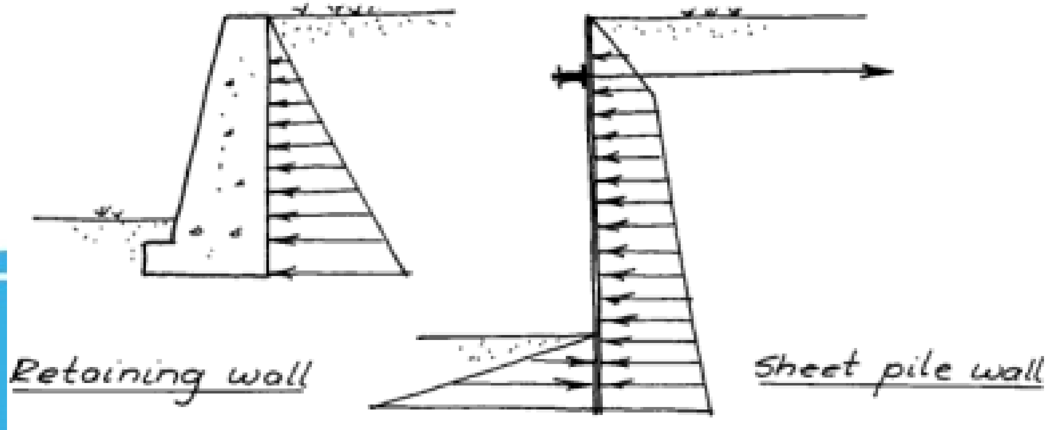
ENCE 4610
Foundation Analysis and Design

Sheet Piling Walls:
Cantilever Walls
Anchored Walls
Braced Cuts

Overview of Sheet Piling as a Retaining Wall

- Sheet piling is a structural “in-situ” type of retaining wall
  - Does not rely on its mass to retain the soil, as opposed to a gravity wall
  - In-situ walls rely on their flexural strength to retain soil, supported either by their own penetration into the soil or by an anchoring system
  - Other types of structural in-situ walls
    - Soldier pile walls – use H-beams to hold timber or concrete lagging to retain soil on a temporary or permanent basis
    - Slurry walls – bentonite slurry is injected into a trench after which reinforcement and concrete are placed into the trench, forming a wall

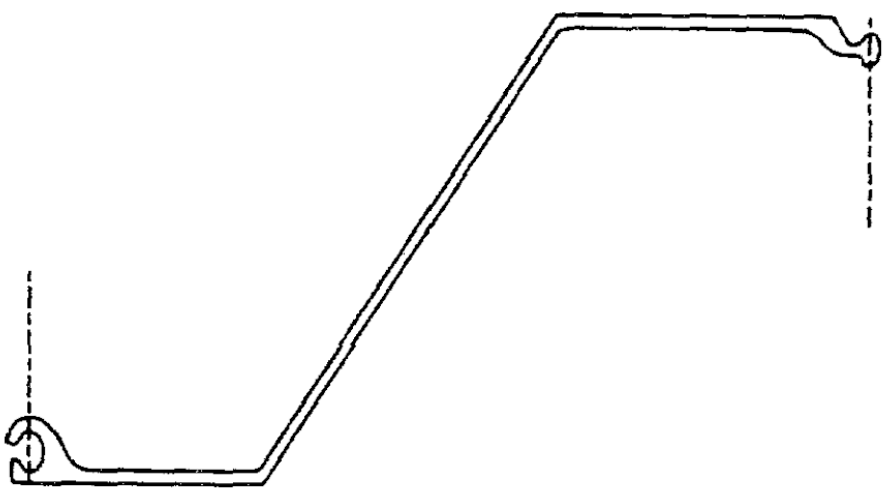


Materials for Sheet Piling

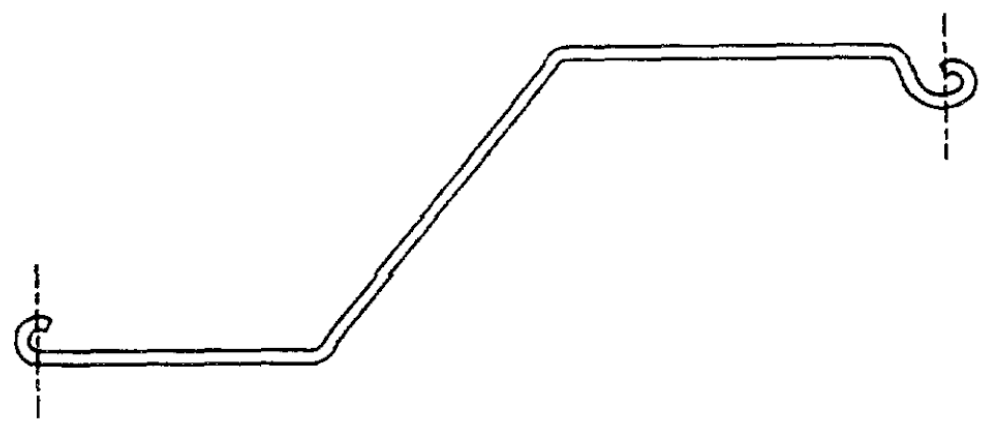
- Steel
  - Cold formed
  - Hot rolled
- Aluminium
  - Extruded
- Vinyl
  - Extruded
- Fibreglass
  - Pultruded
- Concrete
- Wood

Steel Sheet Piles

- Hot rolled
  - Panel and interlocks rolled in one operation
  - "Traditional" form of steel sheet piling
- Cold formed
  - Form rolled cold from steel plate
  - Common with lighter sheet pile profiles
  - Interlocks more prone to breakage



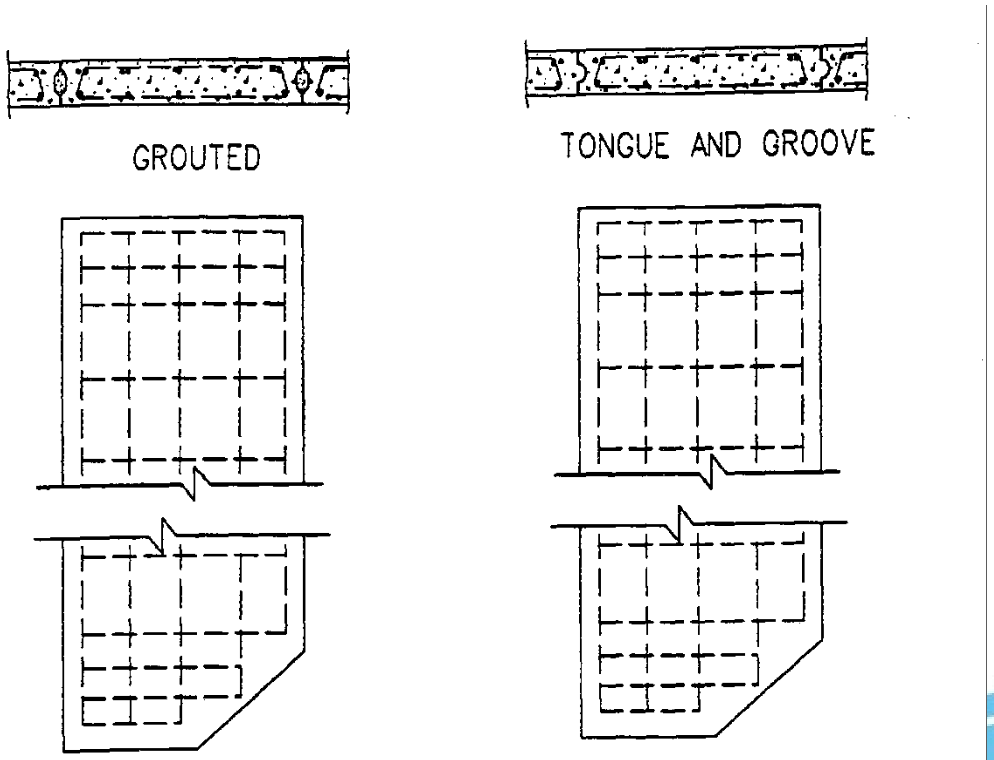
a. Hot-rolled Z-section

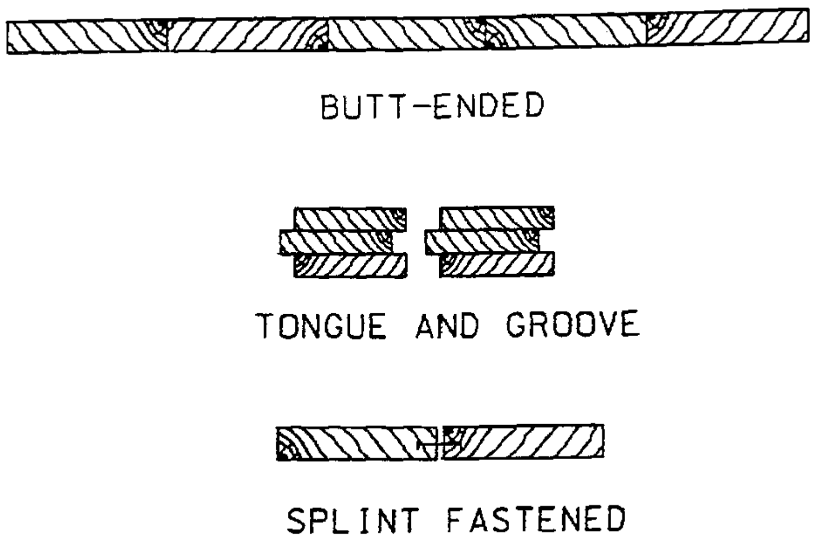


b. Cold-rolled Z-section

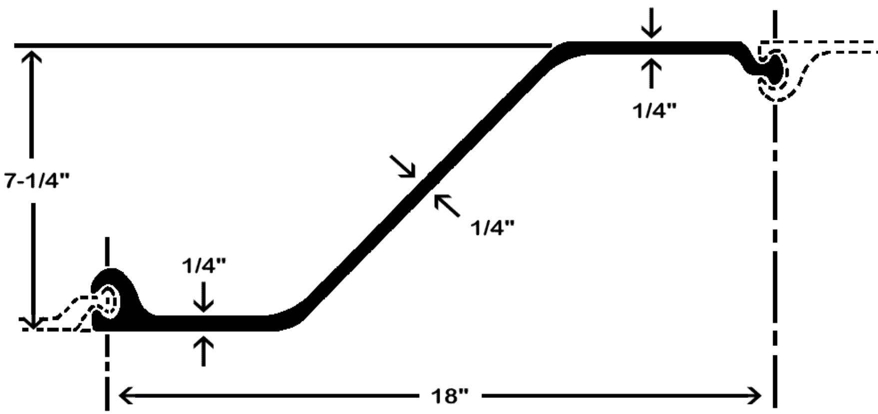
Concrete and Wood Sheeting

- Concrete Sheeting
- Wood Sheeting



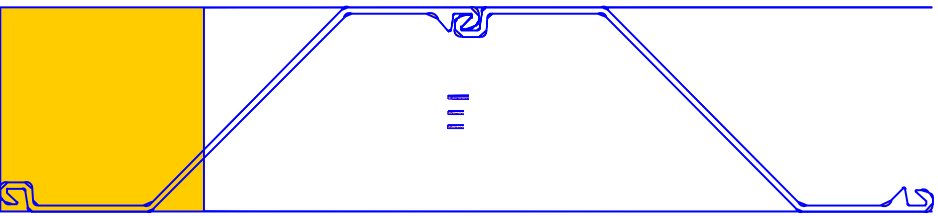


Aluminium, Vinyl and Fibreglass Sheeting



- Made for lightweight and light load applications
- Common substitute for wood or concrete walls
- Require special handling in setting and driving
- Vinyl sheets can be obtained in various colours, but is subject to long term creep

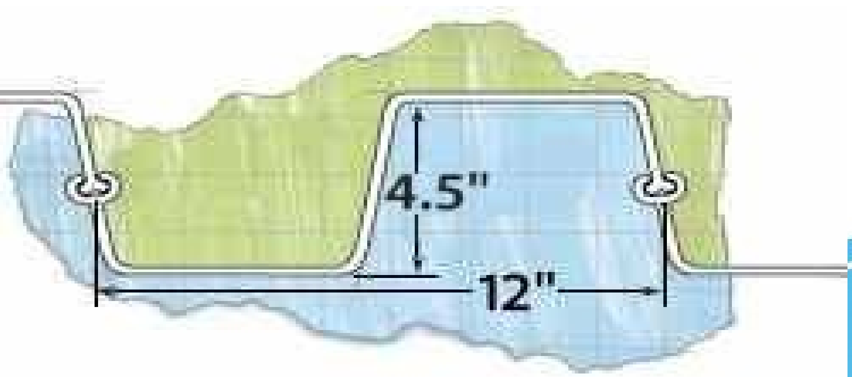
Sections of Sheet Piling



- Z-shaped sheeting
  - Popular in north America
  - Usually drive two at a time with split clamp
  - Wall stiffness developed with each sheet without assumed assistance from the interlocks
- U-shaped sheeting (Larssen, etc.)
  - Very popular in Europe
  - Usually driven one at a time
  - Wall stiffness developed with two sheets and load transferred using the interlocks (European practice; U.S. practice does not assume this load transfer)

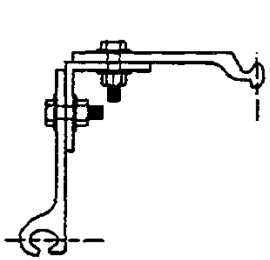
Sections of Sheet Piling

- Arched shaped
  - Used for shallower wall construction
  - Used in cold formed steel and aluminium sheeting
- Flat-web sheeting
  - Almost exclusively used for cellular cofferdams
  - Main stress is tensile through the web and interlocks
  - Can be driven singly or two at a time

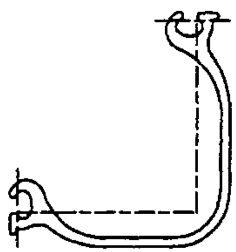


Transitional Sections and Interlock Styles

- Transitional Sections



c. Fabricated corners



d. Rolled corners

Ball and Socket (BS)

Double Jaw (DJ)

Single Jaw (SJ)

Double Hook (DH)

Thumb and Finger - three point contact (TF)

Thumb and Finger - one point contact (TFX)

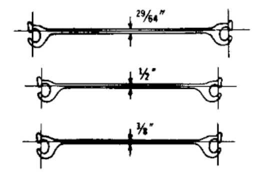
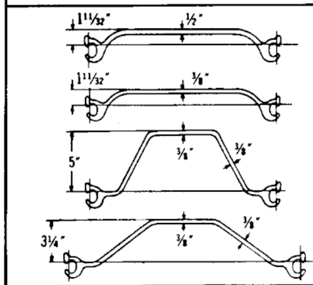
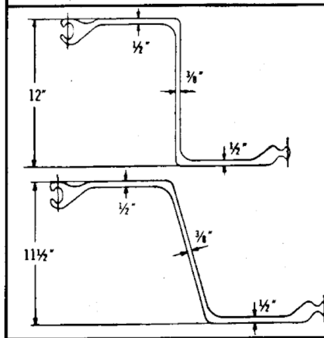
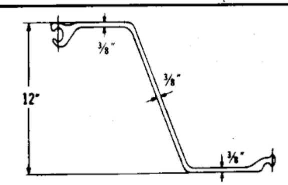
Hook and Grip (HG)

- Interlock Styles
  - Hot rolled and extruded sections
    - Ball and socket
    - Single or double jaw
    - Double hook
    - Thumb and finger
      - One point contact
      - Three point contact
  - Cold formed sections
    - Hook and grip

Specifications for Steel Sheet Piling (USS)

Steel Grade	Allowable Stress, ksi	Allowable Stress, MPa
ASTM A 328	25	172
ASTM A 572 Gr. 45	29	200
ASTM A 572 Gr. 50	32	220
ASTM A 572 Gr. 55	35	241
ASTM A 690	32	220

Steel Sheet Piling Sections

Profile	Section Index		District Rolled	Driving Distance per Pile	Weight		Web Thickness	Section Modulus		Area	Moment of Inertia	
					Per Foot	Per Square Foot of Wall		Per Pile	Per Foot of Wall	Per Pile	Per Pile	Per Foot of Wall
				In.	Lbs.	Lbs.	In.	In.³	In.³	In.²	In.⁴	In.⁴
	Interlock with Each Other	**PSX 32**	H.	16½	44.0	32.0	29/64	3.3	2.4	12.94	5.1	3.7
		PS 32*	H.S.	15	40.0	32.0	½	2.4	1.9	11.77	3.6	2.9
		PS 28	H.S.	15	35.0	28.0	⅜	2.4	1.9	10.30	3.5	2.8
	Interlock with Each Other	**PSA 28***	H.	16	37.3	28.0	½	3.3	2.5	10.98	6.0	4.5
		PSA 23	H.S.	16	30.7	23.0	⅜	3.2	2.4	8.99	5.5	4.1
		PDA 27	H.S.	16	36.0	27.0	⅜	14.3	10.7	10.59	53.0	39.8
		PMA 22	H.S.	19⅝	36.0	22.0	⅜	8.8	5.4	10.59	22.4	13.7
	Interlock with Each Other and with PSA 23 or PSA 28	**PZ 38**	H.	18	57.0	38.0	⅜	70.2	46.8	16.77	421.2	280.8
		PZ 32	H.	21	56.0	32.0	⅜	67.0	38.3	16.47	385.7	220.4
	Interlocks with Itself and with PSA 23 or PSA 28	**PZ 27**	H.	18	40.5	27.0	⅜	45.3	30.2	11.91	276.3	184.2

*Sections PS 32 and PSA 28 are infrequently rolled and we do not advise their use in a design unless an adequate tonnage can be ordered at one time to assure a minimum rolling.

Complete data regarding these sections will be found in a separate publication entitled "USS Steel Sheet Piling."

H—Homestead, Pa. (Pittsburgh District)
S—South Chicago (Chicago District)

Suggested Allowable Design Stresses—Sheet Piling

Steel Brand or Grade	Minimum Yield Point, psi	Allowable Design Stress, psi*
USS-EX-TEN 55 (ASTM A572 GR 55)	55,000	35,000
USS EX-TEN 50 (ASTM A572 GR 50)	50,000	32,000
USS MARINER STEEL	50,000	32,000
USS EX-TEN 45 (ASTM A572 GR 45)	45,000	29,000
Regular Carbon Grade (ASTM A 328)	38,500	25,000

*Based on 65% of minimum yield point. Some increase for temporary overstresses generally permissible.

PZ/PS Sections (Skyline)

PZ/PS

PZ/PS Hot Rolled Steel Sheet Piling

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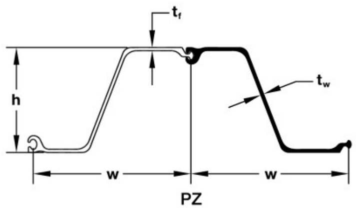
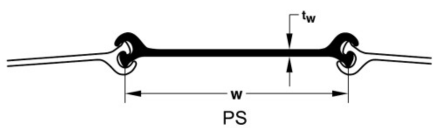


SECTION	Width (w) in (mm)	Height (h) in (mm)	THICKNESS Flange (t_f) in (mm)	THICKNESS Wall (t_w) in (mm)	Cross Sectional Area in²/ft (cm²/m)	WEIGHT Pile lb/ft (kg/m)	WEIGHT Wall lb/ft² (kg/m²)	SECTION MODULUS Elastic in³/ft (cm³/m)	SECTION MODULUS Plastic in³/ft (cm³/m)	Moment of Inertia in⁴/ft (cm⁴/m)	COATING AREA Both Sides ft²/ft of single (m²/m)	COATING AREA Wall Surface ft²/ft² of wall (m²/m²)
PZ 22	22.0 559	9.0 229	0.375 9.50	0.375 9.50	6.47 136.9	40.3 60.0	22.0 107.4	18.1 973	21.79 1171.4	84.38 11500	4.48 1.37	1.22 1.22
PZ 27	18.0 457	12.0 305	0.375 9.50	0.375 9.50	7.94 168.1	40.5 60.3	27.0 131.8	30.2 1620	36.49 1961.9	184.20 25200	4.48 1.37	1.49 1.49
PZ 35	22.6 575	14.9 378	0.600 15.21	0.500 12.67	10.29 217.8	66.0 98.2	35.0 170.9	48.5 2608	57.17 3073.5	361.22 49300	5.37 1.64	1.42 1.42
PZ 40	19.7 500	16.1 409	0.600 15.21	0.500 12.67	11.77 249.1	65.6 97.6	40.0 195.3	60.7 3263	71.92 3866.7	490.85 67000	5.37 1.64	1.64 1.64



SECTION	Width (w) in (mm)	Web (t_w) in (mm)	Maximum Interlock Strength k/in (kN/m)	Minimum Cell Diameter* ft (m)	Cross Sectional Area in²/ft (cm²/m)	WEIGHT Pile lb/ft (kg/m)	WEIGHT Wall lb/ft² (kg/m²)	Elastic Section Modulus in³/sheet (cm³/sheet)	Moment of Inertia in⁴/sheet (cm⁴/sheet)	COATING AREA Both Sides ft²/ft of single (m²/m)	COATING AREA Wall Surface ft²/ft² of wall (m²/m²)
PS 27.5	19.69 500	0.4 10.2	24 4800	30 9.14	8.09 171.2	45.1 67.1	27.5 134.3	3.3 54	5.3 221	3.65 1.11	1.11 1.11
PS 31	19.69 500	0.5 12.7	24 4800	30 9.14	9.12 193.0	50.9 75.7	31.0 151.4	3.3 54	5.3 221	3.65 1.11	1.11 1.11

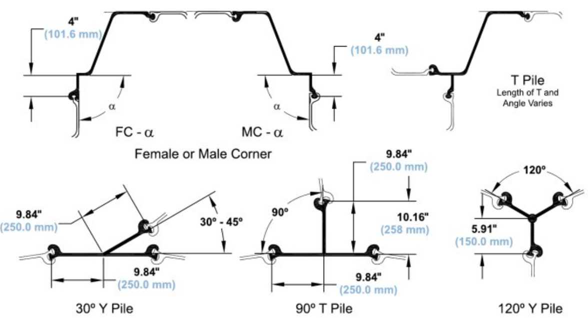
* Minimum cell diameter cannot be guaranteed for piles over 65 feet (19.81 m) in length.
* Minimum cell diameter cannot be guaranteed if piles are spliced.
* 58 Piles are needed to make a 30 foot diameter cell.

PZ/PS

PZ/PS Hot Rolled Steel Sheet Piling

Available Steel Grades							
PZ's			PS's				
ASTM	YIELD STRENGTH (ksi)	YIELD STRENGTH (MPa)	ASTM	YIELD STRENGTH (ksi)	YIELD STRENGTH (MPa)	INTERLOCK STRENGTH (k/in)	INTERLOCK STRENGTH (kN/m)
A 328	39	270	A 328	39	270	16	2800
A 572 Grade 50	50	345	A 572 Grade 50	50	345	20	3500
A 572 Grade 60	60	415	A 572 Grade 60	60	415	24	4200
A 572 Grade 65	65	450	A 572 Grade 65	65	450	24	4200
A 588	50	345	A 588	50	345	20	3500
A 690	50	345	A 690	50	345	20	3500

Corner and Junction Piles



Delivery Conditions & Tolerances

	ASTM A 6	
Mass	± 2.5%	
Length	+ 5 inches	– 0 inches

Maximum Rolled Lengths*

PZ	85 feet for singles, 70 feet for pairs	(25.9 m, 21.3 m)
PS	65 feet	(19.8 m)

* Longer lengths may be possible upon request.

SKZ/SCZ Sections (Skyline)

SKZ/SCZ
SKZ/SCZ Cold Formed Steel Sheet Piling

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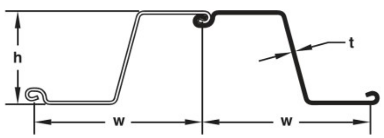
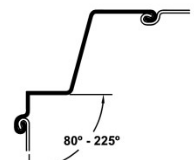


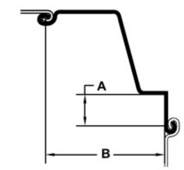
SECTION	Width (w) in (mm)	Height (h) in (mm)	Thickness (t) in (mm)	Cross Sectional Area in²/ft (cm²/m)	WEIGHT Pile lb/ft (kg/m)	WEIGHT Wall lb/ft² (kg/m²)	SECTION MODULUS Elastic in³/ft (cm³/m)	SECTION MODULUS Plastic in³/ft (cm³/m)	Moment of Inertia in⁴/ft (cm⁴/m)	COATING AREA Both Sides ft²/ft (m²/m)	COATING AREA Coating Area ft²/ft² (m²/m²)
SKZ 20	28.50 723.9	16.00 406.4	0.315 8.0	6.00 136.20	48.24 71.79	20.31 99.17	31.69 1704	36.66 1970.97	253.51 34618	7.60 2.32	1.60 1.60
SKZ 22	28.50 723.9	16.00 406.4	0.335 8.5	6.30 145.40	51.30 76.34	21.60 105.46	33.43 1797	38.94 2093.55	267.40 36515	7.60 2.32	1.60 1.60
SKZ 23	28.50 723.9	16.00 406.4	0.354 9.0	6.70 162.50	54.20 80.66	22.82 111.42	35.61 1915	41.12 2210.75	284.90 38905	7.60 2.32	1.60 1.60
SKZ 24	28.50 723.9	16.00 406.4	0.375 9.5	7.10 179.50	57.43 85.47	24.18 118.06	37.73 2028	43.52 2339.78	301.80 41213	7.60 2.32	1.60 1.60
SKZ 25	28.50 723.9	16.00 406.4	0.399 10.1	7.60 188.00	61.10 90.93	25.73 125.61	40.14 2158	46.24 2486.02	321.12 43851	7.60 2.32	1.60 1.60
SCZ 14	28.50 723.9	10.00 254.0	0.250 6.4	4.18 88.48	33.81 50.31	14.23 69.50	14.36 772	16.32 877.4	71.82 9808	6.10 1.86	1.28 1.28
SCZ 16	28.50 723.9	10.00 254.0	0.276 7.0	4.62 97.79	37.37 55.61	15.73 76.82	15.75 847	17.97 965.9	78.73 10751	6.10 1.86	1.28 1.28
SCZ 17	29.95 760.8	10.13 257.3	0.315 8.0	5.16 109.22	43.86 65.27	17.57 85.79	16.86 906	19.57 1051.9	88.77 12122	6.32 1.93	1.27 1.27
SCZ 18	29.95 760.8	10.13 257.3	0.335 8.5	5.49 116.21	46.67 69.45	18.70 91.28	17.86 960	20.85 1121.0	90.48 12356	6.32 1.93	1.27 1.27
SCZ 19	29.95 760.8	10.13 257.3	0.354 9.0	5.80 122.77	49.30 73.37	19.75 96.43	18.74 1008	22.06 1186.0	94.92 12962	6.32 1.93	1.27 1.27
SCZ 21	29.95 760.8	10.13 257.3	0.375 9.5	6.14 129.96	52.19 77.67	20.91 102.10	19.85 1067	23.26 1250.5	100.55 13731	6.32 1.93	1.27 1.27
SCZ 22	24.02 610.0	13.39 340.0	0.315 8.0	6.43 136.20	43.81 65.19	21.89 106.90	29.76 1600	33.75 1814.8	199.19 27200	5.91 1.80	1.48 1.48
SCZ 23	24.02 610.0	13.39 340.0	0.335 8.5	6.87 145.40	46.84 69.70	23.35 114.00	31.62 1700	36.08 1939.9	223.63 28900	5.91 1.80	1.48 1.48
SCZ 25	24.02 610.0	13.39 340.0	0.354 9.0	7.27 153.95	49.60 73.80	24.78 121.00	33.48 1800	38.13 2050.2	224.08 30600	5.91 1.80	1.48 1.48
SCZ 26	24.02 610.0	13.39 340.0	0.375 9.5	7.68 162.50	52.28 77.80	26.22 128.00	35.34 1900	40.28 2165.8	236.53 32300	5.91 1.80	1.48 1.48
SCZ 29	24.02 610.0	13.39 340.0	0.413 10.5	8.48 179.50	57.92 86.20	28.88 141.00	39.06 2100	44.49 2392.2	261.43 35700	5.91 1.80	1.48 1.48
SCZ 30	24.02 610.0	13.39 340.0	0.433 11.0	8.88 188.00	60.68 90.30	30.31 148.00	40.92 2200	46.56 2503.2	273.88 37400	5.91 1.80	1.48 1.48

SKZ/SCZ
SKZ/SCZ Cold Formed Steel Sheet Piling

Corner Piles



B2 Corner Pile



B3 Corner Pile

SCZ 14 - SCZ 16
A = 5.0 inches (127.0 mm)
B = 23.5 inches (596.9 mm)

SKZ 20 - SKZ 25
A = 5.0 inches (127.0 mm)
B = 23.5 inches (596.9 mm)

SCZ 17 - SCZ 21
A = 5.0 inches (127.0 mm)
B = 24.95 inches (633.7 mm)

SCZ 22 - SCZ 30
A = 5.0 inches (127.0 mm)
B = 19.0 inches (482.6 mm)

Delivery Conditions & Tolerances

	ASTM	
Mass	± 2.5%	
Length	+ 5 inches	– 0 inches
Interlock Opening	± 0.08 inches	
Straightness	0.2% of the length	
Twisting	0.4% of the width	

Maximum Rolled Lengths*

SKZ, SCZ	70 feet	(21.3 m)

* Longer lengths may be possible upon request.

Optional Accessories


Sheet Pile Protector


Waler


Cap


Sheet Pile Protector

AZ Sections (Skyline)

AZ

AZ Hot Rolled Steel Sheet Piling

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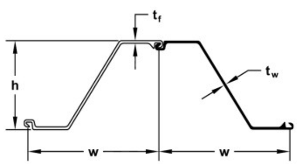

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AZ 12	26.38 670	11.89 302.0	0.335 8.50	0.335 8.50	5.94 125.7	44.42 66.10	20.22 98.70	22.3 1200	26.2 1409	132.8 18140	5.45 1.66	1.23 1.23
AZ 13	26.38 670	11.93 303.0	0.375 9.50	0.375 9.50	6.47 136.9	48.38 72.00	22.02 107.50	24.2 1300	28.4 1528	144.3 19700	5.45 1.66	1.23 1.23
AZ 14	26.38 670	11.97 304.0	0.413 10.50	0.413 10.50	7.03 148.9	52.62 78.30	23.94 116.90	26.0 1400	30.7 1651	156.0 21300	5.45 1.66	1.23 1.23
AZ 12-770	30.31 770	13.52 343.5	0.335 8.50	0.335 8.50	5.67 120.1	48.78 72.60	19.31 94.30	23.2 1245	27.5 1480	156.9 21430	6.10 1.86	1.20 1.20
AZ 13-770	30.31 770	13.54 344.0	0.354 9.00	0.354 9.00	5.94 125.8	51.14 76.10	20.24 98.80	24.2 1300	28.8 1546	163.7 22360	6.10 1.86	1.20 1.20
AZ 14-770	30.31 770	13.56 344.5	0.375 9.50	0.375 9.50	6.21 131.5	53.42 79.50	21.14 103.20	25.2 1355	30.0 1611	170.6 23300	6.10 1.86	1.20 1.20
AZ 17	24.80 630	14.92 379.0	0.335 8.50	0.335 8.50	6.53 138.3	45.96 68.40	22.24 108.60	31.0 1665	36.2 1944	231.3 31580	5.64 1.72	1.35 1.35
AZ 18	24.80 630	14.96 380.0	0.375 9.50	0.375 9.50	7.11 150.4	49.99 74.40	24.19 118.10	33.5 1800	39.1 2104	250.4 34200	5.64 1.72	1.35 1.35
AZ 19	24.80 630	15.00 381.0	0.413 10.50	0.413 10.50	7.74 163.8	54.43 81.00	26.34 128.60	36.1 1940	42.3 2275	270.8 36980	5.64 1.72	1.35 1.35
AZ 17-700	27.56 700	16.52 419.5	0.335 8.50	0.335 8.50	6.28 133.0	49.12 73.10	21.38 104.40	32.2 1730	37.7 2027	265.3 36230	6.10 1.86	1.33 1.33
AZ 18-700	27.56 700	16.54 420.0	0.354 9.00	0.354 9.00	6.58 139.2	51.41 76.50	22.39 109.30	33.5 1800	39.4 2116	276.8 37800	6.10 1.86	1.33 1.33
AZ 19-700	27.56 700	16.56 420.5	0.375 9.50	0.375 9.50	6.88 145.6	53.76 80.00	23.41 114.30	34.8 1870	41.0 2206	288.4 39380	6.10 1.86	1.33 1.33
AZ 25	24.80 630	16.77 426.0	0.472 12.00	0.441 11.20	8.74 185.0	61.49 91.50	29.74 145.20	45.7 2455	53.4 2873	382.6 52250	5.91 1.80	1.41 1.41
AZ 26	24.80 630	16.81 427.0	0.512 13.00	0.480 12.20	9.35 198.0	65.72 97.80	31.79 155.20	48.4 2600	56.9 3059	406.5 55510	5.91 1.80	1.41 1.41
AZ 28	24.80 630	16.85 428.0	0.551 14.00	0.520 13.20	9.97 211.1	70.15 104.40	33.94 165.70	51.2 2755	60.5 3252	431.6 58940	5.91 1.80	1.41 1.41
AZ 24-700	27.56 700	18.07 459.0	0.441 11.20	0.441 11.20	8.23 174.1	64.30 95.70	28.00 136.70	45.2 2430	53.5 2867	408.8 55820	6.33 1.93	1.38 1.38
AZ 26-700	27.56 700	18.11 460.0	0.480 12.20	0.480 12.20	8.84 187.2	69.12 102.90	30.10 146.90	48.4 2600	57.1 3070	437.3 59720	6.33 1.93	1.38 1.38
AZ 28-700	27.56 700	18.15 461.0	0.520 13.20	0.520 13.20	9.46 200.2	73.93 110.00	32.19 157.20	51.3 2760	60.9 3273	465.9 63620	6.33 1.93	1.38 1.38
AZ 37-700	27.56 700	19.65 499.0	0.669 17.00	0.480 12.20	10.68 226.0	83.46 124.20	36.33 177.40	68.9 3705	79.2 4260	676.6 92400	6.76 2.06	1.46 1.46
AZ 39-700	27.56 700	19.69 500.0	0.709 18.00	0.520 13.20	11.34 240.0	88.63 131.90	38.59 188.40	72.5 3900	83.7 4500	714.0 97500	6.76 2.06	1.46 1.46
AZ 41-700	27.56 700	19.72 501.0	0.748 19.00	0.559 14.20	12.00 254.0	93.74 139.50	40.84 199.40	76.2 4095	88.3 4745	751.4 102610	6.76 2.06	1.46 1.46
AZ 46	22.83 580	18.94 481.0	0.709 18.00	0.551 14.00	13.76 291.2	89.10 132.60	46.82 228.60	85.5 4595	98.5 5295	808.8 110450	6.23 1.90	1.63 1.63
AZ 48	22.83 580	18.98 482.0	0.748 19.00	0.591 15.00	14.48 306.5	93.81 139.60	49.28 240.60	89.3 4800	103.3 5553	847.1 115670	6.23 1.90	1.63 1.63
AZ 50	22.83 580	19.02 483.0	0.787 20.00	0.630 16.00	15.22 322.2	98.58 146.70	51.80 252.9	93.3 5015	108.2 5816	886.5 121060	6.23 1.90	1.63 1.63

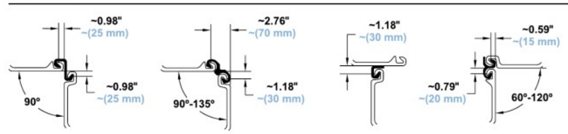
AZ

AZ Hot Rolled Steel Sheet Piling

Available Steel Grades								
AMERICAN			CANADIAN			EUROPEAN		
ASTM	YIELD STRENGTH (ksi)	(MPa)	CSA G40.21	YIELD STRENGTH (ksi)	(MPa)	EN 10248	YIELD STRENGTH (ksi)	(MPa)
A 328	39	270	Grade 260 W	38	260	S 240 GP	35	240
A 572 Grade 42	42	290	Grade 300 W	43	297	S 270 GP	39	270
A 572 Grade 50	50	345	Grade 350 W	51	355	S 320 GP	46	315
A 572 Grade 55	55	380	Grade 400 W	58	400	S 355 GP	51	355
A 572 Grade 60	60	415				S 390 GP	57	390
A 572 Grade 65	65	450				S 430 GP	62	430
A 690	50	345				S 460 AP	67	460
A 690*	57	390						

*Not available for AZ 37-700 and larger.

Corner Piles



C 14
Weight: 9.68 lbs/ft
(14.4 kg/m)

Omega 18
Weight: 12.10 lbs/ft
(18.0 kg/m)

C 9
Weight: 6.25 lbs/ft
(9.3 kg/m)

Delta 13
Weight: 8.73 lbs/ft
(13.0 kg/m)

Delivery Conditions & Tolerances

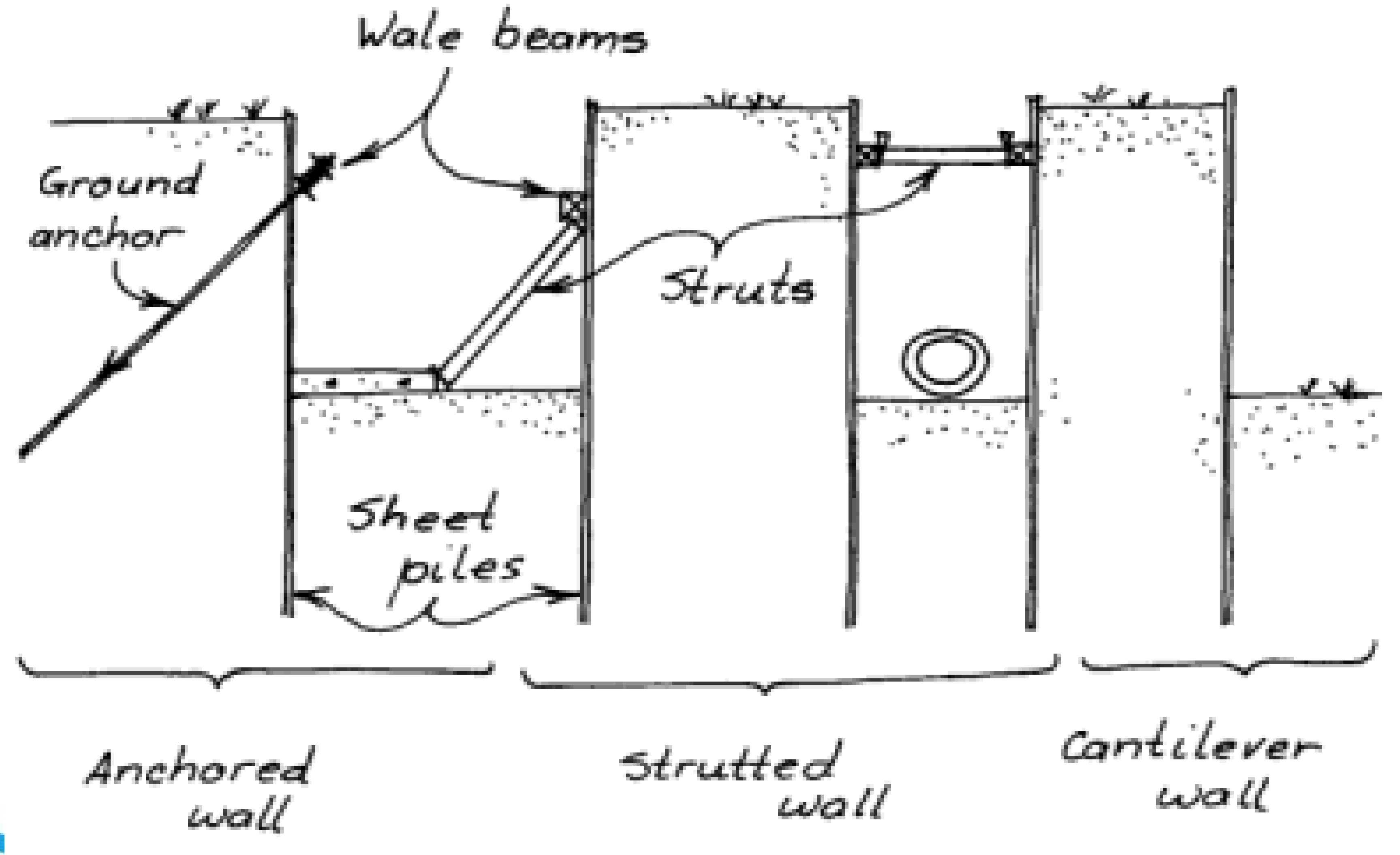
	ASTM A 6		EN 10248	
Mass	± 2.5%		± 5%	
Length	+ 5 inches	– 0 inches	± 200 mm	
Height			± 7 mm	
Thickness			≤ 8.5 mm	± 0.5 mm
			> 8.5 mm	± 6%
Width			± 2%	
Double Pile Width			± 3%	
Straightness			0.2% of the length	
Ends out of Square			2% of the width	

Maximum Rolled Lengths*

AZ	101.7 feet	(31.0 m)
C 9	59.1 feet	(18.0 m)
C 14	59.1 feet	(18.0 m)
Delta 13	59.1 feet	(18.0 m)
Omega 18	52.0 feet	(16.0 m)

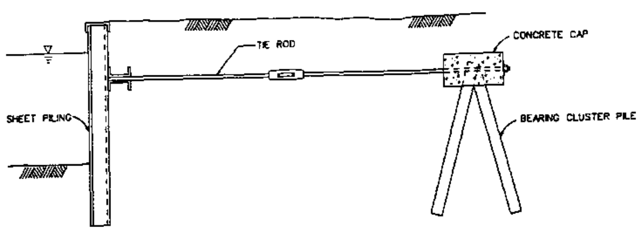
* Longer lengths may be possible upon request.

Types of Sheet Pile Walls

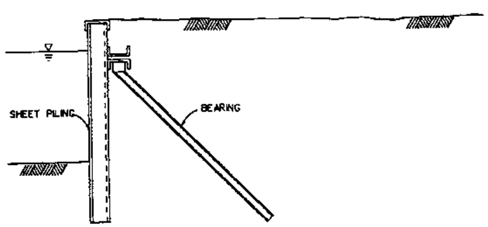


Cantilever and Anchored Walls

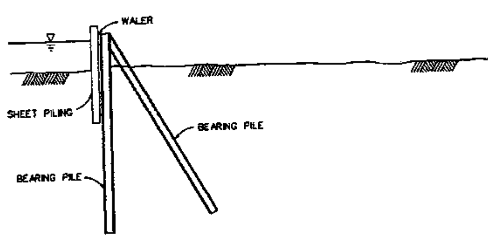
- Anchored Walls
  - Walls which have additional supports buried in the soil (tiebacks)



d. Tie rods and A-frame



e. Steel H-pile tension anchors

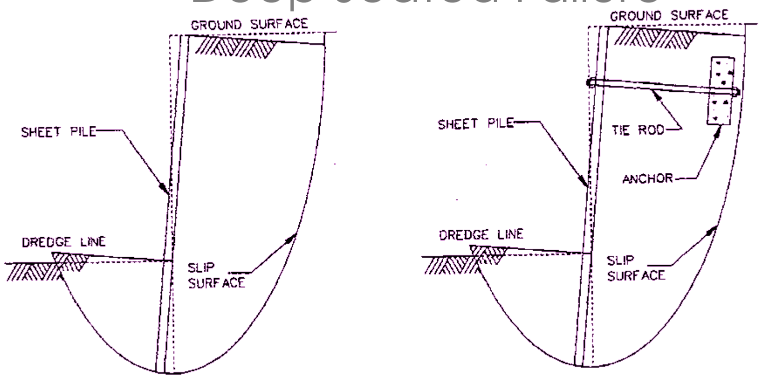


f. Steel H-pile anchors

- Cantilever Walls
  - Walls which have no additional supports, and which rely on the lateral earth pressures in the lower portion of the wall to support the earth in the upper portion
  - Limited in height and soil type
  - Almost exclusively done with steel piling
  - Generally restricted to temporary structures

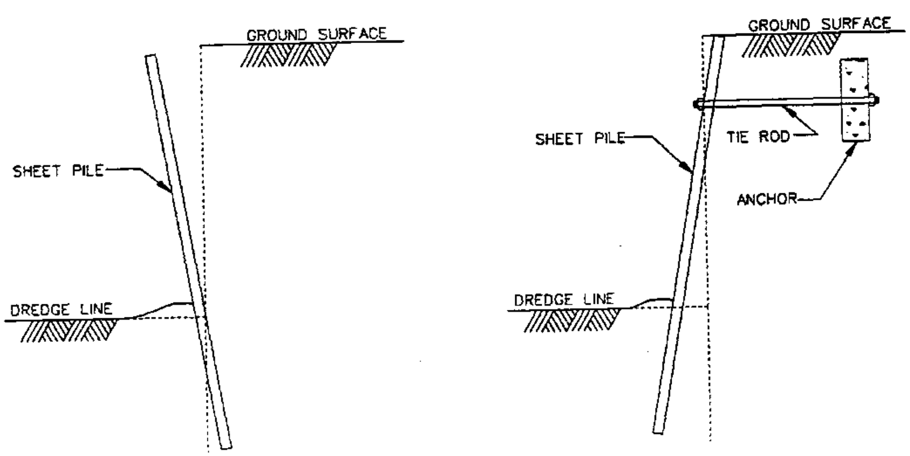
Failure of Sheet Pile Walls

- Geotechnical Failure
  - Deep Seated Failure



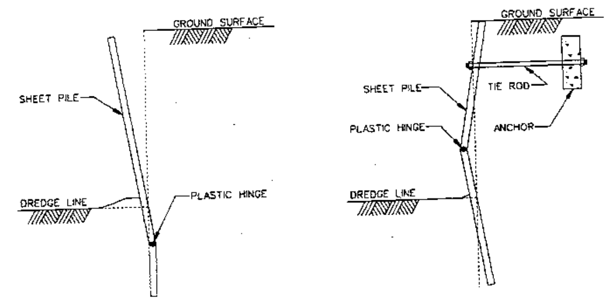
a. Cantilever wall　b. Anchored wall

  - Inadequate Penetration



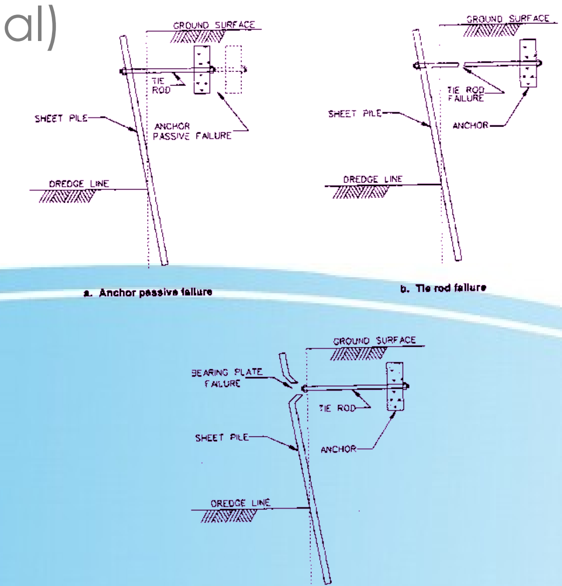
a. Cantilever wall　b. Anchored wall

- Structural Failure
  - Flexural Failure



a. Cantilever wall　b. Anchored wall

  - Anchorage Failure (can be geotechnical)

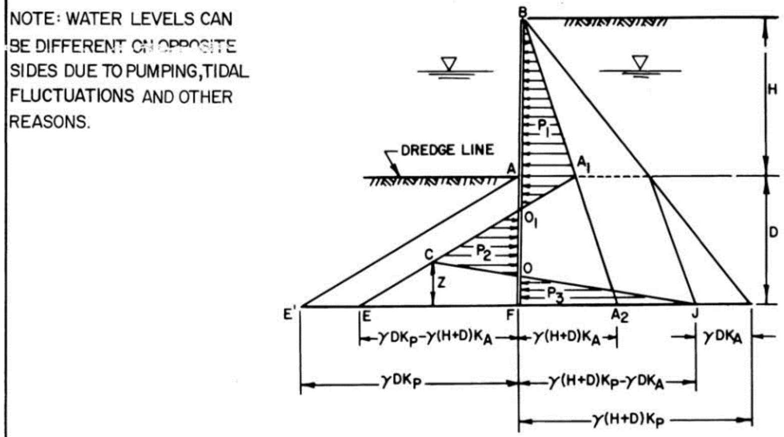


a. Anchor passive failure　b. Tie rod failure　c. Wale system failure

Methods of Solution for Cantilever Walls

- Conventional Method
  - Involves analysing active and passive pressures on sheet pile wall per layer
  - Traditionally the most common method used
  - Versatile but requires some experience for proficiency
  - Complex soil profiles can be difficult
- Simplified Method
  - Variation of conventional method
  - Eliminates problems at wall toe
  - Still requires some proficiency
- Chart Method
  - Very straightforward to use
  - Only applicable to simplest cases
  - Good check on other methods
- Closed Form Solution
  - Math complex but more straightforward
  - Limited number of cases
- Computer Software
  - For complex soil profiles, only practical solution

Design of Cantilever Walls: Conventional Method



1. Assume a trial depth of penetration, D. This may be estimated from the following approximate correlation.

Standard Penetration Resistance, N Blows/foot	Depth of Penetration*
0 - 4	2.0H
5 - 10	1.5H
11 - 30	1.25H
31 - 50	1.0H
+50	0.75H

* H = height of piling above dredge line

2. Determine the active and passive lateral pressure using appropriate coefficients of lateral earth pressure. If the Coulomb method is used, it should be used conservatively for the passive pressure.
3. Satisfy the requirements of static equilibrium: the sum of the forces in the horizontal direction must be zero and the sum of the moments about any point must be zero. The sum of the horizontal forces may be written in terms of pressure areas:

$$\Delta(\overrightarrow{EA_1A_2}) - \Delta(\overleftarrow{FBA_2}) - \Delta(\overleftarrow{ECJ}) = 0$$

Solve the above equation for the distance, Z. For a uniform granular soil,

$$Z = \frac{K_P D^2 - K_A (H+D)^2}{(K_P - K_A)(H+2D)}$$

FIGURE 23
Analysis for Cantilever Wall

4. Take moments about point F. If sum of moments is other than zero, readjust D and repeat calculations until sum of moments around F is zero.
5. Compute maximum moment at point of zero shear.
6. Increase D by 20% - 40% to result in approximate factor of safety of 1.5 to 2.

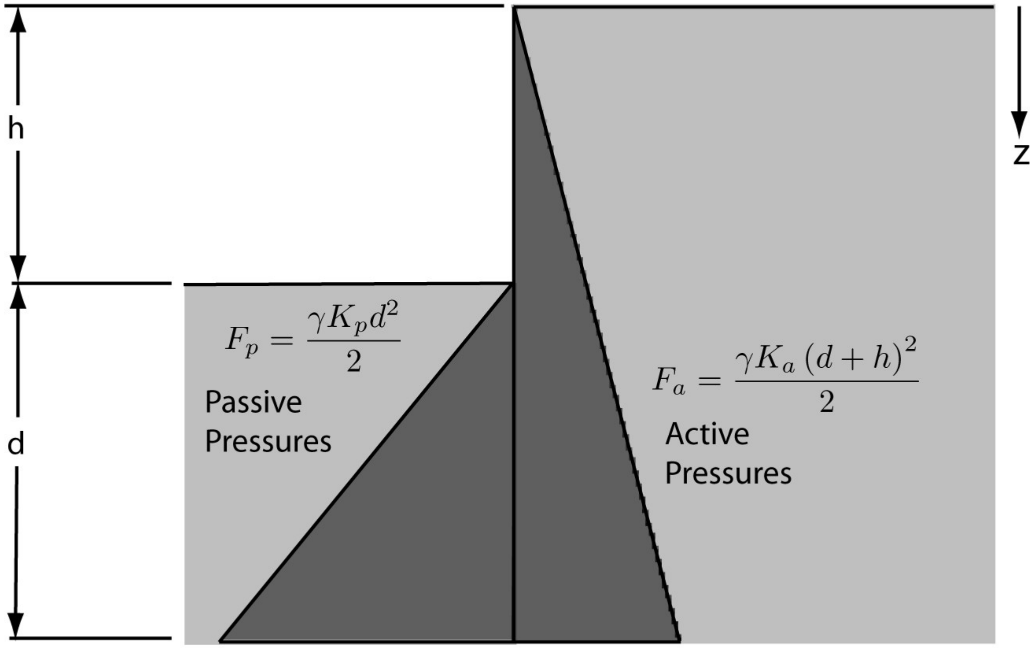
Notes:

a) For cantilever or anchored sheet pile walls, you may use either Rankine earth pressure coefficients for both Ka and Kp or the AASHTO scheme (Coulomb Ka/ log-spiral Kp).

b) Re item 6, a better of way of including the factor of safety is to divide the Kp by 1.5-2. Once this is done, no further consideration of factor of safety is necessary. Murthy suggests this for anchored walls but this is also acceptable for cantilever walls as well, and is better practice in both cases.

c) Do not confuse the method in 6 with the D increase in the "simplified" method discussed in Murthy. They are two entirely different factors. The D increase for the simplified method is a result of the method, not a factor of safety.

●Cantilever Method Closed Form Example: Cohesionless Soil, No Water, Simplified Method



- Simplified method eliminates pressure reversals at pile toe
- Active and passive forces on each side of wall shown, along with nomenclature
- Object is for moment at toe to be zero

Cantilever Method Closed Form Example: Cohesionless Soil, No Water, Simplified Method

- Changes in variables

$$\kappa = \frac{K_p}{K_a} \quad z' = \frac{z}{h} \quad d' = \frac{d}{h}$$

- Dimensionless moment equation at any point below the dredge line:

$$F(z) = 1/6\, {z'}^3 + 1/2\, {z'}^2 + 1/2\, z' + 1/6 - 1/6\, {z'}^3 \kappa$$

- Real root for zero moment at pile toe (solution for *d'* and thus *d*):

$$d' = \frac{\kappa^{2/3} + \sqrt[3]{\kappa} + 1}{\kappa - 1}$$

Note: for simplified method, necessary to add 20-40% to *d*

Cantilever Method Closed Form Example: Cohesionless Soil, No Water, Simplified Method

- Dimensionless shear equation below the dredge line:

$$\frac{\partial F\left(z'\right)}{\partial z'} = 1/2\,{z'}^{2} + z' + 1/2 - 1/2\,{z'}^{2}\kappa$$

- Distance *o* below dredge line for maximum moment

$$o' = \frac{o}{h} = \frac{1+\sqrt{\kappa}}{\kappa - 1}$$

- Value of maximum moment:

$$M_{max} = \frac{-\kappa - 2\,\kappa^{3/2} + 2\,\kappa^{5/2} + \kappa^{3}}{6\left(\kappa - 1\right)^{3}}\gamma K_a h^3$$

Cantilever Method Closed Form Example: Cohesionless Soil, No Water, Simplified Method—Example Problem

- Given
  - Dry cantilever wall, uniform cohesionless soil, level backfill
  - φ = 30°, γ = 109.2 pcf
  - Rankine conditions
  - h = 10'
  - Passive reduction factor of safety = 1.5
- Find
  - Penetration below dredge line
  - Maximum moment on sheeeting
- Solution
  - From Rankine theory, K_a = 1/3, K_p = 3
  - Reduce passive earth pressure coefficient, thus = K_p 3/1.5 = 2
  - From this κ = 2/(1/3) = 6
  - Equation for d':

$$d' = \frac{\kappa^{2/3} + \sqrt[3]{\kappa} + 1}{\kappa - 1}$$

  - Substituting, d' = 1.22, thus d = (1.22)(10') = 12.2
  - We will increase d for design for the simplified method, see next slide

Cantilever Method Closed Form Example: Cohesionless Soil, No Water, Simplified Method—Example Problem

- Solution
  - Equation for maximum moment:

$$M_{max} = \frac{-\kappa - 2\,\kappa^{3/2} + 2\,\kappa^{5/2} + \kappa^3}{6\,(\kappa - 1)^3}\gamma K_a h^3$$

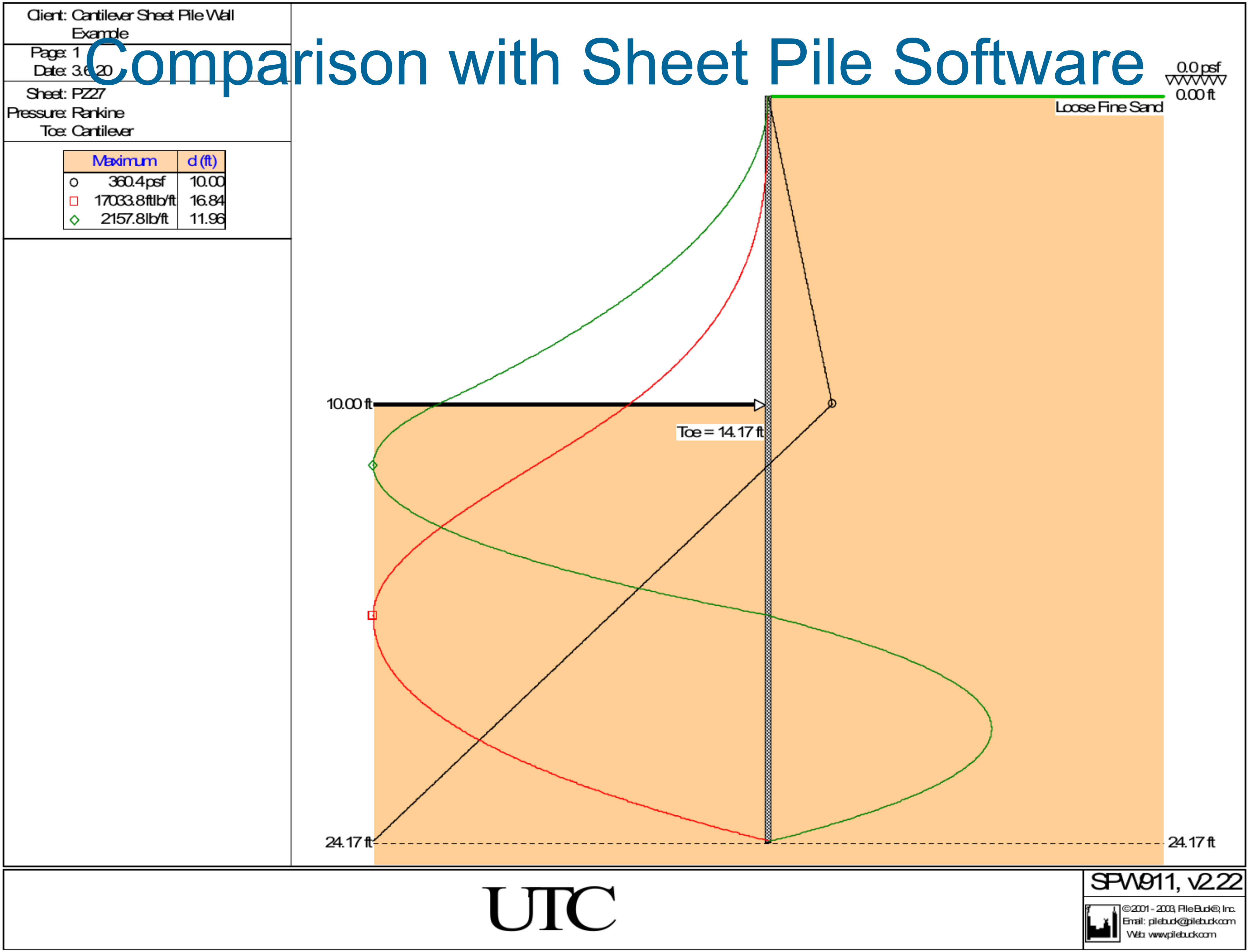
  - Substituting for maximum moment, M_{max} = (.476)(109.2)(1/3)(10)^3 = 17,325 ft-lb/ft of wall

- Solution
  - Location of maximum moment below dredge line:

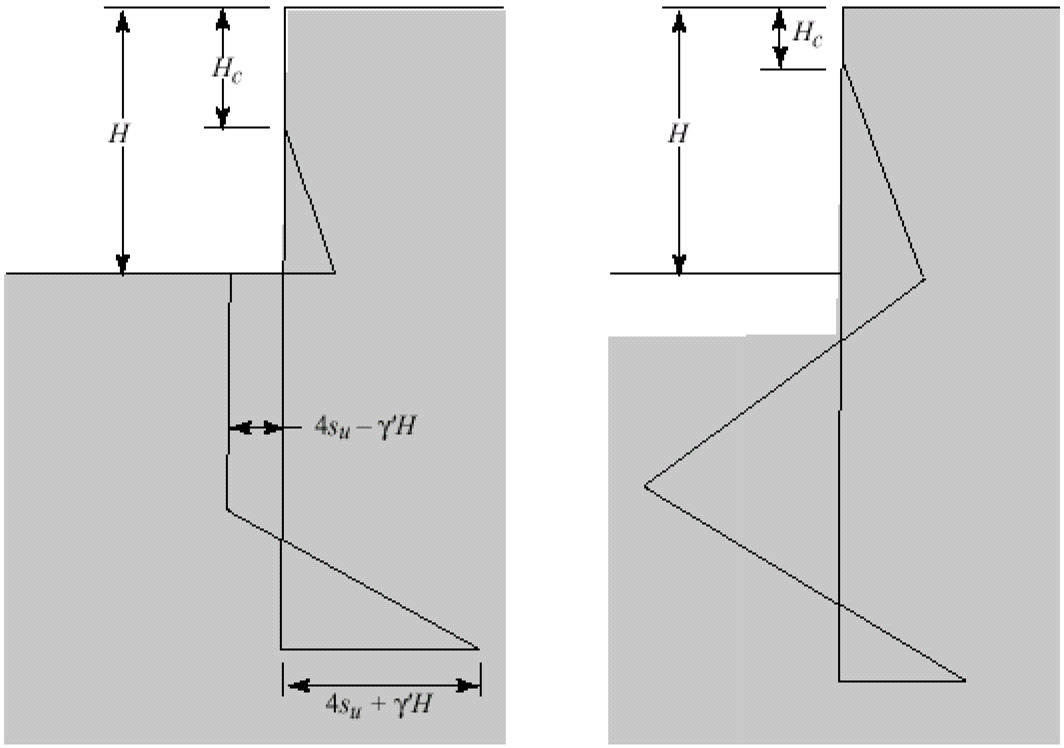
$$o' = \frac{o}{h} = \frac{1 + \sqrt{\kappa}}{\kappa - 1}$$

  - Substituting, *o'* = (.69)(10) = 6.9' below dredge line = 16.9 below top of wall
  - Increase in working *d* for simplified method: add 0.2*d* to *d*, thus 12.2 + 0.2(12.2) = 14.6'
    - This is actually conservative, traditionally simplified method used a shorter length, this done for simplicity

Comparison with Sheet Pile Software



Cantilever Piles in Clay



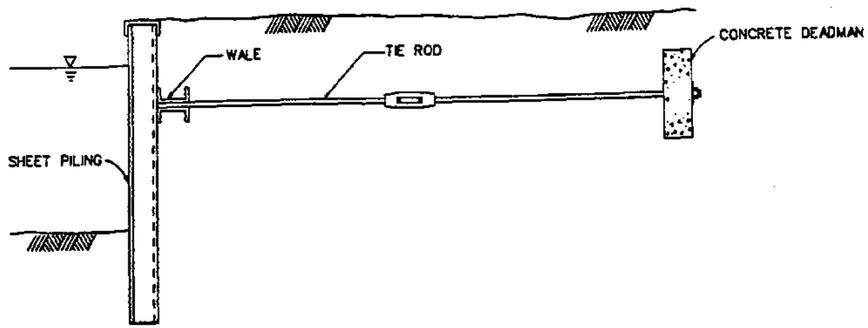
(a) (b)

- Two step analysis
  - Short term, where $\varphi = 0$ and $c = s_u$ (analyse for cohesion only)
  - Long term, where $\varphi > 0$ and $c > 0$ (use strengths from S (C-D) tests)
  - Include critical height considerations

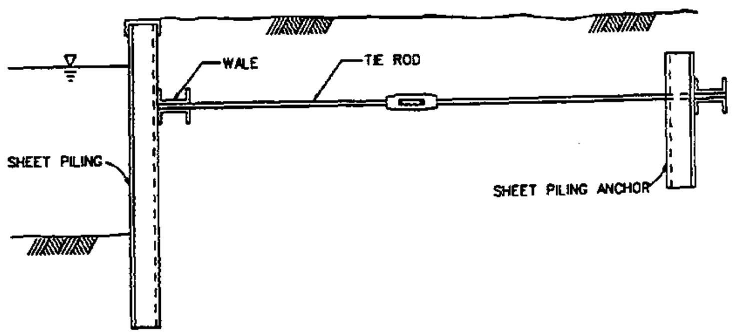
Anchored Sheet Pile Walls

- Includes an anchor or tieback at or near the head of the wall
- More than one set of anchors or tiebacks can be used
- Increases wall stability and enables taller walls to be built and sustained
- Almost a necessity with vinyl, aluminum and fiberglass sheet piles
- Not exclusive to sheet piling; also used with other types of in situ wall systems

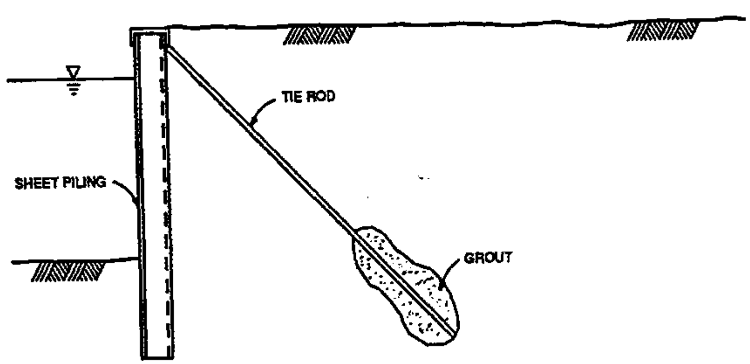
Anchored Sheet Pile Walls



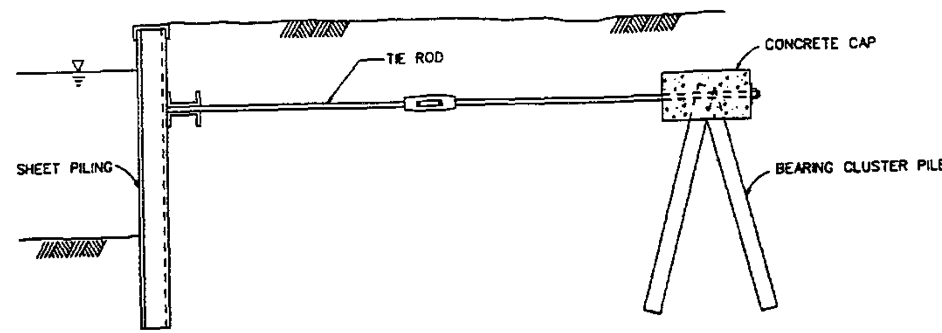
a. Tie rods and dead man



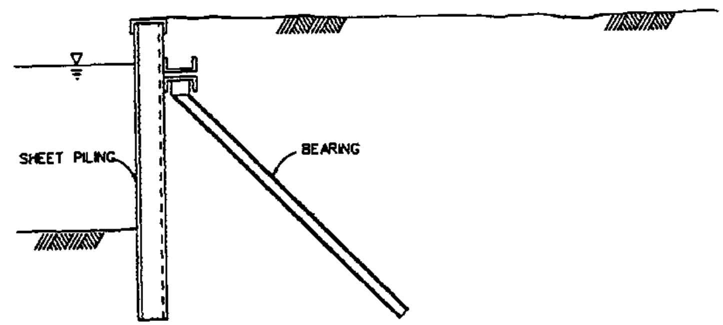
b. Tie rods and anchor wall



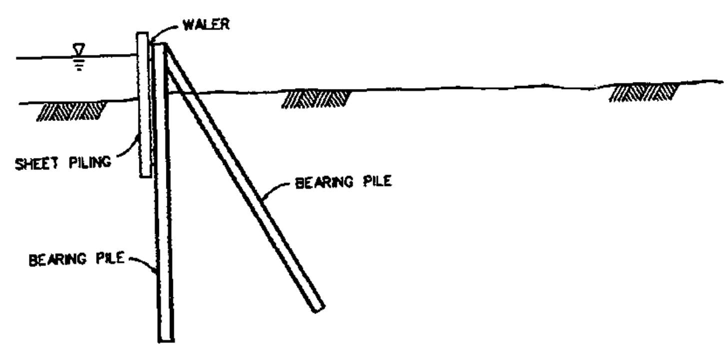
c. Tiebacks with grout anchor



d. Tie rods and A-frame

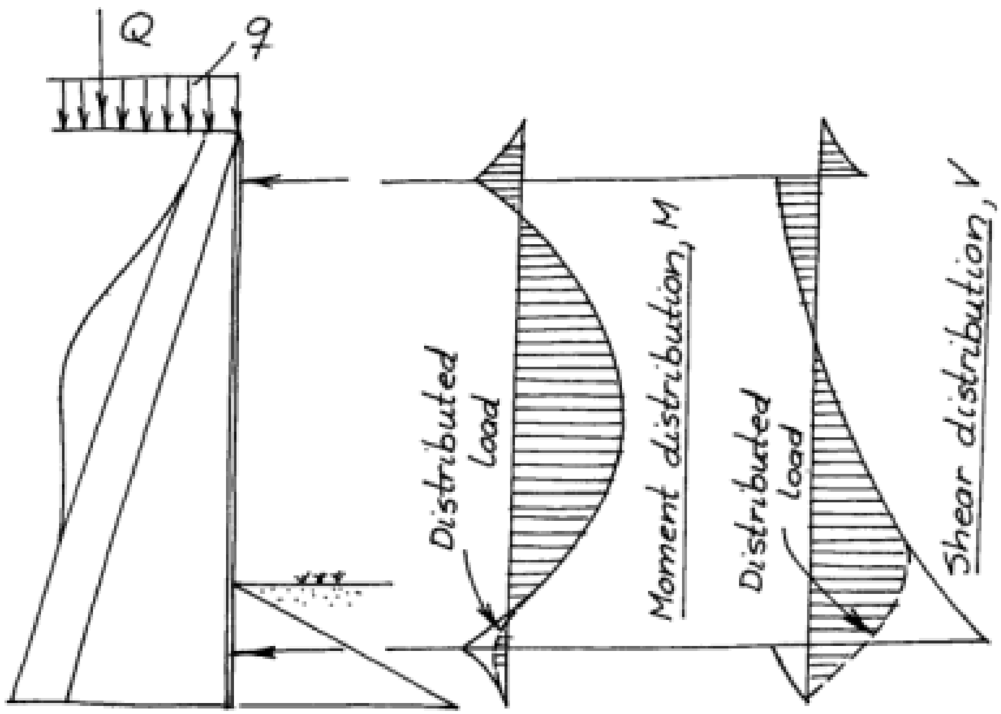


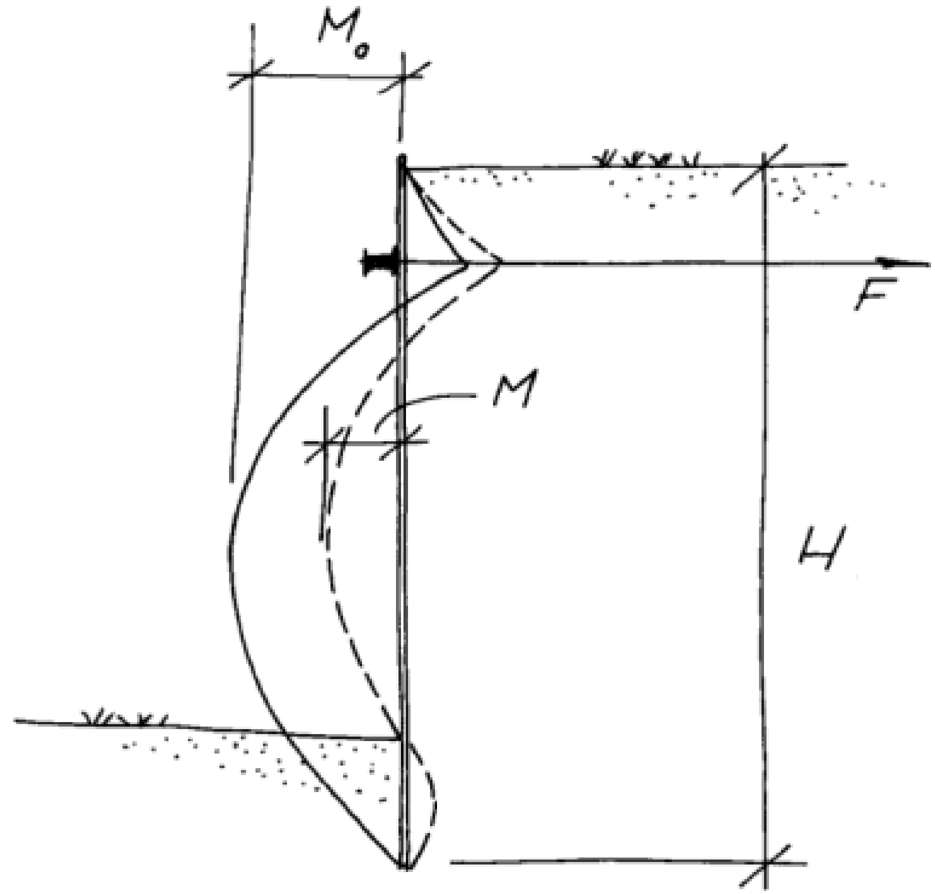
e. Steel H-pile tension anchors



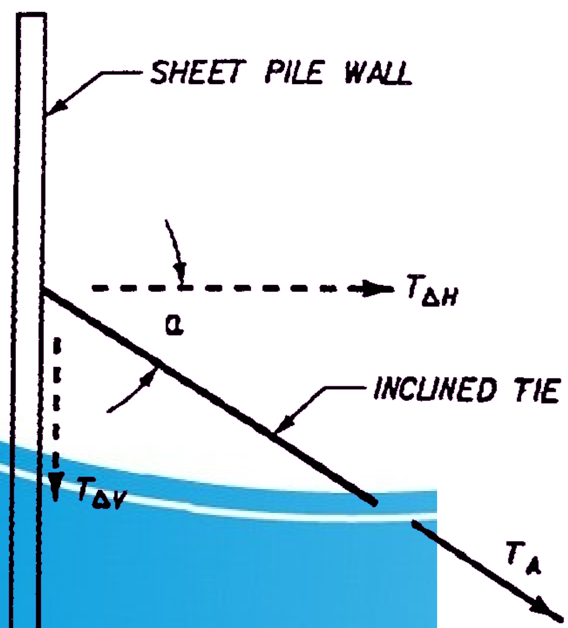
f. Steel H-pile anchors

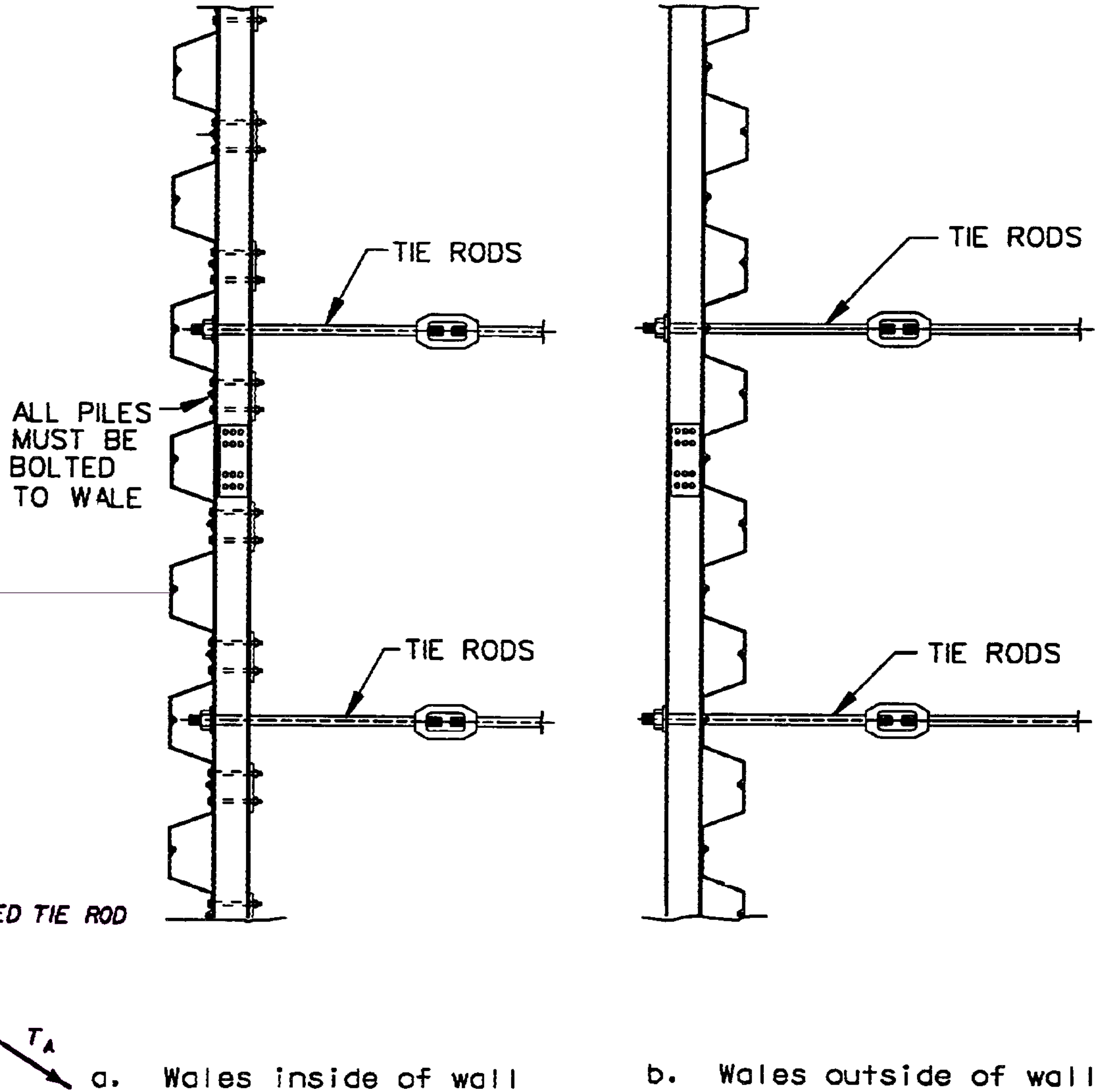
Distribution of Moment and Shear Along Anchored Walls





Wales and Tiebacks in Sheet Pile Walls





Analysis Methods for Anchored Walls

- Design Methods
  - Free Earth Support Method
    - Assumes lower end of the pile incapable of producing negative bending moments
    - Converts problem into a statically determinate one
    - Rowe's Moment Reduction Method used to take in to account flexibility of sheeting
      - Is unnecessary with SSI (soil-structure interaction) solutions such as SPW 2006
  - Fixed Earth Support Method/Blum's Method (Equivalent Beam Method)
    - Makes lower end has no angle like a cantilever beam, but no moment
    - Results in sheeting which is longer but has lower moment (and thus can be lighter)
    - Useful for some kinds of sheeting, more conservative
    - Also does not require Rowe's Moment Reduction
  - Beam on Elastic Foundation Method (generally w/plasticity considered)
- Implementation Methods
  - All of the methods used in cantilever walls can be used in anchored walls as well, with same strengths and weaknesses
  - Anchored walls are both simpler and more complex for hand solution than cantilever ones
  - Key for solution is to take moment around anchor point, solve for sheeting length and then compute anchor force
  - In this course, we will primarily use SPW2006 to analyze these walls
    - Stable wall is arrived at by varying the length of the wall
    - Solution doing this is basically free earth support method with SSI, obviating need for Rowe's moment reduction
  - Blum's Method
    - Discussed in Veruijt for simple cases
    - A more comprehensive closed-form solution is available

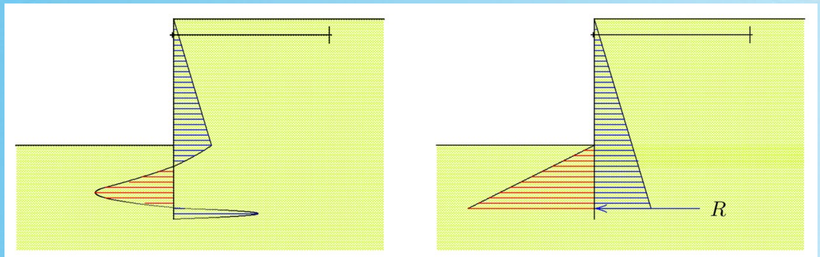


Figure 37.1: Blum's schematization.

Closed Form Example: No Water, Homogeneous Soil

- Similar to cantilever except now there is an anchor distance a from the wall top
- New variable *a' = a/h*

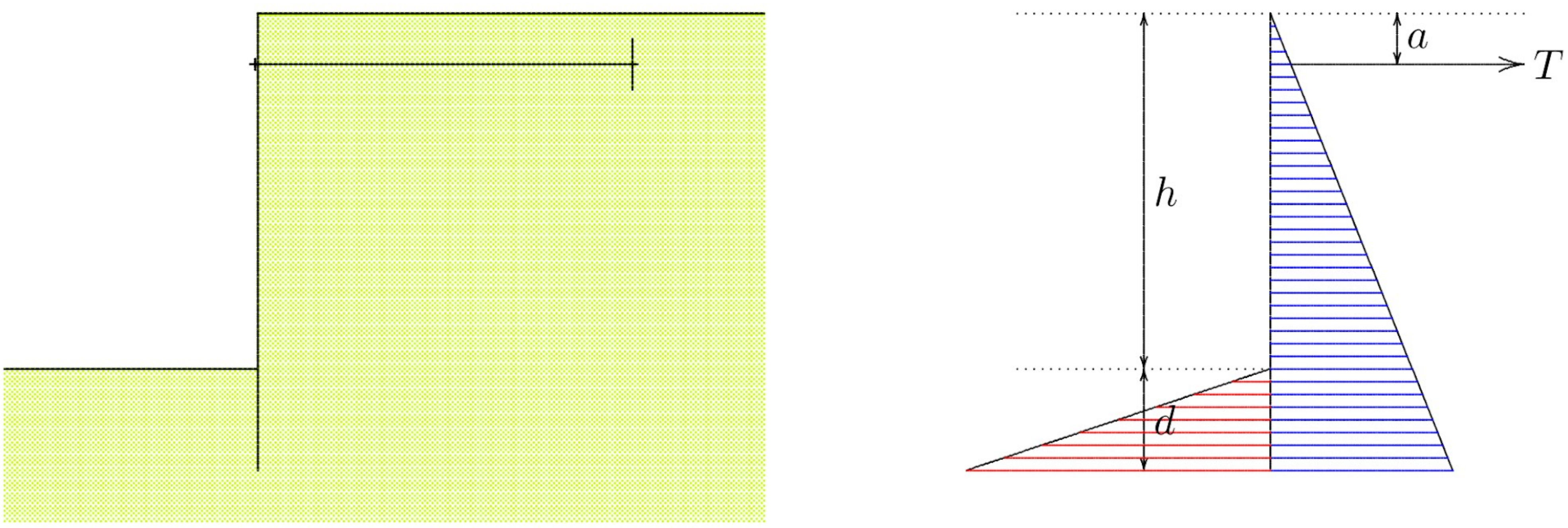


Figure 36.1: Anchored sheet pile wall.

Closed Form Example: No Water, Homogeneous Soil

- Governing Equations

1 Anchored Wall, Penetration Distance Equation:

$$1/3+d'-1/2\,a'+d'^2-d'\,a'+1/3\,d'^3-1/2\,d'^2\,a'-1/2\,\kappa\,d'^2-1/3\,\kappa\,d'^3+1/2\,\kappa\,d'^2\,a'=0$$

2 Anchor Pull Ratio to Active Earth Pressure:

$$\frac{2T}{K_a\gamma h^2\left(1+d'\right)^2}=\frac{1+2d'+d'^2\left(1-\kappa\right)}{\left(1+d'\right)^2}$$

3 Location of Maximum Moment:

$$z'=\sqrt{1+2d'+d'^2\left(1-\kappa\right)}$$

4 Dimensionless Maximum Moment:

$$\frac{M_{max}}{K_a\gamma h^3}=\left(\frac{1}{2}+d'+d'^2\frac{1-\kappa}{2}\right)\left(z'-a'\right)-\frac{z'^3}{6}$$

Closed Form Example: No Water, Homogeneous Soil

1

Values for d/h varying a/h and kappa	kappa											
a/h	4	5	6	7	8	9	10	11	12	13	14	15	16
0	0.793	0.644	0.550	0.486	0.438	0.401	0.371	0.347	0.326	0.309	0.294	0.280	0.269
0.05	0.785	0.637	0.545	0.481	0.433	0.396	0.367	0.343	0.323	0.305	0.290	0.277	0.265
0.1	0.777	0.630	0.539	0.475	0.428	0.392	0.363	0.339	0.319	0.301	0.287	0.274	0.262
0.15	0.768	0.623	0.532	0.469	0.422	0.386	0.358	0.334	0.314	0.297	0.282	0.270	0.258
0.2	0.759	0.615	0.524	0.462	0.416	0.380	0.352	0.329	0.309	0.292	0.278	0.265	0.254
0.25	0.749	0.605	0.516	0.454	0.409	0.374	0.346	0.323	0.303	0.287	0.273	0.260	0.249
0.3	0.737	0.595	0.507	0.446	0.401	0.366	0.339	0.316	0.297	0.281	0.267	0.254	0.243
0.35	0.724	0.584	0.496	0.436	0.392	0.358	0.330	0.308	0.289	0.273	0.260	0.248	0.237
0.4	0.710	0.571	0.484	0.425	0.381	0.348	0.321	0.299	0.281	0.265	0.252	0.240	0.229
0.45	0.693	0.556	0.470	0.412	0.369	0.336	0.310	0.288	0.270	0.255	0.242	0.230	0.220
0.5	0.674	0.538	0.454	0.396	0.354	0.322	0.296	0.275	0.258	0.243	0.230	0.219	0.209

2

Values for T/Fa varying a/h and kappa	kappa											
a/h	4	5	6	7	8	9	10	11	12	13	14	15	16
0	0.218	0.233	0.244	0.252	0.258	0.263	0.267	0.271	0.274	0.276	0.279	0.281	0.283
0.05	0.226	0.242	0.254	0.262	0.269	0.275	0.279	0.283	0.286	0.289	0.292	0.294	0.296
0.1	0.235	0.252	0.265	0.274	0.281	0.287	0.292	0.296	0.300	0.303	0.306	0.308	0.310
0.15	0.245	0.263	0.277	0.287	0.295	0.301	0.306	0.311	0.315	0.318	0.321	0.324	0.326
0.2	0.255	0.276	0.290	0.301	0.309	0.316	0.322	0.327	0.331	0.335	0.338	0.341	0.344
0.25	0.267	0.289	0.305	0.317	0.326	0.334	0.340	0.345	0.350	0.354	0.358	0.361	0.364
0.3	0.280	0.304	0.321	0.334	0.345	0.353	0.360	0.366	0.371	0.376	0.380	0.383	0.387
0.35	0.294	0.321	0.340	0.354	0.366	0.375	0.383	0.390	0.395	0.400	0.405	0.409	0.413
0.4	0.311	0.340	0.361	0.377	0.390	0.401	0.409	0.417	0.423	0.429	0.434	0.439	0.443
0.45	0.329	0.362	0.386	0.404	0.419	0.431	0.441	0.449	0.456	0.463	0.469	0.474	0.478
0.5	0.351	0.388	0.415	0.436	0.453	0.466	0.478	0.488	0.496	0.504	0.510	0.516	0.521

Closed Form Example: No Water, Homogeneous Soil

Values of z/h for maximum moment varying a/h and kappa						3 kappa							
a/h	4	5	6	7	8	9	10	11	12	13	14	15	16
0	0.837	0.794	0.766	0.746	0.730	0.718	0.709	0.701	0.694	0.688	0.683	0.679	0.675
0.05	0.849	0.806	0.778	0.758	0.743	0.732	0.722	0.714	0.707	0.702	0.697	0.692	0.688
0.1	0.862	0.819	0.792	0.772	0.757	0.746	0.736	0.728	0.722	0.716	0.711	0.707	0.703
0.15	0.875	0.833	0.806	0.787	0.772	0.761	0.751	0.744	0.737	0.731	0.727	0.722	0.719
0.2	0.889	0.848	0.821	0.802	0.788	0.776	0.767	0.760	0.753	0.748	0.743	0.739	0.735
0.25	0.903	0.863	0.837	0.818	0.804	0.793	0.785	0.777	0.771	0.766	0.761	0.757	0.753
0.3	0.919	0.879	0.854	0.836	0.822	0.812	0.803	0.796	0.790	0.785	0.781	0.777	0.773
0.35	0.935	0.897	0.872	0.855	0.842	0.832	0.823	0.817	0.811	0.806	0.802	0.798	0.795
0.4	0.953	0.916	0.892	0.875	0.863	0.853	0.845	0.839	0.833	0.829	0.825	0.821	0.818
0.45	0.972	0.936	0.914	0.898	0.886	0.877	0.869	0.863	0.858	0.854	0.850	0.847	0.844
0.5	0.992	0.958	0.937	0.922	0.911	0.903	0.896	0.891	0.886	0.882	0.879	0.876	0.873

Values of Mmax varying a/h and kappa						4 kappa							
a/h	4	5	6	7	8	9	10	11	12	13	14	15	16
0	0.196	0.167	0.150	0.138	0.130	0.124	0.119	0.115	0.111	0.109	0.106	0.104	0.102
0.05	0.186	0.158	0.142	0.131	0.123	0.117	0.112	0.109	0.106	0.103	0.101	0.099	0.097
0.1	0.176	0.150	0.134	0.124	0.116	0.110	0.106	0.102	0.099	0.097	0.095	0.093	0.091
0.15	0.166	0.141	0.126	0.116	0.109	0.103	0.099	0.096	0.093	0.090	0.088	0.086	0.085
0.2	0.155	0.131	0.117	0.108	0.101	0.096	0.092	0.089	0.086	0.084	0.082	0.080	0.078
0.25	0.144	0.121	0.108	0.099	0.093	0.088	0.084	0.081	0.079	0.076	0.075	0.073	0.072
0.3	0.132	0.111	0.098	0.090	0.084	0.079	0.076	0.073	0.071	0.069	0.067	0.066	0.064
0.35	0.120	0.100	0.088	0.080	0.075	0.071	0.067	0.065	0.063	0.061	0.059	0.058	0.057
0.4	0.107	0.088	0.077	0.070	0.065	0.061	0.058	0.056	0.054	0.052	0.051	0.050	0.049
0.45	0.093	0.076	0.066	0.060	0.055	0.052	0.049	0.047	0.045	0.043	0.042	0.041	0.040
0.5	0.079	0.064	0.055	0.049	0.045	0.042	0.039	0.037	0.036	0.034	0.033	0.032	0.031

Closed Form Example: No Water, Homogeneous Soil

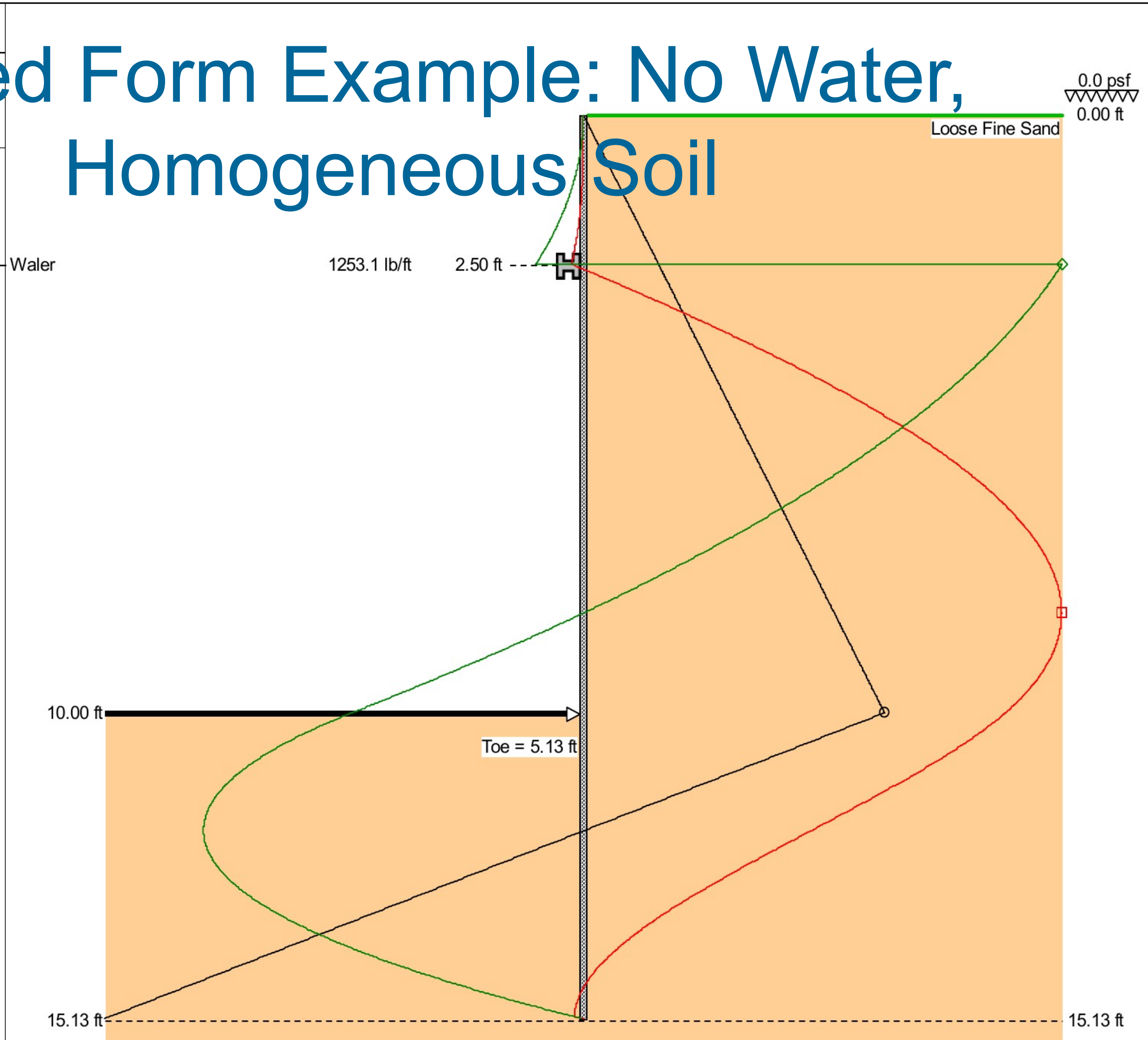
- Use the same basic variables as with cantilever case
  - Simply add an anchor at a depth of 2.5’ from the top, thus *a’* = 2.5/10=.25
- Ratios from equations:
  - *d’* = 0.516
  - Anchor Pull Ratio = 0.305
  - z’ for maximum moment = 0.837
  - Moment ratio = 0.108

- Determine actual quantities from ratios
  - d = (0.516)(10’) = 5.16’
  - T = (Anchor Pull Ratio)$K_a\gamma h^2(1+d')^2/2$ = (0.305)(1/3)(109.2)$(10)^2(1+.516)^2$ = 1274.6 lb/ft of wall
  - z = (0.837)(10) = 8.37’
  - M_{max} = (Moment Ratio) $K_a\gamma h^3$= (0.108)(1/3)(109.2)$(10)^3$ = 3924.5 ft-lb/ft

Closed Form Example: No Water, Homogeneous Soil

Client: Cantilever Sheet Pile Wall Example
Page: 1
Date: 4.6.20
Sheet: PZ27
Pressure: Rankine

	Maximum	d (ft)
○	360.4 psf	10.00
□	3823.5 ftlb/ft	8.33
◇	1139.1 lb/ft	2.50



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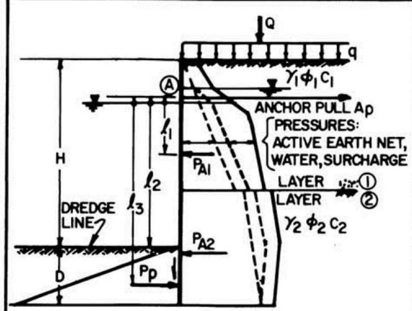
Free Earth Analysis of Anchored Walls



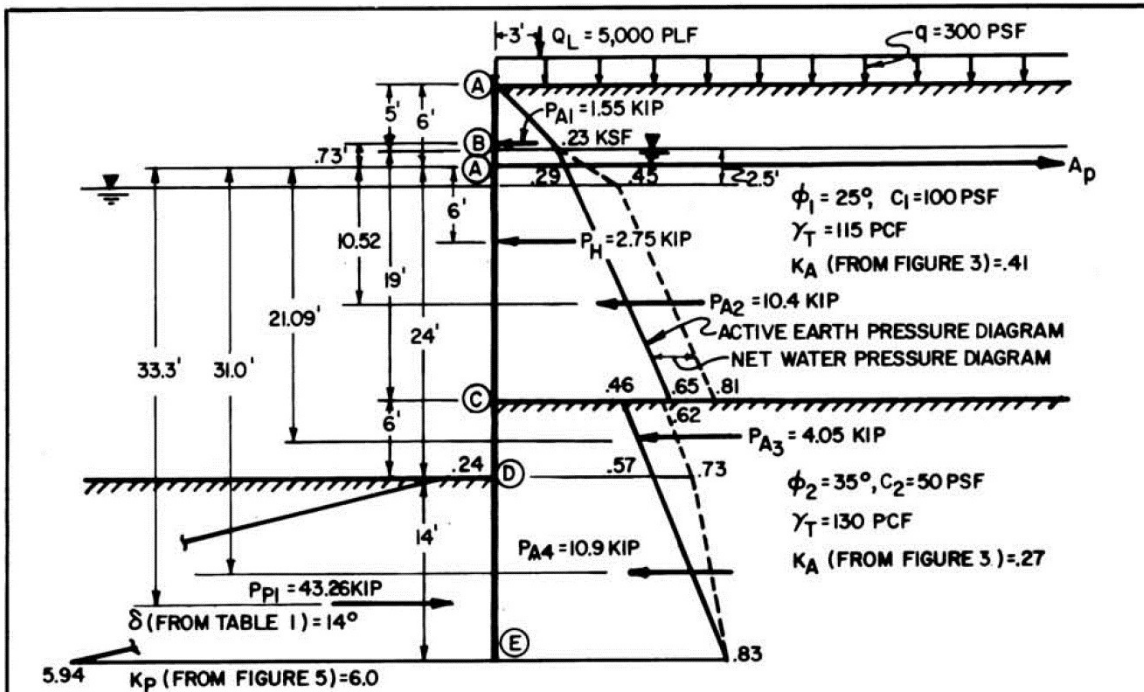
FREE EARTH SUPPORT – GENERAL CASE

1. COMPUTE PRESSURES BY METHODS OF FIGURES 2 TO 7 PASSIVE PRESSURES FOR CLEAN COARSE GRAIN SOILS INCLUDE WALL FRICTION (δ). TABLE I. FOR ACTIVE OR PASSIVE PRESSURES IN ALL OTHER SOIL TYPES, IGNORE WALL FRICTION.
2. DEPTH OF PENETRATION REQUIRED: TAKE MOMENTS ABOUT POINT Ⓐ AND SOLVE FOR D: $P_{A1}\ell_1 + P_{A2}\ell_2 = \frac{P_p}{F_S}\ell_3$
   F_S = 2 TO 3 FOR COARSE GRAINED SOILS
   F_S = 1.5 TO 2 FOR FINE GRAINED SOILS
3. ANCHOR PULL: $A_p = [P_{A1} + P_{A2} - P_p/F_S]\, d$, d = ANCHOR SPACING
4. MAXIMUM BENDING MOMENT ($M_{MAX.}$) IN SHEETING COMPUTED BY THE FREE EARTH SUPPORT METHOD AND APPLYING P_{A1}, P_{A2}, P_p/F_S AND A_p. FOR SHEETING IN SAND APPLY MOMENT REDUCTION FOR FLEXIBILITY OF FIGURE 19.
5. INCRESE PENETRATION COMPUTED (D) BY 20% TO ALLOW FOR DREDGING, SCOUR, ETC.

Notes:

a) #1, "methods of Figures 2-7" refer to methods of computing Ka and Kp and lateral earth pressures previously discussed.

b) #5, same note as with cantilever walls; however, however, consider subsequent changes in level of "dredge line" when designing wall



ACTIVE EARTH PRESSURE (SEE FIGURE 2)
INCLUDING UNIFORM SURCHARGE q

$\sigma_H = \gamma Z K_A - 2C\sqrt{K_A}$

Ⓐ, $\sigma_H = .30 \times .41 - 2 \times .10\sqrt{.41} = 0$

Ⓑ, $\sigma_H = (.30 + 5 \times .115).41 - 2 \times .10\sqrt{.41} = .23$ KSF

Ⓒ, $\sigma_H = (.30 + 5 \times .115 + 19 \times .053).41 - 2 \times .10\sqrt{.41} = .65$ KSF

Ⓒ, $\sigma_H = (.30 + 5 \times .115 + 19 \times .053).27 - 2 \times .05\sqrt{.27} = .46$ KSF

Ⓓ, $\sigma_H = .46 + 6 \times .068 \times .27 = .57$ KSF

Ⓔ, $\sigma_H = .46 + (6 + 14) \times .068 \times .27 = .83$ KSF

PRESSURE OF LINE LOAD SURCHARGE
(SEE FIGURE 11)

$m = \frac{X}{H} = \frac{3}{30} = 0.1$

$P_H = 0.55\, Q_L = 0.55 \times 5 = 2.75$ KIP

LOCATION OF RESULTANT:
$R = .60\,H = .60 \times 30 = 18'$

NET WATER PRESSURE

$\sigma_W = \gamma_W Z = .0625 \times 2.5 = .16$ KSF

PASSIVE PRESSURE

$\sigma_H = \gamma Z K_P + 2C\sqrt{K_P}$

Ⓓ, $\sigma_H = 0 + 2 \times .05\sqrt{6.0} = .24$ KSF

Ⓔ, $\sigma_H = .068 \times 14 \times 6.0 + 2 \times .05\sqrt{6.0} = 5.94$ KSF

SAFETY FACTOR AGAINST TOE FAILURE:
TAKE MOMENTS ABOUT Ⓐ

$F_S = \frac{\Sigma \text{ MOMENTS OF PASSIVE FORCES}}{\Sigma \text{ MOMENTS OF ACTIVE FORCES}}$

$= \frac{43.26 \times 33.3}{1.55 \times 0.73 + 2.75 \times 6 + 10.4 \times 10.52 + 4.05 \times 21.09 + 10.9 \times 31.0}$

$= 2.61 > 2.5$

ANCHOR PULL

$A_p = \Sigma P_A - \Sigma P_p / F_s$
$= 1.55 + 2.75 + 10.4 + 4.05 + 10.9 - \frac{43.26}{2.5} = 12.37$ KIPS

MAXIMUM BENDING MOMENT IN SHEETING
POINT OF ZERO SHEAR:

$12.37 - 1.55 - 2.75 - .45X - .022 \times \frac{X^2}{2} = 0$

$X \cong 13.6'$ BELOW OUTSIDE WATER LEVEL

$M_{MAX} = 1.55 \times 15.7 + 12.37 \times 15.1 - 2.75 \times 9.1$
$- .45 \times \frac{13.6^2}{2} - .022 \times \frac{13.6^2}{2} \times 4.52 = 86.9$ FT-KIPS

MOMENT REDUCTION:
ASSUME: f_s = 27,000 PSI, E = 30,000,000 PSI
TRY ZP 32, I = 385.7 IN^4, S = 38.3 IN^3

ρ = (FROM FIGURE 19) = $\frac{(H+D)4}{EI}$

$\rho = \frac{(30 \times 12 + 14 \times 12)^4}{30{,}000{,}000 \times 385.7} = 6.7 \frac{IN^2}{LB}$

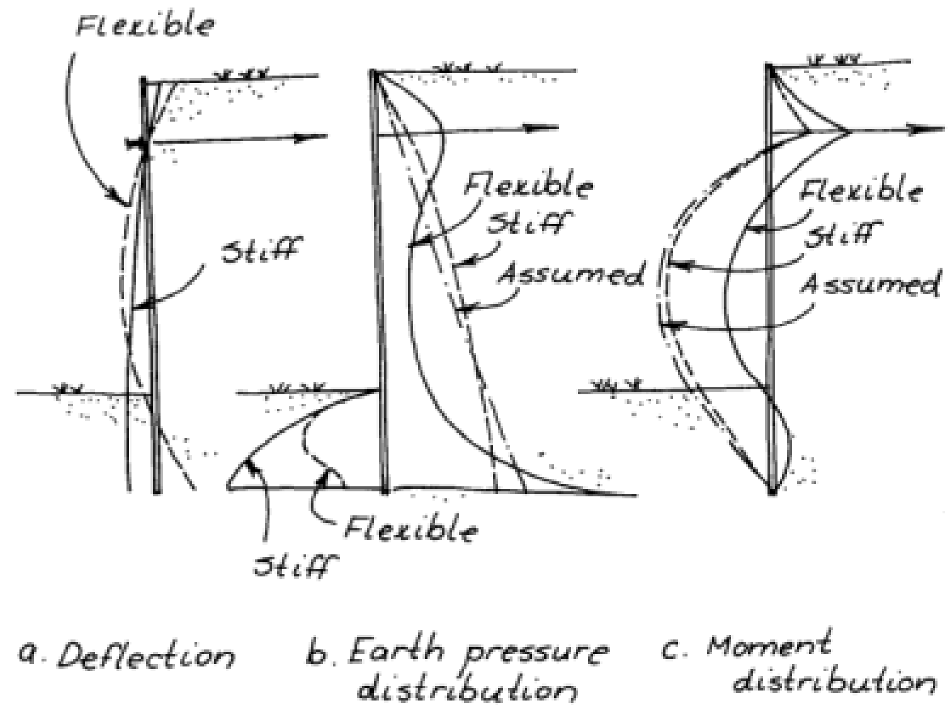
$\frac{M_{DESIGN}}{M_{MAX}} = .83$; $M_{DESIGN} = .83 \times 86.9 = 72.1$ FT-KIPS

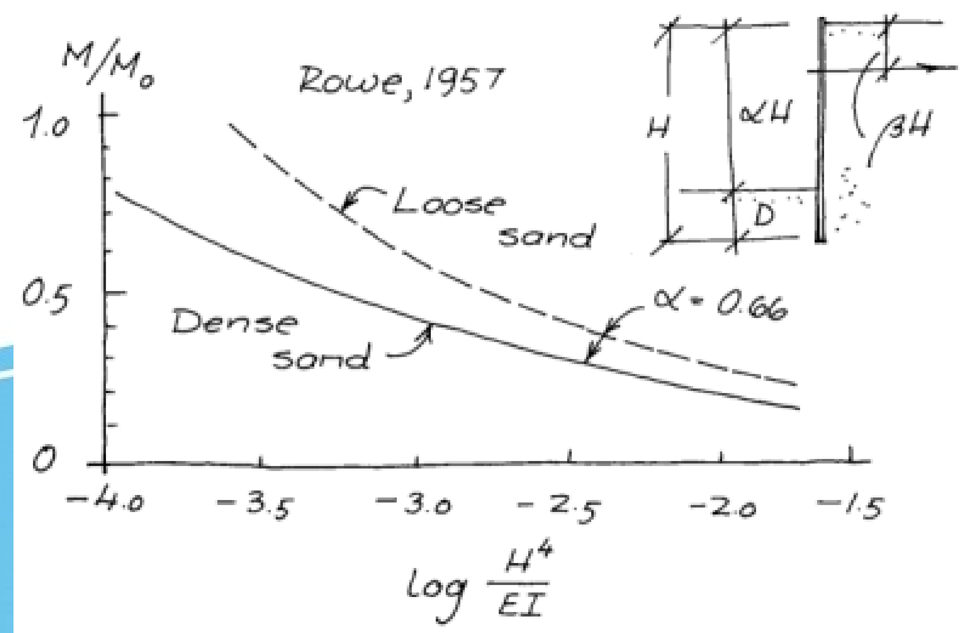
$f_s = \frac{M}{S} = \frac{72.1 \times 1000 \times 12}{38.3} = 22{,}600$ PSI < 27,000

TRY A SMALLER SECTION

Rowe's Moment Reduction Curves

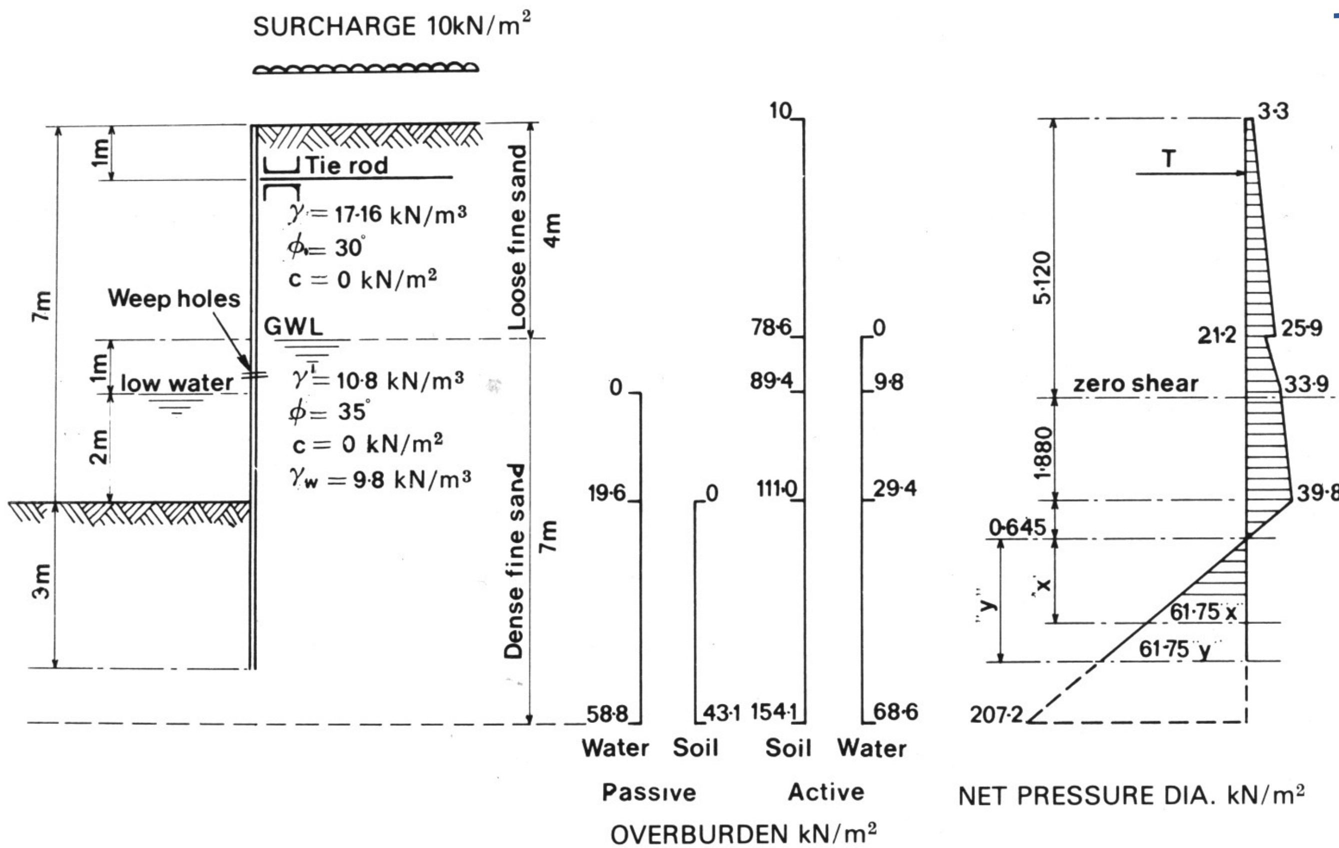
- Used to take into consideration the flexibility of the pile and its effect on relieving the actual bending moment the wall experiences
- Different set of curves for clay and sand





Free Earth Support—Example

Anchored Wall Example



Active Pressure $p_a = \gamma . h . K_a - 2c\sqrt{K_a} + p_w$ kN/m²

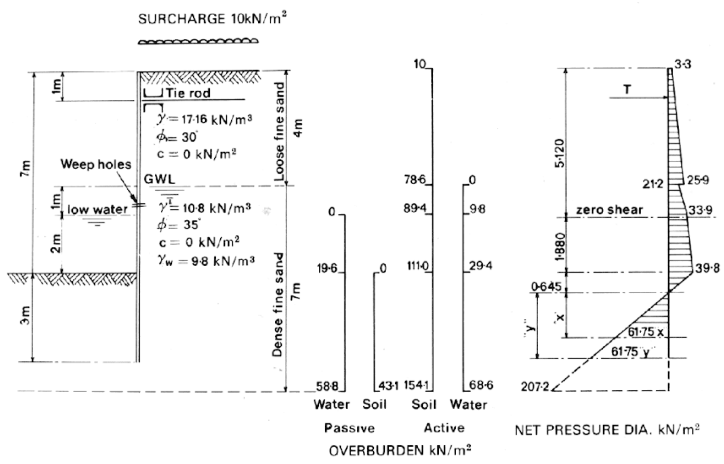
Passive Pressure $p_p = \gamma . h . K_p + 2c\sqrt{K_p} + p_w$ kN/m²

The coefficients of earth pressure are obtained from the tables in the section on earth and water pressures.

Loose fine sand: $K_a = 0{\cdot}33$ $K_p = 4{\cdot}9$; Compact find sand: $K_a = 0{\cdot}27$ $K_p = 6{\cdot}0$

Anchored Wall Example

Free Earth Support—Example



Active Pressure $p_a = \gamma.h.K_a - 2c\sqrt{K_a} + p_w$ kN/m²
Passive Pressure $p_p = \gamma.h.K_p + 2c\sqrt{K_p} + p_w$ kN/m²

The coefficients of earth pressure are obtained from the tables in the section on earth and water pressures.

Loose fine sand: $K_a = 0{\cdot}33$ $K_p = 4{\cdot}9$; Compact find sand: $K_a = 0{\cdot}27$ $K_p = 6{\cdot}0$

p_a at ground level	=	10 x 0·33	=	3·3 kN/m²
p_a at 4 m below ground level in loose fine sand	=	78·6 x 0·33	=	25·9 kN/m²
p_a at 4 m below ground level in dense fine sand	=	78·6 x 0·27	=	21·2 kN/m²
p_a at 5 m below ground level in dense fine sand	=	89·4 x 0·27 + 9·8	=	33·9 kN/m²
p_a at 7 m below ground level in dense fine sand	=	111·0 x 0·27 + 29·4	=	59·4 kN/m²
p_a at 11 m below ground level in dense fine sand	=	154·1 x 0·27 + 68·6	=	110·2 kN/m²
p_w at 7 m below ground level			=	19·6 kN/m²
p_p at 11 m below ground level in dense fine sand	=	43·1 x 6·0 + 58·8	=	317·4 kN/m²
Nett p_a at 7 m below ground level in dense fine sand	=	59·4 − 19·6	=	39·8
Nett p_p at 11 m below ground level in dense fine sand	=	317·4 − 110·2	=	207·2

Moments of Active Pressure about Tie Rod

ΣM ABOUT T = 0

MACTIVE − MPASSIVE = 0

3·3 x 4·000 x 0·5 x 0·333	=	2·2
25·9 x 4·000 x 0·5 x 1·667	=	86·4
21·2 x 1·000 x 0·5 x 3·333	=	35·3
33·9 x 1·000 x 0·5 x 3·667	=	62·2
33·9 x 2·000 x 0·5 x 4·667	=	158·2
39·8 x 2·000 x 0·5 x 5·333	=	212·3
39·8 x 0·645 x 0·5 x 6·215	=	79·8
		636·4 kN/m

Total Active Pressure = 172·5 kN

For stability the moment of Passive Pressure about the tie rod must be equal to, or not less than, the moment of Active Pressure about the tie rod.

SOLVE FOR MIN. DEPTH D,

$$\therefore \frac{61{\cdot}75x^2}{2}\left(6{\cdot}645 + \frac{2x}{3}\right) = 636{\cdot}4, \quad x \simeq 1{\cdot}63 \text{ m}$$

Total Net Passive Pressure = 61·75 x 1·63² x 0·5 = 82·0 kN   TOTAL MIN. PASSIVE

Moment of Nett Passive Pressure about tie rod = 82·0 x 7·732 = 634·0 kN/m   CHECK $M_A - M_P = 0$

Total Net Active Pressure = 172·5 kN
Force in Walings and Tie Rods = 172·5 − 82·0 = 90·5 kN/m run of wall $\Sigma F_H = 0$ $T = P_A - P_P$

Zero Shear (maximum bending moment) occurs at 5·120 m below ground level.

Moments about and below level of zero shear.

82·0 x 3·612	=	296·2
−34·3 x 1·880 x 0·5 x 0·627	=	−20·2
−39·8 x 1·880 x 0·5 x 1·250	=	−46·8
−39·8 x 0·645 x 0·5 x 2·095	=	−26·9
		202·3 kN/m

TAKE MOMENTS ABOVE AND BELOW ZERO SHEAR

B.M. on piles = 202·3 kNm/m run of wall

$$Z \text{ reqd.} = \frac{202{\cdot}3 \times 1000 \times 100}{125 \times 100} = 1618 \text{ cm}^3\text{/m run of wall}$$

Use Larssen No. 3/20 or Frodingham 3N

Penetration required to give a factor of safety of 2 against rotation of wall about the tie rod $= y + 0{\cdot}645 + 7{\cdot}000$

$$\text{To find "y"} \quad \frac{61{\cdot}75y^2}{2}\left(6{\cdot}645 + \frac{2y}{3}\right) = 2 \times 636{\cdot}4, \quad y \simeq 2{\cdot}24 \text{ m}$$

SAFETY FACTOR

Moments of Net Passive Pressure with 2·24 + 0·645 = 2·885 m cut-off
2·24 x 61·75 x 2·24 x 0·5 x 8·138 = 1260·7 kN/m

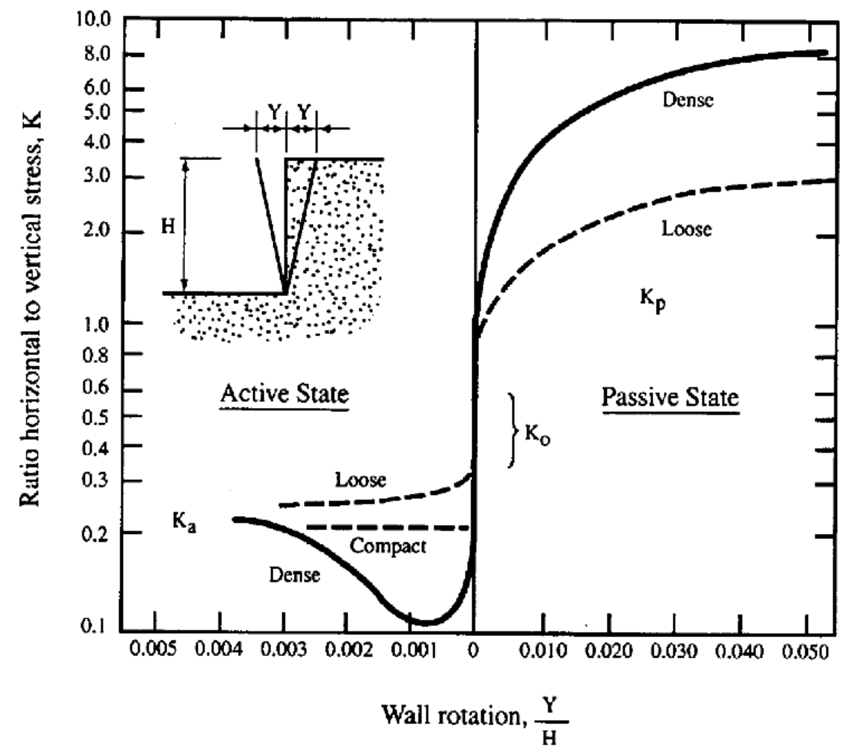
$$\text{S.F. against rotation} = \frac{1260{\cdot}7}{636{\cdot}4} = 1{\cdot}98$$

Penetration reqd. = 0·645 + 2·24 + 7 = 9·885 m

Use Larssen No. 3/20 or Frodingham No. 3N x 10·0 m long in Grade 43A steel

SPW 2006

- Simple software to use, does not require installation
- Input according to instructions
- For active-passive stroke, use chart at right or values in the previous slide set
    - Complete stroke Y/H should be sum of active and passive rotation values, depending upon the soil
    - Y/H sum is then multiplied by height H (as shown) to determine stroke



Magnitude of Wall Rotation to Reach Failure

Soil type and condition	Rotation, Y/H	
	Active	Passive
Dense cohesionless	0.001	0.02
Loose cohesionless	0.004	0.06
Stiff cohesive	0.010	0.02
Soft cohesive	0.020	0.04

Figure 10-4. Effect of wall movement on wall pressures (after Canadian Geotechnical Society, 1992).

Anchored Wall Example

Loading Step : 1 Left Side

No.	Soil Name	H	Wd	Ws	Zw	Cap	q	c	Ka	Kp	Kn	Dw
		m	kN/m³	kN/m³	m	m	kN/m²	kN/m²	--	--	--	m
1	Loose Fine Sanc	1.000	0.000	10.000	5.000	0.000	0.000	0.000	1.000	1.000	1.000	1.000
2	Loose Fine Sanc	3.000	0.000	10.000	5.000	0.000	0.000	0.000	1.000	1.000	1.000	1.000
3	Dense Fine San	1.000	0.000	10.000	5.000	0.000	0.000	0.000	1.000	1.000	1.000	1.000
4	Dense Fine San	2.000	0.000	10.000	5.000	0.000	0.000	0.000	1.000	1.000	1.000	1.000
5	ense Fine Sand	5.000	20.600	20.600	5.000	0.000	0.000	0.000	0.270	4.000	0.426	0.018

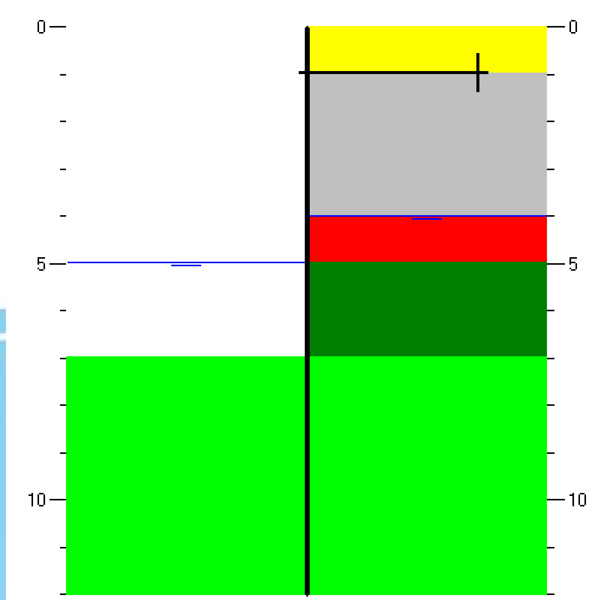
Loading Step : 1 Right Side

No.	Soil Name	H	Wd	Ws	Zw	Cap	q	c	Ka	Kp	Kn	Dw
		m	kN/m³	kN/m³	m	m	kN/m²	kN/m²	--	--	--	m
1	Loose Fine Sanc	1.000	17.160	17.160	4.000	0.000	10.000	0.000	0.333	3.260	1.000	0.056
2	Loose Fine Sanc	3.000	17.160	17.160	4.000	0.000	10.000	0.000	0.333	3.260	0.500	0.056
3	Dense Fine San	1.000	20.600	20.600	1.000	0.000	10.000	0.000	0.270	4.000	0.426	0.018
4	Dense Fine San	2.000	20.600	20.600	1.000	0.000	10.000	0.000	0.270	4.000	0.426	0.018
5	ense Fine Sand	5.000	20.600	20.600	1.000	0.000	10.000	0.000	0.270	4.000	0.426	0.018

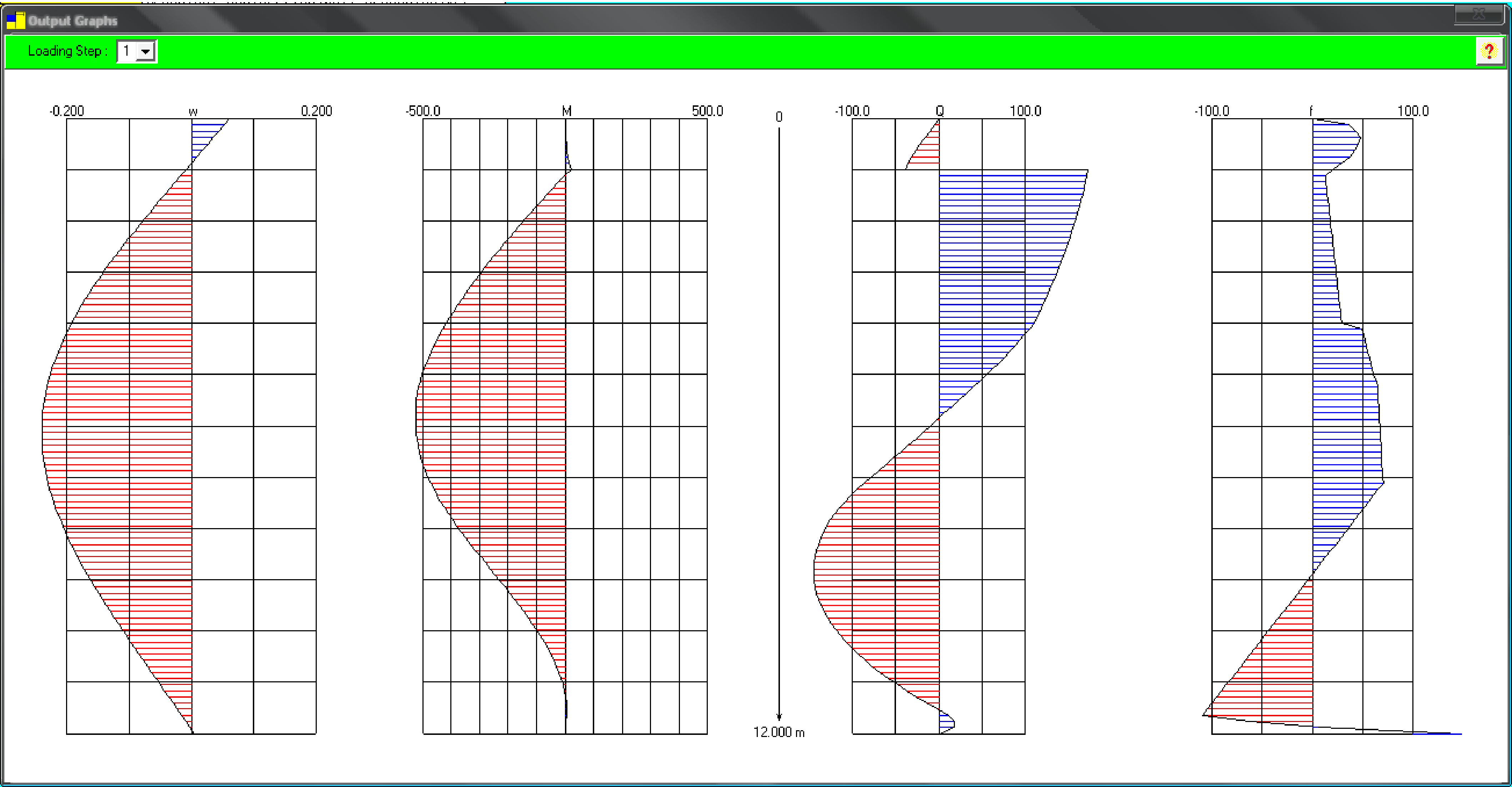
Loading Step : 1

No.	Depth	Fx	Fa	Dw
	m	kN/m	kN/m	m
0	0.000	0.000	0.000	1.000
1	1.000	0.000	500.000	-0.020
2	4.000	0.000	0.000	1.000
3	5.000	0.000	0.000	1.000
4	7.000	0.000	0.000	1.000
5	12.000	0.000	0.000	1.000

Loading Step : 1



Anchored Wall Example



Estimation of Maximum Moment using SPW 2006

- Sheet pile database has an unusual method of input for sheet pile properties
  - Modulus of elasticity "E"
  - "EI" product of modulus of elasticity and moment of inertia per meter of wall
  - "h" distance from neutral axis to face of sheeting = half of depth (this is different from way it's presented in tables)
- Conventional beam theory
  - $\sigma_{max} = (Mc)/I$
  - σ_{max} based on failure criterion, usually = σ_{yield}/FS
  - Maximum permissible stresses given for a variety of materials in previous slide set
- Substitutions using values in SPW 2006
  - I = "EI"/E
  - c = h
  - σ_{max} = (MEh)/("EI")
  - $M_{max} = \sigma_{max}$"EI"/Eh
- To determine whether sheeting meets structural requirements:
  - Determine σ_{max} based on alloy
  - Select section, which gives you "EI," E, h.
  - Determine maximum permissible moment for section using formula above
  - If moment from SPW2006 is greater, use heavier (greater I, h) section
- Valid for both cantilever and anchored walls
- For example:
  - Maximum moment = 520 kN-m/m
  - PZ-22 used in the example
    - h=.1145 m
    - EI = 24150.0 kN-m^2/m
    - E = 210 GPa
    - σ_{max} = 220 MPa (ASTM A 572 Gr. 50)
    - $M_{max} = \sigma_{max}$"EI"/Eh = (24150)(220)(1000)/(210)(1000000)(.1145) = 221 kN-m/m
    - This section is obviously too small; you will need to input a heavier section until you exceed the maximum moment

Free Earth Support Method (Blum)

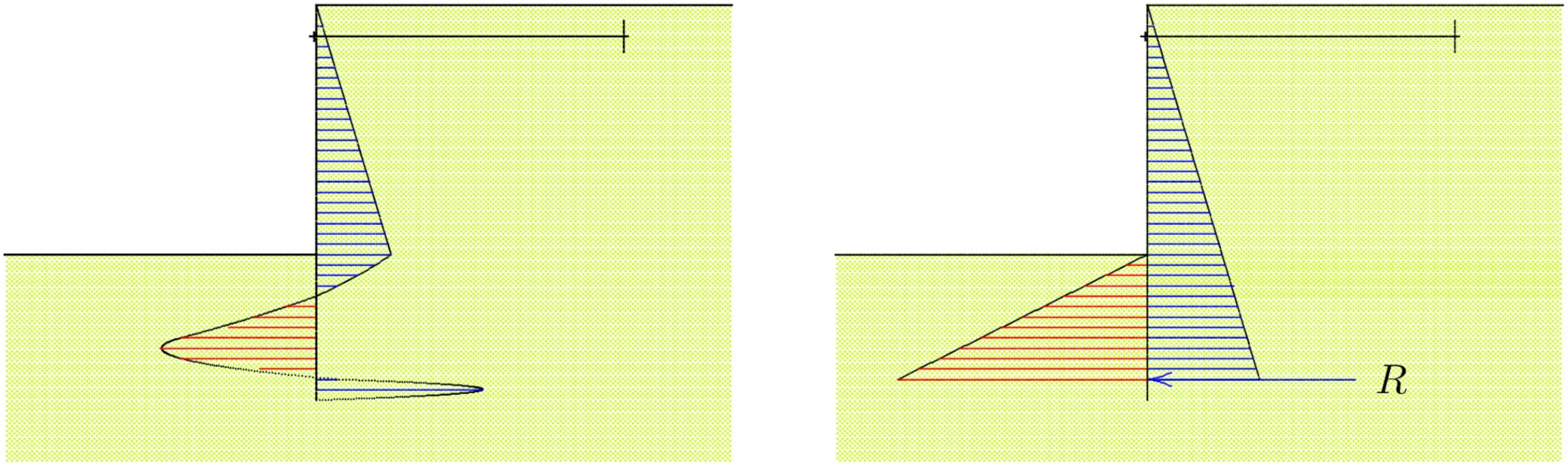


Figure 37.1: Blum's schematization.

Blum's method assumes that the pile toe has no moment, deflection or angle, but does have a reaction. The result is generally sheeting which is lighter than free earth support, but has more penetration. Verruijt has solutions for simple problems but a more comprehensive (and simpler) solution is online.

Tiebacks and Wales

Tieback Formulae:

$$T_{ah} = TS$$

where

- T_{ah} =load per tieback
- T =tieback load per foot of wall
- S =spacing between tiebacks

$$K_{ah} = 1/4\,\frac{E_{ah}\pi\,{d_{ah}}^2}{L_{ah}}$$

where

- K_{ah} =tieback stiffness per tieback
- E_{ah} =tieback modulus of elasticity
- d_{ah} =tieback diameter
- L_{ah} =tieback length

$$M_{\max} = 1/10\,TS$$

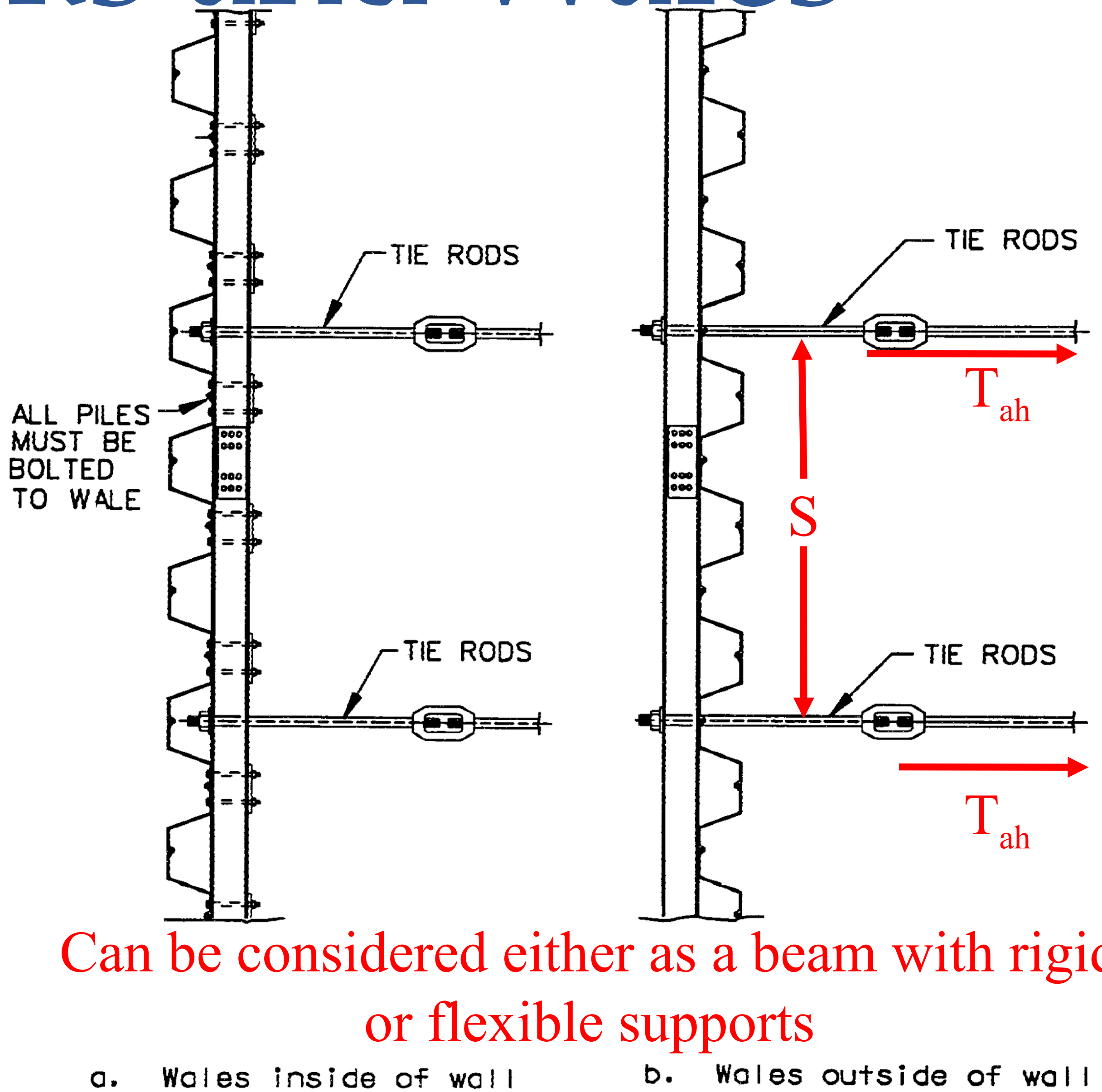
where

- M_{max} =maximum moment on wale

$$K = \frac{K_{ah}}{S}$$

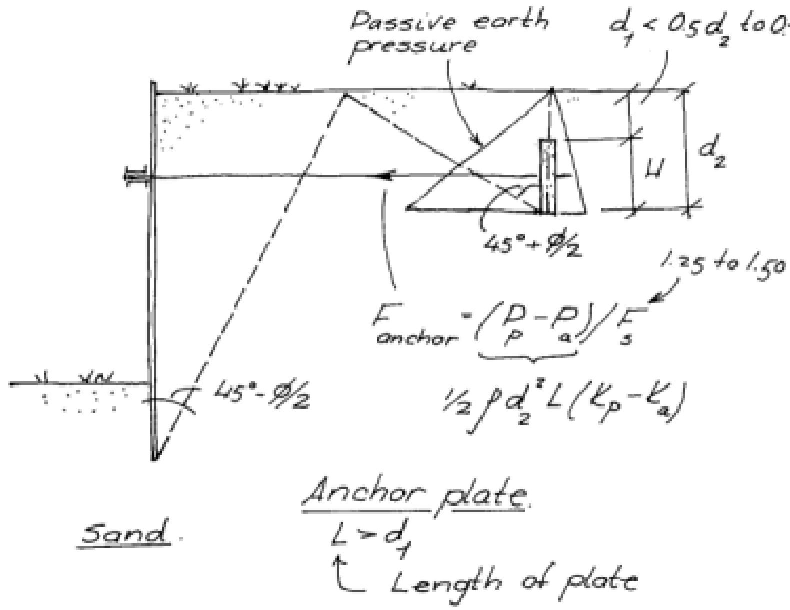
where

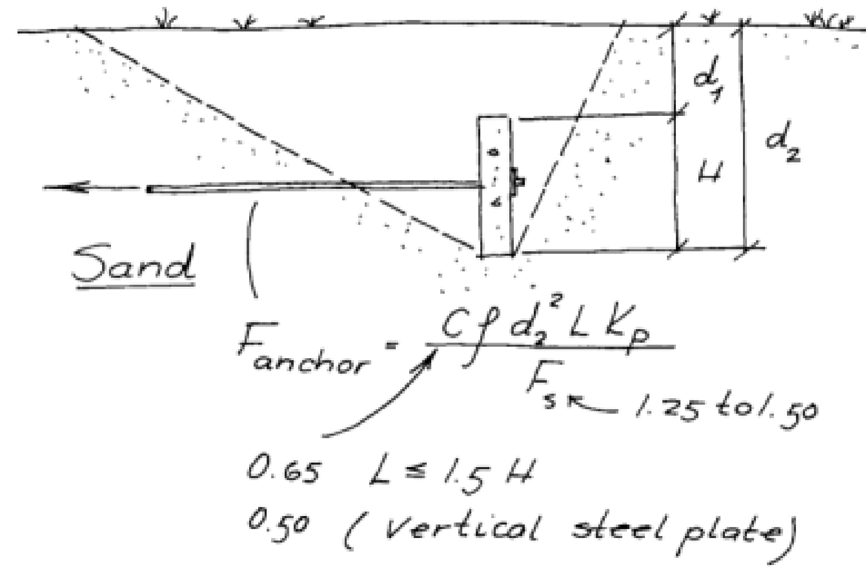
- K =combined stiffness per unit length of wall of tiebac

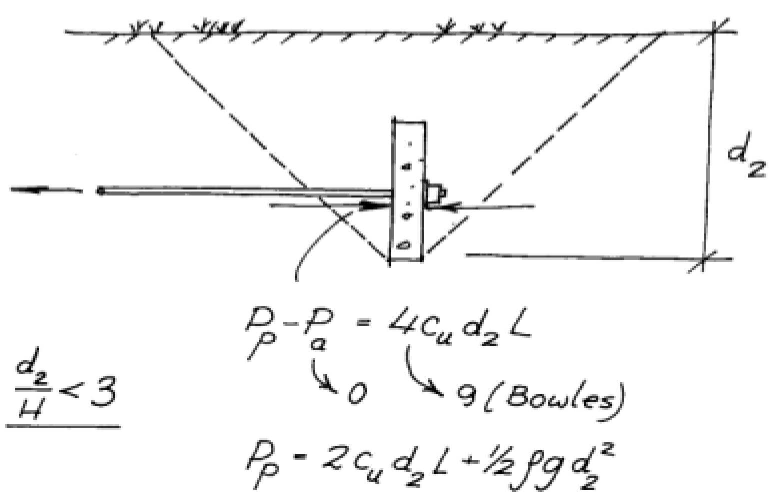


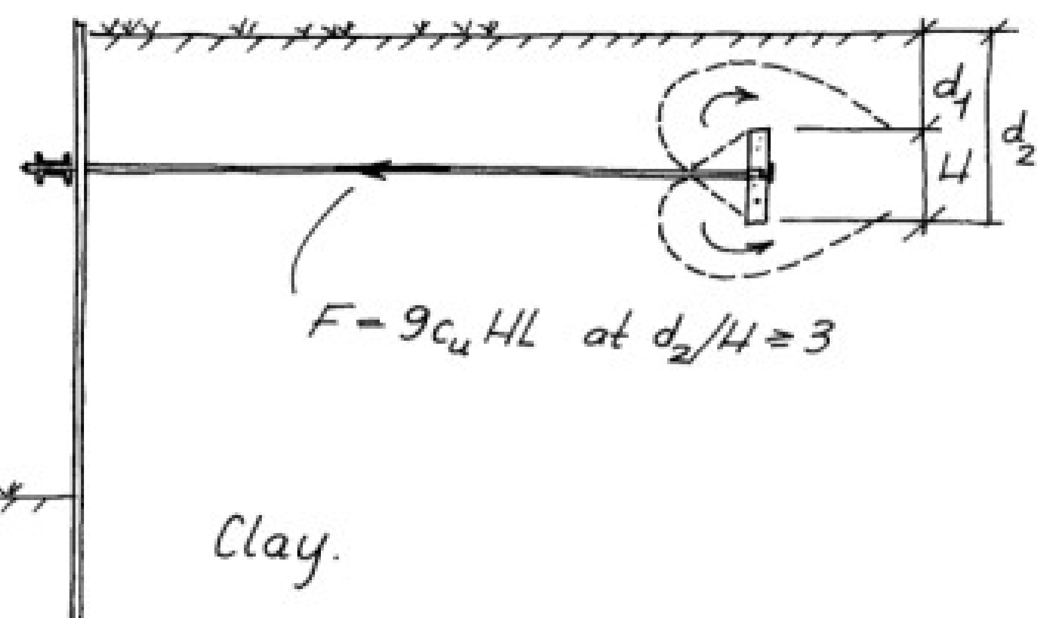
Can be considered either as a beam with rigid or flexible supports

Deadman Anchor Design

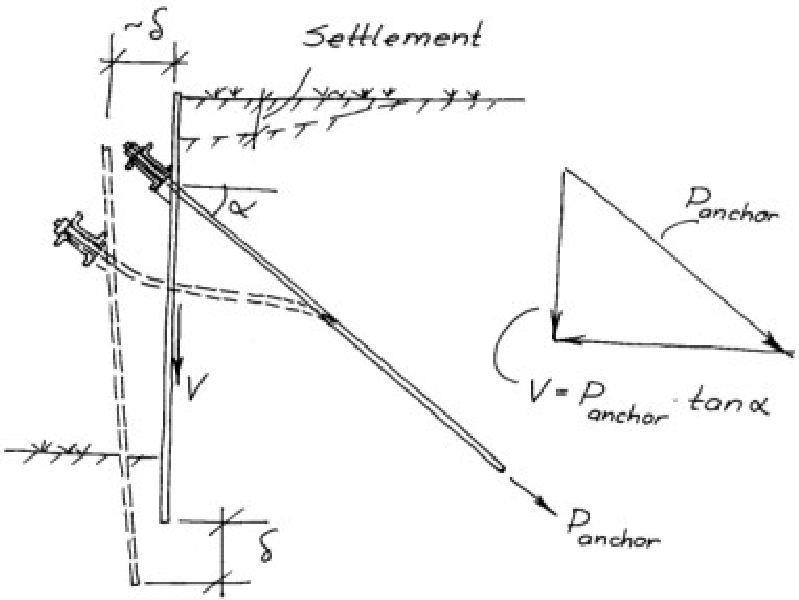


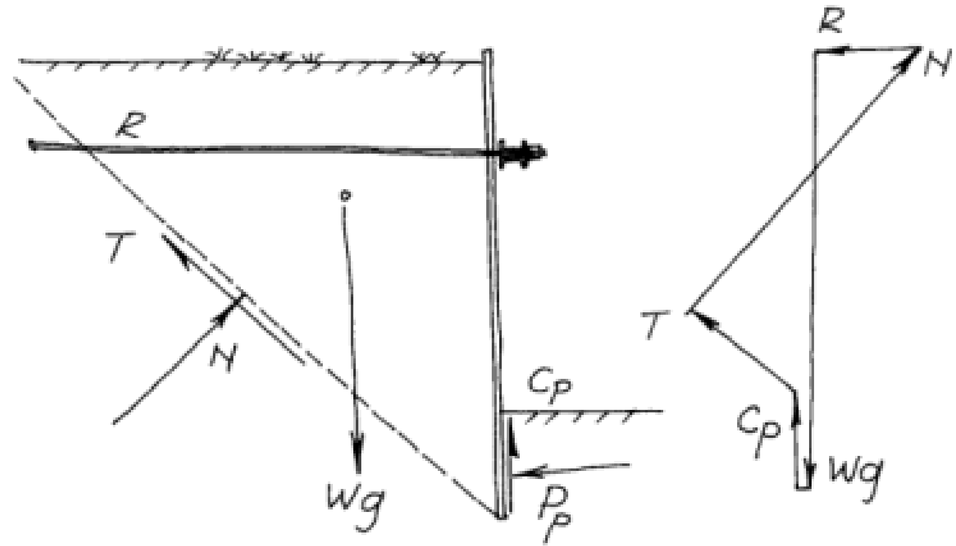


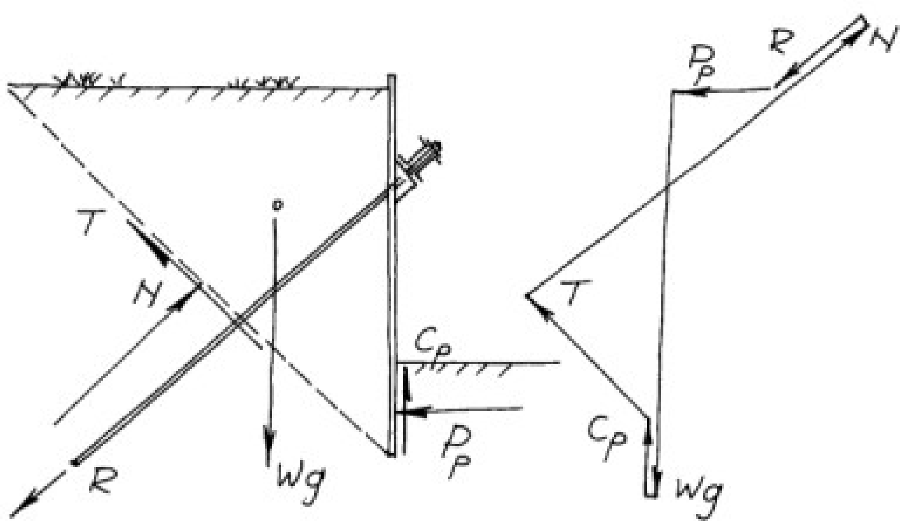


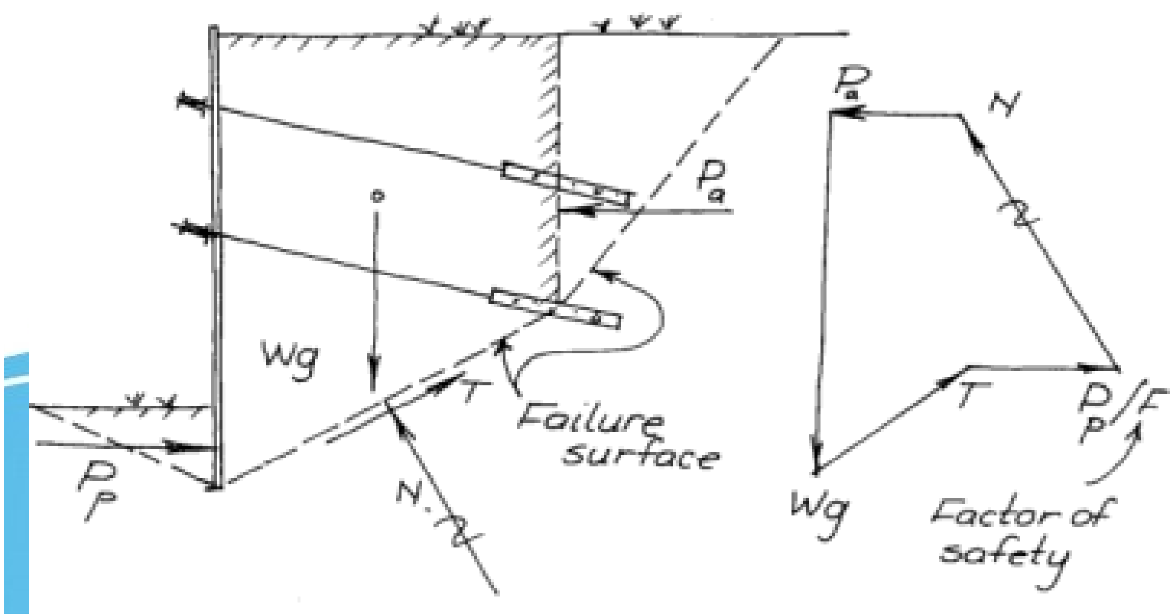


Soil Anchored Walls

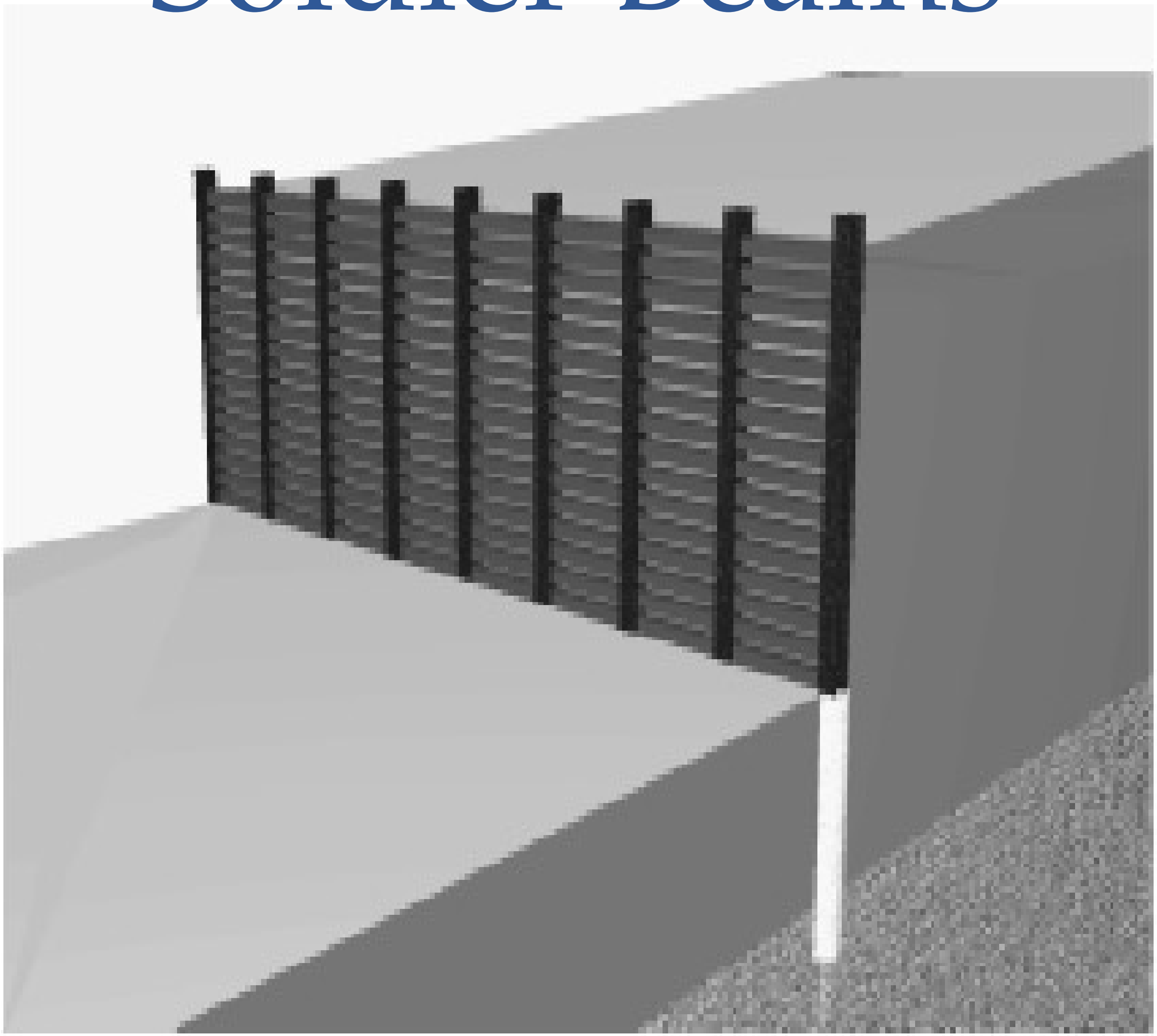








Soldier Beams



Overview of Braced Cuts and Tied Back Excavations

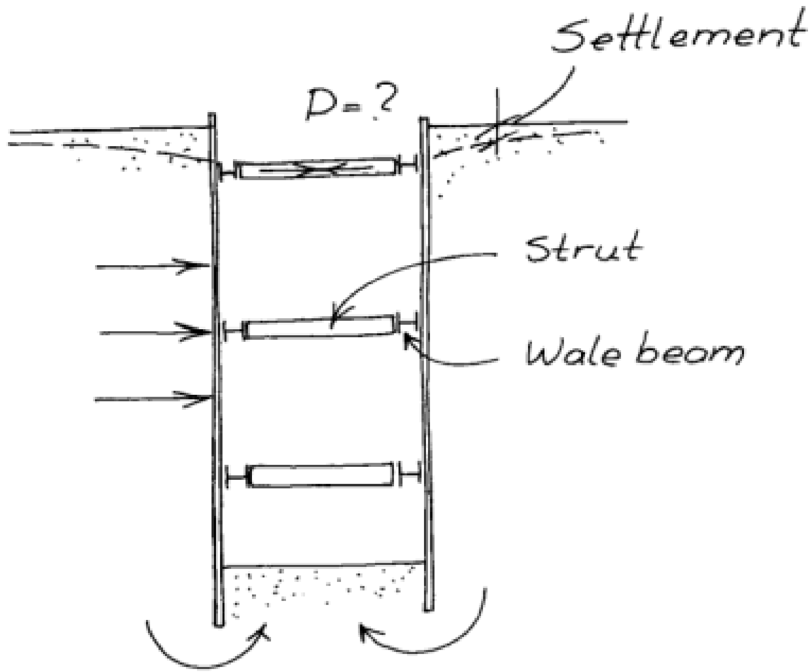
- All of the walls we have looked at up until now have been a single wall with no more than one anchor
- There are situations where either a) we need two facing walls or b) we need more than one anchor or c) both
- Braced cuts are sets of walls (usually sheet pile, but can be slurry) which are used to create a "mechanical ditch" inside of which construction can take place
- Tied back walls have multiple anchors, but the braces are outside of the cut (if any)

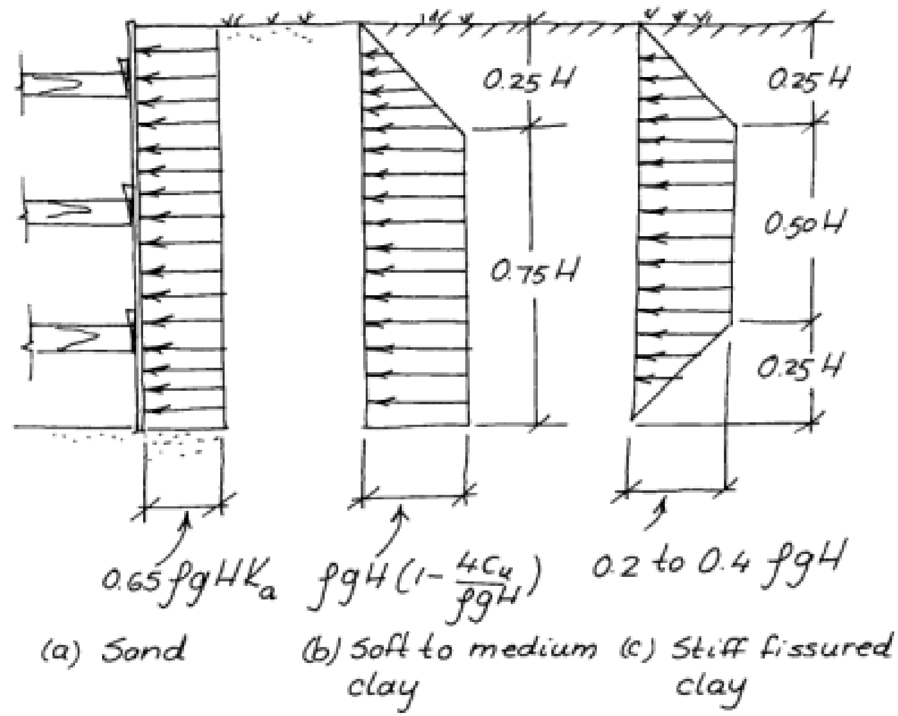
History of Braced Excavation Design

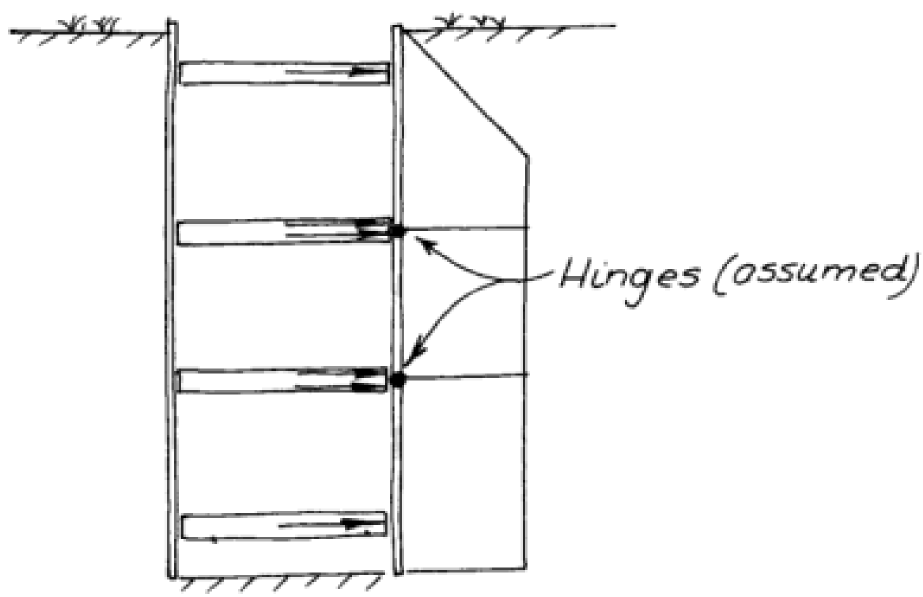
- Original work by Terzaghi and Peck on subway braced excavations in 1940's
- Discovered that progressive excavation and placement of braces altered lateral earth pressure profile
- Toe design entirely different from conventional sheet pile walls

- Important considerations in braced excavation design
  - Suitable for walls constructed "progressively"
  - Strictly speaking, brace loads are statically indeterminate
  - Terzaghi and Peck profiles assume hinges at braces for wall beam loading
  - Must consider bottom heave (esp. cohesionless soils, see ENCE 3610) and bearing capacity failure (esp. cohesive soils)

Braced Excavations







Pressure Distribution for Braced Loads

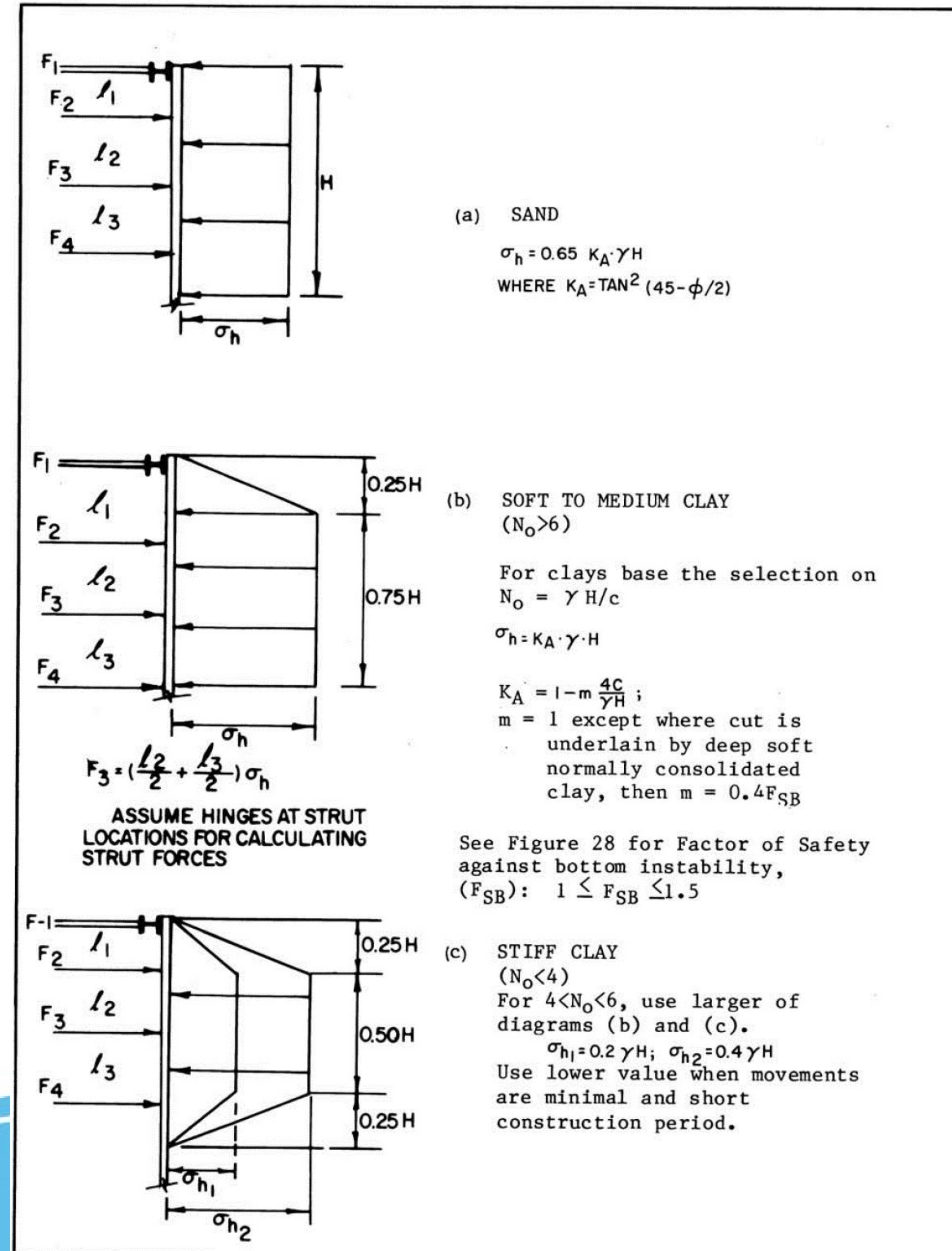
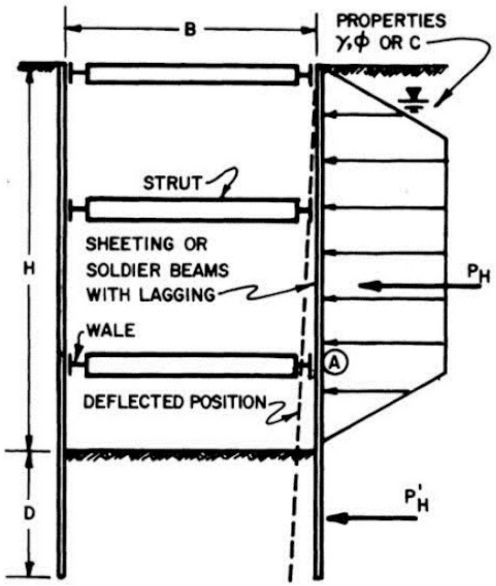


FIGURE 26
Pressure Distribution for Brace Loads in Internally Braced Flexible Walls

Design Criteria for Braced Cuts



FLEXIBLE WALL OF NARROW CUT

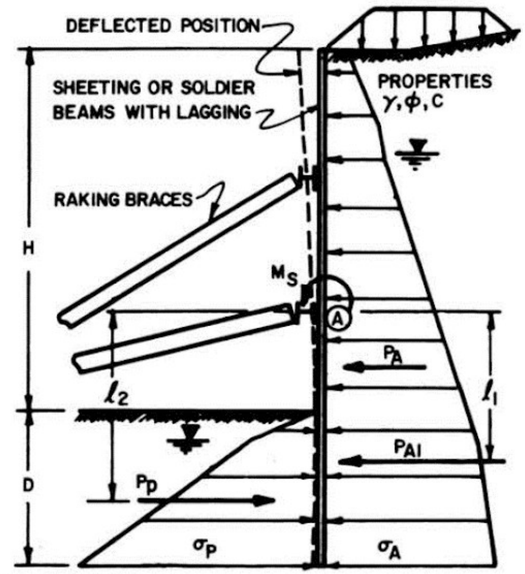
1. COMPUTE PRESSURES ON WALL ABOVE BASE OF CUT BY METHODS OF FIGURE 26. FOR WATER AT BACKFILL SURFACES USE $\gamma = \gamma_{SUB}$ AND ADD PRESSURES FOR UNBALANCED WATER LEVEL. FOR WATER AT BASE OF CUT USE $\gamma = \gamma_T$. INTERPOLATE BETWEEN THESE PRESSURE DIAGRAMS FOR AN INTERMEDIATE WATER LEVEL.

2. DETERMINE STABILITY OF BASE OF CUT BY METHODS OF FIGURE 28. IF BASE IS STABLE, SHEETING TOES IN SEVERAL FEET AND NO FORCE ACTS ON BURIED LENGTH. IF BASE IS UNSTABLE, SHEETING PENETRATES AS SHOWN IN FIGURE 28 AND UNBALANCED FORCE P'_H ACTS ON BURIED LENGTH. IN ANY CASE, PENETRATION MAY BE CONTROLLED BY REQUIREMENT FOR CUT-OFF OF UNDERSEEPAGE.

3. MOMENTS IN SHEETING BETWEEN BRACES = 0.8 x (SIMPLE SPAN MOMENTS), EXCEPT FOR UPPER SPAN WHERE MOMENT = 1.0 x (SIMPLE SPAN MOMENT). MOMENTS IN SHEETING AT POINT (A) IS COMPUTED FOR CANTILEVER SPAN BELOW (A), INCLUDING UNBALANCED FORCE P'_H.

4. REACTION AT BRACES COMPUTED ASSUMING SIMPLE SPAN BETWEEN BRACES.

FIGURE 27
Design Criteria for Braced Flexible Walls



P_A = RESULTANT ACTIVE PRESSURE
P_{AI} = RESULTANT ACTIVE BELOW POINT (A)

FLEXIBLE WALL WITH RAKING BRACES

1. COMPUTE ACTIVE AND PASSIVE PRESSURES BY METHODS IN SECTION 2. PASSIVE PRESSURES FOR CLEAN, COARSE-GRAINED SOILS INCLUDE WALL FRICTION (δ), TABLE 1. IGNORE WALL FRICTION FOR PASSIVE PRESSURES IN OTHER SOIL TYPES AND FOR ACTIVE PRESSURES IN ALL SOILS.

2. MAXIMUM MOMENTS IN SHEETING AND MAXIMUM LOADS IN BRACES ARE USUALLY OBTAINED AT A CONSTRUCTION STAGE WHEN EXCAVATION FOR A BRACE AND WALE IS COMPLETE AND JUST PRIOR TO PLACING THE BRACE. FOR EACH SUCCESSIVE STAGE OF EXCAVATION COMPUTE SHEETING MOMENTS AND BRACE LOADS BY ASSUMING SIMPLE SPAN BETWEEN LOWEST BRACE THEN IN PLACE AND POINT OF ZERO NET PRESSURE BELOW EXCAVATION.

3. FOR TEMPORARY CONSTRUCTION CONDITIONS, APPLY FACTOR OF SAFETY OF 1.5 TO COMPUTE PASSIVE PRESSURES. TO ALLOW FOR POSSIBLE CONSTRUCTION SURCHARGE AND RIGIDITY OF UPPER BRACE POINT, INCREASE LOAD ON UPPER WALE AND BRACE BY 15% OF COMPUTED VALUE.

4. REQUIRED PENETRATION OF SHEETING BELOW FINAL SUBGRADE GENERALLY IS CONTROLLED BY CONDITIONS AT COMPLETION OF EXCAVATION. PENETRATION REQUIRED IS DETERMINED BY EQUILIBRIUM OF FREE ENDED SPAN BELOW POINT (A). ASSUMING FIXITY AT POINT (A):

$$P_{AI}\, l_1 - \frac{P_P}{F_S}\, l_2 - M_S = 0$$

M_S = ALLOWABLE MOMENT IN SHEETING

5. CHECK POSITIVE MOMENTS IN SPAN BELOW POINT (A) FOR THIS FINAL LOADING CONDITION.

FIGURE 27 (continued)
Design Criteria for Braced Flexible Walls

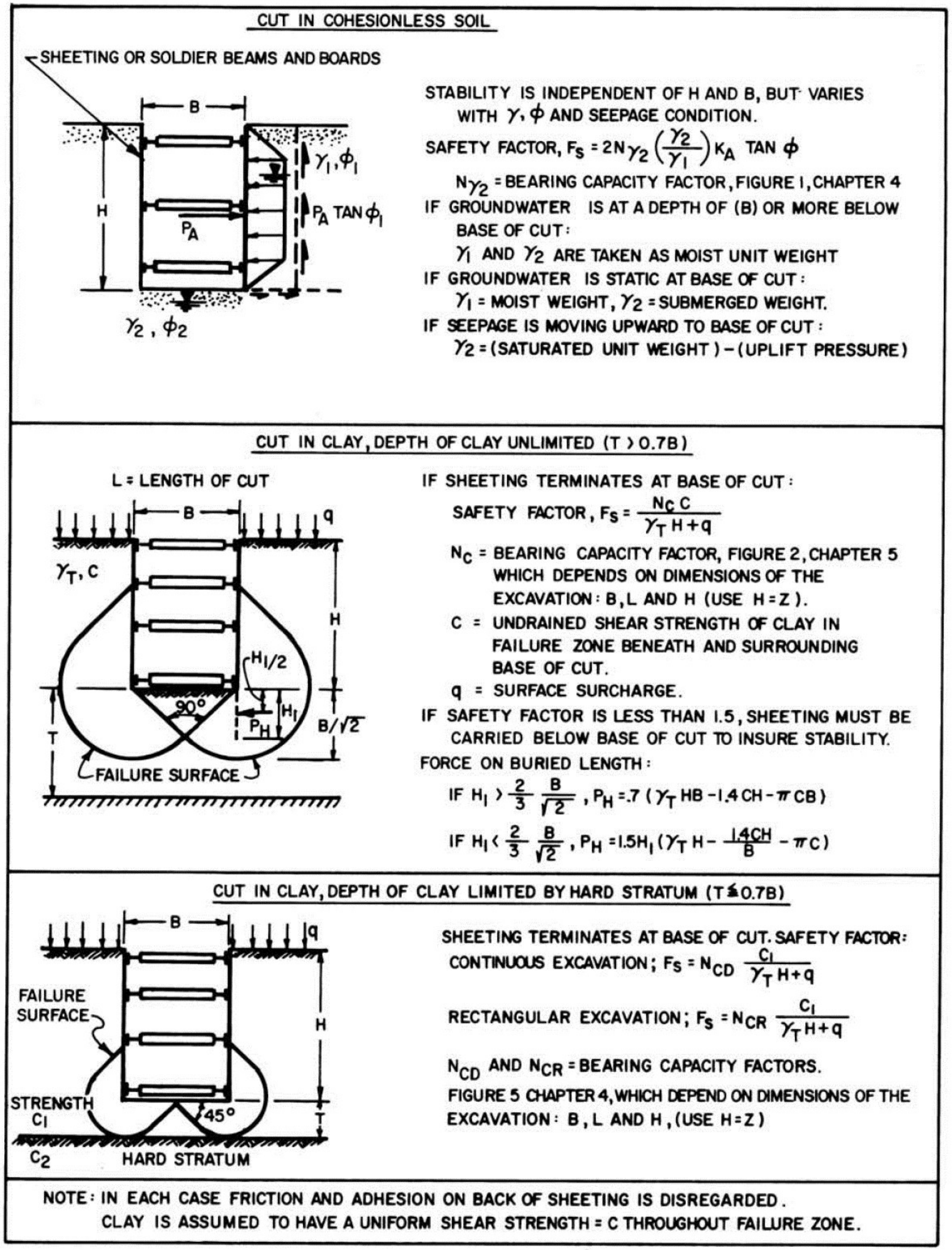
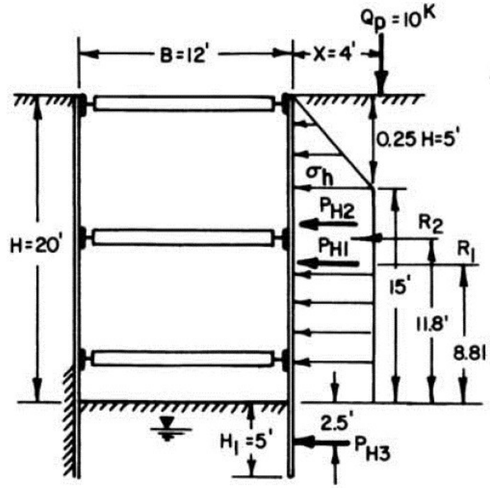


FIGURE 28
Stability of Base for Braced Cut

Base Stability for Braced Cuts

Braced Cuts

Example



GIVEN CONDITIONS:

EXCAVATION IN SILTY CLAY.
$C = 400$ PSF, $\phi = 0$, $\gamma_T = 120$ PCF
LENGTH OF EXCAVATION, L = 80'

DETERMINE: PRESSURES ON WALL. FORCE ON BURIED LENGTH OF SHEETING AND STABILITY OF BASE OF CUT.

STABILITY OF BASE OF CUT (SEE FIGURE 28)

$F_{SB} = \dfrac{N_C C}{\gamma_T H + q}$, $q = 0$ (NO UNIFORM SURCHARGE)

FOR N_C, (FIGURE 2, CHAPTER 5) $\dfrac{H}{B} = \dfrac{Z}{B} = \dfrac{20}{12} = 1.67$,
$\dfrac{B}{L} = \dfrac{12}{80} = 0.15$, $N_{CC} = 6.9$

$N_{CR} = N_{CC}(1 + 0.2\,B/L) = 6.9(1 + 0.2(0.15)) = 7.1$

$F_S = \dfrac{7.1 \times 400}{120 \times 20 + 0} = 1.18 < 1.5$

DRIVE SHEETING BELOW BOTTOM OF EXCAVATION

PRESSURE ON WALL FROM SURROUNDING SOIL (SEE FIGURE 26)

$K_A = 1 - m\,\dfrac{4C}{\gamma H}$: $m = 0.4\,F_{SB} = 0.4 \times 1.18 = 0.47$

$= 1 - (0.47)\left(\dfrac{4 \times 400}{120 \times 20}\right) = 0.69$

$\sigma_h = K_A \gamma H = 0.69 \times 0.12 \times 20 = 1.66$ KSF

$P_{H1} = \dfrac{(15+20)(1.66)}{2} = 29.05$ KIPS

LOCATION OF RESULTANT:

$R_1 = \dfrac{1.66 \times 5/2 \times (15 + 5/3) + 1.66 \times 15 \times 15/2}{29.05} = 8.81'$

PRESSURES ON WALL FROM SURCHARGE (SEE FIGURE 11)

$m = \dfrac{X}{H} = \dfrac{4}{20} = 0.2$

$P_{H2} = .78\,\dfrac{Q_P}{H} = .78\,\dfrac{10}{20} = .39$ KIP

LOCATION OF RESULTANT:

$R_2 = .59H = .59 \times 20 = 11.8'$

FORCE ON BURIED LENGTH OF SHEETING: (SEE FIGURE 28)

ASSUME $H_1 = 5 < \dfrac{2}{3}\dfrac{B}{\sqrt{2}}$, FOR $T > 0.7B$ RESULTANT FORCE P_{H3}:

$P_{H3} = 1.5\,H_1\left(\gamma_T H - \dfrac{1.4CH}{B} - \pi C\right)$

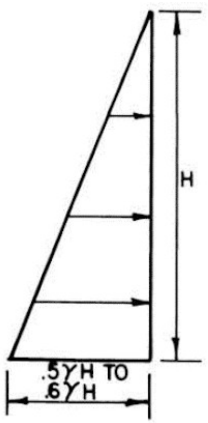
$P_{H3} = 1.5 \times 5\left(0.12 \times 20 - \dfrac{1.4 \times .4 \times 20}{12} - 3.14 \times 4\right) = 1.6$ KIP

NOTE: ALL COMPUTATIONS ARE PER LINEAR FOOT OF WALL.

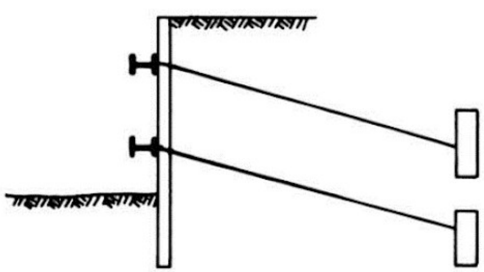
FIGURE 30
Example of Analysis of Pressures on Flexible Wall of Narrow Cut In Clay - Undrained Conditions

Tied Back Walls Pressure Distribution

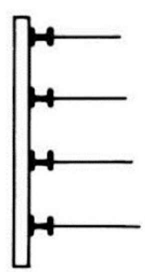
SOFT TO MEDIUM CLAY



Compute pressure based on at-rest conditions with K_o from 0.5 to 0.6. In normally consolidated clays excessive prestressing should not be permitted because of the potential for induced consolidation. Use design procedure as in Figure 26.



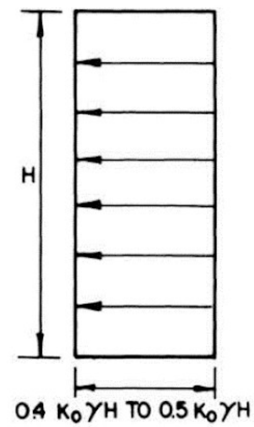
ELEVATION



PLAN

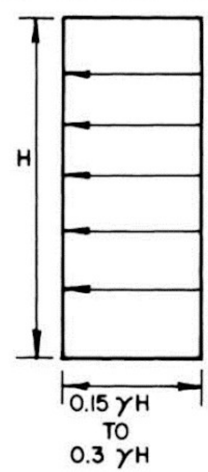
FIGURE 29
Pressure Distribution for Tied-Back Walls

SANDS



Where deformations are critical and tie-backs are prestressed to 100% of desig load, compute pressure based on at-rest conditions. Use K_o = 0.4 for dense sand, and K_o = 0.5 for loose sand.

STIFF TO VERY STIFF CLAY



Use pressure ordinate to produce the same force as for braced excavation. 0.3 is applicable for stability number of about 4, and 0.15 is applicable when stability number is less than 4. Use design procedure as in Figure 26.

FIGURE 29 (continued)
Pressure Distribution for Tied-Back Walls

Questions