Engineering Geology of Worcester County

A Major Qualifying Project Report:

submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements

for the Degree of Bachelor of Science

by

Geoffrey Narlee

January 14, 2019

Approved:

Leonard D. Albano, Advisor

Abstract

This is an addendum to the 1979 MQP "Engineering Geology of Worcester County," that I participated in with Paul Moroney. We used soils from the surrounding Worcester County to solve the engineering problem of creating a 30-foot-deep braced cut for constructing a three-level parking garage for an office building.

This addendum utilizes concepts outlined in the July 5, 2012 article "Earth Retaining Systems Using Ground Anchors", written by Barton Newton, California State Bridge Engineer.

Capstone Design Statement

This amendment to the 1979 MQP, "Engineering Geology of Worcester County," presents a different approach to solving the problem of a braced retaining wall for a deep cut. It incorporates the principles outlined in the article "Earth Retaining Systems Using Ground Anchors" (2012)[1], written by Barton Newton, California State Bridge Engineer. Newton demonstrates a Load Factor and Resistance Design (LFRD) method with assumed lateral earth pressures and point of critical surface failure. I formularized the methodology into an Excel workbook that allows the user to insert chosen variables for an iterative process of optimizing the construction project by running a series of trials with different design element combinations. In addition to the economic aspect, braced retaining walls for deep cuts addresses other concerns, including constructability, social, sustainability, safety and ethics, as described below.

The economics of the problem is solved by inputting different parameters to seek the least amount of construction cost associated with excavating, pile driving, installing lagging, and inserting tie-back anchors, all while saving the cost of the wall's high-side disruption, in this case an active roadway. In addition, by using tie-backs to hold the completed wall in place, the wall's low-side grade is free of footprint obstruction for productive and valuable re-purpose, such as recreation, stream or conservation re-establishment or creation, access ways or buildings.

Regarding constructability, tie-back braced walls are made primarily from the low-side, or soon to be low-side, which decreases the extent of the site that has to be worked, and allows the use of simple, "off the shelf" materials (H-Piles and Sheeting) by virtue of employing a soil-penetration anchoring system that ties these elements together, and this array works in

---

[1] Barton J. Newton, "Earth Retaining Systems Using Ground Anchors," Caltrans Engineering Manuals (website), California Dept. Transportation, accessed October 8, 2018, http://www.dot.ca.gov/des/techpubs/manuals/bridge-memo-to-designer/page/section-5/5-12.pdf

conjunction with the retained earth itself. Project scheduling is simpler because the method does not have to factor in a large amount of coordination with high-side public activities, and it is more flexible because delays and unforeseen conditions can be managed without public impact or negotiation. The simple technique may require less management – keeping it simple avoids errors, safety mishaps, and delays.

The social benefits are multifold. The high-side roadway is kept in active service. This keeps individuals' and companies' pedestrian and vehicular traffic flowing without shut-down, obviates the need for detours, and the associated delays and lost time that would otherwise be incurred. It also means that the high-side noise, debris, repairs, renovation and replacements are eliminated, and abates contractor-to-public safety issues by keeping work away from the active high-side. By keeping the construction within a smaller footprint and isolated, it mitigates construction noise, dust, and contractor-to-public spillover. The project itself benefits because an un-harassed public yields more project "buy-in."

Sustainability is enhanced. By not disturbing the high-side, that environment is unmolested. As well, the mass of construction materials consumed from the environment is less. And, with the use of tie-backs to stabilize the retaining wall structure, the post-construction footprint available for environment-related choices, be they conservation of the existing or creation of the new, is available.

As referenced above, safety issues are reduced on the high-side. Also, because these deep cut braced walls are usually constructed from the low-side grade, in gradual steps downward, high-wall related construction safety issues are minimized. Jobsite security is increased because the public interaction is reduced. Jobsite safety does not have to be concerned with cranes reaching over people or pedestrians falling into excavations. Leaving the high-side earth in place removes the potential of exposing hazardous materials.

All of the above help result in an ethical project. Lower costs benefit society, either through lower taxes or diminished pressure on corporate cost structures. Contractors and the public are safer, and the public is healthier by employment of more remote and contained construction methods. Scare material resource-use is reduced. There is less mass of materials, either constructed or moved around. Land-use options are increased, and the environmental disruption is mitigated.

Professional Licensure Statement

Professional Licensure requirements are society's way of assuring that engineering projects are reviewed, analyzed, and executed with the highest degree of safety, thoughtfulness, thoroughness, standards of excellence, and reliability of result. The professional engineer, although ostensibly a "hard science" problem solver, also includes, in his/her mandate, a duty to look at the spectrum of multi-disciplinary and human related issues that occur in any professional endeavor, by bearing in mind that the ultimate goal is to serve people and the environment in which they live.

Because of the burden of responsibilities the professional takes on, as an engineer and as a person, the path to achieving the privilege to do so entails a challenging regime of preparation, and proof of competence and intent. This includes the following:

- Four years of successful matriculation at an approved learning institution and earning in a degree accredited by the Accreditation Board for Engineering and Technology (ABET).
- Preparing and passing the Fundamentals of Engineering (FE) exam.
- Performing four to five years (depending on jurisdiction) of service as an Engineer-In-Training (EIT), working under, and being mentored by, a licensed professional.
- Preparing and passing the Principles and Practices of Engineering (PE) exam.

Maintaining these standards of acceptance into licensure, and continuing education, assures that the design and construction industry operates with the highest caliber of safety, effectiveness, and efficiency, and gives people the reliability and peace of mind that is a necessary part of a well-functioning society.

Table of Contents

1. Introduction

This is an addendum to the 1979 MQP "Engineering Geology of Worcester County," that I participated in with a partner, Paul Moroney. This earlier work involved sampling and analyzing soils in the surrounding Worcester County, and the results were incorporated into an engineering problem. We used the idea of creating a 30-foot deep braced cut for constructing a three-level parking garage for an office building. Four methods of attack were investigated:

i. Sheet Piles braced by wales and rakers
ii. Sheet piles braced by wales and tiebacks
iii. Soldier piles and lagging braced by wales and rakers
iv. Soldier piles and lagging braced by wales and tiebacks

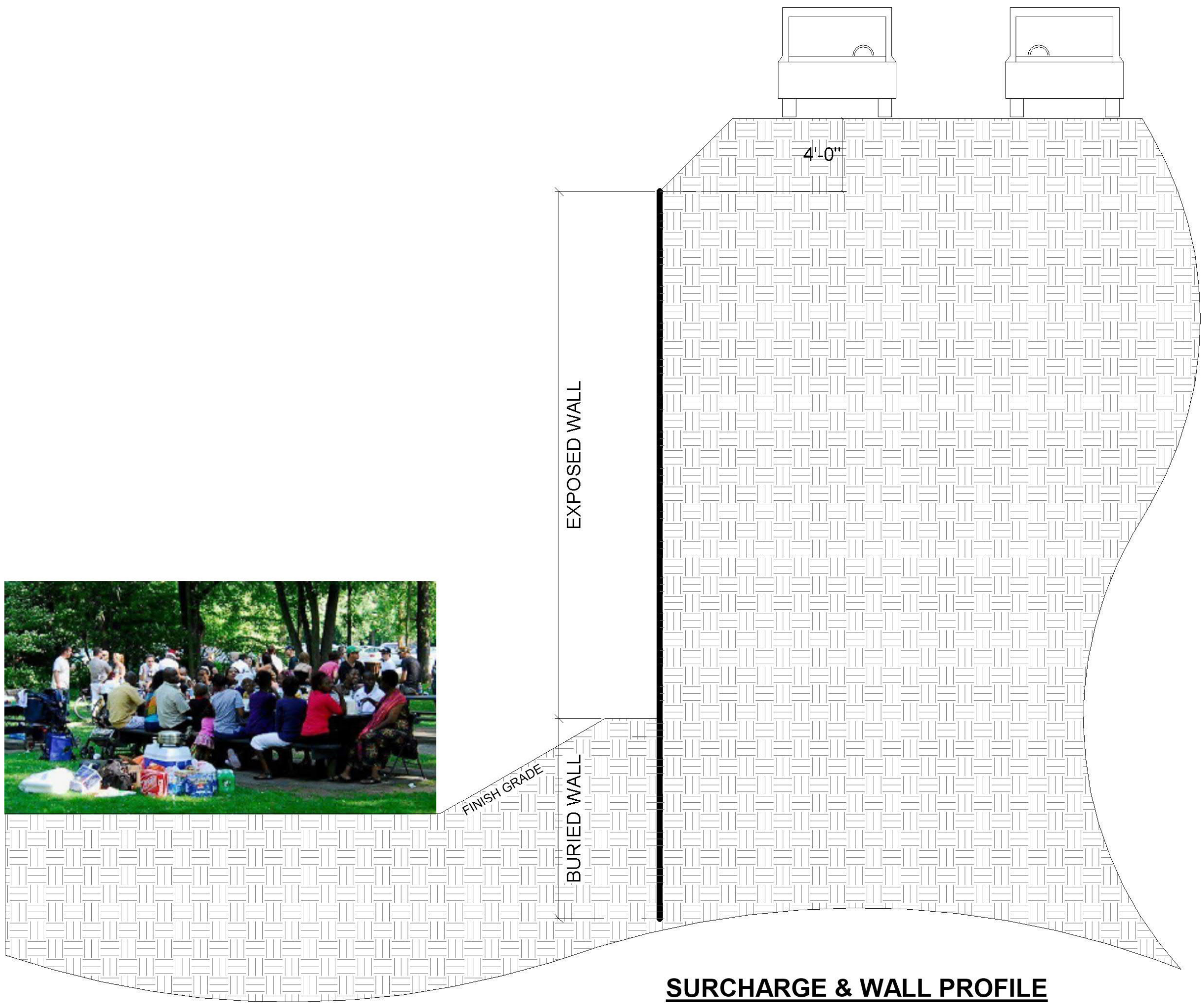
As part of designing the systems, a couple of Fortran computer programs were developed and used to facilitate the design calculations. The associated construction costs were also estimated.

In this addendum, the bracing was analyzed as soldiers, lagging and wales only. In lieu of programming code, an Excel spreadsheet was created to allow users flexibility in exploring solutions. One can insert and adjust different variable values to seek the most effective solution based on economics and construction methods specific to the site and project restrictions. The associated construction costs were also estimated.

This addendum also seeks to take a slightly different engineering method to the solutions. Concepts outlined in the July 5, 2012 article "Earth Retaining Systems Using Ground Anchors", written by Barton Newton, California State Bridge Engineer, were used as an engineering basis for the work. This reference document takes an LRFD (Load Resistance and Factor Design) approach to solving tie-back braced cuts, with several variations on tie-back layout and quantity. As part of working through the solutions contained in the addendum, some retaining wall engineering basics not specifically explicated in the article were revisited, as required for solution, such as soil angle of repose, concrete-to-soil friction, general strength of materials concepts as they pertain to beams, and calculation of anchor depth and dimensions.

Braced walls are a deep-cut retaining wall solution for sites where the construction method is restricted by certain conditions. In this case, it is assumed that the engineering challenge is to contain an embankment that is pre-loaded on the high side of the grade difference, such that the load side cannot be excavated to install a gravity retaining wall. For instance, the high side may support an existing building or roadway. Implementation of the braced wall keeps the excavation to a minimum and the sides of the excavation stable during construction, thus ensuring that soil movement will not damage adjacent structures, utilities, and environmentally sensitive systems. Use of tie-backs to secure the braced wall allows the finished product to be free and clear of supports on the lower grade area, so that the area may be used for purposes other than retaining the cut bracing system. Extending the braced cut system below the lower grade prevents heaving of the load side soils under the system and into the lower grade as illustrated on the next page.

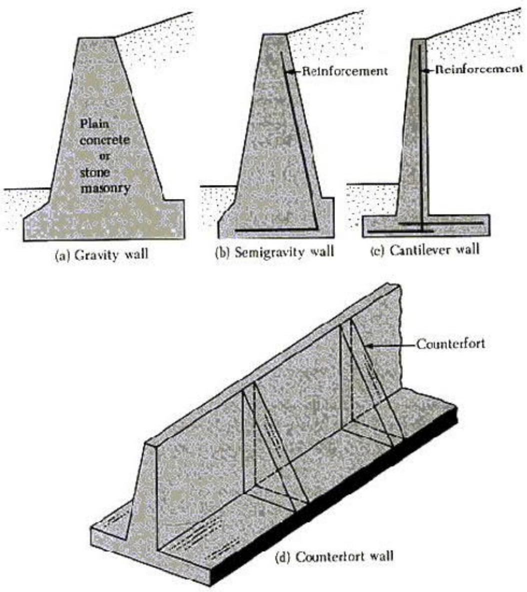
Schematic of engineering problem:



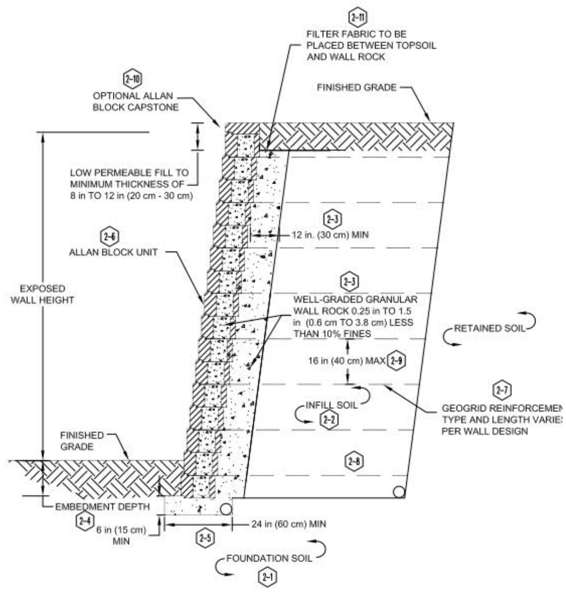
2. Background

Without surrounding site restrictions such as disruption of adjacent existing conditions, provision of minimal footprint impact of the final product, and the means of construction associated with the above, bulk excavation on both sides of a proposed retaining wall is allowed and simple mass concrete structures, or geogrid reinforcement with concrete block, can be pursued.

Examples of Retaining Structures requiring excavation on both sides:



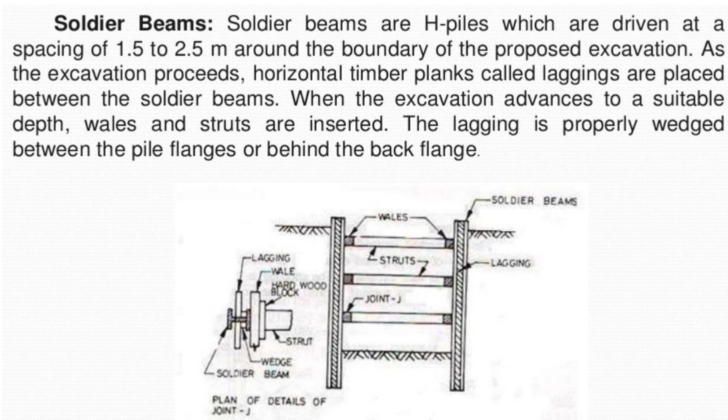
https://www.concretenetwork.com/concrete/poured_concrete_retaining_walls/four_types.htm



https://www.allanblock.com/engineers/pdf/Best-Practices-Typical-Wall-01.pdf

However, in other cases, alternative methods must be employed.

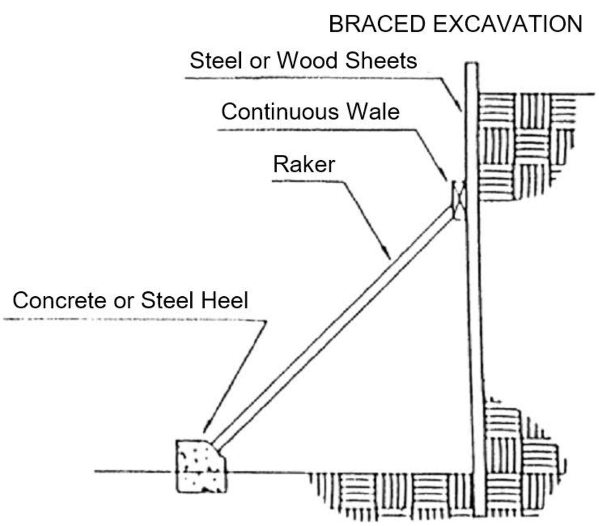
Trench wall bracing is perhaps the simplest example, but has a limited application. It is widely used when cutting down vertically, with modest width, within a nominally horizontal soil plane. It's straightforward, ideal for its purpose (usually for burying utilities), but has a niche capacity.



https://www.slideshare.net/yogeshpandey3005/braced-cut

https://www.cedd.gov.hk/eng/publications/geo/doc/trench_excavations.pdf

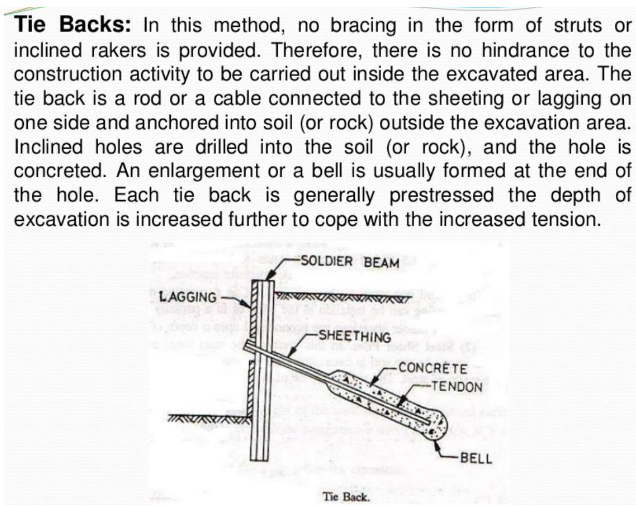
In the more general braced wall case, where a close and opposing earthwork is not available, compression struts (i.e. rakes) are constructed to brace between the high wall and the lower-side grade. This allows the high-side grade to remain in its original condition, but consumes low-grade footprint, not to mention it's aesthetically challenged if not using architectural profiles, or concealed with a cover of some kind.



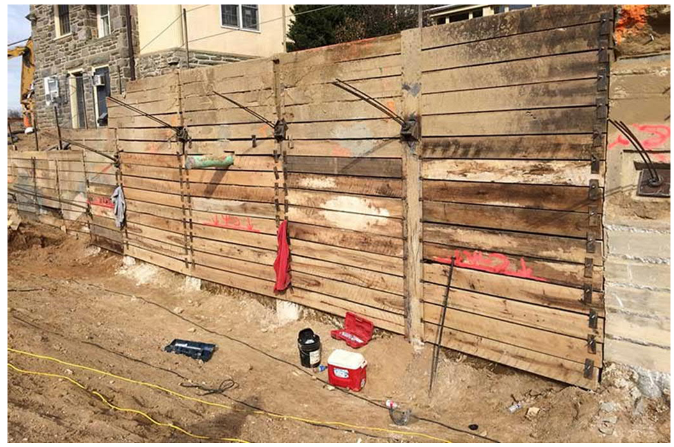
http://eu.lib.kmutt.ac.th/elearning/Courseware/ARC261/chapter3_3.html

http://www.glynngroup.com/wp-content/uploads/2012/09/GM_Massena_Braced_Excavation2.jpg

To solve this dilemma, the bearing weight and holding capacity of the high-side grade is exploited via “tie-backs” that are inserted into that high-side grade. As with the “struts” method, the quantity and configuration of the tie-backs are derived from top-of-wall surcharge loads, soil attributes, and the height of the grade-difference, which account for the resultant distributed lateral earth pressures bearing upon the wall.

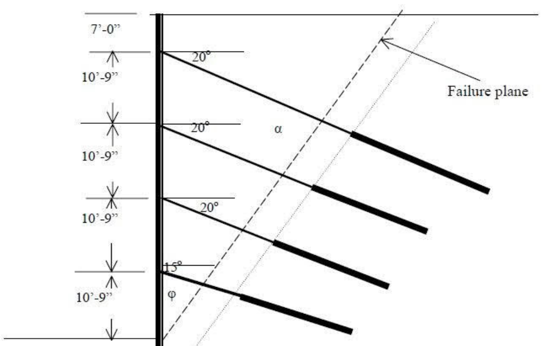

Tie Backs: In this method, no bracing in the form of struts or inclined rakers is provided. Therefore, there is no hindrance to the construction activity to be carried out inside the excavated area. The tie back is a rod or a cable connected to the sheeting or lagging on one side and anchored into soil (or rock) outside the excavation area. Inclined holes are drilled into the soil (or rock), and the hole is concreted. An enlargement or a bell is usually formed at the end of the hole. Each tie back is generally prestressed the depth of excavation is increased further to cope with the increased tension.

https://www.slideshare.net/yogeshpandey3005/braced-cut



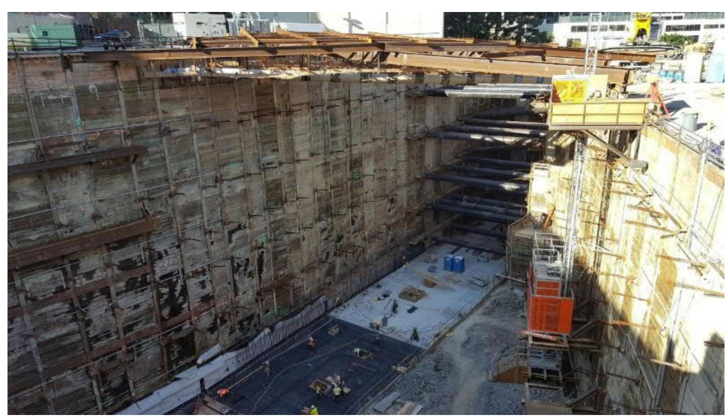
https://www.wagman.com/specialized-services/tieback-walls.asp

Multi-Level tie-back application



Note Anchors must clear Failure Plane

www.soilstructure.comstructural-software/tieback-wall.jpg



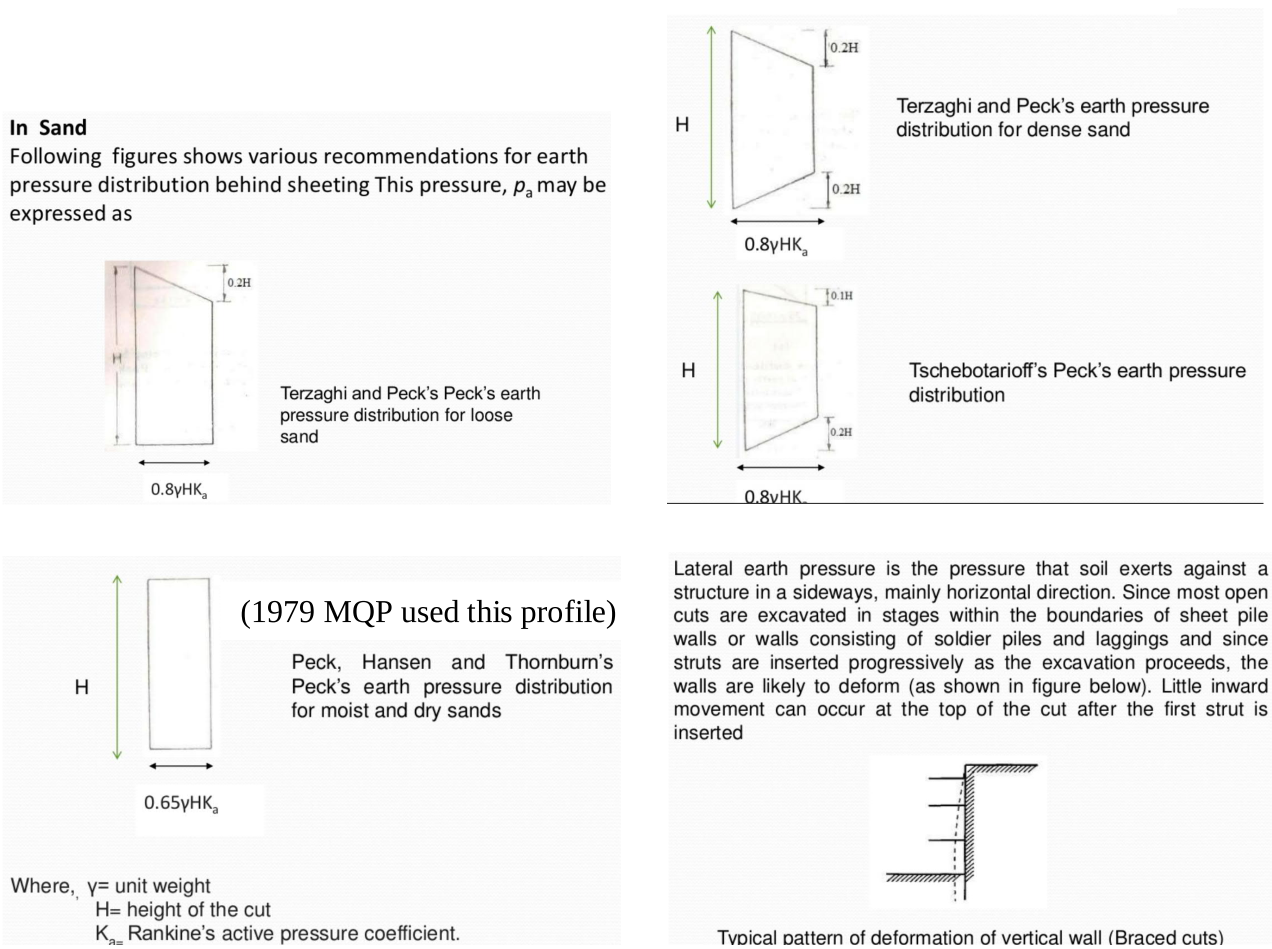
http://www.deepexcavation.com/en/retaining-systems-soldierpile

3. Methodology

As mentioned in the Introduction, this addendum uses a Load Resistance and Factor Design (LRFD) method to solve for design loads. It employs somewhat different assumptions on the lateral earth pressures than what was used in the 1979 MQP, as shown below and on the next page. Also, to note, the 1979 MQP described the medium as sand, but used an angle of repose of 31 degrees, which also falls into the sand and gravel range, and is appropriate for the soils typical of Worcester County. This addendum used 30 degrees, but that is adjustable. The 1979 MQP did not include the wall-bottom embedment calculated by the Fortran code, but did use a formula for estimating it. This analysis, through the spreadsheet variables, allows the user to input the embedment depth as a variable.

The sequence of steps for using the LRFD method to determine optimal wall construction products is shown in a flow chart following the pressure diagrams and LRFD profiles.

Some traditional lateral earth pressure diagrams and their effect on retaining walls



https://www.slideshare.net/yogeshpandey3005/braced-cut

B. Newton's LRFD Lateral Earth Pressure

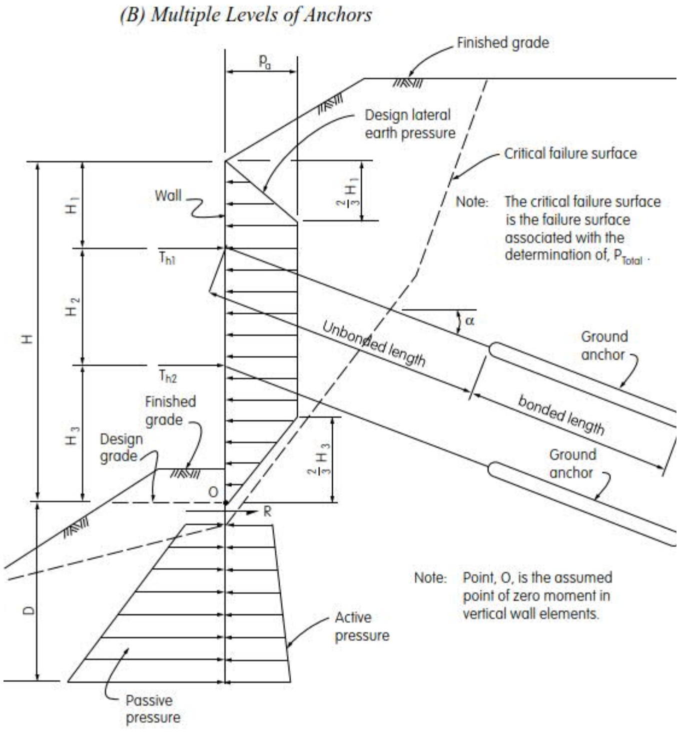
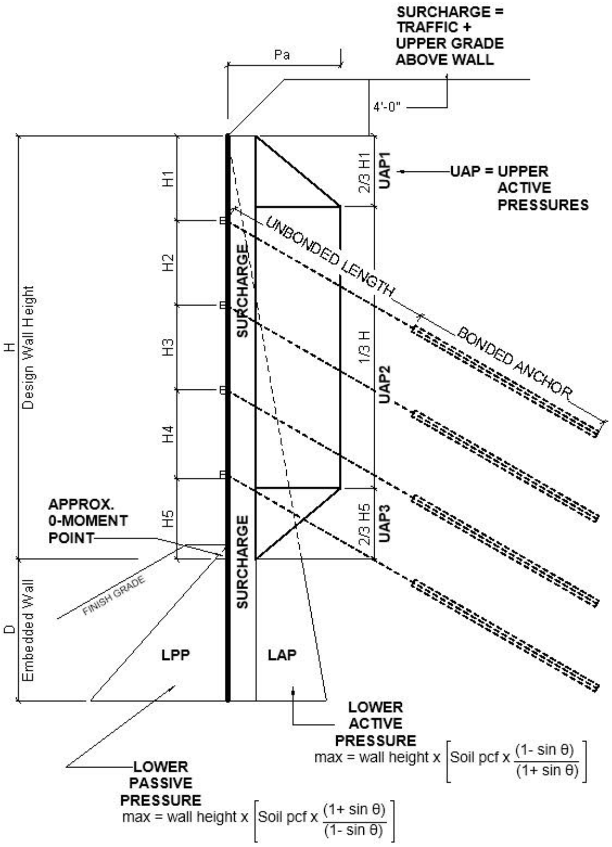


Figure 5-12.5 Anchored Wall with Multiple Levels of Ground Anchors and Critical Failure Surfa Near Bottom of Wall

http://www.dot.ca.gov/des/techpubs/manuals/bridge-memo-to-designer/page/section-5/5-12.pdf

Load Diagram Detail for Project Problem



Coulomb's Active Lateral Earth Pressure Coefficient For Retaining Wall:

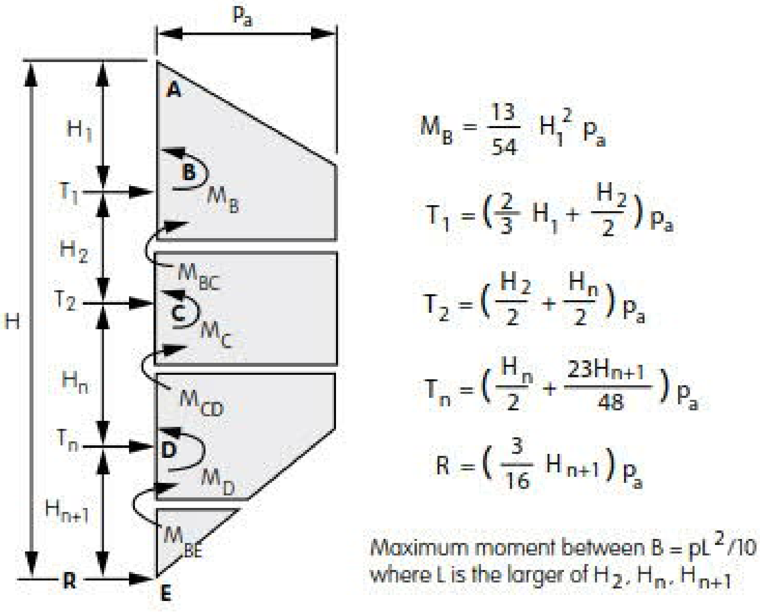
$$K_a = \frac{\cos^2(\phi - \theta)}{\cos^2\theta \cos(\delta+\theta)\left(1 + \sqrt{\frac{\sin(\delta+\phi)\sin(\phi-\beta)}{\cos(\delta+\theta)\cos(\beta-\theta)}}\right)^2}$$

⇨ Pa = (Soil Density)(Ka)(H^2)/2
(adjust for surcharges)

Per B. Newton, Load Factor should range from 1.35 to 1.5, as determined by a limiting equilibrium method of analysis, but not less than 1.44 Pa. As such an analysis (i.e. method of slices) is beyond the scope of this project, the conservative Load Factor of 1.5 is used.

http://www.dot.ca.gov/des/techpubs/manuals/bridge-memo-to-designer/page/section-5/5-12.pdf

B. Newton recommends using either the Hinge Method or the Tributary Area Method to calculate Tie-Back loads. The Tributary Area Method was used:



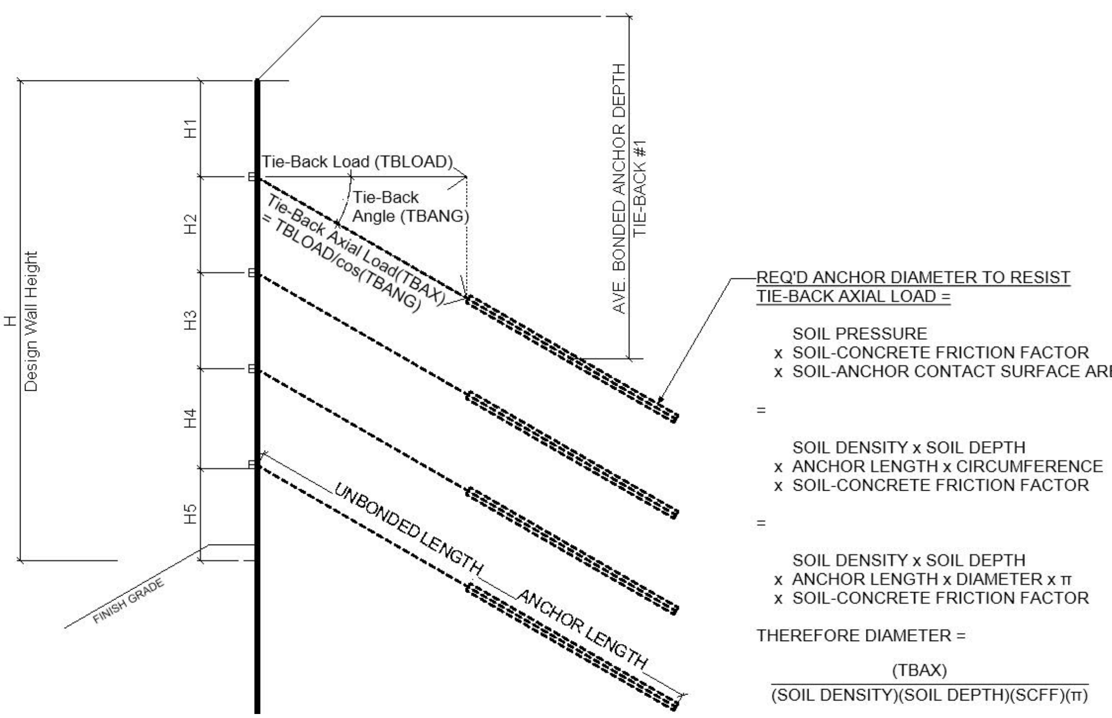
Per B. Newton, R = LPP-LAP and is used to determine 'D'

(b) Walls with multiple level of ground anchors

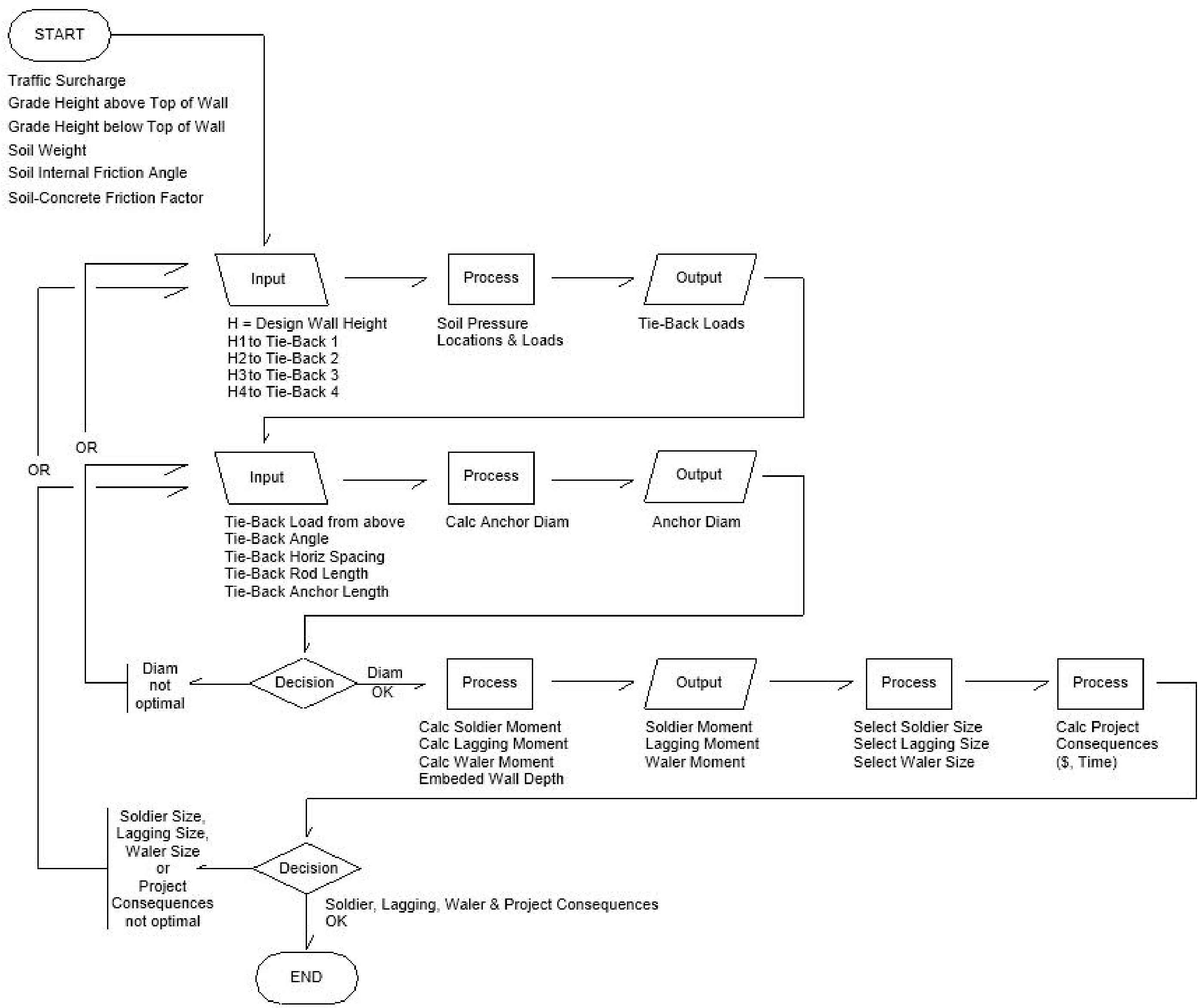
Figure 5-12.8 Calculation of Anchor Loads for Multi-Level Wall Using the Tributary Area Method (After Figure 39, Sabatini, et al, 1999)

http://www.dot.ca.gov/des/techpubs/manuals/bridge-memo-to-designer/page/section-5/5-12.pdf

Method for calculating the circumference of the bonded anchors:



LRFD Solutions Flow Chart



4. Engineering Calculations

Sheet 1 of 4

	A	B	C	D	E
1	Geof Narlee, Tie-Backs for Deep Braced Cut				
2	Calcs to Select Piles, Sheeting & Anchors				
3	Case: 4 Levels of Tie-Backs				
4					
5	***INPUT***	***LABELS***	***Choose***		***FORMULAS USED***
6	Traffic Surcharge	TFC	250	psf	
7	Upper Finished Grade above Top of Wall	UG	4.00	ft	
8	Angle of Surcharge	generally flat	na	0	
9	Lower Design Finish Grade below Top of Wall	LG	28.00	ft	
10	Design Wall Height (not incl embedment)	H	30.00	ft	
11	Tie-Back 1 (T1) Dist Below Top of Wall	H1.	4.00	ft	
12	TB1 to TB2	H2.	7.00	ft	
13	TB2 to TB3	H3.	7.00	ft	
14	TB3 to TB4	H4.	7.00	ft	
15	TB4 to bottom of H	H5.	calculated	5.00	=C10-SUM(C11:C14)
16	TB1 Minimum Length to clear Crit Fail Surface+		Min using Horiz Dist as Safety =>	15.01	=(H5.+H4.+H3.+H2.)*((SIN(rad*SIFA))/(SIN(rad*(90-SIFA)))
17	TB1 Length	TB1UBL	16.00	16.00	=IF(C17<D16,D16,C17)
18	TB2 Minimum Length to clear Crit Fail Surface+		Min using Horiz Dist as Safety =>	10.97	=(H5.+H4.+H3.)*((SIN(rad*SIFA))/(SIN(rad*(90-SIFA)))
19	TB2 Length	TB2UBL	11.00	11.00	=IF(C19<D18,D18,C19)
20	TB3 Minimum Length to clear Crit Fail Surface+		Min using Horiz Dist as Safety =>	6.93	=(H5.+H4.)*((SIN(rad*SIFA))/(SIN(rad*(90-SIFA)))
21	TB3 Length	TB3UBL	7.00	7.00	=IF(C21<D20,D20,C21)
22	TB4 Minimum Length to clear Crit Fail Surface+		Min using Horiz Dist as Safety =>	2.89	=(H5.)*((SIN(rad*SIFA))/(SIN(rad*(90-SIFA)))
23	TB4 Length	TB4UBL	3.00	3.00	=IF(C23<D22,D22,C23)
24	Bonded Anchor Length	TBBL	70	ft	
25	Tie-Back Horizontal Spacing	TBHS	5	ft	
26	Tie-Back Angle	TBA	45	deg	
27			radian to deg convert =>	0.017453	=PI()/180
28	Soil Weight	SW	120	pcf	
29	Soil Internal Friction Angle	SIFA	30	deg	
30	Soil-Concrete Friction Factor	SCFF	0.50	factor	
31					
32	***OUTPUT***		(hyperlinked as indic)		
33	Soldiers Selection		HP14x102		
34	Lagging Selection		HCS7.5 16/16		
35	Waler Selection		W8x48		
36	Tie-Back 1 Axial Force		245,016	#	
37	Tie-Back 1 Concrete Anchors Diameter		25	inch	
38	Tie-Back 1 Total Drilled Length		86	ft	=TB1UBL+TBBL
39	Tie-Back 2 Axial Force		278126	#	
40	Tie-Back 2 Concrete Anchors Diameter		27	inch	
41	Tie-Back 2 Total Drilled Length		81	ft	=TB2UBL+TBBL
42	Tie-Back 3 Axial Force		278126	#	
43	Tie-Back 3 Concrete Anchors Diameter		24	inch	
44	Tie-Back 3 Total Drilled Length		77	ft	=TB3UBL+TBBL
45	Tie-Back 4 Axial Force		234255	#	
46	Tie-Back 4 Concrete Anchors Diameter		19	inch	
47	Tie-Back 4 Total Drilled Length		73	ft	=TB4UBL+TBBL
48	Wall Embedment Depth		10.5	ft	
49					
50	***UPPER LATERAL EARTH PRESSURE CALCULATIONS***	***LABELS***			***FORMULAS USED***
51					
52	Coulomb Active Earth Pressure Coeffient Ka	Ka	0.33		=((COS(rad*(SIFA-0)))^2)/(((COS(rad*0)^2)*(COS(rad*(0+0))))*(1+SQRT((SIN(rad*(0+SIFA)))*(SIN(rad*(SIFA-0)))/...
53					...(COS(rad*(0+0)))*(COS(rad*(0+0)))))^2)
54	Surcharges Overlay:				
55	Traffic Load		250	psf	=TFC
56	Upper Grade Load		480	psf	=SW*UG
57	Total Surcharge Load	SCT	730	psf	=TFC+(UG*SW)
58	Pa per Coulomb's Law		18,000	psf	=SW*Ka*H*H/2
59	Safety Factor		1.50		=1.5
60	Pa Total Used	Pa	28,095	psf	=(C59)*(C57+C58)
61					
62	UAP 1 Load	UAP1LOAD	37,460	psf	=(Pa)*((2/3)*H1.)/2
63					
64	UAP 2 Load	UAP2LOAD	674,280	psf	=(Pa)*(H-((2/3)*H1.)-((2/3)*H5.))
65					
66	UAP 3 Load	UAP3LOAD	46,825	psf	=(Pa)*((2/3)*H5.)/2

Sheet 2 of 4

	A	B	C	D	E
69	***CALCULATIONS AFTER B. NEWTON ARTICLE***				
70					
71	Moment at B ***(after B. Newton)***		108,218	#	=(13/54)*(H1.)*(H1.)*(Pa)
72					
73	T1 Force Horizontal Component ***(after B. Newton)***		173,253	plfw	=((2/3)*(H1.)+(H2.)*(1/2))*(Pa)
74	T1 Force Axial Component		245,016	plfw	=(C73)/(SIN((PI()/180*TBA)))
75	T1 Depth		8.00	ft	=UG+H1.
76	T1 Anchor Average Depth		44.06	ft	=(C75)+(TB1UBL*(SIN(rad*TBA))+(TBBL/2)*(SIN(rad*TBA)))
77	T1 Anchor Load plf Anchor		3,500	#	=C74/TBBL
78	T1 Anchor Circum		15.89	inch plfw	=(C74)*(12)/(TBBL*SW*C76*SCFF)
79	T1 Anchor Circum at Horizontal Tie Spacing		79	inch	=(C78)*TBHS
80	T1 Anchor Diameter		25	inch	=(C79)/(3.14)
81					
82	T2 Force Horizontal Component ***(after B. Newton)***		196,665	plfw	=((H2.)*(1/2)+(H3.)*(1/2))*(Pa)
83	T2 Force Axial Component		278,126	plfw	=(C82)/(SIN((PI()/180*TBA)))
84	T2 Depth		15.00	ft	=UG+H1.+H2.
85	T2 Anchor Average Depth		47.53	ft	=(C84)+(TB2UBL*(SIN(rad*TBA))+(TBBL/2)*(SIN(rad*TBA)))
86	T2 Anchor Load plf Anchor		3,973	#	=C83/TBBL
87	T2 Anchor Circum		16.72	inch plfw	=(C83)*(12)/(TBBL*SW*C85*SCFF)
88	T2 Anchor Circum at Horizontal Tie Spacing		84	inch	=(C87)*TBHS
89	T2 Anchor Diameter		27	inch	=(C88)/(3.14)
90					
91	T3 Force Horizontal Component ***(after B. Newton)***		196,665	plfw	=((H3.)*(1/2)+(H4.)*(1/2))*(Pa)
92	T3 Force Axial Component		278,126	plfw	=(C91)/(SIN((PI()/180*TBA)))
93	T3 Depth		22.00	ft	=UG+H1.+H2.+H3.
94	T3 Anchor Average Depth		51.70	ft	=(C93)+(TB3UBL*(SIN(rad*TBA))+(TBBL/2)*(SIN(rad*TBA)))
95	T3 Anchor Load plf Anchor		3,973	#	=C92/TBBL
96	T3 Anchor Circum		15.37	inch plfw	=(C92)*(12)/(TBBL*SW*C94*SCFF)
97	T3 Anchor Circum at Horizontal Tie Spacing		77	inch	=(C96)*TBHS
98	T3 Anchor Diameter		24	inch	=(C97)/(3.14)
99					
100	T4 Force Horizontal Component ***(after B. Newton)***		165,643	plfw	=((H4.)*(1/2)+(H5.)*(23/48))*(Pa)
101	T4 Force Axial Component		234,255	plfw	=(C100)/(SIN((PI()/180*TBA)))
102	T4 Depth		29.00	ft	=UG+H1.+H2.+H3.+H4.
103	T4 Anchor Average Depth		55.87	ft	=(C102)+(TB4UBL*(SIN(rad*TBA))+(TBBL/2)*(SIN(rad*TBA)))
104	T4 Anchor Load plf Anchor		3,347	#	=C101/TBBL
105	T4 Anchor Circum		11.98	inch plfw	=(C101)*(12)/(TBBL*SW*C103*SCFF)
106	T4 Anchor Circum at Horizontal Tie Spacing		60	inch	=(C105)*TBHS
107	T4 Anchor Diameter		19	inch	=(C106)/(3.14)
108					
109	R Force ***(after B. Newton)***		26,339	plfw	=((3/16)*(H5.))*(Pa)
110					
111	Mmax betw B & R where Hn is largest ***(after B. Newton)***				
112	Largest Tie-Back Hn Spacing		7.00	ft	=MAX(C11:C15)
113	Max Moment between B & R ***(after B. Newton)***		137,666	ft-#	=(Pa)*(C112)*(C112)/10
114					
115	***SOLDIER, LAGGING & WALER SIZING***				
116	Max Moment		137665.5	ft-#	=IF(C113>C71,C113,C71)
117	Horizontal Tie-Back/Soldier Spacing		5	ft	=TBHS
118	Max Moment x Horizontal Spacing		688327.5	ft-#	=C116*TBHS
119					
120	Soldiers' req'd Section Modulus				
121	S = M/f, with f = 50,000 psi, M converted to in-#		165.1986	in^3	=C118*12/50000
122	from HP Pile Selection		HP14x102		(hyperlink to Table below)
123					
124	Using Deep Cellular Decking, Section Modulus req'd				
125	for Spans, pre-select max deck span avail:		HCS7.5 16/16		(hyperlink to Table below)
126	Max Sx listed = 4.65 in^3		4.65	in^3	
127	Therefore Max Deck Span:				
128	S = M/f, with f ==>		40,000	psi	
129	M = S*f = 4.65 in^3) * (40,000 psi) = 186,000 in-#		186000	in-#	
130	in ft-#		15500	ft-#	
131	M = wL^2/8, where w = Pa				
132	L = (8M/w)^1/2		2.10	ft	
133	L = rounded down		2	ft	(hyperlink to Table below)
134					
135	Waler Section Modulus req'd:				
136	Calculated Span from above		2	ft	=C133
137	Section Modulus req'd		42.1425	in^3	=C136*Pa*(TBHS)*(TBHS)*12/(8*50000)
138	from WF Selection		W8x48		(hyperlink to Table below)

Sheet 3 of 4

	A	B	C	D	E
162	SOLDIER PILES SIZING TABLE				
163		HP Piles Selection Table			
164		Section Modulus Req'd	165.20		=C121
165		Line	2		=MATCH(C164,C170:C180,-1)
166		Size	HP14x102		=INDEX(B170:C180,C165,1)
167		Size's Sx Limit	169		=INDEX(B170:C180,C165,2)
168					
169		Shape	Plastic Sx		
170		HP14x117	194		
171		HP14x102	169		
172		HP14x89	146		
173		HP12x84	120		
174		HP14x73	118		
175		HP12x74	105		
176		HP12x63	88.3		
177		HP12x53	74		
178		HP10x57	66.5		
179		HP10x42	48.3		
180		HP8x36	33.6		
181					
182					
183	LAGGING SIZING TABLE				
184		Deck Selection Table (CMC Joist & Deck)			
185		Shape	Plastic Sx*		
186					
187		HCS7.5 16/16	4.65		(pre-selected max avail in catalogue)
188		HCS7.5 16/18	4.62		
189		HCS7.5 18/16	3.9		
190		HCS6 16/16	3.54		
191		HCS6 16/18	3.47		
192		HCS7.5 18/18	3.23		
193		HCS7.5 18/20	3.15		
194		HCS6 18/16	2.94		
195		HCS618/18	2.48		
196		HCS6 18/20	2.51		
197					
198					
199	WALER VERTICAL SPACING BASED ON LAGGING SPAN, ROUNDED DOWN				
200					
201		Vert Span	2.10		=C132
202		Array Line	5		=MATCH(C201,C206:C216,1)
203		Round Down	2		=INDEX(C206:C216,C202,1)
204					
205			Feet, Rounded		
206			0		
207			0.5		
208			1		
209			1.5		
210			2		
211			2.5		
212			3		
213			3.5		
214			4		
215			4.5		
216			5		
217					
218	WALERS SIZING TABLE				
219		WF Waler Selection Table			
220		Section Modulus Req'd	42.14		=C137
221		Line	3		=MATCH(C220,C226:C237,-1)
222		Size	W8x48		=INDEX(B226:C237,C221,1)
223		Size's Sx Limit	49		=INDEX(B226:C237,C221,2)
224					
225		Shape	Plastic Sx		
226		W8x67	70.2		
227		W8x58	59.8		
228		W8x48	49		
229		W8x40	39.8		
230		W8x35	34.7		
231		W8x31	30.4		
232		W8x28	27.2		
233		W8x24	23.2		
234		W8x18	20.4		
235		W8x15	17		
236		W8x13	13.6		
237		W8x10	11.4		
238					

Sheet 4 of 4

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
240	***WALL EMBEDMENT CALCULATIONS BASED ON***													
241	***BALANCING R-FORCE AND EMBEDDED WALL LATERAL EARTH PRESSURES (AFTER B. NEWTON)***													
242		min range value	19	#	=MIN(C247:C277)									
243		located on range line #	18		=MATCH(C242,C247:C277,0)									
244	# feet wall embedment where R approx = LAP - LPP		10.5	ft	=INDEX(A247:C277,C243,1)									
245						R	LAPmax	LAPmin	LAPave	LAPtot	LPPmax	LPPmin	LPPave	LPPtot
246	Feet embedded, rounded	R+LAP-LPP	R+LAP-LPP (absolute value)											
247	19	-59,432	59,432		=ABS(B247)	26,339	1,960	1,200	1,580	30,020	7,560	4,629	6,094	115,791
248	18.5	-55,107	55,107		=ABS(B248)	26,339	1,940	1,200	1,570	29,045	7,380	4,565	5,972	110,491
249	18	-50,881	50,881		=ABS(B249)	26,339	1,920	1,200	1,560	28,080	7,200	4,500	5,850	105,300
250	17.5	-46,756	46,756		=ABS(B250)	26,339	1,900	1,200	1,550	27,125	7,020	4,434	5,727	100,220
251	17	-42,732	42,732		=ABS(B251)	26,339	1,880	1,200	1,540	26,180	6,840	4,366	5,603	95,251
252	16.5	-38,809	38,809		=ABS(B252)	26,339	1,860	1,200	1,530	25,245	6,660	4,297	5,478	90,393
253	16	-34,990	34,990		=ABS(B253)	26,339	1,840	1,200	1,520	24,320	6,480	4,226	5,353	85,649
254	15.5	-31,273	31,273		=ABS(B254)	26,339	1,820	1,200	1,510	23,405	6,300	4,154	5,227	81,017
255	15	-27,661	27,661		=ABS(B255)	26,339	1,800	1,200	1,500	22,500	6,120	4,080	5,100	76,500
256	14.5	-24,154	24,154		=ABS(B256)	26,339	1,780	1,200	1,490	21,605	5,940	4,004	4,972	72,098
257	14	-20,752	20,752		=ABS(B257)	26,339	1,760	1,200	1,480	20,720	5,760	3,927	4,844	67,811
258	13.5	-17,457	17,457		=ABS(B258)	26,339	1,740	1,200	1,470	19,845	5,580	3,848	4,714	63,641
259	13	-14,269	14,269		=ABS(B259)	26,339	1,720	1,200	1,460	18,980	5,400	3,767	4,584	59,588
260	12.5	-11,190	11,190		=ABS(B260)	26,339	1,700	1,200	1,450	18,125	5,220	3,685	4,452	55,654
261	12	-8,221	8,221		=ABS(B261)	26,339	1,680	1,200	1,440	17,280	5,040	3,600	4,320	51,840
262	11.5	-5,362	5,362		=ABS(B262)	26,339	1,660	1,200	1,430	16,445	4,860	3,513	4,187	48,146
263	11	-2,615	2,615		=ABS(B263)	26,339	1,640	1,200	1,420	15,620	4,680	3,424	4,052	44,574
264	10.5	19	19		=ABS(B264)	26,339	1,620	1,200	1,410	14,805	4,500	3,333	3,917	41,125
265	10	2,539	2,539		=ABS(B265)	26,339	1,600	1,200	1,400	14,000	4,320	3,240	3,780	37,800
266	9.5	4,944	4,944		=ABS(B266)	26,339	1,580	1,200	1,390	13,205	4,140	3,144	3,642	34,600
267	9	7,231	7,231		=ABS(B267)	26,339	1,560	1,200	1,380	12,420	3,960	3,046	3,503	31,528
268	8.5	9,401	9,401		=ABS(B268)	26,339	1,540	1,200	1,370	11,645	3,780	2,945	3,363	28,583
269	8	11,451	11,451		=ABS(B269)	26,339	1,520	1,200	1,360	10,880	3,600	2,842	3,221	25,768
270	7.5	13,379	13,379		=ABS(B270)	26,339	1,500	1,200	1,350	10,125	3,420	2,736	3,078	23,085
271	7	15,184	15,184		=ABS(B271)	26,339	1,480	1,200	1,340	9,380	3,240	2,627	2,934	20,535
272	6.5	16,865	16,865		=ABS(B272)	26,339	1,460	1,200	1,330	8,645	3,060	2,515	2,788	18,119
273	6	18,419	18,419		=ABS(B273)	26,339	1,440	1,200	1,320	7,920	2,880	2,400	2,640	15,840
274	5.5	19,844	19,844		=ABS(B274)	26,339	1,420	1,200	1,310	7,205	2,700	2,282	2,491	13,700
275	5	21,139	21,139		=ABS(B275)	26,339	1,400	1,200	1,300	6,500	2,520	2,160	2,340	11,700
276	4.5	22,301	22,301		=ABS(B276)	26,339	1,380	1,200	1,290	5,805	2,340	2,035	2,187	9,843
277	4	23,327	23,327		=ABS(B277)	26,339	1,360	1,200	1,280	5,120	2,160	1,906	2,033	8,132

5. Cost Calculations

Sheet 1 of 2

Geof Narlee, Tie-Backs for Deep Braced Cut								
Construction Cost Calculations								
Case: 4 Levels of Tie-Backs								
(RS Means reference cost pages from				RS Means Location Factor % (Framingham)				
2019 77th Edition Building Construction Costs				applied to final line item costs:				
with RSMeans data (published by RSMeans)				81.4%	102.9%	102.9%	96.1%	calc%
			Instance					TOTAL
	Choose		Per LF Wall	MTL	LAB	EQP	TOTAL	W/OH&P
Excavation								
Stripping & Stockpiling, (RSMeans p. 617), PCY								
300 HP Dozer, Medium-Hard conditions, RSM p.					0.3	0.92	1.22	1.47
for width =	50	ft width	1	0.00	0.57	1.75	2.17	2.62
Bulk Excavation								
Dozer, 460HP, 50' Haul, (RSMeans p. 625), PCY					0.31	1.18	1.49	1.76
H from Eng Calcs	30.00							
H x width from above	50.00							
Excavated Mtl Fluff Factor	1.20							
= Cost PLF Wall			1	0.00	21.27	80.95	95.46	112.76
(Truck Away Distance unknown for estimate)								
Dewatering								
RS Means, 12" Piping, incl Trench 3' Deep, (RSMeans p. 627), PLF Wall				10.7	9.3	2.78	22.78	29
with Location Factors, PLF Wall			1	8.71	11.01	11.01	10.28	13.09
HP Piles								
HP Pile Selection, from Engineering Calcs	HP14x102							
RS Means Costs, from Table below				48.50	6.70	4.77	59.97	69.00
Adjusted for Location Factors				39.48	6.89	4.91	57.63	66.31
Adjusted for Length (H + D), from Eng. Calcs	40.50	ft		1599	279	199	2334	2686
Adjusted for Instance per LF Wall			0.2	320	56	40	467	537
Tie-Backs								
Per RS Means 2019, Tie-Backs for Coffer Dams (as proxy, RSMeans p. 643)								
Ave Cost per VLF, min to account for longer actual holes				15.80	26.00	0.54	42.34	58.00
Cost Tie-Back 1			0.2	221	460	10	700	959
Cost Tie-Back 2			0.2	208	433	9	659	903
Cost Tie-Back 3			0.2	198	412	9	627	858
Cost Tie-Back 4			0.2	188	391	8	594	814
Lagging								
RS Means, Celluar Decking, Max, PSF (RSMeans p. 143)				18.6	1.93	10	20.63	23.5
RS Means, Lagging, Wood, PSF (RSMeans p. 643)				3.02	9	0.19	12.21	17.45
Use Celluar Deck Mtl Cost, Lagging for other				15.14	9.26	0.20	24.60	35.15
Wales								
Wale Selection, from Engineering Calcs	W8x48							
RS Means Costs, from Table below				70.00	5.65	3.09	78.74	89.50
Adjusted for Location Factors				56.98	5.81	3.18	75.67	86.01
Adjusted for Instance per LF Wall			4	228	23	13	303	344
Rough Grade Bottom, (RS Means, p. 617), for 5,000 SF					1075	174	1249	1825
= Cost PLF Wall x Excav Width			1	0.00	11.06	1.79	12.00	17.54
Finish Grading, in Prep for application, (RSMeans p. 617 for large area), PSY					0.38	0.33	1.37	1.81
PLF Wall			1	0.00	2.17	1.89	7.31	9.66
General Conditions & OHP, @ 10%			1	139	183	19	350	461
Totals, PLF Wall				1,526	2,014	204	3,851	5,066
Totals, PSF Wall				51	67	7	128	169

Sheet 2 of 2

Nearest RS Means Piles, pp. 644-645, to Calculated HP Piles

Calc	RS Means		Mtl	Lab	Equip	Total	w/OHP
HP14x117	HP14x117		56.00	6.70	4.77	67.47	77.00
HP14x102	HP14x102		48.50	6.70	4.77	59.97	69.00
HP14x89	HP14x89		42.50	6.30	4.51	53.31	61.00
HP12x84	HP12x84	interpolated values >	40.00	6.30	4.51	50.81	58.43
HP14x73	HP14x73		35.50	6.30	4.51	46.31	53.50
HP12x74	HP12x74		35.50	5.80	4.13	45.53	52.50
HP12x63	HP12x63	interpolated values >	30.00	5.80	3.31	39.11	44.98
HP12x53	HP12x53		25.50	5.80	3.31	34.61	40.50
HP10x57	HP10x57		26.50	5.60	3.20	35.30	41.00
HP10x42	HP10x42		19.60	5.60	3.20	28.40	33.50
HP8x36	HP10x42		16.65	5.35	3.05	25.05	30.00

Nearest RS Means WF Beams, pp. 131-132, to Calculated Wales

Calc	RS Means		Mtl	Lab	Equip	Total	w/OHP
W8x67	W8x67	interpolated values >	97.76	5.65	3.09	106.50	122.48
W8x58	W8x58	interpolated values >	84.61	5.65	3.09	93.35	107.35
W8x48	W8x48		70.00	5.65	3.09	78.74	89.50
W8x40	W8x40	interpolated values >	58.31	5.65	3.09	67.05	77.11
W8x35	W8x35		51.00	5.65	3.09	59.74	68.50
W8x31	W8x31		45.00	5.65	3.09	53.74	62.00
W8x28	W8x28		40.50	5.65	3.09	49.24	57.50
W8x24	W8x24		35.00	5.65	3.09	43.74	51.00
W8x18	W8x18	interpolated values >	26.33	5.65	3.09	35.07	40.33
W8x15	W8x15		22.00	5.20	2.83	30.03	35.50
W8x13	W8x13	interpolated values >	19.02	5.20	2.83	27.05	31.11
W8x10	W8x10		14.55	5.20	2.83	22.58	27.50

6. Conclusions

Employment of Tie-Back Braced Walls is a solution for deep excavation cuts that removes additional disruption and built-structure footprint, thus allowing for a mitigation of construction impact and allows realization of the value that the low-side grade offers to stakeholders, be they public or private, including the ability to consider sensitive environmental concerns. This last benefit may be the most unique, in that it represents areas and activities that are difficult to re-locate.

In this project's example inputs, which may be adjusted by the user, we found the following to work:

Retaining Wall Element Sizes:
Soldier Piles: HP14x102 @ 5' Horizontal Spacing
Lagging: Cellular Metal Decking CMC's HCS7.5 16/16, vertically oriented
Wales: W8x48 @ 2' Vertical Spacing

Retaining Wall Construction Costs:
Cost per LF of Wall: $ 5,066
Cost per SF of Wall: $ 169

There are some real-world conditions, not taken into account in this addendum, which would be interesting for further study. For example: seismic loads; other external loads on or within the high-side grade that have an effect within the load-side of the wall within the braced system (including anchors); effects of groundwater penetration into the braced system (including anchors) soil section; a rigorous limit equilibrium analysis regarding bottom-of-wall depth; and helical anchors in lieu of concrete.

7. Bibliography

Newton, Barton J. "Earth Retaining Systems Using Ground Anchors," Caltrans Engineering Manuals (website), California Dept. Transportation, accessed October 8, 2018, http://www.dot.ca.gov/des/techpubs/manuals/bridge-memo-to-designer/page/section-5/5-12.pdf

"Coulomb's Lateral Earth Pressure." *Civil Engineering Bible* (website). Accessed December 2018,
https://civilengineeringbible.com/subtopics.php?i=8

"Lateral Earth Pressure III." Univerity of Connecticut (website). Accessed December 2018, http://www.engr.uconn.edu/~lanbo/CE240LectW122lateralpressure3.pdf

"Design Manual and Catalogue of Steel Deck Products." *CMC Joist & Deck* (website). Accessed December 2018, http://www.ecs.umass.edu/cee434/handouts/CMCDeckCatalog.pdf

Ambrose, James. *Simplified Engineering for Architects and Builders, 9th Edition.* John Wiley & Sons, Inc., 2000.

Kalodikis, Christopher. "Introduction to Flowchart Symbols." YouTube (website), May 10, 2017. Accessed December 2018,
https://www.youtube.com/watch?v=kxZJv56BxU8

"Chapter 6 Basics Mechanics." Food and Agriculture of the United Nations (website). Accessed December 2018,
http://www.fao.org/docrep/015/i2433e/i2433e03.pdf

Oakeson, Isaac. "Structures-Find the Max Bending Moment in Beam." YouTube (website), December 2, 2014. Accessed December 2018,
https://www.youtube.com/watch?v=f1iixxjB4ac

Tingerthal, John. "Shear and Moment at a given point in a simple beam." YouTube (website), March 19, 2013. Accessed December 2018,
https://www.youtube.com/watch?v=wVwzr0TpdH8

StructureFree. "Shear and Moment Diagram Example 2 - Mechanics of Materials and Statics." YouTube (website), May 10, 2012. Accessed December 2018,
https://www.youtube.com/watch?v=kX3MRuXxFFQ

Allan Block, Inc. (website). Accessed December 2018,
www.allanblock.com

"Guide to Trench Excavations." Govmt Hong Kong (website), February 2003. Accessed December 2018, https://www.cedd.gov.hk/eng/publications/geo/doc/trench_excavations.pdf

Pandy, Yogesh. "Braced Cut in Deep Excavation." Slideshare (website), May 23, 2013. Accessed December 2018, https://www.slideshare.net/yogeshpandey3005/braced-cut

"Four Common Types of Rigid, Monolithic Concrete Retaining Walls." ConcreteNetwork.com (website). Accessed December 2018, https://www.concretenetwork.com/concrete/poured_concrete_retaining_walls/four_types.htm

Boonyachut, Supawadee. "Earthwork." King Mongkut's University of Technology Thonburi (website). Accessed December 2018, http://eu.lib.kmutt.ac.th/elearning/Courseware/ARC261/chapter3_3.html

"Massena Braced Excavation." Glynn Geotechnical Engineering (website). Accessed December 2018, http://www.glynngroup.com/wp-content/uploads/2012/09/GM_Massena_Braced_Excavation2.jpg

"Tie-Back Walls." Wagman (website). Accessed December 2018, https://www.wagman.com/specialized-services/tieback-walls.asp

Soilstructure Software (website). Accessed December 2018, www.soilstructure.com/structural-software/tieback-wall

Cruzan, Jeff. "Law of sines derivation." YouTube (website), Mar 18, 2015. Accessed December 2018, https://www.youtube.com/watch?time_continue=2&v=UYBxAL8-Eps

Dasgupta, Kaustubh. "Beams – SFD and BMD." Indian Institute of Technology (website). Access December 2018, http://www.iitg.ac.in/kd/Lecture%20Notes/ME101-Lecture11-KD.pdf

Noor, Reasat E. "Soil Properties and Foundation." Slideshare (website), January 30, 2017. Accessed December 2018, https://www.slideshare.net/Reasat121/soil-properties-and-foundation

2019 Building Construction Costs, 77th Edition, with RSMeans data. RSMeans, Inc., 2019.