LIMIT-EQUILIBRIUM ANALYSIS OF TANDEM SHEET PILE STRUCTURES

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ABSTRACT

There is an apparent gap in established technical literature regarding tandem sheet pile (TSP) structures, where two parallel rows of sheeting are cross-tied to form a narrow containment for earth fill between. There is a relatively straight forward case where the two walls are distinctly far apart and essentially respond independently to external loading; however, site constraints frequently dictate a restricted footprint and create a strong interaction between the two wall systems. When net lateral loads are applied, the active side acts as a typical sheet pile bulkhead, while the passive side could be considered a cantilevered deadman. For typical TSP structures of this type, a single-level tie rod is highly eccentric (to maintain the points of connection above the water table), the cantilevered deadman is relatively flexible, and the theoretical active wedge of the bulkhead and passive wedge of the deadman wall overlap significantly.

Tandem sheet pile structures are increasingly common despite their inefficient use of material. Two parallel walls can be constructed much faster than caissons or circular coffer cells and can accommodate much greater retained height than solutions such as gravity or L-walls without the need to dewater during construction. They are also specified for retrofit and deepening projects where existing landside facilities preclude placement of a traditional deadman system at sufficient setback from the wharf face.

Understanding the complex structure-soil-structure interactions is essential for ensuring the stability and performance of the wall system. The analysis of this interaction is well suited to finite element techniques using industry-standard software such as Plaxis or FLAC. However, these advanced tools require ground-truthing with conventional methods of analysis to validate their results.

A methodology is proposed herein using conventional 2D bulkhead software (namely CWALSHT) with appropriate K factors to estimate the interplay between setback, embedment, and flexural rigidity required for the deadman bulkhead in cases where wall systems interact. Concepts are borrowed from design of traditional deadman, cantilever and anchored bulkheads, and grouted soil anchors, then expanded and illustrated through simple models. The intent is to provide a conservative, force-based methodology for analyzing TSP's which is both quick to iterate and simple to backcheck.

Key Words

Tandem sheet pile, Double sheet pile, Cantilever deadman, Filled pier, Active and passive wedge interaction, Active and passive wedge overlap

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INTRODUCTION

Tandem Sheet Pile (TSP) structures are increasingly common in the waterfront industry, but literature on how to approach the design of these systems is limited. These structures (sometimes also referred to as double sheet pile wall systems) generally consist of two parallel rows of sheet piling which are cross-tied to form a narrow containment for earth fill between. Common applications of a TSP are filled piers and cantilever deadman, where the deadman serves as the 2nd wall system. See Figure 1 for typical sections.

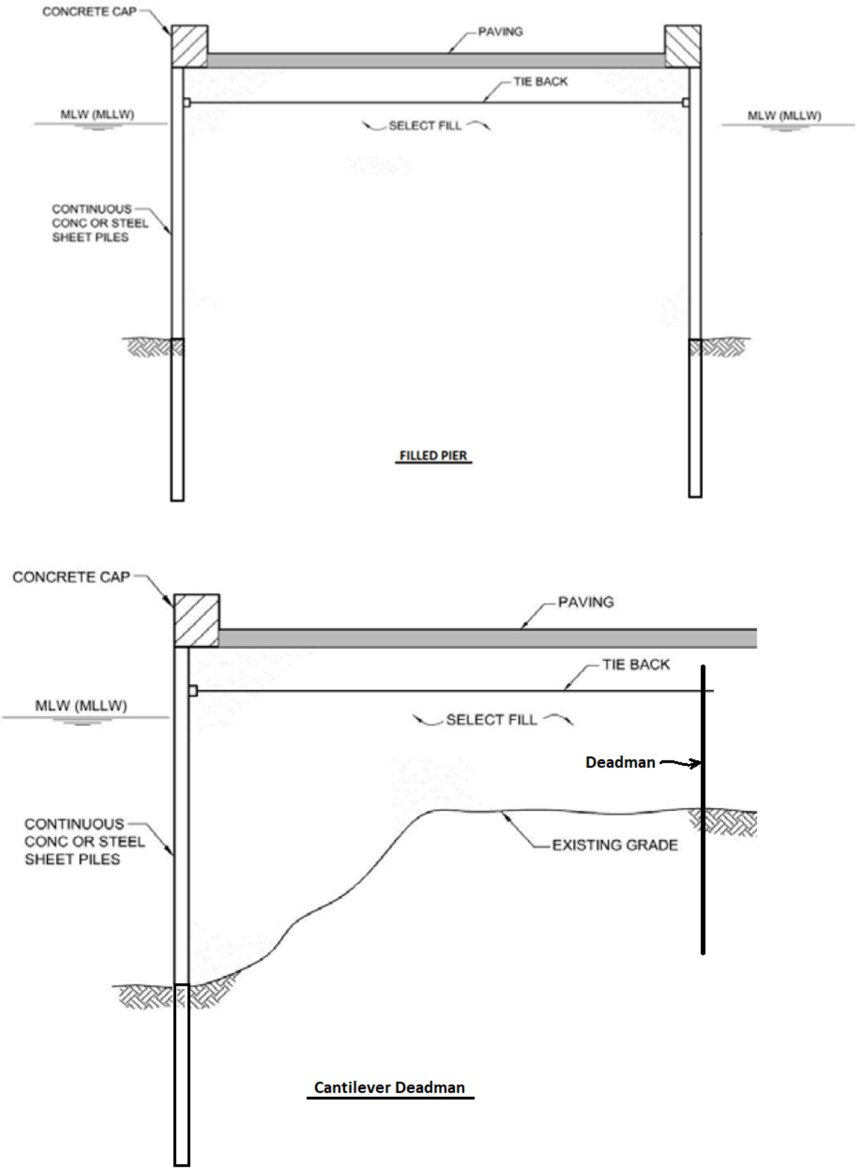


Figure 1, Typical Section of Cantilever Deadman & Filled Pier

There is a relatively straight-forward case where the two walls are distinctly far apart and essentially respond independently to external loading, which will not be considered here; however, site constraints frequently dictate a restricted footprint and create a strong interaction between the two wall systems. Established engineering guidance does not directly address the design of such structures.

When net lateral loads are applied, the active side acts as a typical sheet pile bulkhead, while the passive side acts as a cantilevered deadman. For typical port structures of this type, the single-level tie rod is highly eccentric (to maintain the points of connection above the water table), the cantilevered deadman is relatively flexible, and the theoretical active wedge of the bulkhead and passive wedge of the deadman wall overlap significantly.

The analysis of this interaction is well suited to finite element techniques using industry-standard software such as Plaxis or FLAC. However, these advanced tools require ground-truthing with conventional methods of analysis to validate their results. A methodology is proposed herein using 2D limit-equilibrium bulkhead design software (namely CWALSHT) with appropriate K factors to estimate the interplay between setback, embedment, and flexural rigidity required for the deadman bulkhead in cases where wall systems interact. The intent is to provide a conservative, force-based methodology for analyzing TSP's which is both easy to iterate and to sanity check, as a supplement to more detailed analysis.

TANDEM SHEET PILE APPLICATIONS

There are several uses and advantages in comparison to more conventional earth retaining structures:

- Can be constructed faster than caissons or circular coffer cells.
- Can accommodate greater retained height than solutions such as gravity or L-walls without the need to dewater during construction.
- Solution for retrofit and deepening projects where existing landside facilities preclude placement of a traditional deadman system at sufficient offset from the wharf face.
- Applications where shallow rock or downdrag from compressible soils make A-frame and batter pile solutions uneconomical or infeasible.
- Filled piers and TSP structures have advantages for:
    - Dynamic wave loading, where inertia from the added fill mass reduces demand on structural elements.
    - Ice loading, where pile-supported structures are more likely to experience damage due to ice floes or uplift if ice buildup is permitted beneath the deck.
- In one case example, TSP was the preferred solution to allow for a continuous slurry wall down the length of the filled pier as an environmental cutoff wall.

The primary disadvantage of TSP's is the inefficient use of material. By comparison, traditional deadman at greater setback or circular coffer cells would have significantly lower weight of steel.

Regarding filled pier structures in particular, the shipping industry increasingly demands deep-water berths. As the water depth and exposed wall height increases, the pier width which would be required to achieve negligible interaction between the two walls increases commensurately. However, pier width sufficient to avoid TSP interaction is generally unnecessary from an operational perspective, where the working area required for cargo handling is dependent on the required travel lanes, turning radii for the equipment, and crane rail gauge. Allowing interaction between the two walls can make a filled pier project feasible due to reduction in environmental impacts, required volume of fill, and navigation concerns.

CONVENTIONAL DEADMAN DESIGN

The traditional method for deadman analysis will be briefly discussed as a point of comparison.

Design guidance dictates that the tie rod extends to a point where active and passive earth pressure wedges do not overlap significantly, as shown in Figure 2. If there is overlap, the passive force developed by the overlap region is added to the front wall, creating a circular load path from deadman, through soil to the front wall, to tie rod, back to deadman. This is conservative and appropriately discourages overlapping wedges without deeper investigation. However, it is reasonable only for small deadman systems with little overlap. The methodology breaks down and produces unreasonable solutions as the deadman approaches the front wall.

Key assumptions of the traditional design method are that the deadman is essentially rigid and loaded near the centerline, such that the full waterside face mobilizes passive earth pressure to resist the tie rod pull. For a cantilever deadman, which has a highly eccentric tie rod and is relatively flexible, these assumptions are not valid.

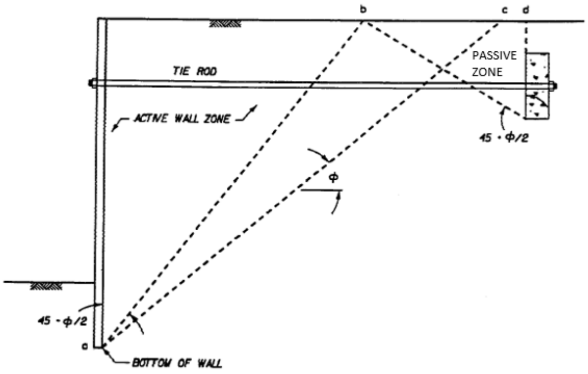


Figure 2, Desired Offset to Conventional Deadman

Various authors have proposed alternative methods for calculating the total pullout resistance of the deadman considering minor wedge overlap in a limit equilibrium framework. Again, these are appropriate where the deadman is relatively rigid and there is small overlap between active and passive wedges. In that scenario, deflection of the tie back system is minimal and strength considerations control the design.

POTENTIAL FAILURE MODES OF TSP

Compared to traditional deadman systems, the TSP configuration does not normally change the failure modes illustrated in Figure 3 for rotational failure (inadequate embedment), bulkhead flexure, tie back tension, or wale flexure / connection rupture. These will not be discussed further.

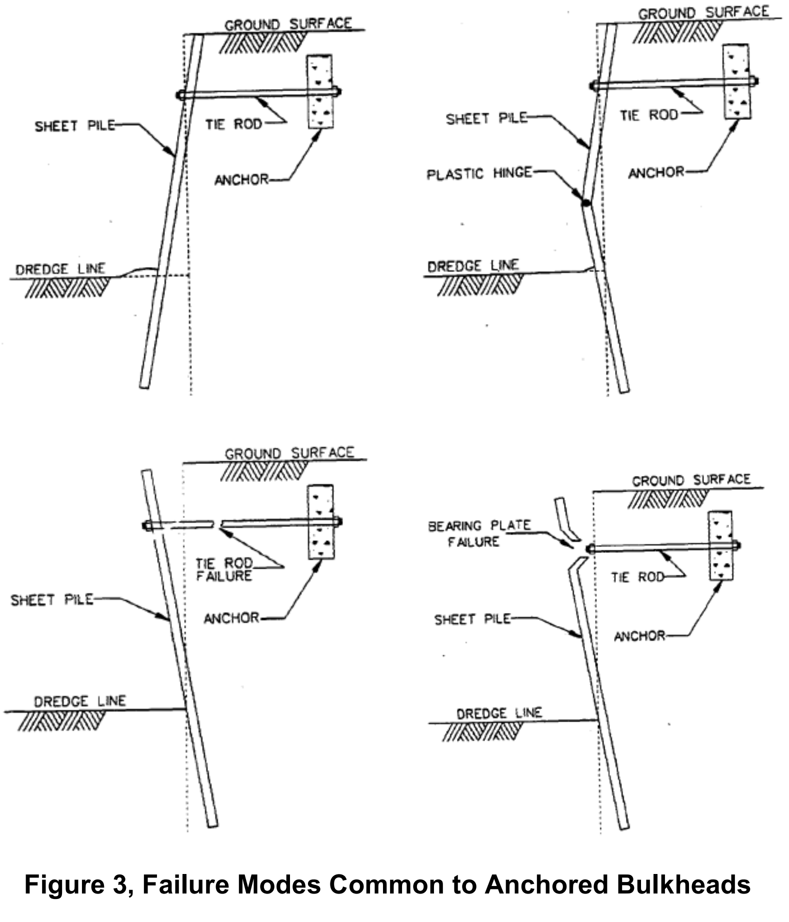


Figure 3, Failure Modes Common to Anchored Bulkheads

The narrow TSP structure does modify or introduce several failure modes. See Figure 4 below for those specific to TSP structures – deep-seated failure, anchor passive failure, and deadman flexure and/or excessive deflection. Note that large deflection of the deadman will be mirrored by large deflection of the bulkhead. Allowable deflection typically controls the overall geometry and stiffness of the TSP section and is the primary failure mode investigated for this discussion. Separate analysis should be conducted to validate global stability, deep-seated failure modes.

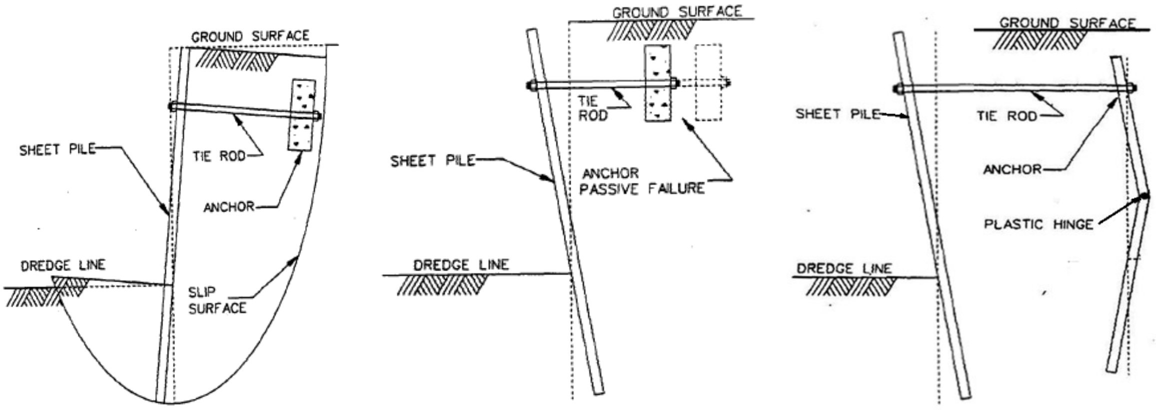


Figure 4, Potential Failure Modes Modified by Cantilever Deadman Design

SCOPE & LIMITATIONS FOR TSP LIMIT-EQUILIBRIUM ANALYSIS METHOD

The methodology proposed is demonstrated using CWALSHT software (freely distributed by the US Army Corps of Engineers) and is intended to elaborate only on the differences required in the analysis as the cantilever deadman setback is reduced. General design principals such as lateral earth pressure, hydrostatic differential, load combinations, etc. are not discussed in detail. US Army Corps EM 1110-2-2504 design guidance may be used for these purposes.

USA design standards and guidance have been considered when setting reasonable member sizes and performance criteria. However, the methodology presented is generalized and shows nominal structural response without explicit reference to any national standard. The nominal behavior can be readily adapted to various specific building codes.

Plane-strain (2D) modeling techniques are used throughout. Effects from seismic loading, liquefaction, and corrosion have not been investigated. Note that only continuous sheet pile deadman walls are considered for this discussion, but analogous cantilever deadman have been constructed with discrete piles or sheet pile pairs as well.

STRUCTURAL BEHAVIOR OF CANTILEVER DEADMAN

For the purposes of illustration, a simple geostructural model has been developed for an anchored steel sheet pile bulkhead with the following parameters:

- Moderate exposed wall height of 20 feet
- Medium-dense sand profile with a saturated unit weight of 120 PCF and friction angle of 30°
- 250 PSF uniform live load (typical for traffic loading)
- A single tie rod located 5 feet below grade
- Passive side water level at Mean Low Water (MLW)
- Active side water level 2 feet above MLW to account for tidal lag
- Free earth support method

The typical section of the design case and key parameters are shown in Figure 5, and the qualitative deflected shape is shown in Figure 6. Note that the tieback force of 5 klf was determined using

CWALSHT software in a separate free-earth analysis for the bulkhead using standard procedures. The same bulkhead and tie rod demand are used for all CWALSHT design cases.

As the deadman setback decreases, the wall system progressively acts more like parallel cantilevers, which are typically controlled by deflection rather than strength or stability considerations. Embedment and stiffness of the deadman must increase to maintain reasonable deflections. For an anchored bulkhead, the anchor point is typically estimated to deflect a nominal amount only, say ½ inch. For a cantilever bulkhead, acceptable deflection criteria for a wall with moderate exposed height may be on the order of 3 inches. Note that established design guidance does not dictate these deflection values, but instead they are left to engineering judgement based on the required structural performance and tolerance of adjacent infrastructure and operations. For the proposed cantilever deadman design process, allowable deflection at the deadman follows an approximately linear trend between these two extreme deflection values and support locations.

This structural behavior is first demonstrated using finite element analysis (FEA), then CWALSHT models are developed to show the ability of the model to quickly and effectively estimate structural member size and performance.

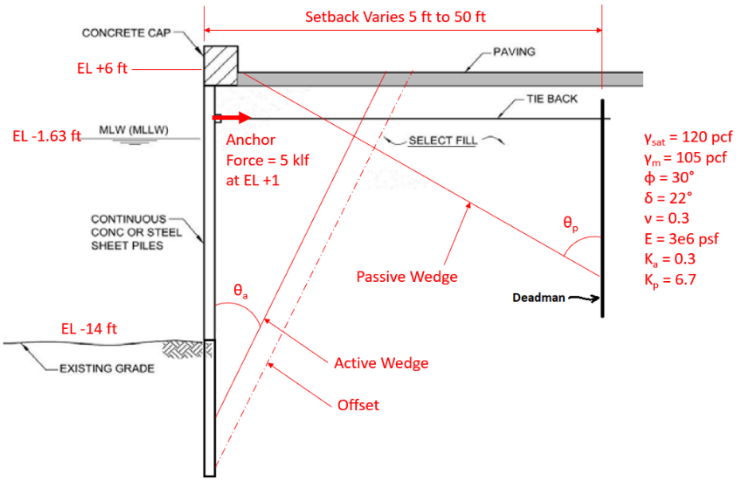


Figure 5, Cantilever Deadman Design Section & Parameters

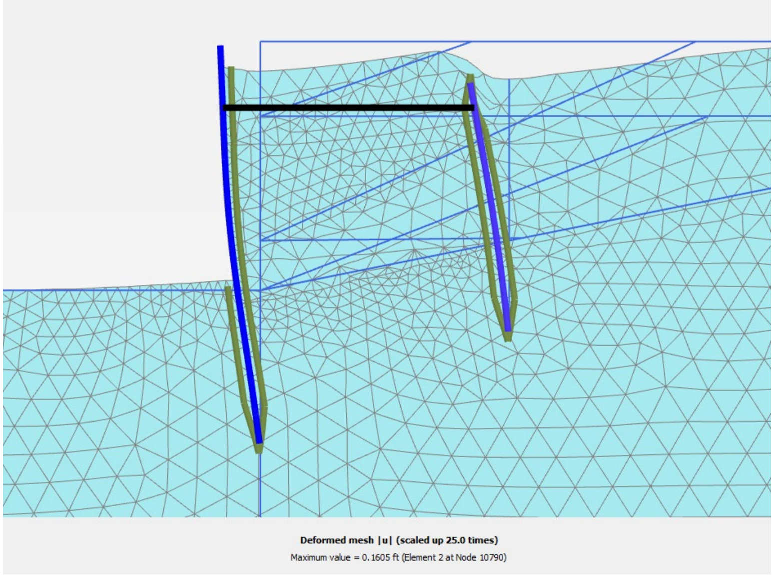


Figure 6, Deflected Shape of Cantilever Deadman

Finite Element Model

Simple models for illustrating overall structural behavior have been created using Plaxis 2D by Bentley Systems, one of several industry-standard tools for FEA for use in geotechnical engineering. Mohr-Coulomb constitutive model was used, which requires definition of deformation parameters (notably Young's modulus and Poisson ratio) in addition to unit weight and shear strength parameters (angle of internal fiction and cohesion). For the sheet pile, embedment and flexural stiffness (EI) are the critical parameters for nominal structural behavior – strength and flexural capacity are left to the designer under local building codes and national standards. Axial stiffness (EA) of the tie rod is relatively large and inconsequential to the overall system deflection for typical tie rod configurations.

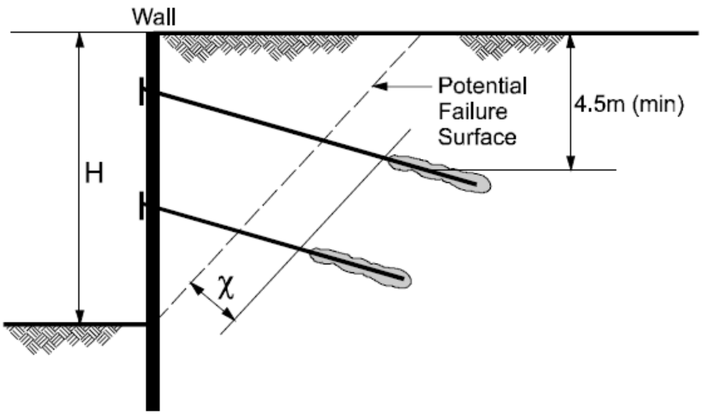
Analysis cases were considered with the deadman setback 1) arbitrarily far away at 50 feet (no overlap between active and passive wedges), 2) adjacent to the active wedge at 20 ft setback, 3) within the active wedge from 10 to 15 ft setback, and 4) very near to the bulkhead at 5 ft setback (with almost complete overlap between active and passive wedges).

Embedment and flexural stiffness of the deadman were increased until allowable deflection criteria was achieved, which linearly increased from approximately ½ inch for a distant deadman to 3 inches for systems approaching a cantilever bulkhead configuration. The primary bulkhead stiffness and embedment were held constant.

Approximation Using CWALSHT

The proposed simplified methodology uses CWALSHT with appropriate coefficients of lateral earth pressure (K values) to estimate the interplay between setback, embedment, and flexural rigidity required for the deadman bulkhead. Note that K is defined as the ratio of lateral earth pressure to vertical earth pressure due to the overlying column of soil. Alternative software which calculates sum of forces and sum of moments to be zero in a limit equilibrium analysis would be equally effective. For the simple geometry shown here, stability could reasonably be calculated by hand using the cantilever bulkhead methodology discussed in EM 1110-2-2504 and taking the tie rod tension as the driving force.

Specific allowances must be made based on the proximity between the deadman and primary bulkhead. First, the assumed active wedge is drawn in accordance with Coulomb earth pressure assumptions. K factors are then set to zero from the ground surface to a point 5 feet distant from the active wedge. This is conceptually aligned with free length for soil anchors or MSE reinforcements, as illustrated in Figure 7 from FHWA Geotechnical Engineering Circular No. 4, Ground Anchors and Anchored Systems. Similar to the cantilever deadman, soil nail walls rely on distributed resistance over a large depth immediately inboard of the active wedge. Note that while $K = 0$, the weight of the soil in the active wedge is still included in the CWALSHT model, and this has substantial effects on resistance developed in deeper coarse-grained strata.



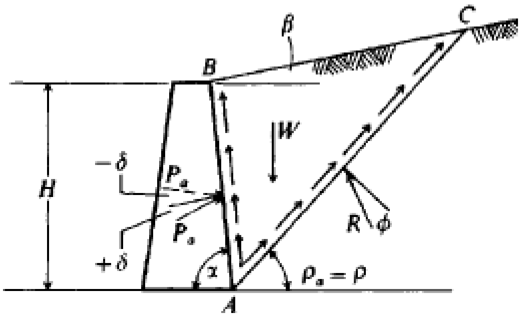
Minimum unbonded length = 3m (bar)
4.5m (strand)

χ = 1.5m or 0.2H, whichever is greater

Figure 7, Assumed Free-Stressing Length for Grouted Anchors

As wall friction has been included in the Plaxis model, it similarly needs to be accounted for in the shape of the active wedge. Per Rankine assumptions (without wall friction) the θ_a angle is equal to 45° - φ/2 or 30° for this case. Extending to Coulomb earth pressure theory to account for wall friction and solving Equation 1 below for maximum lateral load, active wedge angle in this case is equal to 35°. The resulting depth where K = 0 is shown in Table 1 below. Below this depth, K factors are developed internally by the program with the usual method.

Once the geometry, lateral tie rod force (from standard bulkhead analysis), and soil profile (including K value modifications) are defined, CWALSHT will output the scaled deflection (as a function of moment of inertia), bending moment demand, and tip elevation required for the deadman sheet pile.



$$P_a = \frac{\gamma H^2}{2\sin^2\alpha}\left[\sin(\alpha+\rho)\frac{\sin(\alpha+\beta)}{\sin(\rho-\beta)}\right]\frac{\sin(\rho-\phi)}{\sin(180^\circ-\alpha-\rho+\phi+\delta)}$$

Equation 1, Lateral load for Coulomb Wedge as a Function of Wedge Angle, ρ

[Per Bowles Chapter 11, Eqn (c)]

Setback (ft)	Elevation where K = 0
5	-25
10	-17
15	-10
20	-3

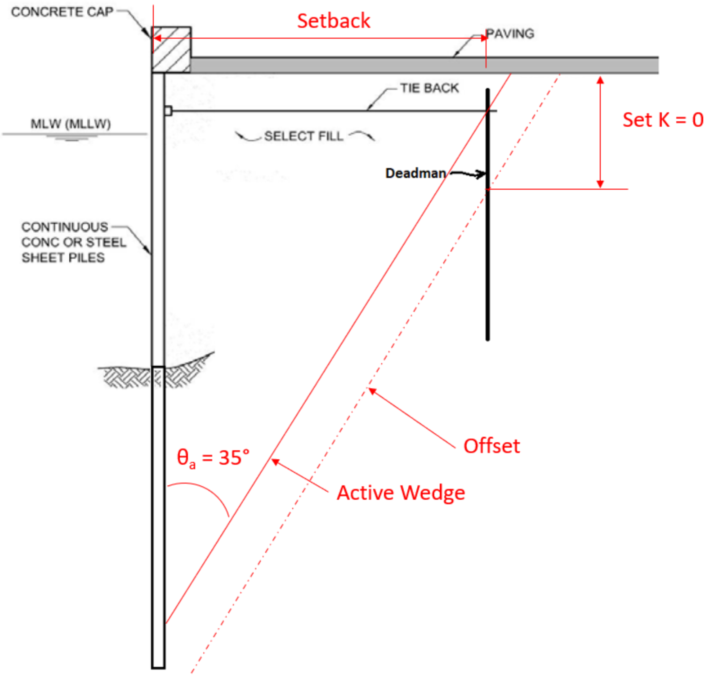


Table 1, Setback vs Depth of Neglected Resistance

Results Comparison

Table 2 shows the key input parameters and results of the two models with varying deadman setback. As cantilever deadman are typically controlled by deflection (similar to cantilever bulkheads), that criteria was the focus of the CWALSHT predictive model, and there is good agreement between the two models across the wide range of setback distances. There is also reasonable agreement between the models regarding tie rod demand. Figure 8 shows the lateral earth pressure and bending moment diagrams for both FEA and CWALSHT methods at 20 ft setback as an example. Overall shape and key results are similar, demonstrating that the simple method can be an effective estimating tool.

				Horizontal Displacement		Maximum Flexural Demand		
	Setback (ft)	Wall Stiffness (in^4/ft)	Wall Tip Elevation (ft)	Bulkhead Maximum (in)	Deadman @ Tie Rod (in)	Bulkhead (k-ft/ft)	Deadman (k-ft/ft)	Maximum Tie Rod Force (k/ft)
Plaxis	5	1400	-43	2.2	2.0	16	84	3900
CWALSHT				3.3	3.0	23	166	5000
Plaxis	10	750	-32	2.5	2.3	15	54	4700
CWALSHT				2.6	2.3	23	108	5000
Plaxis	15	400	-27	1.2	1.1	14	22	4100
CWALSHT				1.6	1.3	23	60	5000
Plaxis	20	200	-12	0.6	0.6	13	8.2	4000
CWALSHT				0.8	0.5	23	30	5000
Plaxis	50	200	-5	0.4	0.2	15	2.9	4600
CWALSHT				0.6	0.3	23	2.1	5000

Table 2, Comparison of Key Output vs Setback

Note that moment demand in CWALSHT is much higher than predicted by FEA; however, in practical applications, steel sheet piles (or combiwall) sections with the required flexural stiffness will have more than sufficient bending capacity even for the higher CWALSHT demand. Flexural capacity is not expected to control the design.

These results show that as deadman setback is reduced, the required stiffness and embedment increase dramatically. While small setback is therefore inefficient for a given bulkhead structure, it may still be preferable in the context of existing structures or other limitations on deadman location and structure type.

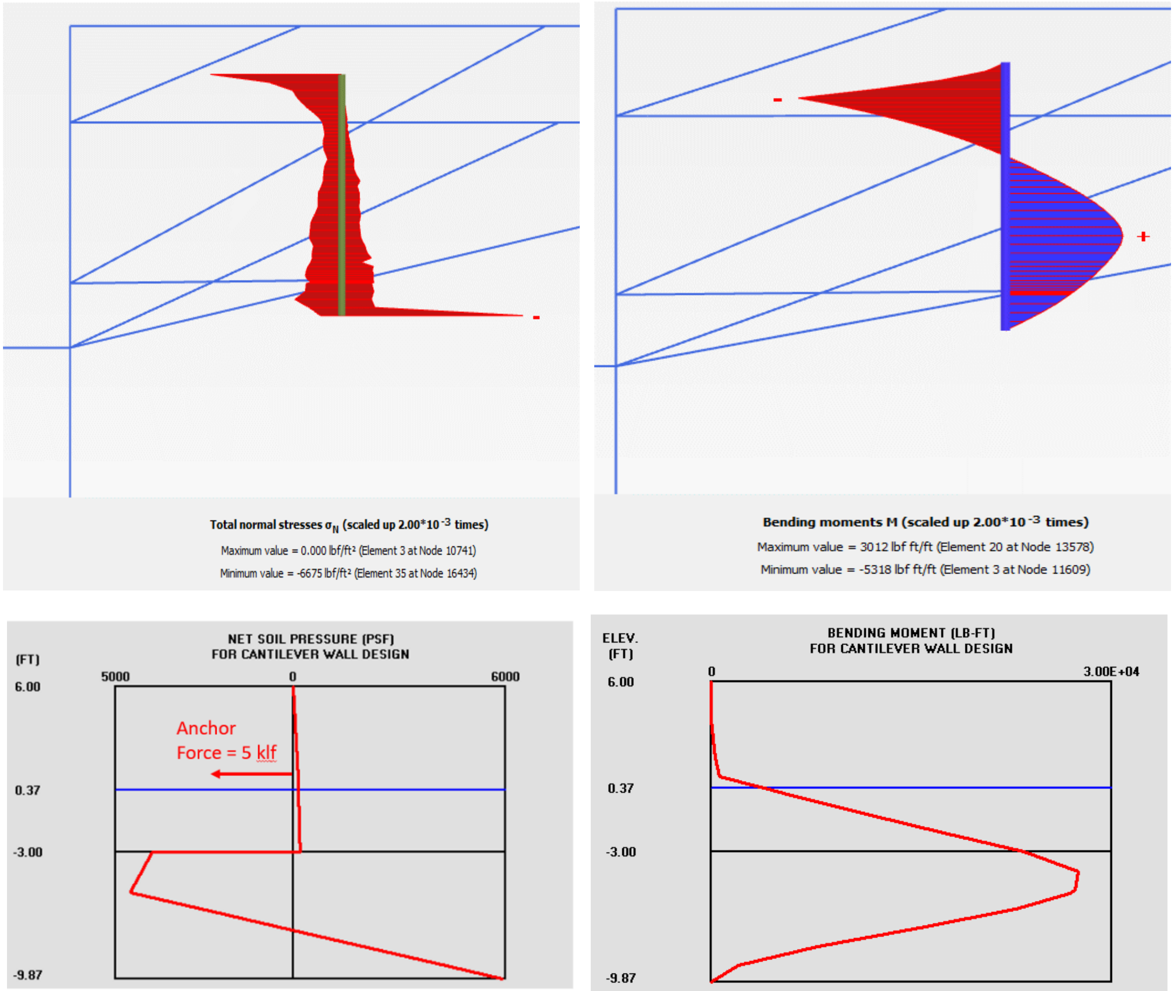


Figure 8, Comparison Figures for Plaxis (above) and CWALSHT (below) at 20ft Setback

EXTENSION TO TSP FILLED PIERS

Solid piers constructed in a Tandem Sheet Pile configuration are a specific case of the cantilever deadman discussed above, wherein lateral loads can typically be applied from either direction and both walls are necessarily the same length and stiffness to create a symmetrical structural section. Passive pressure for the deadman side is developed within the pier section, but the deadman toe kickback can only occur below the exterior mudline, which is much deeper than for most cantilever deadman designs.

A simple model has been developed considering a filled pier with moderate wall height, medium-dense sand profile, and steel sheet pile containment walls with setback that will result in significant overlap of wedges. A single row of tie rods spans across the pier width. The typical section of the design case and key parameters are shown in Figure 9 below. See Figure 10 for general deflected shape with and without lateral loading applied to the pier.

For a pier consisting of parallel, cantilever sheet pile walls, acceptable deflection criteria may be on the order of 3 inches. Again, deflection criteria are left to engineering judgement based on the required structural performance, tolerance of adjacent infrastructure, and operational restrictions.

This structural behavior is first demonstrated using finite element analysis (FEA), then CWALSHT models are developed to show the ability of the simpler model to quickly and effectively estimate and backcheck the structural members sizes required.

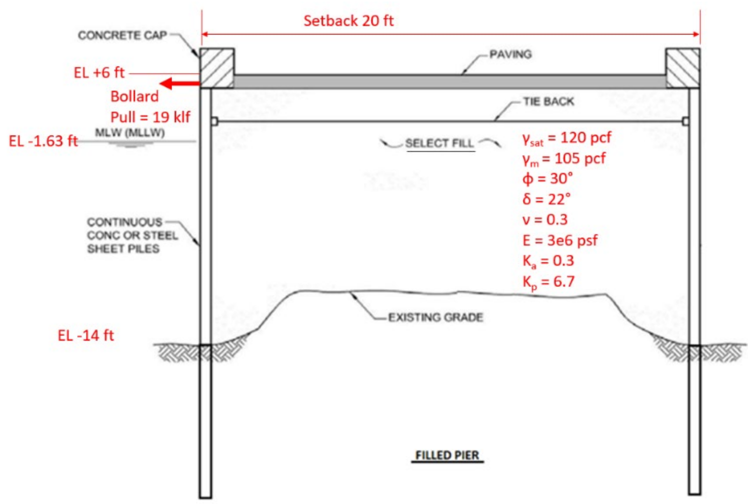


Figure 9, Filled Pier Design Section & Parameters

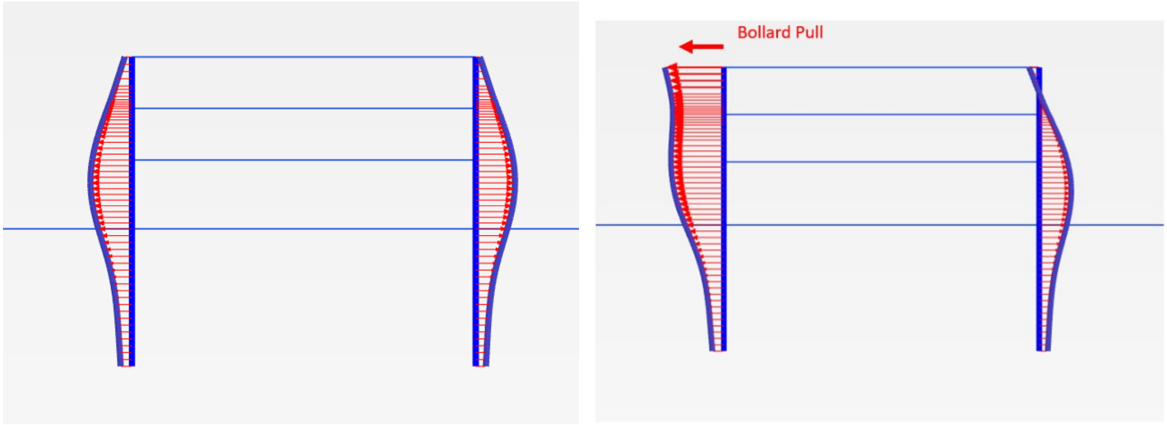


Figure 10, Deflected Shape of Filled Pier with and without Lateral Bollard Pull

Finite Element Model

Simple models for illustrating overall structural behavior have been created using Plaxis 2D. Key parameters and methodology are analogous to that described above for a cantilever deadman.

Analysis considers pier width of 20 feet. Embedment is increased until the sheet pile tip rotation is approximately zero. Flexural stiffness is varied until the design lateral load produces the allowable deflection value.

Approximation Using CWALSHT

Similar to the cantilever deadman case, K factors are set to zero from the ground surface to a point 5 feet distant from the idealized active wedge. The active wedge angle in this case is equal to 35° from vertical, and an offset of 5 feet is considered from the active wedge to the point where full deadman pressure is developed at EL -3.

Because CWALSHT is typically run with active soil pressure on the right, passive soil pressure at a lower elevation on the left, and counter-clockwise rotation, some manual manipulation of the input is required in order for the calculation to be stable and meaningful. Prior to applying lateral load, both sides of the pier are resisting equal and opposite active pressure (see Figure 11). With lateral load applied, the deadman side deflects as shown in Figure 12. To mimic the desired structural performance, left side K values should be manually set to zero from the ground surface to the point of wedge overlap, set to K_p down to the point of zero deflection, and set to K_a below that to the bottom of the wall. Right side K values are calculated internally by the program. The point where K_p values should be applied can be found by hand calculations considering sum of forces equal to zero, or it can be found by iterating the bottom elevation of the $K = K_p$ soil layer lower until the software indicates a clockwise rotation error, which shows the total left side force is exceeding the driving bollard pull.

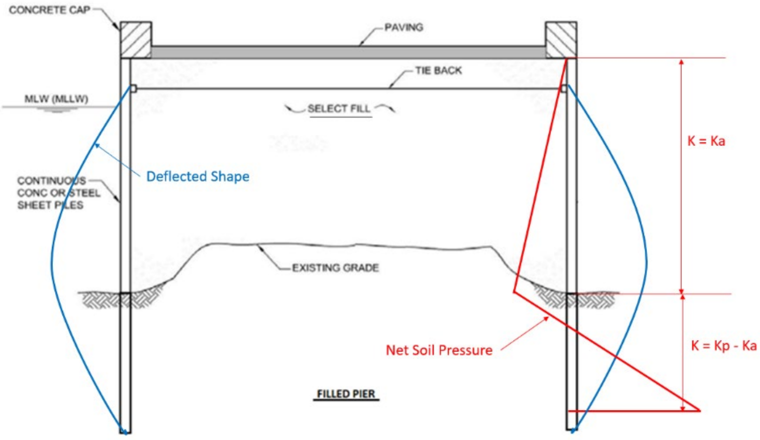


Figure 11, Deflected Shape and Soil Pressure for Dead Load

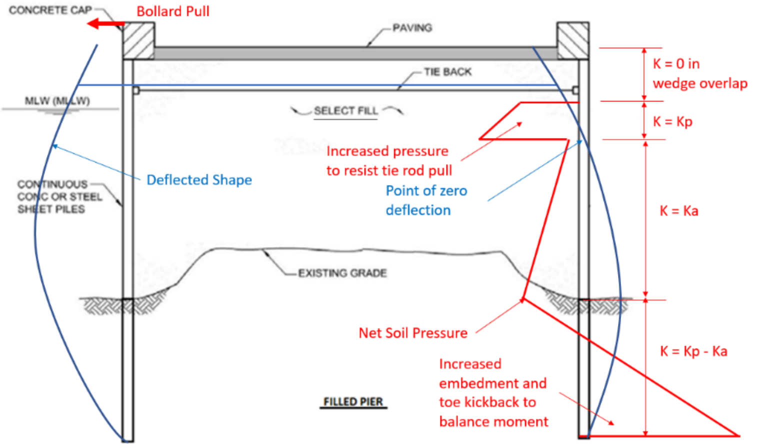


Figure 12, Deflected Shape and Net Soil Pressure Diagram with Lateral Load

Results Comparison

Table 3 shows the key input parameters and results of the two models for a 20 ft wide filled pier structure. As cantilever deadman (similar to cantilever bulkheads) are typically controlled by deflection, that criteria was the focus of the CWALSHT predictive model, and there is good agreement between the two models for the same bulkhead input parameters. There is also reasonable agreement between the models regarding tie rod tension and bulkhead bending demands. Figure 13 shows the lateral earth pressure and bending moment diagrams for both FEA and CWALSHT methods. Overall shape and key results are similar, demonstrating that the simple method can be an effective estimating tool.

	Setback (ft)	Wall Stiffness (in^4/ft)	Wall Tip Elevation (ft)	Bulkhead Deflection (in)	Shear Demand (klf)	Flexural Demand (k-ft/ft)	Maximum Tie Rod Force (k/ft)
Plaxis	20	1500	-40	3	16	117	19
CWALSHT				2.9	17	111	17

Table 3, Comparison of Key Input and Output vs Setback

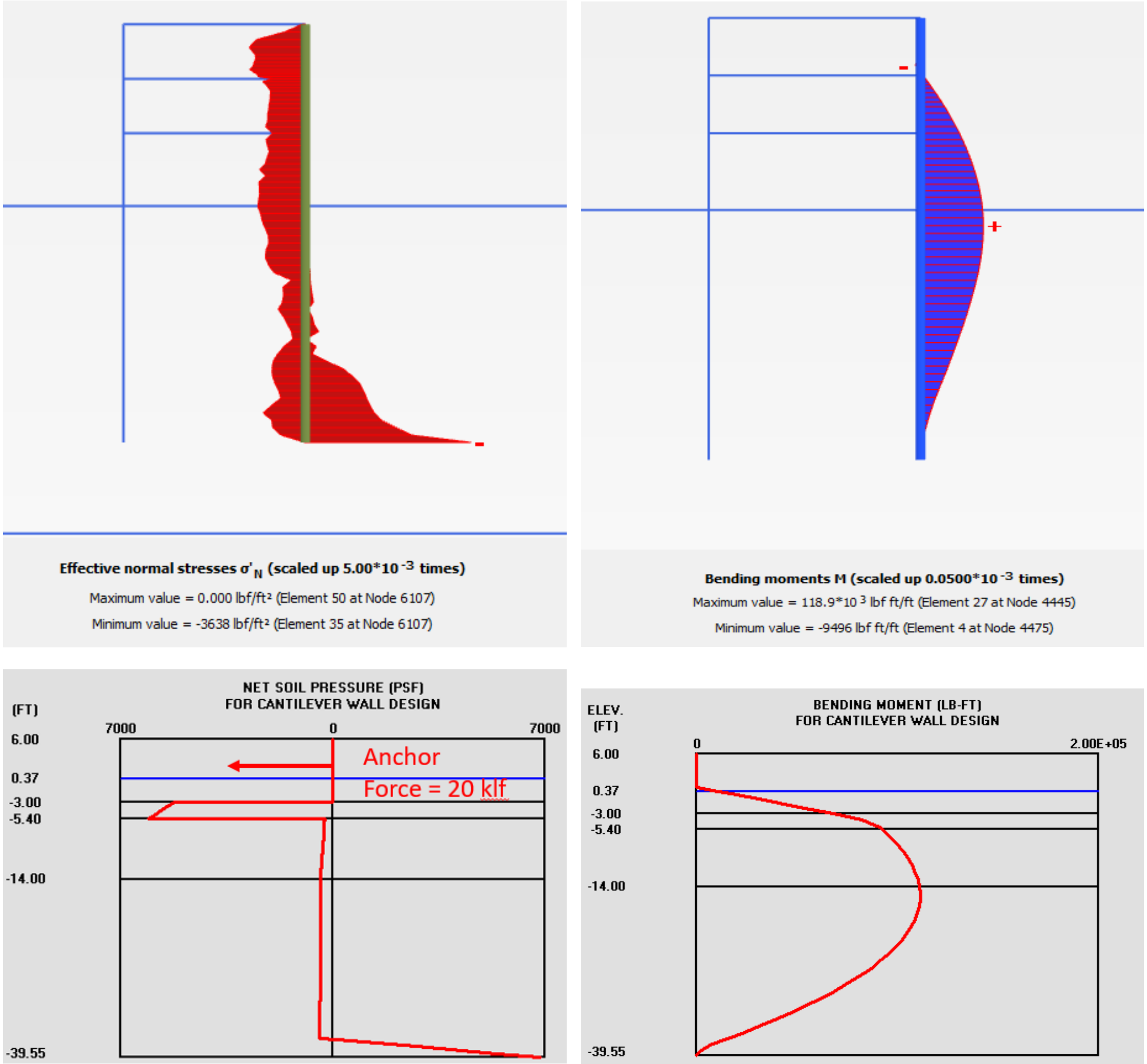


Figure 13, Comparison Figures for Plaxis (above) and CWALSHT (below) at 20ft Pier Width

SUMMARY OF DESIGN WORKFLOW

1. Analyze bulkhead with limit-equilibrium methods to determine sheet pile size, length, and tie back force
2. Determine shape of active wedge and offset line
3. Conduct deadman analysis with limit-equilibrium method (e.g. CWALSHT)
    a. Input
        i. Tie rod demand from bulkhead analysis
        ii. Design subsurface profile
        iii. Assumed setback, which determines:
            1. Zone where K = 0 due to overlap with active wedge and offset line
            2. Allowable deflection, trending from approximately ½ inch where setback is greater than bulkhead height to approximately 3 inches immediately inboard of the bulkhead
    b. Output
        i. Scaled deflection, which can be used to solve for the required moment of inertia per linear foot of sheet pile
        ii. Minimum tip elevation
4. Conduct finite element analysis, with TSP structural sections and tip elevation from the force-based method as the starting point
5. Apply factors of safety on bending and embedment in accordance with local building code

CONSTRUCTABILITY

In terms of constructability and construction sequence, there are a few key considerations. In order to reduce the total deflection when lateral or surcharge loads are applied, the designer should consider pre-tensioning the tie rod system before fully placing bulkhead fill. The majority of the deadman deflection can then occur prior to finishing site works.

Additionally, consideration must be given to the fill sequence and construction stages prior to complete filling. Because the cantilever deadman is located within or near the active wedge, which is typically filled progressively after bulkhead installation, the critical load case may occur when the deadman only has partial support and reduced overburden.

CONCLUSIONS

Tandem Sheet Pile structures are increasingly common despite their inefficient use of material, but established engineering guidance does not directly address the design of such structures. The results above show that as a deadman setback (or width of filled pier structure) is reduced, the required stiffness and embedment increase dramatically. While small setback is therefore undesirable for a given structure, it may still be preferable in the context of existing structures or other limitations on structure width.

Understanding the complex structure-soil-structure interactions is essential for ensuring the stability and performance of the wall. This type of analysis is well suited to finite element techniques using industry-standard tools such as Plaxis or FLAC. However, these advanced tools require ground-truthing with reasonably conservative, conventional methods of analysis. The methodology proposed using CWALSHT software with appropriate K factors will allow the designer to estimate the interplay between setback, embedment, and flexural rigidity required for the deadman bulkhead as either a planning tool, or as a validation of a finite element model. In the author’s experience, these simple examples can also be extended to problems with multiple soil layers, fine-grained soils, moderate seismicity (without liquefaction), and other unique geometry.

While the force-based model allows for faster iteration and simplified checking, it is not necessarily a substitute for detailed analysis using FEA prior to final design, given standard industry practice today. Rather it should be treated as a supplement to more detailed analysis. Considerable engineering judgement is required to use either type of model effectively.

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