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A Conceptual and Analytical Model for the Design of Soldier Pile and Tieback Retaining Systems

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Abstract: ***The Purpose of this paper is to enable and provide new or young Engineers who will be involved in the design and installation of bank retention systems for, as tied back wall systems with tools how to start and optimize their retention systems for design, installation, and take off materials. This method is obtained from more than twenty years of retention system design experience. An illustration of design steps and calculation through during construction to final stage is included in this paper. It is important to mention that the most critical case in the design might be during construction stage not at the final design case.***

Keywords: retention systems, design optimization, bank retention, construction stages, engineering tools

1.Introduction

Deep excavations are becoming increasingly common for the construction of buildings, tunnels, mass rapid transit systems and other facilities at densely built-up areas within city and suburban areas. Soil or rock excavation can be considered as deep excavation if the excavation is typically more than 3 m (10 ft) deep. Such works could affect nearby structures because of ground movement associated with stress changes.

Retaining and support system selection in deep excavation can have significant impact on time, cost and performance of the completed excavation and construction project.

1.1 Tieback, wood lagging, and Soldier piles

By far the most common retention system is soldier piles with horizontal wooden lagging retained by soil tiebacks. In all conventional retention systems, some parts of the membrane will be installed before excavation is begun. Components used to resist lateral earth-pressure forces are installed soon after the membrane is in place (tiebacks or anchors) or are installed as excavation proceeds (wales and struts).

Lengths of grouted tieback anchors are usually 100 percent to 125 percent of the wall height. Sometimes, tieback anchors are much longer to reach rock or soil with sufficient strength to support the design load and may be installed to support an area of approximately 11 sq m (120 sq ft) per tie. Tiebacks are active support members; they are stressed in tension to produce compression on the retained soil higher than the lateral pressures from the weight of the earth and from surcharge before the retained soil moves.

Every tieback anchor is usually proof tested, or performance tested, and Tieback tendons are usually either thread bar tendons (Grade 160) or multi-strand tendons (Grade 270).

Tied back walls often use soldier beams, lagging, and tiebacks with a precast or cast-in-place concrete permanent facing when required.

General:

Retention systems prevent sidewall collapse and reduce lateral movement and settlement of the surrounding ground. In soft clays, retention systems also must prevent base failure and minimize bottom heave. The settlement and lateral movement depend on

1) Soil properties
2) General procedure of excavation
3) Adequacy of the bracing
4) Workmanship

The settlement near an open cut can be reduced only if the inward movement of the sheeting and the heave can be substantially reduced. By experience, they indicate a heavy section of soldier piles or sheeting is usually not enough to have a significant effect on the magnitude of the lateral movement of wall. These movements can be substantially reduced by installing layers of struts relatively close in vertical spacing. The most important variable that determines the amount of movement is not the stiffness of the wall or the vertical spacing of bracing, but the surrounding soil parameters. (Clough and O'Rourke, 1990).

There are several methods of retention systems, like sheet piles, H-Piles and wood lagging, concrete lagging or steel plate lagging, soil nailing and other methods.

Internal Bracing versus Tiebacks

In the case of internal bracing systems, the lateral earth pressure is transferred between opposing walls through compressive struts. Rakers resting on a foundation mat or rock offer another internal bracing alternative. Usually, the struts are either pipe or I- beam sections and are usually preloaded to provide a very stiff system. Installation of the bracing struts is carried out by excavating soil locally around the strut and only continuing the excavation when preloading is complete. The struts rest on a series of whaler beams that distribute the strut load to the diaphragm wall. Pre-loading ensures rigid contact between interacting members and is accomplished by inserting a hydraulic jack when each individual pipe strut between the whale beam and a special jacking plate welded to the strut. Internal bracing makes sense in narrow excavations in cases where tieback installation is not practicable. The struts can bend excessively under their own weight if the excavation spacing is too large. A clear benefit of using struts is that there are no tieback openings. In case of using rakers, the workplace will be limited, and in case of losing one raker due to any workman ship mistakes, that might cause a failure in the retention system. While using tieback retention systems will give a clear, reliable system and if any lateral movement in the retained wall occurred, it could be corrected by stressing on the tieback more.

Installation of conventional systems

These system components of the H-piles and wood lagging consist of H-Pile section steel; usually HP 10x42 or HP 12x53 or different sections, installed at 8 to 10 ft C-C, 3- to 4-inch- thick wood lagging, double C-section channel made as a waler, and tieback anchor. Usually, the wood lagging of the upper 8 ft of the retained wall or down to the first row of tiebacks will be installed behind the soldier pile flanges to accomplish a fast installation. While the lagging of rest the wall will be installed on the front face of the piles by welding studs and plates to hold the wood lagging, and that will slow the work down, therefore the installation cost of the wood lagging for the upper 8 ft is higher than the lower elevations.

To install this system the first thing that will be done is to be predrilled or drive the steel beam (Soldier Piles) in ground on a base line down to the required depth, (depth of the excavation plus the required depth below the dredge line as the design required). Then the excavation starts down to 4 to 6 feet or down to the upper tieback elevation depends on the type of the soil that can hold a vertical face without support until lagging (wood, steel, concrete, etc.…) is installed. After that, the excavation advanced with another lift and so forth. When the excavation level reaches a tieback elevation, the process of tie back installation starts, the tieback installation starts with drilling a hole generally 10 to 15 cm (4 to 6 in) in diameter. The tieback installation started at an angle of about 20 to 30 degrees below the horizontal plane as deep as the design required. The depth of tieback installation depended on the soil (strength) properties, and the design load. Then, a hollow high-tensile-strength threaded steel reinforcing bar will be inserted into the hole and injecting grout through the center of the rebar. The grouted (bonded) zone of the bar length had to extend behind the failure zone which is assumed to extend up from the bottom of the H-piles at a steep angle to the horizontal; the angle depended on the shearing resistance of the soil. A stability analysis should be done to ensure that the mass of soil retained by the piles, lagging and tiebacks would not fail along a shearing surface that extended below the bottom of the excavation in a global shear failure.

Depending on the design, a wale(s) may be installed, or the tieback will be installed through the steel H-pile. If a wale design is used, the tieback goes through the wale (usually two channel sections). The tieback, secured through a steel plate that bears against the wale then will be stressed with hydraulic jacks to provide a pre-stressed lateral resistance. Each tieback will be proof tested to 120 percent of the design load per Post-Tensioning Institute recommendations. (PTI 1996)

Photo 1: Tiebacks with common walers

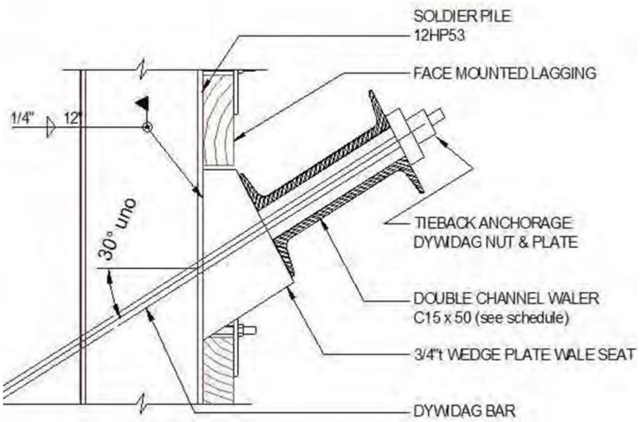


Figure 1: Tieback w/ Common wale details

Photo 2: Tieback through pile penetration

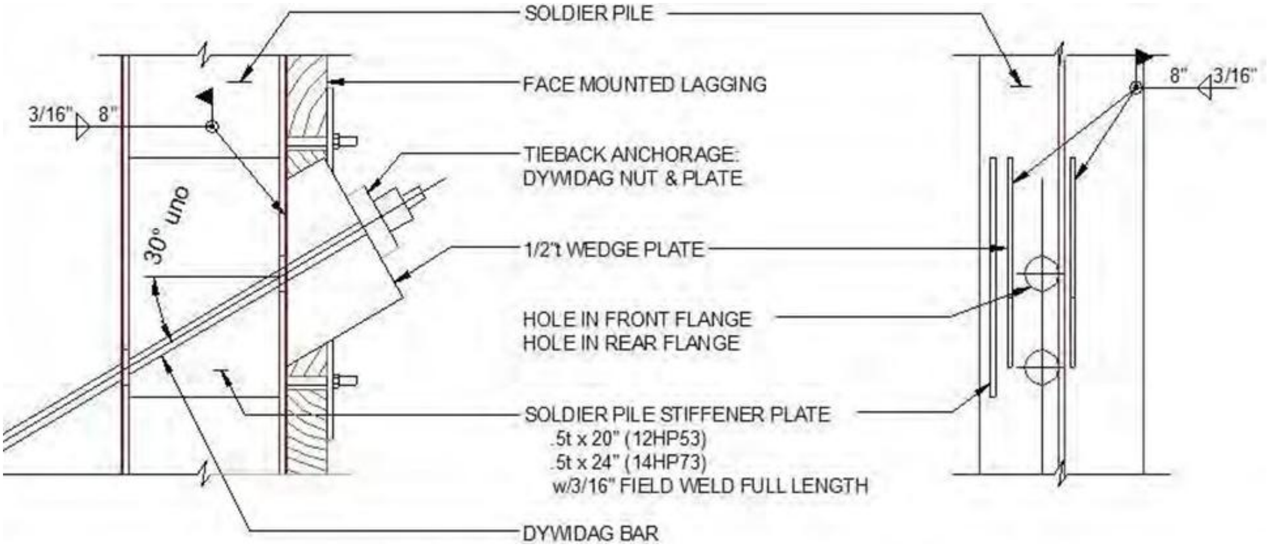


Figure 2: Tieback through soldier pile detail

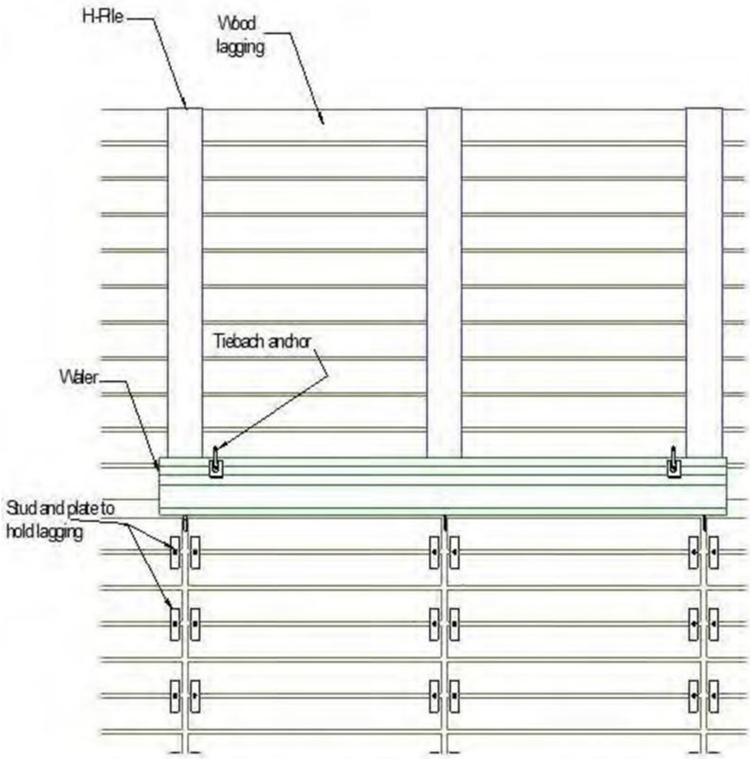


Figure 3: Typical Wood Lagging Wall

Photo 3: Wood Lagging

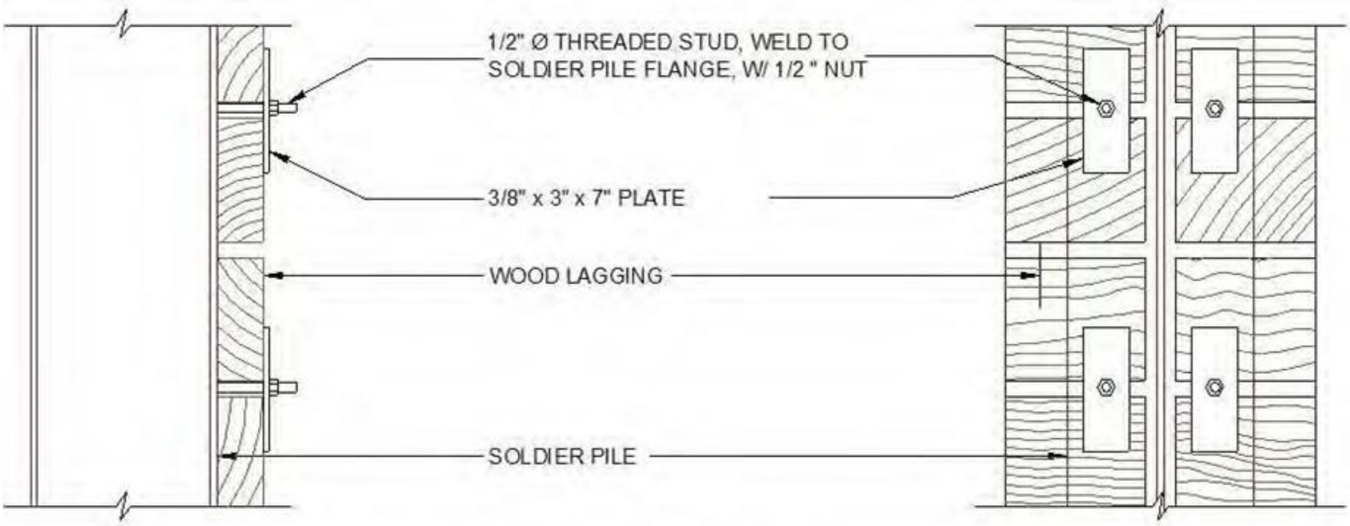


Figure 4: Lagging Stud detail

2.Method of Analysis

To show the steps that have been followed to arrive at the final design, the rationale given in the following paragraphs allows development of a conceptual model of a typical conventional wall.

From experience and PTI recommendations, the length of the bonded zone should not exceed 30 feet, because tiebacks would not get any extra bonded strength even if their length exceeds 30 feet; the tiebacks would fail in tension rather than pull out.

To determine how long the free length will be, two methods are available to define the failure zone or the slip surface: the first method is to draw a line from the bottom of the wall (toe) to the surface with an outer angle of (45 + Ø/2) where Ø is the angle of internal friction. This line was moved 5 feet into the retained soil. This line defines the boundary between the soil that will move with the wall and the soil that will remain stable and is taken to be the boundary between the free length and the bonded length. The other method is to draw a logarithmic spiral slip surface based on the soil properties to choose the most critical line that defines the boundary between the moving soil and the soil that will remain stable. By experience, the first method will give a line located farther from the wall and, thus, more conservative, as shown in Fig. 5 below.

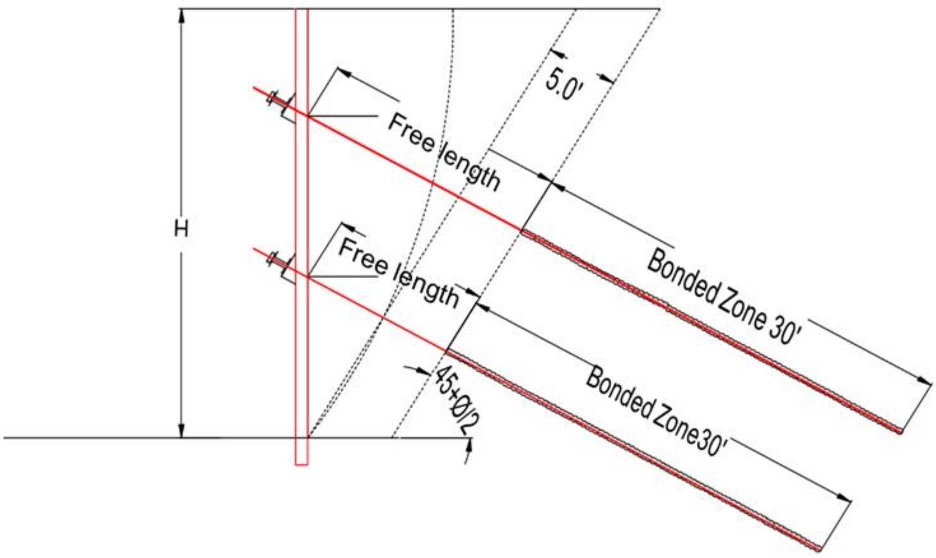


Figure 5: Tieback Bonded Length and Free Length

The total length of tieback is the summation of the bonded length, free length and 5 feet of tieback tail, that extends beyond the wall.

To determine tieback vertical spacing, an empirical approach is used. From experience it is known that if the project requires a single tieback, the best tieback location is about (0.35 to 0.4) of the wall height, H. from the top of the wall, but not more than 10 feet. At any greater spacing, a heavy soldier pile section will be required for the initial cantilever stage during construction. In addition, a bench two feet deep will be required below the tieback location to allow tieback installation, therefore even if the top cantilever section of the wall is 10 feet, the total height to be supported is 12 feet. If the project requires installation of two tiebacks, the location of the upper tieback will be about (0.275 to 0.3) of the total wall height from top of the wall, and lower tieback location will be about (0.3 to 0.4) of the total wall height up from the bottom of the wall. These values have been determined from experience. The designer must check the load on the tieback for the situation during construction just before lower tieback installation to check tieback design load, soldier pile section modulus, and soldier pile embedment in the ground to determine the requirements at this intermediate stage, versus the completed stage, for the configuration as shown in Fig. 6 below.

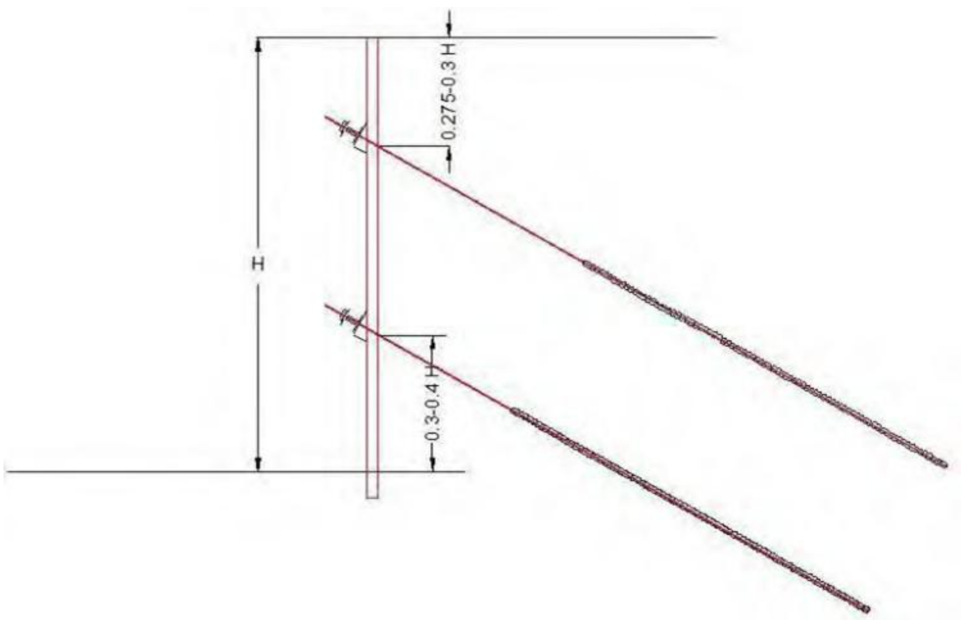


Figure 6: Two-tieback Wall Vertical Spacing

When project design requires installation of three tiebacks, the upper tieback location will be about (0.2 to 0.25) H from the top of the wall, with the same spacing for the lower tieback from the bottom of the wall, and the remaining length between upper and lower tiebacks will be divided into two equal segments for midpoint tieback location, as shown in Fig. 7.

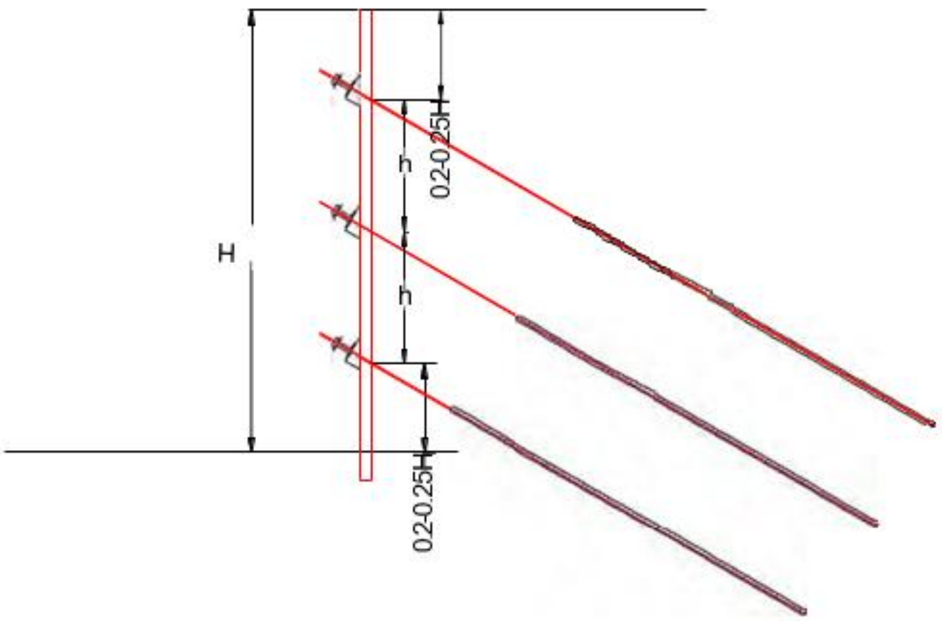


Figure 7: Three-tieback Wall Vertical Spacing

When projects design requires installation of four tiebacks, the upper tieback location will beat (0.175 to 0.2) H and the lower tieback will be the same distance from the bottom of the excavation, and then the spacing between upper and lower tiebacks will be divided into three equal segments for location of the two remaining tiebacks, as shown in Fig. 8.

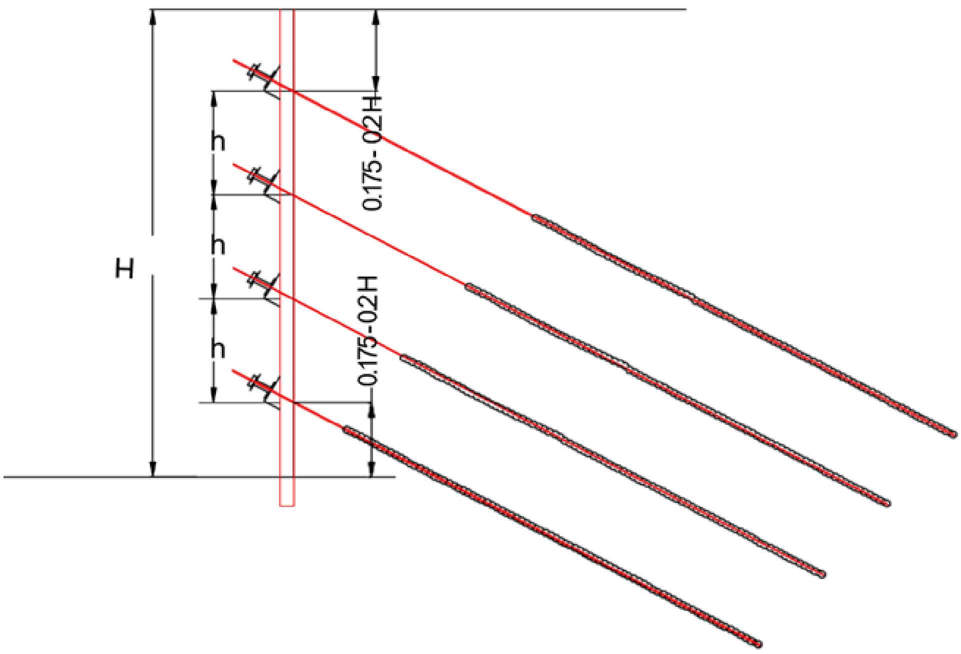


Figure 8: Four-tieback Wall Vertical Spacing

To determine the required soldier pile section, the designer calculates the maximum moment in the pile at all construction stages and at the final stage, and then calculates the section modulus (Sx) required to limit bending stress in the pile to the appropriate code value. Then, the designer chooses the available steel section that will provide at least that section modulus.

An evaluation for tieback design load needs to be conducted to get an economical design; high tensile strength steel rebar with a diameter of 1-1/4 inch will hold up to 100 kips of design load and 120 kips of the proof load.

If the design requires a tieback for each bay (soldier pile to soldier pile), then an evaluation needs to be conducted to find which method will be more economic; to install the tieback through pile penetration or to install the tieback through the wale. Usually, if the selected soldier pile has adequate section modulus remaining after cutting a hole through pile flanges to install a tie back through the pile, then this method will be more economical than using a wale. If the tieback capacity is sufficient to hold more than one bay load (1-1/2 or 2 bays) then using a wale will be the more economic design rather than penetrating each soldier pile for a tieback, because the cost of tiebacks is much higher than the cost of wales.

Illustration of 37.5 FT Wall Design Steps:

To illustrate fully these design steps, a wall of 37.5 feet high will be selected.

Step 1: Assume that steel soldier piles will be driven on a base line to a depth of 2 feet below the bottom of the excavation. Then, the excavation will be advanced to a depth about 18 inches to 2 feet below the first tie location. Run design calculation as a cantilever wall to size the system components, as shown on the following page.

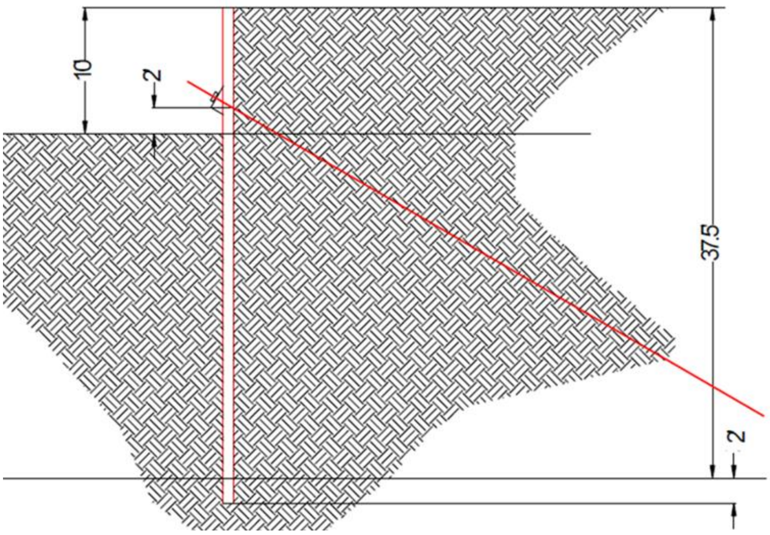


Figure 9: Step 1 of Retention System Design Process (all dimensions in feet)

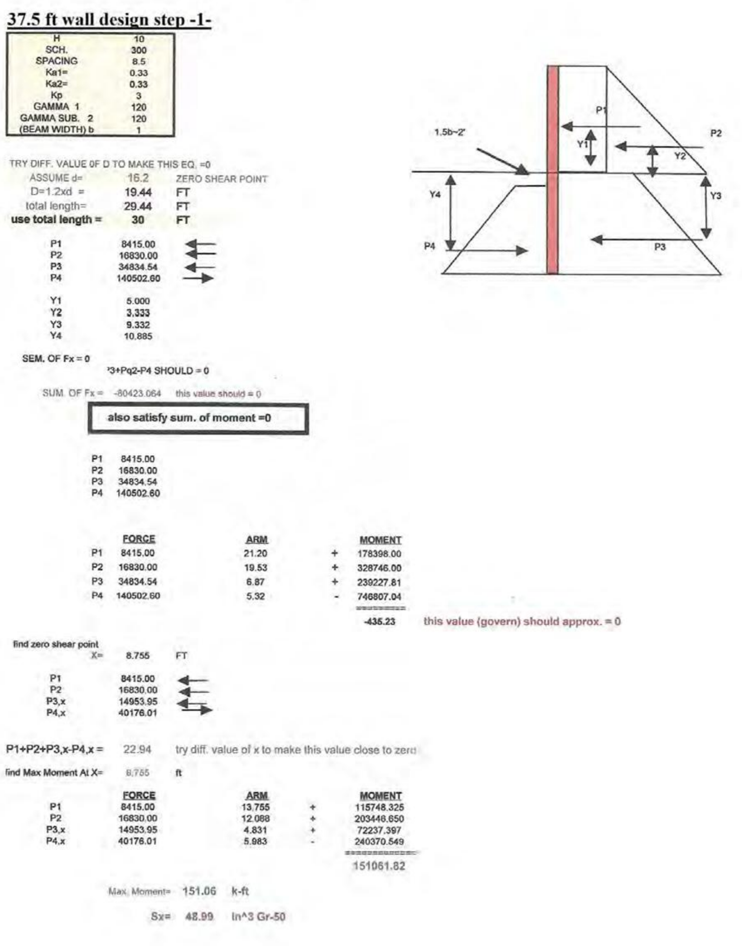


Figure 10: Step 1 Design Calculation

Step 2: In the construction process, the field personnel will drill and install the first tieback, and then advance the excavation to about 18 inches to 2 feet below the second tieback location. Run a design calculation with the first tieback in place, to size the retention system, as shown in the following three figures.

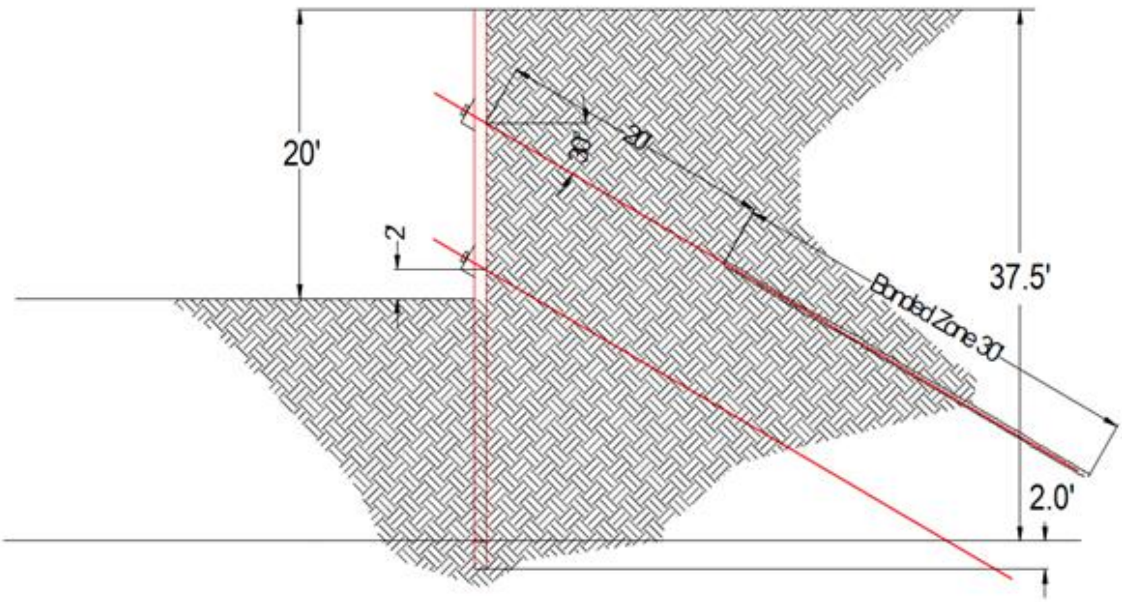
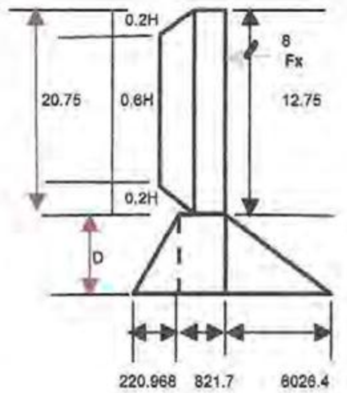


Figure 11: Step 2 of Retention System Design Process (all dimensions in feet)



Step -2- desin Calculation

DEPTH OF EXCA	20.75	FT
FRICTION- PHEE	30	DEGREE
SOIL UNIT WEIGHT	120	#/C.F
SURCHARGE Scu	300	PSF
PILES SPACE s	8.5	FT
PILE FLANGE b	1	FT
PILE EFF. FACTOR	3	
Ka	0.33	
Kp	3	
TIE LOCATION	8	FT
TIE ANGLE X=	30	DEGREE
Pb FACTOR =	22	
ALLOWABLE STRESS =	37	KSI
COS X=	0.8660	
Pb =	456.5	PSF
Pq =	99	PSF
LENGTH OFupper triangle	4.15	FT
LENGTH OF rectangle	12.45	FT

PILE PENETR. D=	5.56	FT
PAS.PRESSUp1=	6026.4	PSF
ACT.PRESSUp1=	821.7	PSF
ACT.PRESSUp2=	220.968	PSF
DIST.FROM DRE-DGE LINE TO TIE	12.75	FT

try diff.value of D

TO FIND PILE PEnetration D
MOMENT @TIEBACK LOCATION

FORCE	ARM		MOMENT
6732	4	+	26928
8051.51875	5.2195	+	42024.90212
14938.9625	1.925	+	28757.50281
10729.125	6.375	-	68398.17188
33370.15	4.3	-	143491.645
8051.51875	9.9695	-	80269.61618
16813.656	16.4328	+	276295.4463
4585.086	15.54	-	71252.23644
616.50072	16.4328	-	10130.83303

TOTAL MOMENT@TIE LOCATION= 463.3 (THIS VALUE SHOULD APPROX.=0)

the (D)should be= used	6.70	FT	
USE D=	18.00	FT	
F.S=	3.23	HENCE	OK
TOTAL LENGTH=D+H=	38.75	FT	

Figure 12: Step 2 design calculation

TO FIND TIEBACK FORCE
MAKE SUM. FOR Fx=0

FI=	17461.125	+
F2=	16103.0375	+
F3=	48309.1125	+
F4=	4585.086	+
F5=	16813.656	-
F6=	616.50072	+

Fx/ONE BAY=	70.26	KIP
Fx/ONE FT=	8.27	KIP/FT
Fx/ BAY =	70.26	KIP
TIE FORCE/1 BAY=	81.13	KIP
PROOFTEST LOAD=	97.36	KIP

FIND MAX. MOMENT

1 @TIEBACK LOCATION = -8 FT

FORCE	ARM	MOMENT
6732	4	26928.00
8051.51875	5.2195	42024.90
14938.9625	1.925	28757.50

MAX. MOMENT= 97.71 KIP.FT

2 @ X-DISTANCE FROM THE TOP OF THE PILE

FIND X WHEN SUM.OF Fx =0 (ZERO SHEAR POINT)

X= 16.58553 FT

FORCE	ARM	MOMENT
13956.72	8.2927648	115739.82
70261.21	8.5855296	603229.66
8051.52	13.80503	111151.45
48252.96	6.2177648	300025.58

MAX. MOMENT= 76.31 KIP.FT

USE MAX. MOMENT= 97.71 KIP.FT
MOD. SECTION = 31.69 CUB. IN (Gr-50)

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Figure 13: Step 2 design calculation (cont.)

Step 3: In the construction process, the field crew will drill and install the second tieback, and then advance the excavation to about 18 inches to 2 feet below the third tieback location. Run a design calculation with two tiebacks in place to size the retention system.

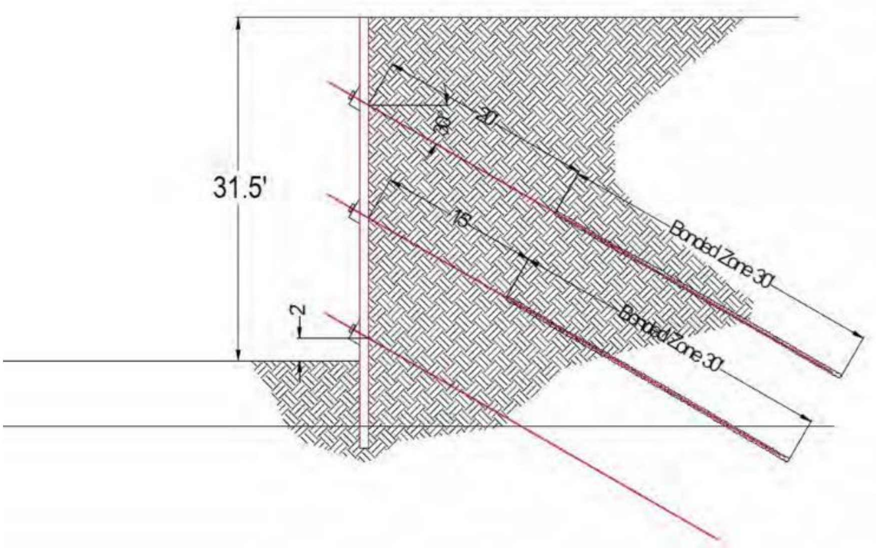
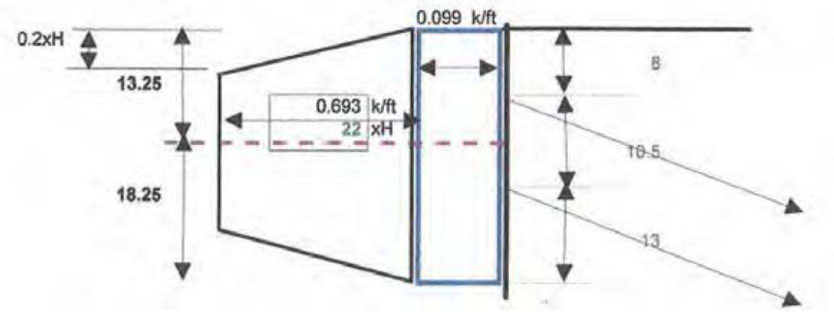


Figure 14: Step 3 of Retention System Design Process (all dimensions in feet)

Step -3- Design Calculation

H=	31.5	FT
S=	8.5	FT
SCH	300	PSF
TIE 1@	8	FT
TIE 2@	18.5	FT
TIE @	30	DEGREE
Ka=	0.33	FT
Pb FACTOR =	22	
upper triangle =	6.3	ft
lower triangle=	6.3	ft



W= 6.732 K/1 VERTICAL FT

Fx1= 70.64 KIP/FT
Fx2= 104.30 KIP/FT

COS X= 0.8660255

DL1= 81.57 KIP/FT
DL2= 120.44 KIP/FT

PROOF LOAD 1.2 X DL

PROOF TIE 1 = 98 KIPS/FT
PROOF TIE 2 = 145 KIPS/FT

MAX MOMENT 1 @ TIE 1 LOCATION

FORCE	ARM		MOMENT
18.56	3.80	+	70.51
6.73	4.00	+	26.93
10.01	0.85	+	8.51
			========
			105.95

FIND ZERO SHEAR POINT

X IS BELOW 0.2 H X= 6.95 FT

FORCE	ARM		MOMENT
5.30	10.10	+	53.54
18.56	9.05	+	167.92
46.79	3.48	+	162.59
70.64	5.25	-	370.88
			========
			13.17

USE MAX. MOMENT = 105.95 FT-KIP
Sx= 34.36 IN^3/FT Gr-50

Figure 15: Step 3 Design Calculation 1st run

The resultant design is not acceptable, because the second tieback design load will exceed 80 percent of the ultimate allowable load for (1¼-inch-diameter) reinforcing bar per PTI recommendations. If (1 3/8-inch-diameter) rebar was used that will increase the cost of tiebacks; therefore, redesign the system to keep the load in the second tiebacks around 100 kips (the proof load will be about 120 kips, or 120 percent of the design load). To do so, rerun the design calculation. Assume the surcharge load during construction will be limited to about 50 pounds per square foot rather than 300 pounds per square foot until the proof load test was performed and assume the tieback load will be locked at 75 percent of the design load. On the final stage design, use the normal surcharge of 300 pounds per square foot.

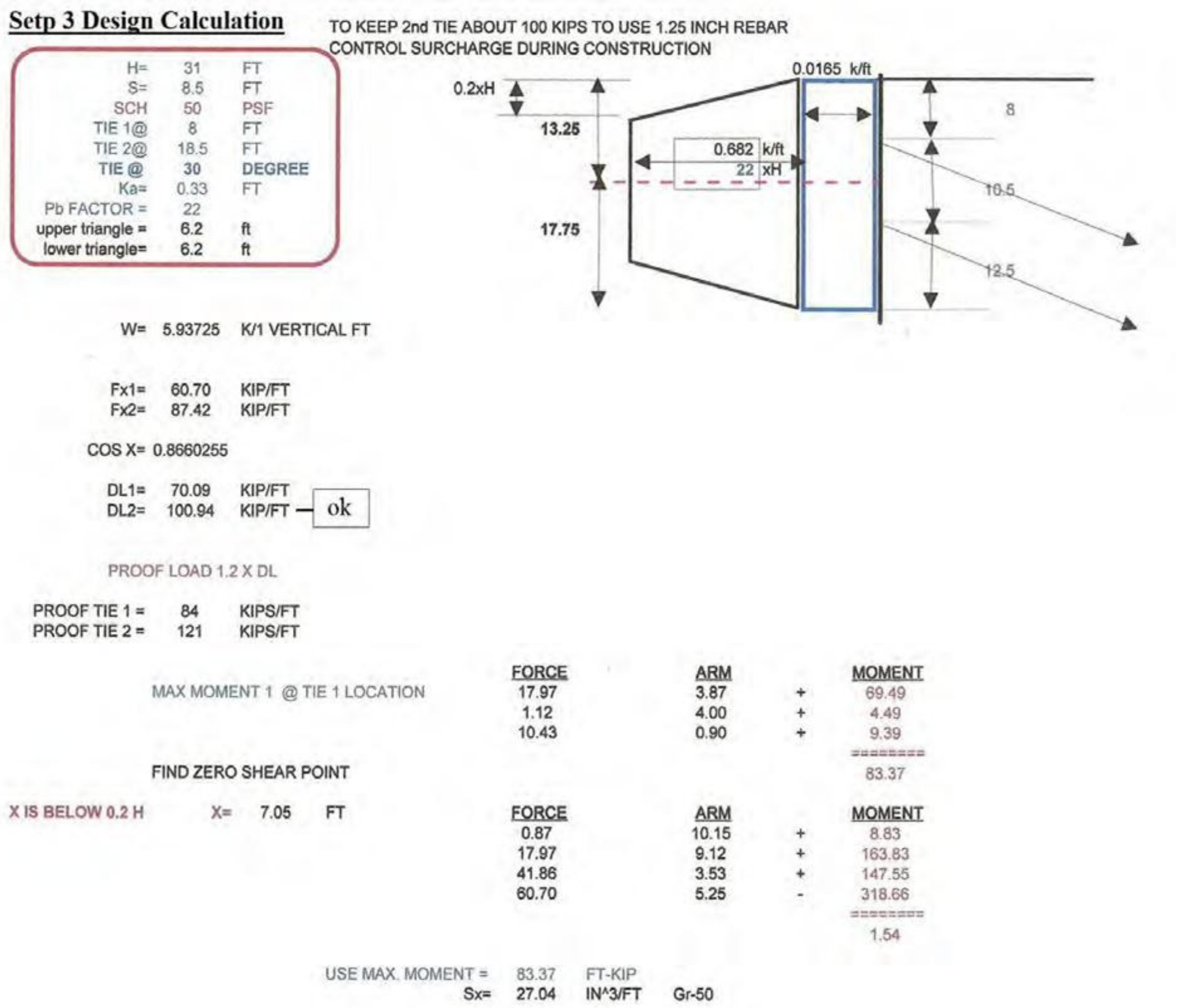


Figure 16: Step 3 Design Calculation 2nd run

Step 4: Field crew will drill and install the third tieback, and then advance the excavation to the planned bottom elevation as the final stage. Run a design calculation for the final stage and use the design that will satisfy the final stage condition and conditions during construction.

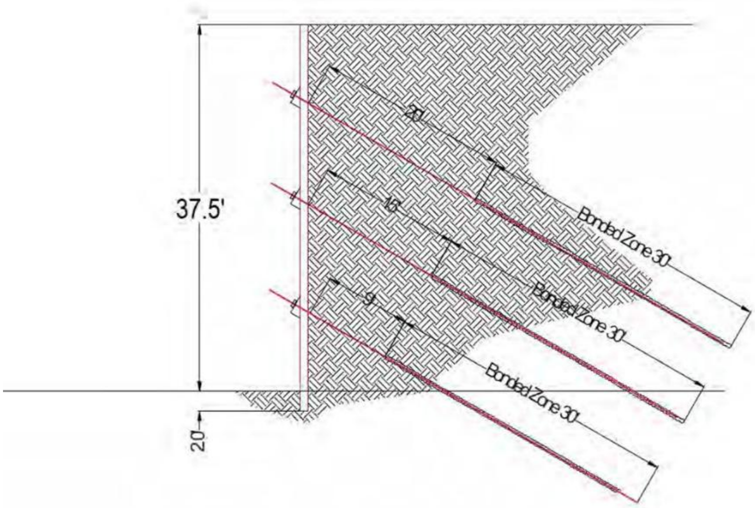
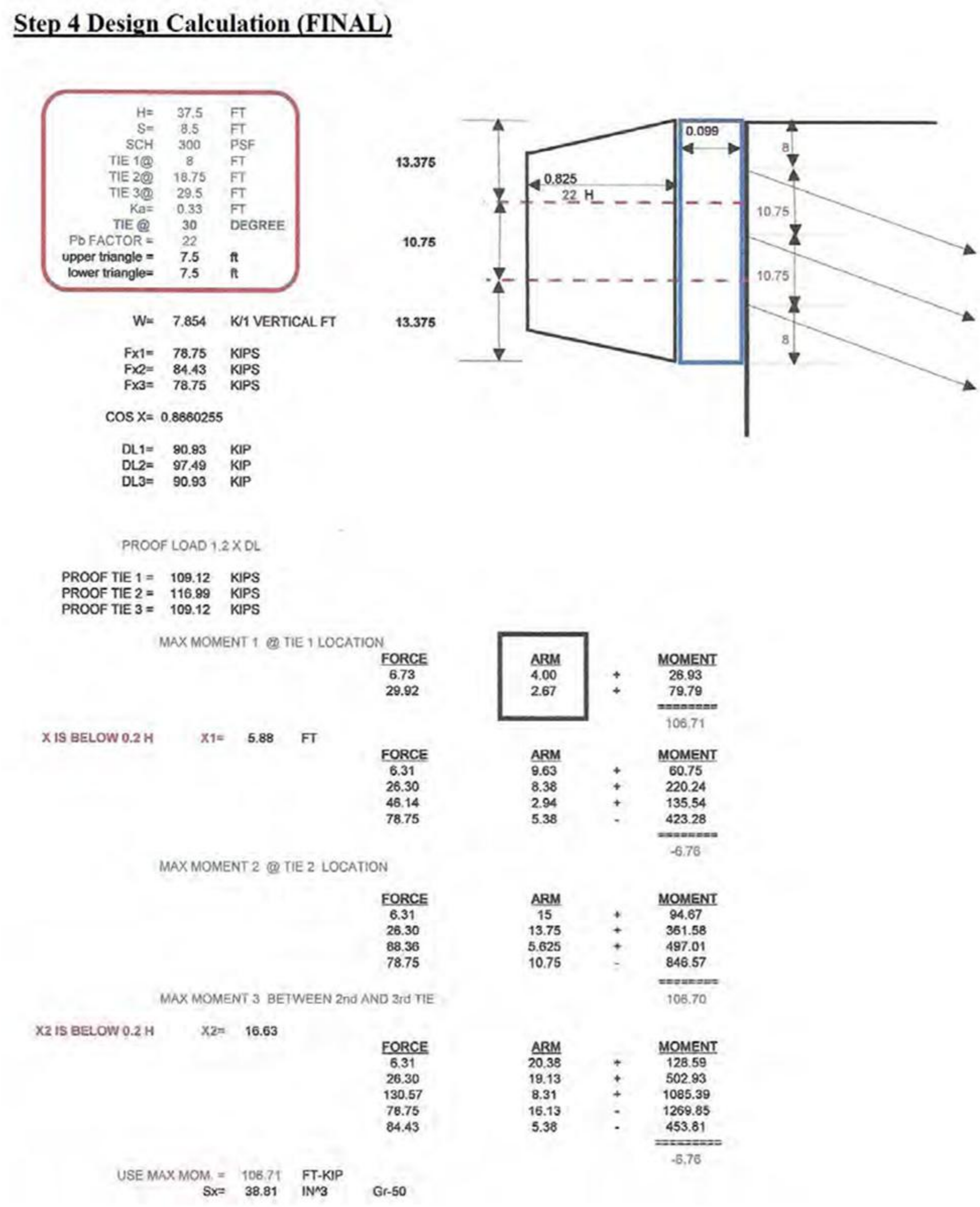


Figure 17: Step 4 of Retention System Design Process (all dimensions in feet)



H=	37.5	FT
S=	8.5	FT
SCH	300	PSF
TIE 1@	8	FT
TIE 2@	18.75	FT
TIE 3@	29.5	FT
Ka=	0.33	FT
TIE @	30	DEGREE
Pb FACTOR =	22	
upper triangle =	7.5	ft
lower triangle=	7.5	ft
W=	7.854	K/1 VERTICAL FT
Fx1=	78.75	KIPS
Fx2=	84.43	KIPS
Fx3=	78.75	KIPS
COS X=	0.8660255	
DL1=	90.93	KIP
DL2=	97.49	KIP
DL3=	90.93	KIP

PROOF LOAD 1.2 X DL

PROOF TIE 1 =	109.12	KIPS
PROOF TIE 2 =	116.99	KIPS
PROOF TIE 3 =	109.12	KIPS

MAX MOMENT 1 @ TIE 1 LOCATION

FORCE	ARM		MOMENT
6.73	4.00	+	26.93
29.92	2.67	+	79.79
			========
			106.71

X IS BELOW 0.2 H X1= 5.88 FT

FORCE	ARM		MOMENT
6.31	9.63	+	60.75
26.30	8.38	+	220.24
46.14	2.94	+	135.54
78.75	5.38	-	423.28
			========
			-6.76

MAX MOMENT 2 @ TIE 2 LOCATION

FORCE	ARM		MOMENT
6.31	15	+	94.67
26.30	13.75	+	361.58
88.36	5.625	+	497.01
78.75	10.75	-	846.57
			========
			106.70

MAX MOMENT 3 BETWEEN 2nd AND 3rd TIE

X2 IS BELOW 0.2 H X2= 16.63

FORCE	ARM		MOMENT
6.31	20.38	+	128.59
26.30	19.13	+	502.93
130.57	8.31	+	1085.39
78.75	16.13	-	1269.85
84.43	5.38	-	453.81
			=========
			-6.76

USE MAX MOM. = 106.71 FT-KIP
Sx= 38.81 IN^3 Gr-50

Figure 18: Step 4 Design Calculation

3.Conclusion

The author tries to use the nineteen years of experience that he has, dealing with retention system design to establish a conceptual modeling for a conventional tied back design.

The intent of this method is to help new and young retention system designers to have first- hand experience of designing a bank retention system and that will give them a road map of how to start and select the retention system component for design, materials, and scheduling.

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