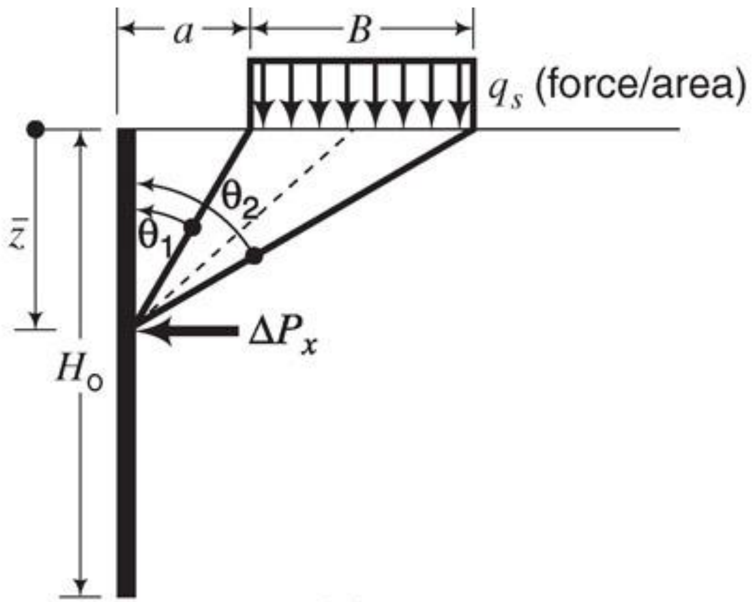
Lateralstresses from surface loads

Theory gives equation for stress increase. The resulting increase in thrust can be found numerically.



Stress change

(a)



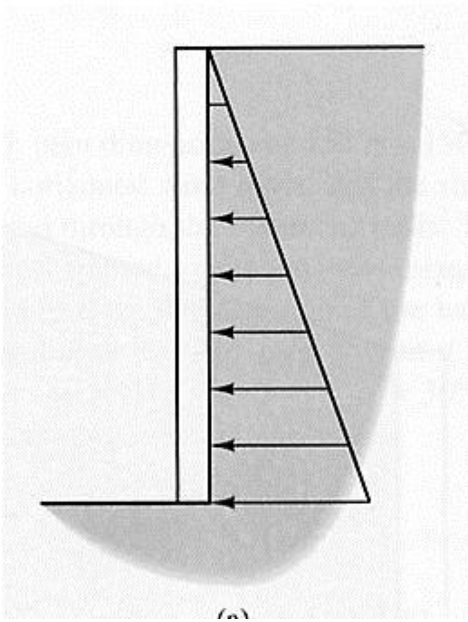
(b)

Estimation of wall pressures

- Wall Pressures based on theory
  - Rankine
  - Coulomb

Know basic assumptions and understand difference between these. See Module 4.

- Presumptive Lateral Pressures
  - Equivalent Fluid Method – Canadian Foundation Engineering Manual, 24.11
  - Presumptive Lateral Pressures – Coduto, Section 23.5



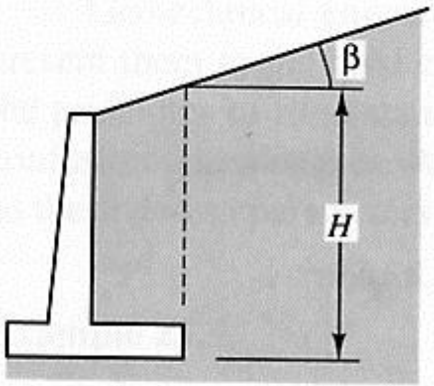
$$P_a/b = \frac{G_h H^2}{2}$$

$$G_h = \gamma K_a$$

TABLE 23.4 PRESUMPTIVE LATERAL EARTH PRESSURES FOR WALLS WITH LEVEL BACKFILLS (Adapted from ASCE, 1996a and ICC, 2000)

Unified Classification and Description of Retained Soils[a,b]		Equivalent Fluid Density, G_h — Active Condition (lb/ft³)	Active Condition (kN/m³)	At-Rest Condition (lb/ft³)	At-Rest Condition (kN/m³)
GW	Well-graded clean gravels and sandy gravels	35	5.5	60	9.4
GP	Poorly-graded clean gravels and sandy gravels	35	5.5	60	9.4
GM GW-GM GP-GM	Silty gravels	35	5.5	60	9.4
GC GW-GC GP-GC GC-GM	Clayey gravels	45	7.1	60	9.4
SW	Well-graded clean sands and gravelly sands	35	5.5	60	9.5
SP	Poorly-graded clean sands and gravelly sands	35	5.5	60	9.5
SM SW-SM SP-SM	Silty sands	45	7.1	60	9.5
SC SW-SC SP-SC SC-SM	Clayey sands	85	13.4	100	15.7
ML	Inorganic silts with low plasticity	85	13.4	100	15.7
CL-ML	Inorganic silty clays with low plasticity	85	13.4	100	15.7
CL	Inorganic clays with low plasticity	100	15.7	100	15.7
OL	Organic silts and clays with low plasticity	Not suitable unless evaluated by a geotechnical engineer.			
MH	Inorganic silts with low plasticity				
CH	Inorganic clays with high plasticity				
OH	Organic silts and clays with high plasticity				

[a]The retained soils are those in the zone above a plane inclined upward at a slope of 1:1 from the bottom rear of the footing. If more than one soil type is present in this zone, the soil lateral load shall be the highest for any of those soils.
[b]The use of this table is limited to walls no more than 2.5 m (8 ft) tall.



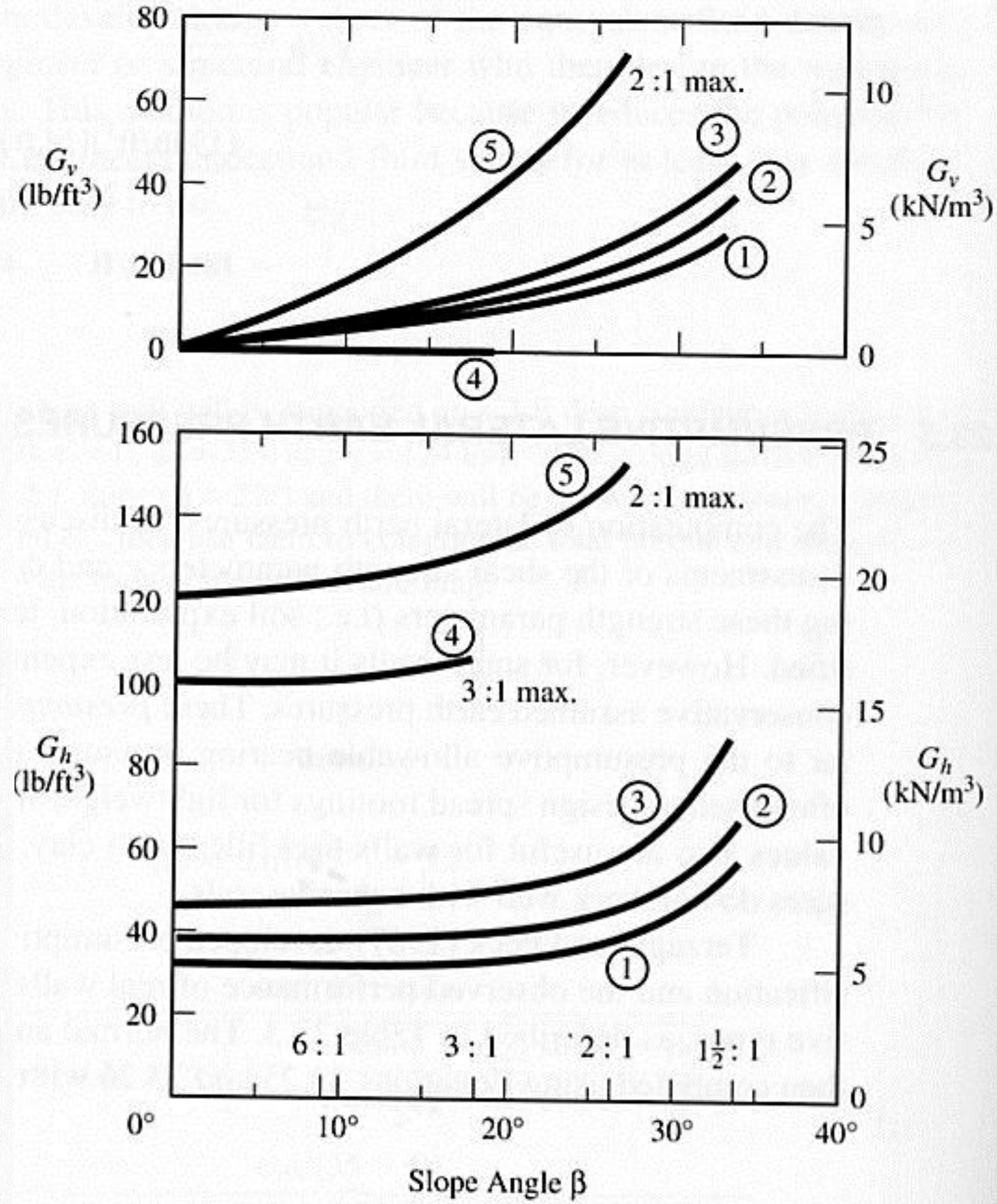


TABLE 23.3 CLASSIFICATION OF SOIL TYPES FOR TERZAGHI & PECK'S METHOD (Adapted from Terzaghi and Peck, 1967).

Soil Type	Description
1	Coarse grained soil without admixture of fine soil particles, very permeable (i.e., clean sand or gravel).
2	Coarse-grained soil of low permeability due to admixture of particles of silt size.
3	Residual soil with stones, fine silty sand, and granular materials with conspicuous clay content.
4	Very soft clay, organic silts, or silty clays.
5	Medium or stiff clay, deposited in chunks and protected in such a way that a negligible amount of water enters the spaces between the chunks during floods or heavy rains. If this condition cannot be satisfied, the clay should not be used as backfill material. With increasing stiffness of the clay, danger to the wall due to infiltration of water increases rapidly.

Typical design criteria for external stability of gravity walls

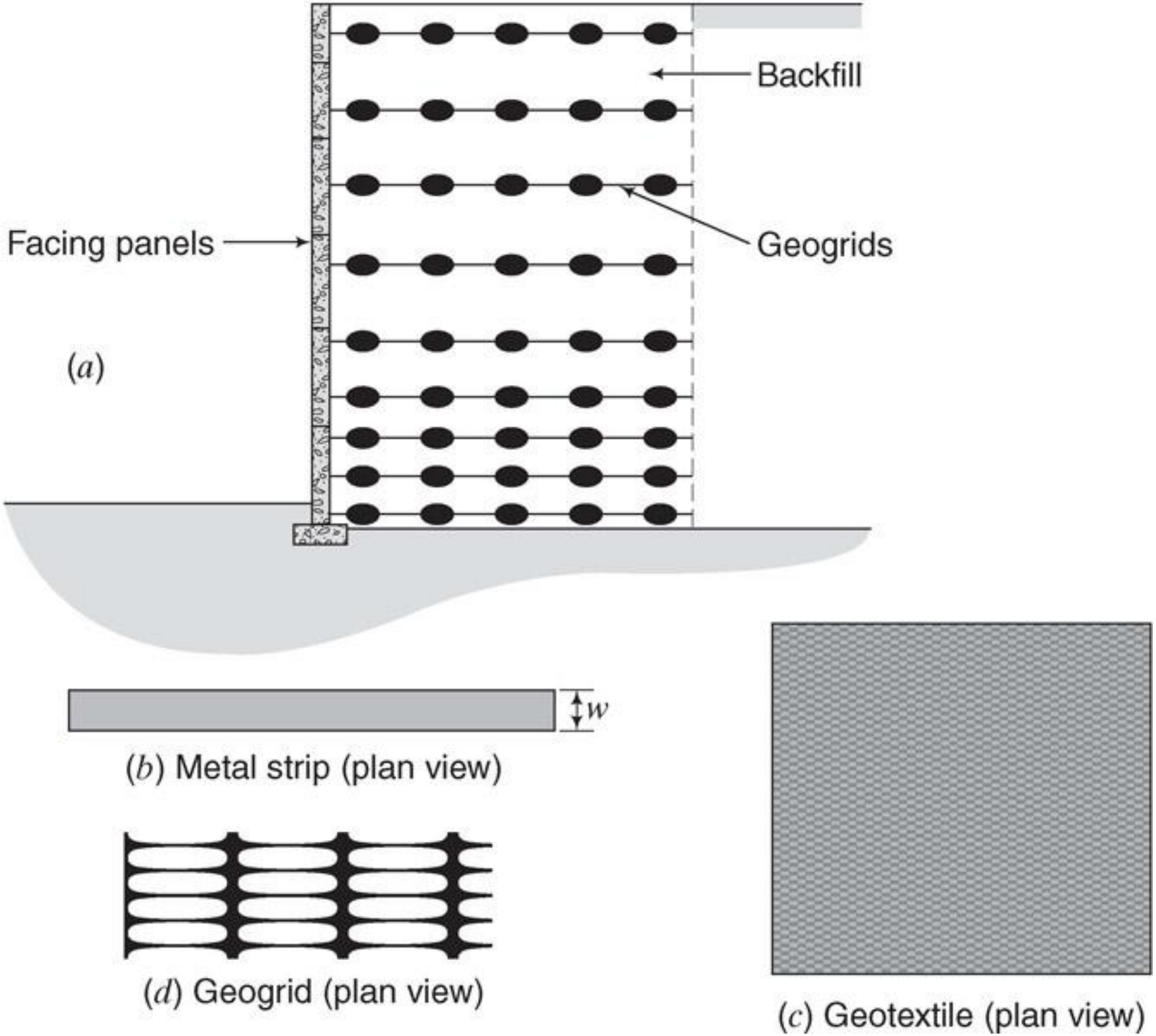
- Factor of safety against sliding = 1.5 for walls based on granular soils
  - If on fine grained soils then use F=2.0
- Factor of safety against overturning = 1.5 for walls on granular soils, 2.0 for walls on fine grained soils
- Resultant should pass through middle third of base
- Factor of safety against bearing capacity failure should be as for shallow foundations with an applied moment

Design for internal stability

- Check that individual components or combinations of components of wall do not fail
  - Structural design of concrete, steel or masonry
  - Consideration of soil structure interaction
  - Design of components of composite walls

Internal stability of composite walls

- Reinforcement varies - steel strips, plastic geotextile, wire mesh,
- Design requires that:
  - Reinforcement does not rupture
  - Reinforcement does not pull out
  - Connection of facing to reinforcement does not fail
- Design methods depend on wall system, particularly strain compatibility of soil and reinforcement
- Design guidelines – FHWA, AASHTO, GEO(HK)


Backfill
Geogrids
Facing panels
(a)
w
(b) Metal strip (plan view)
(d) Geogrid (plan view)
(c) Geotextile (plan view)

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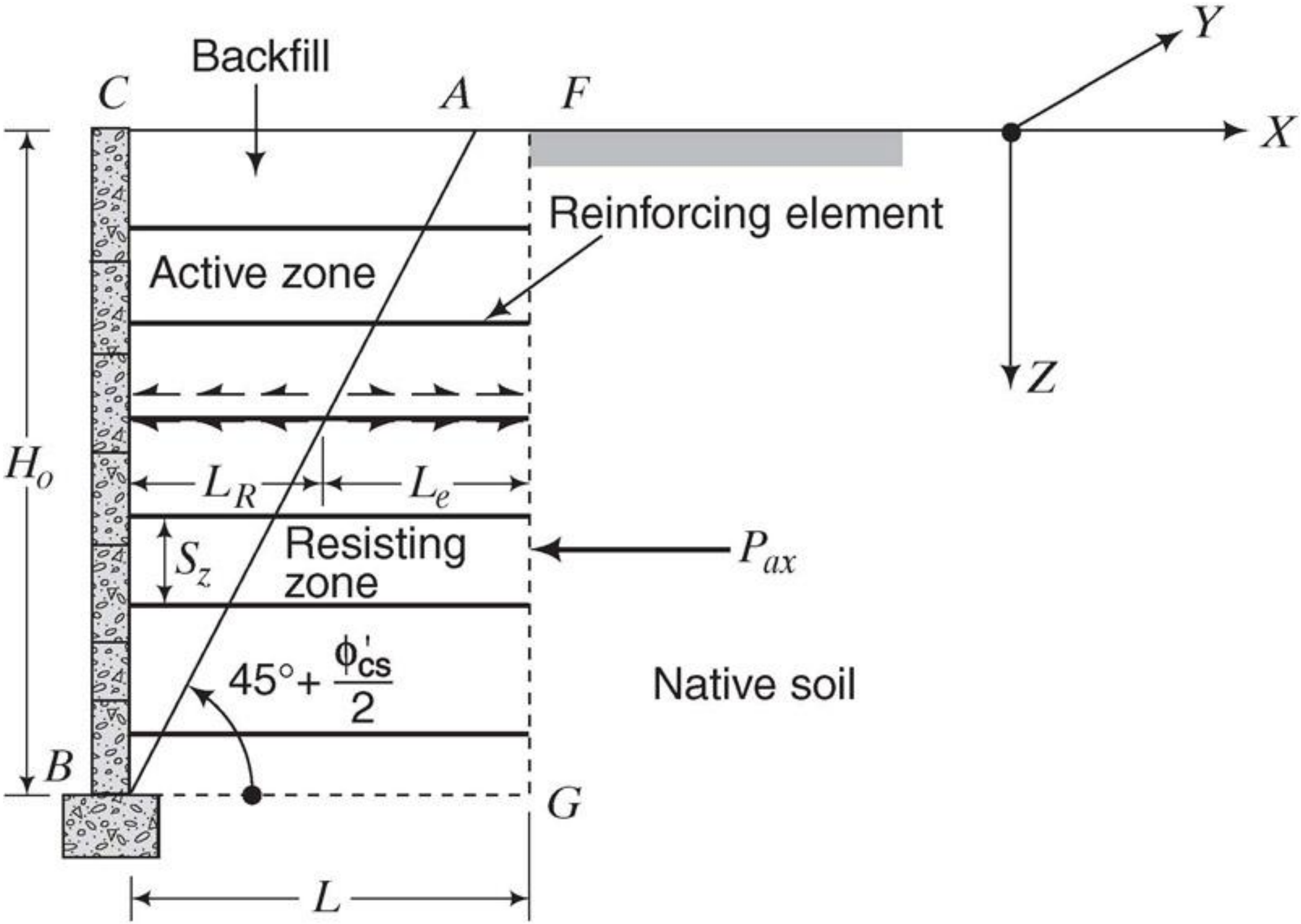

Backfill
C
A
F
Y
X
Z
Reinforcing element
Active zone
H_o
L_R
L_e
S_z
Resisting zone
P_{ax}
$45° + \frac{\phi'_{cs}}{2}$
Native soil
B
G
L

Conclusions on gravity retaining structures

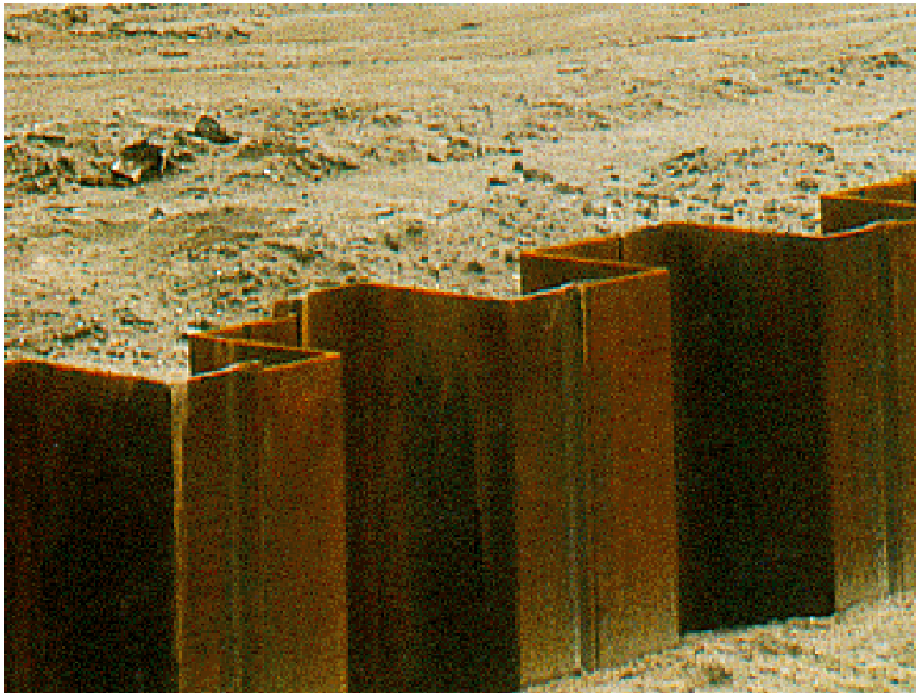
- Design requires consideration of both external and internal stability
- There is strong relationship between ground movements and wall pressures
- For gravity walls, it is appropriate to design for active conditions as small movements result in active pressures behind wall
- Composite walls require consideration of strain compatibility of wall components and soil

Embedded walls

Embedded walls

- Construction
- Analysis and design
  - Cantilever
  - Single prop
  - Multiple props
- Anchors and deadmen
- Failure

Sheet piles



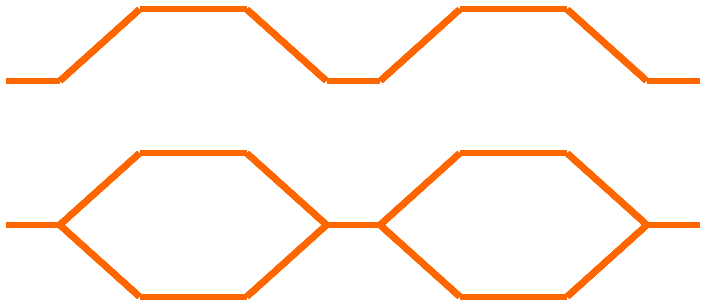
Z piles

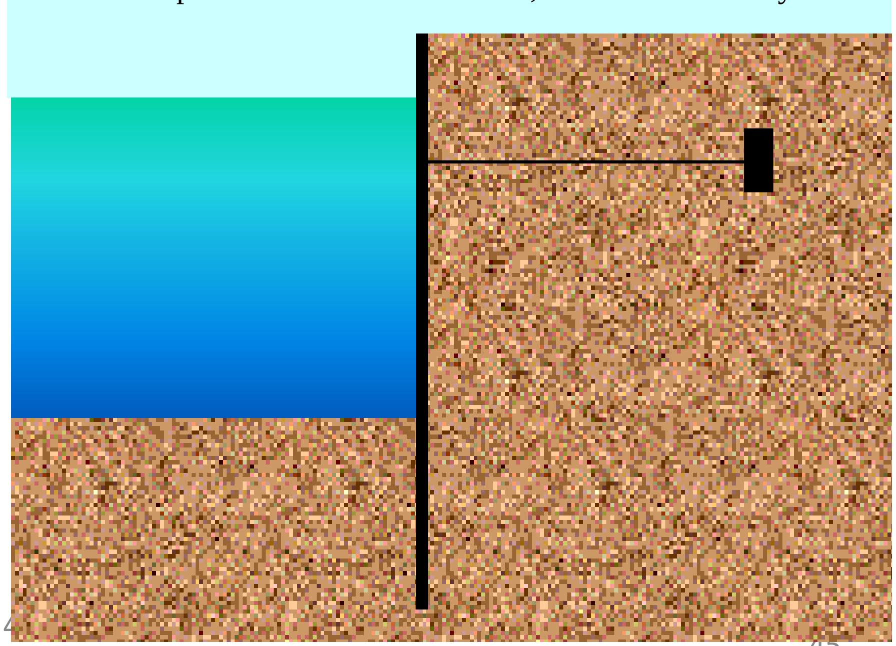
Interlocking steel sections

Adapted from Dr. C. Haberfield, Monash University

Sheet piles - what, where and when

- Flexible wall of interlocking steel plates - single or double
- top may be supported by one or more anchors and ties
- primarily used for wharves & temporary excavations

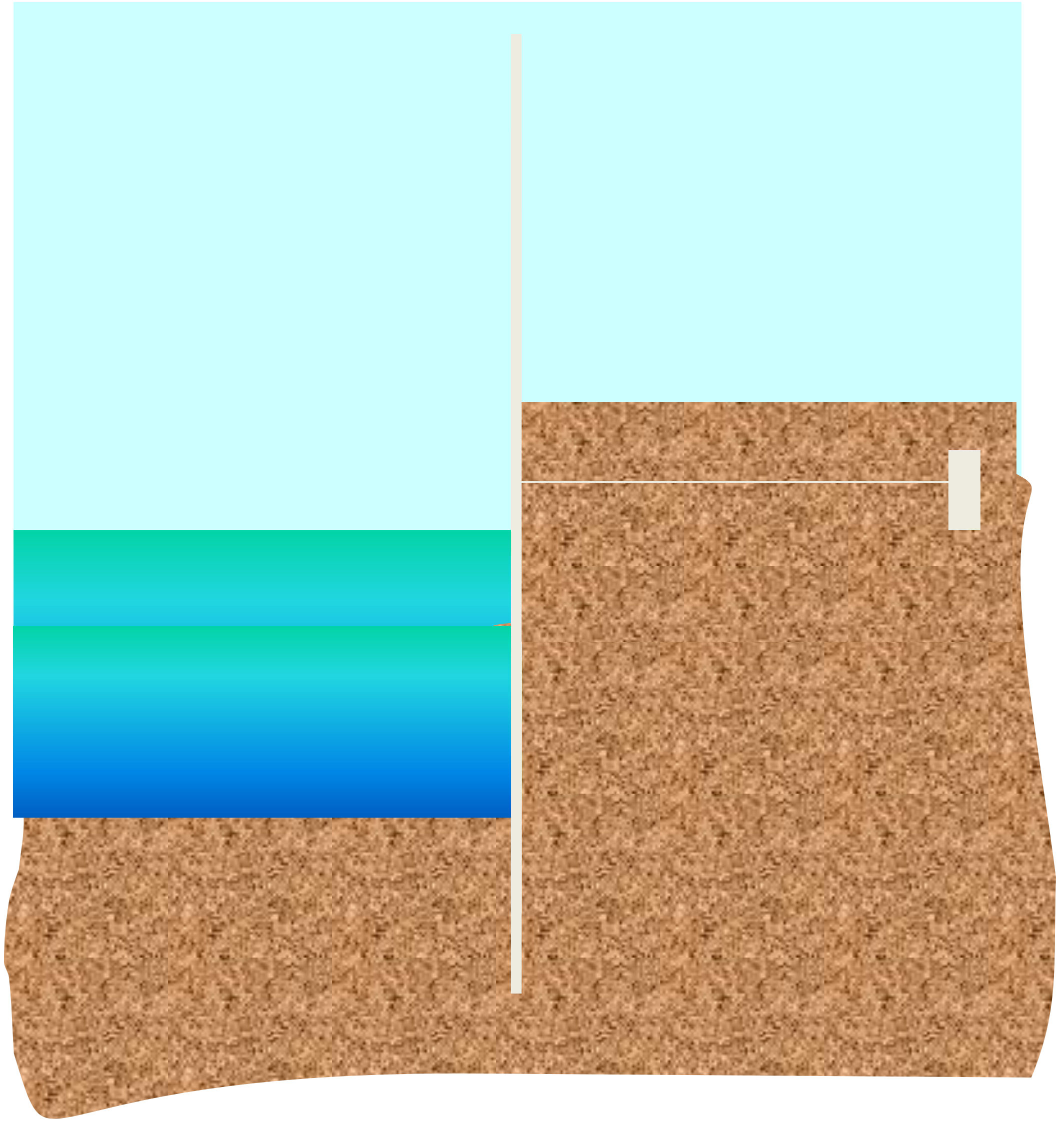




Adapted from Dr. C. Haberfield, Monash University

Construction

- Drive piles into ground
- Place deadmen and connect ties
- Excavate or fill as appropriate



Adapted from Dr. C. Haberfield, Monash University

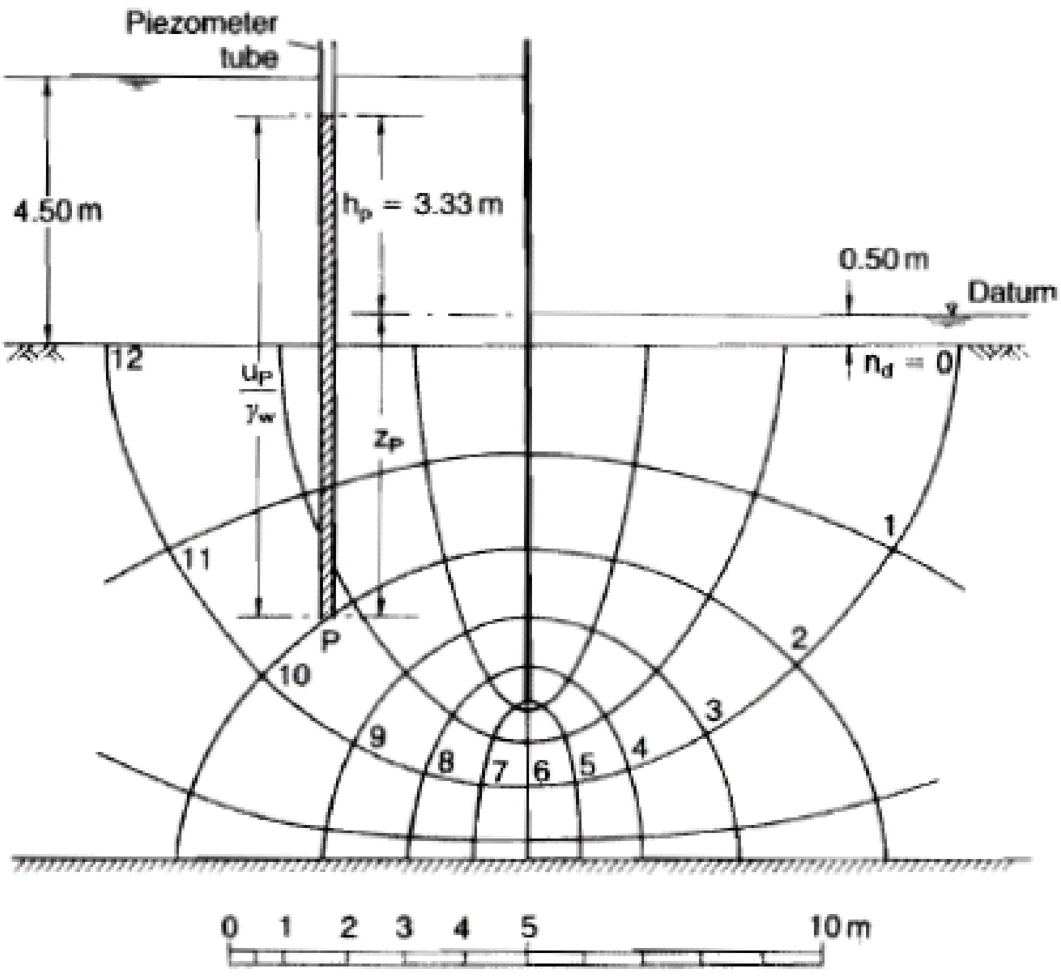
Limit states –embedded walls

- failure by rotation or translation of the wall or parts thereof
- failure by lack of vertical equilibrium of the wall
- Failure of wall element in bending

Estimation of wall pressures for embedded walls

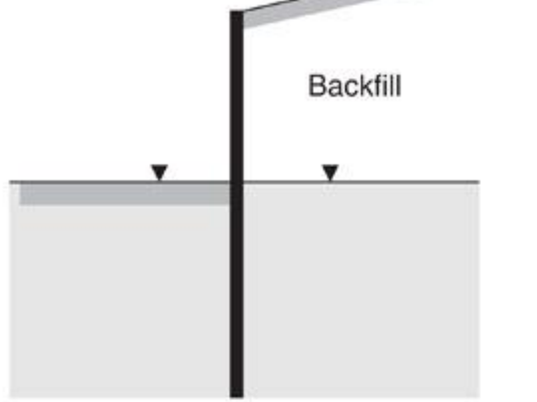
- Cantilever walls and propped walls with single prop
  - Classical lateral earth pressures
  - Several methods available (all approximate)
    - Free earth support
    - Fixed earth support
    - Rowe's moment-reduction method
    - Numerical methods
- Propped walls – multiple props
  - Empirical earth pressure envelopes

Flow nets to define pore pressure



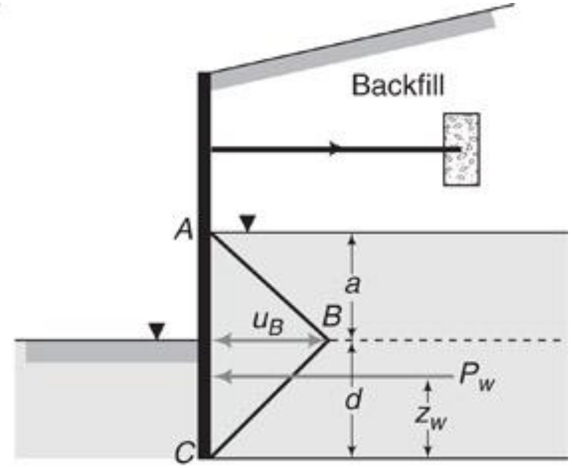
Use linear approximation for wide excavations

Approximate method to estimate pore pressures

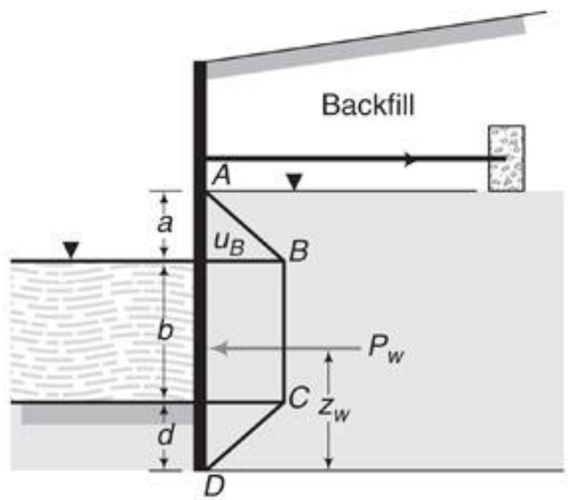


Resultant hydrostatic force is zero

(*a*) Water level on both sides equal



(*b*) Water level in backfill and in front of wall different

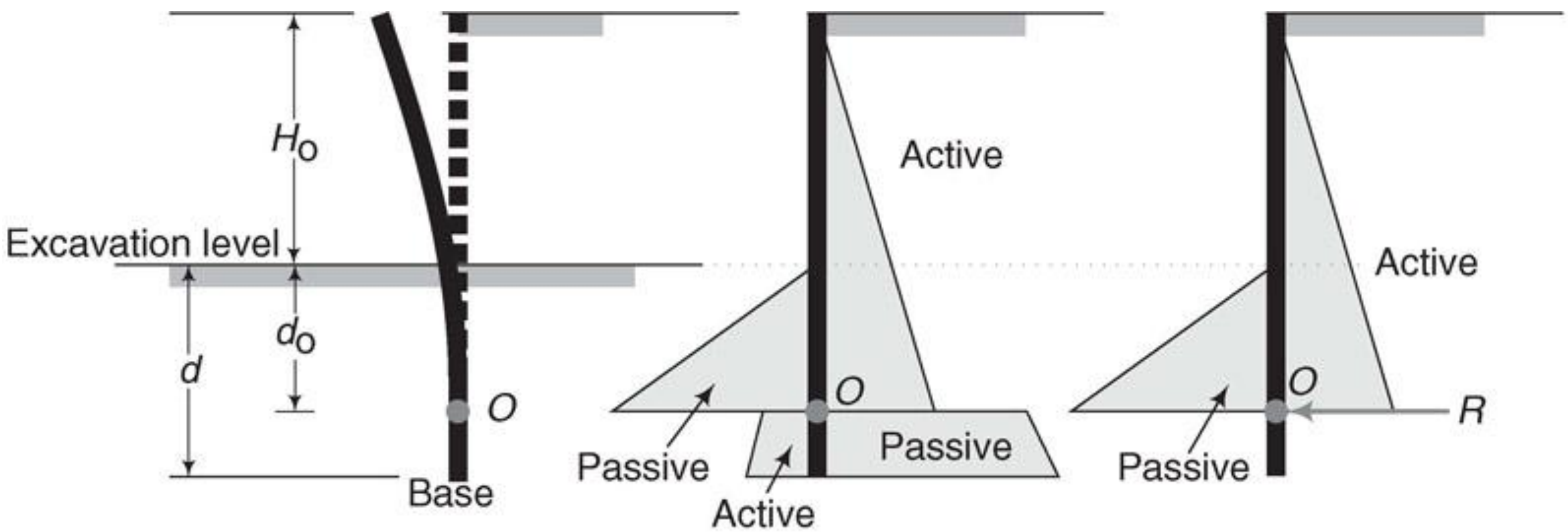


(*c*) Wall supports water in front of it and water level in backfill greater than water level in front of wall

Unpropped Embedded Retaining Walls

- Rely entirely on passive resistance in front of the wall
- Collapse mechanism - rigid body rotation about a horizontal axis within the plane of the wall at some depth d_o below formation level
- In order for the toe to be fixed, the pivot point must be some distance above the tip of the wall
- This assumes structural failure does not occur

Cantilever Walls



(a) Cantilever wall (b) Pressure distribution (c) Approximation of pressure distribution

After Budhu (2008)

Fixed earth support method

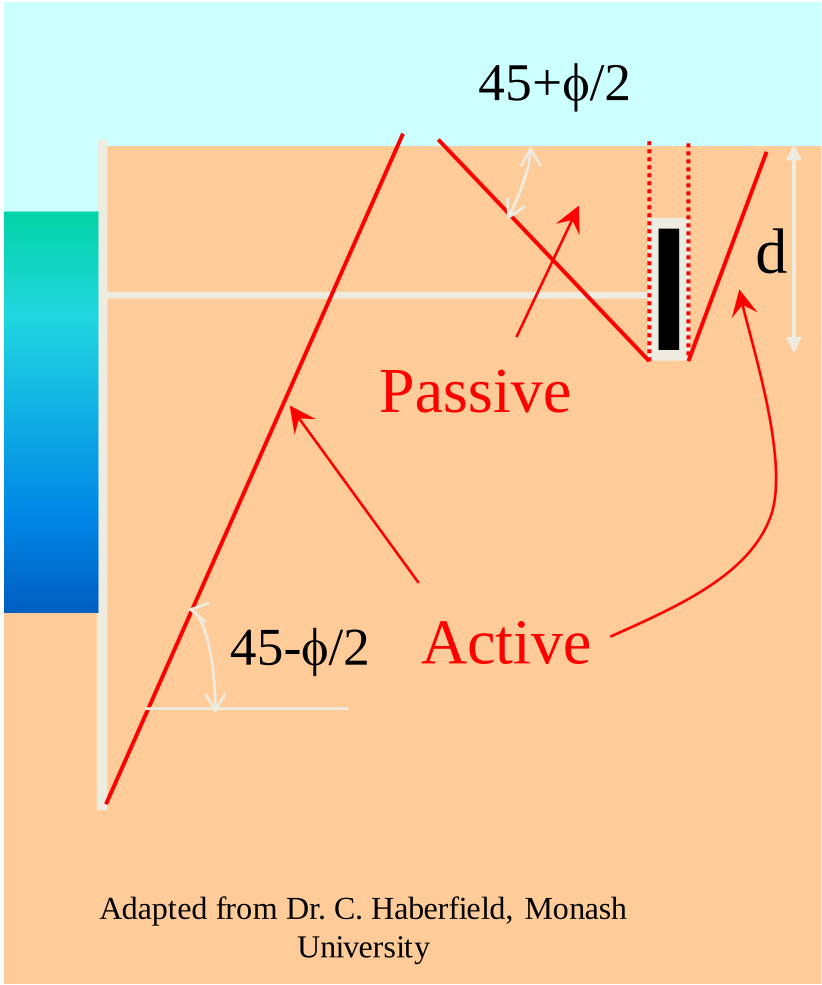
- There are two unknowns:
  - *d* – the depth of embedment to just prevent collapse
  - d_o – depth to pivot point.
- Simplification - replace the passive pressure below the pivot point by an equivalent force acting at the pivot point.
- Take moments about pivot point – calculate d_o
- R obtained from equations of horizontal equilibrium.
- Increase d_o by 20%
- Check whether the net force on the portion of the wall below the pivot point ($0.2d_o$) is approximately equal to R.

Propped Walls

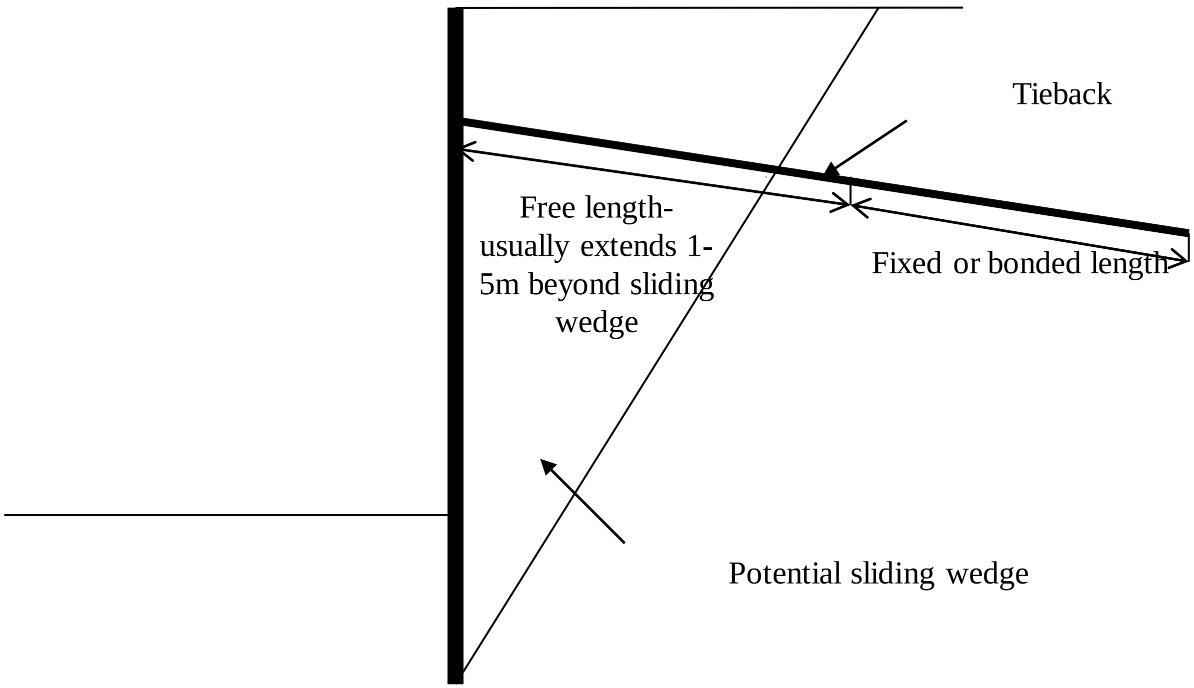
- Often referred to as anchored bulkheads
- Often consist of sheet piles with propping
- Propping by struts, anchors or by tie rod connected to a “deadman”.
- “Deadman” provides resistance by passive pressure and must be well back from wall face
- Calculate prop force using horizontal equilibrium

Design of Deadmen

- Placement - no overlap of active and passive wedges
- must allow for active force on deadmen
- deadmen capacity/unit length
- use buoyant weights as appropriate



Anchor details



Typical anchor capacities
[see "Embedded Walls" on Vista]

(adapted from FHWA 1984)

Soil type	Compactness	Estimated ultimate transfer load (kN/m)
Sand and gravel	Loose	145
	Medium	220
	Dense	290
Sand	Loose	100
	Medium	145
	Dense	190
Sand and silt	Loose	70
	Medium	100
	Dense	130
Silt-clay mixture with low plasticity or fine micaceous sand or silt mixtures	Stiff	30
	Hard	60

Design of anchors

- Fixed length is grouted
- Free length is ungrouted
- Free length extends about 1- 5 m beyond failure wedge
- Anchor may fail at soil – grout interface or at anchor – grout interface
- Anchor could fail by exceeding structural capacity of steel anchor.

Design of propped walls

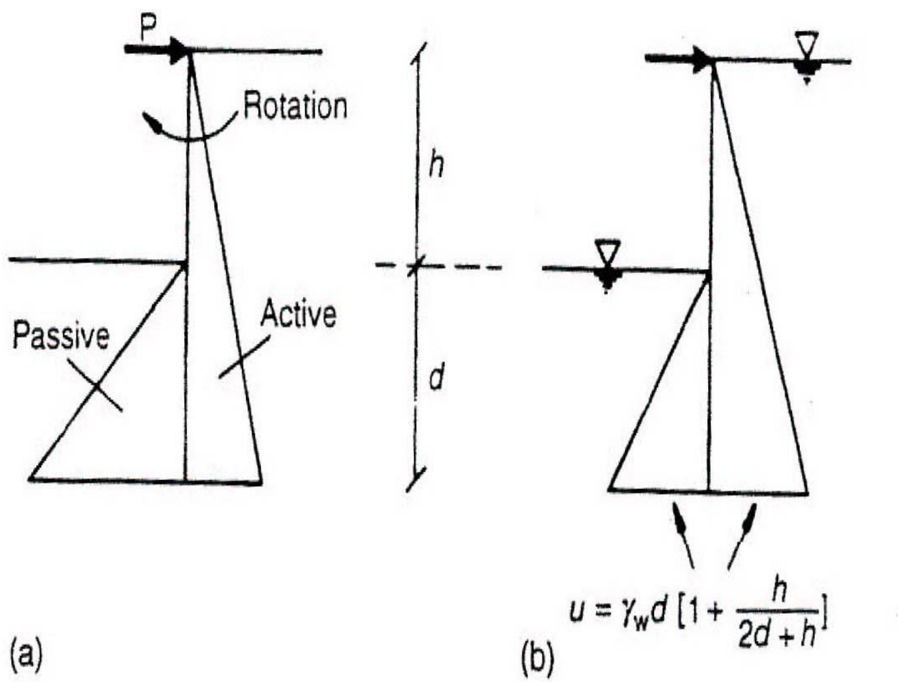


Figure 7.43 *Idealized stress distribution at failure for a stiff wall propped rigidly at the crest; (a) effective stresses; (b) pore water pressures.*

- Stability relies on:
  - passive pressure development in front of wall
  - the flexural resistance of the pile
  - prop force
- Unknowns:
  - prop load
  - depth of embedment

After Powrie (1997)

Free-earth-support method

After Powrie (1997)

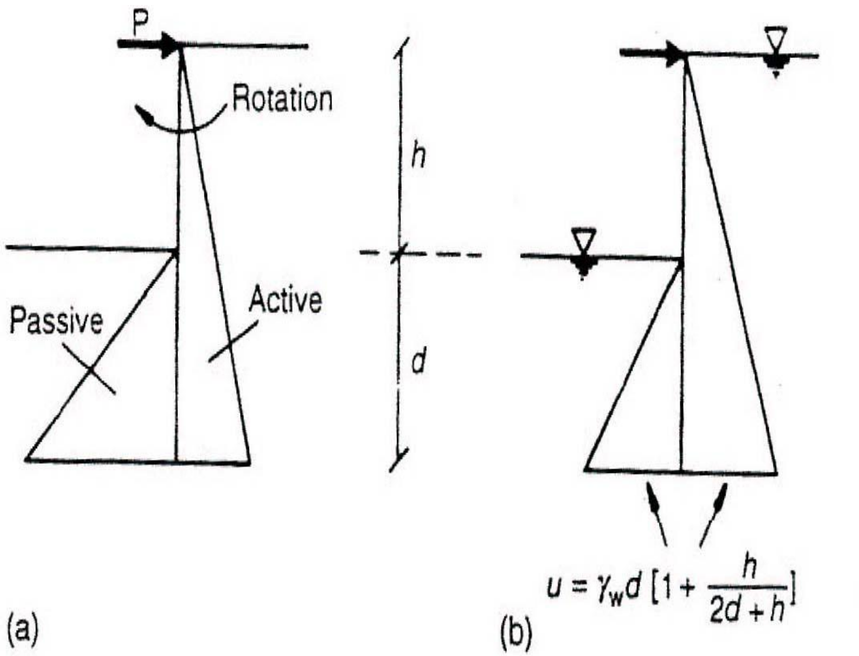


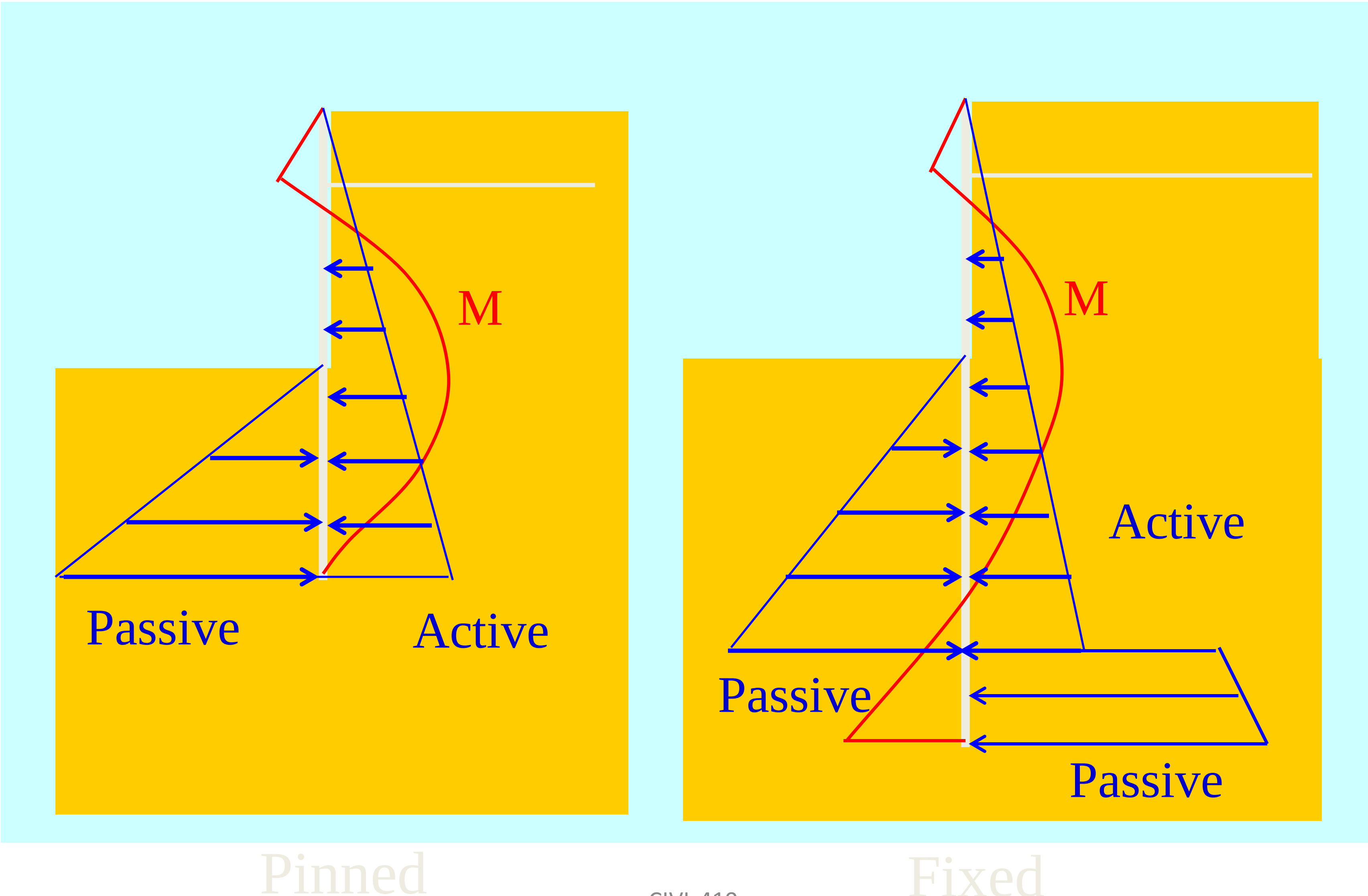
Figure 7.43 *Idealized stress distribution at failure for a stiff wall propped rigidly at the crest; (a) effective stresses; (b) pore water pressures.*

- Assumptions
  - Wall rigid
  - Failure by rotation about anchor point
- Design
  - embedment determined from moment equilibrium about anchor point (**note that there is unbalanced water force too – include in moments**)
  - Prop force from horizontal equilibrium – include water
  - maximum BM determined from Shear Force=0

Limitation of Free-Earth Support

- Real pile is flexible
  - leads to redistribution of active earth pressure depending on anchor yield and fixity of toe
- Partial toe fixity if F> 1.0
  - Contradicts assumption of Free-earth-support
- Result
  - Actual bending moment in pile << theoretical B.M. computed on Free-earth support assumptions.

Propped Walls



Rowe’s moment reduction method

- Used with Free-earth support method.
- Accounts for change in distribution and magnitude of BM due to sheet pile flexibility (i.e. classical distributions are no longer accurate when wall has flexibility- leads to higher estimated BMs)
- Provides moment reduction factors based on model tests

General

Factors of safety

- Design depth of penetration obtained depends on how F_s is introduced into the calculations.
- Options
  - FOS on passive earth coefficients – most common
    - adopts K_p/FOS (FOS =1.5 to 2) for calculations
  - FOS on net passive total pressure
    - **should not be used**
  - FOS on all effective strength parameters
    - **This is considered only rigorous approach**

Factors of safety

$$F_s = \frac{\tan\phi}{\tan\phi_{mob}}$$

Typically F_s=1.2

$$F_s = \frac{s_u}{s_{u_{mob}}}$$

Typically F_s=1.5

Numerical Methods

- Becoming more popular
- Account for wall stiffness (K_o to K_a)
- Can model construction procedure

Causes of failure

- Inadequate design leading to inadequate embedment of piles or capacity of deadmen
- Inappropriate soil parameters or analyses
- Inadequate FOS for temporary works
- Unsuitable backfill or compaction of backfill in front of deadmen
- Inadequate drainage

Design

- Distribution of stress against any retaining system is a function of:
  - flexibility of the system
  - construction sequence
- Design criteria:
  - the support system must be adequate to prevent structural failure of the components which would lead to collapse;
  - the ground movements in the adjacent ground must be within tolerable limits.
- Necessary to design each stage in construction

Excavation support

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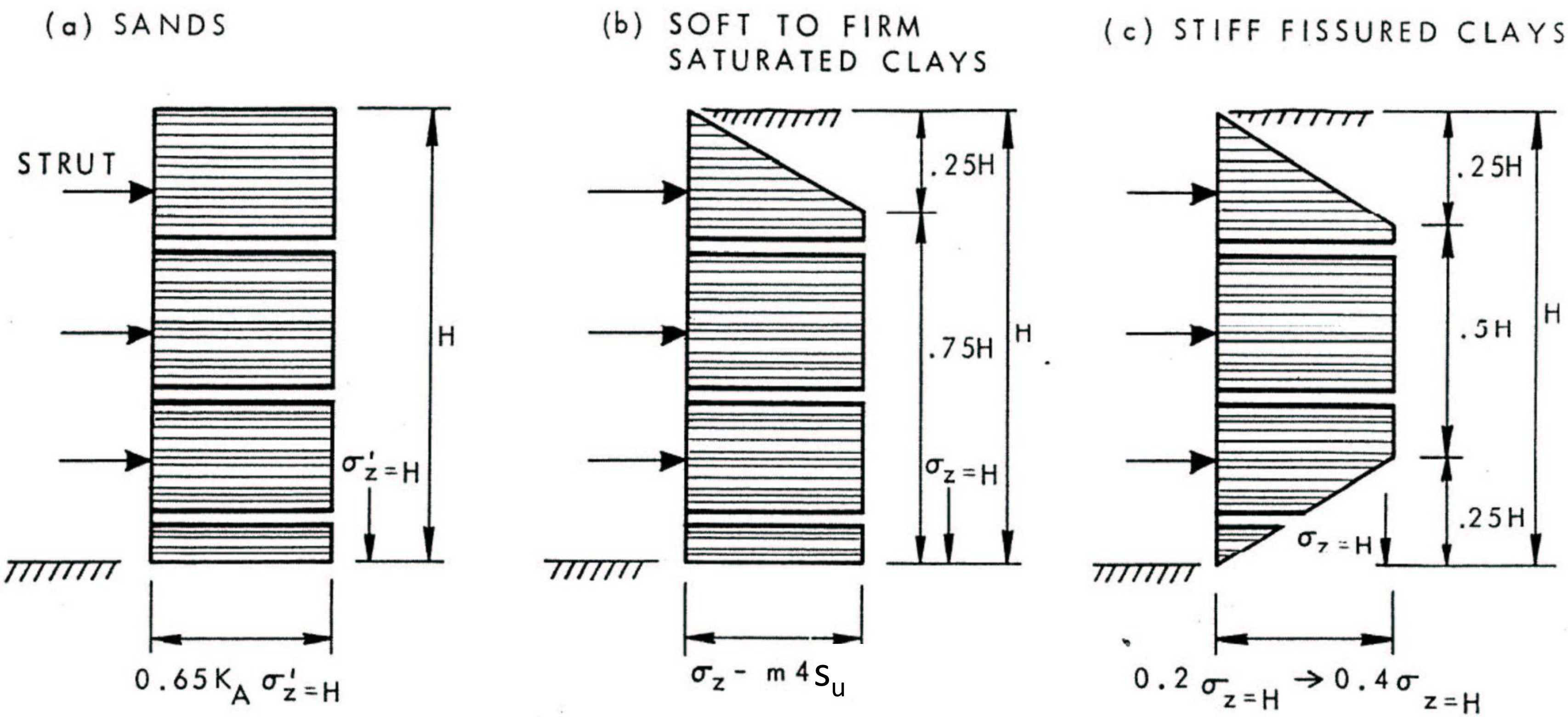
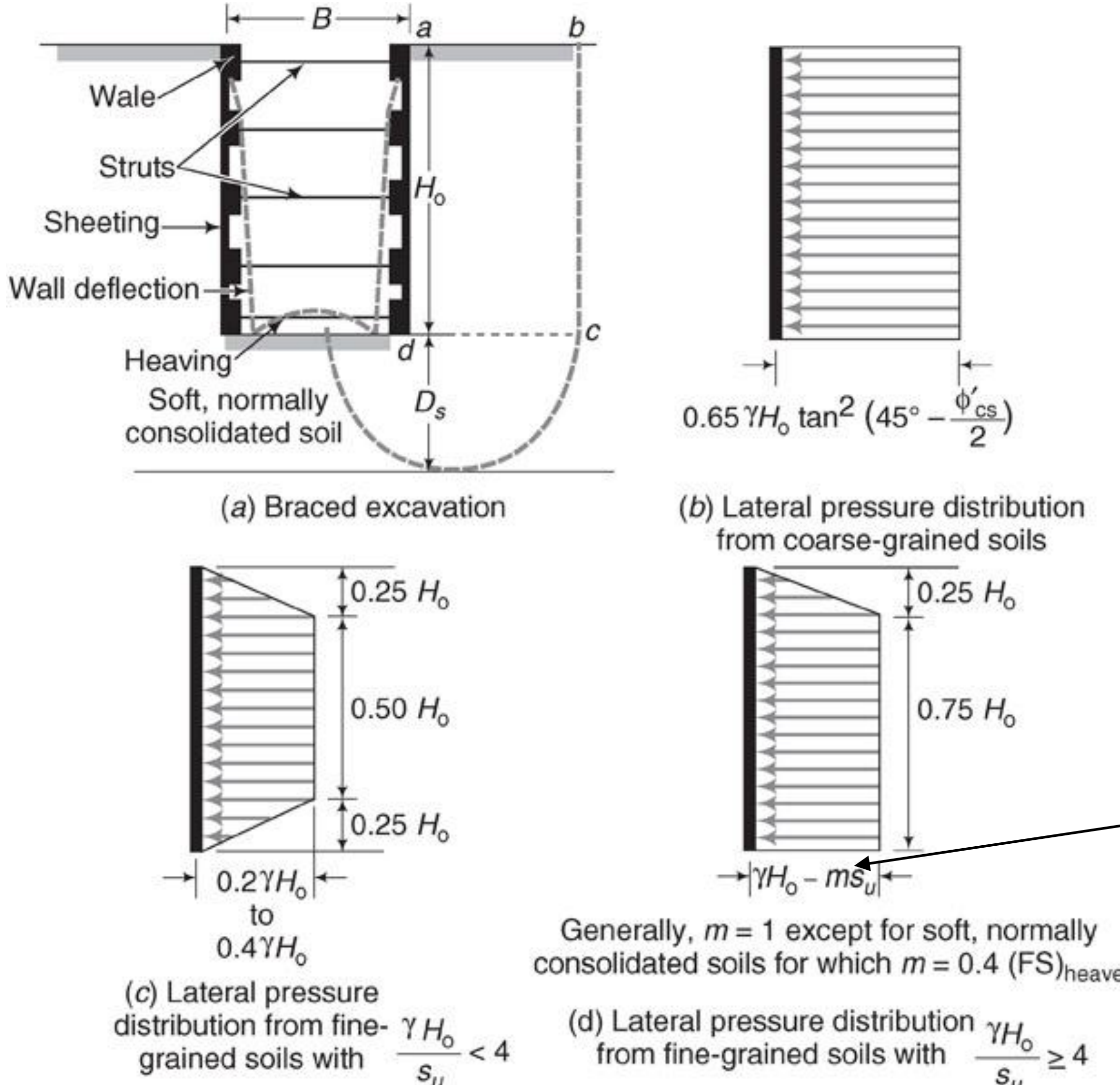


Figure 27.12: Apparent earth-pressure envelopes for determining forces on supports for strutted walls (after Terzaghi and Peck, 1967).

Error in Budhu



'4' is missing

Basis for design envelopes

- Diagrams represent <u>envelope</u> of maximum earth pressure
- Based on records of cuts 8 to 19m deep
- K_A is Rankine coefficient.
- Most probable value of any strut load will be 25% lower than maximum- Terzaghi, Peck and Mesri (1996)
- Ground water table is assumed below base of excavation
  - If the water table is lowered by pumping from an open sump, must allow for seepage pressures against lower part of support system.

Base Stability

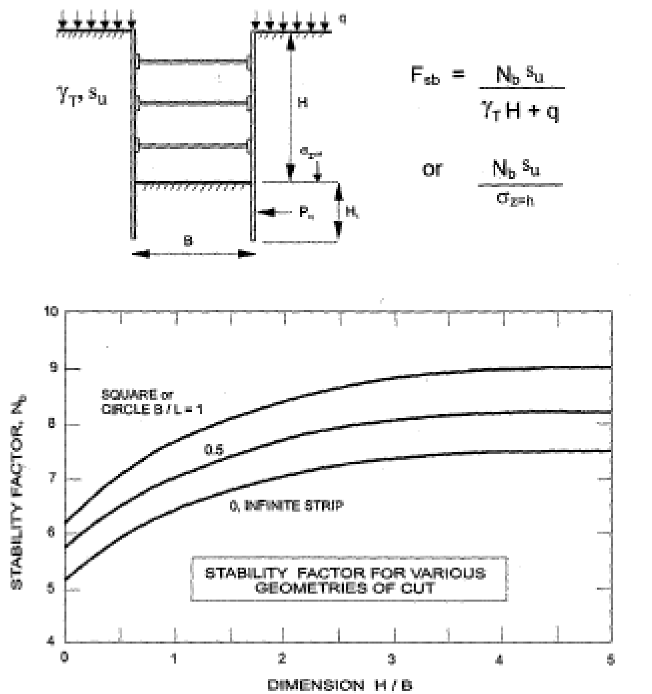


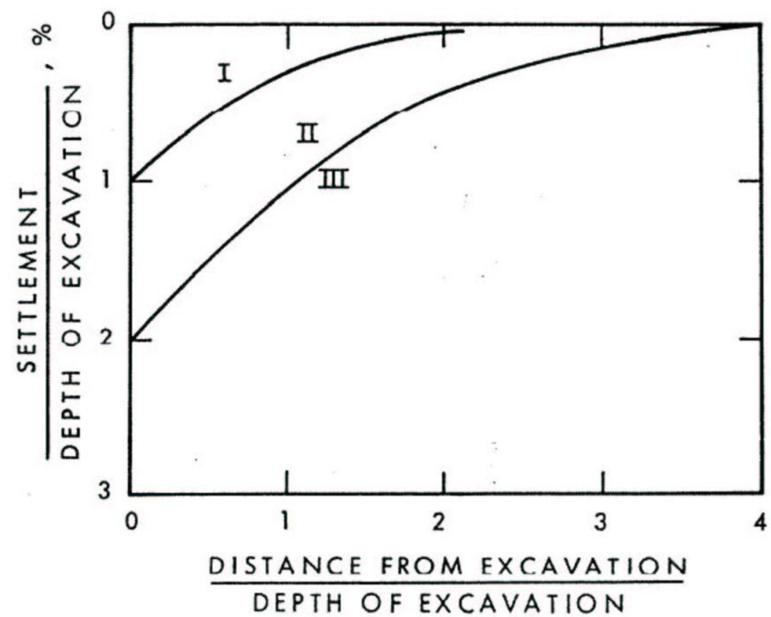
FIGURE 26.9 *Factor of safety with respect to base failure in cohesive soils (after Janbu 1954)*

<u>Note:</u> If Fsb < 2, installation of sheeting below base is of little advantage unless driven to fixity in a hard stratum at depth.

Ground movements around excavations

Soil type	Maximum lateral yield/excavation depth (%)		Surface settlement/ excavation depth (%)	
	Ave	Range	Ave	Range
Soft to firm NC clays	0.30	0.08-0.58	0.8	0.2-1.7
Stiff to hard OC clays	0.16	0.06-0.30	0.3	0.1-0.6
Sands and gravels	0.19	0.04-0.46	0.1	0.1-0.2

Ground movements around excavations



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Zone I	=	Sand and soft-to-hard clay.
Zone II	=	Very soft to soft clay when the depth of clay below excavation is limited, or when $F_{sb} > 1.3$.
Zone III	=	Very soft to soft clay when $F_{sb} < 1.3$.

(F_{sb} is factor of safety against base failure)

Figure 27.15: Settlement adjacent to an open cut (after Peck, 1969).

Conclusions on retaining structures

- Design requires consideration of both external and internal stability
- There is strong relationship between ground movements and wall pressures
- For gravity walls, it is appropriate to design for active conditions as small movements result in active pressures behind wall
- Composite walls require consideration of strain compatibility of wall components and soil
- Embedded walls become more complex to design as the number of props and the complexity of the construction sequence increase